

Marius Daniel CĂLIN

MATERIALS IN ELECTRICAL ENGINEERING







2015 ISBN 978-606-19-0717-5

FOREWORD

A necessity and support

In the last few years, many Electrical Engineering, Science of Materials and Physics Departments looked for a manual about materials and devices at the undergraduate/ graduate level that covers a broad spectrum of electrical and electronic materials, including highly conductive materials, semiconductors, dielectrics and magnetic materials. It was necessary to have applications and extensive problems, to include elementary quantum mechanics, to satisfy various accreditation requirements across international borders.

The present work answers this need, and since 2002, it has become a textbook in Transilvania University of Braşov and a number of higher schools from Braşov area. The text-book represents a first course in electrical engineering materials and devices in English language - suitable for a one- or two-semester course in materials for electrical and electronic engineering at undergraduate level.

It would also be useful as graduate introductory course in materials for electrical engineering and material scientists. The course intends to be a reference material for the teachers who approach electrical technologies and engineering issues.

The present support of course is an improved text-book, which was developed in the frame of VIRTUAL-ELECTR LAB project - a Leonardo Project, to sustain the innovative approach for improvement of the teaching-learning-evaluation methods using e-resources, in which the knowledge are gradually transferred, on three levels: beginner, intermediate and advanced, and the visualization and explanation of the phenomena through ICT tools allow a correct and deep understanding, consequently the obtaining of a high level knowledge for the trainees.

Organization and Features

The course, structured on three study-levels, has as main objective the acquisition of knowledge and the formation of skills concerning the handling of the multifunctional materials used in electrical engineering and technology. The quality and characteristics of the materials are presented in relation to the factors, which influence them, so that the user could adjust the matrix of demands imposed by the electrical or electronic systems and the matrix of the material parameters.

For a better access to the structure of the text-book, at the beginning of each subchapter, the symbol for the study-level is marked:

Beginner level Intermediate level



▲ Beginner level

On the basic level there are to be treated the following issues: the functions/the roles of different classes of materials (conductors, semi-conductors, electro-insulators, dielectrics, magnetic materials); testing methods; characteristic features; examples of specific applications.

M Intermediate level

On the intermediate level are to be treated: functions of materials and justification by means of classic microscopic theories; the testing methods by specifying the particularities of the measuring cells and measuring devices used; justifying the characteristic features; examples of applications of the materials, also considering the technological and environmental implications.

M Advanced level

On the advanced level are to be treated: the characteristic parameters and justification by means of appropriate theories; testing the materials and considering the measurement errors and the factors which influence them; simulating the behaviour of the materials under various circumstances of functioning; some applications which take into account the technical, technological and environmental implications.

The textbook has 5 chapters which provide an overview on material laws in electrotechnics (Ch. 1), conductive materials (Ch. 2), semiconductive materials (Ch. 3), dielectrics (Ch. 4), magnetic materials (Ch. 5), a section of assessment with questions and solutions for each chapter, and reach references.

The present textbook added new concepts and applications on this fascinate world of materials for electric and electronic engineering.

Acknowledgments

Our thanks to the graduate students, especially Dorian Popovici, who contributed to the designing the explicative figures, and to teachers Mariana Streza, Ana Maria Antal and Viviana Moldovan, who read various portions at the manuscript and provided valuable solutions for English translation of the text.

The Authors, Braşov, Autumn, 2015.





PARAMETERS AND LAWS OF MATERIALS IN ELECTRICAL ENGINEERING

Contents

The construction of the electrical and electronic devices supposes various materials, with different functions, whose characteristics are directly connected to their performances.

This chapter presents notions concerning the properties and the parameters of the electrical materials, various classifications as well as important material laws of the theory of electromagnetism.

Course Objectives

- •To explain the notions such as substance, material, material property and parameter, and to do the general classifications of the materials according to various criteria.
- •To define the law of material as a cause-effect connection.
- •To present the electric conductivity law for linear, isotropic and anisotropic media, and to build the scale of the electric conductivity of the materials.
- •To present the temporary electric polarization law for linear, isotropic and anisotropic media, and to build the scale of the electric susceptibility and permittivity of the dielectrics.
- •To present the magnetization law for linear, isotropic and anisotropic media, and to build the scale of the magnetic susceptibility and of the materials magnetic permeability.

1.1. DEFINITIONS AND CLASSIFICATIONS

1.1.1. Definitions. Material Parameters

A large number of substances and materials are used in electrical engineering. The notion **substance** includes the category of objects that are characterized by the homogeneity of the composition and of their constituent structure. **Examples**: water, paper, air, iron etc.

The notion **material** is much wider and includes the objects of different or resembling nature and structure that are used in a certain domain. We may consider the material as a whole made up of one or more substances.

Examples: plastics, stratified materials, composites, ferrites.

Many branches of science study the materials. Thus, among these sciences, **chemistry** and **physics** give an image/explanation of the composition (the nature of constituent particles), of the structure (the way the constituent particles are arranged) and of the physical and chemical properties of substances.

Among applied sciences, **the science of materials** studies the composition and the structure as well as the properties of materials used in certain domains (car industry, electrotechnics, wood industry etc.). **The material engineering science** studies the structure, the producing and processing of materials, their properties and performances.

Before making any classifications, we need a distinction between the notions of material property and material parameter.

A **material property** represents a common characteristic for the specific class of materials that characterize the response of the material to the action of external stresses.

Examples:

- Electrical conductivity defines the way a material behaves when an electric field is applied (the material property of conducting the electric current);
- Magnetic susceptivity characterizes the behavior of the material when a magnetic field is applied etc.

For every material property is associated a physical quantity (which can be scalar, vector, tensor) called **material parameter**, which characterizes the material state under external stress.

Examples:

 Electrical conductivity σ is a material parameter that characterizes the property of electric conduction;

- Electrical susceptivity x is a material parameter that characterizes the property of electrical polarization of dielectrics;
- Melting temperature T_{top} is a material parameter that characterizes the property of fusibility (the property of the material to melt);
- etc.

1.1.2. Classification of Materials

Materials can be classified on different criteria.

A. According to their composition, there are:

- Organic materials, which contain carbon, are obtained from the vegetal or animal kingdom (examples: paper, wood, resins, rubber, etc.);
- Inorganic materials, which don't contain carbon, are obtained from the mineral kingdom (examples: salts, acids, bases, glass, asbestos, etc.).

B. According to the character of the periodical properties of the chemical elements: metals, metalloids and non-metals. Their characteristics are presented in the Table 1.1.

Properties	Metals	Metalloids	Non-metals	
Electronegativity	0.7 – 1.8	1.8 – 2.2	2.2 - 4.0	
Electric conductivity	High	Medium	Low	
Electric resistance	Increases with the rise of temperature	Decreases with the rise of temperature	Is little influenced by the temperature	
Mechanical properties	Malleable, Ductile	Flawed	Neither malleable nor ductile	

Table 1.1. The comparative properties of metals, metalloids and non-metals.

Notes:

- Electronegativity is the property and a criterion of appreciation of the capacity to attract electrons by an atom from a molecule or from a complex structure;
- Malleability is the property of a metal to be drawn into leaves;
- Ductility is the property of a metal to be drawn into wires.

C. According to their state of aggregation and their structure, there are:

- **Gaseous materials**, which have no proper form or volume (examples: air, nitrogen, methane gas, etc.);
- Liquid materials, they have a proper form, but no proper volume (examples: oils, water in liquid state, etc.);
- **Solid materials**, which have proper form and volume and a specific structure, therefore we can be distinguished:

- **Crystalline materials**, which present regularity at long distance of the constituent atoms (examples: metals, silicon, germanium, quartz, etc.);
- **Amorphous materials,** which present only regularity at short distance of the constituent atoms (examples: resins, plastics, rubber, porcelain, etc.);
- Mezomorphous materials, which present the crystalline state only at certain temperature and concentration conditions (examples: liquid crystals, etc.).

D. According to a characteristic property, such as:

- The electrical conductivity:
 - **Electrical conductive materials,** which allow the passing of intense electric currents, of A kA order (examples: silver, copper, gold, aluminum, graphite, etc.);
 - Semiconductive materials, which allow the passing of the low electric current, of μA – mA order (examples: germanium and silicon crystals with impurities, etc.);
 - **Electroinsulating materials,** where the electric currents of conduction have very low values, of nA pA order (examples: mica, shellac, etc.);
- The mass density:
 - **Light materials,** their densities are below 5000 kg/m³ (i.e.: wood, aluminum, magnesium, etc.);
 - **Heavy materials,** their densities are over 5000 kg/m³ (i.e.: copper, iron, lead, platinum, etc.).

E. According to their applications, there are:

- Materials for electrical and electronic industry (i.e.: copper, magnetic steels, silicon, electroinsulating paper, etc.);
- Materials for civil and industrial constructions (i.e. reinforced concrete, cement, wood, etc.);
- Materials for automotive industry (i.e.: metals and alloys, ceramics, stratified materials, composites, etc.);
- Materials for food industry (i.e.: milk, meat, sugar, honey, etc.)

Classifications under various criteria are useful in systematically describing the properties and performances of the materials.

For electrical materials, according to the specific properties of the electrical and electronic domain, the following classification criteria will be used: the electrical conductivity, the electric susceptivity, as well as the magnetic susceptivity.

1.2. MATERIAL LAWS IN ELECTROTECHNICS



1.2.1. Laws and Material Parameters

The properties of different materials can be described with the laws of materials, introduced on the experimental basis.

A **law of material** describes the material behavior under the action of an external stress. In such a law, the parameter of material connects the cause to the effect (it describes the causal relationship).

A general statement of a material law always goes like this: "Whenever a material is submitted to a stress of a certain nature (examples: mechanical and electrical forces, thermal stresses, radiations etc.), which represent THE CAUSE of that particular phenomenon, there will appear within the material an EFFECT which depends on the nature and the structure of the material, through a characteristic parameter of material".

Table 1.2 gives examples of material laws as well as characteristic parameters.

Domain	Laws of material	Parameters of material
Mechanics	Law of elasticity $\frac{F}{S} = E_{Y} \cdot \frac{\Delta I}{I_{0}}$	Young module <i>E</i> _Y [N/m ²]
	Law of friction $F_f = \mu \cdot N$	Friction coefficient µ [-]
	Law of dilatation $I = I_0 (1 + \alpha_1 \Delta \theta)$	Linear dilatation coefficient α _/ [1/K]
Thermo- dynamics	Law of specific heat $Q = m \cdot c \cdot \Delta \theta$	Specific heat c [J/(kgK)]
	Law of thermal conductivity $\frac{\Delta Q}{\Delta S \Delta t} = -\lambda \frac{\Delta T}{\Delta n}$	Thermal conductivity λ [W/mK]
	Law of electrical conduction $\overline{J} = \sigma \cdot \overline{E}$ $\overline{E} = \rho \cdot \overline{J}$	Electrical conductivity σ [1/(Ω m)] Electrical resistivity $\rho = 1/\sigma$ [Ω m]
	Law of temporary electrical polarization $\overline{P} = \varepsilon_0 \cdot \chi_e \cdot \overline{E}$	Electrical susceptivity χ_e Electrical permittivity $\epsilon_r = 1 + \chi_e$ [-]
Electro- technics	Law of temporary magnetization $\overline{M} = \chi_m \cdot \overline{H}$	Magnetic susceptivity χ_m [-] Relative magnetic permeability $\mu_r = 1 + \chi_m$ [-]
	Law of electrolyze $\frac{\Delta m}{\Delta t} = \frac{1}{F} \frac{A}{n} \cdot i$	Chemical equivalent <i>A/n</i> Electrochemical equivalent <i>A/Fn</i>
	Law of imprint electric fields	Contact potential Seebeck coefficient, etc.

Table 1.2. Laws of materials in mechanics, thermo-dynamics and electrotechnics.

As follows, the main material laws in electrotechnics will be presented as well as their way of presentation for different classes of materials.

1.2.2. Electrical Conduction Law

The law of electrical conduction describes that state of the material characterized by the existence of the electrical conduction currents (the electro-kinetic state).

The law is mathematically expressed by the dependence between the density of the electric current of conduction \overline{J} and the intensity of the applied electric field \overline{E} :

$$\overline{J} = f(\overline{E}), \tag{1.1}$$

where J quantity represents the density of the electric current of conduction which passes through the material cross area, having the unit of measurement A/m^2 , and, E quantity characterizes the electric field intensity, measured in V/m.

The law given by the relation (1.1) establishes the causal relation between the two electric quantities, and it states: *"Whenever a material is submitted to an electric field of intensity* \overline{E} *, an electric current of density* \overline{J} *will be established, with a specific value depending on the nature and structure of the material".*

The law of electrical conduction is differently expressed, according to the nature and the properties of the material.

Thus, in the case of linear and isotropic materials, with no imprinted fields, the conduction law states: "In an linear and isotropic material, with no imprinted electric fields, in every point and every moment the current density of conduction \overline{J} is proportional to the intensity of the applied electric field \overline{E} ".

The mathematical expression of the law is:

$$\overline{J} = \sigma \overline{E} , \qquad (1.2)$$

where σ quantity is the parameter of material called **electrical conductivity**, measured in 1/ Ω m. The quantity $\rho = 1/\sigma$ is also a material parameter called **electrical resistivity**, measured in Ω m. The relation (1.2) becomes:

 $\overline{E} = \rho \overline{J} . \tag{1.3}$

Notes:

- An isotropic material has the same electric properties for the various directions of appliance of the electric field;
- A linear material has the linear characteristic J=f(E), that is σ, respectively ρ do not depend on the applied electric field;
- The absence of the imprinted fields: the absence of the physical chemical nonhomogeneities in the material.

These statements show that the parameters of electrical conductivity and electrical resistivity can characterize the electro-kinetic state that is the state accompanied by electric currents of conduction. The materials can be arranged on a scale of conductivity, respectively, of electrical resistivity.

	Ag A Au Cu	l Fe Mr Pt	InSb Ga	As S Ge	i C diamon	d	Paper Polyethylen Bakelite Ceramics Air Ambe				
σ [1/Ωm] 10 ⁹	10 ⁶	10 ³	10°	10 ⁻³	10	⁻⁶ 10 ⁻⁹	10 ⁻¹²	10 ⁻¹⁵		
10 ⁻⁹ 10 ⁻⁶		10-3	10 ⁻³ 10 ⁰ 10 ³ 10 ⁶		⁶ 10 ⁹ 10 ¹²		10 ¹⁵ ρ [Ωm]				
	Conduc materi	tive als	Semicor	nductive	materia	ls	Electroins	sulating r	materials		

Fig. 1.1. Scale of electrical resistivity and conductivity of materials.

Figure 1.1 indicates a very wide specter of conductivity values, respectively of material resistivity.

Table 1.3 presents the classification of materials under the value of electrical resistivity, as well as the types of electrical conduction processes, specific for each class of material.

Table 1.3. Classes	of materials	and types	of electrical	conduction	processes.
	ormaterials	und types		conduction	processes.

Classes of materials	ρ=1/σ [Ω m]	Types of electrical conduction processes
Conductive materials	(10 ⁻⁸ - 10 ⁻⁵)	Electronic conduction
Semiconductive materials	(10 ⁻⁵ - 10 ⁸)	Electronic conduction
Electroinsulating materials	(10 ⁸ - 10 ¹⁸)	Electronic conduction Ionic conduction

The difference between the classes of materials is determined by the different nature of materials:

- The conductive materials have a great number of free electric charge carriers (electrons, ions) which can be easily submitted to a diffusion process, generating intense conductive currents.
- The semiconductive materials have a relatively reduced number of electric charge carriers (electrons, ions) but it can be modified through different ways, which controls the diffusion processes.

> The electroinsulating materials have an extremely reduced number of free electric charge carriers (electrons, ions) thus the electro-kinetic state is insignificant.

The electrical conduction is determined either by the ordered moving of the electrons (the electronic conduction), or by the ions in the material (ionic conduction) or by the moving of some electrified molecule units (molionic conduction).

1.2.3. Temporary Electric Polarization Law

The law of temporary electrical polarization describes that state of materials, also called polarization state, which is characterized by the existence of the **electrical polarization** phenomenon.

The electrical polarization is the phenomenon of deforming, orienting or limited moving of the electric charge systems existing inside of the material, under the action of the electric field. The materials which have electric polarization state are called **dielectrics**.

The law is mathematically expressed by the dependence between the temporary electrical polarization $\overline{P_t}$ and the intensity of the applied electric field \overline{E} :

$$\overline{P}_t = f(\overline{E}), \qquad (1.4)$$

where P_t is the charge accumulated on the surface unit of dielectric, measured in C/m² and *E* characterizes the electric field, measured in V/m.

The temporary electric polarization law, given by the relation (1.4), shows the causal relation between those two electric quantities, and it states: "Whenever a dielectric is submitted to an electric field of intensity \overline{E} there is established a state of polarization given by the quantity of the electrical polarization $\overline{P_t}$ which depends on the nature and the structure of the material".

This dependence is differently expressed, according to the dielectric nature and structure.

In the case of linear and isotropic dielectrics, with no permanent polarization, the law states: "In linear and isotropic dielectrics, with no permanent polarization, in every point and in every moment the quantity of temporary electrical polarization $\overline{P_t}$ is directly proportional to the intensity of the applied electric field \overline{E} ".

The mathematical form of the law is:

$$\overline{P}_t = \varepsilon_0 \chi_e \overline{E} , \qquad (1.5)$$

where χ_e is the parameter of material called **electrical susceptivity**, and the universal constant $\epsilon_0 = 1/(4\pi \cdot 9 \cdot 10^9)$ F/m represents the **absolute permittivity of vacuum**.

Another parameter of material, which is used in characterizing the polarization state of dielectrics, is the **absolute permittivity**, defined by the relation:

10

$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}_0 \ \boldsymbol{\varepsilon}_r \quad , \tag{1.6}$$

where **the relative permittivity** ε_r of the dielectric is connected to the susceptivity by the relation:

$$\varepsilon_r = 1 + \chi_e \,. \tag{1.7}$$

Note:

- Temporary polarization is the state of polarization which is maintained only during the application of the electric field;
- Permanent polarization is the state of polarization which is also maintained and after the removal of the electric field.



Fig. 1.2. Scale of electrical permittivity of dielectrics.

These statements show that the parameters of electrical susceptivity χ_e and relative electric permittivity ε_r can characterize the polarization state. The dielectrics can be arranged on a scale of electrical permittivity.

Figure 1.2 indicates a relatively large spectrum of the values of relative permittivity of dielectrics.

Table 1.4 presents various classes of dielectrics as well as types of polarization processes that can take place.

Table 1.4. Classes of dielectrics and types of electrical polarization processes.

Classes of materials	ε ,=1+ χe	Types of electrical polarization processes
Non nolar linear dialactrica	1 0	Electronic polarization
Non-polar linear dielectrics	1-3	lonic polarization
		Electronic polarization
Polar linear dielectrics	3 - tens	Ionic polarization
		Orientation polarization
Non-linear dielectrics (ferroelectrics)	Tens, hundreds, thousands	Spontaneous polarization

The difference between the different classes of dielectric materials is determined by the different nature of dielectrics:

- > Non-polar dielectrics are formed from non-polar structural units;
- > Polar dielectrics are characterized by the existence of polar structural units;
- Ferroelectrics represent a specific class of dielectrics, sensitive at the action of the external electric field, where intense states of electrical polarization can be induced.

The processes of electrical polarization are determined by movements or orientations of the clouds of electrons (electronic polarization), of ions units (ionic polarization), and in the case of ferroelectrics, by powerful interactions of the electrically bonded charge systems.

1.2.4. Temporary Magnetization Law

The law of temporary magnetization describes the **state of magnetization** of materials (the property to attract the iron filings), characterized by the existence of specific systems of microscopic electric currents. The law is mathematically expressed by the dependence between temporary magnetization $\overline{M_t}$ and the intensity of the applied magnetic field \overline{H} :

 $\overline{M}_t = f(\overline{H}), \tag{1.8}$

where M_t and H are measured in A/m.

The law given by the relation (1.8) shows the causal relation between the two quantities, and it states: "Whenever a material is submitted to a magnetic field of intensity \overline{H} in the material a state of magnetization is established characterized by the quantity of the magnetization $\overline{M_t}$, which depends on the nature, and structure of the material".

The law of the temporary magnetization is differently expressed, according to the nature and structure of the material.

In the case of linear and isotropic materials, with no permanent magnetization the law states: "In isotropic and linear materials, with no permanent magnetization, in every point and every moment the quantity of temporary magnetization $\overline{M_t}$ is proportional to the intensity of the applied magnetic field \overline{H} "

The mathematic form of the law is:

$$\overline{M}_t = \chi_m \overline{H} \tag{1.9}$$

where $\chi_{\rm m}$ is the parameter of material called magnetic susceptivity of the material.

Another parameter of material, which is used to characterize the magnetization state, is the **absolute magnetic permeability**, defined by the relation:

 $\mu = \mu_0 \,\mu_r \tag{1.10}$

where the universal constant $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is called **absolute magnetic permeability of the vacuum** and the **relative magnetic permeability** μ_r is connected to the magnetic susceptivity by the relation:

$$\mu_r = 1 + \chi_m \tag{1.11}$$

Note:

- Temporary magnetization is the magnetization state which is maintained only on the period of appliance of the magnetic field;
- Permanent magnetization is the magnetization state which is maintained after ceasing the action of the magnetic field.

All these statements show that the parameters of magnetic susceptivity χ_m and the relative magnetic permeability μ_r can characterize the magnetization state of bodies under the action of the external applied magnetic field.



Fig. 1.3. Scale of magnetic permeability of materials.

Figure 1.3 indicates a wide spectrum of values of magnetic permeability of technical materials.

Table 1.5 presents a classification of materials according to the magnetic behavior as well as the types of magnetization processes that can take place.

Table 1.5. Classes of materials ant types of magnetization processes.

Classes of materials	μ ,=1+ χ _m	Types of magnetization processes
Linear materials with diamagnetic behavior	1 – (10 ⁻⁶ – 10 ⁻³)	Diamagnetism
Linear materials with paramagnetic behavior	1 + (10 ⁻⁶ – 10 ⁻³)	Paramagnetism
Non-linear magnetic materials	Tens, hundreds, thousands	Ferromagnetism Ferrimagnetism

The difference between the classes of materials according to their magnetization state is determined by their different nature.

- > Linear diamagnetic materials are formed by magnetic non-polar structural units;
- > Linear paramagnetic materials are formed by magnetic polar structural units;
- Non-linear magnetic materials, like ferromagnetic and ferrimagnetic materials, represent a specific class of materials sensitive at the action of the external magnetic field, where intense magnetization states can be induced.

The magnetization processes will be fully treated in the chapter of magnetic materials.

1.3. MATERIAL LAWS IN ANY MEDIUM

1.3.1. Electric Conduction Law in Any Medium

This law has different expressions according to the nature and the structure of the material:

In the case of linear and anisotropic materials, with no electric imprinted fields, the law of electrical conduction shows that: "In an anisotropic material the density of the conduction electric current is not homoparallel with the intensity of the applied electric field".

The mathematic expression of the law is:

$$\overline{J} = \overline{\sigma} \overline{E}$$
(1.12)

where the electrical conductivity tensor $\overline{\sigma}$ has in general 9 components:

$$\overset{=}{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$
(1.13)

The tensor $\bar{\rho}$ of the electrical resistivity is defined in the same way as in the relation (1.13).

In the case of linear materials, with physical chemical non-homogeneities or submitted to acceleration, the electric conduction law states: "The density of the electric current of conduction is proportional to the sum between the intensities of the electric field in a restrained direction \overline{E} and the imprinted electric field \overline{E}_i ".

The mathematic expression of the law is:

$$\overline{J} = \sigma(\overline{E} + \overline{E}_i), \qquad (1.14)$$

where σ is a scalar quantity for isotropic materials and a tensor for anisotropic materials. The imprinted electric field appears in non-homogeneous materials

according to their physical-chemical structure (temperature, concentration, etc.) or in conductors submitted to acceleration.

In the case of non-linear materials the dependence (1.1) cannot be put under one of the forms (1.2) – (1.3), or (1.12) - (1.14); the non-linearity is also kept between the intensity of the electric current and the applied voltage. However, even for those materials, between certain values of the intensity of the electric field \overline{E} , the dependence $\overline{J}=\overline{J}(\overline{E})$ can be approximated as being linear, like (1.2) or (1.3).

1.3.2. Temporary Electric Polarization Law in Any Medium

This law has different expressions according to the nature and the structure of the material:

In the case of linear and anisotropic dielectrics, with no permanent polarization, the temporary electrical polarization law shows that: "In an anisotropic material, the temporary electrical polarization is not homoparallel to the intensity of the applied electric field".

The mathematic relation of the law is:

$$\overline{P}_t = \varepsilon_0 \overline{\chi}_e \overline{E} , \qquad (1.15)$$

where $\overline{\chi}_{e}$ is the tensor for the electrical susceptivity:

$$\begin{split} &= \begin{bmatrix} \chi_{exx} & \chi_{exy} & \chi_{exz} \\ \chi_{eyx} & \chi_{eyy} & \chi_{eyz} \\ \chi_{ezx} & \chi_{ezy} & \chi_{ezz} \end{bmatrix}. \end{split}$$
(1.16)

The connection law between the quantities $\overline{D}, \overline{E}$ and \overline{P} is expressed with the relation:

$$\overline{D} = \varepsilon_0 (\overline{1} + \chi_e) \overline{E} = \varepsilon_0 \overline{\varepsilon}_r \overline{E} = \overline{\overline{\varepsilon}} \overline{E}.$$
(1.17)

where the relative permittivity tensor is given by the sum between the unitary tensor and the electrical susceptivity tensor:

$$\bar{\varepsilon}_r = \bar{1} + \chi_e. \tag{1.18}$$

In the case on non-linear dielectrics, as the case of ferroelectrics, the dependence (1.4) cannot be put under the form (1.5) or (1.15), therefore a definition of the electrical susceptibility cannot be done.

However, between certain values of the applied electric field the dependence can be approximated as being linear.

1.3.3. Temporary Magnetization Law in Any Medium

This law has different expressions according to the nature and the structure of the material.

In the case of linear and anisotropic materials, with no permanent magnetization the law of temporary magnetization shows that: "In an anisotropic, linear material with no permanent magnetization, the temporary magnetization is not homoparallel to the intensity of the applied magnetic field".

The mathematic expression of the law is:

$$\overline{M}_t = \overline{\chi}_m \overline{H} , \qquad (1.19)$$

where $\bar{\chi}_m$ is the tensor of the magnetic susceptivity:

$$\begin{split} &= \left[\begin{array}{ccc} \chi_{mxx} & \chi_{mxy} & \chi_{mxz} \\ \chi_{myx} & \chi_{myy} & \chi_{myz} \\ \chi_{mzx} & \chi_{mzy} & \chi_{mzz} \end{array} \right] \tag{1.20} \end{split}$$

The law of the connection between magnetic induction \overline{B} , magnetic field intensity \overline{H} and magnetization \overline{M} , for the case when permanent magnetization $\overline{M}_p=0$, is expressed with the relation:

$$\overline{B} = \mu_0 \left(\overline{H} + \overline{M}_t + \overline{M}_p \right) = \mu_0 \left(\overline{H} + \overline{M}_t \right) = \mu_0 \left(\overline{1} + \overline{\chi}_m \right) \overline{H} = \mu_0 \overline{\mu}_r \overline{H} = \overline{\mu} \overline{H} , \qquad (1.21)$$

where the tensor of the relative magnetic permeability is:

$$\overline{\mu}_r = \overline{1} + \overline{\chi}_m .$$
 (1.22)

In the case of non-linear materials, it cannot be define a scalar or tensor quantity of magnetic susceptivity, the dependence $\overline{M}_t = f(\overline{H})$ being usually given as a graphic. However, between certain values of the applied magnetic field, the dependence can be approximated as linear.



CONDUCTIVE MATERIALS

Contents

Due to their high electric conductivity the conductive materials have multiple applications in electrical engineering. Their best use supposes a good knowledge of the conduction processes, of the factors that influence these processes and their performances.

This chapter presents the phenomenon of the electrical conduction, determines the expression of the electric conductivity, shows the factors that influence the value of the electric conductivity and gives, synthetically, the properties and the main fields of utilization of the conductive materials.

Course Objectives

- •To explain the electric conduction phenomena using the classical theory of the electric conduction in metals.
- •To show the experimental method of measuring the electric conductivity and resistivity, respectively, of conductive materials.
- •To establish the expression of the electric conductivity in metals and to describe the Mathiessen law.
- •To explain the influence of the temperature, plastic deformations, pressure and frequency of the electric field on the metals conductivity.
- •To describe the properties and performances of the high conductive materials, the high resistive materials, the materials for resistors, electric contacts, fuses, thermocouples, strength gauges.
- •To explain the superconduction state and to describe some applications.

2.1. ELECTRIC CONDUCTION IN METALS

2.1.1. General Presentation of the Electric Conduction

The electrical conduction is the phenomenon of passing of the electric current through a material when it is submitted to the action of an electric field.

The electric current of conduction is defined by the **ordered movement** of free electrical charges (electrons or/and ions) under the action of the electric field.

The metals and their alloys fall under the class of the conductive materials, having the conductivity of the order $10^6 - 10^8 1/(\Omega m)$.

The metals are simple substances, solid at normal temperature (excepting the mercury which is liquid at this temperature), crystallized in compact lattice and which differ from the rest of the substances by a series of properties such as: metallic luster, the property of light absorption, the insolubility in common dissolvent but dissoluble in metals with which they form alloys. Metals present special mechanical, thermal, electrical, and magnetic properties.

The metals are made up of atoms, which have a reduced number of electrons on the last electronic layer (maximum 4 electrons, excepting bismuth Bi, that has 5 electrons on the last electronic layer).

The atoms of metals have the tendency of giving up electrons and transforming into positive ions (cations): $M^0 - n e^- \rightarrow M^{n+}$,

where M^0 is the atom of a metal and M^{n+} is its ion.

The metallic character is founded in:

- Alkaline metals, which are placed in the 1st group of the periodic table,

- **Earth metals**, placed in the 2nd group of the periodic table of elements,

- **Transitional metals**, placed from the 3rd group to the 13^{en} group.

In Table 2.1 there are presented the metallic chemical elements from the periodic system.

Н		Metals															
Li	Ве																
Na	Mg											AI					
Κ	Са	Sc	Ti	V	Cr	Mn	Fe	Со	Ni	Cu	Zn	Ga					
Rb	Sr	Υ	Zr	Nb	Мо	Тс	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb			
Cs	Ва	La	Hf	Та	W	Re	Os	lr	Pt	Au	Hg	ТІ	Pb	Bi	Ро		
Fr	Ra	Ac	Rt	На	Ns	Sg	Hs	Mt									
La-L	-Lanthanide Ce Pr Nd Pm Sm Eu Gd Tb Dy							Но	Er	Tm	Yb	Lu					
Ac	-Actini	de	Th	Ра	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

Table 2.1. Metals in the periodic system of chemical elements.

 Λ

The properties of metals are determined by a special type of bond that establishes between the atoms of the crystal lattice - the metallic bond.

The high **electric conductivity of metals** has been explained since 1900 by P. Drude who formulates a classical microscopic theory of electric conduction, and it was completed later by H. A. Lorentz (1916).

This theory considers that the crystal lattice of metals is made up of the metallic cations through which the electrons move freely. In the metallic lattice, thus, the metallic ions are "sank" in a fluid of free electrons, named **electron gas**. The interaction between the metallic cations and the electron gas represents exactly the **metallic bond**.

The theory, known under the name of "**the theory of the electron gas**" explains some specific properties of metals such as: the metallic luster, the opacity, the thermal conductivity, the electric conductivity, the density, the malleability, the ductility, the chemical reactivity, etc.

The presence of the free (extremely mobile) electrons, which move disorderly in all directions, under the action of the thermal agitation, doesn't permit the establishment of a permanent electric current inside the metal.

Applying an electric field, over each quasi-free electron, an electric force operates, and over the movement of the thermal agitation, an oriented motion of the electrons is developed, which represents in fact the electric current.

The electric current through **metals** doesn't transport substance, being an electronic current (the mass of the electron is very small), unlike **the electrolytes**, where the electric current transports substance (the ions have an important mass compared to that of the electron).

The electric conductivity of the electrolytes increases concurrently with the growth of the temperature (the dissociation and the mobility of ions increase).

The variation of the metal conduction with temperature has at its base from the variation of the frictional forces that operate on the free electrons. The frictional forces are the result of the oscillations of the ions from the edge points of the crystalline lattice and of the interaction of electrons with these particles.

A specific characteristic of the metals is that the electric and thermal conductivities increase simultaneous with the temperature decreasing. At low temperatures, the oscillations are more reduced so, the frictional forces are also reduced, that is why the electric conductivity becomes higher.

At 0 K some metals don't show resistance against the passing electric current anymore, they become **superconductors**.

2.1.2. Experimental Determination of the Resistivity

The resistivity ρ is that physical parameter which expresses the property of a conductor to oppose to the passing of the electric current.

The usual method of determining the resistivity is the volt-ampere method with four electrodes, which consists in the measurement of the voltage drop U on the test sample at the application of a direct current *I*, close to the nominal value of the electric current intensity (Fig. 2.1).



Fig. 2.1. Measurement scheme of metallic materials resistivity using volt-ampere method with four electrodes.

In Fig. 2.1, S is a DC source, R is a variable resistor, and BF is measurement device with metallic sample. The arrangement of the four electrodes on the BF measurement device is shows in Fig 2.2.



Fig. 2.2. Sample with four electrodes: A, B - current electrodes; C, D - voltage electrodes; l_u – distance between voltage electrodes.

The distance between voltage electrodes l_u is maintained constantly during the measurements.

Notes:

- The nominal intensity of the electric current I_n represents the value of the current in stationary regime that can pass through the sample without causing an important heating of the material.
- The **admissible density of the electric current** J_a represents the ratio between the maximum value of electric current intensity I_{max} that can pass through the sample without heating it excessively and the size of the cross-section area *S* of the sample $(J_a=I_{max}/S)$.

21

The value of the electric resistance of the sample is obtained with the measured values of voltage U and current intensity I, with Ohm law:

$$R = \frac{U}{I} \tag{2.1a}$$

Knowing the dependence of the resistance R with geometry of sample

$$R = \rho \cdot \frac{I_u}{S}, \qquad (2.1b)$$

it is obtained the resistivity of the material:

$$\rho = \frac{S}{I_{u}} \cdot R \quad , \tag{2.2}$$

where l_u is distance between voltage electrodes - that portion from the length of the sample on which the measurement of the drop-voltage U is made, and $S = p \cdot w \text{ [m}^2\text{]}$ is the cross section of sample (Fig. 2.2).

Note:

• In the case of conductive materials, the resistivity is of the order of $10^{-6} - 10^{-8} \Omega m$.

2.1.3. Establishing the Electric Conductivity Expression

In order to analyze the mechanism of the electrical conduction in a metallic crystal, we consider an electric circuit made up of a source of DC voltage U_{e} , a metallic conductor of length *L* and a constant section *S*, a switch k (Fig. 2.3a). It will be observe the state of the gas of conduction electrons in the considered conductor, when the switch k is open (in the absence of the electric field) and when the switch k is closed (in the presence of the electric field).

In the absence of the external electric field (Fig. 2.3b) and at normal temperatures, the electrons move chaotically, with a **root-mean-square velocity** given by the same relation for the root-mean-square velocity of thermal agitation of the molecules of the ideal gas:

$$v_{\tau} = \sqrt{\frac{3kT}{m_0}}, \qquad (2.3)$$

where k is Boltzmann constant, m_0 is the electron mass and T is the absolute temperature of the metal.



Fig. 2.3. The electric current in a conductor: a) the schema of the electric circuit; b) the movement of the electron in the conductive crystal in the absence of the electric field; c) the movement of the electron in the conductive crystal in the electric field presence.

Example: An easy calculus shows that for T = 300 K a root-mean-square velocity $v_T \approx 1,17 \cdot 10^5 \text{ m/s}$ will result. The conduction electrons have a very high movement velocity, which increases with the temperature.

Note:

In the absence of the electric field, although the value of the electron movement velocity is very high, the electrons of conduction do not contribute to the producing of the electric current, because their movement is not ordered (the movement in one direction in a crystal is followed by a collision with the atoms of the metallic crystal and a change of direction, therefore in the next period of time the electron will move in the other direction, with the same average thermal velocity, given by the relation (2.3). The projection of the velocity vector of thermal agitation in a given direction Ox will be cancelled.

When an electric field of intensity \overline{E} is applied, the free electrons are moved on the opposite direction of the electric field, thus an ordered movement of electrons appears, called **drift movement** (Fig. 2.3c).

The steps for establishing the electric conductivity, respectively the electric resistivity are presented in following a) – e) section.

a) Establishing the velocity of the conduction electron

Under the action of temperature and electric field, the total velocity of the electron is equal to the sum between the thermal agitation velocity \overline{v}_{τ} and the velocity due to the electric field \overline{v}_e :

$$\overline{V} = \overline{V}_T + \overline{V}_e \,. \tag{2.4}$$

2. Conductive Materials

If the direction of application of the electric field is on the axis Ox, the component on the axis Ox of average velocity of free electron will be equal only with the component of the velocity due to the electric field on the axis Ox, because the component on the axis Ox of thermal agitation velocity $\overline{v_{\tau}}$ will be canceled. It will result:

$$\langle \overline{v} \rangle_{Ox} = \langle \overline{v_T} \rangle_{Ox} + \langle \overline{v_e} \rangle_{Ox} = \langle \overline{v_e} \rangle_{Ox} = v_d.$$
(2.5)

The drift velocity v_d is the average velocity of the electron movement in the direction of the axis Ox of the applied electric field and characterizes the processes of electric conduction.

b) The density of the electric current

In order to establish the electrical conductivity it is necessary to know the quantities that interfere in the law of electrical conduction, which for metallic materials is expressed as $\overline{J}=\sigma\overline{E}$.

An expression of **the density of the electric current** J, in the case of a conductor of a length L and constant cross section S (Fig. 2.3a) can be established starting from the definition of this quantity:

$$J = \frac{I}{S} = \frac{\frac{\Delta q}{\Delta t}}{S} = \frac{N \cdot q_0}{\Delta t} \cdot \frac{1}{S} = \frac{N \cdot q_0}{\Delta t} \cdot \frac{1}{S} \cdot \frac{\Delta L}{\Delta L}, \qquad (2.6)$$

where *I* is the intensity of electric current, $\Delta q = N \cdot q_0$ is the quantity of the electric charge q_0 which is transported by the *N* electrons of conduction, which cross the transversal section *S* in the period of time Δt .

Considering that the volume of the conductor is $V = S \cdot \Delta L$ and that the drift velocity can be defined as the average velocity of the conduction electrons that cross through the length ΔL in the period of time Δt , it will result:

$$J = \frac{N}{V} \cdot q_0 \cdot v_d. \tag{2.7}$$

The volume concentration of the conduction electrons is $n_0=N/V$, thus, the expression of the density of the electric conduction current will become:

$$J = n_0 \cdot q_0 \cdot v_d \,. \tag{2.8}$$

The density of the electric conduction current *J* depends on the electrical charge q_0 of the electron, on their volume concentration n_0 and on their drift velocity v_d .

The relation (2.8), written in a vectorial form, is the following:

$$\overline{J} = -n_0 \cdot q_0 \cdot \overline{V}_d \,. \tag{2.9}$$

The vector of current density has the opposite direction to the one of the drift velocity.

c) Establishing the drift velocity

The expression of the drift velocity is established with the Drude-Lorentz model, which considers that the electrons of conduction behave like billiards balls.

In order to exemplify, Fig. 2.4a shows a part of the metallic crystalline lattice, delimited by two atoms placed at the "a" distance, and a conduction electron is placed between them.



Fig. 2.4. The Drude-Lorentz model of electric conduction in metals: a) the electric force and the velocity vector of the electron of conduction inside the crystalline lattice of metal; b) the time-variation of velocity of the conduction electron.

According to the Drude-Lorentz model, when an electric field is applied, an electric force acts upon the electron. The force is given by the relation:

$$\overline{F}_e = -q_0 \overline{E} , \qquad (2.10)$$

where q_0 is the charge of electron and \overline{E} is the intensity of the electric field.

Under the action of this force, the electron will move opposite the electric field, having a **uniformly accelerated movement** (Fig. 2.4a).

From the equation of the dynamic equilibrium, given by the second law of dynamics:

$$m_0 \overline{a} = -q_0 \overline{E} , \qquad (2.11)$$

the expression of the acceleration of the conduction electron will result:

$$\overline{a} = -\frac{q_0}{m_0} \cdot \overline{E} \,. \tag{2.12}$$

The acceleration of the electron depends on the intensity of the applied electric field and on the parameters of the electron: its mass m_0 and charge q_0 .

The laws of the accelerated uniform movement give the velocity v and the distance *s* crossed by the conduction electron in function of time variation:

$$v=at; s=at^2/2.$$
 (2.13)

The velocity of the electrons increases linearly in time, the electron accumulating kinetic energy. After a certain period of time, the electron collides with the atoms of the crystal lattice and the velocity of the electron decreases to zero (Fig. 2.4b).

The model of the billiard balls considers that at the collision (with other electrons, with lattice imperfections, with the ions in the crystalline lattice), the accumulated energy is fully transferred to the crystalline lattice, which warms (the Joule effect appears). After the collision, the velocity decreases to zero. And again, under the action of the electric force, the electron will be accelerated, the velocity increasing to the maximum value. The velocity profile has a saw-tooth profile (Fig. 2.4b).

The maximum velocity reached by the electron depends on the **average period between two collisions** t_c and according to the relation (2.13) it is:

$$v_{\max} = at_c. \tag{2.14}$$

The drift velocity, which corresponds to the average velocity of movement of the electron results as follows:

$$v_d = v_{av} = \frac{0 + v_{max}}{2} = \frac{at_c}{2}$$
 (2.15)

which, as vector form is:

$$\overline{v}_d = -\frac{q_0 t_c}{2 m_0} \cdot \overline{E} \,. \tag{2.16}$$

Notes:

- The drift velocity depends on the intensity of the electric field and on the average period between two collisions.
- For metals, the drift velocity vector has the opposite direction to the applied electric field.

d) Establishing the mobility of the conduction electron

In order to characterize the easiness how an electron moves under the action of the electric field, **the mobility of the conduction electrons** is defined as:

$$\mu_0 = \frac{\left| \overline{V}_d \right|}{\left| \overline{E} \right|} \,. \tag{2.17}$$

The expression of electron's conduction mobility results from (2.16) and (2.17):

$$\mu_0 = \frac{q_0 t_c}{2m_0}, \qquad (2.18)$$

expression that emphasizes the direct connection between the mobility of the electron μ_0 and the average time between two collisions t_c .

e) Establishing the electrical conductivity

By replacing in the relation (2.9) the expression of the drift velocity, given by the relation (2.16), it will result:

$$\overline{J} = \frac{q_0^2 n_0 t_c}{2m_0} \overline{E}$$
(2.19)

and by comparing it with the law of electrical conduction for the case of homogeneous, linear, isotropic materials (1.2), the expression of electrical conductivity is obtained as:

$$\sigma = \frac{J}{E} = \frac{q_0^2 n_0 t_c}{2m_0}.$$
 (2.20)

Taking into consideration the mobility of the electron μ_0 , given by the relation (2.18), it can also be expressed as:

$$\sigma = q_0 n_0 \mu_0 . \tag{2.21}$$

In the Table 2.2 some data regarding the concentration n_0 of the electrons of conduction are given, the average period between two collisions t_c , the electrical conductivity σ and resistivity ρ for several metals, calculated with the relation (2.20).

Table 2.2. Electrical conductivity data for several metals, calculated with relation (2.20).

Metal	<i>n</i> ₀ [m⁻³]	<i>t</i> _c [s]	σ [1/Ωm]	ρ [Ωm]
Li	$4.6 \cdot 10^{28}$	0.9 · 10 ⁻¹⁴	0.12 · 10 ⁸	8.33 · 10 ⁻⁸
Na	2.5 · 10 ²⁸	3.1 · 10 ⁻¹⁴	0.23 · 10 ⁸	4.34 · 10 ⁻⁸
К	1.3 · 10 ²⁸	$4.4 \cdot 10^{-14}$	0.19 · 10 ⁸	5.26 · 10 ⁻⁸
Cu	8.5 · 10 ²⁸	2.7 · 10 ⁻¹⁴	0.64 · 10 ⁸	1.56 · 10 ⁻⁸
Ag	5.8 · 10 ²⁸	4.1 · 10 ⁻¹⁴	0.68 · 10 ⁸	1.47 · 10 ⁻⁸

The electrical conductivity depends on the volume concentration of the electrons of conduction n_0 and on their mobility μ_0 .

Knowing the electrical charge of the electron $q_0 = 1.602 \cdot 10^{-19}$ C, its mass $m_0 = 9.107 \cdot 10^{-31}$ kg, the volume concentration n_0 and the average period between the collisions t_c or the electrons' mobility μ_0 , using the relations (2.20) or (2.21) it can be established the electrical conductivity of any metallic crystal.

Examples:

Table 2.2 indicates the values of the electric conductivity σ and of the resistance $\rho = 1/\sigma$, calculated for several metals.

With the relation (2.8), it can be evaluated the drift velocity in metals; knowing that in metals the free electron concentration is about $n_0 = 10^{28} \div 10^{29}$ electrons/m³ and the

maximum admitted value of the density of electric current for metals is $J = 10^7 \text{ A/m}^2$, it will result the drift velocity of electrons:

$$v_d = \frac{J}{n_0 q_0} = \frac{10^7}{10^{28} \cdot 1.6 \cdot 10^{-19}} \approx 6 \cdot 10^{-3} \text{ m/s.}$$

Note:

The drift velocity of electrons is very low in comparison to the average velocity of thermal agitation (< v_T > $\approx 10^5$ m/s).

Example:

With the relation (2.18) it can evaluate the mobility of the conduction electron in metals, knowing that the average period between two collisions is about 10^{-14} seconds:

$$\mu_0 = \frac{q_0 t_c}{m_0} \approx \frac{1.602 \cdot 10^{-19} \cdot 4 \cdot 10^{-14}}{9.107 \cdot 10^{-31}} \approx 3.1 \cdot 10^{-3} \text{ m}^2/(\text{Vs}).$$

Note:

The mobility of the electron in metals has a relatively reduced value.

2.1.4. The Mathiessen Law

According to the relations (2.20) and (2.21), the value of the electrical conductivity is influenced by the volume concentration of the electrons of conduction n_0 , by the average time between collisions t_c and by mobility μ_0 .

The dependence of the charge carriers' mobility on the average time between collisions shows that **the collision processes** are responsible for the **resistance** that the conductor manifests when the electrons move orderly.

The collisions determine the slowing of the conduction electron movement. Figure 2.5 shows the types of possible collisions: with the atoms of the crystalline lattice, which presents thermal oscillations under the action of the temperature (Fig. 2.5a), with ionized impurities (Fig. 2.5b) or neutral (Fig. 2.5c), with defects of the crystalline lattice.



Fig. 2.5. Collisions of the conduction electrons: a) with crystalline lattice; b) with ionized impurities; c) with neutral impurities.

The experience shows that in the case of metal with impurities, defects and at other temperatures than zero absolute, the reverse of the average time between the collisions includes three components:

$$\frac{1}{t_{\text{tot}}} = \frac{1}{t_{imp}} + \frac{1}{t_{def}} + \frac{1}{t_{\tau}}, \qquad (2.22)$$

where: t_{tot} represents the total average time between two collisions, and:

- t_{imp} is the average time between two collisions resulted from the collisions with the impurities atoms,
- > t_{def} is the average time between collisions resulted from the collision with the lattice defects (vacancies, dislocations, grain limits, etc.),
- > $t_{\rm T}$ is the average time between two collisions resulted from the thermal oscillations of the crystalline lattice.

Thus, the expression of the resistivity of the metal becomes:

$$\rho = \frac{1}{\sigma} = \frac{m_0}{q_0^2 n_0} \cdot \frac{1}{t_{tot}} = \frac{m_0}{q_0^2 n_0} \cdot \left[\frac{1}{t_{imp}} + \frac{1}{t_{def}} + \frac{1}{t_T} \right].$$
(2.23)

This relation (2.23) describes the law of Mathiessen, expressed as:

$$\rho = \rho_{imp} + \rho_{def} + \rho_{T}, \qquad (2.24)$$

which shows that the resistivity of a metal is formed by a component due to the electron scattering on impurities ρ_{imp} , a component due to lattice defects ρ_{def} and a component due to conduction electron scattering on thermal vibrations of crystalline lattice atoms ρ_{T} .

2.2. METAL ELECTRIC CONDUCTIVITY DEPENDENCE OF VARIOUS FACTORS

Δ

2.2.1. Intrinsic and Extrinsic Factors

The electrical conductivity of **pure metals** depends on their nature and structure. In the case of **chemical compounds**, in general, the resistivity is higher than the one corresponding to the component elements.



Fig. 2.6. Resistivity dependence of metallic compounds on the concentration of components: a) alloys of mechanical mixture with total insolubility in solid state; b) alloys of solid solution with total solubility; c) alloys with compound formation.

Figure 2.6 presents the resistivity dependence of some metal compounds on the concentration of the components. Therefore, in the case of mixtures with total insolubility (Fig. 2.6a), the resistivity depends linearly on % of components. In the case of solid alloys with total solubility (as in the case of Cu-Ni alloys), the obtained alloy can have a much higher resistivity than that of the components (Fig. 2.6b). The same situation is in the case of chemical compounds (Fig. 2.6c).

The resistivity of metals depends on temperature: with the increase of the temperature, the resistivity increases. Fig. 2.7 shows the dependence of resistivity on temperature for the metals that are frequently used in electrical engineering.





It can be observed that metals of great conductivity (Ag, Cu, Al) have a relatively reduced dependence of resistivity on temperature, compared to other metals (Pt, Fe, Pb, etc.).

The mechanic stresses also influence the resistivity through the modifications produced over the crystal lattice.

M

2.2.2. Temperature Dependence

The temperature influences the value of electrical conductivity by modifying the average duration between the electron collisions, according to the Matthiessen law (2.24).

Experimentally it has been ascertained that when the temperature increases (from 0 K to melting temperature of the metal), the electrical resistivity varies with temperature.

The **Debye temperature** T_D is a characteristic parameter for each metallic crystal, which specifies the change of type of variation of the resistivity with the temperature. Above T_D the dependence is linear, and below T_D the dependence is with the fifth power of temperature. These dependences can be expressed as follows:

> For normal and high temperatures ($T >> T_D$):

$$\rho = const \cdot T ; \qquad (2.25)$$

(2.26)

> For low temperatures ($T \ll T_D$):

$$\rho = \operatorname{const} \cdot T^5$$
,

Example:

Table 2.3 indicates the values of Debye temperature and the resistivity for several metals at 0°C.

Table 2.3. The Debye te	emperature and the resistivit	y for some metals at 0 $^{\circ}$	°C.
-------------------------	-------------------------------	-----------------------------------	-----

Metal	Na	Au	Ag	Pt	Cu	ΑΙ	Ni	Fe	Ве
<i>T</i> _D [K]	158	160	214	240	320	428	450	470	1440
ρ [10 ⁻⁸ Ωm]	4.75	2.20	1.61	10.4	1.70	2.74	7.0	9.8	3.25

Figure 2.8 shows the general form of dependence of metal resistivity on temperature.



Fig. 2.8. The general form of the dependence of metal resistivity on temperature.

a) Resistivity variation with the temperature in the range of normal and high temperatures.

The relation (2.25) emphasizes the fact that when the temperature increases, the metal resistivity increases linearly with temperature in the domain of normal and high temperatures.

For the metals of high conductivity the following relation is usually applied:

$$\rho_{T} = \rho_{T_{0}} \cdot \left[1 + \alpha_{\rho} \cdot (T - T) \right], \qquad (2.27)$$

where ρ_T represents the resistivity at temperature *T*, expressed in K, and ρ_{T_0} is the resistivity at temperature $T_0=273,15$ K, which corresponds to 0°C.

With the relation (2.27) the temperature coefficient of electrical resistivity α_{ρ} is defined:

$$\alpha_{\rho} = \frac{1}{\rho_0} \cdot \frac{\rho_0 - \rho_0}{T - T_0}$$
(2.28)

30

2. Conductive Materials

The relations (2.27) and (2.28) can be expressed according to the temperature, measured in Celsius degrees, as:

$$\rho_{\theta} = \rho_0 \cdot (1 + \alpha_{\rho} \theta) \tag{2.29}$$

and

$$\alpha_{\rho} = \frac{1}{\rho_{0}} \cdot \frac{\rho_{\theta} - \rho_{0}}{\theta} = \frac{1}{\theta} \cdot \frac{\Delta \rho}{\rho_{0}} , \qquad (2.30)$$

where ρ_{θ} and ρ_{0} represent the resistivities at temperature θ in ${}^{\circ}C$, respectively at $0{}^{\circ}C$.

Notes:

- The expressions (2.27) and (2.30) define the average value of the temperature coefficient of the electrical resistivity during the temperature interval (*T*-*T*₀) [K], which corresponds to the interval (θ 0) [^oC];
- In pure metals, the variation coefficients of resistivity with temperature have values of the range $\alpha_p \approx 4 \cdot 10^{-3} \text{ K}^{-1}$.

Thus,
$$\alpha_{pCu} = 3.39 \cdot 10^{-3} \text{ K}^{-1}$$
, $\alpha_{pAl} = 4 \cdot 10^{-3} \text{ K}^{-1}$, $\alpha_{pFe} \approx 5.7 \cdot 10^{-3} \text{ K}^{-1}$.

At several metals, as in the case of iron, there will appear some deviations in the linear dependence given by the relation (2.28). For all these the following relation will be available:

$$\rho = \rho_0 (1 + a\theta + b\theta^2 + c\theta^3 + \dots)$$
(2.31)

In this case, it can be only defined an effective temperature coefficient of resistivity $\alpha_{o\theta}$, with the relation:

$$\alpha_{\rho ef} = \frac{1}{\rho_{\theta}} \cdot \lim_{\Delta \theta \to 0} \frac{\Delta \rho}{\Delta \theta} = \frac{1}{\rho_{\theta}} \cdot \frac{d\rho}{d\theta}, \qquad (2.32)$$

with the significance of tangent at the curve $\rho(T)$, in the taken point.

Note:

At conductive materials, the variation coefficients of resistivity on temperature are positive, which specify a certain increasing of resistivity when the temperature itself is increasing.

b) Resistivity variation with the temperature in the domain of low temperatures.

The relation (2.26) underlines that when the temperature increases the metal resistivity increases with the temperature at the fifth power, in the domain of low temperatures.

For a specific number of metals (Hg, Pb, Nb, etc.), at temperatures below a certain value called **critical superconduction temperature** T_c , the resistivity decreases to zero, and the metals pass into the state of superconduction.

For the majority of metals, the resistivity at 0 K has the value ρ_{rez} , which, conform to the relation of Mathiessen (2.23) has the form of:

$$\boldsymbol{\rho}_{rez} = \frac{m_0}{q_0^2 n_0} \cdot \left[\frac{1}{t_{imp}} + \frac{1}{t_{def}} \right] = \boldsymbol{\rho}_{def} + \boldsymbol{\rho}_{imp}$$
(2.33)

The residual resistivity is determined by the existence of defects and impurities. Figure 2.9 presents the variation curves of resistivity with temperature, extrapolated to nearly 0 K for pure copper and other alloys of copper-nickel.





With the increase of the content of the nickel percentage, the resistivity of the alloy Cu-Ni increases too.

2.2.3. The Influence of Plastic Deformation and Pressure

Plastic deformations that take place while processing materials or by device operation influence the value of electrical resistivity, because by plastic deformation the number of linear and surface defects increase and disturb the energy spectrum of the crystalline lattice. The vibrations of the lattice and its one-dimensional defects produce **the isotropic modification of resistivity**, while its dislocations (two-dimensional defects in crystal lattice) give an anisotropic character to resistivity.

The pressure also influences the value of metals resistivity, by modifying the distances between ions and the electronic gas density. For pressures $p < 12 \cdot 10^8 \text{ N/m}^2$ the dependence relation is:

$$\rho_{p} = \rho_{0} (1 + \alpha_{p} \cdot p) \tag{2.34}$$

where ρ_p is resistivity at pressure p, ρ_0 is the resistivity in vacuum in the absence of the pressure, p is pressure and α_p is **the variation coefficient of resistivity with pressure**, having negative values (the resistivity decreases while the pressure increases).

Example: $\alpha_{p \text{ metals}} = -(10^{-11} \div 10^{-10}) \text{ m}^2/\text{N}.$

The mechanical stress influences the resistivity as well, by the changes produced on the crystalline lattice. The dependence relation is:

$$\rho_{\sigma m} = \rho_0 \left(1 + \alpha_{\sigma m} \cdot \sigma_m \right), \tag{2.35}$$

where $\rho_{\sigma m}$ is the resistivity in the presence of a mechanical tension σ_m , ρ_o is the resistivity in the absence of tensions and $\alpha_{\sigma m}$ is the variation coefficient of resistivity with mechanical stress. The coefficient $\alpha_{\sigma m}$ depends on the purity degree of the crystal.

Example: In the case of iron at room temperature, $\alpha_{\sigma m} = (2.11 \div 2.13) \cdot 10^{-11} \text{ m}^2/\text{N}$.

2.2.4. The Influence of Electric Current Frequency

In massive conductors, in the presence of electromagnetic field variable in time, **the skin effect** will appear which consists in increasing the resistance of the conductor in the alternative current compared to the resistance in the continuous current. This fact is due to the currents induced by the variable magnetic field that passes through the conductive material and modifies the distribution of current in the metal.

The depth of penetration is a characteristic of the conductive material and the electrical circuit, being defined as the distance from the surface of the metal until the current decreases with 1/e that is 37% from the current amplitude at the metal surface.

The calculus relation is:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{2.36}$$

where:

 σ represents the electrical conductivity,

 $\mu = \mu_0 \cdot \mu_r$ is the absolute magnetic permeability of the material,

 $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the absolute permeability of the vacuum,

 μ_r - the relative magnetic permeability of material compared to the vacuum's one,

f = 1/T is the frequency of the alternative electric current.

Relative to the dimension *d* of massive conductor, the penetration depth stands for the two situations:

- the case $\delta >> d$, when the resistance in the alternative current has the same value as in the continuous current,
- the case $\delta \ll d$, when the resistance in the alternative current has a lower value than the one corresponding to the continuous current.

Example:

For the copper, with *f* given in MHz, it is obtained:

Materials in Electrical Engineering

$$\delta = \frac{0.0066}{\sqrt{f}} \quad [\text{cm}], \tag{2.37}$$

and for any metal, with f in MHz it will result:

$$\delta = \frac{0.0066}{\sqrt{\mu_r \sigma_r f}} [\text{cm}], \qquad (2.38)$$

where σ_r is the conductivity of the metal reported to the copper's one.

Note:

The conductive materials applied in electrotechnics must be carefully used in order not to modify the parameters of the electrical conduction.

2.3 MATERIALS WITH HIGH ELECTRIC CONDUCTIVITY

 Δ

2.3.1. Requirements for Materials with High Conductivity

The materials with high conductivity have the function of conducting the electrical current, due to the low or negligible resistance opposing the electrical current. In order to use a material as an electrically conductive material, it is necessary to fulfill the following requirements:

- low electrical resistivity,
- the skin effect should be neglected,
- high admitted current density,
- high thermal conductivity,
- appropriate elasticity,
- high mechanical strength,
- high resistance at chemical corrosion,
- easy processing through rolling,
- easy sticking, soldering and durable contacts,
- adequate technologies of obtaining, and recycling possibilities,
- low costs.

The main requirement is to have high electrical conductivity. Table 2.4 presents the electrical conductivity, respectively the electrical resistivity of some metals at normal environmental temperature.

Metal	Ag	Cu	Au	AI	W	Zn	Ni	Fe	Pb	Mn
σ, ×10 ⁷ [1/Ωm]	6.21	5.8	4.55	3.65	1.89	1.69	1.43	1.02	0.48	0.07
ρ, ×10 ⁻⁸ [Ωm]	1.61	1.72	2.20	2.74	5.3	5.92	7.0	9.8	21.0	139

Table 2.4. Conductivity and electrical resistivity of different metals.

34

For copper (Cu), aluminum (Al) and iron (Fe), Table 2.5 presents the characteristic properties in condensed state and some characteristics connected to including these metals into the periodical system of elements.

Characteristics	Cu	AI	Fe
Atomic number Z	29	13	26
Atomic mass A, [kg/kmol]	63.54	26.98	55.85
Atomic radius <i>r₀</i> , [Å]	1.28	1.43	1.26
Atomic volume V _a , [cm ³ /mol]	7.1	10	7.1
Covalent radius <i>r_c</i> , [Å]	1.38	1.18	-
lonic radius <i>r</i> _i , [Å]	0.96	0.50	0.76
First ionization energy <i>W_I</i> , [kJ/mol]	744.04	576.84	535.04
Cohesion energy <i>W_c</i> , [kJ/mol]	338.59	310.99	405.46
Pauli electronegativity	1.19	1.5	1.8
Electrical conductivity σ at 0 ÷ 20°C, ×10 ⁷ [Ω m] ⁻¹	5.8	3.65	1.02
Thermal conductivity λ , [W/m·K]	393.3	209	75.25
Specific heat <i>c</i> , [J/kg·K]	384.5	898.7	459.8
Melting temperature T _t , [°C]	1083	660	1536
Boiling temperature <i>T_f</i> , [^o C]	2595	2450	3000
Crystalline structure	CFC	CFC	CVC
Lattice constant <i>a</i> , [Å]	3.61	4.04	2.86
Density <i>d_m</i> , [kg/m ³]	8960	2700	7860
Magnetic behavior	diamg.	paramg.	ferromg.
Magnetic susceptibility χ_m	-0.9·10 ⁻⁵	+2.1·10 ⁻⁵	nonlinear

Table 2.5. Characteristics of the main conductive metals.

Materials with high conductivity are: **silver**, **copper**, **gold**, **aluminum**, and **iron**. These metals meet almost completely the requirements imposed for their use as conductors. However, among all **gold** and **silve**r are rarely used being precious metals, their performances will be presented as it follows.

2.3.2. Copper and Alloys of Copper

Its name comes from the island of Cyprus where there was discovered a large amount of copper ores. Known for more than 6000 years, since the age of bronze (as alloy of Cu-Sn), it has been used as material for tools, guns and jewels. Only in the 19th Century the copper begin to be used for its electro-conductive properties. The copper is the metal used especially in the electrotechnic industry, as electrolytic copper of 99.6 \div 99.9% purity, and as alloy element.
Natural state

The copper is found under the form of compounds, in minerals, usually polymetallic ones: Cu_2S , Cu_2O , $Cu_2CO_3(OH)_2$, CuS, CuO, $Cu_2(CO_3)_2(OH)_2$, $CuFeS_2$, etc.

Obtaining

The copper is obtained through sulfurous ores and oxidized by pyro- or hydrometallurgical reducing. For obtaining it, the ore is enriched (ore processing), by gravity and flotation processes. The pyro- or hydro-metallurgical reducing methods are applied according to the ore character and its copper content. The obtained copper contains, in variable quantities, S, Fe, Ni, Zn, Co, Sn, Pb.

Purifying the copper is realized by affinage and refinement. By affinage it can obtain **pure copper** 99.99 % and by refinement, **copper of high purity** 99.9999 %. The refinement can be done pyrometalurgically or electrically.

Pyrometallurgical refinement is realized by melting the solid copper at 1100-1200°C in a refinement oven, where compressed air is blown. In this process, the impurities transform into oxides, As_2O_3 , Sb_2O_3 , SO_2 , volatile oxides, and the metal oxides react with SiO₂ from the coating of the oven forming cinders (FeSiO₃, ZnSiO₃, NiSiO₃).

When the cinders are put away in order to de-oxide the copper, partially oxided (Cu₂O), green birch trees are introduced in the melting, they decompose at the cupboard temperature and form water vapors, H_2 , CO, which agitates the melting, enhancing the departure of volatile compounds and reducing Cu₂O to metallic copper.

From the refined copper, the electrolytic copper is obtained.

The electrolytic refinement of the copper is realized in concrete basins coated with walls of lead. The electrolyte is a solution of copper sulfate and sulfuric acid with sodium sulfate. In the absence of H_2SO_4 in the electrolyze process it will result variable quantities of Cu_2O .

In the electrolyze basin there are alternatively arranged anodes from pyrometalurgically refined copper and cathodes from pure copper. The reactions are:

 $CuSO_4 \longrightarrow Cu^{2+} + SO_4^{2-}$

 $CuO + H_2SO_4 = CuSO_4 + H_2O$

which re-enters the process:

 $Cu_2O + 2 H_2SO_4 + O_2 = 2 CuSO_4 + 2 H_2O$ HOH \implies H⁺ + HO⁻

Catode
Cu pure $Cu^{2+} + 2 e^- \rightarrow Cu$
 $2 H^+ \longrightarrow H_2SO_4$ Anode
Cu brute SO_4^{2-}
 $2 HO^- - 2 e^- \rightarrow 2 HO^0;
<math>2 HO^0 \rightarrow H_2O + O;$
 $O + Cu \rightarrow CuO + "mud"$

Usage

According with Romanian standards STAS 643-69 and STAS 270/1-74, the copper sorts are:

- Sorts obtained through thermal refinement: Cu 0 (99.00%), Cu 5 (99.50%), Cu 9 (99.9%)
- Sorts obtained through electrolytic refinement: CuE (99.99%), for industrial use.

M

2.3.3. Aluminum and Alloys of Aluminum

The name of aluminum derives from the Latin *alumen*, the name of the stone, which has double sulphide of aluminum and potassium – used from ancient times as mordant in dyeing.

Natural state

The aluminum is the most encountered metal on the earth, after the oxygen and silicon. Among its compounds, the most important ones are:

> Al_2O_3 - **corundum**, with impure and colored variations used as precious stones:

* **ruby** - red (unpurified corundum with Cr₂O₃)

* topaz – yellow (unpurified corundum with MnO)

* **sapphire** - blue (unpurified corundum with TiO₂, Fe₂O₃),

> $Al_2O_3 \cdot nH_2O - bauxite$,

> $Na_3[A|F_6] - criolite.$

There are over 250 minerals, which contain aluminum, as silicates of aluminum (feldspars, argyle etc.).

Obtaining

The aluminum is obtained by electrometallurgical reducing process. The aluminum metallurgy implies two important stages:

a) obtaining alumina Al₂O₃ from bauxite,

b) obtaining aluminum Al from alumina.

The refinement is realized through electrolyze in melting state at $700 \div 750^{\circ}$ C. The anode is made out of impure aluminum, the cathode from pure aluminum and the electrolyte is a mixture of AIF₃, NaF, BaCl₂.

The process of zonal melting is applied in electronics.

Physical properties

Both in compact and powder state, the aluminum is silver-white. It is a soft metal, having the density $d_m = 2700 \text{ kg/m}^3$, its hardness is 2,7 (Mohs), easily fusible, its melting point is $T_t = 660^{\circ}$ C, plastic, malleable and ductile, a good conductor of heat and electricity.

From the electrical and thermal point of view, the aluminum follows the copper. It is much lighter and cheaper than copper, but with an inferior mechanical strength; it offers a high processing possibility and a good resistance at electrochemical corrosion.

The types of electroconductive aluminum contain maximum 0.5% additions, the main ones being the iron Fe and the silicon Si. Figure 2.10 indicates the influence of the impurities on the aluminum electric conductivity.



Fig. 2.10. Dependence of aluminum electrical conductivity on the impurity percentage.

Chemical properties

The aluminum is a metal with high reactivity. The form of stable and characteristic valence is III, being situated in the periodical table of the elements at the period 2, group III A, with the atomic number Z = 13 and the electronic structure of the atom: $1s^2 2s^2 2p^6 3s^2 3p^1$. Other characteristics are given in Table 2.5.

Thus, with the normal reducing potential $\varepsilon_{Al^{3+}}^0 / Al^0 = -1.66 V$, has a high reducing character. The aluminum is destroyed in contact to technical metals. That is why the connecting clamps between the conductors of the air conductor networks from Cu - Al are special.

The corrosion resistance of aluminum is high because the aluminum is covered with a film of Al_2O_3 , which protects it.

It resists at water, organic substances, ammonium solutions, but it can be easily attacked by chloride, halogen, seawater and organic acids.

Usage

In electrotechnics the aluminum is used for:

- coil conductors and transportation lines;
- armatures for capacitors (malleability and high ductility);
- obtaining the semiconductive materials;
- obtaining the magnetic alloys, the alloys of high resistivity etc.;
- housings, massive parts (specific low weight).

The main alloys of aluminum, with use in electrotechnics are:

duraluminum, (90% Al, 3-5% Cu, 1-2% Mg, 1% Mn, 0.2-1% Si) STAS 7608 - 71, which presents superior mechanical properties to that of the aluminum, but with a lower resistance against corrosion, it is used with a protective layer or pure aluminum;

- siluminum, (Al + 10÷13% Si) STAS 201/1 71, is used for molding various devices or frames with complex geometrical forms having a very low molding contraction coefficient, being superior to the aluminum by its higher resistance to corrosion;
- alduro, (Al + 0.7% Mg + 0.6% Si + 0.25% Fe), also known as aldrey, is used in the air conductors industry for transporting the electrical energy, having a relatively good electrical conductivity and a high mechanical strengths.

The aluminum alloys present low density, high hardness, high electrical and thermal conductivity, and high chemical resistance to air, water and acids. The mechanical properties and the electrical resistivity for different kinds of aluminum as well as for alduro are given in Table 2.6.

Characteristics	Aluminum (soft) 99.6%	Aluminum (hard) 99.6%	Aluminum (molded)	Alduro
Breaking strength, [MN/m ²]	70110	150250	90120	310320
Elongation, [%]	3045	28	1325	-
Brinell hardness, [MN/m ²]	150250	350700	240320	-
Elasticity module, [GN/m ²]	5866	72	-	65
Electric resistivity, ×10 ⁻⁸ [Ωm]	2.8	2.8	2.8	3.22

Table 2.6. Mechanical properties and electrical resistivity for different kinds of aluminum and alduro alloy.

Other uses of the aluminum and its alloys:

- in metallurgy in order to obtain other metals,
- in anticorrosive protection,
- in packing food products and pharmacy,
- in explosive mixtures,
- as salts.
- as alloys it is used to make airships, vehicles, navies, tanks used in transporting the nitric acid, nuclear reactors, etc.



2.3.4. Silver

Silver has special applications in electrotechnics, being the metal with the highest electrical conductivity.

The name of silver comes from the Greek *argentum*. It is known from ancient times because it could be found in pure state. The Phoenicians, famous navigators during Antiquity, have found in Spain large amounts of silver and as they had no more space in their ships, to load it, they have replaced the wood anchor with massive silver ones. In Antiquity, silver was used for trade.

Natural state

Silver can be found free in nature, most of the time it is associated with gold, platinum metals, mercury, copper or antimony.

There are known some other minerals of silver: Ag₂S, Ag₃AsS₃, AgCl.

Obtaining

Native silver is extracted by amalgam process and the technical cooper from compounds by hydrometallurgical reducing process.

Pure silver is obtained by electrochemical refinement of raw silver. The anode is formed by raw silver, the cathode from pure silver and the electrolyte solution is of AgNO₃.

Physical properties

In compact state, silver has a bright white color and as powder it is gray. It is a heavy metal d_m =10500 kg/m³, soft regarding hardness, its melting point is T_t =960.5°C. It presents special mechanical properties, it is very malleable and ductile, good heat and electricity conductor as well as diamagnetic.

Chemical properties

Silver is a metal with a low chemical reactivity: $\varepsilon_{Ag^+}^0 / Ag^0 = +0.799V$, it is a noble metal.

It presents stability in the air with no hydrogen sulphide. In its presence, silver is covered with a black layer of silver sulphide.

$$\begin{array}{c} 4 \text{ Ag} + 2 \text{ H}_2\text{S} + \text{O}_2 = 2 \text{ Ag}_2\text{S} + 2 \text{ H}_2\text{O} \\ \text{from air} \quad \text{black} \end{array}$$

At normal temperature it reacts with halogens, with diluted nitrogen acid and concentrated with alkaline cyanide solutions.

$$3 \text{ Ag} + 4 \text{ HNO}_3 = 3 \text{ Ag NO}_3 + \text{NO} + 2 \text{ H}_2\text{O}$$

diluted
$$Aq + 2 \text{ HNO}_3 = Aq \text{ NO}_3 + \text{NO}_2 + \text{H}_2\text{O}$$

concentrated

At high temperature it also reacts with sulfuric acid.

Usage

Silver is used in alloys to make coins, jewels, plugs, etc. It is used for anticorrosive protection or for decoration, to fabricate mirrors with a high power of reflection, to make laboratory tools, to produce cathodes in unconventional cells, to produce electrical conductors, for photoelectrical films.

Silver and its compounds present anti-bacterium properties. The colloidal silver is used as pharmacy products.

2.3.5. Iron and Alloys of Iron

In certain cases, to fabricate conductors, distribution lines, instead of copper or aluminum, iron is often used, due to its lower costs, its superior mechanical resistivity and due to its good malleability.

The name of the iron derives from the Latin *ferrum*. The Iron Age followed the Bronze Age, when the iron was known especially as meteoric iron. It was very rare and needed a complex technology.

At Louvre, there is displayed an iron amulet engraved in gold, from 1900 B.C., which shows the fact that the iron was a very expensive metal in a period of time, if it was engraved in gold.

Natural state

The iron is found in free state as **meteoric iron** (in fact, an alloy of the iron with 5÷20% Ni) and **telluric iron**, with a maximum amount/content of 2% Ni, 0.3% Co, 0.4% Cu and 0.1% Pt.

Large amounts of iron can be found as compounds:

Fe ₃ O ₄ - magnetite	FeS ₂ - pyrite (crystallized in cubic system)

```
Fe_2O_3 \cdot H_2O - Iimonite \qquad FeS_2 - marcasite (crystallized in rhombic system)
```

Fe₂O₃ - hematite FeCO₃ - siderite

Iron could be also encountered in the composition of silicates, thus all argyles are unpurified with the iron compounds.

Obtaining

Pure iron is obtained by reducing its oxides using hydrogen or aluminum

 $Fe_2O_3 + 3 H_2 = 2 Fe + 3 H_2O$

 $Fe_2O_3 + 2 AI = 2 Fe + AI_2O_3$

 $\mathsf{FeO} + \mathsf{H}_2 = \mathsf{Fe} + \mathsf{H}_2\mathsf{O}.$

Practically, the iron alloys, cast iron and steel, are used more commonly.

Cast iron is an alloy of Fe-C which contains $1.7 \div 5\%$ carbon, and **steel** is an alloy of Fe-C which contains $0.1 \div 1.7\%$ carbon. Cast iron is obtained in furnaces, where the reducer is the carbon. By partial oxidation of the cast irons, steel can be obtained.

Physical properties

In compact state, the iron is silver-gray, and in powder it is gray. It is a heavy metal, d_m =7860 kg/m³, hardly fusible, with its melting point T_t = 1536°C, it is malleable and ductile.

Materials in Electrical Engineering

It presents four allotrope forms, which differ through their crystalline structure and through their magnetic properties:

α-Fe 768°C β-Fe 906°C γ-Fe 1410°C δ-Fe 1536°C Fe-melted Curie point ferromagnetic $\rightarrow \leftarrow$ paramagnetic \rightarrow

It presents a considerable mechanical strength, and it is a very good heat and electricity conductor. We add to the properties presented in Table 2.5 that, in the periodical system table, the iron is placed among the elements from the 4th period, group VIII B, having the atom electronic structure: $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$.

The electrical resistivity of pure iron (99.9%) is high $\rho = 9.8 \cdot 10^{-8} \Omega m$, and the resistivity is strongly influenced by Si, P, Al impurities and less by C content (Fig. 2.11).



Fig. 2.11. Dependence of the iron resistivity on the impurity percentage.

The main properties of different kinds of iron and steel used in electrical engineering are given in Table 2.7.

	Table 2.7.	The main	properties o	f different	kinds of	electrotechnic	c iron and ste	eel.
--	------------	----------	--------------	-------------	----------	----------------	----------------	------

Characteristics	Fe, used in DC (Armco) C 0.03%, Si 0.05% Mn 0.05%, S 0.25% P 0.015%, Cu 0.1%	Steel, used in AC C 0.1 ÷ 0.15% Si 0.08% Mn 0.046%	
Breaking strength, [MN/m ²]	soft 200 300	700 770	
Elongation at breaking,	soft 60 40	5 8	
[%]	hard 6 1.5	56	
Electrical resistivity, ×10 ⁻⁸ [Ωm]	10.5 10.8	13	
Temperature coefficient of resistivity, ×10 ⁻³ [K ⁻¹]	5.7	5.7	

Chemical properties

From the value of normal reducing potentials

 $\varepsilon_{Fe^{2+}}^{0} / Fe^{0} = -0.44V, \varepsilon_{Fe^{3+}}^{0} / Fe^{0} = -0.036V$

it can be stated that iron is an active metal and in chemical reactions it behaves as a reducer. It presents valence II and III, mostly III.

The divalent iron compounds are easily oxidized even with the oxygen from the air. In humid air, the iron rusts.

Fe + 2 H₂O = Fe(OH)₂ + H₂ white rust

4 $Fe(OH)_2 + O_2 = 4$ FeO(OH) + 2 H₂O brown rust

 $Fe(OH)_2 + 2 FeO(OH) = Fe_3O_4 + 2 H_2O$

black rust

It reacts, at normal temperature, with diluted acids (HCl, H_2SO_4 , HNO_3) and it becomes passive with concentrate acid HNO_3 :

 $Fe + 2 HCI = FeCI_2 + H_2$

 $Fe + H_2SO_4 = FeSO_4 + H_2$

4 Fe + 10 HNO₃ = 4 Fe(NO₃)₂ + NH₄NO₃ + 3 H₂O

At high temperature, it reacts with halogens (X), with oxygen, sulfur, water, hydrogen, sulfured hydrogen, forming the corresponding compounds: FeX_3 , Fe_3O_4 , FeS, Fe_2S_3 .

Usage

Large quantities of iron are used as cast iron and steel. In small quantities of 4÷6.5%, it is added to brasses and bronzes for increasing the elasticity, hardness and antifriction properties.

Iron is used for communications lines, for distribution lines of low power, and for electrical lines which have to support high mechanical charges. The iron is mostly used as a conductive material, having the form of a rope, as a core for bimetallic conductors Fe-Al.

The technical iron of Armco type, which contains less than 0.2% impurities, is mostly used for the lines of continuous current.

In alternative current, the steel with 0.1÷0.15% C is used as conductors, having $\rho = 1.3 \cdot 10^{-7} \Omega m$, but, due to the skin effect (equivalent to an energy loss at the surface of the conductor) the resistance in alternative current increases, that why, the steel type armco iron is recommended for DC applications.

Indeed, it is well known that the report between the resistance in alternative current and the one in the continuous current is expressed according to the depth of penetration of the electromagnetic field, given by the relation (2.36). In the iron, the skin effect is very intense, because the depth of penetration of the magnetic field depends

on the electrical conductivity, magnetic permeability and the frequency of the inductive magnetic field.

The telecommunication lines are often made by iron with zinc-covered conductors to protect them from corrosion.

2.4. MATERIALS WITH HIGH RESISTIVITY

2.4.1. Requirements for materials with high resistivity

The materials with high resistivity have the role to control and to delimit the electric current. This is achieved due to the high resistance they oppose when the electric current passes through them.

If a material is used as a material with high resistivity, it should fulfill the following **requirements:**

- high electrical resistivity, to obtain high values of the electrical resistance with a small material size;

- a temperature coefficient of resistivity as low as possible, in order that the influence of the temperature on the electrical resistivity to be as low as possible;

- thermo-electromotive forces in contact with copper should be as low as possible, especially for the materials used to produce shunts, as thermo-electromotive forces which appear at the contact shunt-conductors can modify the indications of the measurement instruments;

- good stability of mechanical properties in time;

- a very high melting temperature and good stability of the properties with the temperature. Example, it is need: 200÷250°C for materials used in the construction of rheostats, and 1000÷1500°C for the heating resistances.

Pure metals do not fulfill all these requirements, due to their low resistivity, to their high variation coefficient of resistivity with temperature, and to their low mechanical strength at high temperature.

High resistivity can be realized by controlled doping of the pure metals, which by increasing the potential of interaction type of electron-impurity (independent on temperature), leads to a decreasing dependence on temperature of the resistivity, but also to an increasing value of resistivity.

Pure technical metals

Pure technical metals are used according to their resistance to oxidation under the action of various gases from the special industrial environments. Their resistance will depend on the stability, hardness and structure of the formed oxides.

One of the disadvantages of using metals as materials for heating resistances is the high value of the temperature coefficient, which is of the order 10^{-3} K⁻¹. This corresponds to an increase of the resistance of heating elements of (2...4) times at a

44

heating of (300...5000)^oC which will not allow the maintaining of a constant temperature in the heated oven with such resistances.

Table 2.8 indicates some of the pure metal properties and their use in the construction of heating elements.

Table 2.8.	Properties	of some	metals	used in	the cons	struction	of the	heating	elements.

Metal	AI	Fe	W	Мо	Ni	Pt
Atomic mass, [kg/mol]	26.97	5584	184	96	58.69	195.23
Density, ×10 ³ [kg/m ³]	2.702	7.876	19.300	10.200	8.900	21.450
Melting temperature, [°C]	660	1531	3370	2620	1454	1755
Vaporizing temperature, [°C]	1800	3235	5930	4188	3147	4901
Dilatation coefficient, ×10 ⁻⁶ [K ⁻¹]	23.03	11.8	4.0	4.0	12.8	8.9
Electrical resistivity at 20°C, 10 ⁻⁸ Ωm	2.7	10.8	5.5	4.7	7.23	10.5
Temperature coefficient of resistivity, ×10 ⁻³ [K ⁻¹]	4.2	5.7	4.0	4.3	6.1	2.5
Brinell hardness, [MN/m ²]	150-250	600-800	2000- 3500	1500- 3000	800	550
Breaking strength, [MN/m ²]	60-150	250-300	1000- 2800	800-2000	400-450	200-300
Elongation coefficient, [%]	20-40	40-50	-	30	25-30	50
Working maximum temperature, [°C]	550	400	1800	1500	1000	1500



2.4.2. Nickel

Although nickel is a rare metal, it has multiple usage in electrotechnics, as a alloying element for obtaining alloys of high resistivity.

Nickel was used in antiquity as an alloy. The most ancient China alloy with the nickel is *pacfongul* (*peitung* - white copper) and it was used for making the gongs, musical instruments, and home devices. During the Middle Ages, in Germany there was known an ore which they believed it was a copper, arsen, cobalt ore. The trying to prepare copper out of this ore failed and the ore was called *kupfernickel* - *devil's copper* (nickel = devil). Later on, from this ore they prepared today's nickel.

Natural state

In nature the nickel is found as compounds: NiS, Ni₂As₂. The nickel compounds in small quantities (essential element, microelement) are found in animal organism, in plants on the ground or under the water, as well as in some insects.

Preparation

Nickel is prepared out of nickel concentrates by pyro-metallurgical reducing process, in solution. The nickel refinement is done by zonal melting, by melting in high vacuum, by electrolyze or by decomposing the carbonyl groups.

Physical properties

In solid state, nickel has a white silver color and as powder it is gray. It is a heavy metal, d_m =8900 kg/m³, hardly fusible, melting point is T_t =1455°C, malleable, ductile, good heat and electricity conductor, ferromagnetic (α -Ni). It presents two allotropic forms, α and β - nickel. The resistivity is given in Table 2.4. Other properties are presented in Table 2.8.

Chemical properties

Nickel is a low active metal ($\varepsilon_{Ni^{2+}}^0 / Ni^0 = -0.25 V$). The characteristic valence is II and in complex compounds III. The reactivity is determined by its state (compact or powder) and by the reaction conditions. In easily devised state it is pyrophoric. At normal temperatures nickel is resistant to air, water corrosion and in the solution of certain substances. At high temperature, it reacts with halogens, oxygen, sulfur and sulfured hydrogen. At normal temperature it slowly reacts with HCl and with H₂SO₄:

$$Ni + 2 HCI = NiCl_2 + H_2$$

 $Ni + H_2SO_4 = NiSO_4 + H_2$

It reacts as a less pure active metal with HNO₃ at normal or high temperature:

3 Ni + 8 HNO₃ = 3 Ni(NO₃)₂ + 2 NO + 4 H₂O

It becomes passive treated with concentrated HNO_3 and the fine devised state has the property to absorb the gases (H₂, CO, NO etc.) being used as a catalyst in many chemical reactions.

Usage

Nickel has limited uses due to its high costs, being one of the most expensive technical metals. It is used as a catalyst, for the manufacture of alkaline accumulators, permanent magnets and for anticorrosive protection, under the form of alloys characterized by low electrical conductivity, and as electrical resistances: *constantan* (40% Ni, 60% Cu), *nickeline* (19÷33% Ni, 55÷68% Cu, till 18% Zn), *manganese compounds* (2÷4% Ni, 82÷84% Cu, 12÷15% Mn), *nicrom* (80÷90% Ni, 10÷20% Cr), *argentan* or *alpaca* (12÷18% Ni, 53÷62% Cu, 19÷36% Zn), *invar* (steel with 35÷37% Ni), *platinit* (steel with 40÷46% Ni), *monel* (65÷70% Ni, 25÷30% Cu, 0.1÷1.6% Si, 3÷4% Mn and Fe).

2.4.3. Molybdenum

The ancient Greeks used the lead sulfur, PbS (galena) to write, as well as graphite carbon, both substances being currently mistaken and called *molibdos*, which means lead. In time, this name extended to other substances, resembling as physical aspect to the former among which to the so-called "sea lead" or *molibdenite* MoS₂. The name derives from the Greek *molibdos*.

Natural state

Molybdenum is found as compounds:

- MoS₂ *molybdenite*
- CaMoO₄ *povelit*
- PbMoO₄ *wulfenit*.

Preparing

The preparing is done by reducing $Mo^{n+} + ne^- \rightarrow Mo^0$. The reducing process is realized by pyro- or electrometallurgical methods. The molybdenum concentration is produces in order to obtain MoO_3 or to obtain the ferromolybdenum.

The purification is realized by reducing the oxides with hydrogen or by decomposing the carbons or the halogens.

Physical properties

Molybdenum has a white-silver color, it is a heavy metal, d_m =10220 kg/m³, hardly fusible, with a melting point $T_t = 2610^{\circ}$ C, it has good thermal and electrical conductivities. In pure state it can be mechanically processed. The impurities make it more breakable. Table 2.8 presents some other properties.

Chemical properties

In normal conditions it is stable in dry or humid air. At high temperatures, over 500°C, it reacts with halogens, oxygen and sulfur (the more finely it is devised, the easier it reacts with sulfur).

The molybdenum powder reacts slowly with the water forming a mixture of compounds known as "molybdenum blue".

At normal temperature it does not react with diluted acids (HCl, H_2SO_4 , HNO_3); it reacts with the royal water, 3 HCl + HNO_3 , forming molybdenum acid, H_2MoO_4 .

At high temperature it reacts with HCl concentrated, with HNO_3 and with mixtures of acids. It reacts in melting, with oxidant alkaline mixtures (NaOH + KNO₃, Na₂O₂) forming the molybdates Na₂MoO₄.

Usage

It is used to produce hard and resistant to corrosion alloys, to make tools, in the construction of cars, planes, turbine axes, shell-protected sheets.

The alloys of Fe-Ni with 2:3% Mo (with or without copper) are ferromagnetic alloys, used to produce cores for transformers, shock coils, wires for the telecommunication installation. It is used also as alloy element for producing the permanent magnets.

The alloys of Mo with Fe, Ni, Mn are used in the technique of electronic tubes, from the bars or blocks of molybdenum are made up the heating electrodes for cupboards for melting the glass or electrodes used to weld in atomic hydrogen environment.

The alloys of Ni-Mo are used as thermocouples and the alloys of Mo-Ta are used instead of platinum. Large amounts of molybdenum are used as catalysts in the oxidation reactions, of hydrogenation, of de-hydrogenation, isomerization process, polymerization, condensation, de-hydration process.

Some of the molybdenum compounds are used to produce the colorants, characterized by a strong shine and a great power of covering. The colorants are used for paint for plastic materials, for hairdryer, skins, furs, for inks, etc. The organic compounds of molybdenum have a role of catalyst in many of the bio-cells.



1 2.4.4. Wolfram

Wolfram is also called tungsten. In the Middle Ages, in the metallurgical processes of obtaining the tin, most of the times, of black and brown color remained. If they were not totally removed from the surface of the melted tin, a "persistent" foam was formed which usually got mixed with the tin. The German melters called it Wolfrahm = the wolf foam, because it "swallowed" the tin like a hungry wolf, damaging its properties.

The name of tungsten comes from the Swedish tung-sten = heavy rock, given to the *scheelite* ore, CaWO₄.

Natural state

In nature the wolfram is found as compounds, wolframites:

- (Mn, Fe) WO₄ wolframit
- CaWO₄ scheelit
- PbWO₄ *stolzit*.

Preparing

The wolfram is prepared by the reducing method $W^{n+1} + ne^{-} \rightarrow W^{0}$. The reducing process can be pyro-metallurgical or electrometallurgical ones.

The purification is done by reducing the oxides with hydrogen or by decomposing the carbonyls or the halogens. The wolfram powder gets compact in hydrogen atmosphere or in vacuum.

Physical properties

In compact state, the metallic wolfram is bright silver white. As powder, it is gray. It is a heavy metal, d_m =19320 kg/m³, hardly fusible, with the melting point of T_t =3380°C, it presents a high power of electronic emission and radiation in incandescent state, it has a low specific heat, it is paramagnetic and a good heat and electricity conductor. In pure and compact state it has superior mechanical properties. Some of these properties are presented in Table 2.8.

Chemical properties

From chemical point of view, wolfram is stable in normal conditions. When it contacts the air and is melted at 900°C, it transforms in trioxide of wolfram WO₃.

The wolfram powder is pyrophoric. It reacts at 600°C with the water steams:

 $W + H_2O = WO_2 + 2 H_2$

At normal temperature it reacts with flour and at high temperature 300÷900°C it reacts with the other halogens and with sulfur.

The wolfram powder reacts with the concentrated nitrogen acid and with the acid mixtures (3 HCL + HNO₃, H_2SO_4 + HF). It reacts with the alkalino-oxiding meltings (KOH + KNO₃, KOH + KClO₃ etc.) and they form wolfram compounds.

Usage

It is used as ferro-wolfram to produce special steel characterized by their high resistance to use, high operation temperatures, inert to chemical agents, superior plasticity and elasticity, high hardness and superior mechanical properties.

The metallic wolfram is used in the electrotechnical and radio-technical industry as plates, wires or filaments in electronic tubes, and in electrical bulbs for lighting. It is also used as tubes, bars, and plates for the heating elements of the electrical heating ovens, as electrodes for welding in atmosphere of atomic hydrogen or as contacts for the electrical current switchers.

It is used to make thermocouples and due to its electrical conductivity and its low coefficient of thermal dilatation, it is used for welding within the glass.

The wolfram combinations are used as chemical reactors, catalysts, colorants for oil paints or ceramics, as ignition materials for wood and fabrics.

2.4.5. Manganese Alloys

Manganese alloys used as high resistivity materials are alloys of **copper with manganese** (Cu-Mn), enriched with other alloy elements: Ni, AI, Fe, with generic name of manganin.

For obtaining manganin with very high resistance, the percentage of Mn is increased to $60\div70\%$, obtaining materials with $\rho=200\cdot10^{-8} \Omega m$. In order to stabilize the properties, the manganin must be submitted to a special thermal treatment. The manganese are easily processed, the operating temperature is about $60^{\circ}C$.

The main characteristics of highly resistive manganese alloy are given in Table 2.9.

Characteristics	Manganese alloy type A, 86% Cu, 12% Mn, 2% Ni
Density, [kg/m ³]	8400
Resistivity at 293 K, ×10 ⁻⁸ [Ωm]	43
Temperature coefficient of resistivity at 293 K, ×10 ⁻⁶ [K ⁻¹]	5 10
Thermoelectromotive force comparison with Cu, $[\mu V/^{o}C]$	+ 1.0
Breaking strength, [MN/m ²]	500 550
Breaking elongation, [%]	15 25
Maximum working temperature, [°C]	60

Table 2.9. The main characteristics of highly resistive manganese alloy type A.

2.4.6. Nickelines

Nickelines are the alloys of copper with nickel (Cu-Ni). These alloys form solid solutions in any proportion:

- **Constantan** is the most used alloy in the construction of wired resistors and it is composed out of **60% Cu and 40% Ni**. It can be used till temperatures of $(400\div550)^{\circ}$ C. At temperature of 300°C it oxides, being covered with a protective and insulating oxide, which will allow to use the wires of constantan coiled on a support, in the construction of variable rheostats. The resistivity $\rho = 50 \cdot 10^{-8} \Omega m$ is sufficient for most of the operating regimes, the low value for $\alpha_{\rho} = 0.00002 \ 1/K$ determines a resistance practically invariable to temperature.

- Nickelines are alloys of copper Cu with maximum 35% Ni. They are less expensive than the constantan, easier to process, but with inferior properties.

- Other alloys for rheostats mostly used are those, which contain until 60% Cu, 15% Ni and the rest of it Zn, with commercial names: Alpaca, Maillechart, Reotan. All of these alloys have the temperature coefficient of resistivity much higher than the constantan.

The characteristics of Cu-Ni alloys for the resistors are given in Tables 2.10 and 2.11.

Alloy	Argentan	Nickeline1	Constantan	Nickeline2	Nickeline3
Composition	60% Cu 17% Ni 23% Zn	58% Cu 22% Ni 20% Zn	60% Cu 40% Ni	54% Cu 26% Ni 20% Zn	67% Cu 30-31% Ni 2-3% Mn
Resistivity, ∗10 ⁻⁸ [Ωm]	30	36	50	43	40
Temperature coefficient of resistivity, ×10 ⁻³ [K ⁻¹]	0.35	0.31	0.02	0.23	0.11
T.e.f. towards Cu, [μV/K]	+ 15	-	+ 12	+ 25	-
Breaking strength, [MN/m²]	400	510 830	400-500 750	680 850	440
Breaking elongation coefficient, ×10 ⁻⁶ [%] - soft - hard	35	34 1	50-40 3	30 1.5	33-15
Thermal dilatation coefficient, ×10 ⁶ [K ⁻¹]	18	16.8	14	16	16
Density, [kg/m³]	8600	8700	8900	8700	8900
Working maximum temperature, [°C]	200-250	250	400	250	300

	Table 2.10.	The characteristics	of alloys	for rheostats.
--	-------------	---------------------	-----------	----------------

For wirewounds power resistors are used alloys with Cu, Mn, Ni and another elements.

Table 2.11.	Other al	loys for	coiled	power	resistors.
-------------	----------	----------	--------	-------	------------

Name	Ferromanganese	Izobeline	Weimer Alloy	Novo- constantan
Chemical composition	Cu - 86% Mn - 12% Fe - 2%	Cu 84% Mn 13% Al 3%	Cu 84% Mn 12% Al 4%	Cu 82,5% Mn 12% Fe 1.5% Al 4%
ρ _{20⁰} с, ×10 ⁻⁸ [Ωm]	48	50	46	45

2.4.7. Resistive Alloys Based on Precious Metals

There are used alloys of Pt, Au and Ag. These alloys have a high stability of properties in time, and the temperature coefficient of resistivity is very low.

For certain alloys of gold Au and silver Ag, the resistive characteristics are given in Table 2.12.

		Ag + 10% Mn + 8% Sn		
Characteristics	Au + 2% Cr	Not aged	After the aging, at 175°C	
Resistivity, ×10 ⁻⁸ [Ωm]	33	55	50	
The temperature coefficient of resistivity, ×10 ⁻⁶ [K ⁻¹]	1	30 55	0	
The thermo electromotive force towards Cu, [µV/°C]	7 8	-	0,5	

Table 2.12. The characteristics of electroconductive alloys of gold and silver.

2.4.8. Iron and Alloys of Iron

The alloys based on nickel - **Nichrom, Feronichrom** – are solid solutions of nickel with chromium, the only metal which can be introduced in enough quantities in the alloy to increase the domain of operating temperatures, decreasing the temperature coefficient of resistivity. The resistivity to heat is increasing due to the addition/enrichment of the superficial foil of the alloy with chromium oxide. In order to improve the mechanical properties, a part of Ni is replaced with Fe, the alloys are called **feronichroms**. In these alloys are also introduced in small quantities other elements to improve the technological process and to accomplish the environment requirements where are working in.

The alloys based on Fe are used due to their lower price. The addition elements, which increase the resistance at heat, are Cr, Ni, Al, Si.

Cr and Ni form with Fe continuous series of solid solution and Al and Si are soluble in the iron α until 33%, respectively 16%.

All Fe alloys with Ni, which contain over 25÷30% Ni, satisfy technological properties. The chromium is introduced in a maximum proportion of 30÷40% for the alloy to be processed.

To increase the resistivity ρ and the decreasing of the temperature coefficient of resistivity, several percentages of Cu and Mn are being introduced, and 3÷5% Co.

The alloys of Fe-Ni contain 20÷25% Ni and 0.5% Cr. The operating temperature is 550÷600°C, therefore they cannot replace the chromium-nickel alloy, except the constantan for the construction of starting rheostats.

The refractor alloys from the category **Ni-Cr-Fe (cromel) and Fe-Cr-Al-Co** (Kanthal) can be used at maximum 1300°C (Tables 2.13, Table 2.14).

At temperatures between 1330°C and 1700°C, for the heating elements it is used the alloy of *Kanthal - Super* type, made with molybdenum–silicon compounds.

The name of	ρ ₂₀₂c,	α ₁ ,	α _ρ , ×10 ⁻³ K ⁻¹		θ_{max} ,	σ,	Observations	
the alloy	×10 ⁻⁸ Ωm	×10 ⁻⁶ K ⁻¹	(20-400)°C	(20-10 ³)°C	°C	MN/m ²	Observations	
Chromium-Nickel (Chromium C) 60-63% Ni 12-15% Cr 22-26% Fe 0,5-2% Mn	109	13	0,2	0,15	1000	680	The less expensive and the easiest to process	
Chromium-Nickel (Chromium A) 79-80% Ni 18-21% Cr 1,5% Fe 0,5-2% Mn	105	14.5	0.9	0.40	1150	750	The most encountered, high resistivity at heat	
Heraeus D 60-62% Ni 23-25% Cr 9-10% Fe	110	14.8	0.3	0.80	1100	800	High mechanical resistivity at heat	
Heraeus E 50-52% Ni 30-32% Cr 11-15% Fe 2-3% Mn	108	15.0	0.5	0.23	1 280	1 000	Very mechanically resistant to heat	
Heraeus B ₇ M 60-62% Ni 13-15% Cr 14-16% Fe 1-7% Mn	115	13.0	-	0.6	1 050	700	-	

Table 2.13. Refractory alloys for the heating elements.

The name of	ρ ₂₀₂c,	α _ρ ,	θ _{max} .	σ r20⁰C,	lleo	
the alloy	×10 ⁻⁸ Ωm	×10 ⁻⁶ K ⁻¹	°C	MN/m ²	USE	
Feronickel						
0,5-5% Cr	Q1	100	550-600	_	Rheostats for motor	
25-35% Ni	51	100	330-000		starting	
% remaining of Fe						
Fechral					Power rheostats,	
15% Cr	115-135	180	850-875	700	electro-heating	
5% AI	110-100	100	000-070	700	systems with	
% remaining of Fe					resistors	
Kanthal						
21% Cr	120-135	80	1150-1250	800-850	Industrial owens,	
5% AI	130-133	00	1130-1230	000-000	home devices	
% remaining of Fe						
Chromal						
30% Cr	125	40	1200	000	Industrial overe	
4,5% Al	155	40	1300	800	industrial overis	
+ Fe						
Kornilov-4 Alloy						
65-67% Cr	200 220		1500		Inductrial overe	
7,5-12,5% Al	200-220	-	1500	-	industrial ovens	
19-27% Fe						

Table 2.14. Refractory alloy with iron.

2.5. APPLICATIONS OF CONDUCTIVE MATERIALS

Δ

2.5.1. Resistors

Resistors are passive circuit components having either the role of limitation of the electric current intensity values, or the division of currents and voltages circuits.

Figure 2.12 presents different types of resistors, the classification being done according to different criteria.

54



2. Conductive Materials

Fig. 2.12. Resistors classifications.

The active element of the resistors is made up of materials with high resistivity.

- a) For the gauge construction and precision resistances (shunts and additional resistances for measurement instruments) there are used alloys of solid disordered solution from the Cu-Mn, Cu-Ni systems, alloys of platinum, gold, silver.
- b) *For rheostat construction* there are used alloys of Cu, Ni, Zn, Fe, Al, alloys that have less stable properties than the manganin, but which are less expensive.
- c) For the construction of heating elements it is necessary a low temperature coefficient of resistivity $(2\div17) \cdot 10^{-5}$ K⁻¹ and a good resistance to high temperatures oxidization.
- d) For the construction of electronic devices there are often needed electrical resistors with very high values ($> 1 M\Omega$), comparatively to the possibilities of realization using technical metals and their alloys. That is why, besides wire wound resistors, two types of resistors are produced, distinguished by their manufacture technology.

Film resistors are made up of a resistive film from carbon powder, crystalline carbon, bore - carbon, metallic film or metallic oxides, a film put on a ceramic support. This technologies make possible to obtain resistors with dissipative energies up to 2 W and a precision high enough, but with a coefficient of thermal stability inferior to the value of $-2.5 \cdot 10^{-4} \text{ K}^{-1}$.

Volume resistors have the property that all the volume takes part in the electric conduction process. These resistors are formed of carbon (graphite or black carbon) and filling material in proportion of $50 \div 55\%$ (titan dioxide, zirconium dioxide, talc, pressed mica, etc). In the case of these resistors, the dissipated energy cannot exceed 10 W, they have tolerances of the resistances of $\pm 10\%$ and the temperature coefficient

of order $(2\div3)\cdot10^{-3}$ K⁻¹. There is a serious disadvantage, namely, their electromotive force of noise, which depends thoroughly on frequency, having a high value.

The parameters which influence the reliability of the resistors and rheostats are: the current density, the surface of heat dissipation, the working temperature, the time constant and the operating regime. The best choice of these parameters determines the use at maximum reliability of the assembly.

The highest current densities are obtained at wires and bands resistor elements, because they can ensure the best cooling environment (Fig. 2.13).



Fig. 2.13. The choice of the resistive wire diameter (1- conductor of nickeline; 2conductor of constantan) according to: a) the admissible current I_{ad} ; b) the density of admissible current J_{ad} .

The calculus of the cooling surface is necessary, so that the admitted overtemperature should reach the optimal value. In the case of a round resistance element, the diameter d is calculated with the relation:

$$d = \frac{4\alpha_{\Sigma} \cdot \Delta \theta_s}{\rho_a \Delta \theta_a J_a^2}, \qquad (2.39)$$

where:

 α_{Σ} - coefficient of heat transmission;

 $\Delta \theta_s$ – stationary over-temperature;

 ρ_a – resistivity at admissible over-temperature θ_s ;

 $\Delta \theta_a$ – admissible over-temperature of the material;

 J_a – the admissible density of electric current.

The optimal choice of the heat transfer surface is very important, because a too high charge leads to the overheating of the resistor elements, corrosion, and metallurgical modifications may appear, which will affect their lifetime.

Power rheostats are made of cast iron alloyed with silicon and carbon having the resistivity of $(0.8 \div 1.) \mu\Omega m$ and $\alpha_{\rho} = 0.001 \text{ K}^{-1}$. Rheostats with cast iron are recommended especially for the shock-current operation regimes, which appear when the electric motors get started. As α_{ρ} is high, they are used where the resistance variation on temperature is not so relevant.

1 2.5.2. Electric Contacts and Brushes

The conductive materials that fulfill the function of contact - commutation must satisfy the following requirements:

- Very low electrical resistivity, to have a contact resistance as reduced as possible;
- High resistance to corrosion, erosion and welding,
- High stability to oxidation and, in the case of forming foils of superficial oxides, they
 need to have the electrical and thermal conductivities close to the basic material;
- High melting temperature for the absence of electric discharges when the contact is interrupted;
- Good elastic properties and high hardness, to resist to a large number of connections;
- To be easily manufactured and processing.

The choice of materials is done according to the contact type which will be realized (fixed or mobile contacts).

The most used materials for **motionless contacts** are the **copper** (STAS 270-74), **aluminum**, **silver** (STAS 8903-71, STAS 8904-71) for pressed contacts. In normal atmosphere, silver is covered with a layer of conductive oxide and protective against corrosion. But the copper oxide which is formed is electro-insulating and its thickness increases in time. This is why the copper contacts are covered with silver or tin.

For the pressed contacts there are also used **zinc**, **iron**, **platinum**, **gold**, **iridium**, **molybdenum**, etc. Several characteristics are presented in Table 2.15.

Metal	d₂₀₀c, [kg/m³]	θ _t , [ºC]	θ _f , [ºC]	ρ₂₀₂с, ×10 ⁻⁶ [Ωm]	λ _{20⁰C} , [W/m⋅K]	HB _{20°C} , [MN/m ²] Soft / Hard	U _{gauge} Ρt, [μV/K]
Ag	10500	960.8	2210	60	418	294/1030	7.4
Au	19300	1063	2970	43	296.78	176/638	7.2
Pt	21400	1769	4530	9,3	71.06	392/1177	0
Pd	12000	1552	3980	9	71.06	392/1177	- 5.7
Rh	12400	1966	4500	22	87.78	1275/3924	
Cu	8900	1083	2595	58	392.92	490/1128	7.8
W	19300	3420	5930	18	167.20	2452/4100	11.2
Мо	10200	2610	5560	19	142.12	1471/3924	14.5
Re	21000	3180	5900	5	71.06	2452/6867	
Ni	8900	1453	2730	14	91.96	784/2452	

Table 2.15. Characteristics for electroconductive materials used for electrical contacts.

Materials for breaking contacts are chosen according to the breaking power of contacts.

For contacts of low and medium power of breaking, there are used:

- **binary alloys**: Ag with Ni, Cu, Cd, Pd, Al; Au with Ag, Pt, Ni, Cu, In; Pt with Ag, Au, Ir, W, Ni; Cu with Ag, Au, Ni, Sn, Zn; W with Re; Mo with Re;

- ternary alloys, as basic element Ag, Au, Pt, Cu (Table 2.16).

Alloy	d₂₀₂c, ×10 ³ [kg/m³]	θ _t , [ºC]	ρ₂₀₂с, ×10 ⁻⁶ [Ωm]	λ _{20⁰C} , [W/m.ºC]	HB, [MN/m ²] Soft / Hard
Ag Ni 0,15	10.5	960	58	413	392/1079
Ag Cu 3	10.4	900	54	367	392/1373
Ag Cu 5	10.4	865	51	334	490/1471
Ag Cd 5	10.4	935	31	196	294/1177
Ag Pd 30	10.9	1160	6.5	58	637/1765
Au Ag 20	10.5	1035	10	326	343/1128
Au Ag 26 Ni 3	15.4	1010	9	58	931/1667
Au Ni 5	18.3	1000	7	83	981/1864
Au Pt 10	19.5	1100	8	54	441/1128
Pt lr 10	21.6	1785	4	29	1030/2109
Pt Ni 8	19.1	1650	3.4	-	1569/3433
Pt Cu 15	11.3	1370	2.5	-	882/2158

Table 2.16. The properties of some alloys used for electrical contacts.

 For the contacts with high breaking power, there are used materials as mixtures of metals-metals, and mixtures metals-nonmetals.

The metalo-ceramic materials are obtained by pressed powders thermally treated at high temperatures and high voltage as plates, which are applied as little plates on the contact devices. The combinations **Ag-Cd**, **Ag-CdO** have high electrical and thermal conductivities and low contact resistance even at low pressures. At the temperature of the electric arc ($\approx 900^{\circ}$ C), the cadmium oxide decomposes and the gas which result, O₂ and the vapors of Cd, prevent the development of the electric arc. In Table 2.21 are presented the characteristics of certain mixtures for the contacts.

The corresponding operation of the contacts depends not only on the nature of materials for the contacts, but also on the nature of materials for the contact support. The support must have a good thermal and electrical conductivity, high melting

58

2. Conductive Materials

temperature, good anticorrosive properties and a corresponding elasticity. As a support there are used the copper, the iron, nickel, and their alloys.

The mixture	d _{20⁰C} , ×10 ³ [kg/m³]	θ _t , [ºC]	ρ₂₀₂с, ×10 ⁻⁶ [Ωm]	HB _{20°C} , [MN/m ²] Soft / Hard
Ag Ni 10	10.1	960	54	490/1275
Ag W 30	12.0	960	40	637/1079
Ag Mo 50	10.2	960	31	481/1373
Ag Cd O 10	10.1	960	45	588/1373
Ag W C 20	11.2	960	40	784/981
Ag C 0,5	10.2	960	55	392/-
Cu W 40	10.8	1083	40	882/1275
Cu Mo 50	9.5	1083	40	1275/-

Table 2.17. Alloys for the electric contacts of high breaking power.

The sliding contacts are mechanically stressed at corrosion and at electric arc. The sliding contacts appear in electric machines to connect the rotor coils with stator electric circuits (example: between the brushes and the mechano-rectifier/ commutator, or the brushes and contact rings). The sliding contacts appear also between the trolley and the trolley cable in the electrical traction, in certain types of switchers.

The mechanic-rectifier slides are made out of **silver**, **copper**, **bronze** with **beryllium and cadmium**, etc., contact rings – out of **bronze**, **steel** and the trolley wires – out of **bronze** and **cadmium with beryllium**.

To make electrical machines brushes, as basic material it is used the **graphite**. The graphite crystallizes in hexagonal system, in which plans 001 and 002 are strongly consolidated, which will confer a high melting point, high heat of vaporization, and high thermal and electrical conductivities. As the distance between the plans 001-002 are much higher for the graphite brush, due to the friction, little parts are falling as "scales" which fill the microscopic holes of the contact surface forming an oiled foil which maintains the contact resistance reduced and constant.

From the chemical composition view point, the brushes are classified in:

- electro-graphite brushes;
- carbon-graphite brushes;
- natural graphite brushes;
- metal-graphite brushes, having 10-80% Cu, Ag, Pb, Sn.

In Table 2.18 are presented the main characteristics (density, hardness, resistivity, the admitted current density, the maximum sliding speed brush - mechanic-rectifier slides, the pressure for certain brushes from electro-graphite made in Romania.

Material type	d _{20°C} , ×10 ³ [kg/m ³]	Hardness, HR 10/60	ρ₂₀₂с, ∗10 ⁻⁸ [Ωm]	J _{ad} , [A/cm²]	<i>v_{max},</i> [m/s]	<i>p_{max},</i> [kN/m²]
EG R ₁	1.63-1.68	62-108	12-29	10	45	20-22
EG R ₈	1.60-1.75	100-120	30-50	10	55	18-22
EG R ₁₄	1.60-1.75	90-120	25-40	10	40	20-50
EG R ₁₈	1.55-1.70	90-115	30-52	10-12	50	18-30

Table 2.18.	Characteristics	of the materials	for the electrical	brushes.
Table 2.18.	Characteristics	of the materials	for the electrical	brushe

When the type of brush for a certain kind of electrical device is chosen, different types of materials are tested, in order to obtain a maximum life-time and to optimize the electrical and mechanical characteristics of the brush.

In figure 2.14 it is presented the general characteristic of the brushes usage from metal-graphite according to the pressure on the brush.





An optimal functioning implies the choice of an optimal working regime. Thus:

- If the specific pressures are too low (zone I from figure 2.14), electrical usage will appear which will disconnect the brush-mechanical commutator system,
- If the specific pressures are too high (zone III from figure 2.14), mechanical usage will appear also, that will pull out of function the system.
- The zone II indicates an optimal choice of the specific pressure on the brush, for the type of the specified brush (MG type).

2.5.3. Fuse Wires

The electrical fuses, due to their property of protecting the electrical devices against thermal and dynamic effects produced by electric currents of over-loads and short-circuits, replace the switches in certain conditions (for currents I < 630 A). The active element of fuses (formed of one or several wires or conductive plates connected in parallel) is connected in series with the protected electric circuit.

The choice of the material for the fusible is done taking into account the following requirements:

- The melting temperature must be as low as possible; according to the melting temperatures, there are the following series: Ni (1460°C), Cu (1083°C), Ag (960°C), Al (658°C), Zn (419°C), Pb (327°C), Sn (231°C);
- The material mass should be as small as possible, in order that the acting time to be reduced;
- ➤ To be hard enough;
- The ionizing temperature of the metallic vapors must be as high as possible in order that the extinction of the vapors to be easily done. The decreasing order of the ionizing temperatures gives the following series: W, Zn, Cd, Ag, Cu, Pb, Mg, Ni, Sn, Al;
- \succ To have a low price.

As none of these materials fulfill all these conditions, several materials are presented with their specific applications as it follows.

Silver is used in the construction of fuses for low currents, although it has a high price. Silver can be easily processed; it is almost non-oxidable and emits few vapors when it melts.

Electrolytic copper (CuE STAS 270/1-74) is the most widespread material for fuses. In case of high values of the nominal currents, the copper fuses plates are silvered by electrolytic film, in order to avoid the oxidation.

Lead is used only to produce fuses for low voltage because it is soft and it has a large mass but a very low melting point.

Zinc is rarely used as fusible element having a relatively high density and resistivity.

Aluminum is not so much widespread in the construction of fuses, because it forms solid oxides at the melting temperature and the ionizing temperature is very low.

The of rapid and extra-rapid fuses operation at short-circuits is conditioned by the presence of some strangled zones in the calibrated band where the current density is increased and it initiates the electrical arc. The electrical arc turns off due to the deionizing action of the environment, usually siliceous sand (STAS 5923-76), with a granulation of (0.3 ± 0.1) mm, having a minimal content of 99%SiO₂ and impurities of iron below 0.05%.

The fuse operation at overloading is based on the melting effect of a pill of eutectic alloy (Sn-Pb) at the temperature of approximately 200°C. This melting initiates the arc and leads to a dissolution of the material from which the fusible band is formed. The circuit is interrupted.

2.5.4. Thermocouples

A **thermocouple** is an assembly of two conductors, welded together at one end (warm junction) and free on the other side (cold side), being disposed at different temperatures. The thermocouple is a thermoelectric sensor. The choice of the materials

for thermocouples must be done according to the characteristic parameters of thermoelectric effects.

Thermoelectric effects are the transportation phenomena which appear as a result of the interdependence between thermal and electrical phenomena. Among these, the most important are the Seebeck effect, the Peltier effect and the Thomson effect.

In a circuit (Fig. 2.15a) formed of two different metals (A) and (B), with the contact points at temperatures of $T_1 \neq T_2$, a thermo-electromotive force will appear U_{AB} whose value depends on the temperatures of the junction points and on the materials which form the circuit. This phenomenon is called **Seebeck effect**. The thermo-electromotive force d U_{AB} that appears at the temperature variation d*T* of the contacts is:

$$dU_{AB} = \alpha_{AB} dT \tag{2.40}$$

where α_{AB} is a material parameter, called Seebeck coefficient.

If the temperature varies from T_1 to T_2 it will result:

$$U_{AB} = \int_{T_1}^{T_2} \alpha_{AB} \, \mathrm{d}T$$
 (2.41)

At the junction between the two metals (Fig. 2.15b), due to the difference of the contact potentials, an imprinted electric field will appear E_n . If the temperature of the contacts is equal, within the circuit the total current is null, because the two electric fields are of opposite sense (from the highest chemical potential towards the lowest chemical one). If the temperature of one of the contacts increases, ($T_2 > T_1$) the chemical potential from this contact increases, it also modifies the imprinted electric field $E_{i2} > E_{i1}$ and, in consequence, an electric current will appear.



Fig. 2.15. The Seebeck effect: a) the measurement assembly; b) establishing the thermo-electromotive force.

For the metals, the Seebeck coefficient α_S has the values of about 10⁻⁶ V/K. In the case of a couple of two metals which have their warm and cold points at different temperatures, the expression of the thermo-electromotive force will be described as:

62

$$U_{AB} = \int_{T_1}^{T_2} \alpha_A dT + \int_{T_2}^{T_1} \alpha_B dT = \int_{T_1}^{T_2} (\alpha_A - \alpha_B) dT = \int_{T_1}^{T_2} \alpha_{AB} dT$$
(2.42)

where $\alpha_{AB} = \alpha_A - \alpha_B$ is the difference between Seebeck coefficients of the two metals.

Table 2.19 indicates the series of thermo-electromotive force $U_{gaugePt}$ of metals opposed to the platinum as a neutral point and at a temperature of $100^{\circ}C$.

Table 2.19.	The series	s of thermo-el	ectromotive	force of	some	metals	compared [•]	to the
platinum or	ie.							

Material	U _{gaugePt} , [mV]	Material	U _{gaugePt} , [mV]
Bismuth	- 7,70	Silver	+ 0,67 + 0,79
Constantan	- 3,47 3,40	Cooper	+ 0,72 + 0,77
Cobalt	- 1,99 1,52	Steel V ₂ A	+ 0,77
Nickel	- 1,94 1,20	Zinc	+ 0,60 + 0,79
Mercury	- 0,07 + 0,04	Manganese	+ 0,57 + 0,82
Platinum	0,00	Iridium	+ 0,65 + 0,68
Graphite	+ 0,22	Gold	+ 0,56 + 0,80
Tantalum	+ 0,34 + 0,51	Cadmium	+ 0,85 + 0,92
Tin	+ 0,4 + 0,44	Molybdenum	+ 1,16 + 1,31
Lead	+ 0,41 + 0,46	Iron	+ 1,87 + 1,89
Magnesium	+ 0,4 + 0,43	Chrome-Nickel	+ 2,20
Aluminum	+ 0,37 + 0,41	Antimony	+ 4,70 + 4,86
Wolfram	+ 0,65 + 0,90	Tellurium	+ 50,0
Rhodium	+ 0,65		

The thermo-electromotive force between the two metals results as a difference between the values indicated in Table 2.19, this phenomenon being the base in constructing the traducers of temperature called thermocouples.

Table 2.20 indicates the characteristics of the most used thermocouples for which the cold weld terminal has the temperature of 0° C.

The temperature of warm weld point, [ºC]	100	500	1000	1500			
Electrodec peir	The thermo-electromotive force,						
Electrodes pair	[mV]						
Iron (+) - Constantan (-)	5,37	27,84	-	-			
Cooper (+) - Constantan (-)	4,25	27,40	-	-			
Chrome Nickel (+) - Nickel (-)	4,04	20,64	41,32	-			
Platinum Rhodium (10%) (+) - Platinum (-)	0,64	4,22	9,60	15,58			

The Peltier phenomenon consists of the heat absorption or emission in the contact zone of the two metals when the electric current passes through the zone. The absorbed or emitted Peltier heat dQ_{AB} depends on the current sense and it is proportional to the electric charge dq that passes through the contact:

$$dQ_{AB} = \pi_{AB} \cdot dq = \pi_{AB} \cdot I \cdot dt \tag{2.43}$$

and

$$dQ_{BA} = \pi_{BA} \cdot dq = -\pi_{AB} \cdot I \cdot dt \tag{2.44}$$

where $\pi_{AB} = -\pi_{BA}$ is called the Peltier coefficient.

The physical nature of the Peltier effect results in the case of a metalsemiconductor junction of *n* type (Fig. 2.16).



Fig. 2.16. The Peltier effect in the junction metal-semiconductor of *n*-type.

The Fermi level corresponding to the metal electrons is lower than the first energetic level of the conduction band BC of the semiconductor with $W_c - W_F$. Under the action of the electric current of intensity *I* oriented from the semiconductor towards metal, the electrons from the metal pass to the semiconductor, but they must surpass the barrier of potential ($W_c - W_F$) in order to reach conduction band BC. For this purpose they absorb energy from the crystalline lattice, cooling the contact. When the direction of the electric current is changed, the electrons pass from the semiconductor to the metal giving a difference of energy ($W_c - W_F$), which will warm the contact.

The Seebeck and Peltier effects are produced even when the contacts are missing, in a single material if it is non-homogenous.

The **Thomson effect** appears in a homogenous material where there is a gradient of temperature (∇T) and an electric current of intensity \overline{J} passes through. According to the direction of the current, there is an absorption or emission of heat. This effect is explained by the fact that in the warm zone the concentration of electrons is higher and it is lower in the cold zone ($n_1 > n_2$). A flux of electrons will appear. At their movement, the established internal electric field \overline{E}_i has opposed sense.

- If the electric current has the direction from the cold zone to the warm one, therefore in the same direction with *E_i* (Fig. 2.17a), the external electric field uses less energy to maintain the current because a part of the energy is supplied by the *E_i* field from the crystalline lattice and as a result the material cools.
- In the case when the current has the direction from the warm to the cold zone, opposite to the \overline{E}_i field (Fig. 2.17b), the external field must use a higher energy to maintain the electric current, which has as effect the warming of the conductor.



Fig. 2.17. The Thomson effect:

a) the conductor is cools down; b) the conductor is warms up.

The Thomson heat in the case of two materials A and B in contact is expressed as:

$$Q_{T}^{A} - Q_{T}^{B} = T \frac{d}{dT} \left(\frac{\pi_{AB}}{T} \right)$$
(2.45)

We have to mention that the thermo-electromotive force which will appear in the circuit of a thermocouple formed by two homogenous conductors is the result of the simultaneous action of the Seebeck and Thomson effects.

The most used thermocouples are those of Fe-Cu, Pt-PtRh, *chromel-alumel* alloy, which have high Seebeck coefficients and are less dependent on temperature.

2.5.5. Strain Gauges

The strain gauge is a transducer, which transforms the mechanical deformation in an electric signal, being an application of the electrical resistivity dependency of the materials with the mechanical deformation.

The transducer is composed from a resistive wire with a resistance of $(50\div1000) \Omega$. The resistive wire consist of one or more conductors connected in series, with very low diameters $(0.015\div0.02)$ mm, which are fixed to a support (paper or synthetic material) or incorporated in the support (Fig. 2.18).

The transducer attached to the device and submitted to mechanical stresses follows closely the deformations of the device causing a variation of the resistive wire. If the initial value of the electrical resistance is:

$$R = \rho \frac{l}{S}, \qquad (2.46)$$

where ρ is the electrical resistivity of the resistive wire, *I* is the length and *S* is the cross-section area of the wire.

After the mechanical stress, the resistor suffers a variation of resistance whose relative value is:

$$\frac{\mathrm{d}R}{R} = \frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}I}{I} - \frac{\mathrm{d}S}{S},\tag{2.47}$$

relation obtained by looking up the logarithm and derivation.





For a finite variation of the quantities, the relation (2.47) becomes:

$$\frac{\Delta R}{R} = \frac{\Delta \rho}{\rho} + \frac{\Delta I}{I} - \frac{\Delta S}{S}.$$
(2.48)

In this relation:

• the relative elongation of the wire $\frac{\Delta I}{I} = \epsilon$ is the specific deformation,

• the relative variation of the surface wire area is $\frac{\Delta S}{S} = -2\mu\epsilon$, where μ is Poisson coefficient

coefficient.

In order to evaluate the $\Delta \rho / \rho$ variation, it must be taken into account the expression of the electrical conduction law written in the tensor form, which in the case of low deformations of a cubic crystal is:

$$\boldsymbol{E}_{i} = \boldsymbol{\rho}_{ij} \boldsymbol{J}_{j} \cdot (\boldsymbol{\delta}_{ij} + \boldsymbol{\pi}_{ijkl} \boldsymbol{T}_{kl}) \tag{2.49}$$

where E_i is the intensity of the electric field, J_j - the current density, ρ_{ij} - resistivity, δ_{ij} - the unit tensor (Kronecker), π_{ijkl} - the 4th order tensor, called tensor of piezoresistivity, T_{kl} - tensor of mechanical stress.

The variation of resistivity on *j* direction is:

$$\frac{\Delta \rho}{\rho} = \sum_{k} \pi_{jk} T_{k}$$
(2.50)

which, in the case of mono-axial stress of the resistive wire, is:

$$\frac{\Delta\rho}{\rho} = \pi T = \pi\sigma = \pi E_{\gamma} \frac{\Delta I}{I}$$
(2.51)

where π is the piezoresistivity coefficient and *E* is the elasticity module.

66

It will result:

$$\frac{\Delta R}{R} = (1 + 2\mu + \pi E_{\gamma}) \cdot \frac{\Delta l}{l}$$
(2.52)

with which the coefficient of tensosensitivity of the wire is defined:

$$K = \frac{1}{\varepsilon} \cdot \frac{\Delta R}{R} = 1 + 2\mu = \pi E_{\gamma}$$
(2.53)

This coefficient depends on the tensoresistive material and the type of mechanically and thermally processing.

As materials for tenso-resistances, there are used those materials or alloys which satisfy the following requirements:

- To have a linear dependence of resistance with the mechanical deformation, in a wide domain;
- > To have a high tensosensitivity coefficient;
- Not to present hysteresis;
- To have high electrical resistivity;
- To have a variation coefficient of the resistance with the temperature as low as possible;
- To have a linear dilatation coefficient close to that of the material submitted to testing.

No material does completely correspond to these conditions.

Nickel has a high tensosensitivity coefficient, but it presents hysteresis during the modification of the resistance with the deformation.

The **chrome-nickel alloy** has a relatively high coefficient of variation of the resistance with temperature.

Constantan is one of the materials, which fulfils most of the conditions mentioned above, although it has a lower K than other materials. For constantan, μ =0.3, π E=0.4 with which K=2 (Fig. 2.19).



Fig. 2.19. The relative variation of the resistance $\Delta R/R$ according to its specific elongation for constantan: a) non-treated (K = 1.7 it remains constant until the wire breaks); b) thermally treated (K=2.2 for $\varepsilon \le 2.4\%$ and K=1 for $\varepsilon=2.4\div4\%$).

An increase of the tensosensitivity coefficient and its linearity domain is obtained by thermal treatment of annealing at 650°C for three hours.

Table 2.21 presents the properties of several materials used as resistances for strain gauges. It can be observed that the values of the tensosensitivity vary in-between very high limits.

Material	Composition, [%]	к	ρ₂₀²с, ×10 ⁻⁸ [Ωm]	α _ρ , ×10 ⁻⁶ [K ⁻¹]	U _{gaugeCu} , [μV/ºC]
Constantan	60 Cu, 40 Ni	2.0 2.1	45 51	10	43
Advans Copel	55 Cu, 45 Ni	2.1 2.4	47.6	10	43
Chrome- Nickel	80 Ni, 20 Cr	2.1 2.3	100 110	15	22
Izoelastic	38 Ni, 8 Cr, 52 Fe, 0,5 Mo, 3.5 Mn, Si, Cu, V	2.8 3.5	111	175	3.0
Nickel	100 Ni	2.1	11.5	-	-

Table 2.21. The properties of some materials used for strain gauges.

2.5.6. Thermo-Bimetals

Thermo-bimetals have the property of transforming a variation of temperature in a movement, due to the modified dimension. It is an extremely useful application of the controlled dilatation of two welded metallic slides (Fig. 2.20), which have different dilatation coefficients. As in warm atmosphere one of the components dilates more than the other, the more the thermobimetal bends at heating, the higher being the difference between the two-dilatation coefficients. The element with the lowest dilatation coefficient constitutes the **passive component** (1 in Fig. 2.20) and the one with the highest dilatation coefficient is the **active component** (2 in Fig. 2.20) of the bimetal.



1 - the active component; 2 - the passive component.

Bimetals are made of metals and alloys that satisfy the following requirements:

➤ The materials for active components must have a coefficient of linear dilatation as high as possible ($\alpha_l \ge 5 \cdot 10^{-6} \ 1/K$), for a large domain of temperatures;

- > The materials for passive components must have a low dilatation coefficient $(\alpha_l \le 5 \cdot 10^{-6} \text{ 1/K})$, for a large domain of temperatures;
- The active and passive components must be welded together adequate, in order to deform in the same time, which will impose the fact that the materials must have high melting points (> 1000°C), high elasticity modes (> 105 MN/m²), low temperature coefficients of elasticity module, high and comparable mechanical resistances;
- They must have the specific heat and the thermal conductivity as high as possible, so that the thermo-bimetallic element would absorb a large quantity of heat necessary for the deformation;
- For bimetals with direct electrical warming, the materials used must have high resistivity.

According to the value of the linear dilatation coefficient α_{I} in the domain of temperature from - 100°C to +500 C, the usable metals can be classified in:

- > Metals and alloys with high α_{I} , as: copper, cadmium, lead, aluminum, metals that have a low melting points and insufficient elasticity and mechanical resistance;
- Metals and alloys with low α_I, as: niobium, tantalum, wolfram and their alloys, materials which can be too expensive.

Generally the dilatation coefficients of metals are in inverse ratio to the melting temperature (Fig. 2.21).



Fig. 2.21. The dependence of the linear dilatation coefficient with the melting temperature of metals.

It can be noticed that although the iron and nickel have close values of $\alpha_I = (11 \div 13) \cdot 10^{-6}$ 1/K, the Fe-Ni alloys have α_1 of a much higher value, thus these alloys combined with Mn, Cr, Mo are used in the construction of active elements.

Figure 2.22 presents the dependence of the linear dilatation coefficient for Fe-Ni alloys with the nickel concentration. We can observe from the figure that the alloy with 20% Ni has the highest dilatation coefficient, of about $(18 \div 10^{-6})$ 1/K, and the alloy with 36% Ni (called *invar*) has the highest α_i coefficient 1.2 \cdot 10⁻⁶ 1/K. *Invar* is used in many cases as passive element.



Fig. 2.22. The dependence of the linear dilatation coefficient for the Fe-Ni alloys with the nikel content, at 20^oC.

On the other hand, it is stated that the thermal dilatation coefficients increase with the temperature, reaching almost constant values of about $20 \cdot 10^{-6}$ 1/K at (800÷900°C, the nickel composition being insignificant (Fig. 2.23).



Fig. 2.23. The dependence of the linear dilatation coefficient for the Fe-Ni alloys with the temperature.

2. Conductive Materials

The different dilatation of the Fe-Ni alloys is explained by their magnetic properties, which modify with the temperature. The magnetization and demagnetization that are connected to the reaching and the surpassing of the Curie point lead to a volumetric magnetostriction, which explains the obtaining of different dilatation coefficients.

To characterize the bimetallic slides, specific quantities are used, such as: sensibility, specific deformation, electrical resistivity, temperature domain and maximum admissible temperature.

A few types of bimetals with their characteristics are given in Table 2.22.

Bimetal	TB115/78	TB110/70	SP175	R15	TB97/16
Composition - active element - passive element	FeNi20Mn6 FeNi36	FeNi20Mn6 FeNi42	-	-	FeNiMn1 FeNi36
Specific deformation at $\Delta \theta = 20 \div 100^{\circ}$ C, $\times 10^{-4}$ [K ⁻¹]	0.155±5%	0.110±5%	0.215	0.095	0.095
Resistivity at 20ºC, ×10 ⁻⁸ [Ωm]	78±5%	70±5%	108	15	16
Villarceau coefficient, ×10 ⁻⁶	-	-	43	19	-
Elasticity module at 20ºC, ×10 ¹⁰ [N/m ²]	160	165	136	180	150
Operating temperature interval, [°C]	-20÷250	-20÷400	0÷175	0÷175	-20÷350
Maximum admissible temperature, [ºC]	400	450	400	500	350

Table 2.22. Characteristics of few materials for bimetals.

The thermo-bimetals have a large use in the construction of electrical devices: automatic switches, protection of electrical machines and transformers, time relays, regulators, temperature compensators, etc.
2.6. SUPERCONDUCTIVE MATERIALS

2.6.1. Characteristics of the Superconductive State

Superconductivity is the property of certain materials to oppose a very low resistant force to the passing of the electric current. The material state, characterized by the total absence of the electrical resistivity at the passing of the electric current is called **state of superconduction** and the respective materials are called **superconductors**.

The phenomenon was first described by Kamerlingh - Onnes în 1911, who discovered that the resistance of a mercury sample at temperatures below 4.2 K suddenly decreases to zero (Fig. 2.24).



Fig. 2.24. The decrease of the electrical resistance of the mercury for temperatures below 4,22÷4,15 K (Kamerlingh - Onnes diagram).

There are some characteristics connected to the state of superconduction:

→ When the resistivity of most of the metals decreases to zero, the temperature interval ΔT is very narrow and it narrows as the homogeneity degree of the material is increasing (for instance, for tin: ΔT =10⁻³ K, for Hg: ΔT =0.07 K). Therefore, it can be stated a well-defined value of temperature at which the passing to the superconductive state takes place. That is called **critical temperature of superconduction** T_c . Table 2.23 indicates the critical temperatures T_c for several pure super-conductive materials and the respective crystalline lattices.

Table 2.23. The critical temperature of superconduction and the type of crystalline structure for several metals.

Element	Al	Hg	In	Мо	Nb	Pb	V	W
<i>T</i> _c , [K]	1,19	4,15	3,4	0,92	9,2	7,2	5,3	0,012
Crystalline structure	CFC	Rhomb.	Tetrad.	CVC	CVC	CFC	CVC	CVC

- A series of metals reach the state of superconduction only at temperatures close to 0 K (for example: Au, Ag, Cu, etc.).
- Ferromagnetic metals are not superconductors. Moreover, a very small percentage of ferromagnetic materials pass in the superconductive state, for very low critical temperature of superconduction T_c.
- It also has been discovered that in the case of the semiconductive materials (Ge, Si etc.) the superconduction state is established only in superficial layers at high pressures.
- > The transition metals, such as **vanadium V** and **niobium Nb**, and their compounds $(V_2Ga, Nb_3Sn, etc.)$ are very important in technical applications, because the superconduction state appears at higher critical temperatures. The metallic compounds which present the superconductive state at higher temperatures have a crystalline structure resembling the wolfram β , of A₃B type (Fig. 2.25). In this structure the atoms of an A element occupy the faces of the cube, and the atoms of the other B element occupy edges of the elementary cube.



Fig. 2.25. The crystalline structure type A_3B characteristic for superconductors with a higher critical temperature of superconduction T_c .

- The experience shows that when passing from the normal state to the superconduction state, the crystalline lattice structure or the mechanical and optical properties do not modify. On the other hand, when the electrical resistivity suddenly decreases, a leap of the thermal conductivity and of the resistivity is produced and the magnetic properties of the metal are modified.
- > A constant magnetic field, perpendicular on the direction of the electric field applied to the conductor, influences the superconduction state. At the increase of the intensity of the magnetic field, there can be reached a value called the **intensity of the critical magnetic field** H_c , depending on the critical temperature T_c , at which the superconduction state disappears, the metal coming back to its normal state of conduction.





Fig. 2.26. The dependence of the intensity of the critical magnetic field H_c on the critical temperature T_c for several super-conductive elements.

Fig. 2.27. The critical density of the electric current J_c for a coil from different super-conductive materials according to the induction *B* of the magnetic field.

The dependence of the critical magnetic field on the critical temperature (Fig. 2.26) is given by the relation:

$$H_{c} = H_{co} \left[1 - \left(\frac{T_{c}}{T_{co}} \right)^{2} \right], \qquad (2.54)$$

where the quantity H_{co} represents the intensity of the critical magnetic field at the temperature T = 0 K and T_{co} is the critical temperature at H = 0.

The domain limited by the axes and the curves from figure 2.26 corresponds to those values of the magnetic field and temperature for which the state of superconduction can exist. Out of this domain, the material behaves like a normal conductor. There is defined a critical density of current J_c for which the state of superconduction disappears (Fig. 2.27).

Table 2.25 indicates the values of critical temperatures T_{co} , the intensity of the critical field H_{co} and the critical magnetic induction B_{co} for certain superconductors.

Table 2.25. The critical temperature T_{co} , the intensity of the critical field H_{co} and the critical magnetic induction B_{co} for certain superconductors.

Super- conductor	AI	Sn	Hg	۷	Pb	Nb	V₃Ga	Nb₃Sn	Nb ₃ (Al _{0,3} Ge _{0,2})
<i>T</i> _{co} , [K]	1.2	3.7	4.15	5.3	7.2	9.5	15	18	20.7
<i>H</i> _{co} , [kA/m]	8	25	33	105	65	156	20·10 ³	18·10 ³	32·10 ³
<i>B</i> _{co} , [T]	0.01	0.032	0.04	0.132	0.082	0.196	25	22	40

> Another property of the superconduction state is the absence of any magnetic field inside the massive superconductors. In the state of superconduction (where $H > H_c$ and $T < T_c$) the lines of the magnetic field are rejected out of the volume of the superconductor. This phenomenon is called **Meissner effect**. It will result that a material in the state of superconduction behaves like an ideal diamagnetic material, characterized by diamagnetic susceptibility $\chi_m = -1$.

All these characteristics show that the super-conductive state is a different state from the normal conduction state, being characterized by higher degree of order, therefore lower entropy.

2.6.2. Justification of the Superconduction State

The microscopic theory of superconduction considers that the responsible for the modification of properties in the state of superconduction is the gas of conduction electrons, which passes in another quantum state.

The very narrow temperature interval where the transition from the normal state to the superconduction state takes place indicates the fact that at critical temperature **it appears a strong correlation between the conduction electrons,** which in normal state behave relatively independent. The cause of this correlation is the interaction between the electrons.

According to the microscopic theory of superconduction (Bardeen, Cooper, Schrieffer), at temperatures below the critical values, the oscillations of the crystalline lattice are relatively small, therefore the influence of the atom movement on the lattice prevails.

Through the crystalline lattice, an interaction of attractive type is possible between the two electrons, which thus form a tied specific connection called **Cooper pair**. The Cooper pair appears only when the attraction energy between the two electrons of conduction is higher than the Coulomb rejection energy between them. The attraction energy between the electrons is established through the crystalline lattice.

The **coherence length** ξ is defined as being the distance at which the attraction force between the electrons of Cooper pair acts. The quantity ξ has a relatively high value $(10^{-7} \div 10^{-6})$ m, opposed to the distance of the free mean path of the conduction electron.

In figure 2.28, the process of forming the Cooper pair is described.



Fig. 2.28. Forming of the Cooper pair.

Thus, it is considered that at lower temperatures than the critical temperature T_c , an electron of conduction attracts the positive ions of the crystalline lattice from their neighborhood (which synchronically oscillate). The lattice deforms and the volume concentration of the positive charge in that area increases. A second electron of conduction is attracted to the area where the first electron is. Thus, the two electrons are connected through the crystalline lattice, forming a Cooper pair.

We must take into consideration that, according to the Pauli principle, the energetic states with anti-parallel spin are more stable than the ones with parallel spin. It will result that at the formation of the connected electron pairs it will also take part electrons with equal and opposed impulses (with anti-parallel spin). The Cooper pair has thus their spin equal to zero and, as a result, it does not submit to the **statistic Fermi-Dirac**, but to the **statistic Bose-Einstein**. According to this statistics, the number of particles which are in a given quantum state is unlimited. As a result, at temperatures $T < T_c$, most of Cooper pairs are found in the fundamental state of total null impulse.

The energetic spectrum of the electrons of normal conduction and of electrons grouped in Cooper pairs is different (Fig. 2.29).





Therefore, the electrons in normal conduction are disposed on energetic levels according to a distribution of Fermi-Dirac type (Fig. 2.29a). In the state of superconduction, the existence of Cooper pairs modifies the energetic spectrum, because the Cooper pairs have a lower energy than the individual electrons. A condensing of the energetic states is obtained (Fig. 2.29b) and this modifies the structure of the energetic bands: compared to the state of normal conduction, where the Fermi level is placed in an allowed energy band, at superconductors the Fermi level is in the middle of a forbidden band of ΔW_{sc} width (Fig. 2.29c).

The presence of the forbidden band ΔW_{sc} justifies the existence of the critical temperature:

- At T = 0 K are occupied the energetic states $W < (W_F \Delta W_{sc}/2)$. In order to pass from a super-conductive state to normal state, an electron needs to spend energy at least equal to ΔW_{sc} .
- When the temperature increases, the value of the energy ΔW_{sc} decreases. There is a critical energy $\Delta W_{sc} = 0$, for which the superconduction state disappears.

The modality in which the electric current is established in a superconductor can be explained starting from the particularities presented by the Cooper pairs. When an external electric field is applied, the two electrons of the pair with the impulses $\pm \overline{p}$ receive а supplementary impulse $\Delta \overline{p}$, therefore. the total impulse $(\overline{p} + \Delta \overline{p}) + (-\overline{p} + \Delta \overline{p}) = 2\Delta \overline{p}$, doesn't have the value zero and thus the Cooper pair moves in the space along with the collectivity of the pairs, determining a macroscopic electric current. If the external electric field does not have a value high enough, and as a result, the intensity of the electric field does not surpass the critical value, the electric current is stable, stationary.

The absence of the electrical resistance at superconductors is explained through the absence of the spreading processes of Cooper pairs on the phonons of the crystalline lattice. At normal conduction state, the electrical resistance appears as a result of the conduction electron scattering, due to the oscillations of the crystalline lattice. Such a process supposes the breaking of Cooper pair, because one electron is submitted to the process of scattering. The breaking of the pair needs an energy $W > 2\Delta W_{sc}$, which at temperatures $T < T_c$ cannot be supplied/ provided in an individual act of scattering. As a consequence, the whole collective of pairs in interaction move in the superconductor without being opposed resistance.

2.6.3. Applications of the Superconduction State

The properties of the superconductive state are useful in the realization of electrotechnical devices with special performances. Thus, there have been carried out **superconductor electromagnets** capable to produce magnetic fields of inductions over 20 T.

Superconductor coils are used for the excitation of powerful electric machines, such as turbo generators, magneto-hydrodynamic generators (MHD), for which fields are created with values of the magnetic induction from 4 T up to 6 T.

The transport of the electric energy on large distances in the continuous current can be done without losses by using the superconductive cables.

A **superconductive cable** is formed from a metallic mass which does not present superconductive properties, in which filaments of superconductive material are introduced. Thus, the conditions of stabilizing the superconduction state are improved. The transversal dimensions of the superconductor cable are very small comparing to the traditional cables for the transport of electric current. Example; for a superconductor cable having the conductive part of (1.9 x 3.8) mm, at the temperature of 4.2 K and at magnetic inductions below 5 T, the intensity of the critical current is $I_c = 2040$ A.

The transport lines in the alternative current are less economical, because in the alternative current, even in the superconductive state it will appear losses. Also, additional cooling stations are necessary to maintain the superconduction state.

The applications of the superconductors are multiple in the technique of the weak currents. **Cryoelectronics** deals with the use of superconductors in electronics and in computing technique. The Josephson effect allows the construction of cryogenic oscillators and some devices of ultra rapid commutation, used for memories in the computing technique.

New trends

The use of superconductors in practice is conditioned by the obtaining of a high value of critical temperature T_c . The actual theoretical research seems to indicate a limit of the value that the critical temperature can reach, limit which is situated much lower under the environmental temperature. But, in reality, the identified superconductive materials have T_c situated far away even from this limit.

Around the 1960 year, only a few superconductive metals were known. Afterwards, through systematic research, this property was found at a large amount of metallic elements (Table 2.26).

Element	Ti	U	Ра	Re	TI	Sn
<i>T</i> _c , [K]	0.39	0.68	1.4	1.698	2.39	3.722

Table 2.26. Critical temperatures of superconductivity at metallic elements.

Element	Mg	Та	V	La	Pb	Тс	Nb
<i>T</i> _c , [K]	4.153	4.483	5.38	6.00	7.193	7.72	9.20

Superconductivity can take place at high pressures. Under those circumstances, Se, Ga, As, P, Cr, Ba, Cs have this property. For the elements from the main groups, T_c does not surpass 7 K.

The alloys of the metallic elements lead to the obtaining of super-conductive materials with higher T_c (Table 2.27).

Table 2.27. Critical temperatures of superconductivity of some metallic alloys.

Compound	La₃In	V₃Ga	Nb ₃ Al	Nb₃Sn	Nb ₃ (Al _{0,8} Ge _{0,2})	Nb₃Ge, film
T _c [K]	10.4	16.5	17.5	18.05	20.05	23

In 1986, G. Bednorz and A. Mueller (laboratories IBM, Zurich) discovered the manifestation of superconductivity at a ceramic material, like La₂CuO₄, doped with barium, at a critical temperature not reached until then, T_{c} = 40 K. Other laboratories

78

2. Conductive Materials

confirmed the results and they determined the conducting of the research in the new domain of the super-conductive ceramics. This had as a result the identification of a very large number of compounds having T_c more and more high, up to125 K (Table 2.28).

Table 2.28. Critical temperatures of superconductivity of complex oxides.

Compound	Bi ₂ Sr ₂ CaCu ₂ O _{8-x}	YBa ₂ Cu ₃ O _{7-x}	Bi ₂ Sr ₂ Ca ₂ Cu ₃ O ₁₀	$TI_2Sr_2Ca_2Cu_3O_{10}$
<i>T</i> _c , [K]	85	93	110	125

These systems made possible the use of superconductors at the temperature of the liquid nitrogen (77 K), much more accessible.

The structure of these compounds is stratified and it presents a strong anisotropy in the electrical conduction at temperatures over T_c . These materials are microcrystalline, with large domains of pseudo-random orientation. Although the mechanism of stratification, responsible for higher values of T_c in complex oxides is still unclear, it is considered that important roles are played by the structural instabilities, the lattice defects, the oxygen vacancies and the atomic neighboring.

The use of superconductive ceramics with high T_c is limited at low densities of current, which they can pass, due to the porosity of the separation surface of the microcrystalline grains and the breaks resulted from the anisotropic thermal expansion. It must be noted that many of these materials become instable at temperatures over the critical one due to the ferro-electric transition.

Although the superconductivity in oxides has been experimentally proved, the mechanism of forming the Cooper pair electrons at relatively high critical values is not completely clarified.

2.7. RE-VALORIZATION OF THE METALS

Metals are necessary in all economical fields. In electrotechnics, metals are the main active materials used in automotive, electrical devices, pipes and electric cables. In electronics, although in a smaller quantity, metals represent the key-elements in the control of the electrical conduction. The new lighting systems contain a series of metals hardly fusible, obtained through special technologies.

Example: metals and alloys used in the construction of the lamps with discharges at high pressure (Fig. 2.30).

The component parts and the types of constructive materials used at a lamp of high pressure are presented in Table 2.29.

Nr.crt.	Components	Material
1	Flack	Thermo resistant glass
2	Screen	Silver, copper, lead
3	Fluorescent layer	Yttrium, vanadium
4	Filling gas	Argon, azotes
5	Shining layer	Iron, titan, zirconium
6	Grating layer	Aluminum
7	Charge wire	Molybdenum
8	Airtight folium	Molybdenum
9	Getter	Zirconium
10	Electrode	Wolfram
11	Emitter	Wolfram, barium and yttrium
12	Breaking contact	Wolfram
13	Getter	Phosphor
14	Discharge tube	Quartz glass
15	Filling gas	Argon, mercury
16	Reflector	Platinum, oxide of zirconium
17	Clamp	Nickel, iron
18	Protection resistance	Ceramic with aluminum oxide
19	Charge wire	Molybdenum
20	Support	Nickel, iron
21	Airtight layer	Copper, wolfram,
22	Charge wire	Copper, nickel
23	Support	Lead glass, boron
24	Insulating base	Silicone resin
25	Insulator	Ceramic, porcelain
26	Base	Brass
27	Insulating support	Ceramic, porcelain
28	Metallic contact	Lead alloy, silver, tin

Table 2.29. Components and materials used in the construction of electric lamps with discharges at high pressure.

80



Fig 2.30. Components and materials used in the construction of electric lamps with discharges at high pressure.

Note:

In the construction of the lamp with high pressure discharges are used over 12 metals and their alloys.

Metals and their alloys characterize the industrial society and its development. However, an irrational use will lead to the loss of natural resources. This is why it is absolutely necessary the development of the techniques and technologies of reducing the use of the raw materials and the re-use and recycle of the waste metallic materials.

Figure 2.31 shows the possible circuit of metals in the production of manufacturing goods.



Fig. 2.31. The circuit of metals.

The process of obtaining metals and their alloys contains complex stages, starting with the extraction of minerals from the mines and ending with their transformation. Metals and their alloys can be transformed through different industrial methods in finite products (industrial or domestic). After the expiration of their life-time, it will result **mixtures of metallic waste**. In order to ensure the circuit of metals, producers and consumers of materials have to act together to **collect, select and transform** the metallic waste.

Reintroducing the metallic waste in the circuit of metals is the only sustainable solution for a development in time.



Chapter **3**

SEMICONDUCTIVE MATERIALS

Contents

This chapter presents the particularities of the electrical conduction in this class of materials, the factors that influence the electrical conductivity, and other material parameters that characterize the transport phenomena and which are the operating basis of the semiconductor devices.

The properties and performances of the semiconductive materials are also presented taking into consideration their main domains of use.

Course Objectives

- •To exemplify some semiconductive material classes.
- •To explain the formation of the energy bands, and to classify the crystals according to Fermi level position.
- •To describe the particularities of the electric conduction in intrinsic semiconductors using the physical model and the energy band model.
- •To describe the particularities of the electric conduction in extrinsic *n*-type and *p*-type semiconductors using the physical model and the energy band model.
- •To interpret the influence of the extrinsic factors on the electric conductivity, such as temperature, magnetic field and pressure.
- •To explain the unidirectional conduction property of the *n-p* junction, and to describe the properties and performances of the semiconductive materials.

3.1. ELECTRIC CONDUCTION IN SEMICONDUCTORS

3.1.1. General Presentation

Semiconductive materials are materials that have the value of their electrical conductivity comprised in the interval $(10^{-6} \div 10^5) \ 1/\Omega m$, strongly dependent on the external conditions (temperature, electric field, magnetic field, etc.) and on their internal structure (the nature of the chemical elements, defects, impurities, etc.).

A series of chemical elements and their compounds are considered semiconductive materials:

- **Chemical elements** from the 13 17 column of the periodical element system (Table 3.1);
- Binary chemical compounds of the elements from the I VII groups (Table 3.2);
- Ternary chemical compounds (such as CuSi₂P₃, In₄SbTe₃, AgBiSe, CdSnAs₂, ZnSnAs₂, etc.);
- Quaternary chemical compounds (CuPbAsS₃, etc.), where in order to obtain semiconductor properties it is necessary the presence of a semi-metal – for example, P, Sb, Bi, As, with σ = 10⁴÷10⁶ [Ωm]⁻¹;
- Chemical combinations of rare earths (LaTe, EuS, EuSe, EuTe) and of actinides (Th₃As₄, Use, etc.);
- Organic compounds (anthracene, methylene blue, etc.).

The properties of the semiconductive materials are directly connected to the nature of the constituent atoms and to their chemical bond. The typical bond is the **pure covalent bond**, which appears at the homo-polar atomic crystals (with a single type of atoms) of the tetravalent elements, as: C, Si, Ge, α -Sn.

For the other semiconductive materials, the chemical bond is hybrid, of a covalent-ionic type. A high level of ionization determines the existence of the dielectric properties, the semiconductor behaving like a dielectric.

The semiconductive materials have specific crystalline structures such as:

- cubic structure of diamond type (C, Ge, Si, Sn), glance type (SiC, GaSb GaAs, etc), wurzit type (AIN, InN, ZnS, ZnSe, ZnTe, CdS, CdSe, etc.);
- rhombohedral structure or trigonal (I₂S, Bi₂Se, Sb₂Te₃);
- six-angled structure(Mg₃Sb₂, GaSe, ZnSb, Cu₂Te);
- orthorhombic structure (CdAs₂, SnS, SnSe, Ag₂Te, SbSe);
- monocline structure (LiAs);
- polycrystal structure (As₂Se₃, AsS₃).

Table 3.1 presents the chemical elements that in crystalline state have semiconductor properties and their main characteristic quantities: Z – the order number, ΔW_i – Fermi forbidden interval, and ρ_i – intrinsic resistivity.

Λ

12	13	14	15	16	17
	5 B *	6 <mark>C</mark> *	7 N	8 O	9 F
		ρ=109 Ωm			
	∆Wi =1.1eV	∆Wi =5.4 eV			
	13 AI	14 <mark>Si</mark> *	15 P *	16 <mark>S</mark> *	17 CI
		ρ=2,3.103 Ωm			
		∆Wi =1.12 eV	∆Wi =1.5 eV		
30 Zn	31 Ga	32 Ge *	33 <mark>As</mark> *	34 <mark>Se</mark> *	35 Br
		ρ=4.7.10-1 Ωm			
		∆Wi =0.68 eV	ΔWi =1.2 eV	ΔWi =1.7 eV	
48 Cd	49 In	50 <mark>Sn</mark> *	51 <mark>Sb</mark> *	52 Te *	53 *
		<i>∆W_i</i> =0.01 eV	<i>∆W</i> ^{<i>i</i>} =0.12 eV	<i>∆W</i> ^{<i>i</i>} =0.36 eV	<i>∆W_i</i> =1.25 eV
80 Hg	81 TI	82 Pb	83 Bi	84 Po	85 At

Table 3.1. Semiconductor chemical elements.

* Semiconductive chemical elements.

Table 3.2 presents some of the semiconductive materials that have multiple technical applications and their main characteristics: a – constant of the crystalline lattice, ε_r – relative permittivity, ΔW_i – width of the Fermi forbidden interval at different temperatures *T*.

Table 3.2. Properties of some elements and chemical binary combinations with semiconductor character.

Semiconductor	Crystalline	а	0	ΔW_i	[eV]
element	structure	[Á]	ε _r	<i>T</i> =300 K	T = 0 K
С		3.56	5.5	5.47	5.51
Ge	diamond	5.65	16	0.68	0.89
Si		5.43	11.07	1.12	1.16
Sn		6.48	-	-	0.08
SiC	glance	4.35	10	3	3.1
GaSb		6.09	15	0.67	0.8
GaAs		5.65	10.9	1.43	1.52
GaP	alanco	5.45	10	2.24	2.40
InSb	giance	6.47	17	0.16	0.26
InP		5.86	14	1.29	1.34
InAs					0.36
CdS		5.83	9.3	2.42	2.56
CdSe	alance	6.05	10	1.7	1.85
ZnS	giance	5.42	8.32	3.6	3.7
HgTe		6.46	-	-	-
PbS	Na Cl	5.93	17	0.41	0.34
PbTe	Na Cl	6.46	30	0.32	0.24

Notes:

- In order to justify the processes of the electrical conduction (in contrast with metallic crystals) in semiconductor crystals new parameters are needed, such as: the Fermi forbidden interval and the Fermi energy. There is a direct correlation between these measurements and resistivity. In Table 3.1 it can be noticed that the Fermi forbidden interval increases on the columns from bottom to top and from left to right and, in the same way, the value of resistivity increases. Example: ρ_{Si} > ρ_{Ge}, ρ_{Ge} > ρ_{As}, etc.
- 2. If the value of the electric permittivity for semiconductive materials is close to that of the dielectric crystals (which demonstrates that there isn't any qualitative difference between **dielectrics** and **semiconductors**, as regards the width of Fermi interval), in the case of semiconductor crystals, this one has smaller values, namely $\Delta W_i < 3 \text{ eV}$ compared to the case of dielectric (insulating) crystals, where $\Delta W_i > 3 \text{ eV}$.
- 3. The crystalline structure presence is not necessary for a material to be semiconductor (semiconductive materials such as As₂Se₃ or As₂Te₃ are amorphous substances).
- 4. A characteristic of semiconductors is the fact that the concentration of free charge carriers can be modified, which modifies also the values of conductivity and resistivity of the material.
- 5. In the case of semiconductors, the resistivity is strongly dependent by temperature.

3.1.2. Energy States in Crystals

Almost all processes of electrical conduction in metals can be explained through the classical model of electrical conduction.

In the case of those materials where do not take place intense processes of electrical conduction (the case of crystals with ionic or covalent bonds), in which the concentration of the free electrons is much more reduced than that of the electrons strongly bonded to the atoms, this model isn't sufficient anymore. A unitary treatment of the conduction processes in conductive, semiconductor crystals and the isolated ones is given by **the theory of the energy bands**.

The model of energy bands considers that, because of the order at a distance of the constituent atoms, in crystals the energy of the electrons groups in permitted bands and forbidden bands (Fig. 3.1), their order depending on the electronic structure of the constituent elements.



Fig. 3.1. The structure of energy bands in crystal.

The formation of the energy bands' structure in crystals can be explained qualitatively, on simple physical grounds, considering the hypothetical case of the formation of a crystal in the proximity of the constituent atoms.

Example:

In the hypothesis of formation of the one-dimensional crystal of **lithium** (Z=3), it is considered the case of 2 distant lithium atoms (Fig. 3.2a), then the case of 2 close atoms (Fig. 3.2b), the case of 5 close lithium atoms (Fig. 3.2c), then the case of *N* close atoms that form the one-dimensional lithium crystal (Fig. 3.2d).

- The electronic structure of a single lithium atom in normalized state is 1s² 2s¹ 2p⁰, corresponding to the existence of two occupied energy levels (Fig. 3.2a). When the two lithium atoms are considered, at long distance, the energy levels don't interact, each level being occupied according to the case of the free atom;
- At the approach of the two atoms (Fig. 3.2b), it appears the **degeneracy of levels** (it cannot be more than two electrons on one orbital level), so, two 1s sublevels correspond to the level 1s, two 2s sublevels correspond to the level 2s, etc. The energy distance between the sublevels that proceed from the same level is very reduced in comparison with the distance between the levels 1s and 2s, between 2s and 2p, etc.;
- Generalizing for a number of 5 lithium atoms situated at low distance, it appears that for each of the orbital levels 1s, 2s, 2p, etc., 5 sublevels will be obtained (Fig. 3.2c);
- For a number of *N* lithium atoms, it appears that every orbital level 1s, 2s, 2p, etc. will split in as many sublevels as the atoms in the system, namely in *N* sublevels. Thus, to every orbital level inside the isolated atom it corresponds *a* **permitted energy band** (Fig. 3.2d) in the crystal, its sub-levels being occupied with electrons according to the **Pauli's principle** (on one orbital level there can't be more than 2 electrons) and **Hund's rule** (the levels of the lowest energy will be the first to be occupied). **A completely occupied band** (band 2s) will be obtained, followed by **bands free of electrons** (unoccupied with electrons).



Fig. 3.2. The formation of the energy bands in one-dimensional Li crystal: a) two distant lithium atoms; b) two lithium atoms in interaction; c) five close lithium atoms in interaction; d) *N* close lithium atoms.

This is the typical situation for **metals**: the existence of some permitted completely occupied bands, followed by an incompletely occupied band and then by bands free of electrons. The fraction of occupied sublevels depends on the type of the level, out of which the band proceeds from (s, p, d...) and on the valence of the constituent atoms. The last level that can be occupied with electrons is **the Fermi level**, noted with $W_{\rm F}$.

A different situation appears in the case of the insulators.

Example:

If is taken the case of **helium** crystal (helium appears in crystalline state at very low temperatures and under pressure), having the order number Z=2, it results the electronic structure of the free atom $1s^2 2s^0 2p^0 \dots$

- At the closeness of 5 helium atoms, the energy levels split into 5 sublevels, the sublevels 1s are completely occupied with electrons and the sublevels 2s, 2p, etc. are free of electrons (Fig. 3.3a);
- At the approach of *N* helium atoms (one-dimensional He crystal) it appears a permitted completely occupied energy band that proceeds from the 1s level and permitted completely free bands, proceeded from 2s, 2p, etc. levels, unoccupied by electrons (Fig. 3.3b).



Fig. 3.3. Energy bands in the helium crystal: a) at the closeness of 5 helium atoms; b) at the closeness of *N* helium atoms.

Conclusions:

- 1. The existence of some permitted completely occupied bands, followed by an unoccupied band is specific to **the insulators** and to **the semiconductors**. The last completely occupied band is **the valence band** BV and the very next unoccupied band is **the conduction band** BC. The forbidden band between BV and BC defines **the Fermi forbidden interval**, noted with ΔW_i (band gap).
- 2. The distinction between different types of crystals is given by the difference in width of the Fermi forbidden band. Thus, in the case of **metals**, the Fermi forbidden band has zero value (ΔW_i =0). In the case of **semiconductors**, the width of Fermi forbidden band ((ΔW_i = \neq 0) is much more reduced than in the case of the **insulating**

electric crystals, a fact that makes possible the thermal excitation of the electrons from semiconductors, from BV to BC.

Note:

The way of construction of the energy bands (by the hypothetical approaching of the constituent atoms) is not always applied: the occupation of the permitted bands by electrons can't be directly correlated with the occupation of the orbital levels from which these bands proceed, due to **the overlapping of some bands** from different orbital levels.

Example:

Thus, in the case of the **beryllium** crystal (*Z*=4), for which the electronic structure of the isolated atom is $1s^2 2s^2 2p^0$..., where the usual structure in bands is maintained, it will result 2 completely occupied permitted energy bands 1s and 2s, followed by the 2p band, that is completely free. So the beryllium crystal should be an insulating crystal (Fig. 3.4a). The experience demonstrated that the beryllium is a metal: in the formation of the beryllium crystal, the 2p band **partially overlaps** the 2s band, resulting **an incompletely occupied hybrid band**, specific to the bivalent metals (Fig. 3.4b).



Fig. 3.4. Energy bands in the beryllium crystal: a) hypothetical case of the approach of 5 beryllium atoms; b) formation of the hybrid band 2s+2p in the real beryllium crystal.

A slightly different case from the previous one appears at the tetravalent elements: **carbon, silicon, germanium**, which are not conductors as it may result from the considered model, on the contrary, they are electro-insulating crystals (semiconductors) because of the **bands' interaction** of type s and p.

Example:

Carbon (Z=6), has the electronic structure of the free atom $1s^2 2s^2 2p^2$... When the crystal is formed with *N* close atoms, firstly the splitting of the levels (the formation of bands) takes place, maintaining the *2N* states with *2N* electrons (state 2s) and the *6N* states with *2N* electrons (state 2p) (Fig. 3.5.).

- For lattice constants *a* (inter-atomic distance) between 6 and 7.5 Å, which correspond to the crystalline structure of **carbon-graphite** type, the overlap of the bands 2s and 2p takes place. The structure with a completely occupied band (1s), followed by an incompletely occupied band (hybrid band 2s+2p), explains the conductive character of carbon-graphite.
- At inter-atomic distances, smaller than 6 Å, these common bands split into two hybrid sub-bands (a mixture of s and p states), the superior one completely free, the inferior one completely occupied, which is a characteristic case for **the carbon-diamond** (Fig. 3.5). The structure of 1s and 2s bands, completely occupied, followed by band 2p, completely free, explains why the carbon in the diamond structure with *a*= 3,56 Å is an electro-insulating material, having a high width of the Fermi forbidden band ($\Delta W_i = 6 \text{ eV}$).



Fig. 3.5. Energy bands in carbon crystal with structure type diamond (insulating) respectively with graphite structure (conductor).

In the same way, explanation can be found regarding the semiconductor character of the **silicon** ($\Delta W_i = 1.1 \text{ eV}$ at inter-atomic distances a = 5.42 Å) and **germanium** ($\Delta W_i = 0.7 \text{ eV}$ at a = 5.62 Å), for which it takes place the overlap of the bands 3s with 3p respectively, 4s with 4p and a forbidden interval results, as in the case of the carbon diamond, but with a small width.

3.1.3. Conduction Mechanism in Energy Bands Theory

In the theory of energy bands, the big differences between the values of electrical conduction (in the case of conductive crystals: $10^8 \div 10^6$ [Ω m]⁻¹, in semiconductors: $10^5 \div 10^{-7}$ [Ω m]⁻¹, and in dielectrics: $10^{-8} \div 10^{-18}$ [Ω m]⁻¹) as well as, the influence of some external factors (temperature, electric and magnetic fields, radiations, etc.) are explained on the basis of the different energy spectrum of the electrons in the

crystal and the different way of occupancy with electrons of the energy states in crystals.

Thus, figure 3.6 show the structure of the energy bands in all the three categories of materials, where the position of the Fermi level (with the significance of the last level occupied with electrons) and the width of the Fermi forbidden interval, have an important role.



Fig. 3.6. The classification of crystals with the criterion of the position of the Fermi level: a) conductive crystals; b) semiconductive crystals; c) electro-insulating crystals.

In the figure 3.6 it can be observed that the Fermi level is situated either in a permitted band (for the conductors), or in a forbidden band (for semiconductors and insulating materials) of different width.

This one permits the classification of the crystals from the point of view of the width of the Fermi forbidden band (band gap) ΔW_i in:

- > Electrically conductive crystals, where $\Delta W_i = 0$;
- > Semiconductive crystals, where $\Delta W_i < 3 \text{ eV}$;
- > Electroinsulating crystals, where $\Delta W_i > 3 \text{ eV}$.

The justification of the processes of electrical conduction in the different categories of crystals with the quantum theory of electrical conduction takes into consideration the following data:

- The electrons from a completely occupied band don't contribute to the production of the electrical current. Thus, at the application of an electric field, the electrons situated in a completely occupied band can't be accelerated (they can't pass on superior energy levels);
- Only the electrons from incompletely occupied bands participate in the production of the electrical current. Thus, by applying an electric field, the electrons situated in an incompletely occupied band will accumulate energy (they can stand only on the unoccupied superior levels from the incompletely occupied band), a fact that macroscopically corresponds with the production of the ordered motion, so with the establishment of the electric current.

The different values of electrical conductivity for different classes of crystals can be justified as follows:

- In the case of semiconductive and insulating crystals, where the Fermi level appears in a forbidden band, because there are only completely occupied bands, there is no possibility of producing electrical current. The electrical conductivity is extremely reduced. Only at relative high temperatures or in strong electric fields, the electrons from the valence band BV can pass to the conduction band BC (by thermal or electric excitation, etc.). Thus, incompletely occupied bands are formed, whose electrons can contribute to the production of electrical current.
- In metallic crystals, where the Fermi level is situated in a permitted band, because there is an incompletely occupied band, a supplementary energy (activation energy) isn't needed for the excitation of electrons. Thus, even a very small excess of electrical energy can lead to the acceleration of the electrons and to the establishment of the electric current. The value of electrical conductivity in metals is high.

Notes:

- There are some particularities of electrical conduction in semiconductive materials, according to their types.
- For that kind of semiconductive materials that have no impurities and form the class of intrinsic semiconductive materials, the processes of conduction are difficult to control.
- For that kind of semiconductive materials that have impurities added under control and form the class of extrinsic semiconductive materials, the processes of conduction can be controlled, permitting thus the realization of multiple applications in electronics.

3.2. INTRINSIC ELECTRIC CONDUCTION

3.2.1. Intrinsic Conduction – Physical Model

An intrinsic semiconductor is a pure semiconductor, whose conductivity is determined by the character of the covalent bond and the crystalline structure.

Example:

Silicon and germanium crystals, without impurities (or with undetectable impurities), which are in the 14th group in the periodic table (Table 3.1, Table 3.2), crystallize in the diamond cubic structure, with highly directional covalent bonds. In this structure, each atom contributes with four valence electrons.

The electrical conduction, named **intrinsic conduction**, can be justified either **with a physical model**, where the phenomena are examined at the level of the chemical bonds in crystals, or with **the energy bands model**, where the processes are examined energetically.

92

The case of an ideal silicon mono-crystal is considered at different conditions of temperature and electric field. In figure 3.7, the circles represent **the silicon positive ions** and the interconnecting lines are **the pair electrons of the covalent bonds**.



Fig. 3.7. The physical model of conduction in intrinsic semiconductors. The case of the silicon mono-crystal in a plane representation: a) at 0 K temperature, in the absence of the electric field; b) at a temperature other than 0 K, in the absence of electric field; c) at a temperature other than 0 K and in the presence of the electric field.

In figure 3.7, the direction and the sense of electric field intensity E is shown.

Cases:

- At 0 K temperature and in the absence of the electric field, all the covalent chemical bonds in the crystal are compensated (Fig 3.7a). The electrons being strongly tied to the crystal atoms, there are no free electric charges, and thus, even if an electric field is applied, the electric current can't be established. The semiconductor behaves like a perfect insulating material.
- At temperatures different from 0 K and in the absence of the applied field, it is possible for the electrons to accumulate enough energy and to leave the covalent bond (Fig. 3.7b). Thus, some of the covalent bonds will break, and it appears quasifree electrons and non-compensated bonds.

Note:

The resulted electrons move chaotically, equally in any direction in the crystal (if there aren't structure defects). Their number is equal to that of the non-compensated (unsatisfied) bonds; in their region **an excess positive charge** results, equal in absolute value with that of the resulted free electrons. But, the total charge remains zero on the unit of volume ΔV , like before to these bonds breaking. The formation of *free electrons* and *of vacant bonds* doesn't affect the electrical neutrality of the crystal.

 At the temperatures higher than 0 K and in the presence of an exterior electric field, the free electrons and the non-compensated covalent bonds will contribute to the production of the electric current (Fig. 3.7c).

Thus, over **the movement of thermal agitation** of free electrons it overlaps an **orientated movement**, with an opposing sense to that of the applied electric field

(under the electric force $\vec{F}_e = -q_o \cdot \vec{E}$, the free electrons will move from right to left in the figure 3.7).

A part of the quasi-free electrons will be attracted by the positives zones of the noncompensated covalent bonds and will be captured by these, realizing the compensation of the bonds. However, on the direction of the electric field, other bonds remain unsatisfied (by the departure of the electron that compensated the unsatisfied bond). In this way, a flow of non-compensated covalent bonds is established in the direction of the applied electric field of intensity <u>E</u>.

Conclusion:

The ordered motions of quasi-free electrons and of the non-compensated covalent bonds generate the electric current in semiconductive crystals.

3.2.2. Intrinsic Conduction – Energy Bands Model

The mechanism of the intrinsic electrical conduction can be described qualitatively and quantitatively with the energy bands model in the crystal. This model considers the energy bands structure of the silicon crystal, where the permitted energy bands alternate with the forbidden bands (Fig. 3.8).



Fig. 3.8. The energy bands model of electrical conduction in intrinsic semiconductors: a) at 0 K temperature; b) at $T \neq 0$ K, in the absence of electric field; c) the formation of the electron-hole pairs in semiconductor.

Cases:

At low temperatures and in the absence of electric field (Fig. 3.8a), the valenceband BV of the crystal is completely occupied with electrons and the conduction band BC is completely free of electrons. At temperatures close to 0 K, the thermal energy isn't sufficient enough for an electron from BV to be able to make transitions in BC. This case corresponds to the absence of electrical conduction processes, because in the unoccupied energy band (BC band), as well as in the completely

94

occupied bands (the BV band, here), at the application of an electric field, the processes of conduction can't appear. It results that at low temperatures, the silicon mono crystal behaves like **a perfectly insulating crystal**.

- At normal temperatures and in the absence of the electric field (Fig. 3.8b), certain electrons from BV will make transitions in BC, if the thermal energy has bigger values than the value of Fermi forbidden interval (ΔW_T > ΔW_i). Thus, as the temperature rises, the superior levels from BV become free of electrons and the inferior levels from BC are occupied with electrons.
- At normal temperatures and in the presence of an exterior electric field (Fig. 3.8c), the free electrons from BC will be accelerated, contributing to the production of the drift motion.
- Electron-hole pair formation justification in valence band.

Fig. 3.8c indicates also the formation process of the pair *electron - hole* in the energy bands model.

Thus, after the transition of the electrons in BC, the BV valence band is an energy band almost completely occupied with electrons (the electrons are marked with blue-dark circles), the unoccupied levels can be completed (imaginary) with electrons (electrons marked with blue circles). In this way, the valence band BV becomes a completely occupied energy band.

But, in order to maintain an balance (of mass and of electric charge), in the crystal must be added simultaneously another category of particles (marked with + red circles), on the levels completed with electrons, thus annulling the contribution of the added electrons. The added particles have the effective mass and the electric charge of opposite sign compared to those of the added electrons. These particles are named **holes** and they are characterized by the effective mass of the opposite sign with that of the electron and by the electric charge + q_o (the electrons have the charge - q_o).

Thus, the valence band, being a completely occupied band, will not contribute to the production of electric current due to the electrons. On the other hand, the holes from the valence band BV will contribute to the process of conduction because, for them, the energy band BV is incompletely occupied.

Conclusion:

- The quasi-free electrons and the holes in valence band BV are particles with meaning only in the semiconductor energy band theory.
- In the intrinsic semiconductors, under thermal excitation, there will be electrons in the conduction band BC equal in number with their hole-pairs from valence band.
- The holes from the valence band and the electrons from the conduction band realize the intrinsic electrical conduction.

MN 3.2.3. Electric Conductivity in Intrinsic Semiconductors

During the electrical conduction in intrinsic semiconductors, the current density \bar{J} is equal to the sum of the current density of the electrons \vec{J}_n and of the current density of the holes \vec{J}_p .

$$\overline{J}_{i} = \overline{J}_{n} + \overline{J}_{p} = nq_{o}\overline{v}_{n} + pq_{o}\overline{v}_{p}, \qquad (3.1)$$

where:

n is number of the electrons from BC per unit of volume,

p is number of the holes from BV per unit of volume,

 q_o is absolute value of electron and hole charge, $q_o = 1.60 \cdot 10^{-19}$ C,

 \vec{v}_n, \vec{v}_p are drift velocities of electrons and holes, respectively.

Dividing J with the electric field intensity E, the expression, in module, of the **intrinsic electrical conductivity** results:

$$\sigma_i = \frac{J}{E} = \frac{nqv_n}{E} + \frac{pqv_p}{E}.$$
(3.2)

The quantities v_p/E and v_p/E are called **the electron and hole mobilities** since they measure how fast the electrons and holes in semiconductors drift in an applied electric field. The symbols μ_n and μ_p are used for the mobilities of electrons and holes, respectively.

Substituting electron and hole mobilities for v_n/E and v_p/E in Eq. (3.2) enables the electrical conductivity of a semiconductor to be expressed as:

$$\sigma_i = \sigma_n + \sigma_p = nq_0\mu_n + pq_0\mu_p \tag{3.3}$$

Conclusion:

In a pure semiconductor, the total conductivity is given by the sum of the conductivity σ_n due to the electrons from BC and the conductivity σ_p due to the holes from BV, being determined by the concentration of the electrical charges and their mobilities.

Temperature influence on intrinsic conduction

In intrinsic semiconductors, electrons and holes are created in pairs and thus the number of conduction electrons *n* equals the number of holes *p* produced, so that $n=p=n_i$ thus, the equation (3.3.) now becomes:

$$\sigma_i = n_i q_0 (\mu_n + \mu_p). \tag{3.4}$$

where n_i is the intrinsic concentration of mobile electric charge carriers.

The calculation of electrons concentration from the conduction band BC and of the holes from the valence band BV is made by taking into consideration the quantum theory applied to the energy bands model in the crystal.

The relation that gives the electron concentration from BC is:

$$n = N_c \exp\left[-\frac{W_c - W_F}{kT}\right],\tag{3.5}$$

where:

 N_{C} represents the number of energy states from BC, dependent on the electrons mass and on the temperature,

 $\Delta W_n = W_c - W_F$ is the width of the electron activation energy,

W_C is the lowest energy level in BC.

This relation demonstrates that the electron concentration in BC rises exponentially with the temperature and decreases exponentially with the increase of the Fermi forbidden interval.

The concentration of holes from the valence band BV is:

$$p = N_V \exp\left[\frac{W_V - W_F}{kT}\right],\tag{3.6}$$

where:

 N_V represents the number of states in BV;

 $\Delta W_{\rho} = W_{V} - W_{F}$ is the width of the hole activation energy,

 W_V is the highest energy level in BV.

For this category of semiconductors, the electrons concentration is equal in number with that of the holes:

$$n = p = n_i, \tag{3.7}$$

where n_i represents the intrinsic carrier concentration.

It results:

$$n \cdot p = n_i^2 = N_V N_C \exp\left[-\frac{W_C - W_V}{kT}\right],$$
(3.8)

relation that leads to the expression of electron concentration from BC and holes from BV, in the case of intrinsic semiconductors of the form:

$$n_{i} = \sqrt{N_{V}N_{c}} \exp\left[-\frac{\Delta W_{i}}{2kT}\right].$$
(3.9)

where $\Delta W_i = W_c - W_v$ is the width of the Fermi forbidden interval.

This relation demonstrates that the intrinsic carrier concentration n_i depends on the width of the forbidden interval ΔW_i and on the temperature T.

Example:

For a number of energy states $N_i = \sqrt{N_v N_c} = 2 \cdot 10^{19} cm^{-3}$ and the temperature *T* equivalent to a thermal energy of kT = 0.025 eV, knowing the value of the Fermi interval energy, the electron concentration can be deduced with the relation (3.9).

It results:

- for germanium ($\Delta W_i = 0.67 \text{ eV}$): $n_i = 10^{13} \text{ carriers/cm}^3$;
- for silicon ($\Delta W_i = 1, 1 \text{ eV}$): $n_i = 10^{10} \text{ carriers/cm}^3$.

Notes:

- 1. The relation (3.9) demonstrates that the higher the energy of the Fermi interval is, the smaller the intrinsic carriers concentration will be.
- 2. For silicon, at normal temperature, the intrinsic concentration n_i of the mobile electrical carriers is of 10^3 times smaller than in the case of germanium, because the energy of Fermi interval is much more increased (Table 3.1). This explains why the silicon conductivity is much more reduced than that of the germanium.
- 3. For the As crystal, which has $\Delta W_i = 1.2$ eV, at constant temperature, a smaller conductivity results than that of the germanium (see Table 3.1, Table 3.2).
- 4. In the case of semiconductor compounds, there is the same correlation: because the energy of Fermi forbidden interval is higher in the case of GaAs than in silicon (Table 3.2), the concentration n_i for GaAs is much more reduced than in Si, that corresponds to a much more reduced electrical conductivity.

The semiconductive properties of the pure silicon crystal and the pure germanium crystal at 300 K are presented in Table 3.3.

Physical properties	Silicon	Germanium
Energy gap E_g or ΔW_i , eV	1.1	0.67
Electron mobility μ_n , m ² / (V·s)	0.135	0.39
Hole mobility μ_p , m ² / (V·s)	0.048	0.19
Intrinsic carrier density <i>n</i> _i , carriers/m ³	1.5 × 10 ¹⁰	2.4 × 10 ¹⁶
Intrinsic resistivity ρ_{i} , $\Omega \cdot m$	2300	0,46
Density <i>d</i> _m , kg/m ³	2.33 × 10 ³	5.32 × 10 ³

Table 3.3. Some physical properties of pure silicon and germanium crystals at 300 K.

Notes:

- The mobilities of the electrons are always higher than those of the holes.
- For intrinsic silicon the electron mobility of 0.135 m²/(V·s) is 2.81 times higher than the hole mobility of 0.048 m²/(V·s) at 300 K.
- The ratio of electron-to-hole mobility for intrinsic germanium is 2.05 at 300 K.

98

The expressions of electron and hole mobilities, introduced in the quantum theory, are similar with those from the classical theory of electrical conduction:

$$\mu_n = \frac{q_0}{m_n^*} < \tau_n > ; \ \mu_p = \frac{q_0}{m_p^*} < \tau_p >, \tag{3.10}$$

where m_n^* is the effective mass of the conduction electron, $< \tau_n >$ is the average relaxation time of electrons in BC, m_p^* is the mass of the hole and $< \tau_p >$ is the average time for relaxation of holes in BV.

The mobility of the electrons differs from that of the holes by the differences between the masses and the times of relaxation. Table 3.4 provides the mobilities μ_n and μ_p at 300 K for some semiconductors.

Table 3.4. Electron and hole mobilities in some semiconductive cryst	tals
--	------

Semiconductor	С	Ge	Si	GaAs	InSb	GaSb	CdS
$\mu_{\rm n}$, cm ² /Vs	1800	3900	1350	8500	7800	4000	300
$\mu_{\rm p}$, cm ² /Vs	1600	1900	480	400	750	1400	50

The expression of electrical conductivity for an intrinsic semiconductor $(n = p = n_i)$ has the following form:

$$\sigma_{i} = \sigma_{n} + \sigma_{p} = \frac{nq_{0}^{2} < \tau_{n} >}{m_{n}^{*}} + \frac{pq_{0}^{2} < \tau_{p} >}{m_{p}^{*}} = n_{i}q_{0}^{2} \left(\frac{<\tau_{n} >}{m_{n}^{*}} + \frac{<\tau_{p} >}{m_{p}^{*}}\right).$$
(3.11)

The relation (3.11) is similar to that obtained with the classical theory Drude-Lorentz, but **the effective mass** of the conduction electrons and holes and the average of **the relaxation time** for all possible values of their energies are taken into consideration.

3.3. EXTRINSIC ELECTRIC CONDUCTION

Λ

Extrinsic semiconductors are very dilute substitution solid solutions in which the solute impurity atoms have different valence characteristics from the solvent atomic lattice. The concentrations of the added impurity atoms in these semiconductors are usually of the order of 100 to 1000 parts per million (ppm).

The conductivity of the extrinsic semiconductor depends primarily on the number of impurities, or dopant atoms. It results that conductivity is controllable and stable.

3.3.1. *n*-Type Extrinsic Conduction – Physical Model

The extrinsic semiconductors of type *n* are obtained by controlled adding (dopping with) the *donor impurities*.

In *n*-type semiconductors, the donor impurity atoms have a bigger valence than the base crystal valence. When introducing them into the crystal, these impurities will form **substitution ions** (ex. P, As, Sb, Bi) or **interstitial ions** (ex. S, Li), which supply the base crystal with one or more electrons. In this case, the semiconductor presents mainly conduction through electrons, named **extrinsic conduction of type n**.

The extrinsic electrical conduction of *n*-type can be justified with the physical model, taking into consideration the phenomena that take place at the level of the chemical bonds in the crystal.

There is the case of **a silicon mono crystal** (Fig. 3.9) where a silicon atom (four-valence element) is replaced with a **phosphorus atom** (five-valence element).



Fig. 3.9. The extrinsic conduction model in a silicon crystal doped with donor impurities
– semiconductor of type *n*: a) at 0 K temperature and in the absence of electric field; b) at temperature different from 0 K and in the absence of the electric field; c) at temperature different from 0 K and in the presence of the electric field.

In figure 3.9, the circles in gray are the Si atoms, the circle in blue is atom of phosphorus (P) as donor impurity, and the circle in red in phosphorus positive ion, fixed in the Si crystal lattice.

Cases:

- At 0 K temperature and in the absence of electric field (Fig. 3.9a).
- In the Si crystal doped with an atom of phosphorus as donor impurity, 4 of the valence electrons of the phosphorus atom will contribute to the formation of the covalent bonds with the 4 silicon atoms and the 5th electron doesn't participate in the formation of the covalent bond. In this situation, in the crystal there aren't **quasi-free electrons** and **uncompensated bonds in Si crystal**.
- At temperatures different from 0 K, in the absence of the electric field (Fig. 3.9b). Due to the thermal agitation, the ionization of the impurity atom will take place, with the detachment (the bond is broken) of the 5-th electron. The ionization is possible because the introducing the impurity atom in the crystal determines the decreasing of the energy bonds between the 5-th valence electron and the phosphorus atom. This makes the probability of detachment of this electron to be

bigger than the probability of detachment of an electron from a covalent bond of the base crystal. Thus, at relatively low temperatures, the ionization of the impurity atoms can take place, with generation of the **free electrons** and the **phosphorus positive ions** (P^+) fixed in the crystalline Si lattice.

Of course, at higher temperatures, under the effect of the thermal energy, simultaneously with the ionization of impurity atoms, the breaking process of the covalent bonds also takes place in the base crystal, with the formation of pairs of **free electrons - uncompensated bonds**.

As the ionization processes are more intense than the processes of breaking covalent bonds in the base crystal, in the extrinsic conduction only the concentration of electrons are taken into consideration that results after the thermal excitation from the impurity atoms.

 At temperatures different from 0 K, in the presence of electric field (Fig. 3.9c). Under the action of electric field, the free electrons originated from donor impurities will move in the opposite direction of the applied electric field.

Conclusion:

At normal temperatures, the electric current in the *n*-type semiconductors is generated by the ordered movement of the electrons resulting from the donor impurities atoms, in the opposite direction of the applied electric field.

3.3.2 *p*-Type Extrinsic Conduction – Physical Model

The extrinsic semiconductors of p type are obtained by the controlled doping with **acceptor impurities**. The atoms of the acceptor impurities (Ex. Zn, B, Al, In), having their valence smaller than the base crystal valence, don't succeed in satisfying all the covalent bonds of the crystal but only by ionization (the capturing of the valence electrons from semiconductor base crystal).

The extrinsic electrical conduction of p - type can be justified with the physical model, taking into consideration the phenomena that take place at the level of chemical bond in crystal.

If in the silicon single crystal (Fig. 3.10a) a trivalent atom of boron (B) is being introduced, a bond of this atom with the silicon atoms will be unsatisfied (in figure - red dotted line). At low temperatures and in the absence of electric field, it doesn't exist a free electrical charge, but there are unsatisfied bonds due to the presence of trivalent impurity.

In order to satisfy this bond, there is the possibility that an electron from an silicon atom to pass in the electronic layer of the acceptor boron atom.

At normal temperature (Fig. 3.10b), the ionization process is realized with a bigger probability than the process of breaking the covalent bonds from the base crystal. The acceptor impurity atom of boron becomes **a negative ion** B⁻ (in figure 3.10 - blue circle), fixed in the crystalline lattice. The electron connected to this one doesn't

participate in the process of electrical conduction. **The unsatisfied bond**, carrying positive charge, is now placed between two atoms of the base crystal.



Fig. 3.10. The extrinsic conduction model in a silicon crystal doped with acceptor impurities - semiconductor of type p: a) at 0 K temperature, in the absence of electric field; b) at temperature different from 0 K, in the absence of electric field; c) at temperature different from 0 K, in the presence of electric field.

Because the concentration of uncompensated bonds is bigger than the concentration of free electrons, resulted from the breaking of the covalent bonds in the base crystal, this type of semiconductor is named **semiconductor of** *p***-type**.

Conclusion:

At normal temperatures, the electric current in the *p*-type semiconductors is generated by the diffusion of the uncompensated bonds resulting from the acceptor impurities atoms, in the direction of the applied electric field.

3.3.3. *n*-Type Extrinsic Conduction – Energy Bands Model

The extrinsic electrical conduction mechanism in the semiconductors doped with donor impurities can be described qualitatively and quantitatively by means of the energy bands model in crystals (Fig. 3.11).

The structure of energy bands does not modify when introducing donor impurities, but in the Fermi forbidden band appear occupied energy levels, corresponding to the excess electrons of the impurity atoms. A donor level W_d corresponding to a phosphorus impurity atom is presented in Fig. 3.11a.

For the *n*-type semiconductors, are chosen those impurities that provide donor levels in the vicinity of the conduction band bottom level (Fig. 3.11b). Thus, the activation energy (ionization) ΔW_d of donor impurities is much more reduced than the ionizing energy of the base crystal atoms (which represents the energy of the Fermi forbidden interval):

$$\Delta W_d = W_c - W_d \ll \Delta W_i, \qquad (3.12)$$

102

3. Semiconductive Materials

where W_d represents the donor level energy of the impurity atom and W_c represents the bottom level energy of the conduction band.



Fig. 3.11. The extrinsic conduction of *n* type (in a silicon crystal doped with donor impurities) in the energy bands model: a) at 0 K; b) at temperatures different from 0 K; c) the hole formation.

In these conditions, even a minor external disturbance (temperature, electric field, etc.) determines the excitation of electrons from the donor levels in the conduction band BC.

Conclusion:

- The extrinsic *n*-type electric conduction is realized by the electrons in the conduction band, resulting from the donor levels of impurity atoms.
- There are many possibilities to obtain the extrinsic conduction character. Table 3.5 indicates the energy levels of different impurity atoms, situated in the Fermi forbidden band of the germanium and silicon crystal, possible for manufacturing the semiconductive devices.
- Table 3.5. The donor and acceptor energy gaps at the controlled doping in germanium and silicon.

Doping	In silicon (ΔW_i = 1.12 eV)		In germanium (ΔW_i = 0.67 eV)	
	ΔW _d [eV]	ΔW_a [eV]	ΔW _d [eV]	ΔW_a [eV]
Р	0.015		0.0120	
As	0.049		0.0127	
Sb	0.039		0.0096	
В		0.045		0.0104
AI		0.057		0.0102
Ga		0.065		0.0108
In		0.160		0.0112

Usually, the donor levels are situated above the half of the forbidden band and the acceptor ones, under its half. The conduction mechanism determined by the acceptor impurities is presented further on.

3.3.4. *p*-Type Extrinsic Conduction – Energy Bands Model

The extrinsic electrical conduction mechanism in semiconductors doped with acceptor impurities can be described qualitatively and quantitatively with the energy bands model in the crystal (Fig 3.12).



Fig. 3.12. The extrinsic *p*-type conduction (in a silicon crystal doped with acceptor impurities) in the energy bands model: a) at 0 K temperature, in the absence of electric field; b) At temperature different from 0 K, in the absence of electric field; c) at temperature different from 0 K, in the presence of electric field.

The structure of energy bands does not modify, but, in addition, energy levels on the Fermi forbidden band (band gap) appear, levels that correspond to the local states of the acceptor impurity atoms. As a rule, those acceptor impurities are chosen which generate levels near the superior level of the valence-bond band (Table 3.3). Thus, the activation energy (ionization) of the acceptor impurities ΔW_a is much more reduced than the ionization energy of the base crystal atoms:

$$\Delta W_a = W_a - W_v \ll \Delta W_i, \qquad (3.13)$$

where W_a represents the acceptor level energy of the impurity atom and W_v represents the energy of the last level from BV.

In these conditions, even a minor external disturbance (temperature, electric field, radiation, etc.) will determine an increase of the concentration of the holes from the valence band. The *p*-type extrinsic conduction is realized by the holes from BV produced by the electrons passing from BV on the acceptor levels of impurity ions.

104

Conclusion:

The extrinsic *p*-type electric conduction is realized by the holes in the valence band, resulting from the transitions of electrons from BV on the acceptor levels of impurity atoms.

W 3.3.5. Electric Conductivity in Extrinsic Semiconductors

For an extrinsic semiconductor, at low temperatures, the intrinsic conductivity is practically null ($\sigma_i \approx 0$), therefore the expression of the conductivity contains only the concentration of the majority carriers. Thus, the extrinsic conductivity expression is:

for *n*-type semiconductors:

$$\sigma_{en} = n_n q_0 \mu_n; \qquad (3.14)$$

• for *p*-type semiconductors:

$$\sigma_{ep} = n_p q_0 \mu_p , \qquad (3.15)$$

where:

 n_n is the electrons concentration from BC, in the case of the *n*-type semiconductors, n_p is the holes concentration from BV, in the case of the *p*-type semiconductors.

In the relations (3.14) and (3.15), the concentration of the mobile charge carriers should be taken in account:

for *n*-type semiconductors (concentration of electrons in BC):

$$n_n = N_{eC} \exp\left[-\frac{W_C - W_d}{kT}\right],\tag{3.16}$$

for *p*-type semiconductors (concentration of holes in BV):

$$n_{p} = N_{ev} \exp\left[-\frac{W_{a} - W_{v}}{kT}\right]$$
(3.17)

where:

 N_{eC} represents the number of ionized donor energy states;

 $\Delta W_d = W_c - W_d$ is the activation energy of the donor impurities;

 N_{eV} represents the number of the ionized acceptor energy states; $\Delta W_a = W_a - W_V$ is the activation energy of the acceptor impurities.

Notes:

- The change of the electrical conductivity values and that of the electrical resistivity
 of the semiconductors is realized by controlled impurities doping.
- The temperature modifies the concentration of the mobile charge carriers, and correspondingly, the electrical conductivity, according to an exponential law.

3.4. FACTORS THAT INLUENCE THE CONDUCTIVITY OF THE SEMICONDUCTORS

3.4.1. Temperature – An Important Factor of Influence

Extrinsic semiconductors are used in many applications, in which temperature is an important stress factor. Experimentally, this category of semiconductors shows usually an increase of conductivity with the increase of temperature.

Figure 3.13 shows the general form of the conductivity dependence on temperature for extrinsic semiconductors and reveals evident three regions where the conductivity has a specific variation with temperature.



Fig. 3.13. General dependence of electrical conductivity with temperature for an extrinsic semiconductor: region I – extrinsic conduction; region II – metallic conduction; region III – intrinsic conduction.

- In region I, for low temperatures (*T*<*T*), the extrinsic electrical conduction predominates. At the rise of the temperature this determines more ionization of the impurity atoms, therefore, the mobile carrier concentration (electrons in *n* type semiconductors and uncompensated bonds (holes) in *p* type semiconductors) increases, and, in the same time, the conductivity σ will increases.
- In region II, for medium temperatures (T"<T<T'), the extrinsic conduction still predominates. Here all the donor and acceptor impurities are ionizated. The result is a constant concentration of mobile charge carriers at the rise of the temperature. In this interval of temperature, a huge influence is exercised by the mobility, which decreases simultaneously with the increase of the temperature. It results that the semiconductor behaves like a metal. Thus, the conduction is of metallic type.</p>
- In region III, for temperatures (T>T"), the intrinsic conduction starts to predominate, by generating mobile carriers through the breaking of the covalent bonds in the semiconductor crystal. In this interval of temperature, the electric conductivity increases a lot simultaneously with the rise of temperature.

 Λ

3.4.2. The Dependency of Intrinsic Conductivity on Temperature

In intrinsic semiconductive materials, the number of mobile charge carriers can be controlled only by checking and controlling the temperature. This control is difficult and unstable.

The intrinsic concentration of thermal activated electrons depends, in accordance with the relation (3.9), exponentially to the temperature. As the temperature rises, more electrons will pass from BV in BC and the conductivity increases.

With the relations (3.9) and (3.4) it results the expression of electrical conductivity σ_i of the intrinsic semiconductor:

$$\sigma_{i} = n_{0} q_{0} (\mu_{n} + \mu_{P}) \cdot \exp\left(-\frac{\Delta W_{i}}{2kT}\right)$$
(3.18)

The relation (3.18), by applying logarithm, becomes:

$$\ln\sigma_{i} = \ln\sigma_{0} - \frac{\Delta W_{i}}{2kT}, \qquad (3.19)$$

where σ_0 is a constant which depends mainly on the electrons and holes mobility.

Notes:

- Semiconductor behavior is opposed to that of metallic materials: with the rise of temperature, the semiconductor conductivity increases too, because a lot of charge carriers will be formed;
- In metals, where the concentration of conductive electrons is constant, with the rise of temperature, the electrons mobility decreases, what makes the conductivity to decrease.

The expression (3.19) is a straight line in coordinates (1/*T*, ln σ). It can be determined the value ΔW_i /2*k* as the slope of the line, and further on ΔW_i . Values of Fermi interval energy are given for a series of semiconductive materials in Tables 3.1-3.3.

For the crystals Ge, Si, GaAs, in the figure 3.14 there is presented the temperature dependence of the intrinsic concentration n_i of the mobile charge carriers.


Fig. 3.14. Temperature dependence of the intrinsic concentration of mobile charge carriers n_i for the semiconductive crystals of Ge, Si, GaAs.

Notes:

1. The straight lines slopes in Fig. 3.14 are proportional to the width of the forbidden interval;

2. It can be defined the operating temperatures domain for semiconductive crystals:

- for germanium, the maximum operating temperature is 75÷100°C,

- for **silicon**, the maximum operating temperature is **200°C**.

3.4.3. The Dependency of Extrinsic Conductivity on Temperature

In extrinsic semiconductive materials, the total conductivity expression will be given by the sum of the intrinsic and extrinsic conductivity:

$$\sigma_{tot} = \sigma_i + \sigma_e = n_i q_0 (\mu_n + \mu_p) + n_e q_0 (\mu_n + \mu_p).$$
(3.20)

where

 $n_{\rm i}$ represents the intrinsic concentration of charges carriers,

 $n_{\rm e}$ represents the extrinsic concentration of charges carriers.

In the calculus of charge carriers concentration of an extrinsic semiconductor, it is necessary to be taken into consideration both the electrons and holes concentration, determined by the intrinsic ionization processes, but also the concentration of the electric charge carriers determined by the extrinsic ionization processes, due to the donor atoms (of N_d concentration) and to the acceptor atoms (of N_a concentration).

Thus, for an extrinsic semiconductor of *p*-type, the total concentration of mobile charge carriers will be:

$$n_{total} = n_p + 2n_i \tag{3.21}$$

$$n_{total} = n_{p0} \cdot \exp\left(-\frac{\Delta W_a}{kT}\right) + 2n_{0i} \cdot \exp\left(-\frac{\Delta W_i}{kT}\right), \qquad (3.22)$$

where: n_{p0} and n_{0i} are relatively constant measurements with temperature.

At low temperature, the holes concentration will predominate:

$$n_{total} \cong n_{po} \cdot \exp\left(-\frac{\Delta W_a}{kT}\right).$$
 (3.23)

If the temperature rises, the ionization processes intensify until the state where all the donor impurities will be ionized. It results a maximum concentration of holes in extrinsic conduction.

Commonly, in extrinsic semiconductors there are mentioned **the concentrations of majority carriers** and **concentrations of minority carriers**, strongly temperature dependent ($n_i \approx \exp(-\Delta W_i/kT)$).

In Fig. 3.15 it is given the variation of the majority carriers concentration in a semiconductor of *n*-type having the base crystal from germanium.



Fig. 3.15. Temperature dependence of the conduction electrons concentration in a Ge semiconductor of *n*-type, for different values of the donor levels concentration N_{d} .

Notes:

To note the fact that the adding process of a certain quantity of impurity atoms in a pure crystal is named **doping**, while the impurity atoms themselves are called **dopants**. The most commonly used method of doping semiconductors is **the planar process**. In this process, dopant atoms are introduced into selected areas of the crystal in order to form regions of **p-type** or **n-type** semiconductor material. The

wafers are usually about 4 in (10 cm) in diameter and about a few hundred micrometers thick.

- Through adequate technologies it can be obtained **partially compensated semiconductors**, where the donor levels concentration is almost equal to that of the acceptor levels ($N_d \approx N_a$). The conduction is mixed, through electrons and holes.
- It can be obtained uncompensated semiconductors, where N_d ≠ N_a. For this class of materials, the conduction is realized through the majority charge carriers, or the electrons (for semiconductors of *n*-type), or the holes (for semiconductors of *p*-type).
- The extrinsic electrical conduction is unipolar, meaning that there are created one sign charge carriers, in contrast with the intrinsic electrical conduction, which is bipolar (in the conduction process participate in equal quantities, both electrons and holes).
- The activation energy of the extrinsic conduction being much more reduced than the width of the Fermi interval, the extrinsic conduction can be activated even at extremely low temperatures.
- In the case of semiconductors formed with silicon or germanium, the mobile electrons and holes concentration, at a constant temperature, remains almost constant, due to the processes of generation and recombination.
- In extrinsic semiconductors, the increase of the concentration of a kind of charge carrier (*n* or *p*) leads to the reduction of the other type concentration, due to the processes of recombination, so the product *n*·*p* remains constant at the given temperature.

The carriers whose concentration in extrinsic semiconductors is bigger are called **majority carriers**, and those with reduced concentration are **minority carriers**. In Table 3.6, the electrons concentration in the semiconductor of *n*-type was noted with n_n and the holes concentration in the semiconductor of *n*-type with p_n . In a similar way, the holes concentration in the semiconductor of *p*-type is noted with p_p and that of the electrons, with n_p .

Semiconductor	Majority carriers concentration	Minority carriers concentration
<i>n-</i> type	n _n	p_n
<i>p-</i> type	$\rho_{ ho}$	n _p

Table 3.6. Charge carriers concentration in extrinsic semiconductors.

Notes:

- For silicon at 300 K, the intrinsic charge carriers concentration is: $n_i = 1.5 \times 10^{13} \text{ carriers/m}^3$.
- For extrinsic silicon doped with As, at the ion concentration of 10²¹ impurity atoms/m³ it results:
 - Majority carriers concentration $n_n = 10^{21}$ electrons/m³
 - Minority carriers concentration $p_n = 2.25 \times 10^{11}$ holes/m³.

It can be observed that the majority carriers' concentration is bigger than the minority carriers' concentration.

Because the concentration of ionized donor or acceptor levels depends on the temperature, as:

$$N_{di} \approx N_{d} \exp\left[\frac{W_{d} - W_{F}}{2kT}\right] = N_{d} \exp\left[-\frac{\Delta W_{n}}{2kT}\right], \qquad (3.24)$$

it results for the case of *n*-type semiconductor, the expression of electrical conductivity:

$$\sigma_{en} \approx C_n \exp\left[-\frac{\Delta W_n}{2kT}\right]$$
(3.25)

and, similarly, for the case of *p*-type semiconductor:

$$\sigma_{ep} \approx C_p \exp\left[-\frac{\Delta W_p}{2kT}\right].$$
(3.26)

In these relations, ΔW_n and ΔW_p represent the activation energies of the conduction in *n*-type semiconductor, respectively, in *p*-type semiconductor.

Then, the total conductivity of semiconductor will depend on the temperature, as:

$$\sigma_{tot} = \sigma_i + \sigma_e \approx C_i \exp\left[-\frac{\Delta W_i}{2kT}\right] + C_e \exp\left[-\frac{\Delta W_e}{2kT}\right].$$
(3.27)

In this relation, C_i and C_e represent quantities that depend on the temperature, and ΔW_i and ΔW_e represent the activation energies of intrinsic conduction, respectively, the extrinsic one.

The temperature dependence for σ can be analyzed starting from the relation (3.27). Unlike metals, where the conduction electrons concentration doesn't modify with the temperature, the dependence $\sigma_{tot} = f(T)$ being given only by the mobility dependence $\mu = f(T)$, in semiconductors, as well as in the insulators, both the concentration and the charge carriers mobility vary with temperature.

The charge carriers' concentration varies exponentially with temperature, both in the intrinsic and extrinsic region.

In the range of impurities exhaustion, the concentration is practically independent with the temperature, thus, the conductivity variation with temperature is dictated only by the mobility dependence with temperature. The dependence is typical (Fig. 3.16):

- at low temperatures with the rise of temperature, the mobility rises also due to the contribution of the scattering effects on the ionized impurities;
- at high temperatures with the rise of temperature, the mobility decreases due to the dependence of the dominated scattering processes that, in this case, represent the scattering (collisions) processes with the crystalline lattice atoms.



Fig. 3.16. Charge carriers mobility dependence with temperature for a silicon crystal doped with boron: 1 - the component due to the scattering on ionized impurities; 2 - the component due to the scattering processes on the crystalline lattice atoms of the semiconductor; 3 - the total mobility.

The typical variation with temperature of the mobile charge carriers' concentration and their mobility makes the general dependence of electrical conductivity for an extrinsic semiconductor, with temperature to be similar to that presented in Fig. 3.13.

3.4.4. Magneto-Electric Effects

At the simultaneous application of an electric field of \overline{E} intensity and of a magnetic field of \overline{B} magnetic induction, at certain materials a series of kinetic phenomena appear, namely the magneto-electric effects. They consist in: the change of the electrical conductivity σ and the thermal conductivity λ on the direction of the electric field and the appearance of an electric potential difference and temperature gradient on perpendicular direction on \overline{E} and \overline{B} .

The magneto-electric effects are:

- The Hall effect, which consist in the appearance of an electric potential difference, perpendicular on the \overline{E} and \overline{B} ;
- **The magnetoresistive effect**, which consist in the modification of the electrical resistivity of the material in the presence of the magnetic field;
- The Ettinghausen effect, which consist in the appearance of a difference of temperature, perpendicular on the vectors \overline{E} and \overline{B} ;
- **The Nernst effect,** which is, like the Ettinghausen effect, a galvanic-thermalmagnetic effect, not transversally, but longitudinally according to the applied direction of the external electric field.

In correlation with the direction of the applied electric field, **the magneto-electric effects are even or odd**. The effect is even if the physical quantity that characterizes that effect doesn't modify his sign at the reversal of the applied field, and odd in the case of sign change.

The category of the even effects includes the magnetoresistive effect and the Nernst effect.

The Hall effect and the Ettinghausen effect are odd effects related to the applied electric field direction.

M 3.4.5. Hall Effect in Metals and Semiconductors

The microscopic theory considers that the Hall effect, as well as the magnetoresistive effect is due to the influence exercised by the external magnetic field on the path of the mobile charge carriers from semiconductors and metals.

Because these effects are more intense in semiconductors and some semimetals, the microscopic study of the Hall effect will be made for semiconductors in general, and for metals and semimetals in particular.

There are considered two semiconductive plates of Si, one of *n*-type (Fig. 3.17a) and another one of p- type (Fig. 3.17b), with isotropic properties.



Fig. 3.17. The production of the Hall effect: a) in the case of a *n*-type semiconductor; b) the case of a *p*-type semiconductor. The mobile carriers are electrons (marked in blue circles) and the holes (marked in red circles).

It will be analyzed simultaneously the phenomena that appear in the two types of semiconductors.

At the application of an electric field of intensity \overline{E} on the axis Ox (Fig. 3.17a and b), the majority charge carriers (the electrons in the semiconductor of Si-*n* and the holes in the semiconductor of Si-*p*) will move, in the limits of the quasi-free electron theory, on linear paths:

- Holes (with the charge + q₀) in the field direction,
- Electrons (with the charge q_0) in the reverse direction of the applied field.

The drift velocities will be:

$$\overline{V}_{dn} = -\frac{q_0 < \tau_n >}{m_n^*} \overline{E}; \ \overline{V}_{dp} = +\frac{q_0 < \tau_p >}{m_n^*} \overline{E} , \qquad (3.28)$$

relations where the *n* index refers to the conduction in *n*-type semiconductor and the *p* index refers to the holes in *p*-type semiconductor.

Thus, in the semiconductive plates, electrical currents appear with the current densities expressed as:

$$\overline{J}_{n} = -n_{n}q_{0}\overline{V}_{dn} = \frac{q_{0}^{2}n_{n} < \tau_{n} >}{m_{n}^{*}}\overline{E}$$

$$\overline{J}_{p} = n_{p}q_{0}\overline{V}_{dp} = \frac{q_{0}^{2}n_{p} < \tau_{p} >}{m_{n}^{*}}\overline{E}$$
(3.29)

where n_n and n_p refers to the volume concentrations of the conduction electrons, respectively of the holes.

The relations (3.29) show that the current density vectors have the same direction with the intensity vector of the electric field, regardless the sign of the charge carriers (electrons or holes).

At the simultaneous application of an electric field by the axis Ox and of a magnetic field of induction \overline{B} by the direction of the axis Oz, on every charge carrier will operate an additional force - the Lorentz force - given by the expression:

$$\overline{F}_{Ln} = -q_0 \left(\overline{v}_{dn} \times \overline{B} \right) = \frac{q_0^2 < \tau_n >}{m_n^*} \left(\overline{E} \times \overline{B} \right), \tag{3.30}$$

for the *n*-type semiconductor and orientated as in figure 3.17a, and by the expression:

$$\overline{F}_{Lp} = -q_0 \left(\overline{V}_{dp} \times \overline{B} \right) = \frac{q_0^2 < \tau_p >}{m_p^*} \left(\overline{E} \times \overline{B} \right), \qquad (3.31)$$

for the holes in the *p*-type semiconductor, orientated like in the figure 3.17b.

These relations demonstrate that the Lorentz force, which acts on the majority charge carriers, depends only on the directions of the \overline{E} and \overline{B} , having the same direction for holes and electrons.

Under the action of the Lorentz force, the more the electron and hole paths will curve towards the same edge of the semiconductive plate, the more intense the magnetic field will be applied.

The deviation of the majority charge carriers from the linear path determines the modification of the volume concentration n_n , n_p on the deviation direction Oy. On this direction, an internal electric field named **the Hall field** will result. The deviation process continues until the action of the internal electric field on the electrons or the holes compensate the Lorentz forces.

The conditions of the dynamic equilibrium are:

$$-q_0 \overline{E}_{Hn} = \overline{F}_{Ln} ; \ q_0 \overline{E}_{Hp} = \overline{F}_{Lp} . \tag{3.32}$$

With these relations, the expressions of the Hall electric field intensity in the semiconductors of *n*-type, respectively of *p*-type are:

$$\overline{E}_{Hn} = -\frac{q_0 < \tau_n >}{m_n^*} \left(\overline{E} \times \overline{B} \right); \quad \overline{E}_{Hp} = \frac{q < \tau_p >}{m_p^*} \left(\overline{E} \times \overline{B} \right). \tag{3.33}$$

With the relations (3.29), the expressions (3.32) and (3.33) will become:

for the semiconductors of n type:

$$\overline{E}_{Hn} = -\frac{1}{q_0 n_n} \left(\overline{J}_n \times \overline{B} \right); \tag{3.34}$$

for the semiconductors of p type:

$$\overline{E}_{Hp} = \frac{1}{q_0 n_p} \left(\overline{J}_p \times \overline{B} \right)$$
(3.35)

Hall was the first who experimentally established a relation of the form (3.34) for metals. Afterwards, the coefficient with which it multiplies the vectorial product $\overline{J} \times \overline{B}$ was named **the Hall constant**. From the microscopic theory it results the expression of the Hall coefficients for:

the n-type semiconductors:

$$R_{Hn} = -\frac{1}{q_0 n_n} ; \qquad (3.36)$$

the *p*-type semiconductors:

$$R_{Hp} = \frac{1}{q_0 n_p}.$$
 (3.37)

Thus, in the classical microscopic theory, the Hall constants are determined by the reverse of the product between the charge carrier concentration and the elementary charge, the unit of measurement being m^3/C .

Notes:

- The sign of the \overline{E}_{H} and R_{H} depends on the sign of the charge carriers. Thus, the Hall effect can be useful in the determination of the type of the charge carriers and of their concentration.
- With the product of the electrical conductivity and the Hall constant the mobility of the charge carrier can be obtained:

o for electrons:

$$\sigma_n \cdot \left| \mathcal{R}_{Hn} \right| = n_n q_0 \mu_n \cdot \frac{1}{n_n q_o} = \mu_n \tag{3.38}$$

o for holes:

$$\sigma_{\rho} \cdot \mathcal{R}_{H\rho} = \mu_{\rho} \tag{3.39}$$

A modality to obtain an expression for Hall constant in a mixed (n and p) semiconductor is analyzed in the following.

The Hall effect can be characterized also by the quantity of the Hall angle, defined as the angle between the total electric field intensity and the electric current density (Fig. 3.18)



Fig. 3.18. Defining the Hall angle for: a) *n*-type semiconductor; b) *p*-type semiconductor; c) semiconductor with mixed (*n* and *p*) conduction.

With the notations from the Fig 3.18 and taking into consideration the above relations, it results:

$$tg\theta_{Hn} = \frac{E_y}{E_x} = \frac{E_{Hn}}{E} = \frac{R_{Hn}J_nB}{E} = R_{Hn}\sigma_nB = \mu_nB, \qquad (3.40)$$

respectively,

$$tg\theta_{H_0} = \mu_0 B. \tag{3.41}$$

The Hall constant in the case of a semiconductor with two types of charge carriers can be easily calculated if it is considered that the current densities, \overline{J}_n and \overline{J}_p make the angles θ_{Hn} , respectively θ_{Hp} with the axis Ox, and the total current density $\overline{J}=\overline{J}_n+\overline{J}_p$ makes the angle θ_H with the axis Ox (Fig. 3.18c).

It results, in the case of small fields, (cos $\theta_H \approx 1$; sin $\theta_H \approx tg \theta_H$):

$$J_{x} = J_{n} \cos \theta_{Hn} + J_{p} \cos \theta_{Hp} \approx J_{n} + J_{p} = (n_{n}q_{0}\mu_{n} + n_{p}q_{0}\mu_{p})E$$
(3.42)

and

$$J_{y} = J_{n} \sin \theta_{Hn} + J_{p} \sin \theta_{Hp} \approx J_{n} \operatorname{tg} \theta_{Hn} + J_{p} \operatorname{tg} \theta_{Hp}$$
$$= \left(-nq_{0}^{2}\mu_{n}^{2} + pq_{0}^{2}\mu_{p}^{2}\right) EB \qquad (3.43)$$

relations that can be used to calculate tg θ_{H} :

$$tg\theta_{H} = \frac{J_{y}}{J_{x}} = \frac{n_{p}q_{0}^{2}\mu_{p}^{2} - n_{n}q_{0}^{2}\mu_{n}^{2}}{n_{n}q_{0}\mu_{n} + n_{p}q_{0}\mu_{p}}.$$
(3.44)

With the relation for θ_{H} angle, it results the equivalent Hall constant:

$$R_{H} = \frac{\text{tg}\theta_{H}}{\sigma B} = \frac{n_{p}\mu_{p}^{2} - n_{n}\mu_{n}^{2}}{q_{0}(n_{n}\mu_{n} + n_{p}\mu_{p})^{2}}$$
(3.45)

It can be observed that, for a semiconductor with mixed conduction, the Hall constant is being annulated for $n_p \cdot \mu_p^2 = n_n \cdot \mu_n^2$. This condition is applied in some devices.

For the intrinsic semiconductors ($p = n = n_i$), the Hall constant can be obtained from (3.45):

$$R_{H} = \frac{\mu_{p} - \mu_{n}}{n_{i} q_{0} (\mu_{p} + \mu_{n})}$$
(3.46)

In this case, the Hall constant depends on the difference of the mobilities, and generally it is negative, because in most cases $\mu_n > \mu_p$.

For metals, the relation of Hall constant is given by (3.36). Table 3.7 presents the calculated values for R_H for some metals by using the relation (3.36) and knowing the values of the conduction electron concentration n_o .

 Table 3.7. Hall constants in some metals.

Metal	<i>R</i> н [m ³ /C]		n _{atoms} [m⁻³]
Silver	- 8.4 · 10 ⁻¹¹	$0.75 \cdot 10^{29}$	$0.59 \cdot 10^{29}$
Gold	- 7.2 · 10 ⁻¹¹	$0.85 \cdot 10^{29}$	$0.48 \cdot 10^{29}$
Aluminum	- 3.0 · 10 ⁻¹¹	2.1 · 10 ²⁹	0.60 · 10 ²⁹
Cooper	- 5.5 · 10 ⁻¹¹	$1.1 \cdot 10^{29}$	$0.85 \cdot 10^{29}$

Notes:

- The experimental researches proved that, if some metals like Li, Na, K, Rb, Cs, Ag, Au, Mg, Ca, Hg, Al, Ga, In, Ti, Mn, Ni, Bi, Pd, Pb have negative Hall coefficient (*R*_H < 0), a series of metals such as: Be, Zn, Cd, Te, V, Cr, Fe, Co, Pb, Mo, Ru, Rh, As, Sb, Ta, W, Re, Ir have positive Hall coefficient (*R*_H > 0).
- The cause of this discrepancy between theory and experiment results from the fact that it was considered the hypothesis that the valence electrons are free charge carriers. For a correct calculus of the Hall constant, it must be taken into consideration the distribution of the velocities of the conduction electrons or, from another point of view, the relaxation time dependence on energy.
- For the semiconductors with a single type of charge carriers, the calculus of the Hall constant is made with the relation (3.46), where the averaging is made according to the different mechanisms of dispersion in semiconductor.
- In the case of a semiconductor with mixed conduction in weak magnetic fields, it results a similar relation to (3.45):

$$R_{H} = \frac{\langle \tau^{2} \rangle}{e \langle \tau \rangle^{2}} \cdot \frac{n_{p} \mu_{p}^{2} - n_{n} \mu_{n}^{2}}{(n_{n} \mu_{n} + n_{p} \mu_{p})^{2}}$$
(3.47)

The Hall constant in semiconductors has positive or negative values depending on the product value $p \cdot \mu_p > \text{ or } < n \cdot \mu_n$. This quantity can change its sign even for the same material, at different conditions of temperature and application of the magnetic field.

Note:

The Hall constant has values of the order of 10^{-11} m³/C in metals, and $10^{-6} \div 10^{-1}$ m³/C in semiconductors, conjuncture which makes the devices based on the Hall effect to be recommended in the case of semiconductive materials.

M 3.4.6. Magneto-Resistive Effect in Semiconductors

In the presence of the magnetic field in semiconductive materials, it appears a modification of the resistivity value, a phenomenon named the magnetoresistive effect.

The material parameter which characterizes the magnetoresistive effect is **magnetoresistivity**, defined as a ratio between the resistivity variation ρ_H of the material in the presence of a magnetic field compared to the resistivity ρ_0 of the material in the absence of a magnetic field, and the resistivity ρ_0 :

$$\Delta \rho = \frac{\rho_H - \rho_0}{\rho_0} \,. \tag{3.48}$$

In **the classical microscopic theory**, magnetoresistive effect can be explained by the flexing of the conduction electron paths; when a magnetic field is applied.

118

The projection of the averaged free path of charge carriers on the direction of the applied electric field (according to which the resistivity is measured) is smaller in the presence of the magnetic field. (Fig. 3.19)



Fig. 3.19. Reference to the magnetoresistivity calculus, where the blue circle is the mobile electron.

For weak magnetic fields, the angle ϑ_H is small and the difference of the averaged free path will be given by the expressions:

$$\Delta I = I_0 - I = I_0 (1 - \cos \theta_H) = I_0 2 \sin^2 \frac{\theta_H}{2} \approx \frac{I_0}{2} \theta_H^2.$$
(3.49)

However, the average length is proportional to the electrical conductivity. With the relations (3.48) and (3.49), the expression of magnetoresistivity becomes:

$$\Delta \rho = \frac{\rho_H - \rho_0}{\rho_0} = \frac{\frac{1}{\sigma_H} - \frac{1}{\sigma_0}}{\frac{1}{\sigma_0}} = \frac{\sigma_0 - \sigma_H}{\sigma_H} = \frac{\sigma_0 - \sigma_H}{\sigma_0 + \Delta \sigma} \approx \frac{\sigma_0 - \sigma_H}{\sigma_0} = \frac{\Delta I}{I_0}.$$
(3.50)

With this relation for the Hall angle, approximating tg $\theta_H \approx \theta_H$, it results:

$$\Delta \rho \approx \frac{1}{2} \mu_H^2 B^2. \tag{3.51}$$

This relation demonstrates that the magnetoresistivity is an even effect compared to the applied magnetic field, an effect that depends on both the nature of the material through the value of the Hall mobility μ_{H} , but also through the value of the magnetic induction of the applied field.

In this approach, it wasn't taken into account the distribution of the charge carriers according to the velocities. A correct approach must also take into consideration the energy dependence of the relaxation period. In this approach, the expression of magnetoresistivity is put under the form:

$$\frac{\Delta \rho}{\rho_0} = \frac{\rho_H}{\rho} - 1 = \sigma_0 \cdot \rho_H - 1, \qquad (3.52)$$

where $\sigma_0 = E/J$ represents the electrical conductivity in the absence of magnetic field.

The quantum theory demonstrates that, only in the case of intense magnetic fields, the magnetoresistivity doesn't depend on the magnetic field, and only on the type of the dispersion mechanism, by the form:

$$\frac{\Delta\rho}{\rho_0} = \langle \tau \rangle \left\langle \frac{1}{\tau} \right\rangle_H - 1.$$
(3.53)

The difficulties of the free electron model in Somerfield model are also connected to the impossibility of explaining the magnetoresistive effect in some metals.

3.5. PROPERTIES AND USE OF THE SEMICONDUCTIVE MATERIALS

The semiconductive materials have large utilization fields in electrotechnics and electronics. This chapter presents the main performances of the semiconductive materials and their applications.

Δ

3.5.1. Performances and Fields of Use

Table 3.8 presents the main uses of semiconductive materials and some specific parameters: the width of the Fermi forbidden interval ΔW_i , the mobility of the charge carriers of electron type μ_n and of hole type μ_p .

Semiconductive material	<i>∆W</i> i at 0 K [eV]	μ _n at 300 K, [cm²/Vs]	μ _ρ at 300 K, [cm²/Vs]	Applications
				Rectifier, Sun-cell,
Si	1 1 2	1900	125	Radiations detector,
0	1.12	1900	425	Transistor,
				Controlled rectifier diode
Ge	0.78	3900	1700	Rectifier, Radiations detector, Transistor
Ge-Si	0.78-0.12	-	-	Thermoelectric generator
Se	1.6-1.9	-	1	Rectifier
GaP	2.33	100	150	Self-luminous diode
GaAs	1.52	7000	450	Tunnel diode, Self- luminous diode, Laser
InP	1.42	4500	150	Infrared filter

Table 3.8. Parameters and use of the semiconductive materials.

120

Semiconductive material	∆ <i>W</i> i at 0 K [eV]	μ _n at 300 K, [cm²/Vs]	μ _ρ at 300 K, [cm²/Vs]	Applications
lnΔe	0.43	27000	450	Infrared filter,
11773	0.40	27000	400	Hall generator
				Infrared filter,
InSb	0.24	76000	760	Radiations detector,
				Hall generator
Cu ₂ O	2.06	-	100	Rectifier
ZnO	3.2	200	-	
ZnS	3.5-3.8	-	-	
040	2.5			Photoelectric resistance,
Cus	2.5	-	-	X ray dosimeter
CdSe	1.84	240	-	Photooloctric resistance
PbS	0.37	640	350	
PbSe	0.45	1400	640	Dhototuboo
PbTe	0.45	2100	840	
Bi ₂ Te ₃	0.15	310	400	
Bi ₂ Se ₃	0.28	600	-	

The different uses of these semiconductive materials are determined by their characteristic performances.

Δ

3.5.2. Semiconductive Materials used for Voltage Control Conduction

The materials with controlled conduction have their operation based on the disturbance phenomenon of the distribution of the charge carriers compared to the distribution suitable to the thermal balance, this phenomenon being produced by an internal or external electric field. Consequently, it appears a macroscopic electric current of density:

$$\overline{J} = \sigma \overline{E} = (\sigma_n + \sigma_p) \overline{E} , \qquad (3.54)$$

where \overline{E} represents the intensity of electric field and σ represents the electrical conductivity of the material. The index *n* and *p* refers to the type of the charge carriers: n – conduction electrons, and p – holes.

The material conductivity is related to the mobility of the charge carriers μ and to their volume concentrations *n* and *p*, by the relation:

$$\sigma = \sigma_n + \sigma_p = q_0 (n\mu_n + \rho\mu_p). \tag{3.55}$$

If the semiconductive material contains a non-uniform spatial distribution of the charge carrier concentration $n = f(\bar{r})$ and $p = f(\bar{r})$, then, through the charge carrier injection, it appears an electric diffusion current, whose current density has the expression:

$$\overline{J}_{dif} = q_0 (D_n \operatorname{grad} n - D_p \operatorname{grad} p), \tag{3.56}$$

where D_n and D_p represent the scattering coefficient of the charge carriers, and grad n and grad p characterize the increase of the charge carriers concentration of n-type, respectively, p-type.

The controlled conduction is conditioned by the realization of the crystalline structure of the intrinsic semiconductive material, and later on, by the introduction in the semiconductor of a certain quantity of donor and acceptor impurities.

The property of unidirectional conduction is realized with junctions of the different semiconductive materials, by putting in common two semiconductors with different charge carrier concentration.

For the realization of voltage control of conduction process, the semiconductors must fulfill the following **requirements**:

- to permit the realization of an electrical conductivity which is easily controlled and technologically reproducible;
- to permit the establishment of an electrical conductivity whose values are comprised in a wide domain;
- to present electrical conductivity variations as small as possible in the presence of disturbance factors (ex. frequency of electric field, temperature, etc.);
- to have dielectric permittivity values as small as possible.

The main materials that fulfil these requirements are **silicon**, **germanium** and **gallium arsenide**.

M 3.5.3. Silicon

Technical silicon, under the form of powder, is obtained by the reduction of the quartzite (SiO_2) in the electric ovens. As it contains numerous impurities, it is necessary to proceed to the synthesis and to the advanced purification of silicon chemical compounds: haloids $(SiCl_4, SiCl_2, Sil_2)$ silanes $(SiH_4, SiHCl_3)$, nitrogen compounds and oxides (SiO, SiO_2) .

Figure 3.20 presents the technology of electrolyze in order to obtain melted silicon of metallurgical quality.

122



Fig. 3.20. The electrolyze technology for obtaining melted silicon of metallurgical quality.

The reducing process is:

SiC (liquid) + SiO₂ (liquid) \rightarrow Si (liquid) + SiO (gas) + CO (gas).

Silicon with 98% of purity is obtained.

The next stage is that of the decomposition (pyrolysis) of these compounds and the realization of **the silicon single crystal** through different technologies (zonal melting, drawing from the crucible, epitaxial growth, etc.).

The controlled doping is usually realized simultaneously with the realization of the mono-crystal.

After this operation, silicon of metallurgic quality (with 98% purity) can be obtained.

The purification of the silicon requires chemical methods. As there are many impurities, the next step is the synthesis and the advanced purification of the chemical compounds of the silicon: halogens (SiCl₄, SiCl₂, Sil₂), silanes (SiH₄, SiHCl₃), nitrides and oxides (SiO, SiO₂).

One of the usual methods is to dissolve the silicon in a liquid chemical at room temperature and to distillate the mixture. As a result, silicon halogens appear as intermediary liquid chemicals:

- tetrachlorosilan SiCl₄ (at Rhône-Poulenc, Westinghouse, Texas, Saint Gobain companies, etc.),
- trichlorosilan SiHCl₃ (at Siemens, Union Carbide companies, etc.),
- dichlorosilan SiH₂Cl₂ (at the Wacker company);
- tetrafluorosilan SiF₄ or silicon tetraiodure Sil₄.

Trichlorosilan is obtained by atomizing the solid silicon in hydrochloric gaseous acid, according to the following reaction:

Si (solid) + 3HCl (gas) $-300^{\circ}C \rightarrow SiHCl_3$ (gas) + H₂ (gas)

The reaction with the chlorine allows a first purification because the chlorate precipitates do not dissolve in trichlorosilan. Superior purities are obtained through distillation. Then, the purified trichlorosilan is reduced in order to free the silicon. Such a reactor is presented in figure 3.21.

The balance chemical reaction is the following:

 $SiHCl_3$ (gas) + H_2 (gas) \longrightarrow Si (solid) + 3HCl (gas)



Fig. 3.21. The distillation of a chlorate compound of the silicon.

The silicon single-crystal can be obtained by different technologies (zone melting, extracting from the melting pot, epitaxial growth, etc.).

The controlled doping is a complex operation. The main problem is the chemical purity of the basic semi-conductive material, which should be higher than the concentration of the dopants.

Example:

For a silicon crystal with $5 \cdot 10^{22}$ atoms on cm³, at a purity of 0.9999999 (very difficult to reach), the equivalent concentration of dopants can be of $5 \cdot 10^{16}$ cm⁻³.

As a rule, the phase of **controlled doping** is simultaneous with the phase of obtaining the single-crystal.

The intrinsic electrical conductivity of the silicon depends on temperature, the expression of dependence being of the form:

$$\sigma_{i} = \frac{1}{\rho_{i}} = 1,04 \cdot 10^{6} \cdot \exp\left(-\frac{6500}{T}\right), \ 1/\Omega m$$
(3.57)

The high intrinsic resistivity (at T = 300 K, $\rho \approx 3000 \Omega$ m) is correlated to the high width of the Fermi energy interval ΔW_i .

The electrical resistivity of the silicon single-crystal depends on the donor impurity concentration (Si-n) or that of the acceptor (Si-p), as in the figure 3.22.



Fig. 3.22. The resistivity variation for the Si, Ge, GaAs semiconductors depending on the acceptor impurity concentration, at the temperature T=300 K.

Note:

The charge carrier mobility in a silicon single-crystal has the maximum value at low levels of pollution and low values with the decrease of the impurity concentration.

The charge carrier concentration in silicon intrinsic conduction depends on the temperature, after a law of the form:

$$n_i^2 = 1,5 \cdot 10^{33} \cdot T^3 \cdot \exp\left[-\frac{1,21}{kT}\right], \, \mathrm{cm}^{-6}$$
 (3.58)

Example:

For T= 300 K, it is obtained the value $n_i = 2.2 \cdot 10^{20}$ carriers/cm³.

It must be noted that the charge carrier mobility modifies according to the impurity concentration (Fig. 3.22).

3.5.4. Germanium

Germanium can be rarely found as an ore such as *germanite* (Cu_3GeS_4) or *argirodite* (4 Ag₂SGeS₂) and it is usually extracted from the residues of the gasifiable powders from zinc, copper, from coal burning, etc. From the technical germanium, chemical compounds are obtained such as the halogens (GeCl₄, GeBr₄), which are transformed afterwards in order to obtain *the* **germanium of high purity**. The germanium single-crystal is obtained by zonal melting or by pulling from the melting charge.

The intrinsic electrical conductivity of germanium is calculated with the expression:

$$\sigma_i = \frac{1}{\rho_i} = 3.9 \cdot 10^5 \exp\left(-\frac{3890}{T}\right), 1/\Omega m$$
 (3.59)

Depending on the impurity concentration, the electrical resistivity modifies (Fig. 3.20 § 3.5.3). It must be noted that the charge carrier mobility modifies along with the impurity concentration (Fig. 3.21 § 3.5.3).

The intrinsic concentration of charge carriers depends on the temperature, after a law of the form:

$$n_i^2 = 3,1.10^{32} \cdot T^3 \exp\left(-\frac{7,56}{kT}\right), \text{cm}^{-6}$$
 (3.60)

Example:

For the temperature *T*=300 K, the intrinsic concentration $n_i = 4.5 \cdot 10^{26}$ carriers/cm³ is obtained.





In the presence of the magnetic field, in germanium a strong magnetoresistance phenomenon appears. The magnetoresistance process can be evaluated with the relation:

$$\frac{\Delta\rho}{\rho_0} = 3.8 \cdot 10^{-16} \,\mu B^2 \,, \tag{3.61}$$

where μ is the semiconductor charge carrier mobility and *B* is the magnetic induction.

Note:

The mobility can be modified depending on the impurities' concentration (Fig. 3.21), relation that determines the variation of magnetoresistance.

3.5.5. Varistors

Varistors are structures whose resistance is controlled by the applied voltage at the terminals (Fig. 3.24a).



Fig. 3.24. The variator structure: a) constructional form; b) structure detail: grains plunged in the binder mass and the paths of some micro-currents.

In the figure 3.24, the components significance is: 1 - terminals, 2 - armatures, 3 - active element; 4 - skeleton.

The materials for the active element of the varistors (3 in figure 3.24) are the silicon carbide (SiC) or the metallic oxides (ZnO, TiO₂, ZnO₂, CaO, MnO₂, CuO, etc.)

The manufacturing technology is close to that of the fictile materials: the silicon carbide obtained by the reduction of the silicon dioxide with carbon is crumbled, obtaining grains with 20-180 μ m in diameter. By the combination of it with a binder (clay, silicon-organic resin, water glass), a compound is obtained from which, by molding or extrusion, the wanted form results (disc, cylinder, etc). The tablet is pressed between the armatures 2, and after this operation, terminals 1 are applied. It follows a thermal treatment at 1000÷1300°C by which the properties are stabilized. As a result, between the material grains, stable electrical contacts are obtained.

The current – voltage characteristics for varistors can be approximated with the relations:

$$I = AU^{\alpha} ; U = BI^{\beta}, \qquad (3.62)$$

where *A* and *B* represent the parameters that fix the working voltage value of the varistor and there are dependent on the form, the dimensions and the fabrication technology.

In the relations (3.62), only the constants A and B depend on the temperature:

$$a = \frac{1}{A} \frac{\Delta A}{\Delta T} ; \ b = \frac{1}{B} \frac{\Delta B}{\Delta T}.$$
(3.63)

The values of *b* coefficients for varistors are comprised in the interval:

$$(-1 \div 1.8) \cdot 10^{-3} \text{ K}^{-1}$$

The exponents α and β from (3.62) characterize the non-linearity of characteristics. For the usual variators, they are constant with temperature ($\alpha_{SiC} \approx 5$, $\alpha_{ZnC} \approx 25$).

From the relation (3.62) it results that, at low voltages, the resistance is almost constant, but with the increase of voltage, the resistance decreases. The cause of the voltage decrease must be found in the phenomena that take place at the surface of grains. One of the phenomena is related to the processes of electrical conduction established at the contacts between grains, contacts that are micro-junctions formed during the incipient fusion. Thus, at the contact between grains, a conductive path appears, modeled by two diodes in opposition.

At the increase of the electric field intensity, the micro-junctions pierce one another, the more the voltage rises - the more micro-breakdowns appear. The path of the micro-currents that appears in these electrical micro-breakdowns is indicated in figure 3.24b. The characteristic of the micro-junction is not dependent on the polarity of the applied voltage. The general form of the curve I=f(U) is obtained by the summing up of the micro-junctions characteristics (Fig. 3.25)



Fig. 3.25. The current – voltage characteristics for varistors.

The variators are used to over-voltage protection, as frequency multipliers, current balancers or voltage balancers. For the stabilization function, the variators permit a larger range of currents and voltages ($I_v \le 8$ kA; $U_v \le 1.8$ kV) compared to the Zener diodes.

3.5.6. Materials for Thermo-Electric Conversion

The electrical conductivity in semiconductors is strongly influenced by the temperature, through the influence of temperature on the values of the mobile charge carrier concentrations and their mobilities.

The temperature influences the electric current, and it can even generate one: a temperature gradient, by the diffusion of the carriers situated in those regions with higher temperature (of higher concentration) towards the regions with lower temperature, generates an electric current.

The imprinted electric field, which opposes to the movement tendency of the charge carriers, has the intensity given by the expression:

$$\overline{E}_i = \alpha_s \operatorname{grad} T , \qquad (3.64)$$

where α_S is called the coefficient of differential voltage and *T* represents the increase of temperature after the normal one. The so called Seebeck effect is the conversion of the temperature differences directly into the electricity. Higher values for αS of the order tens of mV/K are obtained for SnSb, PbSb, PbSe, PbTe, Bi₂Te3, Bi₂Se₃.

A material has to fulfill the following requirements in order to be used with its thermo-electrical conversion function:

• to have a high value of the conductivity variation coefficient with the temperature

$$\alpha_{\sigma} = \frac{1}{\sigma} \frac{\Delta \sigma}{\Delta T} , \qquad (3.65)$$

- to have high electrical conductivity in the domain of the working temperatures (high sensitivity),
- to have the electrical (τ_e) and thermal (τT) relaxation times values as reduced as possible,
- to have a high value of Seebeck coefficient.

Table 3.10 presents the main materials with thermo-electrical conversion function.

Semiconductive materials	ρ [Ωm]	α _ρ [K ⁻¹]	α _s [mV/K]
UC ₂	10 ² - 10 ³	- 1.5	0,1 - 10
Cu ₂ O	10 ⁻¹ - 10 ³	- 2.6	1 - 100
Oxides of Co, Cr, Ni, Mn	10 ⁻¹ - 10 ⁴	- 3.5	1 - 100
Oxides of Mg, Ti	10 - 10 ³	- 2	10 - 100

The most famous applications of the thermal effect in semiconductors are the thermistors.



3.5.7. Thermistors

The thermistors are passive circuit components whose resistivity modifies (in the direction of the increase or decrease) with the variation of the temperature. In general, the resistivity variation is higher than that of the usual resistors. The resistivity variation coefficient can be negative or positive.

Thermistors with negative temperature coefficient

These thermistors operates on the basis of the decreasing the semiconductors resistivity ρ at the rise of temperature *T*. The extrinsic *n* or *p* type semiconductors are used depending on the impurity ions that are added to the oxides or the transitional elements from the iron group such as: Cr, Mn, Fe, Co or Ni.

Examples:

- The Fe₂O₃ oxide, which naturally has a very high resistivity, doped with the titan *Ti*⁴⁺ ions becomes an extrinsic semiconductor of *n*-type. With the rise of temperature, the electron concentration increases, leading also to the increase of the electrical conductivity.
- The NiO oxide, if it is doped with litiu Li¹⁺ ions, becomes a semiconductor of *p* type.
 With the rise of temperature, the hole concentration increases, leading also to the increase of the electrical conductivity.

The **characteristic of the resistance-temperature dependence**, regardless of the geometrical form (disc, cylinders, tubes, fibers, etc.) of the thermistor can be expressed as:

$$R_{T} = R_{0} \exp\beta\left(\frac{1}{T} - \frac{1}{T_{0}}\right), \qquad (3.66)$$

where:

 R_0 - resistance at absolute temperature T_0 ;

 β - index of material thermal sensibility;

 R_T - resistance at absolute temperatures T;

 T_0 and T - are absolute normal and working temperature.

Note:

The resistance-temperature characteristic R=f(T) is exponential for both the thermistors - with a negative coefficient of temperature and a positive coefficient of temperature.

The thermistors with negative temperature coefficient are used in temperature measurement and for the compensation of the electrical resistance increase of the various circuit elements (active or passive components) with the rise of temperature. The heating of the thermistors can be realized directly by the current that penetrates the thermistor, or indirectly, by thermal contact.

For a thermistor with a negative temperature coefficient (NTR), the curve of the resistance-temperature characteristic, indicated in the figure 3.26a, is decreasing with the rise of temperature.

130



Fig. 3.26. Thermistor characteristics: a) Resistance-temperature characteristic of the N-type thermistors (NTR) and P-type thermistors (PTR), comparatively to the metals characteristic: b) Voltage-current characteristic at different operating temperatures for a NTR thermistor.

The volt-ampere characteristic U(I) at a given temperature (Fig. 3.26b) is typical for every type of thermistor. The thermistors that function as temperature detectors, operate on the OA linear portion of characteristic, of positive incremental resistance, at relatively minor currents, thus, the self-heating of active element would not take place.

Thermistors with positive temperature coefficient

These thermistors are usually made from barium titanate (BaTiO₃) or solid solution of BaTiO₃ with strontium titanate (SrTiO₃). By the substitution of the Ba²⁺ bivalent ions with La³⁺ trivalent ions or of the Ti⁴⁺ tetravalent ions with Sb⁵⁺, Nb⁵⁺ five-valence ions, it results a conduction of *p*-type. By controlled oxidation at high temperatures, the oxygen atoms penetrate through the pores of the crystals surface, and they become during the cooling O²⁻ negative ions, collecting electrons from the superficial layer of the semiconductive crystallites.

Thus, it appears a potential barrier (the negative superficial charge and the positive spatial charge resulted from the movement of the electrons towards the surface); in the thermistor, a supplementary resistance is established, proportional to:

$$R \approx N \cdot \exp \frac{q_0 V_b}{kT}$$
(3.67)

where:

N - number of barriers on the thermistor length,

- V_b barrier potential,
- q_0 electron charge,
- k Boltzmann's constant,
- T absolute temperature.

Note:

- In the case of the barium titanate, which is a ferro-electric material, the permittivity is dependent on the temperature and the V_b potential, and consequently the resistance value also, which are strongly dependent on the temperature.
- For temperatures which are lower than the ferro-electrical transition temperature T_c, the spontaneous polarization compensates the volume charge, the potential barrier being neglected.
- For temperatures $T > T_c$, the barrier potential increases and implicitly, the resistance value.

The limitation effect of the increase and decrease of resistance with continuous temperature rise can be explained through the release of electrons captured by the oxygen atoms, due to the thermal agitation increase and the barrier potential decrease.

The increase effect of the resistance is limited $(-30 \div +180)^{\circ}$ C and it generates at temperatures $T > T_c$, *t*he law of the resistance variation in this interval being of the form:

$$R_{\tau} = A + C \cdot \exp(BT), \qquad (3.68)$$

from which it results the temperature coefficient:

$$\alpha_{RT} = \frac{1}{R_{T}} \cdot \frac{dR_{T}}{dT} = \frac{BC\exp(BT)}{A + C\exp(BT)}$$
(3.69)

where A, B and C are constants.

For a thermistor with a positive temperature coefficient (PTR), the resistancetemperature characteristic indicated in figure 4.26a is growing along with the temperature rise.

This type of thermistor is used for stabilized temperature detectors, for ballasts, for the short-circuit and over-voltage protection. Table 3.11 presents a few types of NTC and PTC thermistors, together with their characteristics.

Table 3.11. The characterist	cs of some thermistors.
------------------------------	-------------------------

Characteristics	Thermistor type					
Characteristics	NTR	PTR				
	2650÷4200					
B [K]	3350÷4650					
	2600÷3680					
	1 1+22	50÷60				
R ₂₅ [Ω]	1,1.32	100				
	$2.2 \cdot 220 \times 10^3$	250				
	5.3-330 × 10	36÷50				

132

	0÷120	
Operation temperature	- 25÷155	
	- 25÷100	
		7÷40
Maximum voltage		35
[V]		5
		35
		7÷40
Temperature coefficient,		35
10 ⁻² × [K ⁻¹]		5
		35

3. Semiconductive Materials

3.5.8. Semiconductive Materials for Optic-Electric Conversion

The optic-electronic conversion is the phenomenon of transforming the optical signal in electrical signal on the basis of the increase effect of mobile charge carrier volume concentration in a semiconductor under the action of an optical signal. The consequence is the electrical conductivity modification of the semiconductive material.

The incident optical radiation (the electromagnetic radiation in the wavelengths domain $(0.1 \div 100) \mu m$ is partially reflected by the semiconductor surface, partially transmitted, and the semiconductive material **absorbs** the rest of the optical radiation. The absorbed radiation determines the ionization of the atoms of the crystalline lattice and the creation of the mobile charge carriers, phenomenon known as the **photoelectric effect**.

Depending on the incident radiation intensity on the semiconductor surface, electric charge carriers can appear in connection with the **internal and external photoelectric effects**.

The internal photoelectric effect appears if the energy received from the photons by the electrons is smaller than the extraction work, but sufficient for the production of mobile charge carriers in the semiconductor by breaking some bonds in the crystalline lattice. The internal photoelectric effect appears as a result of the intrinsic absorption or of the absorption due to the impurities (the ionization of the base lattice atoms or the impurity atoms).

The intrinsic absorption consists in the interaction between a valence electron and a photon, its result being the fact that the valence electron moves in BC band (Fig. 3.27a). This takes place only if the radiated photon energy W_r exceed the forbidden band energy ΔW_i of the semiconductor:

$$W_r = \hbar \omega \ge \Delta W_i \,, \tag{3.70}$$

where $\omega = 2\pi f$ represents the angular frequency of the optical radiation, and *f* is the corresponding frequency.

133



Fig. 3.27. Optic-electric and electro-optical conversions: a) absorption mechanisms of the optical radiation (electro-optical-conversion); b) recombination mechanisms with optical radiation (opto-electric conversion).

The lowest energy threshold is ΔW_i . For those energies that are lower than this energy threshold, the semiconductor actually becomes transparent at this radiation. With the condition (3.70) it is defined a **threshold wavelength**:

$$\lambda_i = \frac{2\pi\hbar c}{W_i}, \qquad (3.71)$$

for which the radiations with $\lambda > \lambda_i$ are no longer absorbed by the semiconductor.

Table 3.12 presents the limited wavelength values (optical threshold) for a series of semiconductive materials where the opto-electrical conversion appears through proper absorption.

Table 3.12. The optic-electronic conversion through intrinsic absorption in semiconductive materials.

Semiconductor	CdS	GaP	CdTe	GaAs	Si	Ge	PbS	InAs	InSb	PbSe
ΔW_{i} [eV]	2.4	2.24	1.5	1.35	1.12	0.67	0.42	0.39	0.23	0.23
λ _i [μm]	0.52	0.56	0.83	0.92	1.1	1.8	2.9	3.2	5.4	5.4

The absorption due to impurities, as extrinsic absorption process, consists in the interaction between photons and the impurity atoms from semiconductor, through which the ionization of the impurity atoms is possible. Mobile charge carriers will result (Fig. 3.27a). The local levels introduced by the impurity atoms in the Fermi forbidden band are responsible for the decrease of the activation energy value at ΔW_a and ΔW_d .

The threshold wavelength will be:

$$\lambda_e = \frac{2\pi\hbar c}{\Delta W_e},\tag{3.72}$$

higher than in the intrinsic absorption mechanism.

Table 3.13 presents the activation energy values ΔW_e and those of the limited wavelength λ_e for extrinsic semiconductors.

Table 3.13. The optic-electric conversion by impurity absorption for the Si and Ge crystals.

Somiconductor	Silicon doped with							Germanium doped with				
Semiconductor	In	Ga	Bi	AI	As	Sb	Au	Hg	Cd	Cu	Zn	В
ΔW_{e} [eV]	0.15	0.072	0.070	0.0685	0.05	0.042	0.15	0.09	0.06	0.04	0.03	0.01
λ _e [μm]	8	17	18	18	23	29	8,3	14	21	30	38	120

A semiconductive material can be used with the opto-electric conversion function if it satisfies the following requirements:

- to have high sensibility to the electromagnetic radiation within a wavelength domain as large as possible,
- to have a reduced optical threshold,
- the recombination processes of the excessive carriers to be less intense,
- the charge carrier mobility to be high, so that the response velocity to be high.

From Tables 3.12 and 3.13 it can be noticed that the extrinsic semiconductors have the advantage of a more reduced absorption threshold than the intrinsic ones. They also present a high sensibility, but the disadvantage is that they have to work at low temperatures. At normal temperatures it results $\Delta W_e < kT/q_0$, that makes the impurities – thermally ionized – unable to contribute to the optical radiation absorption.

The most often used materials with opto-electric function are: Ge doped with Au or Hg, InSb, $Hg_{0.8}Gd_{0.2}$.

3.5.9. Semiconductive Materials for Electric-Optic Conversion

The electro-optical conversion represents the process of transformation of the electrical signal into optical signal, on the basis of the radiative recombination effect of the mobile charge carriers in a semiconductor, in the case when an electric field of a certain value is being applied.

The radiative recombination phenomenon consists in the electron transition from the energy levels W_1 on the levels $W_2 < W_1$, with a release of energy:

$$(h/2\pi)\omega = W_1 - W_2. \tag{3.73}$$

The process is called **recombination** because the number of electrons and holes from semiconductor, as a result of this transition, decreases (Fig. 3.27b).

There are various recombination mechanisms.

The direct recombination consists in the disappearance of a hole-electron pair through the passing of the electron from BC to BV with release of energy. The released energy can be delivered to the crystalline lattice, resulting the heating of the material (un-radiative recombination) or it can be released under the form of **photons** (radiative recombination). At the direct recombination the charge carriers participate. After the

recombination, two of the three disappear and the released energy is taken by the third charge carrier.

The indirect recombination is realized by means of the local energy levels that exist in the Fermi forbidden band. The conduction electron realizes a transition from BC on the local level and from here in the BV band. The indirect recombination has a prevalent un-radiative character.

The recombination through capturing is specific to the extrinsic semiconductive materials at normal temperatures and consists in the capturing the conduction electron by the impurity ions.

The processes of radiative recombination can have a **spontaneous character**, in the case of a state of equilibrium, or a **stimulated character** in the case of a state of imbalance state.

Spontaneous emission

The common type of light emitting consists of spontaneous recombination between an excited electron from conduction band and a hole from valence band. The energy difference is emitted in the form of a light quantum (**photon**).

Depending on the duration τ of the radiative recombination processes of the charge carriers, there are two categories of radiative spontaneous recombination phenomena:

- **Fluorescence**, when $\tau = (10^{-5} \div 10^{-8})$ s;
- **Phosphorescence**, when $\tau = (1 \div 10^{-4})$ s.

The emitted photon has the frequency corresponding to the difference between the two levels. Other properties of the emitted radiation, such as phase, polarization and direction are randomly (incoherent optical radiation).

Stimulated emission

The stimulated recombination generates a coherent optical radiation of a constant and unique frequency, phase and direction. The recombination occurs though interactions with electromagnetic field, having the frequency in strong correlation with the frequency corresponding to the difference of the energy levels. Thus, a photon can stimulate an e-h pair to recombine, without being destroyed itself. The new photon that forms during recombination is identical to the incident photon.

Notes:

- The stimulated emission is the inverse of the absorption and the probabilities of these processes are equal, depending on the number of e-h pair of each energy level.
- A semiconductor can be used with an electro-optic conversion function, only if the stimulated recombination is stronger than the light absorption,
- The process of obtaining the unbalance between the concentration of available holes and electrons on each level is known as population inversion.

136

3. Semiconductive Materials

The population inversion consists in the occupation of the inferior levels from BC band to the W_{Fc} Fermi quasi-level and the release of the superior levels from BV band to the W_{Fv} Fermi quasi-level (Fig. 3.28).



Fig. 3.28. The photo-emissive diode (LED): a) energy band configuration in the conditions of the population inversion; b) the structure of a LED diode.

Thus, all the energy states implicated in the emissive processes are no longer available for absorption. An efficient and simple method of excitation is the injection of minority carriers into a p-n junction.

The characteristic parameters of the radiative recombination are:

- $n_{\rm i}$ volume concentration of charge carriers,
- r_i recombination velocity of mobile charge carriers at thermal equilibrium,
- τ_i life time of mobile charge carriers at thermal equilibrium,
- r_r radiative recombination velocity,
- τ_r life time of the excessive carriers at unbalance.

Table 3.14 presents the characteristics of some semiconductive materials used in the construction of the electro-optical devices.

Semiconductor	<i>n</i> i [10 ¹⁸ ×m⁻³]	<i>r</i> i [m ⁻³ s ⁻¹]	τ _i [s]	<i>r</i> r [m⁻³ s⁻¹]	τ _r [s]	λ _{emission} [μm]
Si	0.015	4.5 · 10 ⁻¹	4.6 h	$4 \ \cdot \ 10^{15}$	2500	-
GaSb	4.3	$2.4\cdot10^8$	5000	$\textbf{2.7}\cdot\textbf{10}^{19}$	0.37	1.55
InAs	1600	$5.38 \cdot 10^{13}$	15	$4.2\cdot 10^{19}$	0.24	3.1
PbS	710	$2.42 \cdot 10^{13}$	15	4.8 · 10 ¹⁹	0.21	4.3
PbTe	4000	1.33 ·10 ¹³	2.4	$5.3\cdot10^{19}$	0.19	6.5
PbSe	6200	1.54 ·10 ¹⁵	2	$4\cdot 10^{19}$	0.25	8.5
GaAs	9 · 10 ⁻⁶	8.1 ·10 ⁻²	-	$1\cdot 10^{22}$	0.001	0.83-0.91
InSb	2000	1.6 ·10 ¹⁴	0.62	$8.3\cdot 10^{19}$	0.12	5.2

Table 3.14. Materials properties with electro-optical and opto-electrical conversion functions.

From the table it can be observed that the radiative recombination velocity in the case of a semiconductor with a direct structure of energy bands (GaAs, InP, InAs, InSb, PbSe, PbTe) is approximately 10⁷ times higher than in the case of semiconductors with indirect band structure (Si, GaP, Ge).

The materials used in the electro-optical conversion are the compounds of $A_{13}B_{15}$ type and of $A_{12}B_{16}$ type, but also ternary compounds which, by intrinsic excitation in intense electric field (*E* > 10 MV/m) or excitation by an electric current injection, determines optical characteristic radiations through the wavelength $\lambda_{emission}$.

The devices based on the electro-optic conversion principle are: laser diodes (Light Amplification through Stimulated Emission of Radiation) and LED-devices (Light Emitting Diodes). These devices are important components in local area networks, computer application and systems for long distance communication.

LED-s operates according to the principle of spontaneous emission and are manufactured (Fig. 3.28b) with the same combination of materials as those used for laser diodes.

LED-s emit radiations of different colors, depending on the wavelength where the emission efficiency is maximum:

- infrared GaAs,
- red yellow GaAsP,
- . red GaPZn,
- green yellow GaPN,
- blue ZnSe.

By the modification of the impurities concentration, **color combinations** can result.

3.5.10. Semiconductive Materials for Magneto-Electric Conversion

The use of semiconductive materials as magneto-electrical transducers is based on **the magneto-electric phenomena** that appear in these materials at the simultaneous application of an electric and magnetic field.

A material can fulfill the magneto-electrical conversion function only if the material accomplishes the following requirements:

- to have a sensibility as high as possible (Hall field of high intensity for a given B magnetic induction),
- the Hall magnetic field must not be influenced by the external parameters (temperature, pressure, etc.),
- to have the admissible current density as high as possible.

These requirements are fulfilled if the Hall constant $R_{\rm H}$ is high and constant to the temperature.

Table 3.15 indicates some characteristics for the main semiconductive materials with magneto-electrical conversion function.

Table 3.15. The characteristics of some semiconductive materials with magnetoelectrical conversion function.

Semiconductor material	ρ _i [Ωm]	μ _n [cm²/Vs]	μ _p [cm²/Vs]	<i>R</i> н [m³/C]	α _{RH} [K ⁻¹]
Ge	0.46	3900	1900	0.1	- 0.4
InSb	7 · 10⁻⁵	63000	700	-4.7·10 ⁻⁴	-1.5
InAs	2.5·10 ⁻³	30000	200	-9·10 ⁻³	-0.03
HgSe	2·10 ⁻⁵	0.5	-	-7.4·10 ⁻⁶	-

Fig. 3.29 indicates the dependence of the Hall constant on temperature for some semiconductive materials.



Fig. 3.29. The dependence of the Hall constant on temperature for the InSb, InAsP, InAs semiconductors.

The Hall gauge is a semiconductive device used in applications as: the measurement of magnetic fields, the circuits of analogical multiplication, the indication without contact of the position, the deciphering of the dates stored magnetically.

The magnetoresistive gauge is made up of a resistant pellicle of indium antimonite (InSb) used as a contactless potentiometer in magnetic field measurements, for determining the position of some mobile elements.

3.5.11. Semiconductive Materials for Mechano-Electric Conversion

The strain gauges with semiconductors appeared in 1970 as a result of the research on the piezoresistivity phenomena in silicon and germanium crystals.

The piezoresistivity is the electrical resistivity variation phenomenon in the case of the semiconductive materials stressed with mechanical loading. This principle is often used in the strain-measuring domain. It offers important advantages, whatever the disadvantages may appear (i.e. the high variation of resistivity with temperature).

The piezoresistivity in the silicon or germanium single-crystal is maximal on one of the symmetry axis, for example (111) for *p*-type silicon and (100) for *n*-type silicon. This phenomenon appears as a consequence of the disappearance of the isotropy of the crystal properties under the action of a mechanical stress.

Notes:

- For the silicon single-crystal, the electric conductivity increases on one direction, and on the other ones it decreases.
- The tenso-sensitivity coefficient K is positive for p-type silicon and negative for ntype silicon.

Example:

Figure 3.30 shows the variation of the tenso-sensitivity coefficient *K* for silicon depending on the crystalline directions and on the resistivity ρ .



Fig. 3.30. The variation of the tenso-sensitivity coefficient *K* in doped silicon with acceptor impurities, for different crystallographic directions.

The semiconductors materials used in strain gauges are indicated in Table 3.16.

Material	Туре	Resistivity		Constant	Crystalline
		ρ [Ωcm]	<i>T</i> [K]	K	directions
Si	р	7.8	300	175	111
Si	n	11.7	300	- 133	100
Ge	р	15.0	300	102	111
Ge	n	16.6	300	- 157	111
InSb	р	0.54	77	- 45	100
TiO ₂	n	50.0	300	28	001

Table 3.16. The characteristics of the semiconductive materials for strain gauges.

The high value of the *K* constant, comparatively to that of the metallic resistive materials, permits the use of semiconductive materials as very simple measurement devices. Because of the narrow domain of linearity of the dependence between resistivity $\frac{\Delta \rho}{\rho}$ and elongation $\frac{\Delta l}{l}$, the applications are in the domain of low amplitudes $\frac{\Delta l}{l} < 10^{-8}$.

The strain gauges with semiconductors are realized under the form of parallelepiped sticks with the length 2...7 mm, width 0.1...0.5 mm and thickness 10...50 μ m. The fixing and binding technology in the electrical diagram is specific to that used at the majority of gauges.

M 3.5.12. Usual Structures for Semiconductive Devices

There are different semiconductive structures used in the construction of semiconductive devices. All are based on the phenomena that take place in n-p junctions.

In the Si-*n* single-crystal at room temperature, the atoms of the donor impurities (as phosphorus atoms) lose the valence electrons and become positive ions, fixed in the crystalline lattice. In the crystal, there are an equal number of quasi-free electrons.

In the Si-*p* single-crystal at room temperature, the atoms of the acceptor impurities (as boron atoms) receive electrons from the atoms of silicon crystalline lattice, becoming negative ions fixed in the crystalline lattice. In the crystal, there are an equal number of uncompensated bonds, equivalent to the number of positive particles - holes.

Figure 3.31 describes the physical model of the *p*-*n* junction formation:

- Figure 3.31a shows the case of a two single-crystals Si-*n* and Si-*p*, which are not in contact.

- Figure 3.31b shows the case of a two single-crystals Si-*n* and Si-*p*, which are in contact.



Fig. 3.31. The physical model of the *p*-*n* junction formation: a) in the absence of contact; b) at the contact between Si-*n* and Si-*p* single-crystals.

To compensate the imbalance between the excess of electrons in the *n*-material, and the excess of holes in *p*-material (Figure 3.31b), a space-charge region is formed around the *p*-*n* junction: in junction region, the electrons and holes recombine and the impurity ions form an electric imprinted field of intensity \overline{E}_0 . This field operates on the rest of free electrons and holes, removing them from the junction. The junction will have the width I_{b0} .

The formation of the *p*-*n* junction can be justified with the energy band theory (Fig. 3.32).



Fig. 3.32. The energy band model of the *p*-*n* junction formation: a) in the absence of contact; b) at the contact between Si-*n* and Si-*p* single-crystals.

Figure 3.32a shows the structures of the energy bands for the case of Si-*n* and Si-*p* single-crystals, which are not in contact. The ionization processes of the impurity atoms correspond to the electrons presence in BC (for Si-*n*) and to the holes in BV (for Si-*p*). The Fermi levels, noted with W_{Fn} and W_{Fp} have specific positions.

Figure 3.32b illustrates the energy band structures for the case when the Si-*n* and Si-*p* single-crystals are put in contact. This is equivalent to the equalizing of the Fermi energies ($W_{Fn} = W_{Fp}$), phenomenon that determines a variation in the level of bands structures, on a width equivalent to the width of the I_{b0} junction. The variation of level position corresponds to the **energy variation** ΔW_0 that determines the appearance of the **electric imprinted field of the contact**.

The space-charge prevents the current to flow from the p to n side. Since the external voltage over the device is zero, no current flows through it.

If an external voltage is applied across the junction, it can either **add to** the existing internal voltage created by the space charge (**reverse bias**), or the external voltage can **subtract from** the internal voltage (**forward bias**), as shown in Fig. 3.33.



Fig. 3.33. The supplying of the *p*-*n* junction: a) forward bias; b) reverse bias.

The forward-biased voltage (Fig. 3.33a) – the external electric field of \overline{E}_d intensity is opposed to the electric imprinted field of contact, of \overline{E}_0 intensity. The total electric field, having a lower intensity, determines the **decrease of the** junction width from I_{b0} to I_{bd} .

The reverse voltage bias (Fig. 3.33b) – the external electric field of \overline{E}_i intensity has direction to the electric imprinted field of contact of \overline{E}_0 intensity. The junction width increases. This is the cause for the reduced value of the electron and hole fluxes that penetrate the junction. The intensity of the reverse current I_i is low (the junction has **high resistivity**). If the total electric field has high intensity, it can appear the **electrical breakdown** of the junction.

The property of *p*-*n* junction of **single-directional conduction**, through which the current in forward voltage bias is favored, permits the realization of many types of electronic devices.

The integrated circuits are those circuits in which a number of circuit elements are associated and electric interconnected in an inseparable way. From the point of view of the way of realization, the integrated circuits can be: semiconductors, epitaxial or hybrid.

The semiconductive integrated circuits are structures formed in the interior or on the surface of a semiconductive single crystal. Among these, the monolithic ones have circuit elements formed in a single semiconductive structure (MOS), and the fragmental ones are formed with more monolithic structures, interconnected.
The epitaxial integrated circuits are structures formed as a result of the application of some pellicles on the surface of a dielectric material, the pellicles being either thin (under 1 μ m), or thick (over 10 μ m).

The hybrid integrated circuits are structures in which some circuit elements are mounted on a dielectric sub-layer and the remaining elements are realized through the deposition on the surface of the dielectric support.

All these structures rely on the unidirectional conduction property of the *n-p* junction.



Chapter 4

DIELECTRICS

Contents

The contribution of the electroinsulating materials to the improvement of the performances of the electrical devices is very relevant. On the one hand the insulating materials determine the lifetime of these products, being the first to yield under the action of complex functional and environmental stress. On the other hand, they have a great diversity, due to the dynamic development of the macromolecular chemistry, which constantly proposes new types of materials especially composites and nanomaterials.

This chapter presents the main characteristics, measuring methods and describes the main phenomena, which take place in the electroinsulating materials. It also describes the main material applications and their characteristic properties.

Course Objectives

- •To explain the particularities of the electric conduction processes in the electroinsulating materials.
- •To show the experimental method of measuring the volume and surface resistivity, and to explain the particularities of the conduction in the metal-insulator interfaces.
- •To describe the polarization processes and the particularities of electronic, ionic and orientation polarizations, and to establish the Clausius-Mosotti equation.
- •To calculate the permittivity for the dielectrics with complex structure.
- To present the principles of the high voltage testing techniques.
- •To establish the losses in dielectrics and to describe models for the breakdown of the ectroinsulating materials and prevention methods.
- •To describe the properties and performances of the electroinsulating materials.

4.1. GENERAL CHARACTERISTICS

4.1.1. Electroinsulating Materials and Dielectrics

The electroinsulating materials belong to the category of materials called dielectrics. **Dielectrics** are materials used either for insulating the electric conductive parts between themselves and/or against the ground, as **electroinsulating materials**, or for making **capacitive elements** of certain components, circuits or systems.

A. The electroinsulating property attributed to the dielectrics is directly connected to the low concentration of free electric charges ($q_{free} \sim 0$) and to the irrelevant phenomena of electrical conduction. Thus, within the dielectric subjected to an electric field, the free charge will start moving and low valued electric current will be soon established. In a dielectric, the conduction current is due to electrons and also to other charge carriers (ions), usually associated with the processes of impurities' contamination and with relaxation processes occurring in time variable regime. In many cases, the two latter contributions are significant compared to the contribution of the conduction electrons. A dielectric – solid, liquid or gaseous (unionized) - is often considered to be a material that does not contain free electric charge. In this case, it can be said that the dielectric is a **perfect insulator**.

B. The property of making capacitive elements with the support of dielectrics is strictly related to the existence of the bound electric charge, and to **the polarization phenomenon**. The polarization phenomenon cannot be studied unless the discontinuous structure of the dielectric is taken into account. The material is made of structural units (atoms, molecules, macromolecules), neutral from the electrical point of view. By definition, the **bound electric charges** q_{bo} are considered to be a positive electric charge (protons, positive ions) or a negative electric charge (electrons, negative ions) joining the constitution of these structural units and which, under the influence of the electric field, cannot displace along large distances comparable with the interatomic distance. The polarization phenomenon consists in the microscopic deformation and/or displacement of the bound electric field. It is established in the **real dielectrics** ($q_{free} \neq 0$ and $q_{bo} \neq 0$). (The **ideal dielectric** contains only bound electric charge.) This is the reason why the study of dielectric properties implies the approach of the electric conduction processes, as well as polarization processes.

It is worth mentioning that the term "dielectric" is usually used to take in account the material ability to store energy when an external electric field is applied. **Notes**:

- Dielectrics are materials, which are characterized by intense electrical polarization states and by relatively reduced electrical conduction states.
- **The polarization phenomenon** is encountered at semiconductive materials as well, which at low temperature present electrically insulating properties.

4.1.2. Requirements for Electroinsulating Materials

The requirements that electroinsulating materials must fulfill are:

- \circ high resistivity in order to achieve the electroinsulating function;
- no electrical polarization state (a low permittivity) in order to avoid the capacitive connection between the insulated pieces, especially in the domain of high frequencies;
- o resistance at high electrical stresses;
- o resistance at high operating temperatures;
- good mechanical properties;
- high stability of properties in time (a long lifetime);
- o resistance at environmental chemical agents;
- o good use of it and possibility of recycling;
- $\circ~$ good price.

These requests are partially satisfied by a series of natural or synthetic materials. The present technologies follow the frame of properties by: modifying the molecular structure, obtaining the composite materials or with a sandwich structure, etc., and thus, the request matrix must be in concordance with the property matrix of electroinsulating materials.

It is worth to mention that for capacitive devices, the main requirements are connected with high and stable state of polarization (high permittivity) and also low electric conduction (high resistivity).

4.1.3. Durability of the Electrical Insulation

Whichever their function may be – electric insulation, dielectric for capacitors or transducers – all dielectric materials are submitted to different electrical, thermal and mechanical stresses. The influence factors from the surrounding environment may also be added: humidity, atmospheric oxygen, the action of the ultraviolet radiation, the action of the industrial pollution, etc.

Electric stresses	Environmental factors		
Service voltage	Air		
Overvoltage	Oxygen		
Frequency	Hydrogen		
Partial discharges	Nitrogen		
Fartial discharges	Inert Gases		

Table 4.1. The factors that influence the properties of materials.

Mechanical stresses	Hexafluoride Sulfur			
Electrodynamic vibrations	Industrial pollution (SO ₂ , NaCl)			
Electrodynamic shock	Ultraviolet radiation			
Mechanical vibrations	Vacuum			
Mechanical shock	Lubricants			
Bending	Solvents			
Pressure	Isolating liquids			
Stretching	Water			
Compression	Acids, bases			
Twisting	Semiconductive dust			
Thermal stresses	Dust and sand			
Maximum operation temperature	Fungi			
Environmental minimum temperature	Rodents			
Environmental maximum temperature	Termite			
Temperature gradient	Humidity			

These stresses determine modification of the structure and/or of the composition of the dielectric and this fact determines the degradation of one property or the whole properties. This phenomenon is also called **degradation** or **ageing**. Table 4.1 presents the main influence ageing factors of electroinsulating materials.

The material composition and structure, being conditioned by the stress amplitude and the operation regime, determine the **ageing degree**. The ensemble of stresses and the influencing factors are called **ageing factors** when the ageing processes are studied or **factors of diagnosis** when the purpose is to establish the insulation state at a certain moment. As a rule, an ensemble of ageing factors will determine the ageing degree of a dielectric.

Examples:

- The main ageing factors for a transformer in operation regime with variable voltages are: the average and peak values of the applied voltage, frequency, frequency of overvoltage, and environmental corresponding factors.
- In the case of thermal stresses, the set of variables that characterizes the ageing is: the maximum and minimum of the environmental temperature, the temperature gradient in insulation, the maximum temperature accepted in operation.
- In the same manner, the mechanical stress character will differ from the compression stress, stretching, twisting and/or bending/curving.

Moreover, as a result, the ageing velocity will be different if all the stress factors will act (electrically, thermally and mechanically) in the same time, separately or in a certain order.

148

Table 4.2 presents the values of intensity of the electric field, applied on the isolations of electrical systems under voltage operation.

Table 4.2. Levels of electric insulation stresses.

Device type		The nature of the main insulation	<i>E_{service,}</i> at 50 Hz [kV/mm]		
Medium voltage capacitors		Polypropylene paper impregnated with polyclor diphenyl	35÷38		
		Polypropylene paper impregnated with non-chloride oils	41÷46		
		Polypropylene film with non-chloride oil	50÷60		
Impreg- nated		Impregnated paper with viscous oil	3.5÷4.5		
		Impregnated paper with fluid oil	10÷15		
High		Polyethylene	R _e core	<i>R_e</i> screen	
voltage cables Extru- ded		63 kV	6	3	
		225 kV	11	4	
		400 kV	15	6	
Alternators		Micallex band, support for glass texture or polyester texture impregnated with thermosetting resin without solvents	2÷3		
Power transformers		Paper impregnated with oil Oil channels	1÷3		

Table 4.3 presents the mechanical efforts due to the short-circuits in different electrical devices for different levels of symmetrical and asymmetrical short-circuits.

Device type	$rac{I_{scsim}}{\sqrt{2}I_n}$	$\frac{I_{scasim}}{\sqrt{2}I_n}$	$rac{F_{sc}}{F_n}$
Connections and bars of connections in high voltage distribution stations	20	36	1300
Medium voltage distribution transformers	25	45	2000
Interconnection transformers	7÷10	13÷18	150÷300
Electrical generators	2.5÷5	4.5÷8	20÷80

In this table, I_n is the nominal value of the current, $I_{sc sim}$ is the peak value of the periodical components of the shortcircuit current, $I_{sc asim}$ is the value of the short-circuit current at first maximum in the case of an a-symmetric short-circuit ($I_{sc asim} \approx \sqrt{3} \cdot I_{sc sim}$), F_{sc} is the mechanical stress at the shortcircuit and F_n is the mechanical stress in normal operation regime.

The stress process of the material can be:

- o continuous,
- o of a short period,
- o intermittent,
- o determined by storage and transport.

Stresses can be appreciated starting from the real functioning conditions of the electronic or electrical devices. It can distinguish:

- Permanent acceptance regimes also called regimes of continuous functioning; these are the regimes that are taken into consideration at the isolation dimensioning;
- Overloading regimes (they operate intermittently) which conduct to a limited time functioning, with higher stresses than the ones in continuous operating regime;
- Normal operating regimes, of short periods (fractions of seconds), which appear due to accidental phenomena – overvoltages or short-circuits, which determine very strong stresses, electric shocks, mechanical shocks, etc.

Table 4.4 presents the acceptance values of temperatures in short-circuit regime for some electrical insulations.

It must be taken into consideration that a separate analysis of degradations produced by each type of stress is useful, in order to establish the causes and the methods for reducing the ageing.

Devices	Insulation type	Temperature	
	Polyethylene of low density	150 <i>°</i> C	
Power cables	Polyethylene of high density	180 <i>°</i> C	
	Polyethylene chemically reticulated	250 <i>°</i> C	
Medium voltage transformers	Paper impregnated with oil	250 <i>°</i> C	
High voltage	Paper with resin	200.00	
transformers	Paper impregnated with oil	200 C	

Table 4.4. Temperature acceptable values for some insulations in short-circuit regime.

A degradation study that takes into consideration the ensemble of the stresses and mutual interaction is also necessary in order to establish the set of functional testing, which reflects as much as possible the stresses from exploitation.

150

4.2. ELECTRICAL CONDUCTION IN DIELECTRICS

4.2.1. General Characteristics of Electrical Conduction

Although dielectrics are considered materials which, submitted to continuous voltage, do not conduct electrical current, practically any dielectric, having finite resistivity, allows the passing of the electric current of a relatively low intensity i(t) (Fig. 4.1).



Fig. 4.1. Electric currents in a dielectric sample: a) electric scheme; b) curve i=f(t).

The conduction in dielectrics has specific characteristics comparing to the conduction in conductors or semiconductors:

> The dependence on time of the current intensity i(t) when a constant voltage U is applied, is specific. Thus, by applying a continuous voltage to the metallic electrode system in which a dielectric material is placed (Fig. 4.1a), an electric current is established (passing through volume $-i_V$ and surface $-i_S$ of dielectric sample), whose intensity i(t) sensitively decreases to a much lower value I, called intensity of **leakage current** or **conduction current**. This value serves to define the electrical resistivity, being determined from the electrical conduction (Fig. 4.1b).

The curve i(t) from figure 4.1b is obtained by overlapping the following components of electric current:

- Geometric capacitor charge loading current, defined by the geometrical capacity *C* and the resistance *R* of the circuit, a component decreasing in time with the time constant $\tau = RC$;
- Polarization current, which decreases in time,
- Absorption current, which decreases in time, determined by the phenomena of incomplete conduction in dielectric;
- **Conduction current**, with a constant value in time, determined by the displacement of the free electric charge.

As a rule, the first two components decrease fast in time in intervals of the order of $10^{-2} \div 10^{-1}$ seconds. The third component of current is due to the formation of spatial charge. The accumulations of electric charges are associated to the non-homogeneities in the material, to the agglomerations of impurity ions neighboring the electrodes, or to chemical modifications occurring in the layers around the electrodes. As the phenomenon of redistribution (absorption) of the electric charge takes place, this component decreases.

Thus, it is only the time invariable component which remains in permanent regime and it is called **leakage current**, of intensity *I*, characterizing the ordered movement of the free charge carriers.

- The low values of the conduction current intensity are correlated with the high value of resistivity:
 - from values of the order of $(10^6 \div 10^8) \Omega m$ (for wood, cement, etc.),
 - to values of the order of $(10^{14} \div 10^{18}) \Omega m$ (for polyethylene PE, polytetrafluoroethylene PTFE, quartz, etc.).

The higher the resistivity, the lower the conduction current is. Thus, currents of the order of tenth nA are obtained (a level difficult to detect by classical means of measuring due to the parasite currents that interfere).

- The electrical conduction processes take place inside material volume and along its surface. Generally, there are two components of the conduction current:
 - \circ Leakage volume current, of intensity $I_{V_{i}}$
 - Leakage surface current, of intensity I_S.

The total conduction current in permanent regime has the expression:

$$I = I_V + I_S. \tag{4.1}$$

By measuring the electrical parameters, the two components of the current are considered and they define the **volume conductance** $G_V = I_V / U$ and the **surface conductance** $G_S = I_S / U$, the total conductance being:

$$G = \frac{I}{U} = \frac{I_{V} + I_{S}}{U} = G_{V} + G_{S}$$
(4.2)

The volume resistance $R_V = 1/G_V$ and the superficial resistance $R_S = 1/G_S$ are considered connected in parallel, thus, the total sample resistance can be define:

$$R = \frac{1}{G} = \frac{1}{G_V + G_S} = \frac{1}{\frac{1}{R_V} + \frac{1}{R_S}} = \frac{R_V \cdot R_S}{R_V + R_S}$$
(4.3)

The volume resistance R_V and surface resistance R_S of the materials sample are the basis for the method of determining the volume resistivity ρ_V and the surface resistivity ρ_S .

4.2.2. Determining the Volume and Surface Resistivity

These material parameters are determined by a measurement system with three electrodes, disposed like in Fig. 4.2



Fig. 4.2. The measurement system with three metallic electrodes: 1 -cylindrical electrode; 2 - plate electrode; 3 - ring electrode; dielectric sample.

With the volt-ampere method, the DC voltage U is applied on the dielectric sample, and the volume I_V , and surface I_S conduction current intensities are measured. Fig. 4.3 shows the measurement scheme, where S_{DC} is DC supply, V is voltmeter, μ A is the micro-ampermeter for volume and surface current intensity measurements.





The volume resistance of the sample is calculated with the relation:

$$R_{\nu} = \frac{U}{I_{\nu}}, \qquad (4.4)$$

and, with the expression of the resistance:

$$R_{V} = \rho_{V} \cdot \frac{d}{S_{ef}}, \qquad (4.5)$$

the volume resistivity is obtained:

$$\rho_V = \frac{R_V \cdot S_{ef}}{d} \,. \tag{4.6}$$

In the above relation, d is the thickness of dielectric sample, and S_{ef} is the crosssection area of the dielectric, by which the volume conduction current passes. Having in view the geometry of the measurement system (Fig. 4.2), the cross-section area is further calculated:

$$S_{ef} = \frac{\pi \cdot D_{av}^2}{4},\tag{4.7}$$

where $D_{av}=(D_1+D_2)/2$ is the average diameter of the effective cross section of the sample. The diameters D_1 and D_2 are indicated in figure 4.2.

The surface resistance is defined with the relation

$$R_{s} = \frac{U}{I_{s}}.$$
(4.8)

Taking into account the definition relation for surface resistance:

$$R_{S} = \rho_{S} \cdot \frac{L}{D}, \qquad (4.9)$$

where ρ_S is the surface resistivity, *L* is the distance between the electrodes and *D* is the average distance on which the surface current leakage passes.

For the case when the measurement electrodes are cylinder and concentric rings, the relation (4.9) for R_s becomes:

$$R_{S} = \rho_{S} \cdot \frac{(D_{2} - D_{1})/2}{\pi \cdot D_{av}}, \qquad (4.10)$$

Thus, the surface resistivity is obtained:

$$\rho_{S} = \frac{R_{S} \cdot \pi \cdot D_{av}}{(D_{2} - D_{1})/2}.$$
(4.11)

Notes:

 Surface resistivity is a quantity which characterizes the conduction phenomenon through the surface layers of the dielectric, being dependent on the dielectric nature, on external factors as: humidity, contamination with different substances, oxidation degree, etc.

It worth to note that for electroinsulating materials:

- Volume resistivity is of the order of (10⁸ ÷ 10¹⁸) Ωm;
- Surface resistivity is of the order of $(10^6 \div 10^{16}) \Omega$.

4.2.3. Electrical Conduction Mechanisms

The conduction mechanisms in dielectrics differ according to the charge carrier type which participates in the conduction. There can be distinguished:

- > ionic or electrolytic conduction;
- molionic or electrophoresis conduction;
- electronic conduction.

lonic conduction is conditioned by the macroscopic displacement under the action of the electric field of the positive and negative ions or of the interstitial impurities. An ionic conduction process is also considered the ordered displacement of ions on vacancy type defects, which has as an effect the migration of the vacancies.

Molionic conduction is produced by moving the molecular ions (molions) or the ionized molecules groups under the action of the electric field. This type of conduction, encountered especially with amorphous and liquid dielectrics, has an important role in colloidal systems, at the interface solid-liquid dielectric, etc.

Electronic conduction is conditioned by the free electron moving under the action of the applied electric field. The free electrons occur in dielectric by injection from the electrodes, by photoelectric effect, by hopping among the atoms with identical or different valences.

In general, electroinsulating materials present **a mixed electrical conduction**, their conductivity being dependent on the intrinsic factors (the nature of the dielectric, the aggregation state, structure, defects, etc.) and on the extrinsic factors (electric field, temperature, humidity, radiation, etc.).

The total conductivity is given by the sum between the ionic conductivity σ_{ion} and the electronic conductivity σ_e (when there is no molionic conduction):

$$\sigma_{tot} = \sigma_{ion} + \sigma_e. \tag{4.12}$$

The electrical conductivity of an electroinsulating material which contains many electric carrier types can be expressed as:

$$\sigma_{tot} = n_1 q_1 \mu_1 + n_2 q_2 \mu_2 + \dots \tag{4.13}$$

Examples:

- Experimentally, it was shown that, in the case of AgCl, the Ag⁺ ions have an essential contribution to the conduction process. For KCl, at high electric fields, the contribution is given in equal parts, by K⁺ ions and Cl⁻ ions.
- The different contribution of ion types to the conduction processes is explained by the existence of the different mobilities of different types of ions.

For electroinsulating material manufacturers and users, the main task is to obtain the materials with very low electric conductivity (higher resistivity).

The electric conductivity of electroinsulating materials depends on the intensity of the applied electric field of intensity E and operating temperature T.

Figure 4.4a presents the general dependence $\sigma = f(E)$ in the case of an electroinsulating material which has ionic and electronic conductivity.



Fig. 4.4. The dependence of the electric conductivity on: a) the electric field intensity; b) on the temperature.

Notes:

- Figure 4.4a shows that the electronic conductivity σ_e is smaller than the ionic conductivity σ_{ion} .
- In the case of electric fields of low and medium intensity, the ionic conductivity σ_{ion} and the electronic conductivity σ_e do not depend on the intensity of the applied electric field. This is **the Ohm domain**, where σ = constant, and Ohm law is valid. The dielectric has a linear character.
- For the high electric field intensity, the electronic and ionic conductivity increase with the intensity of field. It is the Poole domain, where σ= f(E). The dielectric has a non-linear character.
- Practically, all dielectrics lose their electroinsulating properties at the values of electric field intensity up to and over 10⁸ V/m, the phenomenon being named electric breakdown. The value of the electric field intensity *E*_{str} corresponding to the establishing of electric breakdown is named electric strength.

Fig. 4.4b shows the strong dependence of the some composites on the temperature variation.

In crystalline electroinsulating materials, the impurity ions have an essential contribution at the electrical conduction.

For ionic crystals, at low temperatures, it is possible that the conduction of a certain type of interstitial ions to be predominant. At high temperature, the contribution of the current can significantly appear by generating vacancies (intrinsic conduction, similar to that of semiconductive materials). The changing of the characteristic slope $\ln\sigma_{ion} = f(1/T)$ indicates the changing of the conduction mechanism (Fig. 4.4b).

The first domain (I) in Fig. 4.4b corresponds to the zone of low temperatures, where, probably certain types of interstitial ions define the conduction phenomenon.

The second domain (II) in Fig. 4.4b corresponds to higher temperatures, where the processes of electrical conduction can be determined by the increasing of the vacancy concentration, etc.

Note:

 While the temperature is increasing, the electrical conductivity is decreasing. The electrical isolation conditions suffer degradation.

The electrical conductivity of organic electroinsulating materials, in a certain limit of variation of temperature T and electric field E, can be expressed as:

$$\sigma(E,T) = \sigma_0 \cdot \exp\left[-\frac{W - \beta E}{kT}\right]$$
(4.14)

where *W* is the **thermal activation energy** and the parameter β is the parameter which characterize the influence of the electric field upon the activation processes of electrical conduction.

If the temperature remains constant $(T=T_0)$, the relation (4.14) describes the **Poole-Frenkel law**:

$$\sigma(E,T_0) = \sigma'_0 \cdot \exp(\alpha E) \tag{4.15}$$

where the parameter α is the sensitivity index with the applied electric field, and comparatively with relation (4.14), is:

$$\alpha = \frac{\beta}{kT_0}, \qquad (4.16)$$

having the same significance as β in relation (4.14).

Relation (4.16), in coordinates (In σ , *E*) is a straight line, with the slope α .

Values for the sensitivity index with the electric field of the electrical conductivity for polymers are of order of $\alpha = (1 \div 5) \ 10^{-8} \text{ m/V}$ order. For impregnated electroinsulating paper it is obtained $\alpha = 4 \cdot 10^{-8} \text{ m/V}$.

If the electric field remains constant ($E=E_0$), the relation (4.14) become:

$$\sigma(E_0, T) = A \cdot exp(-\frac{B}{T})$$
(4.17)

For most of the polymers, in constant electric fields, in coordinates ($\lg \sigma$, 1/*T*), the conductivity dependency on the reversed absolute temperature 1/*T* represents a straight line.

$$\lg \sigma(E_0,T) = A - B \cdot \frac{1}{T}.$$
(4.18)

The *A* parameter from the relation (4.18) is the pre-exponential factor, dependent on the conductivity corresponding to the temperature *T* and on the intensity of the electric field E_0 .

The *B* parameter from the relation (4.18) is connected to the thermal activating energy *W* from the relation (4.14).

The exponential dependency on temperature, in a small domain of temperature variation, in constant electric fields, can be described as it follows:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_0 \cdot exp[\boldsymbol{a}(T - T_0)] = \boldsymbol{\sigma}_0 \cdot exp[\boldsymbol{a} \cdot \boldsymbol{\theta}], \qquad (4.19)$$

where the parameter *a* characterize the average coefficient of thermal sensitivity and θ is the over-temperature of material, in Celsius degrees.

For a small variation of the temperature $(T-T_0=\theta)$, the relations (4.17) and (4.19) are equivalent. Indeed, through serial decomposing of 1/T, and neglecting the superior terms of series, it will result:

$$\frac{1}{T} = \frac{1}{T_0 + \theta} = \frac{1}{T_0 \left(1 + \frac{\theta}{T_0}\right)} = \frac{1}{T_0} \left[1 - \frac{\theta}{T_0} + \frac{1}{2} \left(\frac{\theta}{T_0}\right)^2 + \cdots\right] \equiv \frac{1}{T_0} \left(1 - \frac{\theta}{T_0}\right) = \frac{T_0 - \theta}{T_0^2} = \frac{1}{T_0} - \frac{T - T_0}{T_0^2}$$

and the relation (4.17) becomes:

$$\sigma(\mathbf{T}) = \mathbf{A} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} -\frac{\mathbf{B}}{\mathbf{T}} \end{bmatrix} = \mathbf{A} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} \left(\frac{-1}{T_0} + \frac{\mathbf{T} - T_0}{T_0^2} \right) \cdot \mathbf{B} \end{bmatrix} =$$

$$= \mathbf{A} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} -\frac{1}{T_0} \end{bmatrix} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} \frac{\mathbf{B}}{T_0^2} \cdot \mathbf{T} - T_0 \end{bmatrix}$$

$$(4.20)$$

$$= \mathbf{A} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} -\frac{1}{T_0} \end{bmatrix} \cdot \mathbf{e}_{\mathbf{X}} \begin{bmatrix} \frac{\mathbf{B}}{T_0^2} \cdot \mathbf{T} - T_0 \end{bmatrix}$$

By comparing (4.20)^r to (4.17) if will result:

$$a = \frac{B}{T_0^2}.$$
 (4.21)

For most of the polymers, the dependency on temperature of the electrical conductivity is exponentially.

4.2.4. Influencing Factors on the Electric Conductivity

For analyzing the influence of the intensity of the electric field and the temperature on the volume resistivity of dielectrics, a case study was done for some epoxy resins of DINOX 110 E type, having as an additive phtalic anhydride (RE 25 and

RE 27 with a percentage of 25%, respectively 27% additive) and for terephthalate of polyethylene samples (PETF). The measurements were done at the temperature of 293.15 K.

The results of measurements are shown in Figure 4.5.



Fig. 4.5. The dependence of the electric conductivity on the electric field intensity for epoxy resins (RE) and polyethylene terephthalate (PETF).

Indeed, at constant temperatures, the conductivity dependency on the intensity of the electric field in coordinates ($\lg \sigma$, *E*) represents a straight line.

The study of the dependence of the conductivity on temperature becomes more complicated because of the application time of the electric stress. In Fig. 2.6 is shown the experimental results of the variation of volume conductivity of the epoxy resin samples (RE 28) with temperature, measured at different time intervals of applied voltages (500 V DC).



Fig. 4.6. Dependency of volume conductivity on temperature for epoxy resin (RE 28).

In Fig. 4.7, for epoxy resins with different reinforcement components' concentrations (RE25, RE26, RE27, RE28) and in Fig. 4.8, for impregnation lacquer ALM and terephthalic films PETF, the same dependencies are presented.



Fig. 4.7. The dependency of the electrical conductivity on temperature for epoxide resins with different reinforcement component concentration, from 25% (RE25) to 28% (RE28).



Fig. 4.8. Dependency of electrical conductivity on temperature for lacquer ALM (curve 1, E=1.0 MV/m) and for terephthalic films PETF (curve 2, E=0.5 MV/m and curve 3, E=2.55 MV/m).

The dependence from figure 4.8 underlines the fact that the lake ALM is more sensitive at the temperature variation. The value of the conductivity at terephthallic foils is influenced by the electric field: when the electric field is increasing, the electrical conductivity is increasing.

Notes:

- There is a temperature T_{cr} over which the curve $\sigma = f(1/T)$ is no longer influenced by the application time of voltage. This temperature marks the beginning of the dependency of exponential type. For $T > T_{cr}$ the conduction could have an ionic character.
- At temperatures $T < T_{cr}$ it will appear a zone of negative dynamic conductivity. The peaks measured at small time intervals, connected with the presence of the impurities and humidity, displace to the domain of the high temperatures.
- That is why it is necessary that in the comparative tests of the insulation systems should be specified the duration of voltage application, as well as, the intensity of the measurement electric field.

For polymers, the **superficial electric properties** differ from those in their volume, due to the existence of the carriers arranged on superficial energetic levels or due to forming of the spatial charge. It will result **a non-uniform distribution of the electric field in the superficial layer**, which can determine different mobilities. The superficial conductivity depends on **humidity** and on various diffusion mechanisms that take place.

Non-polar dielectrics present higher values for the surface resistivity as compared to the polar dielectrics, which attract water molecules or other polar fluids they might come into contact (Fig. 4.9).



Fig. 4.9. Surface resistivity dependency on relative humidity for ceresin (curve 1), alkaline glass (curve 2), bakelite (curve 3).

Surface resistivity for ceresin (wax), which is an electrically non-polar material, is higher than for the alkaline glass. Modifying the forming technological conditions can decrease the influence of humidity.

Humidity, in the case of plastics based on phenol-formaldehyde with organic or inorganic reinforcing additive, have a pronounced influence on the values of surface conductivity, respectively on surface resistivity (Fig. 4.10, Fig. 4.11).

In figure 4.10 are indicated the measure dependence ρ_V at bakelite (P 31.5) on the maintaining time in humidity 80%, at temperatures of 20°C, respectively 60°C.



Fig. 4.10. Volume resistivity dependency on the time of stressing at humidity of 80% at 60°C, respectively, at 20°C, for bakelite samples (P31.5).

In figure 4.11 is presented the dependency of the volume resistivity ρ_v with the maintaining time of the samples at temperatures of 20°C and 60°C in 80% humidity, corresponding to those two processes of forming through pressing with pre-heating at 80°C for 1,7 minutes (curve 1) and, respectively, for 45 minutes (curve 2).



Fig. 4.11. Surface resistivity dependency ρ_S on humidity for bakelite (P 31.5) after 7 days of acclimatization at 20°C.

Note:

By heating at 80°C for 45 minutes and pressing, it can obtain pressing masses with better electroinsulating properties, with a higher resistivity and less influenced by humidity.

4.2.5. Electrical Conduction in Glasses, Ceramics and Cermets

As for the composition, **glasses** contain **lattice formers** (SiO₂, B₂O₃, P₂O₅), **modifiers** (Na₂O, K₂O, CaO, MnO) and **intermediate compounds** (Al₂O₃, PbO). At the end of the vitrifying the group Si-O-Si, where the oxygen bridges are partially filled up by the ions of alkaline metals or alkaline-grounded metals, it is given the basis structure in glass. This is the reason that the electronic conduction is lower in glasses, and it is more strong observed at the metal-oxide glass contact.

The ionic conduction in glass is attributed, generally, to the mobile ions of Li⁺, Na⁺, K⁺, H⁺ migration under the action of the applied electric field.

At temperatures over 200° C, when the electric current is established, bivalent ions (Ca²⁺, Mg²⁺, O²⁻, etc) can also contribute to electric conduction. Their contribution is lower due to lower values of mobilities (the number of transfer is almost 1.0 for the alkaline metal ions and much lower for bivalent ions).

The ionic conduction in glasses is strongly influenced by its composition, temperature and thermal treatments.

Higher the metallic ion quantity is, lesser the number of direct oxygen bridges. It decreases, thus, the coherence of the structure and the metallic ions become more and more mobile. The activation energy of electrical conduction processes has a low value and the electrical conductivity is increasing.

Alkaline glass with Na₂O (Fig. 4.12) have a higher conductivity than those with K₂O because, ions of Na⁺, having the diameter smaller than the ions of K⁺, will have higher mobility and thus the conduction will be favorable.



Fig. 4.12. Silicate glass volume resistivity dependence on the volume concentration of alkaline oxide.

The blocking of the ions mobility appears at mixed glass, like borosilicate with lead oxide and alkaline oxides (Fig. 4.13).



Fig. 4.13. Borosilicate glass (SiO₂-B₂O₃-PbO) with alkaline oxides modifiers (Na₂O+K₂O) volume resistivity dependency on the modifier concentration.

Therefore, for a concentration of (Na_2O+K_2O) modifiers in proportion of 50% from each alkaline oxide component, the resistivity will increases with more than twice, as in the case when a single type of modifier is added.

For most of the glasses, the conductivity dependence on temperature is significant (Fig. 4.14). Only the glass of SiO₂ and the bore-silicate glass have resistivities with higher values and less influenced by temperature.



Fig. 4.14. Electrical resistivity dependency on temperature for different glasses: SiO_2 with Na_2O (curve 1), SiO_2 with B_2O_3 (curve 2), $SiO_296\%$ (curve 3), silicate vitreous (curve 4), SiO_2 with B_2O_3 and modifiers (curve 5), alumino-silicate (curve 6).

Note:

The resistivity values are of $(10^{18} \div 10^{13}) \Omega m$ degree and, for high temperatures, they reach the limit of semiconductors.

With **ceramics**, the resistivity is of $(10^9 \div 0^{12}) \Omega m$ degree at normal temperature, a value that can significantly decrease in the presence of impurities. As the ions of alkaline metals are less connected in vitreous phase than they are in crystalline phase, a large quantity of vitreous phase will determine the decreasing of the resistivity when the temperature is rising. It is the case of ceramics of cordierite, steatite, and porcelain of alumina types (Fig. 4.15).



Fig. 4.15. Volume resistivity dependency on temperature for ceramics: mulite - $SiO_2 Al_2O_3 BaO$ (curve 1), $Al_2O_3 96\%$ (curve 2), steatite $Al_2O_3 MgO$ (curve 3), Al_2O_3 (curve 4), $Al_2O_3 99,5\%$ (curve 5), BeO 99,5% (curve 6).

Ceramics, which contain oxides of alkalino-earth elements, have higher resistivity. Pure ceramics, without vitreous phases (AI_2O_3 , BeO, MgO, SiO₂) at high temperature have also high resistivity. But, with ceramics, the resistivity values are influenced by humidity.

In **oxides**, at high temperatures, the electronic conduction is predominant and at lower temperatures it can be meet a mixed conduction.

Thus, alumina (Al₂O₃) presents (Fig. 4.15), at temperatures over 1300°C, a conductivity of electronic type. Under this temperature, the conductivity is mixed: electronic and ionic. Alumina of high purity, polycrystalline, under 450°C behaves as an extrinsic semiconductor of *n*-type and/or of *p*-type, with the width of the energy gap $\Delta W_i = (5.0 \div 5.8)$ eV.

Cermets

Cermets are ceramics and their role is to control the conduction of the electric current. From cermets are produced the resistive elements for surface and volume resistors. The most encountered ceramics of this type are those based on silicon oxides.

Cermet of Cr/SiO is a mixture of α -Cr, Cr₃Si and SiO₂ amorphous. By transforming the silicon monoxide at the deposition in a reactive component (Si) and in an insulating one (SiO₂), expansion of both non-conductive and conductive zones are blocked. The dimensions of Cr and Cr₂Si crystals in amorphous SiO₂ are controlled by thermal treatments.

The cermet of Au/SiO is obtained by the deposition on glass support and consists in conductive particles of gold speeded in amorphous matrix of SiO₂. The electric conductivity depends on dimension of grains and the distribution mode of gold.

Another cermets used in building of electrical resistors are: Ni,Cr/SiO₂, Ti/SiO₂, Al/SiO₂, Mn/SiO₂.

The electrical conduction in cermets is of **metallic type**, the resistivity being in range of $\rho = (10^{-7} \div 10^{-4}) \Omega m$, and the variation coefficient of resistivity with the temperature α_{ρ} being positive. It is the case of cermets with a great concentration of metal.

If the dielectric phase is dominant and metallic particles are uniform distributed in small ratio, the electric conductivity is smaller, with the resistivity $\rho = (10^{-4} \div 10^{-8}) \Omega m$, and thermal coefficient of resistivity $\alpha_{\rho} < 0$. With hypothesis of semiconductive conduction in **the model of conduction through tunneling**, an expression of electric conductivity can be established.

 In thermo-electric emission model, it considers that only the electrons with specific high energy may be transferred from one to another atom. The height of the potential barrier is:

$$\Delta W_{b} = \gamma \frac{q_{0}^{2}}{d}, \qquad (4.22)$$

where γ is a parameter which depends on the metallic zone dimensions and *d* is the average distance between the metallic particles.

- The thermo-emission current will be defined by the difference between the emission currents over the barrier in both directions:

$$J = 2AT^{2} \operatorname{sh} \frac{q_{0}U}{2kT} \exp\left(-\frac{\Delta W_{b}}{kT}\right).$$
(4.23)

In low fields ($q_0 U \ll 2kT$) it will result:

$$J=2AT^{2} \cdot \frac{q_{0}U}{2kT} exp\left(-\frac{\Delta W_{b}}{kT}\right).$$
(4.24)

With (4.24), if the voltage difference between the electrodes is U = Ed, it can be obtained:

$$\sigma = AT^{2} \frac{q_{0}}{kT} d\exp\left(-\frac{\Delta W_{b}}{kT}\right).$$
(4.25)

This model shows that in electric fields of low intensities, the electrical conductivity does not depend on voltage.

Thus, at low voltage for which $q_0 U < kT$, the relation (4.25) indicates a linear dependency between *J* and *U* and an exponential dependency on temperature.

These conduction models are confirmed for different metal-insulator systems (MIM), as:

- Al-Al₂O₃ Al, where the insulating material can also be SiO, SiO₂, Ta₂O₃, BeO, GeO₂, Zn O₂, TiO, TiO₂, Cu₂O etc.;
- *AI-AI₂O₃ M*, where metal M can be: Ag, Au, Ba, Bi, Cu, Mg, Ni, Pb, Sn, Sb etc.

A model of conduction through tunneling cannot be considered for thick insulating foils. A source of charge carriers in the insulating material could be the **injection from the cathode** (metal M1) of electrons in the conduction area of dielectric, which determines the establishment of a spatial charge localized near the cathode. This spatial charge generates an electric field of a sense opposed to the injection current.

Other sources of producing the electrons in the conduction band BC are the transitions from the donor levels of the impurity atoms to BC, ionizing through collision or through tunneling.

W 4.2.6. Metal-Dielectric Interfaces

Under certain conditions, a material can pass from its characteristic state of dielectric to a conductive state (metal) and the reversed, and this phenomenon is named **metal-dielectric transition**.

Metal-dielectric transition may be justified qualitatively and quantitatively with energy bands model. It is know that the conductor crystal state corresponds to a structure of energy bands with valence band BV partial overlaps to the conduction band BC. By increasing the inter-atomic distance, a modification of the values for the two bands is produced and it is possible even the separation and the apparition of the Fermi interval. But, the phenomenon may be produced and vice-versa: by increasing the pressure, the inter-atomic distance becomes smaller, the energy bands enlarge and BV is closer on BC. It is the case of oxides Cr_2O_3 , NiO, Fe_2O_3 , etc.

A series of oxides and sulphides of the transition metals as: V_2O_3 , VO_2 , Ti_2O_3 , NiS, present the metal-dielectric transition at the increasing of the temperature. Thus, for V_2O_3 , the transition temperature is 180 K, the volume suddenly decreasing and the

oxide presents the state of metallic conduction, the resistivity is modifying according to temperature as in normal metallic conduction. In the phase of insulator, the vanadium three-oxide presents anti-ferromagnetic behavior.

Another model considers the local energy states in cermets. In this model, the dielectric is considered as an amorphous semiconductor with a Fermi forbidden band of a large width, strongly and non-uniformly impurified with atoms of the metal from the mixture. The conduction may appear through transitions metal-localized state of a higher probability than the transition metal-metal.

The study of **metal-insulator-metal systems** (MIM) and **metal-insulatorsemiconductor** (MIS) was stimulated by the applications in the domain of electrical engineering and microelectronics.

The insulating materials are oxides, halogens, sulphides, and polymers of small thickness under 50 Å (thin films) or of large thickness of 10³ Å (thick films).

The electrical conduction in a MIM system is based on the modification phenomena of concentration and distribution of electrons in the two metals.

The model of potential barrier depth (Fig. 4.16), for the interface MIM, allows the explanation of the conduction phenomena.





When the system parts of metal-dielectric (or insulation-metal) are in contact, the two potential barrier depth are put together by a potential barrier defined through extraction work of the metal 1, that is W_1 , and respectively, W_2 . The potential barrier M_1 . I - M_2 is asymmetrically if the metals are of different nature (Fig. 4.16a).

To pass from potential BARRIER depth of M_1 in the zone of M_2 barrier it needs a value of energy at list of W_1 , equivalent with extraction work. The same thing is for M_2 .

When an electric field is applied, a dropping of the energy barrier is produced (Schottky effect), and it is possible the electron to pass from 1 potential barrier depth of metal 1 in potential barrier depth of metal 2. Indeed, in absence of electric field (Fig. 4.16a), the probability of passing the potential barrier from M_1 to M_2 is the same as the probability of passing from M_2 to M_1 . In the presence of electric field (Fig. 4.16b),

4. Dielectrics

the probability of passing the potential barrier from M_1 to M_2 is greater than those from M_2 to M_1 . It is appearing an electronic flow oriented from M_1 to M_2 that means establishing of an electric current. The current density is:

$$J = AT^{2} \exp\left[-\frac{W_{max}}{kT}\right] \left[1 - \exp\left(-\frac{q_{0}U}{kT}\right)\right],$$
(4.26)

where W_{max} is the maximum height of the potential barrier, and thus, the electron passes over the barrier.

Another conduction mechanism of the electron passing from a conductive zone to another considers the **thermo-electrical emission**.

One modality of movement is **the tunneling** (thermo-ionic emission) - from the metal M_1 - through the forbidden zone of the dielectric - to the metal M_2 . This phenomenon can take place in more intense electric fields, when the applied electric field determines the inclination of the energy bands. This inclination can be sufficiently high so that Fermi level for the metal M2 to decrease under the reference level.

A possible mechanism of conduction among the conductive zones separated through a dielectric zone can be the one based on the **electronic tunneling** thermally activated. The experimental results indicate an exponential dependency of the conductivity of the temperature layer and this fact confirms the possibility of the electrodes tunneling towards the traps from the dielectric layer.

Electronic devices performances are connected to the organic and inorganic film insulation quality. There are also surface effects. For insulating sub-layers are usually used dielectrics as: SiO₂, SiO and Si₃N₄, Al₂O₃, epoxy and silicon films.

The main properties (*a* – crystalline lattice constant, ε'_r – real component of relative permittivity, E_{str} – electric strength, ρ_{V-} volume resistivity) of the materials used for electronic devices as electro-insulation are presented in Table 4.5.

Dielectric	Structure	Hardness [mho]	Crystal system	<i>a</i> [Å]	٤r	<i>E_{str}</i> [V/cm]	ρ _ν [Ωm]
Si	Crystalline	7	diamond	2.34	11.7-12	4·10 ⁵	2.5·10 ³
SiO	Amorphous	-	-	7.09·10 ³	3-6	>5·10 ⁶	>4.10 ¹⁰
SiO ₂	Crystalline (β-quartz)	5 – 7	Н	a= 4.9 c = 5.4	4.4	> 5.5·10 ⁶	10 ¹²
Si ₃ N ₄	Crystalline	> 9	Н	a= 7.7 c = 5.6	~ 10	5·10 ⁶	10 ¹⁰
Al ₂ O ₃	Amorphous	-	-	-	8.8	0 8 10 ⁴	10 ¹²
	Crystalline	9	Н	a= 4.76 c = 13	8.6-10	>10 ⁵	10 ¹⁴

Table 4.5. The main properties of dielectrics used as electroinsulating materials in electronic devices.

In designing the electroinsulating films for MIM systems, the volume and the surface resistivity values should be taken into account.

4.2.7. Electrical Conduction in Electroinsulating Liquids

In most of the insulating liquids, **the electrical conduction is of ionic or molionic type**, realized mainly through the convection of the positive and/or negative ions which are produced by the diffusion of their own molecules (for liquids with ionic bonds) or of the soluble impurities.

Contrary to the solids, where the atoms oscillate around the equilibrium positions, at normal temperature, the molecules and the ions of liquids produce (during a relaxation period τ) a number of oscillations around some fixed positions, with a frequency of the order of $f = (10^{12} \div 10^{13})$ Hz, and afterwards they change their neighbors. Thus, the electrical conduction processes in liquids and even in viscous-elastic materials (resins, compounds, etc.) strongly depend on viscosity.

A. Characteristics and particularities

The phenomenon of viscosity or of internal friction is characterized by the coefficient of dynamic viscosity η and/or the coefficient of kinetic viscosity v.

The dynamic viscosity coefficient is defined according to the molecule velocity *v* and the resistive force *F* between two liquid layers on a unitary surface *S*. If dF_t is the elementary tangential force exerting on the area element dS, and $\tau = dF_t/dS$ is the corresponding tangential stress, then, in the case of the laminar flow, the stress τ is proportional to the normal component of the velocity *v* gradient, and this brings into discussion Newton's law. From the relation:

$$\frac{F}{S} = \eta \cdot \frac{v}{d}, \qquad (4.27)$$

where *d* is the distance between the fluid layers, and η is the dynamic coefficient of viscosity. From relation (4.27) it will result the measure unit for $[\eta]_{SI} = Pa \cdot s$. In the CGS system η is measured in cP (centipoise), the conversion relation being 1 Pa \cdot s = 10³ cP.

The kinetic viscosity coefficient v is determined with the report between dynamic coefficient η and the fluid density d_m :

$$v = \frac{\eta}{d_m},\tag{4.28}$$

The measure unit for Kinetic viscosity coefficient in SI is $[v]_{Si} = m^2/s$. In the CGS system is $[v]_{CGS} = 1$ St (Stokes), the conversion relation being 1 m²/s = 10⁴ St.

Example:

The dynamic viscosity coefficient of the water at 20°C is $\eta_{20} = 0.0010$ Pa·s and at 0°C $\eta_0 = 0.0018$ Pa·s, which corresponds to the kinetic viscosity coefficient of the values $v_{20} = 1.0 \cdot 10^{-6}$ m²/s, respectively $v_0 = 1.8 \cdot 10^{-6}$ m²/s.

In engineering practice, many times the viscosity of oils and lacquers are determined with the Engler viscosity meter, measured in conventional units.

The viscosity decreases slowly with temperature. The dependence of the dynamic coefficient η on the temperature *T* is exponential with 1/T:

$$\eta = \mathsf{A}(T) \cdot \exp\left[\frac{W}{kT}\right],\tag{4.29}$$

where A(T) is the pre-exponential factor slightly dependent on temperature, W is the activating energy of the viscosity.

B. Establishing the electric conductivity

Stokes' law indicates the relation for the velocity v of a spherical particle of liquid which moves under the action of electric force F, in the process of a viscous flowing:

$$\nu = \frac{F}{6\pi r\eta},\tag{4.30}$$

where *r* is the particle radius and η is the dynamic coefficient of viscosity.

With these relations it can be established the expression of the electrical conduction of ionic type. In a stationary process of electrical conduction, the force F which acts upon the ion q_i is:

$$F = q_i \cdot E \,, \tag{4.31}$$

where q_i is the ion charge.

For the current density *J*, it will results the expression:

$$J=n_i q_i W=\eta_i q_i \cdot \frac{q_i E}{6\pi r \eta}, \qquad (4.32)$$

and, having in view the expression of electric conduction law (1.2), it results the expression for the ionic conductivity:

$$\sigma_{ion} = \frac{n_i q_i^2}{6\pi r \eta} \,. \tag{4.33}$$

With the relation (4.29) for η , the relation (4.33) becomes:

$$\sigma_{ion}(T) = \frac{n_i(T) \cdot q_i^2}{6\pi r \cdot A(T)} \cdot \exp\left[-\frac{W}{kT}\right].$$
(4.34)

This relation (4.34) allows the establishing of the *Pisarevski-Valden law*:

$$\sigma(T) \cdot \eta(T) = \text{const.} \tag{4.35}$$

The product between conductivity and dynamic viscosity coefficient of a fluid remains constant. When temperature increases, the viscosity decreases and conductivity increases.

Notes:

- This relation (4.34) is similar to the expression of the ionic conductivity for solid insulating materials. As for the amorphous solid conductivity processes, they take place as insulating liquids. The amorphous solids may be considered as overcooled liquids, but the relaxation time is much longer (of the order of years).
- The relation (4.34) indicates that, in electroinsulating liquids, the conductivity σ, respectively, the resistivity ρ, depends on the viscosity η(*T*) as well as on the ion concentration *n_{ion}*(*T*), directly connected to the thermal dissociation of molecules.
- The organic molecules dissociate more easily in polar liquids than in nonpolar liquids. This fact will lead to a higher electro-conductivity of the polar liquids than that of the non-polar liquids.

Examples:

- high polar liquids, as distilled water, ethanol, acetone, have resistivity values $\rho = 10^3 \div 10^5 \Omega m$;
- **low polar liquids**, as bisphenol chlorate, castor oil, have the resistivity values $\rho = 10^8 \div 10^{10} \Omega m$;
- **nonpolar liquids**, as benzene, transformer oil, have the resistivity values $\rho > 10^{10} \div 10^{18} \Omega m$.

In non-polar liquids, the molecules do not dissociate. The electrical conduction is determined only by impurities, especially non-polar ones. For instance, the transformer oil, which is a non-polar dielectric, is used only after its purification, thus, the moister, the lint and the dust are being removed.

Some of the electroinsulating liquid properties (θ is the measurement temperature, ε_r is the permittivity corresponding to 50 Hz, ρ_V is the volume resistivity) are presented in Table 4.6.

Liquid	<i>θ</i> [°С]	<i>€</i> r at 50 Hz	ρ [Ωm]	Dielectric type	Observations	
Transformer oil	80 80 20	2.2 2.1	$2 \cdot 10^{10} \ 5 \cdot 10^{12} \ 10^{16}$	Non-polar	Non-purified Purified Extra purified	
Silicon oil	20	2.4	10 ¹²	Non-polar	Non-purified	
Castor oil	20 100	4.5	10 ¹⁰ 10 ⁶	Low polar	Technique Technique	
Sovol	80	5.5	10 ⁹	Polar	Technique	
Ethylic alcohol	20	25.7	10 ⁶	High polar	Purified	
Water	20	81	10 ⁵	High polar	Non-distilled	

Table 4.6. Electrical characteristics of electroinsulating liquids.

172

In ionic liquid dielectrics, molionic conduction can be established, similar to the ionic conduction. The molionic conduction is encountered especially in **colloidal systems** – systems that are formed from a phase, dispersed (particles, grains) in a dispersion environment.

The electroinsulating colloidal systems in which both phases are liquids are named **emulsions**. The colloidal systems in which the solid dispersed phase is placed in a liquid dispersion environment are named **suspensions**.

The emulsion and suspension stability – that is their property to maintain themselves in the mixture without sedimentation due to their density difference – could be explained through the presence of the electric charges on the particle surface of the dispersed phase, which, due to the electrostatic repulsion, maintains them in the dispersed phase. These charged particles are named **molions**.

The **molionic conduction process**, also called **electrophoreses**, consists in moving the molions under the action of the electric field. This process differs from the electrolyze process because there are no new substances which are created, but in certain zones of the colloidal system, the concentration of the dispersed phase is modified (changed). Molionic conduction is also emphasized in some lacquers, compounds, humid oils, etc.

In order to describe this type of conduction, it can be used the relation (4.33). It is considered that a molion of spherical form of radius r, has the capacity towards the dispersion medium as:

$$C = 4\pi\varepsilon_0\varepsilon_r r, \qquad (4.36)$$

and its electric charge:

$$q_i = C \cdot V = 4\pi\varepsilon_0 \varepsilon_r r V , \qquad (4.37)$$

where V is the electric potential of the molion towards the dispersion medium.

Introducing (4.37) into (4.33), the molionic conductivity expression will result:

$$\sigma_{mol} = \frac{8\pi}{3} \varepsilon_0^2 \varepsilon_r^2 \frac{r n_{ion}}{\eta} V^2$$
(4.38)

The relation underlines the fact that colloidal systems with high permittivity have a high electrical conductivity.

Fig. 4.17 shows the variation of ρ_V , resistivity in the case of a colloidal system of lacquer from bituminous oil having as a solvent the benzene, according to the component concentration.





A small supplement of lacquer into the solvent makes the resistivity decrease, because the charge carrier concentration increases. The resistivity decreases reaching a minimum, and afterwards it begins to increase as the viscosity increases.

Notes:

- It can be observed that for the same concentrations of the colloidal system, the resistivity at high temperatures has lower values.
- As a general rule, dielectrics with ionic conductivity cannot be used as electric insulators at high temperatures.
- The usage of the high polar liquids (as water, glycerin and acetone) is avoided in insulating systems, because, having a high capacity of dissociation, they present a high electrical conductivity.

4.3. ELECTRICAL POLARIZATION IN DIELECTRICS

4.3.1. Polar and Non-Polar Dielectrics

For characterizing the polarization phenomenon, the **dipolar electric moment** p is defined by the relation:

$$\overline{\rho} = q_{leg} \,\overline{h} \,, \tag{4.39}$$

where \overline{p} is the electric moment of an electric dipole (Fig. 4.18a) measured in C·m, q_{leg} is the electrical bonded charge of the dipole, measured in C (Coulomb) and \overline{h} is the distance vector between the two dipole charges, considered from $-q_{leg}$ to $+q_{leg}$.

For the hydrogenous atom, the model of the electric dipole (Fig. 4.18a) corresponds to the distribution system at a given moment of the nucleus charge $+ q_0$ and the electron charge - q, the dipolar distance being the radius of the atom.



Fig. 4.18. The model of electric dipole in: a) one-electron atom; b) multi-electron atom.

For the multi-electron atom (Fig. 4.18b), each pair of electron-proton from nucleus form a dipolar moment, so that the **atomic electrical moment** is defined by expression:

$$\overline{p}_{atom} = \sum_{i=1}^{N} q_{ileg} \,\overline{h}_i \,\,, \tag{4.40}$$

where *N* is the total number of electrons (bound electric charge) of considered atom.

The electrical moments of the molecules, macromolecules or of the other structural units are obtained by vectorial summation of the atomic electric moments.

Depending on the way of the arrangement of the bound electric charge, the vectorial sum (4.40) can be close to zero or much different from zero. Depending on the value of the total electric moment \overline{p} , molecules, or other structural units, can be:

non-polar, when they do not have spontaneous electrical moment (microscopic);

Example:

The molecules made from identical atoms or from different atoms but symmetrically arranged (Fig. 4.19), with a symmetric distribution of the bound electric charge;

• **polar**, when they have an electric moment $p \neq 0$ even in the absence of the external electric fields;

Example:

The molecules made from different atoms, non-symmetrically arranged (Fig. 4.20, Fig. 4.21).



Fig. 4.19. Structures of non-polar molecules: a) CO₂ molecule; b) CH₄ methane molecule.

The materials made up of non-polar molecules (structural units) are called **non-polar** dielectrics or **dia-electric materials**. The CO₂ molecule (Fig. 4.19a) has a symmetrical construction, achieved through energy states p of the electrons of covalent bound, which leads to total null electrical moment:

$$\overline{p} = \overline{p_1} + \overline{p_2} = 0$$
.

The methane molecule CH_4 (Fig. 4.19b) has a symmetrical construction, the carbon atom being situated at the centre of a regular tetrahedron, in its angles with the hydrogen atoms; consequently, although the carbon atom is slightly negative and the hydrogen atoms are slightly positive, the molecule is electric non-polar.

Notes:

- It is evident that the molecules made up of similar atoms (H₂, O₂, N₂, etc.) are not polar as the pair of bonded electrons is usually found in an area equally distanced from the two atoms and therefore, the resulting moment is null.
- The non-polar dielectric category includes also the crystals of Si, Ge, C diamond, etc.
- There are organic compounds, like hydrocarbons (C₆H₆, paraffin, polyethylene, etc.), which have arrangements of permanent electric dipoles, but which, on summing up all the electric moments in a structural unit, have the electric moment of low or null resulting value.

The materials made up of polar materials (atoms) are called **polar materials**. These include the **para-electric and ferro-electric materials**.

The hydroxyl grouping –OH is a polar grouping. The bound is achieved between the hydrogen electron *s* and the oxygen electron of *p* energy state, and due to the fact that the oxygen is slightly negative and the hydrogen is slightly positive, a dipole with moment $p \neq 0$ is formed.

Figure 4.20 shows the configuration of the water molecule that is strongly polar.



Fig. 4.20. The polar structure of water molecule.

176

The polar character is due to its asymmetrical construction, where the directions of the bounds between the oxygen atom and the two hydrogen atoms form up an angle of nearly 105° , so that the electrical dipolar moments of the pairs O⁻ - H⁺ give a non-null resultant.

The HI, HBr, HCI molecules have permanent electrical moment, due to the fact that when the molecule is formed, part of the electronic cloud of the hydrogen atom is transferred to the iodine, bromine or chlorine atoms. Therefore, an excess of positive electric charge remains at the end of the molecule towards the hydrogen atom and an excess of negative electric charge at the other end.

Fig. 4.21 displays several types of polar molecules and the direction of the corresponding electrical moments.



Fig. 4.21. Types of polar molecules: HCl, HBr, HI, NH₃.

In order to simplify, there have been represented the atoms from electronic cloud that surrounds the sphere-shaped positive nucleus. The non-symmetry arises from the different dimensions of the constituent atoms.

Table 4.7 presents the values of the permanent electric moment for several dielectrics with polar molecules. It can be noticed that the lower the number of electrons (atomic radius) of the halogen X, the higher the permanent electrical moment for the compounds HX.

Molecule	СО	HI	HBr	HCI	NH₃	H ₂ S	SO ₂	H ₂ O
<i>p</i> _p [10 ⁻³⁰ Cm]	0.40	1.26	2.6	3.43	5.0	5.3	5.3	6.2

Table 4.7. Values of the permanent electric moment for polar molecules.

Relative to the value of permanent electric moment, it can be noted the high value of permanent moment for water ($P_p=6.2\cdot10^{-30}$ Cm), which explains the specific properties, known as anomaly of water.

As for the molecules with more atoms, the total electrical moment is obtained by vectorial composing of the dipolar moments of the constituent atoms, its value depending on the angle between the electrical moments related to the atoms from the molecule.

In the assessment of the polar or non-polar character of the dielectric, it is necessary to consider the spatial distribution of the electric charge from the structural unit.

Examples:

- Figure 4.19b represents the structure of the methane molecule, which is electrically non-polar. However, by replacing a hydrogen atom with a chlorine atom, a polar molecule of methyl chloride (CH₃-Cl) is obtained, having the electrical moment P_p = 6.2·10⁻³⁰ Cm. By successively replacing a hydrogen atom, the result is CH₂-Cl₂ with P_p = 5.2·10⁻³⁰ Cm, respectively, CH-Cl₃ cu P_p = 3.8·10⁻³⁰ Cm. Having a symmetric structure, the carbon tetrachloride molecule (CCl₄) is, like CH₄, electrically non-polar.
- The same effect occurs if the benzene is added to the polar grouping NO₂. The nitrobenzene (C₆H₅-NO₂) is electrically polar, having a permanent electric moment P_p=1.3·10⁻³⁰ Cm.

Notes:

- There are dielectrics with semiconductive character, which are electrically polar. It is the case of the compounds of the type III-V (GaAs, InSb, GaP): there is a crystalline sub-lattice with positive ionic character (group V) and another with negative character (group III). Thus, the total crystalline lattice is characterized by the existence of a conglomerate of permanent electrical moments that alters whenever an electric field is applied.
- The category of polar dielectrics includes also materials with ionic bounds.

4.3.2. A General Approach to the Polarization Phenomena

It can be considered specific to dielectrics that whenever an electric field is applied in the dielectric, either **electric dipoles occur**, or the existing **ones re-orient themselves**. This is the **electric polarization phenomenon**.

There are various modalities of settling the dipoles in dielectrics. The action of the electric field can cause displacements or rotations of the bonded charge system of the structural units, accompanied by the appearance or ordering of the dipolar electrical moments.

For instance:

The displacement polarization phenomenon of **electronic type** is taken into account. It can be studied by considering that the dielectric forms a system of atoms made of positive nuclei, each surrounded by an electronic cloud of negative electric charges. In the absence of the electric field, the centre of the positive charges coincides with that of the negative charges. On applying an electric field, there will occur a certain displacement *h* between the centre of the positive charge and the centre of the negative charge for each constituent atom. In this way, electric dipoles are formed, whose induced electrical moments, by definition, are given by the relation (4.39), where q is the total charge of the nucleus, respectively of the electronic cloud of the atom.

To return to the **microscopic approach**, the quantity of charge occurring on the surface of the dielectric may be calculated.

178

4. Dielectrics

If the centre of the electric charges nucleus-electronic cloud covers the distance h for each constituent atom, then, the volume occupied by the formed electric dipoles will be *S*·*h*, where *S* is the surface of the cylinder base where the dipoles are arranged, and it results the electric polarization expression:

$$P = \frac{\Delta \rho}{\Delta V} = \frac{N}{S} \cdot \rho = n \cdot \rho .$$
(4.41)

With the relations (4.39), and (4.41), turning to vectorial description, a relation will be obtained between the electric polarization \overline{P} and the electric moment \overline{p} :

 $\overline{P} = n\overline{p}. \tag{4.42}$

The electric polarization \overline{P} is numerically equal to the product between the electrical moment \overline{p} of the structural unit of the dielectric and its volume concentration *n*.

As regarding the **permittivity** calculus, as well as the electrical **susceptivity** in low and medium electric fields, it is admitted that the dipolar electrical moment is proportional with the intensity of the effective electric field $\overline{E_0}$:

$$\overline{\rho} = \alpha_e \,\overline{E}_0 \,, \tag{4.43}$$

where α_e is the *electric polarizability* of the atom or of the structural unit of the dielectric, depending on the nature and internal structure of the dielectric.

The electric field \overline{E}_0 , called **effective electric field** (active or internal), meaning a field that exercises direct actions upon the bound electric charge, does not coincide with the macroscopic field \overline{E} . The macroscopic electric field \overline{E} represents the timespace average, effectuated in the physical-small volume ΔV and physical-small time Δt , of the microscopic electric field \overline{E}_{micro} . The electric field \overline{E}_0 represents the same average, but effectuated in the absence of the particle upon which is considered the action of the field.

The intensity of the effective electric field \overline{E}_0 takes into consideration the action of the neighboring electric dipoles, being given the sum between the intensity of the applied external electric field \overline{E} and the effect given by the other dipoles in a certain point of the dielectric:

$$\overline{E}_{0} = \overline{E} + \frac{\gamma}{\varepsilon_{0}} \overline{P}.$$
(4.44)

Generally, the structural coefficient γ is hard to calculate. Only in the case of non-polar dielectrics can there be made some simplifying hypotheses, which give results according to the experiments made. For materials which present a structural spherical symmetry, the coefficient γ from the relation (4.44) has the value $\gamma=1/3$.

In the case of the gases, whose molecules are very distant one from each other, it can be considered $\gamma \approx 0$, the result being $E_0 \approx E$. Generally, the coefficient γ must be determined for each type of structure.
A general expression for the electric polarization may be obtained by the relations (4.42), (4.43) and (4.44):

$$\overline{P} = \frac{n\alpha_e}{1 - \frac{\gamma n\alpha_e}{\varepsilon_0}}\overline{E} .$$
(4.45)

By comparing the relation (4.45) with the electric polarization law, the result will be the expression of the dielectric susceptivity:

$$\chi_{e} = \frac{\frac{n \,\alpha_{e}}{\varepsilon_{0}}}{1 - \frac{\gamma n \,\alpha_{e}}{\varepsilon_{0}}}.$$
(4.46)

Thus, the relative permittivity of the dielectric is:

 $\varepsilon_r = 1 + \chi_e \tag{4.47}$

The relation (4.46) and (4.47) highlight the dependence of the macroscopic parameters – electric susceptivity χ_e and relative permittivity ε_r – on the structure of the dielectric.

The relative permittivity ε_r can be determined as the ratio between the capacity *C* of a capacitor in which the space between the electrodes is integrally and exclusively filled with the respective material, and the capacity C_0 of the same capacitor with the same geometry and the electrodes disposed in vacuum:

$$\varepsilon_r = \frac{C}{C_0}.$$
(4.48)

The capacity of the vacuum plan capacitor is defined by the relation:

$$C_0 = \frac{\varepsilon_0 S}{d}, \qquad (4.49)$$

where *S* is the area of the plate electrodes of the capacitor, *d* is the distance between the plates, equal with the thickness of the dielectric, and the permittivity of vacuum is: $\epsilon_0=1/(4\pi \times 9 \times 10^9)$ F/m.

The capacity C of measurement system in constant field can be obtained by measurement of the charge quantity Q accumulated on the electrodes and the voltage V on the terminal of the system:

$$C = \frac{Q}{V} \tag{4.50}$$

A material may have several dielectric mechanisms or polarization effects that contribute to its overall permittivity.

4.3.3. Electronic Polarization

The electronic polarization state in a dielectric occurs whenever an electric field is applied, and consists by a displacement of the negative electric charges (electronic clouds) from the centre (positive nucleus) of each atom, which leads to the establishing of the dipolar electric moments. These electric moments depend on the intensity of applied electric field, as well as on the nature of the dielectric.

For the linear and isotropic dielectrics, the **induced electric moments** may be considered to be parallel with the effective electric field:

$$\overline{p}_e = \alpha_e \overline{E}_0, \qquad (4.51)$$

where $\overline{E_0}$ is the intensity of the effective electric field, given by the relation (4.44), and α_e is the mean value of the polarizability of the electronic gas.

The calculus of the electronic polarizability α_e may be made by the means of the classical microscopic theory of the electric polarization.

The case of a non-polar gas is considered, formed of atoms with the atomic radius *r* and electric charge Zq_0 , where q_0 is the electric charge of the electron and *Z* is the atomic number.

In the absence of the electric field, the centre of the positive electric charges of each atomic nucleus coincides with that of the electronic cloud considered spherical, whose radius is equal to the atomic one (Fig. 4.22a).



Fig. 4.24. The distribution of the electronic cloud in the atom: a) in the absence of the electric field; b) in the presence of the electric field; c) the electronic polarization model.

While applying the electric field, the electronic cloud is distorted (Fig. 4.22b). For the calculus of the induced electric dipole moment it is considered that the electronic cloud behaves like a rigid sphere of charge $-Zq_0$ whose centre displaces with the distance *h* from the centre of the nucleus (Fig. 4.22c). The electric moment is:

$$\overline{p}_e = Zq_0 h . \tag{4.52}$$

The displacement between the nucleus and the negative sphere increases so far as the electric field of dipole E_h equals the local electric field E_0 . In this situation, the sum of the forces that run over the nucleus will be null:

$$Zq_0 \overline{E}_h + Zq_0 \overline{E}_0 = 0.$$
(4.53)

The results is:

$$\overline{E}_{h} = -\overline{E}_{0}. \tag{4.54}$$

For the sphere of radius *h*, the electric flux law may be applied:

$$\int_{\Sigma} \vec{D} \cdot d\vec{S} = q_{\Sigma} \,. \tag{4.55}$$

The result is:

$$\int_{\Sigma} \varepsilon_0 \vec{E}_h \cdot d\vec{S} = \int_V \rho_v \, dV \,. \tag{4.56}$$

Having in view that the vector \overline{E}_h is opposed as sense to the vector $d\overline{S}$ (field created by a negative electric charge), it has a spherical symmetry, and the density of electric charge of volume ρ_V is:

$$\rho_{v} = \frac{-Zq_{0}}{\frac{4\pi r^{3}}{3}}, \qquad (4.57)$$

the relation (4.56) can be written either:

$$-\int_{\Sigma} \varepsilon_{0} E_{h} dS = -\int_{V} \frac{Zq_{0}}{\frac{4\pi r^{3}}{3}} dV, \qquad (4.58)$$

or:

$$\varepsilon_0 E_h 4\pi h^2 = \frac{Zq_0}{\frac{4\pi r^3}{3}} \cdot \frac{4\pi h^3}{3}, \qquad (4.59)$$

hence:

$$\varepsilon_0 E_h 4\pi r^3 = Zq_0 h. \tag{4.60}$$

The electric moment induced by the electronic polarization is $p_e = 4 \pi r^3 \varepsilon_0 E_h$, or, in a vectorial form:

$$\vec{p}_e = 4\pi\varepsilon_0 \ r^3 \vec{E}_0 \,. \tag{4.61}$$

Comparing the relation (4.43) with relation (4.61), the following expression results for **the electronic polarizability**:

$$\alpha_e = 4\pi\varepsilon_0 r^3. \tag{4.62}$$

The electronic polarizability α_e depends on the atomic radius.

Example:

For the hydrogen atom with $r \approx 10^{-10} \mathring{A}$, the electronic polarizability has the value: $\alpha_e = 4\pi \cdot \frac{1}{4\pi \cdot 9 \cdot 10^9} \cdot 10^{-30} \cong 10^{-40} F \cdot m^2$.

The values of the electric polarizability for the atoms of some chemical elements, calculated by the relation (4.62), are shown in Table 4.8.

Table 4.8. The electronic polarizabilities of the atoms of some chemical elements.

Atom	н	Не	Ne	Ar	С	Li	Na	К
$\alpha_{\rm e} [10^{-41} {\rm F} {\rm m}^2]$	7.34	2.34	4.45	17.80	16.68	134.4	300.4	378.2

Notes:

- For the atoms of the rare gases (He, Ne or Ar), where the electrons are strongly bonded to the nucleus, the polarizability is very low.
- For the alkaline metal atoms (Li, Na, K) where the valence electrons is weakly bound, determine a stronger polarization, therefore a greater dipolar moment.
- In the case of the non-polar molecules with spherical symmetry, such as the molecules of CO₂ or CH₄ (Fig. 4.19), the value of the induced electric moment, in first approximation, does not depend on the direction of the external field, the relation (4.51) being available, in which the molecular polarizability is not given by the algebraic sum of the polarizability of the constituent atoms. This is due to the distortion of the electronic clouds of constituent atoms at the molecule formation.
- In the case of some non-polar molecules with no spherical symmetry, their polarizability depends on the direction of the applied electric field.

By the relations (4.46) and (4.62), the expression of the permittivity of the dielectric will result, in the case of dielectrics with only the electronic polarization:

$$\varepsilon_r = 1 + \frac{4\pi n r^3}{1 - 4\pi n \gamma r^3} \,. \tag{4.63}$$

For gases (where $\gamma \approx 0$), there will be a simpler relation for permittivity:

$$\varepsilon_{rgaze} = 1 + 4\pi n r^3 , \qquad (4.64)$$

which allows a first approximation of the permittivity value.

With $n \approx N_A \approx 6,02.10^{26}$ atom/m³ and $r \approx 1$ Å= 10⁻¹⁰ m, the result is:

 $\epsilon_{rgaze} \approx 1 + 4\pi \cdot 6,02 \cdot 10^{26} \cdot 10^{-30} \approx 1 + 10^{-3}$.

Indeed, as regards the gases, the susceptivity is of the order $10^{-5} \div 10^{-3}$. Although the number of constituent particles is high, the effect of the electronic polarization is not significantly above the value of the total electric susceptivity of the dielectric.

Note:

- A characteristic of the non-polar dielectrics is the fact that they present only the electronic polarization phenomenon. For these, the square of the refraction index corresponding to the optic wavelengths is nearly equal with the permittivity measured at low and medium frequencies (Table 4.9).
- Only for the non-polar and slightly polar dielectrics, the permittivity is determined by the component of the electronic susceptivity. For the strongly polar dielectrics, there are also other polarization mechanisms, which contribute to the total value of the permittivity.
- Practically, the electronic polarizability does not depend on temperatures when exposed at normal temperatures, because at these temperatures the electronic cloud does not suffer great distortions.

Dielectric	n ²	έr	<i>f</i> [Hz]
Non-polar dielectrics			
C – diamond	5.660	5.680	10 ⁸
H ₂ (liquid)	1.232	1.228	10 ⁷
Slightly polar dielectrics			
PE	2.28	2.30	$10^2 \div 10^{10}$
Paraffin	2.19	2.20	10 ³
PTFE	1.89	2.10	$10^{2} \div 10^{9}$
Polar dielectrics			
NaCl	2.25	5.90	10 ³
TiO ₂ (rutil)	6.80	94.0	10 ³
SiO ₂ (quartz)	2.13	3.85	10 ³
Alkaline glass	2.30	7.60	10 ³
Al ₂ O ₃	3.13	4.31	10 ³
Methanol	1.85	24.3	-
Acetone	1.84	20.7	-
Water	1.77	80.4	-

Table 4.9. The permittivity and index of refraction for polar and non-polar dielectrics.

184

4. Dielectrics

On gases, the effect of the pressure and temperature is stronger. The Tables 4.10 and 4.11 provide with the values of the electric susceptivity for certain gases at p = 1 atm and $\theta \approx 20^{\circ}$ C and the values of the gaseous nitrogen susceptivity depending on pressure, at temperatures of 0° C and 100° C.

Table 4.10. The electric susceptivity of some gases.

Gas	χe
Hydrogen	2.73·10 ⁻⁴
Argon	5.20·10 ⁻⁴
Nitrogen	5.87·10 ⁻⁴
Xenon	1.30·10 ⁻³
Chloride	1.43·10 ⁻³

Table 4.11. The susceptivity of nitrogen.

Pressure	Temperature			
[atm]	0ºC	100ºC		
10	6.08·10 ⁻³	4.4·10 ⁻³		
20	1.2·10 ⁻²	8.8·10 ⁻³		
40	2.4·10 ⁻²	1.7·10 ⁻²		
80	4.9·10 ⁻²	3.5·10 ⁻²		
150	9.3·10 ⁻²	6.4·10 ⁻²		
230	1.4·10 ⁻¹	1.0·10 ⁻¹		

Notes:

- In the case of gases, as the bigger is the atomic radius, the higher is the susceptivity.
- During the pressure increase, the concentration of atoms increases as well, which determines the increase of the electric susceptivity.

4.3.4. Ionic Polarization

The ionic polarization state occurs whenever an electric field is applied in dielectrics where the bonds are of ionic-nature, and consists in the displacement of the ions from the initial position in the absence of the applied electric field, which determines the appearance of supplementary electric moments.

The phenomenon is easily highlighted in the case of the NaCl crystal, represented by a one-dimensional crystalline structure (Fig. 4.23).

The polarizability of each structural unit, made up of three consecutive ions, like in figure 4.25a, may be determined by means of the classical microscopic theory of the ionic polarization, in the hypothesis of the interaction between the ions neighboring this structural unit. In the absence of the external electric field, the positive ions of Na⁺ alternate with the negative ions of Cl⁻, placed at equal distances to the constant of the crystal lattice *a* (Fig. 4.23a).



Fig. 4.23. The distribution of ions in one-dimensional crystal: a) in the absence of the electric field; b) in the presence of the electric field.

The electric moments of the dipole are equal and have opposite direction:

$$|\vec{p}_1| = |\vec{p}_2| = q_i a.$$
 (4.65)

When applying the electric field, the ions displace (the positive ones in the field direction, the negative ones in the opposite direction to the field) on the distance δ .

The result is an electric moment induced on the direction of the applied electric field:

$$p_i = p'_1 - p'_2 = q_i (a + 2\delta) - q_i (a - 2\delta) = q_i 4\delta.$$
 (4.66)

The displacement between ions increases until it reaches an energetic equilibrium.

The electric energy necessary for the displacement of the ions, calculated as the difference between the final energy and the initial energy of the system of bonded electric charges is:

$$\Delta W_{depl} = \frac{-q_i^2}{4\pi\varepsilon_0 \cdot (a-2\delta)} + \frac{-q_i^2}{4\pi\varepsilon_0 \cdot (a+2\delta)} - \frac{-2q_i^2}{4\pi\varepsilon_0 a}, \qquad (4.67)$$

or:

$$\Delta W_{depl} = \frac{-q_i^2}{4\pi\varepsilon_0 \cdot (a-2\delta)} + \frac{-q_i^2}{4\pi\varepsilon_0 \cdot (a+2\delta)} - \frac{-2q_i^2}{4\pi\varepsilon_0 a}.$$
(4.68)

4. Dielectrics

When the equilibrium is established, this energy is equalized by the energy of the dipole in the electric field:

$$-p_i \cdot E_0 = \frac{2q_i^2}{4\pi\varepsilon_0 a} - \left(\frac{q_i^2}{4\pi\varepsilon_0 (a-2\delta)} + \frac{q_i^2}{4\pi\varepsilon_0 (a+2\delta)}\right),$$

or:

$$-p_i \cdot E_0 = \frac{-8q_i^2 \delta^2}{4\pi\varepsilon_0 (a-2\delta)(a-2\delta) \cdot a}.$$
(4.69)

Taking into account that the distance δ is small in comparison with the constant of the crystalline lattice ($\delta << a$), it results:

$$p_i \cdot E_0 = \frac{2q_i^2 \,\delta^2}{\pi \varepsilon_0 \,a^3} \,. \tag{4.70}$$

or:

$$p_i \cdot E_0 = \frac{8q_i^2 \delta^2}{4\pi\varepsilon_0 a^3}, \qquad (4.71)$$

Taking into account the relation (4.66) for the ionic electric moment p_i , the following will result:

$$\overline{p}_{i} = 8\pi\varepsilon_{0} a^{3} \overline{E}_{0}, \qquad (4.72)$$

By comparing this relation with the relation (4.43), the expression of the ionic polarizability will result:

$$\alpha_i = 8\pi\varepsilon_0 a^3 . \tag{4.73}$$

The ionic polarizability depends on the crystalline lattice constant *a*.

Using the relation (4.73), there will result the expression of the susceptivity and permittivity in the case of the materials with ionic polarization:

$$\chi_{e} = \frac{8\pi n a^{3}}{1 - 8\pi n a^{3} \gamma}; \quad \varepsilon_{r} = 1 + \chi_{e} = 1 + \frac{8\pi n a^{3}}{1 - 8\pi n a^{3} \gamma}.$$
(4.74)

The factor γ depends on the crystalline structure. For instance, for the cubic symmetry crystals, $\gamma = 1/3$.

Notes:

Since the constant of the crystalline lattice (the inter-atomic distance) is much bigger than the atomic radius, it is evident that the relation (4.73) provides higher values than the relation (4.62). Indeed, the ionic crystals have their permittivity of the order of 7 ÷ 8 up to tens of units. Taking into consideration that the mass of the ions occurring in the process of ionic polarization is much larger than the mass of the electrons, it may be assumed that the response to the electric field application is slower in the case of the ionic crystals. The ionic polarization takes longer with 10⁻¹² ÷ 10⁻¹³ seconds compared to the electronic polarization.

4.3.5. Orientation Polarization

The dipolar or orientation polarization occurs in the dielectrics that provide permanent electric moments. The **polar dielectrics** hold two factors that determine the dipoles' orientation: the local electric field \bar{E}_0 and thermal movement. Except for the **ferroelectrics**, where the dipoles are in strong interaction one another, which determines the property of homoparallel arranging on large distances compared to the inter-atomic distance, for most of the dielectrics the electric dipoles have a chaotic orientation because of the thermal movement.

In the absence of the external electric field, due to the thermal movement, the electric moments $\overline{p_p}$ associated to the polar molecules are chaotically oriented, so that their resulting effect is null (Fig. 4.24a). When applying the electric field, the dipolar moments tend to reorient themselves on the direction of the external electric field (Fig. 4.24b).



Fig. 4.24. Distribution of polar molecules: a) in the absence of the electric field; b) in the presence of the electric field.

The polar fluids susceptivity may be evaluated by means of the classical theory of the orientation polarization, in the **Debye model**.

The case of a polar fluid is considered, where each molecule has a permanent electric moment $\overline{p_{\rho}}$ (Fig. 4.25a).

In the absence of the applied electric field, the electric moments $\overline{p_{\rho}}$ of the constituent molecules are randomly oriented, so that the *dn* number of electric moments comprised in the elementary solid angle $d\Omega$ is independent with its orientation.

188



Fig. 4.25. Orientation polarization: a) polar molecule in electric field; b) dipole energy in electric field.

When the electric field \overline{E} is applied, under the action of effective electric field, a tendency of orientation of the electric molecules in the field direction will appear. This tendency is counter-attacked by the tendency of disorder given by thermal motion, of homogenous repartition re-establishment, respectively.

The electrostatic potential energy of the dipole in effective electric field of \overline{E}_0 intensity is:

$$W_{\rho} = -\vec{\rho}_{\rho} \cdot \vec{E}_{0} = -\rho_{\rho} E_{0} \cos\theta, \qquad (4.75)$$

where θ stands for the angle between $\overline{p_p}$ and \overline{E}_0 vectors.

The number of electric moments which exist in the solid elementary angle d Ω is calculated by admitting Maxwell-Boltzmann statistics: at thermal equilibrium, the molecule number of W_p energy is proportional with $exp[-W_p/kT]$. Therefore:

$$dn = \operatorname{A} \exp\left[-\frac{W_{\rho}}{kT}\right] d\Omega = \operatorname{A} \exp\left[\frac{p_{\rho} E_{0} \cos\theta}{kT}\right] 2\pi \sin\theta \,d\theta \,, \qquad (4.76)$$

where A is a constant.

The contribution to the dipole moment of a molecule having the angle θ between the vectors $\overline{p_p}$ and $\overline{E_0}$ is $p_p \cos\theta$.

The averaged value for the dipolar electric moment in orientational polarization is obtained by calculating the averaged value of all contributions $p_p \cos\theta$, with orientation comprised between 0 and π (from parallels to anti-parallels), reported on the total number of moments:

$$p_{0} = \langle p_{\rho} \cos\theta \rangle = \frac{\int_{0}^{\pi} \left[p_{\rho} \cos\theta \right] \operatorname{Aexp} \left[\frac{p_{\rho} E_{0} \cos\theta}{kT} \right] 2\pi \sin\theta \, d\theta}{\int_{0}^{\pi} \operatorname{Aexp} \left[\frac{p_{\rho} E_{0} \cos\theta}{kT} \right] 2\pi \sin\theta \, d\theta}$$
(4.77)

By noting:

$$a = \frac{p_p E_0}{kT}, \qquad (4.78)$$

and changing the variable $x = \cos\theta$, it will result:

$$\frac{p_o}{p_p} = \frac{\int_{-1}^{1} e^{ax} x dx}{\int_{-1}^{1} e^{ax} dx} = \frac{d}{da} \left[\log \int_{-1}^{1} e^{ax} dx \right] = \frac{d}{da} \left[\log \frac{e^{ax}}{a} \Big|_{-1}^{1} \right] = \operatorname{cth} a - \frac{1}{a}.$$
 (4.79)

The following expression is assigned with L(a):

$$L(a) = \operatorname{cth} a - \frac{1}{a}, \qquad (4.80)$$

called Langevin function. This function has a typical variation (Fig. 4.26):

- for a << 1, calculus lead to the value 1/3;
- for a >> 1, it will result $L(a) \approx a/3$.



For low values of *a* arguments, corresponding to the electric fields of low values, it can be obtained:

$$p_0 = p_p \frac{a}{3} = \frac{p_p^2}{3kT} E_0.$$
(4.81)

With the relations above, the orientation polarizability will result:

$$\alpha_0 = \frac{\rho_p^2}{3 \, kT} \,, \tag{4.82}$$

which is dependent explicitly on the quantity of the permanent electric momentum and temperature.

4. Dielectrics

With the relation (4.82) it is obtained the **electric susceptivity** expression, respectively the **permittivity** for the dielectrics with orientation polarization:

$$\chi_{e} = \frac{\frac{p_{p}^{2}}{3k\epsilon_{0}T}}{1 - \gamma \cdot \frac{p_{p}^{2}}{3k\epsilon_{0}T}}; \quad \epsilon_{r} = 1 + \chi_{e} = 1 + \frac{\frac{p_{p}^{2}}{3k\epsilon_{0}T}}{1 - \gamma \cdot \frac{p_{p}^{2}}{3k\epsilon_{0}T}}.$$
(4.83)

For polar gases ($\gamma \approx 0$) it can be obtained:

$$\varepsilon_{rgases} = 1 + \frac{p_p^2}{3k\varepsilon_0 T}.$$
(4.84)

The relation (4.84) shows the explicit dependency on temperature of the permittivity at polar dielectrics. The permittivity decreases hyperbolically with the temperature raising.

4.3.6. Temperature Influence on the Polarization State

Temperature influences the polarization state of the dielectrics, especially of those which are polar dielectrics.

In Fig. 4.27 is shown the susceptivity dependence on the reversed temperature for the compounds $CH_{4-x} Cl_x$, which for values *x*=1-3 are polar compounds.



Fig. 4.27. Temperature dependence of electrical susceptivity for the compounds CH_{4-x} CI_x (x = 0, 1, 2, 3, 4).

Notes:

- The CH₃Cl, CH₂Cl₂, CHCl₃ molecules, possessing a permanent dipole moment, present high temperature variations for χ_e,
- The gas molecules of CH₄ and carbon tetrachloride (CCl₄), with no permanent dipole moment, have their electric susceptivity independent on temperature.

Crystals with polar molecules, at low enough temperatures, have their dipolar moments "frozen", which will make the permittivity to be much lower than of the same dielectric in liquid state. It is the case of nytro-carbureted hydrogen (Fig. 4.28): when they pass to a liquid state, a jump of the permittivity value is produced, and then, when the temperature increases, the permittivity wills hyperbolically decreases, corresponding to the behavior of polar dielectrics.



Fig. 4.28. Permittivity variation with temperature for nytro-carbureted hydrogen.

The permittivity of polar liquids has high values. For example, at normal (room) temperature, the relative permittivity of water is $\varepsilon_r = 81$. When temperature is increasing, the permittivity decreases very much (Fig. 4.29).



Fig. 4.29. Water permittivity variation with temperature.

Generally, in Fig. 4.30 is shown the typical dependence of electrical susceptivity with the temperature for polar dielectrics.



Fig. 4.30. Typical dependence of electrical susceptivity with the temperature in polar dielectrics.

Notes:

- For the gases, if the temperature increases the susceptibility decreases.
- For the polar liquids and solids, there is a domain of temperature where the susceptivity increases (the temperature is favorable for the dipoles' orientation on the direction of the applied field) and afterwards the permittivity decreases while temperature is further rising (the effect of disorder is predominant).

For a T_{critic} value, the susceptivity decreases while the temperature is increasing.

The passing from the liquid aggregation state to the solid one is usually done by suddenly decreasing the value for χ_{e} .

4.3.7. The Clausius - Mosotti Equation

For a homogenous dielectric, when the electronic, ionic and orientation polarizations coexist, the total electric polarization \overline{P} is calculated as a sum of the electronic polarization $\overline{P_e}$, the ionic polarization $\overline{P_i}$ and the orientation polarization $\overline{P_o}$:

$$\overline{P} = \overline{P}_e + \overline{P}_i + \overline{P}_0 = (n_e \alpha_e + n_i \alpha_i + n_0 \alpha_0) \overline{E}_0, \qquad (4.85)$$

where n_e , n_i , n_0 and α_e , α_i , α_0 are the volume densities of bonded electric charges, respectively, structural unit polarizabilities.

Using the expression (4.44) for the intensity of the effective electric field E_0 , and the expression (4.85) for the electric polarization, we can obtain:

$$\overline{P} = \frac{n_e \alpha_e + n_i \alpha_i + n_0 \alpha_0}{1 - \frac{\gamma}{\varepsilon_0} (n_e \alpha_e + n_i \alpha_i + n_0 \alpha_0)} \overline{E} .$$
(4.86)

By comparing this relation with the law of electric polarization - relation (1.5), the expression of the electric susceptivity results:

$$\chi_{e} = \varepsilon_{r} - 1 = \frac{\frac{1}{\varepsilon_{0}} \cdot (n_{e} \alpha_{e} + n_{i} \alpha_{i} + n_{0} \alpha_{0})}{1 - \frac{\gamma}{\varepsilon_{0}} \cdot (n_{e} \alpha_{e} + n_{i} \alpha_{i} + n_{0} \alpha_{0})} \quad .$$

$$(4.87)$$

For the case of crystalline solids with cubic structure ($\gamma = 1/3$), this relation can be put in the following form:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{1}{3\varepsilon_0} \cdot \sum_{k=1}^3 n_k \alpha_k .$$
(4.88)

The relation (4.88) is named **Clausius-Mosotti equation**. This relation can be written in function on molar mass M_k and mass density d_{mk} , quantities which are in direct connection with the volume concentration of the molecules n_k :

$$\frac{1}{n_k} = \frac{1}{N_A} \cdot \frac{d_{mk}}{M_k}, \qquad (4.89)$$

where N_A is Avogadro number. The relation (4.88) becomes:

$$\frac{\varepsilon_r - 1}{\varepsilon_r + 2} = \frac{N_A}{3\varepsilon_0} \sum_k \frac{d_{mk}}{M_k} \alpha_k .$$
(4.90)

Note:

- The equation Clausius-Mosotti connects the macroscopic material parameter ε_r with the microscopic structure parameters n_k and α_k ;
- Knowing the microscopic parameters it can be determined the macroscopic parameters and reverse;
- Gases at high pressure also have proved the relations (4.88) and (4.90).

4.3.8. Dielectric Permittivity of Composite Materials

Most dielectrics are composite materials - a mixture of various homogeneous substances. For an efficient utilisation of the composite dielectrics, it is important to knowing the **averaged value of the permittivity**, in correlation with the permittivity of the components:

- For optimal designing of composites, is also useful to know the relationships between the averaged permittivity of the composite dielectrics and the volume concentration of the components.
- By an appropriate choosing of the volume concentration of the components could be obtained the **optimal combined properties** required in special applications: in

the case of liquid dielectrics it could modify the properties like: viscosity, solidification point, permittivity, etc. In plastics with thermoplastic behavior, the addition of some substances could increase the thermal stability, mechanical strength, etc.

 To know the dependence of average permittivity of composite dielectrics is useful also in measurement techniques. Knowing the relation between the permittivity of mixture ε_m, the permittivity of dispersed phase ε_d and the one of continuous faze ε_c, it can determined the permittivity of unknown component.

Permittivity of Homogeneous Mixtures

There are different methods for estimation of the averaged value of permittivity for mixtures. Clausius-Mosotti equation could be used to obtain the relative averaged permittivity ε_m for perfect homogeneously mixtures:

$$\frac{\varepsilon_m - 1}{\varepsilon_m + 2} = \sum_{i=1}^n v_i \frac{\varepsilon_i - 1}{\varepsilon_i + 2}, \qquad (4.91)$$

where ε_i is the relative permittivity of *i*-component having the volume concentration v_i .

For the mixture of two dielectrics (considered like small spheres having the permittivity ϵ_1 , respectively, ϵ_2 , plunged in the medium with permittivity ϵ_m), the relation of Böttcher indicates the dependence between the average permittivity ϵ_m of a dielectric made of a homogenous mixture of two dielectrics with absolute permittivity ϵ_1 , ϵ_2 :

$$\frac{\boldsymbol{\varepsilon}_m - \boldsymbol{\varepsilon}_1}{3\boldsymbol{\varepsilon}_m} = \delta \frac{\boldsymbol{\varepsilon}_2 - \boldsymbol{\varepsilon}_1}{\boldsymbol{\varepsilon}_2 - 2\boldsymbol{\varepsilon}_m}.$$
(4.92)

The relation is obtained for the case in which in a dielectric mixture of two homogeneous components, one, with permittivity ε_2 having the percent concentration δ and other, with permittivity ε_1 having the percent concentration (1- δ). A relative averaged permittivity ε_m is obtained.

For **particle dispersed mixtures** formed by dielectric medium having the relative permittivity ε_1 in which is dispersed another dielectric formed by spherical particles having the radius r_2 and the relative permittivity ε_2 , an expression of the averaged permittivity of the mixture is:

$$\frac{\varepsilon_m}{\varepsilon_1} = \frac{\frac{\varepsilon_2}{\varepsilon_1} + 2 + 2\nu(\frac{\varepsilon_2}{\varepsilon_1} - 1)}{\frac{\varepsilon_2}{\varepsilon_1} + 2 - \nu(\frac{\varepsilon_2}{\varepsilon_1} - 1)},$$
(4.93)

where $v=N(r_2)^3/R^3$ is the volume concentration of dispersed phase.

Permittivity of certain stratified structures

A **stratified structure** is made of a number of homogeneous dielectric layers arranged either serial, or parallel (Fig. 4.31).





Fig. 4.31: Stratified dielectric with: a) *n* parallel layers; b) *n* serial layers.

In the figure 4.33a there is presented the model of a **multi-layer dielectric** with *n* homogenous layers parallel arranged, having v_i and ε_i the volume content of the *i*-component and permittivity of the component, respectively.

An expression of the average permittivity can be obtained for a stratified structure by considering the capacity equivalent to a connection in parallel

$$C_{p} = \sum_{i=1}^{n} C_{i}$$
, (4.94)

whose result is the average permittivity of the stratified structure:

$$\varepsilon_{mp} = \sum_{i=1}^{n} \left(v_i \varepsilon_i \right).$$
(4.95)

Note:

The permittivity of a multi-layer dielectric complies the pondered arithmetic rule of mixing.

In the figure 4.33b there is presented the model of a dielectric of *n* dielectric layers serial arranged, of volume concentrations v_i and permittivity ε_i .

The expression of the average permittivity for stratified structure can be obtained, by considering the capacity equivalent to a serial connection:

$$1/C_s = \sum 1/C_i$$
, (4.96)

whose result is the average permittivity of the stratified structure:

$$\frac{1}{\varepsilon_{ms}} = \sum_{i=1}^{n} \frac{v_i}{\varepsilon_i} \,. \tag{4.97}$$

Note:

The reciprocal of average permittivity is determined like a pondered arithmetic sum of the reciprocal of component permittivity.

These relations are used for calculating the permittivity of the stratified paper, polymeric paper and sheets, and solid dielectrics impregnated with dielectric liquids.

4.4. DIELECTRICS IN ALTERNATIVE ELECTRIC FIELDS

4.4.1. Complex Permittivity

For characterizing the polarization phenomena in sinusoidal regime, the complex permittivity quantity ε is introduced.

When a harmonic intensity field is applied:

$$E(t) = \sqrt{2} E_{ef} \sin \omega t \tag{4.98}$$

the electric induction will vary also sinusoidally, with a delay given by the δ_h angle:

$$D(t) = \sqrt{2} D_{ef} \sin(\omega t - \delta_h)$$
(4.99)

Considering the law of connection of \overline{D} , and \overline{E} , transposed in complex, it follows that the **complex permittivity** is numerically equal to the ratio between the electric induction phasor D and the intensity phasor of the electric field E:

$$\underline{\varepsilon}_{r} = \frac{1}{\varepsilon_{o}} \cdot \frac{\underline{D}}{\underline{E}} = \frac{1}{\varepsilon_{o}} \cdot \frac{D_{ef}}{E_{ef}} e^{-j\delta_{h}} = \frac{1}{\varepsilon_{o}} \cdot \frac{D_{ef}}{E_{ef}} (\cos\delta_{h} - j\sin\delta_{h})$$
(4.100)

Hence, the complex permittivity has two terms:

$$\underline{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r^{''} \tag{4.101}$$

by whose identification in the relation (4.102), the following expression results for the **real component of permittivity**:

$$\varepsilon_{r}' = Re\{\underline{\varepsilon}_{r}\} = \frac{1}{\varepsilon_{o}} \cdot \frac{D_{ef}}{E_{ef}} \cos \delta_{h}$$
(4.102)

and for the imaginary component of permittivity:

$$\varepsilon_r'' = Im\{ \underline{\varepsilon}_r \} = \frac{1}{\varepsilon_o} \cdot \frac{D_{ef}}{E_{ef}} \sin \delta_h$$
(4.103)

The ratio between the imaginary component and the real component of the complex permittivity is named **tangent of the angle of dielectric losses**:

$$tg\,\delta_h = \frac{\varepsilon_r''}{\varepsilon_r'} \tag{4.104}$$

The physical interpretation of these quantities can be obtained if it is considered the case of a linear and isotropic dielectric placed between the armatures of a condenser (Fig. 4.32).



Fig. 4.32. Ideal and real dielectric: (a) dielectric in sinusoidal field; (b) phasors diagram for an ideal dielectric; (c) phasors diagram for a dielectric with losses through polarization; (d) phasors diagram for a dielectric with losses through polarization and conduction

(a) Ideal dielectric

In the case of a dielectric without free electric charge (without conduction currents), on applying a sinusoidal electric field of intensity E, a displacement current appear in the dielectric, determined by the induction of the polarization state, characterised by the density of the electric current of displacement, of the form:

$$\underline{J}_{D} = j \omega \underline{D} = j \omega \varepsilon_{0} \varepsilon_{r} \underline{E}$$
(4.105)

The phasors \underline{J}_D and \underline{E} will be dephased with $\pi/2$ because the imaginary component of the permittivity is null (zero losses). The diagram of phasors from figure 4.32b relieves the case of an **ideal dielectric**. The relation (4.102) emphasizes the fact that the term $\varepsilon'_r = Re\{\varepsilon_r\}$ characterizes the polarization phenomena in the dielectric.

(b) Dielectric with losses by electric post-effect

In reality, the induction of the polarization state on applying a sinusoidal electric field is accompanied by losses of energy, named polarization losses, due to the electric post-effect, characterized by the dephasing of the density of the displacement electric current J_D relative to the intensity of electric field <u>*E*</u> with an angle smaller than $\pi/2$.

4. Dielectrics	

$$\underline{J}_{D} = j \underline{\omega} \underline{D} = j \underline{\omega} \varepsilon_{o} \underline{\varepsilon}_{r} \underline{E} = j \underline{\omega} \varepsilon_{o} (\varepsilon_{r}' - j \varepsilon_{r}'') \underline{E}$$
(4.106)

In figure 4.32c is presented the diagram of a dielectric with losses through electric post-effect, in which the active component of the phasor \underline{J}_D is determined with the relation (4.106) by the term $\varepsilon_r^{"} = Im\{\varepsilon_r\}$.

In this way, the imaginary component of the complex permittivity describes the dielectric losses due to the electric post-effect (through electric viscosity). For this reason it is also called **factor of dielectric losses**, being connected to the other vectors through the relation:

 $\varepsilon_r^{''} = \varepsilon_r' \, tg \,\delta_h \tag{4.107}$

(c) Dielectric with losses through conduction and electric post-effect.

In the case when in the dielectric there is also free electric charge, besides losses through electric post-effect, there are developed also losses through electric conduction. The diagram of phasors in this case is shown in figure 4.32d. An evaluation of the total losses in dielectrics is given in the next sub-chapter.

It is worth to mention that each dielectric polarization mechanism has a characteristic "cutoff frequency":

- As frequency increases, the slow mechanisms drop out in turn, leaving the faster ones to contribute to the permittivity component ε'_r .
- The loss factor $\varepsilon_r^{"}$ correspond to the peak at each critical frequency (Fig. 4.33).

The magnitude and "cutoff frequency" of each mechanism is unique for different materials. Water has a strong dipolar effect at low frequencies - but its dielectric constant rolls off dramatically around 22 GHz. PTFE, on the other hand, has no dipolar mechanisms and its permittivity is remarkably constant well into the millimeter-wave region.



Fig. 4.33. The dependence of the real and imaginary components of permittivity on the frequency of the applied electric field.

Resonant effects are usually associated with electronic or atomic polarization. A relaxation effect is usually associated with orientation polarization.

M 4.4.2. Electric Polarization Losses

In electric fields variable in time, in dielectrics, supplementary losses will appear, mainly due to the electric post-effect, by which the electrical polarization quantity \overline{P} does not synchronically follow the electric field intensity \overline{E} . These losses, called **losses through electrical polarization**, appear in linear dielectrics and in non-linear dielectrics (in this case there are called **losses through dielectric hysteresis**). In ferroelectric materials, which present the hysteresis cycle, the losses are proportional with the area of the hysteresis cycle. In linear materials, the losses depend on $\overline{J_D}$, given by the relation (4.106) (see figure 4.32c).

In harmonic fields, the energy necessary for the polarization of dielectric for a period of variation of the electric field T = 1/f is given by the relation:

$$w = \oint \overline{P}(t) \cdot d\overline{E}(t), \qquad (4.108)$$

being numerically equal to the curve area P(E).

Fig. 4.34 shows the dependency of the electrical polarization on the intensity of the electric field, in the case of a linear dielectric, submitted to the action of an electric field with sinusoidal variation in time, at different frequencies.



Fig. 4.34. The influence of the electric field frequency upon the losses through polarization, at: a) low frequencies; b) resonance; c) high frequencies.

Cases:

a) If the relaxation duration τ is much lower than the period $T_1 = 1/f'$ of the electric field variation (Fig. 4.34a), then the vector \overline{P} has enough time to arrange on the vector direction \overline{E} . The electric field does not consume energy in order to establish

200

the polarization state on the period of a variation cycle. In this case $\oint \overline{P} d\overline{E} = 0$.

There are no losses through polarization.

- b) When the relaxation period τ is comparable with the period $T_0=1/f_0$ (Fig. 4.34b), the vector \overline{P} tends to arrange itself on the vector direction \overline{E} . Because of the internal frictions, the alignment does not happen simultaneously, and therefore there is a certain delay between the vector \overline{P} and the vector \overline{E} . The electric field consumes energy in order to entertain the polarization state. This energy represents the dielectric losses through polarization. In this case $\oint \overline{P}d\overline{E}\neq 0$.
- c) If the relaxation period τ is much longer than the period $T_{2}=1/f''$ of the electric field variation (Fig. 4.34c) the case of high frequencies as compared to the resonance frequency then the vector quantity \overline{P} decreases very much in amplitude, therefore it can be considered a decreasing of the dielectric losses.

Conclusion:

Losses through polarization have maximal value when the oscillation period of the field coincides with the relaxation period.

Losses through electrical polarization in the unit of volume are calculated with the following energetic considerations.

At an infinite small variation of the electric field, the electric energy in a unit of volume varies with $dw_e = E \cdot dD$. The variation of the density of electric energy in time unit is the **instantaneous power**:

$$\rho_d(t) = \frac{\mathrm{d}w_e}{\mathrm{d}t} = E \frac{\mathrm{d}D}{\mathrm{d}t} = E J_D, \qquad (4.109)$$

where *D* is the electric induction, measured in C/m^2 and $J_D = dD/dt$ is the density of the electric displacement current, measured in A/m^2 , given by the relation (4.106).

In complex, the relation (4.109) defines the density of apparent complex power:

$$\boldsymbol{s}_{d} = \underline{\boldsymbol{E}} \cdot \underline{\boldsymbol{J}}_{D}^{*} = \underline{\boldsymbol{E}} \cdot \left[j \boldsymbol{\omega} \boldsymbol{\varepsilon}_{0} \left(\boldsymbol{\varepsilon}_{r}^{'} - j \boldsymbol{\varepsilon}_{r}^{''} \right) \underline{\boldsymbol{E}} \right]^{*}.$$
(4.110)

By comparing this relation to the general expression of the density of apparent complex power:

$$\underline{\mathbf{s}}_d = \mathbf{p}_d + jq_d \tag{4.111}$$

it will result the expression of the volume density of losses through polarization:

$$p_d = \omega \varepsilon_0 \varepsilon_r^{"} E_{ef}^2 \tag{4.112}$$

and the expression of the density of reactive power accumulated in capacitive element, as:

$$q_{d} = \omega \varepsilon_{0} \varepsilon_{r}^{'} E_{ef}^{2}$$
(4.113)

By considering the expression for the dielectric losses coefficient ε_r , the relation (4.107) for the volume density of losses through polarization p_d becomes:

$$p_d = \omega \varepsilon_0 \varepsilon'_r \operatorname{tg} \delta_h E_{ef}^2 \quad . \tag{4.114}$$

The polarization losses p_d depend on the dielectric losses coefficient $\varepsilon_r' = \varepsilon_r t \, \delta_h$. This parameter is determined by a series of intrinsic factors (nature and structure of dielectric) and extrinsic factors (temperature, humidity, electric field, etc.). All these factors will also influence the value of polarization losses.

Notes:

- Each losses mechanism presents a typical characteristic for tg δ_h.
- For the case when the temperature remains constant, the curve tg $\delta_h = f(\omega)$ presents a maximum for a certain frequency ω_0 , called **absorption pulsation** (Fig. 4.35).
- The curve tg $\delta_h = f(\omega)$ is dependent on structure, on its width and its homogeneity of dielectric, on the applied voltage, on temperature.



Fig. 4.35. Dependence of the permittivity components and of the tangent of dielectric losses angle at polar dielectrics with the electric field pulsation.

If the dielectric is formed of more dipole categories, each one being characterized by an average relaxation time, then the curve tg $\delta_h = f(\omega)$ will be obtained by overlapping the curves characteristic for each relaxation time. It will be obtained a dispersion curve with an extended maximum (Fig. 4.36).



Fig. 4.36. Loss factor variation with the frequency for a dielectric with different relaxation times of the constituent dipoles.

Such dependence is obtained for a series of polymers, such as the polyester film (Mylar) (Fig. 4.37).



Fig. 4.37. Dependence of the permittivity and the loss factor at polyester (Mylar) film with the frequency.

For Mylar, in a large domain of frequencies $(10^4 \div 10^8)$ Hz, the value tg $\delta_{h max}$ is practically maintained constant, which indicates a dispersion of the relaxation times of polarization processes.

4.4.3. Total Losses in Dielectrics

The **energy losses** in dielectrics represent one of the main causes of the electrical breakdown. The energy losses in dielectrics correspond to energy dissipation, which appears at the movement of the free charge carriers (ions, electrons), and at the limited movements during the polarization processes. **Total losses** in electroinsulating material on unit of volume are obtained by summing all the energy losses:

$$p_{tot} = p_{\sigma} + p_{d} + p_{ss} + p_{supl}$$
, (4.115)

where:

 p_{σ} - the losses through electrical conduction,

 p_d - the losses through electronic, ionic, orientation polarization and through the polarization of non-homogeneity,

 p_{ss} - the losses through accumulation of spatial charges,

 p_{supl} - the supplementary losses.

The losses through electrical conduction and through the polarization are significantly higher than the losses through accumulation of spatial charges and supplementary losses.

A connection between the angle of losses due to the polarization phenomena δ_h and the angle of total losses in dielectric δ can be established starting from the expression of the density of the total electric current that settles in the dielectric (Fig. 4.32d).

The expression of the total density of current in the dielectric with losses through polarization and through conduction is:

$$\underline{J}_{tot} = \underline{J}_{\sigma} + \underline{J}_{D} \tag{4.116}$$

where the density of the conduction current is:

$$\underline{J}_{\sigma} = \sigma \underline{E} \tag{4.117}$$

and the density of the displacement current has the expression (4.106).

The active component of the density of the total current will be (Fig. 4.32d):

$$\underline{J}_{cond tot} = (\sigma + \omega \varepsilon_o \varepsilon'_r tg \delta_h) \underline{E}$$
(4.118)

The relation (4.118) can be written as:

$$\underline{J}_{cond \ tot} = \omega \varepsilon_{o} \varepsilon_{r} \left(\frac{\sigma}{\omega \varepsilon_{o} \varepsilon_{r}} + t \delta_{h} \right) \underline{E}$$
(4.119)

The **factor of total losses**, which takes into account the conduction and also the polarization phenomena occurring in the dielectric, is defined by the relation:

$$tg\,\delta = tg\,\delta_h + \frac{\sigma}{\omega\varepsilon_o\varepsilon'_r} \tag{4.120}$$

This relation indicates the explicit mode of dependency of the factor of total losses to pulsation ω , to frequency of the electric field, respectively.

Losses through electrical conduction per unit of the volume unit of dielectric, measured in W/m^3 , are calculated taken in account the energy transformation law and the electrical conduction law for media without imprinted fields:

$$p_{tot} = \underline{E} \cdot \underline{J}_{condtot} = \sigma_{tot} E_{ef}^2 , \qquad (4.121)$$

204

where \underline{E} is the corresponding phasorial representation of the applied electric field intensity, and $\underline{J}_{condtot}^{*}$ is the reverse of phasorial representation of the total electric conduction current density.

With the relations (4.119)-(4.121), it is obtained:

$$p_{tot} = \omega \varepsilon_0 \varepsilon_r' \operatorname{tg} \delta E_{ef}^2 \,. \tag{4.122}$$

which defines the total equivalent conductivity of a dielectric in alternative fields, when the conduction and polarization losses are present:

$$\sigma_{tot} = \omega \varepsilon_0 \varepsilon'_r t \delta$$
(4.123)

The total conductivity of the dielectric σ_{tot} depends on a series of intrinsic factors (the nature and the structure of the electroinsulating material) and extrinsic factors (temperature, humidity, electric field pulsation, etc.). All these factors also influence the value of the losses through conduction.

With these relations, the total losses for a volume of the dielectric can be evaluated.

Considering the case of a dielectric of *d* thickness, introduced between the armatures of a plan capacitor with area *S* of armatures, supplied with alternative sinusoidal voltage of effective value $U = E_{ef} d$, the expressions for the active power *P*, respectively reactive power *Q* absorbed by the capacitor are obtained:

- The total active power, measured in W:

$$P = p_{tot} Sd = \omega \varepsilon_0 \varepsilon'_r tg\delta \left(\frac{U}{d}\right)^2 Sd, \qquad (4.124)$$

- The total reactive power, measured in VAr:

$$Q = q_{tot} S d = -\omega \varepsilon_0 \varepsilon'_r \left(\frac{U}{d}\right)^2 S d .$$
(4.125)

Identifying the terms that enter in the expression of the plan capacitor capacity $C = \varepsilon_{o} \varepsilon_{r,S} d$, the expression of the active power is obtained:

$$P = \omega \varepsilon_0 \varepsilon'_r \operatorname{tg} \delta C U^2, \qquad (4.126)$$

and of the reactive power:

 $Q = \omega C U^2 \,. \tag{4.127}$

It will result the tangent of the total loss angle:

$$tg\delta = \frac{P}{|Q|} = \frac{1}{tg\phi}, \qquad (4.128)$$

where φ is the de-phasing angle between the voltage and the current through the capacitor. The total loss angle δ is complementary to the de-phasing angle φ .

The reverse of this quantity is the **quality factor** of the capacitive element:

$$Q = \frac{1}{\mathrm{tg}\delta}.$$
 (4.129)

If $tg \delta$ is lower than the quality factor of the capacitive element, it behaves more like an **ideal capacitor**.

If the total dielectric losses are higher, the heating processes are more intense and they will stimulate the breakdown process. This is the reason for why it is very important to know the origin of these losses and to elaborate more efficient methods for reducing them.

4.5. ELECTRICAL BREAKDOWN PHENOMENA

4.5.1. High Voltage Testing

Any dielectric has a limit of electrical strength and when it surpasses this limit it losses his insulation capacity. Generally, the breakdown is pointed out by drastically increasing the electrical current *I*.

The corresponding electrical voltage at which the breakdown is produced is called **breakdown voltage** U_{str} and the corresponding value of the electrical field intensity is called **dielectric strength** or **breakdown strength** E_{str} , defined by the relation:

$$E_{str} = \frac{U_{str}}{d}, \qquad (4.130)$$

where d is the distance between the electrodes, and also the thickness of the insulating plates.

To determine the electric strength, the value of the voltage will be measured when the breakdown of the insulating sample appears. The test can be done in different ways, and different types of tests are developed:

> According to the form of the applied voltage wave, there are:

- Tests with continuous voltage (test specific for cables);
- Tests with alternative voltage at the frequency of 50 Hz (test specific for high and low voltage devices);
- Tests with voltage pulse (test specific for electric and electronic devices).

> According to the time period of the applied voltage, there are:

 Tests with short or long term voltage, where the breakdown of thermal type is predominant;

206

 Tests for sudden voltage application (voltage pulse), when the electrical breakdown is predominant.

The test of short duration is characterized by the increasing of the voltage from zero to the value of the breakdown voltage, with high velocity ($\geq 1kV/s$). This test is done in two ways:

- With a continuing control voltage when the voltage constantly increases from zero up to the breakdown moment. The ratio between voltage breakdown and the distance between the electrodes defined the dielectric strength at short term testing with the continuous control voltage;
- With step control voltage where it is determined the step breakdown voltage
 U_{str1}.

Long-term high voltage test is done after having determined the value U_{str1} , with short-term step regular tests.

The test at voltage pulse - to the dielectric or to the electrical device, a voltage pulse of a given form is applied, with amplitude close to the value of the breakdown voltage U_{strl} .

Example:

A typical electrical connection diagram of AC voltage breakdown testing is presented in Fig. 4.38. The characteristics of the main devices used are presented in Table 4.12.



Fig. 4.38. The electrical breakdown testing diagram with AC voltage.

Table 4.12.	Devices	used in	AC electrical	breakdown	testing.
-------------	---------	---------	---------------	-----------	----------

Devices	Symbol in diagram
Single pole switch	b
AC contactors	<i>C</i> ₁ , <i>C</i> ₂
Over-current relay	d
High voltage signal lamp	h ₁
High voltage signal lamp	h ₂
Breakdown signal lamp	h_3
Autotransformer	m_0
High voltage transformer	<i>m</i> ₁
Resistor for breakdown current limiter	Rı
AC Voltmeter	V
High voltage cell with metallic enclosure and connected to earth protected system	D

The testing installation needs a screened and protected room where the testing material is disposed and it is connected to the secondary of the high voltage transformer.

The scheme allows the determination of the breakdown voltage value. The dielectric strength can be determined with the relation (4.130).

W 4.5.2. Electrical Breakdown Models

The dielectric strength depends on a lot of factors: the nature of the dielectric, the aggregation state, its geometry, the nature and the dimensions of the electrodes, the frequency of the electric field, the environmental conditions. The presence of humidity, dust, fats, and, also, fog, wind influences also the values of dielectric strength.

If an increasing electrical voltage U is applied on a system of electrodes and on an electroinsulating material/ dielectric at a specific value of U, electrical discharges will appear between the electroinsulating materials and the electrodes (Fig. 4.39a), inside the electroinsulating material (Fig. 4.39b), or outside of it (Fig. 4.39c).



Fig. 4.39. Electrical discharges: a) between the armature and the dielectric; b) inside of the dielectric; c) at the surface of the dielectric.

With increasing the voltage, these discharges will be amplified, the dielectric will not be capable to support a new increase of the voltage and a breakdown will be produced between the electrodes, through the increasing of electric conduction current.

Electro-mechanic, electro-thermal and electro-dynamic effects appear and they could determine the degradation or total destruction of the dielectric (burning of the inorganic dielectrics and carbonization for the organic dielectrics).

Gaseous and liquid dielectrics are regenerative when the breakdown produces – it means that after a breakdown, a new electrical stress can be applied, the dielectric having again a high value of resistivity.

But, **in solid dielectrics**, because of the formation of highly-conductive channels, as well as the creeps and shivers, the breakdown provides the character of losing the insulating capacity. As a rule, the system of protection acts before the beginning of this catastrophic phenomenon.

Knowledge about the dielectric breakdown is important for the reliability of the electrical and electronic devices, and for the direct technical applications of this phenomenon.

There are several types of breakdown mechanisms:

- The thermal breakdown is produced when the developed local heat surpasses the evacuated heat (through thermal conduction, radiation or convection). The breakdown process is determined by an increase of temperature.
- **The electrical** or **pure breakdown** has electronic nature, developed by the increasing of number of free or quasi-free electrons in dielectrics.
- There are, also, other mechanisms with cumulative effects, which could progressively lead to breakdown. For example, the **electro-chemical** effects degrade the dielectric leading to the increase of the electrical conductivity.

The electrochemical breakdown can be developed independently or combined with other types of breakdown. In certain dielectrics, in constant or low frequency electric fields, electrochemical processes (decomposing, ionizations) are established which will lead to the increase of the electrical conductivity and to breakdown. These processes are very slow and they appear along with the ageing of the dielectric.

• Partial discharge breakdown is due to the presence of the cavities, empty or full with the gaseous. Partial electric discharges are those discharges, which occur in those cavities filled with gases in the solid dielectrics and under the action of intense electric fields. The starting voltage of these discharges is much lower than the breakdown voltage of the solid dielectric. Being repeated at a certain frequency, the partial discharges erode the walls of the cavities, advance and produce a system of tree-shaped ramifications within the solid dielectric, which can reach the electrodes by propagating themselves with a certain velocity.

Electrical trees comprise an ensemble of fine channels that appear and develop in solid dielectrics due to the local destruction. The destruction appears in

the parts of the dielectric where there is the concentration of the electrical field intensity (cavities, conductive impurities, sharp edges, etc.).

Thus, in a high voltage cable (Fig. 4.40), in which the main insulation is polyethylene, during the stressing with the high voltage applied between the conductive core 1 and the ground, the partial discharges appear and they determine the cavity and micro-cracks propagation from the core to the screen.



Fig. 4.40. Electrical tree developed in high voltage cable insulation: 1- conductor core; 2- semiconductive material; 3- electroinsulating material; 4- screen.

The tree channels (Fig. 4.40) are developed through the decomposition of the material under the combined action of the electrical field, the partial discharges (inside the cavities and inside the channels), the heat and of the mechanical stresses produced by the electrical field and the gas pressure.

It is necessary to know the hypotheses and the limits of the breakdown theories in order to use acquired knowledge for technical design of electrical insulation, for establishing the maximum level of working voltage, for evaluating the operating reliability of the system. The character of breakdown is different for different aggregation states of dielectrics.

Example:

The gases lose their electrical insulating properties at values of units of kV, for distances between the electrodes of 1 mm (ex. for air $E_{str} \approx 3.2$ kV/mm in normal conditions).

In homogenous electric field, the breakdown is produced in a small time interval $(10^{-6} \div 10^{-8})$ seconds, the threshold voltage U_{str} being dependent on the pressure *p*, the distance *d* between electrodes, and the gas temperature.



Fig. 4.41. Paschen curves for neon, hydrogen, nitrogen and oxygen.

On lower pressures and small distances between electrodes, the spatial electric charge accumulation is low and determines a certain breakdown character, the breakdown voltage of a gaseous dielectric being dependent on the gas nature, on the temperature T and the *pd* product between pressure and electrodes distance.

The experimental characteristics of the voltage breakdown on gases are represented graphically under the form of **Paschen curves** (Fig. 4.41).

Note:

Every gas is characterized by a well-defined minimum of the breakdown voltage, for a given value of the product *pd.* For air, this minimum value of breakdown voltage is about 180 V.

W 4.5.3. Electrical Breakdown Prevention

Knowing the **prevention and avoidance techniques** of the electric breakdown of the dielectrics is useful to the designers and the manufacturers of electric and electronic equipment, as well as to those exploiting this equipment. The operational conditions of the high voltage equipment are various.

Examples:

- Many of the electric flight equipment are stressed with normal launching pressures and afterwards, in the aerial or cosmic space, the pressure being modified, reaching extremely low values.
- Other characteristics are in relation with the operating in an expanded frequency domain, in various environments, in the presence of various ionising particles, etc.

Regarding the accomplishment of the systems employing high voltages, the two main designing principles must be taken into account:

- A preventing design, using materials, components and configurations of electrodes in order to avoid any possible flashover and breakdown;
- An adequate design, which should allow control over tests having periodically applied voltages, in any stage - at the fabrication, assemblage or functioning.

Some of the prevention design principles of the systems employing electroinsulating materials undergoing high voltages will be enumerated below.

(a) Avoiding the sharp edges and extremities

A system of needle type electrodes (small radii of curvature) determines intense electric fields. If a needle electrode having its radius of curvature R_1 has its radius of curvature reduced to R_2 , this determines a rising of the electric field with the ratio R_2/R_1 .

As a matter of fact, considering the case of the metallic sphere charged with the electric charge Q and which is placed in the air, the following results are obtained regarding the electric field:

$$E_{1} = \frac{Q}{4\pi\epsilon_{0}R_{1}^{2}}; E_{2} = \frac{Q}{4\pi\epsilon_{0}R_{2}^{2}} , \qquad (4.131)$$

or

$$\frac{E_1}{E_2} = \left(\frac{R_2}{R_1}\right)^2.$$
(4.132)

The ratio of the intensities of the electric fields depends on the reverse square of the radii of the spheres. Thus, if in the proximity of the electrode the electric field has the intensity $E_1 = 20$ V/mm, by reducing the radius of curvature from 1 cm to 1 mm, it is obtained $E_2 = 2000$ V/mm. If the radius of curvature is reduced to 0,1 mm, then the electric field in the proximity of the electrode becomes $E_2 = 2000$ V/mm, exceeding the dielectric strength of the air ($E_{str}=3200$ V/mm).

(b) The setting of the distance among components

The setting of the distance among components is done according to the voltage level and the dielectric environment. For example, if the dielectric environment is the air, Paschen curves will provide data regarding the admissible stresses:

- at pressures of 10^{-4} torr can be applied electric fields 20 times larger without producing the breakdown for d = 1 cm;
- at intermediate pressures, Paschen curve indicates a minimum for air of approximately 10 V/mm.

(c) The accumulation of electric charge

At the application of an electric harmonic field having a certain frequency, there is the possibility of accumulating electric charge among the electrodes, process which leads to the lowering of the performances of the system. The phenomenon is dependent on the distance among the electrodes, on the level of the frequencies and of the applied voltages. The avoidance of this phenomenon can be done as it follows:

212

- the insertion of adequate dielectrics;
- the treatment of the metallic electrodes in order to reduce the phenomenon of secondary emission;
- the increase of the pressure of the air space among the electrodes;
- the adequate choice of the dimensions.

(d) Isolations and enclosing

For the high voltage systems, several types of dielectrics are used: high quality dielectrics, homogenous, lacking of cavities and holes, well fixed and compacted around the electrodes.

Their **connection to the ground** is recommendable, in all the possible cases. The **enclosing** can be achieved by the pressured in protective frames (containing air, nitrogen, SF_6 , CCl_2F_2 , C_3F_8 , etc.). The used gases should be non-flammable, non-explosive, and in most of the cases non-toxically. Their encapsulation by covering or stiffening by impregnation is done by the help of resins and plastics resistant at high voltage (polyurethane, silicon rubber, epoxy resins, etc.). For protection it is used the painting or varnishing of the components.

(e) The ventilation

The ventilation is a frequently used method for avoiding the breakdown. Thus, the gases which are released are evacuated from the high voltage system.

(f) The avoidance of the accidental voltages

The static electricity is accumulated especially in the isolations of plastics in case the humidity is reduced, or at the terminals in the case of the condensers which remain charged after the disconnection, in the case of the over-voltage in transition operation.

The electrical systems are protected by means of discharge resistance, by means of ground connection systems, by means of adequate ventilation circuits, being correlated to the other avoidance breakdown techniques.

4.6. GENERAL PROPERTIES OF DIELECTRICS

Dielectrics are materials used either for insulating electric conductive parts between themselves and/ or against the ground, or for achieving capacitive elements of certain components, circuits or systems. In this chapter the general properties of electroinsulating materials are presented.

4.6.1. Electric Properties

Electric properties of the dielectric materials depend on the electrical conductivity, electrical polarization, dissipation of energy, and the dielectric breakdown.

In order to better understand electroinsulating materials behavior, some of their characteristic parameters are presented as follows.

Electric conductivity σ , respectively **electric volume resistivity** $\rho_v=1/\sigma$, are the material parameters in connection with electric conduction processes in the volume of material. At room temperature and for E< 10^5 - 10^6 V/m, the volume resistivity ρ_v have the values from 10^8 to $10^{18} \Omega m$ (Table 4.13).

For solid electroinsulating materials, the **surface resistivity** ρ_s is defined. This material parameter takes values of the same order like volume resistivity, but it is strongly influence by humidity and irregularities of surfaces.

The absolute permittivity ε , respectively the relative permittivity ε_r is material parameter in connection with electric polarization processes, complex phenomena which consist of displacement of electrons and ions, rotations and displacements of electric charges of structural units of materials under the action of the electric field. These parameters are connected by the relation $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$, where $\varepsilon_0 = 1/(4\pi \times 9 \times 10^9) = 8.84 \cdot 10^{-12}$ F/m is the absolute permittivity of vacuum.

The relative permittivity values of some electroinsulating materials are presented in Table 4.13.

Loss factor tg δ , or **dissipation factor**, characterizes the intensity of dielectric losses in dielectrics. The phase-shifting angle φ of the current wave of an ideal dielectric is 90° on the voltage wave. The phase-shift angle of the current wave of a real dielectric is less than 90° and the difference δ =90- φ is called the **loss angle** (Fig. 4.22).

At room temperature and industrial frequency values, tg δ is between $10^{-5} \div 10^{-1}$, the decreased values corresponding to the high quality dielectrics. The values of loss factor tg δ of some of dielectrics are listed in Table 4.13.

Dielectric strength E_{str} , respectively **breakdown voltage** U_{str} are material parameters which characterize the ability of material to resist at electrical stresses. For plane samples in uniform field, the relation between these quantities is: $E_{str} = U_{str} / d$.

Dielectric strength, expressed as kV/mm, is the voltage gradient at which a continuous arc is formed through the specimen.

To be comparable, samples of different materials must be identical in geometry and conditioning factors, since values decrease as specimen thickness increase and are adversely affected with increasing moisture content and test environment temperature. Dielectric strength of some dielectrics are listed in Table 4.13.

	Volume	Relative	Loss	Dielectric
Electroinsulating	resistivity	permittivity	tangent	strength
materials	at 20ºC,	at 20ºC, 50 Hz	at 20ºC, 50 Hz	at 20ºC, 50 Hz
	ρ _ν [Ωm]	٤ _r	tg δ	<i>E_{str}</i> , [kV/mm]
Pure paraffin	10 ¹⁷	1.9	<10 ⁻⁵	-
Technical paraffin	10 ¹⁵	2.2	<10 ⁻⁴	-
Polyethylene	10 ¹⁵ – 10 ¹⁶	2.20 – 2.50	<10 ⁻⁵	20 – 50
Polytetrafluoroethylene	10 ¹⁵ -10 ¹⁶	2.10 – 2.50	<10 ⁻⁴	20 - 80

Table 4.13. Electrical properties of some electroinsulating materials.

214

4. Dielectrics

			1	1
Polystyrene	10 ¹² - 10 ¹⁵	2.2 – 2.4	<10 ⁻⁴	50 – 70
Polyvinylchloride - PVC	10 ¹¹ - 10 ¹³	4.2 - 4.5	<10 ⁻²	40 - 70
Colophony	10 ^{15 -} 10 ¹⁷	2.0 - 2.5	-	-
Phenol formaldehyde	10 ¹³	40 95	0.02 0.20	10 50
resin	10	4.0 - 0.5	0.03 - 0.20	10 - 50
Plexiglas	10 ¹⁴	3.4	10 ⁻²	10 – 50
Acetyl cellulose	10 ¹⁴	2.0 - 4.0	-	-
Rubber	-	2.4	10 ⁻³	10 – 20
Vulcan fiber	10 ¹¹ – 10 ¹²	-	-	-
Paper	10 ¹⁴ – 10 ¹⁵	2.0 - 4.0	10 ⁻²	7 – 10
Mica	10 ¹⁴ – 10 ¹⁵	-	-	-
Glass	10 ¹⁴ – 10 ¹⁷	4 – 15	<10 ⁻⁴	100
Quartz glass	10 ¹⁶ - 10 ¹⁷	-	<10 ⁻⁵	100 – 300
Porcelain, ceramic	10 ¹² – 10 ¹³	5.6 - 6.5	<10 ⁻³	10 – 20
Marble	10 ¹⁰ – 10 ¹³	5.0 - 6.0	-	10 – 20
Pure transformer oil	10 ¹⁶	2.2	<10 ⁻⁴	20 – 35
Purified oil	5.10 ¹²	2.4	<10 ⁻⁴	20 - 30
Silicon oil	(80°C) 10 ⁻¹²	_	_	15 _ 25
	10 10	-	-	10 10
	10	4.0	-	12 - 18
Capacitor oil	10 °	3.2 - 5.2	<10 ⁻⁴	14 – 20
Askarel	(80 ⁰ C)			
Pure ethylic alcohol	10 ⁶	60	-	-
Distilled water	10 ⁶	81	-	-
Air	10 ¹³	1. 00059	<10 ⁻⁵	3.2

Δ

4.6.2. Mechanic properties

Mechanic properties must be known because the majority of dielectrics are also used as mechanical support. During the use, dielectrics are simultaneously submitted to the electrical, thermal and mechanical stresses. Because the most of dielectrics posed modest/ poor mechanical properties, in practice are used combined materials such: foils of synthetic resins, laminates based on mica with paper or fiber glass support, etc.

The most interesting mechanical properties of electroinsulating solid materials are: tensile strength, bending strength, strength under shocks, abrasion proof, strength under split (for stratified materials), hardness and elasticity (for elastomers), endurance proof, etc.

The average values of some mechanical characteristics of electroinsulating materials/ dielectrics are listed in Table 4.14.
Materials in Electrical Engineering

Electro- insulating materials	Tensile strength [daN/cm ²]	Elongation at break [%]	Modulus of elasticity [10 ⁵ daN/cm ^{2]}	Compressive strength [daN/cm ²]	Bending strength [daN/cm ²]	Brinell hardness [daN/cm ²]
Pressed phenol resin with wood flour filler	460 – 670	0.45 – 0.8	0.7 – 1.05	1800 – 2500	650 – 850	32 – 40
ldem, with textile filler	300 - 560	0.7	0.63 – 0.99	1400 – 2200	630 – 900	_
Idem, with mineral filler	280 – 560	-	0.7 – 1.2	1000 – 1800	-	30 – 45
Laminated paper	500 - 900	0.7	0.28 – 2.11	1400 – 2800	900 – 1400	42
Laminated textiles	550 - 850	0.7	0.25 – 1.05	2100 – 3100	900 – 2100	30 – 45
Laminated glass cloth and phenol resin	1400 – 3300	0.7	0.7 – 1.76	2900 – 3300	1400 – 1900	35 – 45
Laminated asbestos cloth and phenolic resin	500 – 850	0.7	0.25 – 1.05	1300 – 3000	700 – 2400	30 – 45
Acetyl- cellulose	210 – 490	-	0.07 – 0.24	300 – 2100	300 – 700	Ι
Acetobutyrat -cellulose	100 – 470	_	_	500 – 1500	800 – 1100	_
Vulcan fiber	380 - 850		_	1400 - 2200	800 – 1500	8 – 15
Poly- ethylene	90 – 105	50 - 500	_	_	120	20 – 30
Polystyrene	350 - 630	2 – 5		800 - 1000	600 – 1300	20 - 30
Polyvinyl chloride (PVC)	70 – 630	2 – 500	_	800	1100	15 – 25

	Table 4.14. Mechanical	properties	of electroinsulating	materials.
--	------------------------	------------	----------------------	------------

The quality of coating electroinsulating materials essentially depends on the viscosity of lacquers, compounds and glue.

4.6.3. Chemical and Physical Properties

A lot of physical and chemical properties enter in property matrix of electroinsulating materials.

Mass density d_m is the weight per unit volume of a material at 20°C and is expressed in kg/m³, with relation:

$$d_m = \frac{m}{V},\tag{4.133}$$

where m represents the mass for a material sample with volume V.

4. Dielectrics

Mass density of some organic solid dielectrics is listed in Table 4.14. Generally, dielectrics, having density of $1000 \div 2500 \text{ kg/m}^3$, are not heavy materials.

Porosity *p* of a material refers to the pore volume (V_p) reported to the total volume (V_t), and the relationship for this parameter is:

$$p = V_p / V_t \cdot 100. \tag{4.134}$$

Porosity can reach at 50% for very porous materials as cellulose. Materials with an open porosity can be used as dielectrics only impregnated, in order to avoid filling the pores with water, air or other materials, which can reduce the dielectric properties.

Hygroscopicity represents the property of a material to absorb water from the environment, conventionally defined by relation:

$$H_{\%} = (G - G_0) / G_0 \cdot 100, \qquad (4.135)$$

where G_0 represents the mass for dry sample and G is the mass of the same sample after water absorption in certain conditions.

Hygroscopicity depends on the material porosity. Porous materials possess a great hygroscopicity (paper, wood, porcelain, etc.). That is why these materials are used only after impregnation with insulating lacquers or compounds, in order to protect them against water penetration.

Permeability at water vapors is connected with the diffusion coefficient *D* of water vapor into the material, defined by relation:

$$m_{H_2O} = D \cdot \frac{S(p_1 - p_2)}{d} \cdot t$$
, (4.136)

where m_{H_eO} is the vapors water quantity which diffuse through a thin layer of material, *S* is the sample surface with thickness *d*, and p_1 , p_2 are pressure of water vapor and material sample. Diffusion coefficient of some of materials is listened in Table 4.15. The higher values correspond to the materials with greater permeability.

Dielectric	Water absorption after 24 h [%]	Diffusion coefficient <i>D</i> [10 ⁻⁸ cm/cm ² ⋅h⋅torr)	Mass density <i>d_m</i> [kg/m³]
Phenol resin	0.1 – 0.4	4.8	1200 – 1300
Idem, with wood filler	0.4 – 1.0	_	1100 – 1200
Idem, with mineral filler	0.2 – 0.3	—	1500 – 2200
Laminates with paper, cotton and phenol resin	0.3 – 9.0	_	1300 – 1400
Natural vulcanized rubber (vulcanite)	-	6.5 - 8.0	930 – 1400
Chloroprene rubber	0.006	_	1640

Table 4.15. Physical properties of some dielectrics.

		<u>Z</u>	
Polyethylene	0.01	0.1 – 0.2	920 – 960
Polystyrene	0.01 – 0.05	2.7 – 3.5	1050
Polyvinyl chloride (PVC)	0.01 – 1.0	0.5 – 1.1	1380
Epoxy resin	0.1 – 0.4	1.0 – 1.1	1200 – 1400
Polyamide resin	0.4 – 2.0	11.2	1200 – 1400
Cellulose acetate	2.0 - 6.0	114 – 160	1330
Vulcan fiber	18.0 – 70.0	Ι	1100 – 1450

Materials in Electrical Engineering

Compatibility of dielectrics consists on the possibility of assembling together different structural and functional materials without affecting their physical, chemical, electrical and mechanical properties.

The compatibility is necessary because during application, the dielectric is in contact with other different materials, such as: conductors, insulators, semiconductors, magnetic materials, etc.

Resistance of dielectrics at chemical corrosion characterizes the capacity of dielectric to resists to the action of chemical agents, such as: water, oxygen, acids, bases, solvents, etc. Water can produce the hydrolysis of macromolecular dielectrics, modifying their molecular mass, and releasing micro-molecular compounds.

Oxidative degradation causes on organic materials used as dielectrics, chain scission and/ or crosslinking, forming hydroxyl, carbonyl, acid groups and unstable peroxide radicals, initiating further degradation and significant breakdown of materials.

It is necessary to known the stability of dielectrics at chemical corrosion and oxidation, in order to better choose the domain of applicability of dielectrics.

The acidity of dielectric represents the variation of pH-value and determines especially the chemical stability of insulating oils and resins. The acidity is expressed as **acidity index**, defined as mg of KOH used to neutralize the free organic acids from 1 g of material.

Acidity is correlated with the compatibility of dielectrics and their ageing degree.

Solubility of a dielectric material in solvents is an important parameter for obtaining oil, lacquer or glue insulators.

The solubility depends on chemical characteristics of material and increases with temperature and decreases with molecular mass, polymerization degree (for polymers), etc. Solubility can be appreciated upon the concentration of saturated solution of material dissolved in the solvent. For solid dielectrics, solubility depends on the quantity of dielectric from solution in surface unit and time unit.

1.6.4. Thermal properties

Thermal conductivity is the principal property that determines the dissipation of local heating, produced in the electrical equipments.

Heat evacuation is realized by processes of conduction, radiation and convection, depending on thermal properties of dielectrics, such as: specific heat, thermal conductivity, melting point, etc.

Specific heat *c* characterizes the capacity of heat absorption of material, and can be defined with the relation:

$$Q = mc\Delta \Theta$$
,

where Q is the quantity of heat, measured in J (Joules), absorbed by a material with mass *m*, which is submitted of a difference of temperature $\Delta \theta$. Unit of measurement for **specific heat** *c* results from relation (4.137): J/(Kg·K).

This parameter depends on the material type and temperature. Specific heats of some dielectrics are presented in Table 4.16.

Hydrogen, water and insulating oil have high specific heat and can be used both as cooling fluids or heat accumulators.

Thermal conductivity λ characterizes the capacity of transferring the heat through thermal conduction, and can be defined by relation:

$$\frac{\Delta Q}{\Delta S} = -\lambda \cdot \frac{\Delta T}{\Delta x}, \qquad (4.138)$$

where $\Delta Q / \Delta S$ is the heat flux, in J/m², which is transmitted through a sample with thickness of Δx , submitted to o temperature difference of ΔT . Unit of measurement for **thermal conductivity** λ results from relation (4.138): J/(m·K).

A parameter which globally characterizes the thermal inertia of material is **thermal diffusivity**, defined by relation:

$$a = \frac{\lambda}{c \cdot d_m}, \qquad (4.139)$$

where d_m is the mass density of material, c is specific heat, and λ is thermal conductivity. These parameters depend on material type, temperature and moisture.

Thermal conductivity of some dielectrics is presented in Table 4.16. Better thermal conductivity has crystalline materials, comparing with amorphous materials (for example, crystalline and amorphous quartz). Hydrogen, with thermal conductivity of 0.18 W/(m-K), is utilized as cooler in high frequency equipments.

Thermal conductivity of dielectrics can be improved by using adequate fillers (for plastics it is used an inorganic crystalline filler, as quartz powder).

Coefficient of heat transmission α characterizes the change of heat by convection, between the solids and fluids, and is defined by relation:

$$\Delta Q / \Delta t = \alpha S \Delta \theta, \qquad (4.140)$$

where $\Delta Q / \Delta t$ represents the quantity of heat transferred in unit of time by convection, *S* is the surface area of the solid body in contact with the cooling fluid and $\Delta \theta$ is the temperature difference between the solid body and the moving fluid. Unit of measurement for **coefficient of heat transmission** α results from relation (4.140): W/(m^{2,o}C).

(4.137)

The coefficients of heat transmission depend on physical properties of solid body and cooling fluid, on the speed flow, kind of flow, state of surface of solid body and temperature.

Coefficient of thermal radiation e_r represents the capacity of heat transmission through radiation (at temperatures above 200° C). It is defined in correlation with the capacity of radiation of the black body in vacuum, at a certain temperature.

Coefficient of linear expansion α_I characterizes the thermal dilatation of materials, being defined by relation:

$$I(T) = I(T_0) \cdot [1 + \alpha_1 (T - T_0)], \qquad (4.141)$$

where I(T) și $I(T_0)$ are the length of a material sample at temperature *T*, respectively *T*₀.

For some of dielectrics, for example insulating oil, it is important **the coefficient** of volume dilatation α_V , which represents the variation of body volume unit for increasing temperature with 1°C, conforming to relation:

$$\alpha_{V} \cong 3\alpha_{I} \,. \tag{4.142}$$

The coefficients of dilatation of some of dielectrics are listed in Table 4.16. For better insulating is necessary that the values of the coefficient of linear expansion, both for dielectrics and metallic support to be as closed as possible.

Table 4.16.	Thermal	properties of	of some	electroinsulating	materials.
				J	

Electroinsulating material	Specific heat <i>c</i> [J/(kg K)]	Thermal conductivity λ [W/m K]	Coefficient of linear expansion α _I [10 ⁻⁶ 1/ºC]
Air at room temperature	1.009	0.025	-
Nitrogen at room temperature	-	0.019	_
Hydrogen	14.350	0.18	-
Water at 20 °C	4.180	0.595	69
Insulating oil	1.670	0.13 – 0.16	750 (of volume)
Insulating oil with intense circulation	-	0.32 - 0.4	_
Cellulose	1.540	0.23	-
Paper	_	0.05 – 0.16	-
Impregnated paper	1.250 – 2.500	0.15 – 0.20	—
Laminates based on paper	1.260 – 1.680	0.21 – 0.30	15 – 60
Cotton	1.600 – 1.680	0.063 0.07	-
Cotton impregnated	1.250 – 2.500	0.128 – 0.138	
Laminates based on tissues	1.260-1.680	0.34	30 – 50
Міса	860	0.36	_
Vulcanite	2.140	1.13 – 0.23	_
Ebonite	1.430	0.16 – 0.22	50 – 90
Silicone rubber	_	0.30	-
Plastics (PVC, etc.)	1.350 – 2.150	0.15 – 0.29	_

	D ·		
1	1 1 0	Inotr	00
4	тле	есн	

Phenolic plastics pressed	1.320 - 1.450	0.23	_
Idem, with sawdust filler	-	0.35	10 – 30
Idem, with inorganic filler	-	0.45 - 0.70	15 – 30
Asbestos fibber	840	0.15	-
Glass (Jena)	700 – 850	0.8 – 1.05	3
Quartz	760	6 – 12	8 – 14
Fiber glass	—	0.58 – 1.2	_
Porcelain	920	0.80 - 1.85	4.5

4.6.5. Influence of the Frequency on Dielectric Properties

The parameter which characterizes the total losses in a dielectric is the imaginary component of the complex permittivity $\underline{\varepsilon}_{r=\varepsilon'_{r}} - j \varepsilon''_{r}$. Under operation in sinusoidal regime, the report between the complex permittivity components defines the power loss in dielectrics.

For a dielectric which presents losses through polarization and losses through conduction, the general form of the curve $tg\delta = f(\omega)$ is presented in Figure 4.42.



Fig. 4.42. Dependence of $tg\delta$ on: a) frequency: b) temperature and frequency.

Notes:

- At high frequencies (Fig. 4.42a) the conductive component $tg\delta_{\sigma}$ has low values (under 10⁻⁴). At low frequencies this parameter becomes significant: for the pulsation ω =0 the conduction losses corresponding to the static regime.
- The component $tg\delta_h$ presents a maximal value (Fig. 4.42a) for approaching the resonance pulsation ω_o .
- The temperature changes the curve shape $tg\delta = f(\omega)$, moving the maximum of the curve towards the domain of higher temperatures (Fig. 4.42b). This phenomenon is mainly determined by the increasing of the dielectric conductivity when the temperature is increasing.

For polar dielectrics, the dependence of permittivity components on frequency and temperature is significant. For example, at polytrifluorochlorethylene polymer, which is a polar dielectric, the variation of the real component of permittivity is not high, but tg δ has the maximum which is moving towards higher frequencies when temperature increases (Fig. 4.43).



Fig. 4.43. Dependence on frequency and temperature of ε'_r and $tg\delta$ quantities for polytrifluorochlorethylene.

For a dielectric which presents several polarization types (electronic, ionic, orientation, non-homogeneity polarization), the general form of the curves imaginary and real components of permittivity is presented in Figure 4.44.



Fig. 4. 44. Variation spectrum for imaginary and real components of permittivity in a dielectric with states of electronic, ionic, orientation and non-homogeneity polarization.

Notes:

- In the domain of X ray (over 10¹⁷ Hz) where the wavelength is comparable to atom dimension, the polarization phenomenon does not take place. The dielectric susceptivity is zero; the permittivity is 1. No dielectric losses are produced.
- In the domain of frequencies of the visible and ultraviolet spectrum, it is specific the contribution of the electronic polarization. In the domain of electronic dispersion $(10^{14} \div 10^{16})$ Hz, where the field frequency coincides with the frequency corresponding to the resonance pulsation ω_{0e} , a narrow maximum is obtained for the imaginary component of permittivity. The susceptivity practically remains at the value zero; its permittivity ε'_r has the value one.
- In the domain of infrared spectrum (10¹²÷10¹⁴) Hz, at the producing of the polarization state, the ionic polarization contributes. In the domain of ionic dispersion, when the wavelength coincides with the frequency corresponding to the resonance pulse ω_{0i}, a maximum more pronounced for the imaginary component of permittivity is obtained. Susceptivity, respectively, the permittivity ε'_r are increasing. Losses of ionic polarization will appear.
- In the domain of radio frequencies (10⁸÷10¹¹) Hz, to the producing of the polarization state contributes the orientation polarization. In the domain of dipolar dispersion, where the wavelength coincides with the frequency corresponding to the resonance pulsation ω₀, it can be obtained a maximum. The susceptivity values, respectively, the permittivity values ε'_r are increasing. The value of the losses increases with 3 until 6 size orders.

Dielectrics with non-homogenous structures present a polarization of non-homogeneity in the domain of industrial frequencies $(10^0 \div 10^6)$ Hz, corresponding to the resonance pulsation for the polarization of non-homogeneity.

W 4.6.6. Thermal Stability of Dielectrics

Thermal stability represents the material ability to operate at a certain temperature, without decreasing the electrical and mechanical characteristics under a limit, which can determine the loss of material functionality.

Temperature is a factor that can seriously affects the physical and chemical properties of dielectrics. The action of the heat upon dielectrics can modified the electrical conductivity, the permittivity, the tangent loss and the dielectric strength.

The heat acts upon materials by oxidation, which is the principal degrading reaction that limits the useful life of dielectrics. This process is often initiated by the presence of impurities with exposure to oxygen or other oxidizing agents. Oxidation is accelerated by heat, light, humidity and radiation.

The influence of temperature on the physical properties is defined by:

$$\alpha_{xT} = \frac{1}{x_0} \cdot \frac{\Delta x}{\Delta T}, \qquad (4.129)$$

where *x*, can be electric conductivity σ , dielectric permittivity ϵ , thermal conductivity λ , etc., at temperature *T*, and *x*₀ corresponds to the same quantity at temperature *T*₀.

Temperature represents together with electrical, mechanical and chemical agents, one of the main factor that determines the ageing of dielectrics. Thermal stability determines the durability and reliability of electrical insulation. Depending on their thermal stability, dielectrics have been classified in insulation classes (Table 4.17).

Insulation Class	Relative thermal endurance index [ºC]	Electroinsulating materials
Y (90ºC)	>90-105	Un-impregnated paper, Textile materials based on un-impregnated: cellulose, polyamides fibber, cellulose paper, cardboard; Thermoplastics, Polyethylene, polystyrene, natural rubber (vulcanite).
A (105ºC)	>105-120	Textile materials based on: cellulose, polyamide, cellulose paper, cardboard - impregnated with oleaginous-, oleo-resinous-, oleo- bituminous lacquers; Insulating oils; Foils of: polyamide, cellulose triacetate, composites; Butadiene – acrylonitrile rubber, chloroprene rubber, etc.
E (120ºC)	>120-130	Enameled conductors insulating varnish based on: polyvinylacetate, polyurethane, epoxy resins; Phenol plastics with organic filler, paper and tissues based laminates; Polyethylene terephthalate and other materials that have shown usable lifetime at this temperature
В (130ºС)	>130-155	Inorganic materials based on mica or mica paper without support or with fiber glass and asbestos support - impregnated with oleo-bituminous or natural resin,s lacquers, bakelite, epoxy, polyurethane, glyptic lacquers; Plastics with inorganic filler; fiber glass and asbestos based laminates; Enameled conductors; terephthallic lacquers based insulating varnish
F (155ºC)	>155-180	Materials based on mica or mica paper without support or with inorganic support; Materials based on fiber glass and asbestos impregnated with alkyds, epoxy, polyesters and modified silicone resins with high thermal stability
H (180ºC)	>180-200	Materials based on mica or mica paper without support or with inorganic support; Materials based on fiber glass and asbestos impregnated with silicone lacquers; Plastics with inorganic filler; Silicone rubber.
N (200ºC)	200-220	Materials based on mica or mica paper without support or with fiber glass and asbestos support - impregnated with inorganic compounds or with silicone resins with thermal stability over 220°C; Polytetrafluorethylene (Teflon), etc.

Standards on thermal ageing and stability of electroinsulating materials have introduced new characterization criterion, such as **thermal index** IT, respectively **thermal endurance profile** PET. These criterions define the maximum temperatures to which materials do not lose the technical properties during 20000 hours, respectively 5000 hours of a continuous operation. The International Electrotechnical Commission Standard 60085 "Electrical Insulation- Thermal Evaluation and Designation", 3rd edition, 2004 indicates the relative thermal endurance index [^oC] for system of insulation (see Table 4.17).



Chapter 5

MAGNETIC MATERIALS

Contents

Magnetic materials have multiple applications in electrical engineering, such as: cores for electric transformers, cores for coils, stators and rotors for electrical machines and generators, permanent magnets for microphones and telephone receivers stators and rotors for synchronous electrical machines, and for electrical machines without brushes, auto starters etc.

This chapter describes magnetization states for bodies, by briefly examining the behaviour of the materials in a magnetic field. It also presents the characteristics of the magnetic materials as well as the influence of temperature and of the magnetic field frequency on the magnetic materials. For the main domains of use of magnetic materials their properties and performances are presented.

Course Objectives

- •To describe the magnetization state, the characteristic parameters and to classify the magnetic materials by various criteria and to explain the difference between polar and non-polar magnetic materials and the behaviour of the materials in external magnetic field.
- •To show the principle of the Epstein frame method for the experimental determination of the magnetic characteristics of the Fe-Si sheets.
- •To justify the ferromagnetic state using the theory of the magnetic domains and to explain the origin of the magnetic losses and the diminution methods.
- •To present the evolution of the performances of the soft magnetic materials.
- •To describe the properties and the performances of the soft and hard magnetic materials.

5.1. MAGNETIZATION STATES

5.1.1. Characteristic Quantities

When a magnetic material is introduced in a magnetic field, the material is magnetized (it attracts the iron filings), i.e. it produces itself a magnetic field in its interior and exterior.

This state, called **magnetization state**, can be **temporary**, if it is maintained just as long as the body is introduced in the external magnetic field, or **permanent**, if it does not depend on the existence of the external magnetic field.

The microscopic theory of magnetism justifies the magnetization state of bodies by the existence in the interior of the material of some microscopic currents, called **amperean (molecular) currents** that generate an internal magnetic field.

The macroscopic theory of magnetization states that the magnetization state of bodies can be characterized by the **amperean magnetic moment** \overline{m} and by their volume density, called **magnetization** \overline{M} .

In figure 5.1, the definition manner for the magnetic moment is shown: an electron is moving on a closed trajectory, a microscopic current of intensity *i* determines a magnetic field, characterized by the amperean magnetic moment \overline{m} . Its direction is considered taking into account the direction of the orientated area using right-hand rule with respect to the current direction.



Fig. 5.1. Illustration of the amperean magnetic moment.

The amperean magnetic moment is defined by:

$$\overline{m} = i \cdot \overline{S} . \tag{5.1}$$

where \vec{S} is oriented area of the electron orbit.

The magnetization \overline{M} is defined by the relation:

$$\overline{M} = \frac{\Delta \overline{m}}{\Delta V} \,. \tag{5.2}$$

where ΔV is the element of volume of material, and $\Delta \vec{m}$ is the corresponding magnetic moments in ΔV volume.

The temporary magnetization state is macroscopically described by the temporary magnetization law (see §1.2.4). Globally, the magnetization state of a material can be also described by the law relating to \overline{B} , \overline{H} and \overline{M} , which, for homogeneous, isotropic and linear material has the expression given by relation (1.19).

Material parameters which characterize the magnetization state are: the magnetic susceptivity and the magnetic permeability, related by:

$$\mu = \mu_0 \mu_r = \mu_0 (1 + \chi_m) \tag{5.3}$$

where:

 $\boldsymbol{\mu}$ is the absolute magnetic permeability of the material, measured in H/m,

 $\mu_0=4\pi\cdot 10^{-7}$ H/m is the absolute magnetic permeability of vacuum,

 $\mu_r = 1 + \chi_m$ is the relative magnetic permeability,

 χ_m is the magnetic susceptivity.

Notes:

- > The magnetic field intensity \overline{H} and the magnetization \overline{M} have the same unit of measure, that is A/m;
- > According to relation (5.1), the amperean magnetic moment is measured in $A \cdot m^2$;
- > Both the magnetic susceptivity χ_m and the relative permeability μ_r are nondimensional material parameters;
- > The absolute permeability of the material μ has the same unit of measure as the absolute permeability of vacuum μ_0 , that is H/m (Henry / meter).



5.1.2. Classifications

The classification of the magnetic materials (or, more exactly, of different forms of magnetism states) can be made in several manners.

- The purely phenomenological classification uses as criterion the value of the magnetic susceptivity and its dependence on various physical factors (temperature, external field). According to this criterion the magnetic material are:
 - Diamagnetic, for which the magnetic susceptivity takes small negative values (χ_m < 0);
 - Paramagnetic, for which the magnetic susceptivity takes relative low positive values (χ_m > 0);
 - **Ferromagnetic**, for which the magnetic susceptivity takes large positive values, that depend on the value of applied field and temperature ($\chi_m >> 0$).
- **Technical classification** of materials with respect to the magnetic properties uses as a criterion the value of the relative magnetic permeability. Thus, for:
 - **Diamagnetic** materials, with $\mu_r < 1$,
 - **Paramagnetic** materials, with $\mu_r > 1$,
 - **Ferromagnetic** materials, with $\mu_r >> 1$.

Some examples are given in §1.2.4, §1.3.3, and Fig. 1.3. According to these classes, materials can be rejected (diamagnetic ones) or attracted (paramagnetic ones) by a magnetic field, or they can strengthen the external magnetic field (ferromagnetic ones).

• **Physical classification** takes into account the physical nature of the atomic magnetism carriers and the interaction between them.

This classification is directly related to the existence of the total atomic magnetic moment \overline{m}_{atom} , which averaged macroscopically, gives the value of the spontaneous or permanent magnetic moment \overline{m}_{p} of each structural unit of the considered material. According to the value of the moment \overline{m}_{atom} , the magnetic materials can be classified into:

- Non polar magnetic materials, that have atoms with zero magnetic moment (m_{atom}=0);
- Polar magnetic materials, that have atoms with magnetic moment different from zero (m
 _{atom} ≠0).

A part of the polar magnetic materials can have **parallel** or **anti-parallel arrangement states** of the atomic magnetic moments, states that are characteristic to ferromagnetic, and ferrimagnetic materials, respectively.

Notes:

- The technical classification is useful in engineering and designing, in the adequate choice of the materials with different magnetic properties. But this classification does not take into account the structure and the particularities of different classes of materials, when they are introduced in a magnetic field.
- In the traditional (technical) classification, not all the magnetization states are included, such as the ferrimagnetic materials, which with the ferromagnetic materials are included in the category of materials with magnetic ordering.
- Only with the physical theory of magnetism, which is based on the atom-molecular theory, the magnetization states, the behavior of the materials in external magnetic field and various properties characteristic to the magnetic ordering state can be justified.

5.1.3. Uni-Electronic Atom Magnetism

The physical theory of magnetism considers that the magnetic properties of materials are obtained by the spatial-temporal mediating of the magnetic properties of constituent atoms and molecules.

The magnetism of the atoms is due to the movement of the electrically charged subatomic particles, which, when moving on their closed trajectories determine the apparition of amperean currents, that generate the magnetic field.

In the atom there can be:

- > orbital magnetic moments \overline{m}_{orb} , determined by the orbital movement of the electrons;
- > spin magnetic moments \overline{m}_{soin} , determined by the spin movements of electrons,
- > nuclear magnetic moments \overline{m}_{nucleu} , determined by the movement on closed trajectories of electrically charged particles from the nucleus.

The model of the one-electronic atom considers the case of atoms of H, He⁺, Li⁺⁺ etc., when the orbital movement of the electron around its nucleus determines an amperean electric current of intensity *i* (Fig. 5.2).





Due to the negative charge of the electron, it can notice that the direction of the amperean current is inversely with respect to the movement direction of the electron. This is because the electric current is defined as a flux of positive particles that displace on a closed trajectory.

Orbital magnetic moment, determined by the movement of the electron on the orbit, has the expression:

$$\overline{m}_{orb} = i \cdot \overline{S}, \qquad (5.4)$$

where \overline{S} represents the vector of the oriented area of the electron orbit.

For the particular case of the circular orbit of radius *r*, the area of the orbit is $S = \pi r^2$, and the expression of the amperean current intensity *i* is:

 $i = \frac{q_0}{T} = q_0 \cdot f , \qquad (5.5)$

where:

 q_0 is the electric charge of the electron,

T is the rotation period,

f is the rotation frequency of the electron.

There results:

Materials in Electrical Engineering

$$m_{orb} = q_0 f \pi r^2 = \frac{q_0 v r}{2}, \qquad (5.6)$$

relation in which $v = f \cdot 2\pi r = \omega \cdot r$ represents the linear velocity, and ω is the angular velocity of the electron on its orbit.

The sense of the orbital magnetic moment is given by the sense of the oriented surface vector \overline{S} , associated with right-drill rule with the sense of amperean current (Fig. 5.2).

There is a close dependence between the orbital magnetic moment and the kinetic magnetic moment. The expression of the **orbital kinetic moment** is:

$$\overline{K}_{orb} = \overline{r} \times m_0 \overline{v} , \qquad (5.7)$$

that, in the case of a circular orbit, when the quantities \overline{r} and \overline{v} are perpendicular, has modulus:

$$K_{orb} = r m_0 v , \qquad (5.8)$$

being oriented perpendicular on the orbit plane (Fig. 5.2). In these relations m_0 represents the stationary mass of the electron (at rest).

From relations (5.6) and (5.8) it results the relation between orbital magnetic moment and the kinetic orbital moment:

$$m_{orb} = \frac{q_0}{2m_0} K_{orb},$$
 (5.9)

relation that can be written in vectorial form:

$$\overline{m}_{orb} = -\frac{q_0}{2m_0}\overline{K}_{orb}.$$
(5.10)

In relation (5.10), the minus sign of the electron charge was taken into account, fact that shows that **the orbital magnetic moment always apposes to the orbital kinetic moment of the electron**.

If we take into account that the orbital kinetic moment is quantified by the secondary quantum number l = 0, 1, ..., (n - 1), as:

$$K_{orb} = \sqrt{I(I+1)} \hbar, \qquad (5.11)$$

where $\hbar = h/2\pi$, and *h* is Plank constant, it results that the orbital magnetic moment is quantified by the same quantum number:

$$m_{orb} = \sqrt{I(I+1)} \cdot \frac{q_0 \hbar}{2m_0}$$
(5.12)

The relation corresponding to the minimum value of the orbital magnetic moment is called **Bohr-Procopiu magneton**:

$$m_{B-P} = \frac{q_0 \hbar}{2m_0} = 0.9273 \cdot 10^{-23} \text{ A} \cdot \text{m}^2$$
 (5.13)

and represents the magnetic moment natural unity.

The ratio between the orbital magnetic moment and the kinetic orbital moment is called **orbital giro-magnetic ratio**, given by:

$$g_{orb} = \frac{m_{orb}}{\kappa_{orb}} = \frac{1}{2} \cdot \frac{q_0}{m_0}.$$
(5.14)

Note:

Regarding on the shape of the orbit of electron in the atom, the orbital movement of the electron generates a magnetic field, characterized by the orbital magnetic moment having an expression given by (5.4).

The movement of the electron around its axis determines **spin magnetic moment**. The electron **spin kinetic moment** K_{spin} is quantified by the spin quantum number *s*:

$$K_{spin} = \sqrt{s(s+1)}\hbar, \qquad (5.15)$$

where $s = \pm 1/2$.

Related to this movement, the spin magnetic moment is defined, according to relation:

$$\overline{m}_{spin} = -\frac{q_0}{m_0} \cdot \overline{K}_{spin} \,. \tag{5.16}$$

Relations (5.15) and (5.16) underline that the spin magnetic moment is also quantified by the spin quantum number:

$$m_{spin} = \sqrt{s(s+1)} \cdot \frac{q_0 \hbar}{m_0} \,. \tag{5.17}$$

The **spin giro-magnetic ratio** is similarly defined to relation (5.14):

$$g_{spin} = \frac{m_{spin}}{K_{spin}} = \frac{q_0}{m_0}.$$
(5.18)

Notes:

- Spin giro-magnetic ratio is the double of the orbital giro-magnetic ratio, phenomena known as giro-magnetic anomaly.
- Spin magnetic moment takes double values that the quantifiable values of the orbital magnetic moment.

The movement of the protons on closed orbits determines the **nuclear magnetic moment**. For the one-electronic atom, the nucleus is formed by a proton of **kinetic nuclear moment** \overline{K}_{nucleu} , quantified according to:

$$K_{\text{nucleu}} = \sqrt{i(i+1)}\hbar, i=0,1,2,\dots$$
 (5.19)

By following the same reasoning, the elementary nuclear magnetic moment is defined, according to relation:

$$m_{nucleu} = \frac{q_0 \hbar}{2M_p}, \qquad (5.20)$$

where M_p is the proton mass.

From relations (5.13) and (5.20), it results that the value of the nuclear magneton is much smaller than the value of the Bohr-Procopiu magneton, because the mass of the proton is much greater than the mass of the electron ($M_p >> m_0$).

Thus, the contribution of the nuclear magnetic moment for the atom magnetism can be neglected for a first approximation.

The **total magnetic moment of the one-electronic atom**, if it is neglected the nuclear magnetic moment, is determined by the sum between the orbital magnetic moment and the spin magnetic moment of the electron:

$$\overline{m}_{atom} = \overline{m}_{orb} + \overline{m}_{spin} \,. \tag{5.21}$$

Taking into account the orbital kinetic moment and spin kinetic moment, it results:

$$\overline{m}_{atom} = -\frac{m_{B-P}}{\hbar} \left(\overline{K}_{orb} + 2\overline{K}_{spin} \right).$$
(5.22)

Notes:

- The magnetism of the one-electronic atom is determined by the orbital and by the spin electron movement;
- > The total magnetic moment of the one-electronic atom \overline{m}_{atom} is determined by the vectorial sum between the orbital kinetic moment and the double of the spin kinetic moment, and by the value of the Bohr-Procopiu magneton;
- Due to the giro-magnetic anomaly, the direction of the magnetic moment vector in the one-electronic atom cannot coincide with the direction of the resulting kinetic moment;
- > For the calculus of the atomic magnetic moment, the physical theory utilizes the **vectorial model** of the one-electronic atom, with various manners of composing of vectors \overline{K}_{orb} and \overline{K}_{soin} .

M 5.1.4. Multi-Electronic Atom Magnetism

In the case of the multi-electronic atom, the magnetism is created by the orbital and spin movements of all constituent electrons.

Atomic magnetic moment is determined by the sum of orbital magnetic moments and spin magnetic moments of all constituent electrons.

$$\overline{m}_{atom} = \sum_{i,k} \left[\overline{m}_{orb} + \overline{m}_{spin} \right], \tag{5.23}$$

where:

i is orbit order number, *k* is electron order number.

The vectorial model of the multi-electronic atom introduces, beside the four quantum numbers *n*, *l*, *m*_{*l*}, *s*, an internal quantum number J = 1 + S, that determines the total kinetic number. This model allows the calculus of the sum given by relation (5.23), taking into account the specific manners of composing the orbital kinetic and spin moments of the electrons, according to the intensity of the electrostatic and magnetic interactions.

For this case, by neglecting the nuclear magnetic moment, the total magnetic moment of atom \overline{m}_{atom} results as a sum of the total orbital magnetic moment \overline{m}_{Lorb} and the total spin magnetic moment \overline{m}_{Ssoin} :

$$\overline{m}_{atom} = \overline{m}_{Lorb} + \overline{m}_{Sspin} = -\frac{m_B}{\hbar} \left(\overline{K}_{Lorb} + 2\overline{K}_{Sspin} \right)$$
(5.24)

Due to the giro-magnetic anomaly, the resulting magnetic moment of electronic shell no longer corresponds in direction with the resulting kinetic moment. In a diagram composition with relative quantities (m_B/\hbar =1), thus $\overline{m}_{atom} = -K_{Lorb} - 2\overline{K}_{Sspin}$, it results that \overline{m}_{atom} does not correspond in direction with \overline{K}_{atom} . In figure 5.3 the composition of orbital kinetic moment and spin moment for obtaining the atomic magnetic moment is illustrated.



Fig. 5.3. The vectorial model of the multi electronic atom.

Using the vectorial model, it is sufficient to know the projection of the total magnetic moment \overline{m}_{atom} on the direction of the total kinetic moment \overline{K}_{atom} , in order to evaluate the magnetic properties of the atom.

The general expression of the atomic magnetic moment is:

$$m_{Jatom} = g_J \cdot J \cdot m_B, \tag{5.25}$$

where g_J is the Landé factor, that takes into account the composition of the vectorial quantities in relation (5.23), J is the internal quantum number and m_B is Bohr magneton.

Conclusions:

- The atomic magnetic moment for the multi-electronic atom depends on the quantum number, on the magnetic moment unity (Bohr-Procopiu magneton) and on the composition of the constituent magnetic moments.
- ➤ The total magnetic moment of the multi electronic atom depends on the distribution of the orbital and spin magnetic moments. This determines the existence of some materials in which the atoms have zero or different from zero magnetic moments $(\overline{m}_{\text{Jatom}} = 0 \text{ or } \overline{m}_{\text{Jatom}} \neq 0$, respectively).

W 5.1.5. Polar or non-polar magnetic materials

The total magnetic moment of the multi-electronic atom can be zero or different from zero, according to the distribution of the orbital and spin magnetic moments. Thus:

- Elements that have electronic sub-layers completely occupied do not have atomic magnetic moment. Indeed, in general, the contribution of the orbital magnetic moments is small, and, in this case, the spin moments of the electrons compensate themselves because there is an even number of electrons, having the spins anti parallel oriented. Examples of non-polar magnetic materials: chemical elements belonging to the 18th group of the element periodic system (Ne, Ar, Kr, etc.);
- Transitional elements (belonging to the group of iron, of the rare earths and actinides), that have inner sub-layers incompletely occupied and that have non-pair electrons, exhibit significant atomic magnetic moments. Examples of polar magnetic materials: chemical elements belonging to the group of iron: V, Cr, Fe, Co, etc.

The materials from the first category are called **non-polar magnetic materials**, and those from the second category are called **polar magnetic materials**.

In figure 5.4, the electronic structure of the elements belonging to the group of iron is presented. There can be noticed that all the elements that have the 3d sub-layer incompletely occupied with electrons have a certain number of non-pair electrons that contribute the value of the atomic magnetic moment.

	5. Magnetic Materials								235	
Electro numbe	ns Atom er	1s	2s	2р	3s	3р	3d	4s	Un-paired 3d electrons	
21	Sc	1↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	†	↑↓	1	
22	Ti	↑ ↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	↑ ↑	^↓	2	
23	v	^↓	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$		↑↓	3	
24	Cr	↑↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	$\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$	1	5	
25	Mn	↑↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow \uparrow\downarrow \uparrow\downarrow$	$\uparrow \uparrow \uparrow \uparrow \uparrow \uparrow$	↑↓	5	
26	Fe	↑↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	$\uparrow \downarrow \uparrow \uparrow \uparrow \uparrow$	↑↓	4	
27	Co	↑↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow \uparrow\downarrow \uparrow\downarrow$	$\uparrow \downarrow \uparrow \downarrow \uparrow \uparrow \uparrow \uparrow$	↑↓	3	
28	Ni	†↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	^↓	$\uparrow\downarrow\uparrow\uparrow\downarrow\uparrow\downarrow$	$\uparrow \downarrow \uparrow \downarrow \uparrow \downarrow \uparrow \downarrow \uparrow$	^↓	2	
29	Cu	1↓	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	↑↓	$\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	$\uparrow\downarrow\uparrow\downarrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow\uparrow\downarrow$	1	0	

Fig. 5.4. Arrangement of the electron spins for the elements belonging to the group of iron ($Z=21 \div 28$).

The figure 5.4 shows the 3d electron spin orientation diagrams, where the arrows show the direction of spin kinetic moment. The 3d-electrons orientate their spins in the same direction for the first 5 electrons, and in the opposite direction for the others. Thus, in the **manganese** atom, for example, the five 3d-electrons have the spins oriented in the same direction, and contributing with five Bohr-Procopiu magnetons for the atomic magnetic moment. The elements Mn, Sc, Ti, V, Cr, Fe, Co, Ni are **polar magnetic elements**.

In Table 5.1 the values of the maximum projection of the total magnetic moment for the atoms belonging to group of rare earths (lanthanides) are presented (in Bohr-Procopiu magneton units). Notice that these elements that have the 4f sub-layer incompletely occupied are **polar magnetic substances**, with the atomic moment different from zero.

Atomic Number, <i>Z</i>	Element	Exterior layer configuration	g,	$\frac{m_{Jatom}}{m_B} = g_J J$
57	La	5d ¹ 6 s ²	4/5	1,2
58	Ce	4f ¹ 5d ¹ 6s ²	4/5	3,2
59	Pr	4f ³ 6s ²	8/11	3,9
60	Nd	4f ⁴ ss ²	3/5	2,4
61	Pm	4f ⁵ 6s ²	24/35	1,72
62	Sm	4f ⁶ 6s ²	0	0
63	Eu	4f ⁷ 6s ²	2	7
64	Gd	4f ⁷ 5d ¹ 6s ²	8/3	5,35

Table 5.1. Exterior electronic layer configuration, Landé factor, and the number of magnetons for the elements belonging lanthanides group ($Z=57 \div 70$).

Atomic Number, <i>Z</i>	Element	Exterior layer configuration	g J	$\frac{m_{Jatom}}{m_B} = g_J J$
65	Tb	4f ⁸ 5d ¹ 6s ²	24/17	12
66	Dy	4f ¹⁰ 5d ¹ 6s ²	10/8	10
67	Ho	4f ¹¹ 6s ²	18/15	9
68	Er	4f ¹² 6s ²	7/6	7
69	Tm	4f ¹³ 6s ²	8/7	4
70	Yb	4f ¹⁴ 6s ²	0	0

Materials in Electrical Engineering

Among the chemical elements, **iron, cobalt, nickel** (Fe, Co, Ni), **gadolinium** (Gd) and **dysprosium** (Dy), and their alloys, exhibit, at room temperature, **ordering property of the atomic magnetic moments** for relatively large distances (μ m - mm), and form the class of **ferromagnetic materials**. Other materials, such as oxide composites, that are also polar magnetic, exhibit **anti-parallel arrangements of the atomic magnetic moments**, forming the class of **anti ferromagnetic materials**.

5.2. MATERIAL BEHAVIOUR IN EXTERNAL MAGNETIC FIELD

The external magnetic field acts upon the atomic magnetic moments, and determine the apparition of phenomena called diamagnetism and paramagnetism.

The **diamagnetism** represents the phenomenon of decreasing (weakening) the total magnetic field due to the magnetic moment supplementary induced by the external magnetic field in each electronic orbit of the constituent atoms of a material.

The **paramagnetism** represents the phenomenon of increasing (strengthening) the total magnetic moment due to the orientation of the orbital and spin magnetic moments of the polar magnetic material on the direction of the external magnetic field.

5.2.1. Material Diamagnetism

The external magnetic field acts on the electrically charged particles (free or bonded particles) moving on closed trajectories, determining the apparition of a supplementary movement and, thus, of a supplementary magnetic moment for each moving particle. As the effect opposes to the cause, the **magnetic susceptivity will take negative values**.

The diamagnetism is a universal phenomenon, found in all materials introduced in a magnetic field. As the produced effect is relatively reduced, in the polar magnetic materials the diamagnetism is covered (shielded) by the paramagnetic or ferromagnetic effects, which are much stronger. This is the reason why the diamagnetism can be evidenced in the case of **non-polar magnetic materials**, for which the constituent atoms, ions or molecules do not have permanent magnetic moment ($\overline{m}_p = 0$).

The diamagnetism is generated by the supplementary (precession) movements of the bound electrons (*Langevin diamagnetism*) and of the conduction electrons (*Landau diamagnetism*) that appear when the material is introduced in a magnetic field.

The classical theory of the **bonded electrons diamagnetism** in the atom was developed by Langevin, reason for which the bonded electrons diamagnetism is also called **Langevin diamagnetism**.

For the calculus of the magnetic susceptivity generated by the Langevin diamagnetism, the case of the hydrogen atom placed in a homogeneous magnetic field of intensity \overline{H} with the perpendicular direction on the electron orbit plane is considered (Fig. 5.5).

When a magnetic field is applied, the forces acting upon the electron will depend on the direction of the magnetic field relative to the electron orbit plane (angular velocity vector $\overline{\omega}_0$ is either parallel with \overline{H}_0 , or anti-parallel with \overline{H}_0).

It has to be mentioned that \overline{H}_0 represents the intensity of the local (effective) magnetic field that acts upon the atom, having the general expression given by relation (5.9). For gases, such as the hydrogen gas, γ coefficient has a small value, such that the intensity of the local magnetic field is approximately equal with the intensity of the external applied magnetic field ($\overline{H}_0 \cong \overline{H}$).



Fig. 5.5. The diamagnetism when applying a magnetic field on a perpendicular direction on the electron orbit plane: a) $\overline{\omega}_0$ is parallel with \overline{H}_0 ; b) $\overline{\omega}_0$ is anti parallel with \overline{H}_0 .

By examining the electron movement (Fig. 5.5), it can be noticed that in the absence of the external magnetic field, the stability of the electron is obtained when the following condition fulfilled:

$$F_e + F_{cf} = 0$$
, (5.26)

where $F_e = q_0^2/(4 \pi \epsilon_0 r^2)$ is the interaction force between the nucleus and the electron, $F_{cf} = m_0 r \omega_0^2$ is the centrifugal force, m_0 is the electron mass, r is the circular orbit radius, and ω_0 is the electron angular velocity.

Relation (5.26) can be written:

$$m_0 r \omega_0^2 = \frac{q_0^2}{4\pi\epsilon_0 r^2}.$$
 (5.27)

Due to the action of the magnetic field of intensity \overline{H}_0 , considered perpendicular on the orbit plane, a supplementary force acting on the electron appears, called **Lorentz force**, that has the expression:

$$\overline{F_{L}} = -q_{0}\overline{v} \times \mu_{0}\overline{H}_{0}, \qquad (5.28)$$

which has the modulus:

$$F_{L} = q_{0} \nu \mu_{0} H_{0} = q_{0} \omega r \mu_{0} H_{0}.$$
(5.29)

Because the electron moves on a stationary orbit (the orbit radius does not modify), in order to maintain the dynamic equilibrium, the Lorentz force will have to be compensated by the increasing (Fig 5.5a) or decreasing (Fig 5.5b) of the inertial centrifugal force, thus by the modification of the angular velocity of electron, from $\overline{\omega}_0$ to $\overline{\omega} = \overline{\omega}_0 \pm \Delta \overline{\omega}$.

Dynamic equilibrium condition, for the case from figure 5.5, will be:

$$m_0 r (\omega_0 + \Delta \omega)^2 = \frac{q_0^2}{4\pi\varepsilon_0 r^2} + q_0 r (\omega_0 + \Delta \omega) \mu_0 H$$
(5.30)

By using relation (5.27), relation (5.30) can be written as:

$$\boldsymbol{m}_{0}\boldsymbol{r} \, \boldsymbol{\varrho}\boldsymbol{\omega}_{0}\Delta\boldsymbol{\omega} + \Delta\boldsymbol{\omega}^{2} = \boldsymbol{q}_{0}\boldsymbol{r} \, \boldsymbol{\omega}_{0} + \Delta\boldsymbol{\omega} \, \boldsymbol{\mu}_{0}\boldsymbol{H} \,. \tag{5.31}$$

For a small variation of the angular velocity (magnetic fields of relatively small intensity), the following approximations are done:

- in the left side: $2\omega_0\Delta\omega \gg \Delta\omega^2$
- in the right side: $\omega_0 >> \Delta \omega$,

and thus the relation (5.31) becomes: $m_0 r \cdot 2\omega_0 \Delta \omega = q_0 r \cdot \omega_0 \cdot \mu_0 H$.

The expression of angular velocity results:

$$\Delta \omega = \frac{q_0}{2m_0} \mu_0 \mathcal{H}_0. \tag{5.32}$$

Relation (5.32) shows that when an external magnetic field is applied the angular velocity of the electron is increased (Fig. 5.5.a) or decreased (Fig. 5.5.b) according to the rotational direction of the electron relative to the direction of the applied magnetic field. In both cases, $\Delta \overline{\omega}$ has the same direction as the applied magnetic field.

Larmor frequency corresponds to the variation of the rotational frequency of the electron when the external field is applied, and has the expression:

$$\Delta f = \frac{\Delta \omega}{2\pi} = \frac{\mathbf{q}_0}{4\pi m_0} \boldsymbol{\mu}_0 \boldsymbol{H}_0 \,. \tag{5.33}$$

5. Magnetic Materials

2

Calculus of the induced magnetic moment is done having in view that the supplementary orbital movement, which is established for each electron due to a magnetic field, determines the apparition of an induced magnetic field. In the case of a circular orbit, perpendicular on the direction of vector \overline{H}_0 (Fig. 5.5), the expression of the induced magnetic moment in an atom is obtained by using relations (5.6) and (5.33):

$$\Delta m_i = q_0 \Delta f \pi r^2 = \frac{q_0^2 r^2}{4m_0} \mu_0 H_0 .$$
 (5.34)

In order to write in vectorial form, the relation (5.4) must be taken into account. Thus, it results that the induced magnetic moment is oriented in the opposite direction relative to the applied field:

$$\Delta \overline{m}_i = -\frac{q_0^2 r^2}{4m_0} \mu_0 \overline{H}_0.$$
(5.35)

Note:

The induced magnetic moment depends on the orbit radius and on the local magnetic field intensity.

In order to compute the **Langevin diamagnetism susceptivity**, the sum of all induced electronic moments is computed:

$$<\Delta \overline{m}_i > = -\frac{q_0^2 \mu_0 \overline{H}_0}{4m_0} < \sum_{i=1}^{Z} r_i^2 >,$$
 (5.36)

where signs < > mean temporal average of $\Delta \overline{m}_i$ and r_i^2 which are microscopic quantities, and the sum is computed for all r_i^2 trajectory radii of the *Z* electrons of the atom.

If all the atoms of the considered substance are identical and have the volume concentration *n*, then the expression for the magnetization is:

$$\overline{M} = n < \Delta \overline{m}_i > = -\frac{nq_0^2 \mu_0 \overline{H}_0}{4m_0} \cdot \left[< \sum_{i=1}^z r_i^2 > \right].$$
(5.37)

By comparing the temporary magnetization law expression (1.15), with relation (5.37), and considering that the applied magnetic field strength has about the same value as the local magnetic field ($\overline{H} \approx \overline{H}_0$), the expression of the magnetic susceptivity for diamagnetic materials is obtained:

$$\chi_{md} = -\frac{nq_0^2 \mu_0}{4m_0} \cdot \left[< \sum_{i=1}^{Z} r_i^2 > \right],$$
(5.38)

Another relation can be obtained considering that the electric charge distribution in atoms is isotropic and, thus, the three spatial coordinates of the electrons are equivalent, that is $\langle x_i^2 \rangle = \langle y_i^2 \rangle = \langle z_i^2 \rangle = (1/3) \langle r_i^2 \rangle$. Therefore:

$$\chi_{md} \approx -\frac{nq_0^2\mu_0}{6m_0}\sum_{i=1}^{z} < r_i^2 > = -\frac{nq_0^2\mu_0 Z}{6m_0} < r_i^2 > .$$
(5.39)

Notes:

- ▶ Diamagnetic materials susceptivity is proportional to the volume concentration *n* of the constituent atoms, to the average of the trajectory radii squares $< r^2 >$ of the electrons and to the number *Z* of electrons in the atom;
- Diamagnetic materials susceptivity does not explicitly depend on the temperature;
- The linear behavior of the material is underlined by the fact that the external magnetic field strength does not appear in the expression of the diamagnetic susceptivity: when the external magnetic field is increased, the magnetization increases proportionally, in modulus;
- > The magnetic susceptivity takes negative values, that is, the magnetization vector \overline{M} has an anti parallel orientation relative to the external magnetic field strength \overline{H} : the magnetic field is weakened inside the material;
- > The magnitude order for the magnetic susceptivity is obtained with relation (5.39). By considering $n = N_A = 6.02 \cdot 10^{25}$ atoms/kmol and $< r^2 > \approx 10^{-20}$ m² and with the known values for q_0 , m_0 and μ_0 , it results that:

$$\chi_{md} \approx -10^{-6} Z;$$
 (5.40)

- > The computations made using relation (5.39) lead to the following values for the magnetic susceptivity: $\chi_{md} = 10^{-5} \div 10^{-4}$; and for the relative magnetic permeability: $\mu_{rd} = 1 (10^{-5} \div 10^{-4})$;
- The diamagnetic susceptivity increases when the ordering number Z of chemical elements is increased.

5.2.2. Diamagnetic Materials Classes

For non-metallic substances, the diamagnetism is determined only by the bonded electrons of the constituent atoms (Langevin diamagnetism). For some substances, the values of the diamagnetic susceptivity experimentally determined at room temperature are presented in Table 5.2.

Gases, for 1 at and 20ºC	$\chi_m \cdot 10^6$	Crystalline halides	$\chi_{m} \cdot 10^{6}$	Oxides	$\chi_{m} \cdot 10^{6}$
H ₂	- 0.002	LiF	- 10.4	MnO	- 18.4
He	- 2.02	LiCl	- 24.3	CaO	- 28.3
Ne	- 6.96	NaCl	- 30.4	SrO	- 39.9
Ar	- 19.2	KCI	- 39.0	BaO	- 57.0
Kr	- 29.0	RbCl	- 51.0	ZnO	- 32.7
Xe	- 45.5	CaCl	- 65.0	CdO	- 46.2

Table 5.2. Magnetic suscer	ptivity for gases,	crystalline halides	and oxides.
J 1		3	

A great number of metals have diamagnetic behavior. The dependence between the magnetic susceptivity for some chemical elements and the atomic number Z is shown in figure 5.6.



Fig. 5.6. Magnetic susceptivity for some chemical elements relative to the atomic number *Z*.

It can be noticed that high conductive materials (Ag, Cu, Au) have a diamagnetic behavior, and their magnetic susceptivity is negative, of around -10^{-4} . Values of the magnetic susceptivity for diamagnetic metals and for the corresponding ions are shown in Table 5.3.

Metal	$\chi_m \cdot 10^6$	Corresponding ion	$\chi_m \cdot 10^6$
Cu	- 5.5	Cu⁺	- 18
Ag	- 21.6	Ag ⁺	- 31
Au	- 29.6	Au ⁺	- 44.8

Table 5.3. Magnetic susceptivities for some diamagnetic metals and for the corresponding ions.

Values of the magnetic susceptivity at 20°C temperature for some conductive and semiconductive crystals that exhibit diamagnetic behavior are shown in Table 5.4.

Table 5.4. Magnetic susceptivities for some diamagnetic conductive crystals and semiconductive crystals.

Crystal	χ _m [10 ⁻⁶]	Crystal	χ _m [10 ⁻⁶]	Crystal	χ _m ·[10 ⁻⁶]
Cu	- 5.4	Hg	- 33.8	Pb	- 24.8
Ag	- 21.6	В	- 6.7	As	- 5.5
Au	- 29.6	Ga	- 18.8	Sb	- 107
Be	- 9.02	In	- 12.3	Bi	- 265
Zn	- 10.26	Та	- 49.0	Se	- 26.5
Cd	- 19.6	Ge	- 8.9	Те	- 10.8

It can be noticed that among the diamagnetic materials, the magnetic susceptivity for bismuth takes large values that strongly depend on the value of the applied magnetic field and on the temperature.

The superconduction state, encountered at a range of metals and their alloys (Hg, Pb, Sn, Zn, Cd, etc.), is characterized by an ideal diamagnetic behavior: a superconductor rejects the magnetic field lines in its exterior, and the diamagnetic susceptivity is negative, taking values in the vicinity of -1.

Due to this fact, a certain value of the magnetic field strength H_c induced in the superconductors can destroy the superconduction state. Thus, the diamagnetism phenomenon limits the maximum value of the magnetic field created using superconducting coils.

5.2.3. Material Paramagnetism

Paramagnetism is encountered in the case of the polar magnetic substances, thus, for $\overline{m}_{atom} \neq 0$. The corresponding magnetic susceptivity takes positive values.

The permanent magnetic moments are oriented on the direction of the magnetizing field \overline{H}_0 , generating a magnetic field in the same direction as the magnetizing (external) field.

The substances for which the paramagnetism is predominant, in a nonhomogeneous magnetic field are attracted to the maximum intensity regions.

The paramagnetism is generated by bound electrons (Langevin paramagnetism) and by conduction electrons (Pauli paramagnetism).

The classical theory of paramagnetism of the bonded electrons, elaborated by Langevin, considers that in a polar magnetic material, there are magnetic dipoles, with a volume concentration *n*, and a permanent magnetic moment \overline{m}_p , that behave as an ideal gas (Fig. 5.7).

In the absence of an external magnetic field (Fig. 5.7a), the magnetic moments of the magnetic dipoles are chaotically distributed due to the thermal movement. In the presence of the magnetic field (Fig. 5.7b), the magnetic dipoles tend to orientate in the direction of the applied field.



Fig. 5.7. The paramagnetism state. The distribution of the magnetic moments: a) in the absence of the magnetic field; b) in the presence of the magnetic field.

An evaluation of the susceptibility can be made by considering the contribution of the magnetic dipoles that orientate in the direction of the magnetic field and in the opposite direction.

In the classical approach, the probability for the magnetic moments \overline{m}_{ρ} to orientate under the angle θ can be computed using the relation:

$$P = \text{Const.e}_{\mathbf{X}} \begin{bmatrix} -\frac{\Delta W_{\text{m}}}{kT} \end{bmatrix} = \text{Const.e}_{\mathbf{X}} \begin{bmatrix} \frac{m_{\text{p}}\mu_{0}H_{0}\mathbf{c} \cdot \theta}{kT_{s}^{0}} \end{bmatrix} = \text{Const.e}_{\mathbf{X}} \begin{pmatrix} a\mathbf{c} & \theta \end{pmatrix}, \quad (5.41)$$

where parameter a represents the ratio of the energies that contribute to the magnetic dipole state:

$$a = \frac{m_{p}\mu_{0}H_{0}}{kT}.$$
 (5.42)

Considering that only two cases are possible: parallel and anti parallel orientation of the dipole to the direction of the applied magnetic field, the average value of the atomic magnetic moment can be computed using the relation:

$$\frac{-}{m_{med}} = \frac{N_{\uparrow\uparrow} m_{\rho} + N_{\uparrow\downarrow} m_{\rho}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} , \qquad (5.43)$$

where $N_{\uparrow\uparrow}$ is the number of atoms that have \overline{m}_{ρ} orientated parallel with the external magnetic field \vec{H} , and $N_{\uparrow\downarrow}$ is the number of atoms that have \overline{m}_{ρ} orientated in opposite direction to the external magnetic field \vec{H} .

The projection of the average magnetic moment on applied field direction will be:

$$m_{med\,Ox} = \frac{N_{\uparrow\uparrow} m_p - N_{\uparrow\downarrow} m_p}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} \quad .$$
(5.44)

The number of atoms that orientate parallel or anti-parallel is statistically determined, taking into account the classical distribution of the orientation probability, represented by relation (5.41), where the orientation angles are $\theta = 0^{\circ}$ and $\theta = 180^{\circ}$. Therefore:

$$N_{\uparrow\uparrow} = \operatorname{const} \cdot \operatorname{e}_{\mathbf{X}} \left(\frac{m_{p}\mu_{0}H}{k} \right)$$

$$p_{\uparrow\downarrow} = \operatorname{const} \cdot \operatorname{e}_{\mathbf{X}} \left(\frac{T}{-\frac{m_{p}\mu_{0}H}{k}} \right)$$

$$n_{\uparrow\downarrow} = \frac{1}{2} \operatorname{const} \cdot \operatorname{e}_{\mathbf{X}} \left(\frac{T}{-\frac{m_{p}\mu_{0}H}{k}} \right)$$
(5.45)

With these relations, the projection of the average magnetic moment on the direction of the field is obtained:

$$m_{med \ Ox} = m_p \ th \frac{m_p \mu_0 H}{kT} \cong \frac{m_p^2 \cdot \mu_0 H}{kT}, \qquad (5.46)$$

where th $\alpha \approx \alpha$. The approximation made is valid when the magnetic fields are small, or when the temperatures are high.

The expression for the magnetization is computed with relation (5.46), and compared with the temporary magnetization law:

$$\begin{cases} M = n \cdot m_{medox} = \frac{n \cdot m_p^2 \mu_0}{kT} H \\ M_t = \chi_{mp} H \end{cases}$$
(5.47)

The expression of the paramagnetic susceptivity is obtained:

$$\chi_{mp} = \frac{n \cdot m_p^2 \mu_0}{kT} \,. \tag{5.48}$$

Note:

- > The magnetic susceptivity in the case of a paramagnetic behaviour is directly proportional with the volume concentration *n* of the magnetic moments, with the square of the permanent magnetic moment m_p of the structural unit (atom, molecule, basic cell in the case of the crystals etc.) and with 1/T;
- ► The susceptivity takes small positive values $(\chi_{mp} \approx 10^{-5} \div 10^{-4})$ and therefore, the relative magnetic permeability will also take relatively small values: $\mu_{mp} = 1 + (10^{-5} \div 10^{-4});$
- In the category of the paramagnetic materials are included the oxygen, materials that include the –OH group, alkaline metals, ferromagnetic materials at high temperatures, etc.

Unlike the diamagnetic susceptivity of the bonded electrons that depends on the temperature, the paramagnetic susceptivity of systems of bound electrons depends with the inverse of the temperature. Thus:

$$\chi_{mp} = \frac{\text{const.}}{T}$$
(5.49)

relation called **Curie law**. The graphical representation of this dependence is shown in figure 5.8. This figure underlines the fact that the paramagnetic susceptivity determined by the bonded electrons magnetism decreases when the temperature increases.





Note:

The calculus of the magnetic susceptivity using the previous relations give values close to the experimental data only in the case of *mono-atomic gases* at high temperatures, case in which the atom interactions are practically absent, and in the case of *lanthanides ions* ($Z = 58 \div 70$) - cerium and ytterbium ions, respectively. For these elements, the 4f incomplete layers that give the atomic magnetic moments are screened by $5s^2$ and $5p^6$ layers, such that the lanthanides ions have a behaviour resembling to the polar magnetic gases.

For the transitional elements belonging to the group of iron ($Z = 21 \div 28$), palladium group ($Z = 39 \div 45$), platinum group ($Z = 71 \div 78$), that are in a paramagnetic state, a deviation from Curie law appears, determined by the action of the crystalline potential on the atomic magnetic moments. In this case, **Curie-Weiss law** is applied:

$$\chi_{mp} = \frac{\text{const.}}{T - T_c},\tag{5.50}$$

where T_c is the passing temperature into the paramagnetic state, called **Curie** temperature.

1 5.2.4. Paramagnetic Materials Classes

Most of the metals are paramagnetic. Their susceptivity is given by:

- the paramagnetic contribution of the bonded and of the conduction electrons;
- the diamagnetic contribution of the bonded and of the free (conduction) electrons.

For *alkaline metals*, the contribution of the conduction electron paramagnetism is very large, and these metals have a paramagnetic susceptivity independent on the temperature.

The values of the magnetic susceptivity for some paramagnetic elements according to their atomic number *Z* are shown in figure 5.5. It can be noticed that the elements belonging to the *group of iron*, excepting Fe, Ni, Co, and those belonging to the *group of palladium*, exhibit a paramagnetic behavior, having the magnetic susceptivity of around $(+10^{-2})$. The bismuth is paramagnetic, with a magnetic susceptivity of around $(+10^{-1})$.

Table 5.5 shows the values of the susceptivity for some paramagnetic metals, at 20°C temperature, and also the dependence of this material parameter with temperature.

Metal	χ _m [·10 ⁻⁶]	f(T)	Metal	χ _m [·10 ⁻⁶]	f(T)	Metal	χ _m [·10 ⁻⁶]	f(T)	Metal	χ _m [·10 ⁻⁶]	f(T)
Lithium	25.2		Titan	150		Cerium	2300	Curie Weiss	Rutheniu m	44	
Sodium	15.6		Zirconium	120	abnor mal	Praseody mium	2500	law	Rhodium	113	
Potassium	21.5		Thorium	130		Neo- dymium	5600		Palladium	580	Curie Weiss
Rubidium	19.2		White Tin	4.4		Samarium	1820		Osmium	76	law
Caesium	29.9		Vanadium	230		Europium	30400		Iridium	20	
			Tantalum	143	small	Gadoli- nium	75500		Platinum	200	
Magnesium	6	small				Terbium	115000				

Table 5.5. Susceptivity of some paramagnetic metals.

Calcium	44		Chromium	160		Dysprosi um	102100		
Strontium	92		Molybde- num	54	small	Holmium	68200		
Barium	20		Wolfram	40		Erbium	44500		
						Thulium	25600		
Aluminium	16		Uranium	620		Ytterbium	250		
Scandium	315	unk- nown	Manga- nese	527	abnor mal				
Yttrium	191		Rhenium	68.7					
Lantana	140								

5. Magnetic Materials

Large values of the magnetic susceptivities are encountered only in the case of materials with magnetic ordering.

5.3. INTERPRETING THE FERRI- AND FERRO-MAGNETIC STATES

5.3.1. Characteristics of Ferromagnetic Materials

The ferromagnetic materials are those materials with homo-parallel order of the atomic magnetic moments. These have multiple uses in electrical and electronic engineering due to *their property of concentrating and amplifying within them the magnetic field*. Thus, an iron core introduced in a solenoid (Fig. 5.9) concentrates and amplifies the magnetic field to the inside of the solenoid, and this phenomenon determines the increase of the coil inductivity.





The ferromagnetic materials present a series of specific properties, such as:

- a. Non-linearity and saturation,
- b. Hysteresis cycle,
- c. Remanence,
- d. Coercitivity,
- e. Pronounced dependence on temperature of the magnetic characteristics.

a. Non-linearity and saturation

Any ferromagnetic material, placed in a magnetic field, presents a very high value of magnetization, which modifies when the intensity of the magnetized field is modified. The modification of the magnetization is not proportional, which will make the material parameters of magnetic susceptivity χ_m and the permeability μ_r to modify with the applied magnetic field, reaching values of $10^2 \div 10^6$ order. The ferromagnetic materials are **non-linear materials** from magnetic point of view. The ferromagnetic material presents a **limitation phenomenon** (saturation) of the magnetization state.

In figure 5.10 is presented the curve form of the magnetic induction in dependence with the intensity of applied magnetic field. It can be noticed that when the magnetic field increases over a certain value, the magnetic induction within the material stops. It is obtained the **state of technical saturation** and then the **physical saturation state**.

Due to the specific form of the curve of the first magnetization (obtained through the constant increasing of the intensity of the magnetic field, for a material demagnetized in the initial state), the value of the magnetic permeability modifies along with the value of the intensity of the magnetic field: from an initial state, the permeability reaches a maximal point and then tends downwards to the value 1 (Fig. 5.10).



Fig. 5.10. The first-magnetization curve of a ferromagnetic material and the curve of the magnetic permeability.

From a macroscopically point of view, the ferromagnetic materials are characterized through **a family of magnetization curves**, given by the dependencies B = f(H), which have similar shapes as the dependencies M = f(H), in the case of low and average magnetic fields.

5. Magnetic Materials

At the magnetization in a continuous current it is obtained **the curve of first-magnetization**, and in variable magnetic fields there are obtained non-linear and nonunivocal dependences between the magnetic induction and the intensity of the applied magnetic field.

The characterization of a ferromagnetic material around a certain state, defined with a pair of values (B, H), is done with different expressions for relative magnetic permeability:

> Relative static permeability, defined with the relation:

$$\mu_{rst} = \frac{B}{\mu_0 H},\tag{5.51}$$

which varies with the increase of the intensity of the magnetic field, increasing from an initial value, reaching a maximum and then, at high values $(H \rightarrow \infty)$ to tend down-wards the unitary value (Fig. 5.10);

> Relative incremental permeability, given by the relation:

$$\mu_{r\Delta} = \lim_{\Delta H \to 0} \left(\frac{\Delta B}{\Delta H} \right), \tag{5.52}$$

which it is defined by the magnetization curve slope to the axe of the abscises, for a low variation of H in the opposite direction.

> Relative reversible permeability, given by the relation:

$$\mu_{rrev} = \lim_{\Delta H' \to 0} \left(\frac{\Delta B'}{\mu_0 \Delta H'} \right), \tag{5.53}$$

which is proportional with the hysteresis reversible minor cycle slope whose peak is in the point of coordinates (*B*, *H*). Usually, $\mu_{rrev} < \mu_{r\Delta}$ and it reaches its maximum at *H* = 0, where it can be confused with the initial relative permeability:

$$\mu_{ri} = \lim_{\Delta H \to 0} \left(\frac{\Delta B}{\mu_0 \Delta H} \right), \text{ la } B = 0, H = 0.$$
(5.54)

Relative dynamic permeability, defined in a non-stationary regime with the relation:

$$\mu_{rdin} = \frac{\Delta B}{\mu_0 \Delta H},\tag{5.55}$$

which is proportional with the average curve of the hysteresis cycle described around the characteristic point of the considered state. Due to its magnetic viscosity, determined by the fact that in non-stationary regime the induction variations cannot follow the variations of the magnetic field, the dynamic permeability has lower values than those in the stationary regime and decrease while the frequency increases.

> Relative permanent permeability, given by the relation:

$$\mu_{rp} = \frac{1}{\mu_0} \cdot \frac{\Delta B}{\Delta H}, \qquad (5.56)$$

which is proportional with the hysteresis cycle curve whose basis is on the curve of demagnetization of a permanent magnet and presents a great importance in the case of permanent magnets submitted to a supplementary magnetizations.

b. The hysteresis cycle

The ferromagnetic behavior is dependent on the history of magnetic stress: the ferromagnetic materials present a hysteresis cycle. Representing the measurement of magnetic induction B according to the intensity of magnetic field H, at a cyclic variation of this one it is obtained a typical curve called **the hysteresis cycle** (Fig. 5.11).

At first magnetization (curve 0A from figure 5.11), the value of the magnetic induction *B* increases proportionally with the intensity of the magnetic field *H*, for low fields, and then suddenly decreases and tends towards a certain limit in intense fields, limit that is called **magnetic induction of saturation** B_s .

By decreasing the intensity of the magnetic field (curve AC) it is noticed a diminishing of the value of magnetic induction, which does not reproduce the values from the magnetization process and indicates a **remanence**, at H=0. This one has as a result the fact that when the magnetized field comes to the value zero, the ferromagnetic material has another state of magnetization, characterized by the measurement of the vertical segment 0C, which represents the remanent magnetic induction B_r .



Fig. 5.11. The magnetic hysteresis cycle.

In order to cancel the remanent magnetization it is necessary to apply a magnetized field of an opposite direction, represented by the segment 0D, called **coercitive field**, of intensity H_c .

In a ferromagnetic material, for different magnetization regimes, different hysteresis curves are obtained (Fig. 5.12).



Fig. 5.12. Magnetic hysteresis curves in ferromagnetic material: 1 – maximum curve;
 2 - symmetric minor curves; 3- dynamic curve; 4 – first magnetization curve;
 5 – non-symmetric minor curve.

Due to the hysteresis, by remaining behind, the magnetization value M, respectively the magnetic induction B, as opposed to the value of the magnetized field H, in the process of magnetization of the ferromagnetic substance, it is necessary a certain magnetic energy, given by the magnetized field, proportional with the area of the magnetization cycle ACDEFGA and which dissipates as **heat** in the material mass. The ferromagnetic material presents **energy losses, called iron losses**.

The width of the hysteresis cycle is a criterion of classification of the ferromagnetic materials. Thus, there are (Fig. 5.13):

- soft magnetic materials, which have the width of the hysteresis cycle very low, below 1 kA/m (H_c << 1kA/m);</p>
- hard ferromagnetic materials, which have hysteresis cycles very large, of kA/m order (*H*_c >> 1kA/m).



Fig. 5.13. Width of the hysteresis cycle: 1 - a narrow cycle (for soft magnetic materials); 2 - a large cycle (for hard magnetic materials).

The applications for these classes of materials are specific.
c. Remanence

A magnetic material brought to the saturation state by application of a magnetic field H_{sat} will present, when the magnetic field is removed, a non-null magnetization, characterized by the quantity of the remanent induction B_r . This phenomenon can be viewed on the hysteresis cycle from figure 5.11 - by the points C and F.

d. Coercivity

The coercive field H_c corresponds to that intensity of the magnetic field demagnetized for which it returns to the state of de-magnetization (B=0) of the material. This phenomenon can be viewed on the hysteresis cycle from figure 5.11 - by the points D and G.

The value of the coercive field H_c separates the soft magnetic materials ($H_c < 1$ kA/m) from hard magnetic materials ($H_c > 1$ kA/m).

It must be observed that the name of soft or hard magnetic material refers to magnetic characteristics, not to its physical hardness, some alloys used for producing the magnets having a lower hardness than a series of cast iron and steel used as soft magnetic materials.

5.3.2. Temperature Dependence of Magnetic Properties

If the temperature of the ferromagnetic materials increases, then the thermal agitation energy has the tendency to reduce the state of magnetic ordering. The effect of temperature on remanent induction is indicated in figure 5.14.



Fig. 5.14. Dependence of remanent magnetic induction of a ferromagnetic material on temperature

If the temperature increases, the remanent induction decreases. Therefore for a certain temperature, called the **Curie temperature** T_{C} , the ferromagnetic material loses its state of magnetic ordering. Over the Curie temperature, the ferromagnetic material behaves **paramagnetic**. In the Table 5.6, the values of the Curie temperature for certain ferromagnetic elements are presented.

Table 5.6.	The Curie	temperature	at certain	ferromagnetic	materials.
				0	

Material	Gd	Ni	Fe	Со	
Curie Temperature [ºC]	16	358	770	1131	

Gadolinium (Gd) at temperature over 16°C becomes paramagnetic.

In figure 5.15, it is show the dependence of the magnetic induction at saturation on the temperature for iron, nickel and cobalt.



Fig. 5.15. Dependence of the magnetic induction at saturation on the temperature for iron, nickel and cobalt.

In general, the saturation, the remanence and the coercivity decrease when the temperature is increasing. The highest variation of the magnetization value with temperature takes place at the **technical Curie temperature** T_{Cf} . Over this temperature, the material will lose its ferromagnetic properties and behaves paramagnetic, the susceptivity respecting the **Curie-Weiss law**:

$$\chi_m = \frac{C}{T - T_c},\tag{5.57}$$

where *C* is the Curie constant, and T_c is the **paramagnetic temperature Curie**, with 10-15°C higher than the technical Curie temperature T_{Cf} .

In order to explain these macro-physical aspects, a series of micro-physical models are proposed: Weiss model, Heisenberg's theory, the spherical model of Isig, the spin wave model of Bloch, etc. Several considerations are presented in the next chapter.

M 5.3.3. Ferrimagnetic Materials

Ferrite materials are widely used in electronic equipment such as computers, communication devices, power management systems, etc. They serve as inductive components, transformers, magnets, magnetic field absorbers and suppressors.

Evaluation of magnetic characteristics of those materials is important in predicting the performance of the components. Performance includes permeability and loss of the material at various frequencies where the devices are used.

The ferrimagnetic materials are those magnetic materials formed by two crystalline sub-lattices whose structural units have spontaneous magnetic moments with different values $(\overline{m}_x \neq \overline{m}_y)$, which are anti-parallel ordered.

Representatives for this class of substances are a series of ceramic materials, called **ferrites**. The most used ferrites are obtained by replacing the bivalent iron from **magnetite** (FeO.Fe₂O₃, where the iron has the valence two and three: Fe⁺⁺ Fe₂⁺⁺⁺O₄) with bivalent elements, as: Mn, Co, Ni, Cu, Mg, Ba, Zn, Cd. Various combinations of MeO.Fe₂O₃ will result, where Me is a metallic bivalent ion.

Among the structural crystalline structures for ferrites - spinel, hexagonal and of granite type – the most often encountered is the spinel structure.

Ferrites with spinel structure (type $MgFe_2O_4$) have as a characteristic the fact that the ions of the bivalent metal and the trivalent iron, having their radius smaller than the oxygen anion ones, are distributed within the sub-lattice interstices of oxygen ions, forming a sub-lattice with a cubic symmetry. The elementary cell of the spinel lattice is formed of 8 octants, characterized by a certain type of structure.

The increasing of the magnetic moment on the elementary cell can be realized by replacing in a certain proportion the cations of the ferromagnetic material with cations of the non-magnetic metals (Zn, Cd). For instance, the case of the **mixed ferrite of nickel and zinc** with the composition $Zn_xNi_{1-x}O.Fe_2O_3$, because the zinc cations are placed in the tetrahedral interstices, remaining only (1-*x*) interstices for iron. As a result, the octahedral interstices will be approximately occupied of (1-*x*) cations of nickel and (1+*x*) cations of iron. The total magnetic moment will increase.

The hexagonal structure is specific for ferrites of type $(Me^+ O^- 6Fe_2O_3)$ where Me is a bivalent ion of barium (Ba), strontium (Sr), lead (Pb). The structure BaO.6Fe₂O₃ is constituted from a series of spinel cells separated by separation layers. The spinals contain 16 anions of oxygen, which form tetrahedral and octahedral interstices, in which

there are 9 cations of Fe^{++} (six in octahedral interstices and three in the tetrahedral). The separated layers contain an ion of Ba^{++} , an ion of Fe^{+++} and three ions of O^{-} .

The structure of garnet type is characteristic for ferrites of $Me_3Fe_5O_{12}$, where Me is an element from the group of rare earth (Y, Gd, Tb, Dy, Mo, Lu).

In Table 5.6 are shown the properties of several ferrimagnetic materials (ferrites), and that is; the intensity of spontaneous magnetization J_s at temperature T=0 K, noted with $J_{0 \text{ K}}$ and at normal temperature T = 300 K, noted $J_{300 \text{ K}}$ and the Curie temperature T_c .

Note:

- Relation between the intensity of the spontaneous intensity of magnetization J_s and the spontaneous magnetization M_s is: J_{s=} µ₀ M_s;
- Relation between the measurement Gauss unit (Gs) and Tesla (T) is: 1Gs=10⁻⁴ T.

Ferrite	<i>Т_с</i> , К	Ј 0К, Gs	<i>J</i> _{300 к} , Gs	Ferrite	<i>Т_с,</i> К	J _{0 К} , Gs	<i>J</i> _{300 к} , Gs
Normal spinels			Re	versed s	pinels		
MnCr ₂ O ₄	43	-	-	Fe ₃ O ₄ (magnetite)	858	510	480
FeCr ₂ O ₄	180	-	-	CoFe ₂ O ₄	793	475	425
CoCr ₂ O ₄	_	-	_	NiFe ₂ O ₄	858	300	270
				Li _{0,5} Fe _{2,5} O ₄	942	318	289
Mixed spinels			Hexa	igonal sti	ructures		
CuFe ₂ O ₄	728	160	135	BaFe ₁₂ O ₁₉	723	380	300
MgFe ₂ O ₄	713	140	120	BasCosFes4O41	683	_	270
MnFe ₂ O ₄	573	560	400		200		

Table 5.6. Properties of several ferrimagnetic substances.

The ferrites properties are similar to the ferromagnetic materials: they are nonlinear materials and present hysteresis cycle. But the performances are different: the values of saturation induction and remanent induction are lower ($B_s < 0.6$ T), magnetic permeability is lower and more sensitive at the action of external magnetic fields.

The temperatures influence the properties of ferrimagnetic materials similar to ferromagnetic materials. Over a certain temperature the ferrites become paramagnetic.

Evaluation of magnetic characteristics of those materials is important in predicting performance of the components. Performance includes magnetic permeability and magnetic losses of the material at various frequencies where the devices are used.

The value of the effective permeability is obtained using specific instruments in which the inductance of a coil with and without magnetic material as core is measured.

$$\mu_r = \frac{L - L_o}{\mu_o} \cdot \frac{2\pi}{h \cdot l \left(\frac{c}{d}\right)}$$

(5.58)

where the significance of the quantities are:

 μ_r – relative magnetic permeability,

L – measured value of inductance with magnetic core,

 L_{o} - measured value of inductance without magnetic core,

 μ_o – magnetic permeability of free space,

h – height of the material under test,

c-outer diameter of material under test,

b-inner diameter of material under test.

In figure 5.16 the dimensions and the view of a magnetic sample with toroidal shape are shown. The material under test is placed in a specific test fixture, which provides an ideal structure: there is no leakage flux in the single-turn inductor and the magnetic field in the fixture is strictly calculated from the electromagnetic theory.





Fig. 5.16. Dimensions of the toroidal magnetic sample located in a specific test fixture.

Complex permeability is a magnetic property of a material connected with magnetization in alternative sinusoidal magnetic fields. Complex permeability is determined by the impedance of the inductor formed with the material:

$$\underline{\mu}_{r} = \mu_{r}^{'} - j\mu_{r}^{''} = 1 + \frac{2\pi(\underline{Z}m - \underline{Z}s)}{j\omega \overline{\omega}_{0}h \prod_{n} \frac{c}{b}}$$
(5.59)
$$t \qquad \delta_{m} = \frac{\mu_{r}^{''}}{\mu_{r}^{'}}$$
(5.60)

where the significance the quantities are:

 $\boldsymbol{\mu}$ - complex magnetic permeability,

 μ_o – permeability of free space,

 \underline{Z}_m – measured impedance,

 \underline{Z}_{s} – short impedance,

 ω – angular frequency,

h, c, b – dimensions of the toroidal core,

 $tan \delta_m$ – tangent of loss angle.

The real and imaginary part of the complex permeability represents the ability of a material to conduct magnetic flux and, respectively, the losses dissipated in the material. Material with large permeability is desired to reduce size and weight. Losses should be minimized for maximum efficiency, while large losses are required for magnetic shielding.

In most of the cases, the permeability components are not a constant over the frequency and must be characterized at the frequency for which the device is operated.

The graph in figure 5.17 shows the permeability dependence of three different ferrite cores with the frequency.



Fig. 5.17. The permeability dependence of three different ferrite cores on the frequency.

From the electrical conductivity point of view, most of ferrites are **semiconductors**, having their resistivity $\rho = 0.1 \div 10^4 \Omega m$. Due to this fact, ferrites have losses through eddy currents very low, which allow the extension of their function until frequencies of MHz order. Ferrites have multiple uses in electrical and electronic engineering.

5.3.4. Magnetic Domains Theory

The ferromagnetic materials properties can be justified with the **theory of the magnetic domains**, stated by Weiss during 1906-1907, and then improved. The theory of magnetic domains admits that the ferromagnetic material is divided in domains of sub-millimeter order where magnetic atomic moments are oriented after the direction of the easy magnetization of the ferromagnetic crystal. Passing from one domain to another can be done with the domain walls.

In the absence of the magnetic field, the domains are oriented randomly, therefore there is no effective magnetization of the material. It is the case presented in figure 5.18a.



Fig. 5.18. Magnetic domains in the ferromagnetic material: a) randomly orientation for the case H = 0; b) increasing of favorable domains for $H \neq 0$.

When an external field is applied, the shape and the volume of the magnetic domains modify: the number and the domain volume increase on the direction of the applied field relative to those with anti-parallel orientation (Fig. 5.18b). Thus, it is produced an effect of amplification of the magnetic field within the material, due to the increasing of the magnetization field.

At ferromagnetic materials, the **domain structure** determines their specific properties. This structure can be energetically justified.

The domain structure of a ferromagnetic material is determined by the energetic configuration of the ferromagnetic material. The total energy in the ferromagnetic crystal is formed by:

- The exchange energy;
- The magnetostatic energy;
- The magnetocrystalline anisotropy energy;
- The energy of domain walls;
- The magnetostrictive energy.

It will be analyzed the structure and the condition of minimum of the assembly of these forms of energy, for the case of a ferromagnetic single-crystal.

A. The exchange energy

Within the magnetic single-crystal, the potential energy is minimal when all magnetic atomic moments are ordered on the same direction and the same sense. It is the case presented in figure 5.19a, where it is admitted the hypothesis of forming a single domain.



Fig. 5.19. The domain structure: a) the hypothesis of forming a single domain; b) dividing the single-domain into two sub-domains; c) multi-domains structure which favors a minimum of energy.

The single-crystal, containing a single magnetic domain has the magnetic moments of the constituent atoms homoparallel oriented due to the exchange forces between them. But, although aligning the magnetic moments the potential energy within the domain is minimal, outside the sample the energy increases due to the appearance of the de-magnetizing magnetic field. This hypothesis cannot justify the existence of a de-magnetizing state of a ferromagnetic material (when on its outside there are no lines of magnetic field).

B. The magnetostatic energy

The magnetostatic energy is determined by energy of interaction of the magnetic atomic moments with the external magnetic field in the case of a single-domain hypothesis (presented in figure 5.19a) with the de-magnetizing field.

For a ferromagnetic single-crystal, the hypothesis of the existence of a single magnetic domain leads to a maximum of the magnetostatic energy. Dividing the material sample in domains can do a minimization of this energy, as it is presented in figure 5.19b.

Thus, by dividing the single-domain into two domains, the intensity of the external magnetic field reduces itself. By new dividing, with an adequate structure, it can be reached a structure where the external magnetic field is totally eliminated (Fig. 5.19c).

C. The anisotropy energy of single-crystal

Before analyzing the effect of this form of energy on the forming of domain structure, it should analyze the effect that the angle made by the direction of external magnetic field with the main crystallographic directions from a ferromagnetic crystal on the characteristic form B = f(H).

The magnetic anisotropy is the property of ferromagnetic and ferrimagnetic substances to have magnetic properties different for different directions of the applied magnetic field.

There are several types of anisotropy: **magnetocrystalline**, of form, induced, of exchange, etc. Sometimes it is desired a certain type of anisotropy.

The induced anisotropy can be realized through various technological procedures, such as:

- Cold-rolling, used to produce textured sheets from iron-silicon alloys, iron-cobalt, ironnickel. This method makes the elementary curves to orient the parallel edges on the laminated directions or they are double-oriented, and it is called **Goss structure**. In the first case, the direction of soft magnetization is on the rolling direction, in the other case, there are two directions of soft magnetization, perpendicular on each other;
- Thermal treatment in the presence of an external magnetic field, which orients the elementary spontaneous magnetic moments on the direction of easy magnetization, the same with the direction of the magnetic field. The procedure is used to produce some materials with the rectangular hysteresis cycle;
- Cooling the material warmed at a superior to Curie temperature in the presence of a magnetic field, which produces changes in the crystalline structure of the material, by increasing the crystalline concentration whose magnetization corresponds to the direction of the external magnetic field in report with the other directions. Anisotropy is fully influenced by the cooling velocity of the material.

The magnetocrystalline anisotropy contributes to the establishing of domain structure and allows obtaining special performances of the ferromagnetic materials. Thus, in figure 5.20a are presented the curves of magnetization for a single-crystal of iron, when the magnetic field is applied after various directions within the crystal.



Fig. 5.20. The effect of magnetic anisotropy: a) the curves of primary magnetization at iron (CVC) for different crystallographic directions; b) the directions of easy, medium and hard magnetization, within the iron single-crystal.

It can be noticed that the magnetic saturation is produced more rapidly if a magnetic field is applied on the direction [100]. This direction represents for **iron**, which crystallizes in cubic structure with a centered volume (CVC), and it is called the **direction of easy magnetization**. The saturation magnetization is obtained at a value much higher of the applied field, in the case when the field is applied on the direction [111]. This is the direction of **hard magnetization** within iron. The direction [110], which corresponds to the diagonal of the elementary cube face, is the **medium direction of magnetization**.

For **nickel**, which crystallizes within the **cubic structure with centered faces** (CFC), the direction of easy magnetization is [111], and the direction of hard magnetization is [100]. In the case of **cobalt**, which crystallizes in **compact hexagonal system** (HC), the directions of **easy magnetization** are parallel to the axis of the hexagonal prism, and those of **hard magnetization** are perpendicular to this one.

In the case of polycrystalline materials, the crystalline grains will have different orientations, thus when a magnetic field is applied, the magnetic saturation will be obtained at different values of the applied magnetic field. The grains, which have their orientation after the direction of easy magnetization, will saturate at lower intensities of the magnetic field, as opposed to the grains oriented after the direction of hard magnetization, which will have to rotate firstly the resulting magnetic moment after the direction of the applied field, and thus the saturation will be obtained at higher magnetic fields.

These performances depend on the **work of crystalline anisotropy** necessary to rotate the magnetic moments of the constituent atoms on certain direction of the applied magnetic field, defined by the **energy of magnetocrystalline anisotropy**.

D. The energy of domain walls

A domain wall is an area of a certain thickness between two magnetic domains. As opposed to the limit between the crystalline grains, which suddenly modify their orientation, in the case of domain walls, the direction of the moments are slowly modified on a distance of hundreds of inter-atomic distances.



Fig. 5.21. Magnetic domain walls: a) magnetic atomic moments disposal in domains I and II and the domain wall; b) the magnetic anisotropy energy and the energy of the domain wall dependences on the wall thickness.

Figure 5.21a shows a domain wall, which separates two domains in which the orientation of the magnetic moments is at 180°. The modification of the direction of the magnetic moments along the wall is done gradually.

The application of an external magnetic field determines a movement of the wall toward the direction which favors the parallel alignment of the magnetic moments. When the field disappears, the domain wall, also called **Bloch wall**, tries to come to its initial position of stable equilibrium. If the initial magnetization was lower, the proper energy of the wall allows to come-back to the initial state, the **magnetization phenomenon being reversible**.

When a more intense magnetic field is applied, the magnetization is realized through energy jumps called **Barkhausen jumps**. When the external field is interrupted, the Bloch wall does not recover to its initial position because the movement of the Bloch wall is irreversible. This is the justification for the existence of a remanent magnetization within the ferromagnetic material.

The width of domain wall d_B is established according to the thermal equilibrium conditions, between the magnetostatic anisotropy energy and the exchange energy.

In the theory of the magnetic domains, there are established the expressions of the magnetic anisotropy energy W_{aniz} and the exchange energy W_{sch} . The variation mode of the magnetic anisotropy energy and the exchange energy of the domain walls with the thickness of the wall is presented in figure 5.21b.

It can notice that the exchange energy has the tendency to increase the thickness of the wall. But this one corresponds to a great number of magnetic moments, which have different direction from the direction of easy magnetization. This fact leads to the increasing of the magnetocrystalline anisotropy energy. Thus, it is established a thickness of equilibrium for the wall domain only when the minimal energetic equilibrium is realized between the two types of interactions.

E. The magnetostrictive energy

When a sample of ferromagnetic material is magnetized, its sizes are modified, the sample expands or contracts after the direction of the magnetic field application.

The magnetostriction is the phenomenon of reversible deformation of a magnetic material submitted to the action of the magnetic field. The magnetostriction is characterized by the **magnetostriction constant**:

$$\lambda = \frac{\Delta I}{I_0},\tag{5.61}$$

where Δl is the total expansion or contraction of a bar of ferromagnetic material, of its initial length l_0 under the action of the magnetic field.

The constant of magnetostriction depends on the crystallographic directions and on the nature of the material. For certain values of the magnetic field, it reaches a maximal value called the **constant of magnetostriction of saturation** λ_s , having the order of measurement 10⁻⁵. For iron, the magnetostriction is positive at reduced fields and negative at high fields (Fig. 5.22).



Fig. 5.22. The dependence of the magnetostriction coefficient on the intensity of the magnetic field for single-crystal of iron, at different magnetization directions.

The energy due to mechanical stresses created by the magnetostriction phenomenon is called **magnetostriction energy**.

The main cause of magnetostriction is attributed to the modification of the interatomic distance when magnetic moments of spin are aligned in external field. The field between the dipoles attracts or rejects them, which will determine the contraction or the expansion of the crystal in the magnetization process.

Notes:

- The domain structures formed within the ferromagnetic material is determined by various contributions of exchange energy, magnetostatic, of magnetocrystalline anisotropy, of domain walls and of magnetostrictive energies.
- The most stable configuration of magnetic domains is obtained for the case when the sum of these energies is minimal.

5.3.5. Explanation for the Magnetization Curves

In order to justify the form of the curve of primary magnetization of ferromagnetic materials, it is considered the case of magnetization of a ferromagnetic single-crystal with a constantly increasing magnetic field, initially in a de-magnetized state (Fig. 5.23a).

In state 0, which corresponds to the de-magnetized single-crystal, this one is formed out of magnetic domains of equal volume, where the vector of magnetization is anti-parallel, thus, for the whole single-crystal, M=0 when H=0.



Fig. 5.23. The modification of form and structure of the magnetic domains for first magnetization curve (0-a-b-c).

In state *a*, when a magnetic field of H_a intensity is applied, the magnetization increases in the upper domain of the single-crystal as opposed to the other domains because within this domain the orientation of the magnetic moments is closer to the orientation of the external magnetic field (Bloch walls between the upper and down domains move downwards). The region $(0-H_a)$, corresponding to 0-a on the magnetization curve, is called the **Rayleigh domain**, where reversible transformations take place when the action of the magnetic field stops, the domain structure returning to the 0 state.

At the increase of the magnetic state between *a* and *b*, irreversible movements of Bloch walls take place. The favorable domains on the direction of the external field are increasing.

In state *b*, corresponding to the magnetic field of intensity H_b , the single-crystal contains a single-magnetic domain, whose magnetization is oriented after the axis of easy magnetization. The point b on the characteristic defines the **technical state of saturation**. As it follows, at the increasing of the intensity of the magnetic field, there take place rotations of the magnetization vector towards the direction of the applied magnetic field. In the zone b-c, the irreversible transformations will take place.

In state *c*, appears the physical saturation in this state; the magnetization vector is oriented on the direction of the applied field.

In order to justify the hysteresis cycle, it is considered the de-magnetization process of ferromagnetic single-crystal, magnetized to saturation (the state c in figure 5.24).



Fig. 5.24. Magnetic domain structure for de-magnetization curve (c-d-e).

A decrease of the intensity of the magnetizing field leads to the re-appearance of the ferromagnetic domains. Due to the irreversible processes, for H=0, the structure from the state 0 is not found anymore. The coming from the point c to the corresponding state for H=0 (state d) is realized on **the limit hysteresis curve**.

Any other coming from b to d' is realized after a **minor hysteresis curve**.

A return to the demagnetized state (state e) it can be realized only by applying on the opposite direction of the magnetic field applied initially, of value *H*c, named **coercive field intensity**.

The width of the cycle depends on the volume and elasticity of the magnetic domains. The magnetization is done with a small or large support of energy from outside, in direct dependence on the thickness and mobility of the Bloch walls:

- Non-elastic and of high thickness of Bloch walls have low mobilities and does not allow modification of the domain structure in large limits of the applied magnetic fields – it is the case of hard magnetic materials (high coercitive fields);
- Thin elastic with high mobilities of Bloch walls the magnetization needs a small contribution of re-magnetization energy – it is the case of soft magnetic materials (low coercitive fields).

Notes:

- The non-linear form of the curve of primary magnetization, the saturation and the remanence are justified through the existence of the domain structure and the specific magnetization processes.
- The form and the structure of the magnetic domains modify, which will determine the modification of form of the magnetization curves.

5.4. LOSSES IN FERROMAGNETIC MATERIALS

A magnetic material introduced in a constant or variable external magnetic field consumes some of the magnetic field energy for magnetization, because many of the magnetization processes are irreversible. The consumed active energy, which transforms into heat in a time unit, defines **the measurement of the re-magnetization losses**.

According to the nature of the dissipative processes, there are several types of magnetic losses:

- Hysteresis losses;
- Eddy current losses;
- Supplementary losses.

5.4.1. Losses Due to the Hysteresis Loop

Losses due to magnetic hysteresis are determined by the energy spent by the external magnetic field during the magnetization cycle. The dissipated energy on the volume unit during a complete cycle has the following expression:

$$W_h = \oint B \, dH \,, \tag{5.62}$$

and it is numerically equal to the area of the magnetic cycle surface.

To calculate this integral, it is necessary to know the analytical expression of the hysteresis cycle loop B=f(H).

A valid model for the case of magnetization in low magnetic fields is the **model proposed by Rayleigh**, where the hysteresis cycle is approximated with an ellipsis.

In this model, the magnetic permeability is:

$$\boldsymbol{\mu}_{rR} = \boldsymbol{\mu}_{ri} + \boldsymbol{\nu}_R \boldsymbol{H}_m, \tag{5.63}$$

where μ_{rR} is the Rayleigh relative permeability, μ_{ri} is the initial relative permeability and v_R is the Rayleigh coefficient, specific for each material.

The relation (5.63) shows that the Rayleigh relative permeability is a linear function on the magnitude of the applied harmonic magnetic field $H_{\rm m}$.

By multiplying the member coefficients of the relation (5.63) by $\mu_0 H_m$ is obtained the equation of **the primary magnetization curve** (curve o-a-b-c, Fig. 5.23):

$$B_m = \mu_0 \mu_{r_R} H_m = \mu_0 \mu_{r_i} H_m + \nu_R \mu_0 H_m^2.$$
 (5.64)

For modeling the branches of the hysteresis loop, with maximum coordinates (H_m, B_m) , Rayleigh proposes the equation:

$$B = \mu_0 \left[\left(\mu_{ri} + \nu_R H_m \right) H \pm \frac{\nu_R}{2} \cdot \left(H^2 - H_m^2 \right) \right], \qquad (5.65)$$

where *B* and *H* are the instantaneous values of the magnetic induction, respectively of the intensity of the magnetizing field. The sign (+) corresponds to the superior branch of the cycle, and the sign (-) corresponds to the inferior branch of the hysteresis cycle.

The magnetic energy density corresponding to remagnetization of the material equals with the area of the hysteresis cycle, given by the relation:

$$w_{mg} = \oint_{\Gamma} B dH =$$

$$= \int_{-H_m}^{+H_m} \mu_0 \bigg[(\mu_{ri} + \nu_R H_m) H - \frac{\nu_R}{2} (H^2 - H_m^2) \bigg] dH + . \qquad (5.66)$$

$$+ \int_{+H_m}^{-H_m} \mu_0 \bigg[(\mu_{ri} + \nu_R H_m) H + \frac{\nu_R}{2} (H^2 - H_m^2) \bigg] dH$$

After calculating the data, it is obtained:

$$w_{mg} = \mu_0 v_R \cdot \frac{4H_m^3}{3} \left[\frac{J}{m^3} \right].$$
(5.67)

For a period T=1/f of passing the cycle, respectively for the frequency *f* of magnetization, it will result the re-magnetization losses on the volume unit:

$$\rho_{h} = \frac{W_{mg}}{T} = W_{mg} \cdot f = \mu_{0} v_{R} \cdot f \cdot \frac{4H_{m}^{3}}{3} \left[\frac{W}{m^{3}}\right], \qquad (5.68)$$

or considering the relation (5.64):

$$p_{h} = \frac{\mu_{0} \nu_{R} \cdot 4}{3} \cdot \frac{B_{m}^{3}}{(\mu_{0} \mu_{rR})^{3}} \cdot f.$$
(5.69)

The specific losses can be expressed in W/kg, considering the material density d_m :

$$p_{h} = \mu_{0} \nu_{R} \cdot f \cdot \frac{4H_{m}^{3}}{3d_{m}} \left[\frac{W}{kg} \right].$$
(5.70)

The relation (5.70) underlines that the losses due to hysteresis loop depend on the material nature through the Rayleigh coefficient, on the magnetization regime through the amplitude H_m and the frequency *f* of the magnetizing field.

For magnetization regimes with sinusoidal variation in time, it is useful the experimental relation of Steinmetz:

$$p_h = \operatorname{cons} t \cdot f \cdot B_m^n , \qquad (5.71)$$

where index *n* takes values between 1.2 and 1.8.

In magnetic fields of non-sinusoidal form, the losses due to hysteresis loop increase, by adding all the harmonics, which will appear, by the serial decomposing of the wave-form for H, respectively B.

5.4.2. Losses Due to the Eddy Currents

Eddy current losses are due to the currents induced into the materials with finite conductivity, when they are placed in a magnetic field variable in time.

In figure 5.25 is presented the case of a coil with ferromagnetic core supplied in the alternative current. The variable magnetic field in time induces in the Γ circuit the currents, called **eddy currents**, which produce losses.



Ferromagnetic core

Fig. 5.25. The eddy currents induced in a ferromagnetic material.

The losses through eddy currents p_{ct} can be evaluated with the relation:

$$p_{ct} = \sum R_i \cdot i_{industrient}^2 = \sum \frac{u_{e\Gamma_i}^2}{R_i} = \text{const.} \cdot \left(\frac{d\Phi_{inductor}}{dt}\right)^2, \qquad (5.72)$$

where R_i is the electric resistance of the frames Γ_i traced in the ferromagnetic material, $u_{e\Gamma_i}$ is the electromotive voltage induced by the magnetic field $\Phi_{inductor}$.

The specific losses on the mass unit, in a steel sheet, in a harmonic regime of low frequency magnetization (for which the depth of penetration δ of the magnetic field is higher than the sheet's thickness), in the hypothesis that the other sizes of the sheet are much higher than the thickness Δ of the sheet and the orientation of the magnetic field is normal on the transversal section of the sheet, is determined with the relation:

$$\rho_{ct} = \frac{\pi^2}{6\rho d_m} \Delta^2 \cdot f^2 \cdot B_m^2 \quad [W/kg], \qquad (5.73)$$

where: ρ is the sheet resistivity, d_m is the mass density of the sheet, Δ is the sheet's thickness, *f* is the frequency of the magnetic field, B_m is the amplitude (magnitude) of the magnetic induction in the transversal section of the sheet.

Notes:

- The relation (5.73) suggests the possibilities of reducing the eddy losses: by reducing the thickness Δ of the sheets, by increasing the resistivity of the magnetic materials (example, Si in FeSi alloys).
- The usual thickness of the ferromagnetic sheet is of 0.2 ÷ 0.65 mm.
- To increase the sheet resistivity, the electrical steel sheets are alloyed with the silicon, which will decrease the eddy losses. Although a higher percentage of 11% Si in Fe-Si sheets increase the sheet hardness and it makes it more brittle. For rotating electrical machines, there are used Fe-Si sheets with approximately 2% Si, and for the electric transformers' cores with approximately 4-6% Si.
- The relation (5.73) underlines the effect of the frequency on the losses: the specific losses due to eddy currents increase with the square of magnetization frequency.

1 5.4.3. Additional Magnetic Losses

The additional magnetic losses are determined by:

- Magnetic resonance phenomena;
- Relaxation phenomena due to impurities and defects;
- Viscosity phenomena at the limits between the crystalline grains, etc.

An external sinusoidal magnetic field of a certain frequency can produce the magnetic resonance. The resonance phenomena determine losses at high magnetization frequencies. Thus, a ferromagnetic material submitted to a continuous magnetic field H_0 present the diamagnetism phenomenon: the constituent electrons will make precession movements, of different Larmor frequencies. If simultaneously, it is applied an additional alternative magnetic field H_1 perpendicular on H_0 , whose frequency coincides with the Larmor frequency, this one entertains the precession movement. The phenomenon of **magnetic resonance** can be in interaction with the internal field H_0 , being also determined by the magnetocrystalline anisotropy.

The Larmor frequency has the measurement order of hundreds of MHz, and thus the supplementary magnetic losses produced with this phenomenon are taken into consideration only in this domain of frequencies.

5.4.4. Total Losses in Magnetic Materials

Total specific losses in magnetic materials are given by the sum of the magnetic hysteresis losses, eddy current losses and supplementary magnetic losses:

$$p_{tot} = p_h + p_{ct} + p_{supl}. (5.74)$$

The weighting of these components is different, according to the nature of the material, the sheet thickness, the position of the operating point on the magnetization loop, the frequency domain, the amplitudes of the magnetizing field, temperature, etc.

In the case of magnetization in harmonic fields at industrial frequencies, preponderant are the hysteresis losses and the eddy current losses. With the relations (5.68) and (5.72), if all quantities are constant, except for frequency, it will result that the total specific losses in a ferromagnetic material, also called iron losses, depend on frequency like:

$$p_{tot} = p_{Fe} = af + bf^2. \tag{5.75}$$

By dividing the relation (5.74) to *f*, it results:

$$\frac{p_{Fe}}{f} = a + bf , \qquad (5.76)$$

which it a line dependence on frequency.

This relation emphasizes the experimental method of determining the hysteresis losses and eddy losses from the total losses p_{Fe} , by separating the components. The following steps of the method are done:

- > The losses are measured at two frequencies: f_1 and f_2 , for the same value of the maximal induction B_m ;
- > The graphic is traced $p_{Fe}/f = f(f)$;

14 12

10

8

From the intersection of this curve with the ordinates axis it can be obtained the a factor from the relation (5.76) and, as a result, it can be calculated the component of the hysteresis losses, with the relation:

$$p_h = af; (5.77)$$

 \succ From the slope of the line curve, the factor b is determined, the eddy losses are calculated as:

> $p_{ct} = bf^2$. (5.78)

Usually, most of the ferromagnetic material producers show in the catalogues the graphics $p_{Fe}=f(B_m)$, at different frequencies. In figure 5.26 there are presented the specific losses for electrical steel sheets of 0.35 mm thickness, obtained with an automated Brockhaus Messtechnik measurement installation.

60 Hz

p [W/kg] 50 Hz 6 4 30 Hz 2 0 -0 0.5 1 2 1.5 B [T]



In producer catalogues, sometime there are given only the values for specific losses at certain values of magnetic induction. Thus, for the electrical sheets, the standards give the data for magnetic induction of values: 1.0 T; 1.5 T and 1.7 T, at f = 50 Hz. The specific losses of re-magnetization are noted with P₁₀; P₁₅; P₁₇, corresponding to the values of magnetic induction. At other frequencies it will mention the frequency (ex. P_{10/40} represents the specific losses at the induction of 1T and the remagnetization frequency of 40 Hz).

The magnetic characteristic B=f(H) is shown in figure 5.27, for the same type of electrical sheets as those obtained in Fig. 5.26, measured with the same installation.



Fig. 5.27. The variation of the magnetic induction with the magnetic field intensity, for hot-rolling steel sheets of 0,35 mm.

It can be observed the non-linear character and magnetic saturation phenomenon at the steel sheets.

5.5. EXPERIMENTAL STUDY OF Fe-Si SHEETS

5.5.1. What are the Fe-Si Sheets

The Fe-Si sheets belong to the category of soft magnetic materials. These materials have as characteristic the ability to concentrate the magnetic field inside them, which will make possible the producing of intense magnetic flux that will create intense electromagnetic forces and electromotive forces (t.e.m.), with a small supplementary energy from the outside.

The electrical Fe-Si sheets are materials with crystalline structure, where the main alloy elements are the **iron** - in proportion of (88.00 \div 99.8) % and **silicon** – in proportion of (0.2 \div 12.0) %.

The influence of the alloy elements:

- > **The iron** induces the magnetic properties in Fe-Si alloys.
- > **The silicon** as an alloy element in Fe-Si sheet has:
 - o benefit effects:
 - increase the magnetic permeability,
 - reduce the coercive field,
 - reduce the losses through hysteresis and eddy currents,
 - increase the stability in time of the characteristics.
 - <u>negative effects</u>:
 - reduce the magnetic induction of saturation;
 - increase the fragility of the material;
 - increase the strength and the mechanical rigidity.

Other alloy elements

- o benefit effects:
 - nickel increases the permeability and decreases the coercitive field;
 - **cobalt** increases the saturation induction;
 - **aluminum** prevents the ageing of the sheet, it increases the permeability and the ductility of the alloy.
- <u>negative effects</u>: carbon, oxygen, hydrogen, nitrogen, sulphur, phosphor, manganese - reduce the magnetic properties performances.

Use domains

The electrical steel sheets are used in electrical engineering and electronics as cores for magnetic circuits:

- Transformers, generators, motors;
- Electromagnetic relays;
- Magnetic components in power electronics (shock coils, impulse transformers, etc);
- Magnetic heads for information recording;
- Mechanic filters, transducers for ultrasounds;
- Compensation devices of the variation with temperature.

The electrical Fe-Si sheets are produced with different qualities, their characteristics depending on the content of the alloy elements, on the impurity presence and on the non-metallic inclusions, on the size of the crystalline grains, anisotropy, etc. There are Fe-Si sheets with oriented crystalline grains and Fe-Si sheets with non-oriented grains.

The quality of the Fe-Si sheets is specified in standards (Table 5.8), where there are proposed as indicators:

The specific losses, measured in W/kg, for certain values of the magnetic induction (for example: P₁₀ corresponds to the specific losses corresponding for 1.0 T, etc.);

5. Magnetic Materials

• **The magnetic induction**, measured in T (Tesla), at different values of the magnetic field intensity (for example: *B*₁₅ corresponds to the magnetic induction measured at a magnetic field with 10 A/cm, etc.).

Quality	P ₁₀ [W/kg]	P ₁₅ [W/kg]	<i>В</i> 25 [Т]	<i>В</i> 50 [T]	<i>В</i> 100 [T]	<i>В</i> ₃₀₀ [T]	d _m [kg/m³]
El-3,5	3.5	8.2	1.53	1.63	1.73	1.98	7800
EII-3.0	3.0	7.1	1.50	1.62	1.75	1.98	7775
Ell-2,6	2.6	6.1	1.5	1.62	1.75	1.98	7775
Ell-2,4	2.4	5.8	1.48	1.59	1.73	1.95	7775

Table 5.8. Electrical Fe-Si sheet types.



5.5.2. Characteristic Parameters

The Fe-Si sheets present characteristic properties of soft magnetic materials described by a series of dependencies and quality indicators.

The characteristic properties of the soft magnetic materials are:

- Saturation,
- Hysteresis cycle,
- Remanence,
- Coercivity,
- Dependence on temperature of the magnetic properties.

Specific dependences for soft magnetic materials are:

- > The magnetization characteristic, which represents the dependence of the magnetic induction \overline{B} on the intensity of the applied magnetic field \overline{H} . This is given, usually, under the form of **the hysteresis cycle**;
- The dynamic characteristic of magnetization, which represents the geometric point of the hysteresis peak cycles obtained through the constant increasing of the magnetization until saturation;
- The characteristic of the magnetic losses, which represents the dependence of total losses (due to hysteresis magnetic effect, to the eddy currents and other supplementary effects that are produced during the magnetization process) with to the magnetic induction.

Quality indicators for soft magnetic materials are:

274

- > **Magnetic permeability** μ is a parameter of the magnetic material, which characterizes the intensity of the magnetization processes in the magnetic material and it is defined as the ratio between the quantity of the magnetic induction and the measure of the applied magnetic field. There are considered the effective magnitude values (r.m.s.) of these quantities.
- > The specific magnetic losses (of re-magnetization) $p_{B,f}$ is an indicator of the sheets quality and there are defined as a ratio between the re-magnetization losses and the mass of the material sample, determined for a certain magnetic induction *B* and at a certain frequency *f* of the magnetization current.

The electrical steel sheets have special performances:

- Saturation is established at high values of the applied magnetic field (the maximal magnetic induction: B_s=1.6÷1.9 T);
- > Remanence is reduced (remanent magnetic induction $B_r=0.1 \div 0.2 \text{ T}$);
- > Reduced coercivity (intensity of the coercive magnetic field: $H_c=10 \div 100 \text{ A/m}$);
- > Pronounced dependency of the magnetic properties with temperature appears at high temperatures (Curie temperature $\theta_C = 760 \div 780^{\circ}$ C).

5.5.3. The Principle of the Measurement Method with Epstein Frame

The measurement method with Epstein frame allows the study of electrical steel sheets properties, generally used in sinusoidal regime of magnetization for:

- a) Raising the dynamic characteristic of magnetization $B_m = f(H_m)$;
- b) Determining the curve of effective magnetic permeability $\mu_{ef} = f(H_{ef})$;
- c) Raising the curve of the specific magnetic losses $p=f(B_m)$.

The Epstein frame is formed by **four solenoids** identically disposed so that they form a square frame. Each solenoid is composed from two windings covered with an insulating non-magnetic material - a primary winding (coil of magnetization/ excitation) and a secondary one (coil of measurement). Inside the coils there are introduced the electrical steel samples, which form a closed magnetic circuit (Fig. 5.28).



Fig. 5.28. The schema of the Epstein frame: 1 - the primary winding; 2 - the secondary winding; 3 - FeSi sheet samples.

5. Magnetic Materials

The Epstein frame together with the electrical steel sheet samples constitutes a mono-phased transformer. Thus, the measurement method is based on the operating principle of the transformer with iron core (Fig. 5.29)



Fig. 5.29. Magnetic circuit realized with the electrical steel sheets.

When the primary winding, having N_1 turns, is supplied with an alternative and sinusoidal voltage u(t), in the Epstein frame core a current $i_1(t)$ is established, and a magnetic field is developed, whose intensity H(t) is given according to the law of magnetic circuit:

$$H \cdot I_m = i_1 \cdot N_1, \tag{5.79}$$

where:

 I_m – the average length of the magnetic circuit, in this case the average length of the FeSi sheet magnetic circuit;

 i_1 – the intensity of the electric current of magnetization,

 N_1 – number of turns of magnetizing coil.

The total magnetic flux Φ which enchains the secondary coil of the Epstein frame is:

$$\Phi(\mathbf{t}) = N_2 \cdot B(\mathbf{t}) S, \qquad (5.80)$$

where:

B(t) – the magnetic induction established in the sample;

S – the cross-section area of the ferromagnetic circuit formed with the electrical steel sheet samples;

 N_2 – number of turns of secondary measurement coil.

In the secondary coil of the Epstein frame, the magnetic flux variation induces a t.e.m. whose instantaneous value is given by the law of electromotive force:

$$u_2 = -N_2 \frac{d\Phi}{dt} = -N_2 \cdot S \cdot \frac{dB}{dt}.$$
(5.81)

The relations (5.79) and (5.81) allow the determination of the r.m.s. value of the intensity of the magnetic field:

$$H_{\rm ef} = \frac{N_1}{I_{\rm m}} \cdot I_1, \tag{5.82}$$

respectively, of the magnitude of the magnetic induction:

$$B_m = \frac{U_2}{4,44 \cdot f \cdot N_2 \cdot S}.$$
(5.83)

In these relations, I_1 is the r.m.s. value of current in primary coil, and U_2 is r.m.s. value of the voltage at terminals of secondary coil.

The connection schema for determining the steel sheet characteristics with the Epstein frame is presented in figure 5.30.



Fig. 5.30. The connection scheme for determining the characteristics with the Epstein frame.

Notes:

- In order to measure the magnetic quantities H_{ef} and B_m it is sufficient to know the geometry of the sample (I_m , S) and of the Epstein frame (N_1 , N_2 , I_m , S) and to measure the electrical quantities (i_1 , u_2).
- A model of table with experimental data and results is presented in Table 5.9.

Table 5.9. Model of sheet with experimental data and results.

Sheet	heet Nr. Int Hat Unit B		Pw			5				
type	crt.	[A]	[A/m]	[V]	<i>В</i> _т [Т]	μ _{ef,r}	<i>k_W</i> [w/div]	α _w [div]	<i>P</i> w [w]	[W/kg]

With the data from Table 5.9, the following characteristics can be raised: $B_m = f(H_{ef}); \ p_{Fe} = f(B_m); \ \mu_{efr} = f(H_{ef}).$

1 5.5.4. Automated Measurements and Results

There is the possibility of automating the measurement sequences and the processing of data for establishing the performances the electrical steel sheets.

The installation DEM-25 from the Brockhaus Company allows the realization of automated measurements with Epstein frame of 25 cm and a single-sheet tester (SST).

Bloc scheme of the components contents (Fig. 5.31):

- Power circuits;
- Control circuits and data acquisition components;
- The measurement device (Epstein or SST).



Fig. 5.31. Bloc scheme of the automation measurement of the magnetic sheets characteristics.

The installation operation: The alternative sinusoidal signal from the signal generator is amplified and it is applied to the primary winding of the measurement system. The signals from the primary and secondary of the measurement device are converted by the A/D converter and transmitted with the acquisition device at the process computer for determining H and B.

The condition of constant maintaining of the voltage wave of sinusoidal form is realized with the control element and the regulator.

The steps and work sequences for establishing the magnetization characteristics are:

- Preparing the sample measurement;
- Establishing the measurement device type;
- De-magnetization of the sample, by increasing the magnetization current until saturation and its decreasing to zero;
- Establishing the measurement operating regime;
- > Starting the measurement by increasing, with a certain velocity of the magnetization current until the wanted value of the magnetic induction $(\rightarrow U_2)$ or of the magnetic field intensity $(\rightarrow I_1)$;
- Acquisition of the data obtained, and their processing.

The DEM-25 installation of the Brockhaus Company allows the automation of the most work sequences:

- the preparing procedure of measurements by de-magnetizing the sample (increasing the amplitude of the magnetized field until its saturation and then with a certain velocity it reduces to zero);
- the starting procedure of the data sample (the introduction as input data of the physical and geometric characteristics of the sample and the measurement device);
- the starting procedure of the magnetization regime (frequency, maximal induction and the intensity of the maximal magnetic field);
- the sampling procedure;
- > the data acquisition procedure (output data: *B*, *H*, μ , *P_s*, *S*, *B_r*, *H_c*, hysteresis cycle, wave forms);
- processing the data with specialized programs.

Thus, it can automatically be obtained the following characteristics: $B_m = f(H_{ef})$;

 $p_{\scriptscriptstyle Fe} = f(B_m) \, ; \, \mu_{\scriptscriptstyle efr} = f(H_{\scriptscriptstyle ef}) \, .$

For magnetization frequencies from 10 Hz to 750 Hz it can be make comparative studies of performances of the electrical steel sheets and other magnetic materials of sheet type.

In figure 5.32 there are illustrated the principal magnetic characteristics for the FeSi steel sheet samples with oriented grains, and with different thickness, of $0.23 \div 0.30$ mm.















Fig. 5.32. Characteristics for FeSi alloy with oriented grains and thickness of 0.23÷0.30 mm: a) dynamic curve $J_m = f(H_{ef})$; b) effective permeability $\mu_r = f(H_{ef})$; c) specific magnetic losses with magnetic polarization $p=f(J_m)$; d) specific magnetic losses with frequency p=f(f).

Note

The quantity J_m has the significance of the magnetic polarisation: $J_m = \mu_0 \cdot M$ and it has the unit of measurement Tesla.

5.6. PROPERTIES AND FIELDS OF USE OF THE SOFT MAGNETIC MATERIALS

5.6.1. Performances and Development Trends

Soft magnetic materials are materials used for concentrating and amplifying of the magnetic field. These materials are characterized by a narrow magnetic hysteresis loop (low coercive fields), high saturation inductions, high values of the magnetic permeability and low magnetic losses. Soft magnetic materials are considered those materials that have the coercive field lower than 1 kA/m.

The use of soft magnetic materials is strictly related to the hysteresis loop characteristics. The **rectangularity factor** k_r of the hysteresis loop is defined as:

$$k_r = \frac{B_r}{B_s} , \qquad (5.84)$$

where B_r is the remanent magnetic induction, and B_s is the saturation magnetic induction.

According to the rectangularity factor, materials can be:

- > Materials having low rectangularity factor ($k_r < 0.5$), that has oblique hysteresis loop. Their magnetic permeability is low and constant relative to the magnitude of the magnetizing field. These materials are used for coils cores that request a constant inductivity;
- > Materials having medium rectangularity factor ($k_r = 0.5 \div 0.8$), that have the hysteresis loop closer to the vertical axis. Their magnetic permeability is high and proportional to *H*. These materials are used for the manufacture of transformer cores, electromagnet cores, etc.
- > Materials having high rectangularity factor ($k_r > 0.8$), that have a rectangular hysteresis loop. These materials are used for the manufacture of magnetic memories and switching devices.

Soft magnetic material performances have increased, once the knowledge about magnetism has increased, and the techniques and technology have been developed.

The first soft magnetic materials were industrially manufactured at the beginning of the 19th century. Afterwards, new materials were elaborated and improvements were made, accordingly:

- Reducing the specific magnetic losses was achieved according to the improvement of the manufacturing and processing technologies. The evolution was:
 - hot rolled Fe-Si sheets, $p_{Fe}=5 \div 1 \text{ W/kg} (1900 1920)$,
 - Fe-Si sheet with non-oriented crystals, *p_{Fe}*=1÷0.8 W/kg (1920 1940),
 - Goss type Fe-Si sheets and thin sheet, $p_{Fe}=0.8 \div 0.2$ W/kg (1940 1970),
 - Amorphous alloys FeSiB, p_{Fe} below 0.2 W/kg (1970 1990).
- Reducing the coercive magnetic field and increasing the saturation magnetic induction. The obtained performances have continuously increased. Thus:

•	for soft ferrites:	<i>H_c</i> =10-100 A/m; <i>B_s</i> =0.4 T;
•	for 70-80%Ni-Fe alloys:	<i>H_c</i> =0.1-100 A/m; <i>B_s</i> =0.8 T;
•	for 40-50%Ni-Fe alloys:	<i>H_c</i> =10-100 A/m; <i>B_s</i> =1.2 T;
•	for Fe-Si alloys:	<i>H_c</i> =100-1000 A/m; <i>B_s</i> =1.7 T;
•	for Fe-Co alloys:	<i>H_c</i> =100-1000 A/m; <i>B_s</i> =2.2 T;

- Reducing the influence of the temperature and of the magnetizing field frequency. New types of materials are being developed. For example, *Vitrovac* is a soft magnetic alloy that contains α-Fe particles in an amorphous phase of FeCuNbB, obtaining magnetic anisotropy constants and low re-magnetization losses, in a large range of temperatures. New materials with larger magnetization frequency have been developed. Thus:
 - Permalloy (50 µm plates) used up to 10 kHz frequency;
 - Vitrovac 6025F (50 µm plates) used up to 1 MHz frequency;
 - MnZn ferrite, used up to 10 MHz frequency, etc.

- Explanation of the magnetization processes for an optimal use. The knowledge acquired allowed the diversification of the working regimes for soft magnetic materials. Thus, it begin to be optimal used magnetic materials for:
 - **Operation in direct current**, when the working point on the *B*=f(*H*) characteristic does not modify;
 - Operation in sinusoidal current, when the working point moves, describing a hysteresis loop for each period of the current;
 - Operation in sinusoidal current with pre-magnetization in direct current, when the working point moves, describing a hysteresis loop for each period of the current, displaced relative to the origin;
 - **Operation in pulses**, when the magnetization processes are specific, according to the shape of the pulse.

The efficacy of the electromagnetic devices depends on both the nature and the dimensions of the used magnetic materials, and on the type of the magnetization regime and the circuit parameters. Further on, some performances of the most used soft magnetic materials in electronics and electrotechnics will be presented.

Δ

5.6.2. Iron as a Soft Ferromagnetic Material

The denomination of **soft iron** is used for the iron with low carbon content, although other types of steel have the same name. Soft iron, delivered in different forms and dimensions (bars, sheets, tubes, etc.), can be:

- Pure chemical iron that has very good magnetic characteristics. Still, because of its high price, it is not a practical material;
- Pure technical iron is obtained by heating the iron close to the melting point in a hydrogen atmosphere, eliminating, by diffusion, the impurities. It does not present interest for industrial applications due a too high price;
- Electrolytic iron is made of particles, having a high purity. It is mostly used for the manufacture of Alni and Alnico alloys for permanent magnets;
- Carbonyl iron is obtained as a fine powder from liquid iron penta-carbonyl Fe(CO)₅. The particles have spherical shape, which represents an advantage, because there are no isolation breakdowns. It is used for obtaining, by pressing, the high frequency magnetic cores, sintered Alni and Alnico magnets;
- Swedish iron, Armco iron and low carbon iron. These types of iron differ from each other by the impurity percentage. The Swedish iron is obtained from extra pure cast iron and has low carbon content (about 0.03% C). Armco iron is usually made of Swedish iron through hydrogen injection. The magnetic characteristics increase when the impurities are reduced. Low carbon iron, also called soft iron, is less pure than Armco iron.

The magnetic characteristics of different types of iron are shown in Table 5.10.

	Relative p	Coercive field		
Material	initial	maximum	<i>H</i> _c ,	
	μ _{ri}	μ _{r<i>max</i>}	[A /m]	
Pure technical iron	250	7000	64	
Electrolytic iron	600	15000	28	
Carbonyl iron	3300	21000	6,4	
Electrolytic iron vacuum molten	-	61000	3,2	
Pure technical iron	-	142000	0,8	

It has to be taken into consideration that the mechanical processing will damage the magnetic properties of these types of iron. This is the reason why different thermal treatments are recommended in order to increase the magnetic characteristic performances. For example:

- for the ferromagnetic cores of the relays, a thermal treatment at 820 ± 10°C in a hydrogen atmosphere is recommended;
- in order to obtain superior values of the magnetic induction, some types of Armco iron are treated in a hydrogen atmosphere at temperatures between 1150°C and 1300°C.

Different types of soft iron are used for the manufacture of polar pieces, yokes for electromagnets, cores for coils, relays, magnetic screens, breaks and electromagnetic couplings, electromagnetic plates, diffusers armatures with permanent magnets, measuring devices, etc.

Λ

5.6.3. Steel and Soft Magnetic Cast Iron

Steels are used for the manufacture of magnetic circuits that require superior mechanical characteristics. These materials have high magnetic saturation induction (1.4 ÷ 2) T, but low magnetic permeability ($\mu_r max = 2000$) and high coercive field (2 kA/m).

Alloyed steels that contain chromium-nickel, nickel-vanadium, nickelmolybdenum and chromium-scandium are used when there are special mechanical requirements.

The mechanical and magnetic characteristics for some low carbon steels are shown in Table 5.11.

Types	Composition	Composition		Hardness	Perme μ [T/	Permeability μ [T/kA/m]	
	[/0]	[kgf/mm ²]	[/0]	נייין	at 1 T	at 1 T	
	Α	- for electric	cal machines	S			
Steel as rolled and welded	0.4-0.55 Mn 0.2 Si	35-40	20-24	105-135	2.25	0,112-	
tubes	P+S traces					0,125	
E	B - used for n	nagnetic po	les of elect	ric machin	ies		
Soft steel in bright drawn bars	0.08-0.15 C 0.4-0.55 Mn	35-40	20-24	105-135	2.25-2.5	0,112- 0,125	
	C - used	for rotors o	of electric m	achines			
Steel sheet 0.4÷0.5 mm	0.2-0.25 C 0.25 Mn 0.9-1.05 Si P+S < 0.2	35-40	20-24	-	4.25- 4.37	0,15- 0,162	

Table 5.11. Mechanic	al and magne	tic performance	s for some	low carbon steels.
	a and magne	lio poriornarioo		

Cast irons have inferior characteristics compared to steels, but are cheaper. Their magnetic characteristics vary very much according to their nature and structure. For example, cementite has $H_c = 8$ kA/m, while the ferritic cast iron or α -iron have $H_c \leq 200$ A/m.

The magnetic properties of cast iron vary with the impurity content. Thus, phosphorus increases the coercive field and decreases the permeability; manganese and sulphur reduce the saturation induction and the permeability and increase the coercive field, carbon as cementite decreases all the magnetic characteristics (Table 5.12).

Material		Co	Br	H _c			
	С	Si	Mn	S	Р	[T]	[kA/m]
Cast iron 1	3.45	1.51	0.43	0.08	0.08	0.7	0.240
Cast iron 2	3.45	1.58	0.44	0.08	0.51	0.84	0.52
Cast iron 3	3.77	1.99	0.6	0.07	0.16	1.1	0.200
Cast iron 4	3.87	1.90	0.01	0.06	0.03	1.18	0.450

Table 5.12. Composition and properties of some soft magnetic cast irons.

Cast irons are mostly used for the manufacture of cases, yokes and polar pieces of electric devices.

5.6.4. Fe-Si Alloys

Soft iron has the disadvantage that in alternative fields the magnetic losses are higher (approx. 20 W/kg for induction of about 1.5 T) and it is subjected to magnetic ageing.

By alloying the iron with silicon, the losses through hysteresis and eddy currents are reduced considerably, and the ageing phenomena practically disappear. Thus, **iron-silicon alloys** are obtained, that have good magnetic properties, known as **electrical steel sheets**.

For the sheets that have silicon content up to 6%, the magnetostricton energy becomes practically zero, internal tension are absent, determining a high permeability.

The silicon content is though limited by material processing possibilities, thus the iron addition is used up to 3.3% for cold rolling, and up to 4.5% for sheet stamping.

The influence of the carbon content on the coercive field, the hysteresis losses and the magnetic susceptibilities for iron-silicon alloys containing 3% C (curve 1), 4% C (curve 2) and 5-6% C (curve 3) are shown in figure 5.33.

A high carbon percentage increases the coercive field and the hysteresis losses and decreases the magnetic permeability. A high bismuth percentage prevents a significant variation of these parameters when the carbon content increases.



Fig. 5.33. Carbon influence on the coercive field, specific hysteresis losses and on the magnetic permeability for Fe-Si alloys containing 3% Si (curve 1), 4% Si (curve 2) and 5-6% Si (curve 3).

Iron-silicon alloys are used as sheets (in order to reduce the losses through eddy currents), bars or different profiles, as different types:

Hot rolled silicon sheet is manufactured with a silicon content between 0,5 and 4.5%. The sheets with various thicknesses are obtained from iron-silicon blocks through rolling and successive annealing. After having obtained the required

dimensions, a short thermal treatment is applied (800°C), followed by a slow cooling, due to which the crystalline grains increase and the internal tension decrease.

Low alloyed sheet (up to 1% Si) has high saturation induction, and super-alloyed sheet (more than 4% Si) has low specific losses. The carbon content is inferior to 0.08% for E I and E II sheets and to 0.07% for E III and E IV sheets (STAS 673-60) (E I and E II are commercial denominations). Standard values are shown in Table 5.13.

Fe-Si sheets type	Thickness	Si content	Density	Specific losses [W/kg]		ity Specific losses [W/kg]			gnetic ir nagneti [kA/n	nduction zation fi n] of:	i [T] elds
-71	[mm]	[%]	[kg/m³]	p ₁₀	p 15	2.5	5.0	10.0	30		
E I-3.6	0.5	0.7	7850	3.6	8.6	1.53	1.63	1.75	1.98		
E I-3.2	0.5	1.0	7800	3.2	7.5	1.60	1.62	1.75	1.98		
E II-2.8	0.5	1.7	7800	2.8	6.5	1.50	1.62	1.75	1.98		
E III-2.5	0.5	2.3	7700	2.5	6.1	1.48	1.59	1.73	1.95		
E III-2.2	0.5	2.3	7700	2.5	5.3	1.48	1.59	1.73	1.94		
E III-2.0	0.5	2.7	7700	2.0	4.9	1.46	1.57	1.72	1.92		
E IV-1.8	0.5	3.4	7700	1.8	4.4	1.46	1.57	1.71	1.92		
E IV-1.6	0.35	3.9	7600	1.6	3.9	1.46	1.57	1.71	1.92		
E IV-1.4	0.35	3.9	7600	1.4	3.4	1.46	1.54	1.71	1.90		
E IV-1.3	0.35	4.3	7600	1.3	3.1	1.46	1.57	1.69	1.89		
E IV-1.2	0.35	4.3	7550	1.2	2.9	1.45	1.56	1.69	1.89		
E IV-1.1	0.35	4.3	7500	1.1	2.7	1.44	1.55	1.69	1.89		
E IV-1.0	0.35	4.3	7550	1.0	2.6	1.44	1.55	1.69	1.89		
E IV-0.9	0.35	4.3	7550	0.9	2.4	1.44	1.55	1.69	1.89		

Table 5.13. Types and performances of Fe-Si sheets.

> Cold rolled, textured silicon sheet. Obtaining the textured sheet involves the orientation during the manufacturing process along an axis of the iron crystals (obviously, the easy magnetization axis, [100]) towards the lamination direction. Thus, a **Goss structure** is obtained. Introducing the sheet in a magnetic field whose direction coincides with the lamination direction (that now presents an easy magnetization direction), the sheet is easily magnetized, the magnetic permeability being very large, and the specific losses at 1 T are lower ($p_{10} < 0.6$ W/kg).

The variation curves for the re-magnetization specific losses p_{Fe} with magnetic induction *B* for the Fe-Si sheet having 0.35 mm thickness are shown in figure 5.34: for a hot rolled type (curve 1) and for a type with oriented grains (curve 2).



Fig 5.34. Variation of the re-magnetization specific losses with the magnetic induction for 0,35 mm Fe-Si sheets, hot-rolled (curve 1) and textured (curve 2).

A significant decrease of the specific losses can be noticed for the textured sheet type. But if the direction of the magnetizing field differs from the lamination direction, the specific losses increase, and can take even greater values than in the case of a hot-rolled sheets.

Notes:

- Goss structure textured sheets, used for the manufacture of transformers, cannot be used for the manufacture of rotating electric machines, where the direction of the magnetic flux permanently changes.
- For the construction of rotating electric machines, the textured cubic sheets can used, due to its high permeability and low losses both in the lamination direction and in a direction perpendicular to it.
- The main characteristics of the textured sheets are $B_s = 2.03$ T, $H_c = 16$ A/m.
- The textured sheets are very sensitive to the mechanical stresses and treatments: for example, the maximum magnetic permeability decreases 2.5 times when the pressure is increased from zero to 10⁵ N/m². Thus, after some mechanical processing has been made, the sheets are subjected to thermal treatments at temperatures between (790 ÷ 800)^oC, in order to increase their performances.

For reducing the eddy currents losses, the Fe-Si sheets are isolated from each other, by various meanings:

- by oxidation,
- by paper insulating,
- by varnishing,
- by ceramic oxides covering.
Isolation by oxidation is used for the hot-rolled sheets. As the resistivity varies according to the applied pressure, high pressures must be avoided for assembling the sheets, which leads to a relatively low filling factor.

Isolation by paper is made by applying the paper on one side of the sheet, the thickness of the paper being about 0.03 mm. Sometimes special electroinsulating paper is used, having only about 13 μ m thickness.

Varnish isolation ensures an isolation thickness of about 0.02 mm and a very good resistivity (almost ten times greater than the one obtained through oxidation). The isolation of the textured sheet is made with **ceramic oxides** (Carlit) or with films based on phosphates. As the isolating, layers are very smooth and thin, thus, the magnetic cores made of textured sheets will be characterised by high values of the filling factor $(0.96 \div 0.97)$.

In the industrial application, other Fe-Si alloys are also used.

- Silicon sheet with nickel contains 5% Si and 5.5% Ni, is hot rolled, isotropic, and it is used in the rotative electric machines manufacturing;
- Silicon sheet with aluminium contains (2-3)% Si and (2-3)% Al, is cold rolled, isotropic, and has very high magnetic permeability;
- Sintered iron silicon alloys contain (6-9)% Si, having low values of the anisotropy and of the magnetostricton constants. The alloy having 9% Si has $\mu_{rmax} = 10800$, $H_C = 17.2 \text{ A/m}$, $B_r = 0.6 \text{ T}$, $p_{10} = 0.41 \text{ W/kg}$;
- Aluminium-silicon-iron alloys (Alsifer) contain 7.5% Si, 5.5,% Al and 87% Fe, have negative temperature variation coefficient of the resistivity, and properties resembling to those of nickel-iron alloys. They are processed by sintering. It has to be mentioned that iron-aluminium alloys, having 16% Al and very low impurity content (<0.0025% C), have remarkable properties: $\mu_{ri} = 4000$, $\mu_{rmax} = 10^5$, $H_c < 0,002$ kA/m, $B_s = 0.8$ T. They are hot rolled, are isolated by oxidation and can be agglutinated by tinning.

5.6.5. Fe-Ni Alloys

Iron-nickel alloys are high performance soft magnetic materials, having very high magnetic permeability (~ 2 H/m), low hysteresis losses and much reduced coercive field (~ 0.3 A/m).

The properties of these alloys vary very much with the nickel content. Thus, alloys having a high nickel content $(65\div70)$ % Ni have very large permeability, low coercive field and hysteresis losses, but have relatively low saturation induction and B_r/B_s ratio ($B_s \approx 1$ T). The alloys having a low nickel content, below 35% Ni, have low permeability (below 9 mH/m), but high resistivity and, thus, low eddy currents losses.

By adding low quantities of Mo, Co, Cu, Cr, Ti, etc., new alloys having better characteristics are obtained. For example, a 2% Mo content determines an increase of

the alloy permeability (in the same time, the resistivity is also increased), and if Cu and Co are also added, alloys having constant permeability are obtained.

The Fe-Ni types are defined by the nickel content:

- Fe-Ni alloys having high nickel content (76÷79% Ni) are characterised by high values of the magnetic permeability (0.13÷2 H/m), low coercive fields (0.015÷5 A/m) and low re-magnetization losses (0.015÷0,046 W/kg at 0.5 T), and also by low values of the saturation inductance (0.8 T). They are ductile, and can be laminated at much reduced dimensions. Several commercial denominations are known: Permalloy, Supermalloy, Mumetal, etc. (Table 5.14). By eliminating unfavourable impurities (O, C, etc.), alloys having zero magnetostriction and anisotropic constants are obtained.
- Fe-Ni alloys having medium nickel content (65÷50% Ni) have rectangular hysteresis loop. These materials are obtained by cold rolling, followed by a series of thermal treatments (quick heating for recrystallization, cooling in a magnetic field, etc.) of some alloys based on nickel (Permalloy, Deltamax, Rectimphy, Dynamax etc.) or even of the textured sheet (Table 5.14).
- Fe-Ni alloys having lower nickel content (45÷30% Ni) have constant magnetic permeability. These alloys with lower nickel content are obtained by special processes of complete crystallization. Perminvar alloys that contain only nickel and iron are used only in weak magnetic fields. If Cu or Co is added, then these alloys can be used in magnetic fields up to 8 kA/m (Table 5.14).

Comparative characteristics of some soft magnetic materials are shown in the Table 5.14.

Matarial	Co	mposition, %			H _c	Bs
Material	Fe Other elements		μ_{ri}	µr max	[kA/m]	[T]
Iron	99.9	-	200	5000	0.08	2.15
Iron-Silicon	96	Si-4	450	8000	0.048	1.97
Alsifer	85	Si-9	30000	120000	0.004	1.0
Permalloy 78	21.5	Ni-78.5	8000	100000	0.004	1.0
Cr-permalloy	17.7	Ni-78.5	5 120000		-	0.8
Mo-permalloy	alloy 16 <i>Ni-78.5</i>		12000	120000	0.0032	0.87
Mumetal	17	Ni-76 Cu-4 Mo-3	25000	110000	0.0016	0.8
Supermalloy	Supermalloy 15.5 Ni-79 (Mn+Si)-0.5 (Mn+Si)-0.5		100000	800000	0.016·10 ⁻³	0.8
Dynamax (B _r /B _s = 0.95)	32.7	Ni-65 Mo-2 Mn-0.3	-	1530000	0.4·10 ⁻³	1.26

Table 5.14. Performances of Fe-Ni alloys and other feromagnetic materials.

Rectimphy (B _r /B _s = 0.96)	49	Ni-50	-	100000	0.011	1.6
Perminvar	20	Ni-45 Co-25 Mo-7	-	3800	0.04	1.03
Permenorm	64	Ni-36	2000	7000	0.065	1.3
Permendur	49	Co-49	800	5000	0.16	2.36
Supermendur (anisotropic)	49	Co-49 V-2	800	100000	-	2.35

It must also consider the materials for thin shells and ferromagnetic films, obtained from Fe-Ni alloys or from pure ferromagnetic elements. They have low eddy currents losses and rectangular hysteresis loop; the magnetization is realised only by rotating the magnetic moments. These materials are used for the manufacture of electronic devices with fast switching, magnetic memories, computers, etc.

Special properties alloys

Special categories of soft magnetic materials are used due to their special performances they exhibit when they are magnetized under certain conditions.

Thermo-magnetic alloys

These alloys are usually liquid solutions based on nickel, containing iron, chromium, silicon, Ni-Fe, Ni-Fe-Cr, Ni-Cu, Ni-Si-Fe type, that have highly temperature dependent properties, in certain variation domains.

Thermo-magnetic alloys have very low Curie temperature (below 100°C) and negative resistivity temperature variation coefficient. As the magnetic induction varies with temperature, these materials are used in the manufacture of magnetic shunts for compensating temperature errors in measuring devices.

These materials have very low saturation induction $(0.2 \div 0.3)$ T. The most known are Calmalloy (70% Ni, 30% Cu), Thermalloy (70% Fe, 30% Ni) and Compensator (57% Fe, 35% Ni, 8% Cr).

Magnetostrictive materials

For these materials, the magnetostriction phenomenon is very intense. The dimensional variations of the magnetostrictive materials introduced in a magnetic field are positive or negative, according the variation of the geometrical dimensions. Magnetostriction depends on the nature of the basic material and on the impurity content. Thus, for the iron, a 10% aluminium addition increases significantly the magnetostriction coefficient.

The variation of the magnetostriction coefficient in the case of iron, nickel and cobalt are shown in figure 5.35.



Fig. 5.35. Variation of the magnetostriction coefficient in the case of iron, nickel and cobalt according to the magnetic field strength.

Notes:

- In the case of iron, for lower magnetic fields, the magnetostriction coefficient has positive values (iron dilates) and for higher values of the magnetic field, it has negative values (iron contracts).
- The maximum value of the magnetostriction coefficient is obtained for magnetizing fields of a frequency f_0 equal to a resonance proper frequency of the material (the resonant frequencies are in the range of $f_0 = 5 \div 100 \text{ kHz}$).

Magnetostriction materials are Ni ($\lambda < 0$), Co ($\lambda = 0$), Ni-Fe, Ni-Co, Co-Fe, Fe-Pt ($\lambda = 18 \cdot 10^{-5}$) and Fe-Al alloys, some ferrites and especially alloys of iron with terbium (**TbFe**₂) or erbium (**EbFe**₂), for which λ is 16 times greater than in the case of ferrites or of Fe-Pt alloys.

These materials are used for the manufacture of sonic and ultra-sonic generators, for water purification, acceleration of chemical reactions, welding plastics, etc.

5.6.6. Soft Magnetic Ferrites

Unlike the ferromagnetic materials, ferrites present the advantages of high resistivity and high stability of the magnetic characteristics. The disadvantages are related to the low values of the magnetic saturation induction (< 0.6 T), of the Curie temperature ($60 \div 450^{\circ}$ C), and to the difficult processing (they are hard and brittle).

In the case of the ferrites, both the saturation induction and the magnetic permeability are temperature and frequency dependent. Hysteresis losses also, exhibit maximum values for frequencies close to the resonant proper frequency.

Manganese-Zinc and **Nickel-Cobalt** ferrites have multiple technical applications. Different performances can be obtained in the case of these ferrites, according to the chemical composition and treatments applied (Table 5.15). There are

obtained high magnetic permeability values, very low or very high anisotropy and magnetostriction constants, narrow or rectangular hysteresis loops.

Proporty				S	Soft Ferr	ites				
Fioperty	MZ-1	MZ-2	MZ-3	MZ-4	MZ-5	MZ-6	MZ-7	NC-4	NC-5	NC-6
Initial permeability μ _{ri}	400	1000	1200	1250	1500	2200	1500	50	80	120
Frequency domain, <i>f</i> , kHz	0.02-1.5	-	0.004-0.2	0.001- 0.2	0.001- 0.1	0.001- 0.1	-	10-50	3-30	15-10
Saturation magnetic induction <i>B</i> in T, la <i>H</i> =3 kA/m	0.38	-	0.38	0.42	0.38	0.40	0.30	-	-	-
Resistivity ρ, Ωcm	10 ²	-	10	10 ²	10 ²	10 ²	-	3.10 ⁶	3.10 ⁶	3.10 ⁶
Curie temperature, °C	180	210	130	210	170	150	200	450	400	300
Half-finish materials	cylindrical core	Core U+I	Deflection core TV	tube cylinder	core ladle	E	U+T	Cylindi ad	rical co justmer	re with nts

Table 5.15. Manganese-zinc and nickel-cobalt ferrites performances.

Ferrites are especially used in the high frequency range: coil cores, magnetic memories and amplifiers, antennae, TV transformers, etc.

M 5.6.7. Magneto-Dielectric Materials

Magneto-dielectrics are made of ferromagnetic or ferrimagnetic grains included in a dielectric. Due to the reduced dimensions of the grains and to the high resistivity of the dielectric, the eddy currents losses are very low, so that the magneto-dielectrics are used in the high frequency range. There are:

- Thermo-rigid magneto-dielectrics (based on shellac, polyesters, bakelite, etc.) are brittle materials, having low coercive field and relatively low permeability (tens, hundreds) and they are used for the manufacture of coil cores and transformers.
- Thermo-plastic magneto-dielectrics (based on rubber, PVC, PE, etc.) have high elasticity and low magnetic permeability, being used in the manufacture of magnetic screens, as microwave absorbents, etc.

The properties of the magneto-dielectrics depend both on the nature and contents of the magnetic materials, and on the binder (dielectric) characteristics. Thus, by using carbonyl iron or ferrite grains, there are obtained materials having relative permeability in the range of units as for **Alsifer** (7÷8% Al, 9÷10% Si): μ_r = 10÷90, and as for **Permalloy**: μ_r = 10÷200. The content of the dielectric is between 4 and 8% for magneto-dielectrics having μ_r = 40.

5.7. PROPERTIES AND FIELDS OF USE OF THE HARD MAGNETIC MATERIALS

5.7.1. Characteristic Parameters of the Materials Used for Permanent Magnets

Hard magnetic materials keep the magnetization state after the ends of the magnetic field action. These materials are used in the manufacture of permanent magnets, used for generating magnetic fluxes in open or closed magnetic circuits, replacing excitation coils.

Hard magnetic materials are characterised by large hysteresis loops, having high remanent inductions B_r and coercive fields H_c . The maximum value of the product (*BH*), called **quality index** and denoted by $(BH)_{max}$, increases as the hysteresis loop becomes wider and approaches the rectangular shape.

Note:

The denomination soft or hard magnetic material refers especially to the magnetic characteristics, and not to the physical hardness of the materials. Certain alloys in the manufacture of permanent magnets have lower hardness than a series of cast irons and steels used as soft magnetic materials.

The performances of hard magnetic materials are expressed by a series of characteristics and curves:

- > **Demagnetization curve** is the corresponding portion of the magnetic hysteresis loop B = f(H) of the second quadrant in which the working point of the permanent magnet $P_m(H_m, B_m)$ is defined;
- Remanent induction B_r is the value of the magnetic induction which corresponds to the maximum magnetic flux that can be generated by the magnet. B_r depends on the nature and domain structure of the material, on the demagnetizing factors, on the temperature. Usual values are 0.2 T; 1.7 T; 2.5 T;
- ➤ Coercive field intensity H_c characterises the manner in which the magnet opposes to the demagnetizing factors. The magnitudes that define induction coercive magnetic field intensity and magnetization coercive magnetic field intensity, respectively, depend on the material nature and structure, on the applied thermomagnetic and thermo-mechanical treatments. These magnitudes are defined on the B=f(H) curve , and M=f(H), respectively. The usual values are 4÷200 kA/m;
- ▶ Magnetic energy density curve (BH) = f(B) and (BH) = f(H) represent the dependence of the (BH) product on *B* and *H*, respectively. This curve exhibits a maximum called **quality index**, that means the maximum value of the volumetric energy stored by the magnet, measured in kJ/m³ or MGs.Oe (1 MGs.Oe = 8 kJ/m³).

The typical characteristic curves for a hard magnetic material are shown in figure 5.36.





The quality index can be appreciated by computing the area of the rectangle determined by the parallel lines that pass through the remanence and coercivity points and dividing it to two (Fig. 5.36).

The usual values of the quality index are:

 $(BH)_{max} \sim (B_r H_c)/2 = (1.2 \text{ T}. 4 \text{ kA/m})/2 = 2.4 \text{ kJ/m}^3 - \text{for martensitic steels}$ $(BH)_{max} \sim (B_r H_c)/2 = (0.3 \text{ T}. 200 \text{ kA/m})/2 = 30 \text{ kJ/m}^3 - \text{for barium ferrite};$ $(BH)_{max} \sim 300 \text{ kJ/m}^3 - \text{for neodymium-iron-boron}.$

5.7.2. Establishment of the Operation Point for Magnets

The magnetic fields generated by permanent magnets are concentrated in a small volume, usually a functional air gap, which must be optimally designed regarding the materials properties and shape of the magnet. The amplitude of these fields depend on the remanent induction of the magnet, on the demagnetising curve shape, on the specific energy density that can be accumulated in the magnet volume and on the geometry of the circuit in which the permanent magnet is placed.

Usual, a magnetic circuit with permanent magnets (Fig. 5.37) contains the **magnet** (1), made of hard magnetic material, and behaving as a magnetic field source, **polar pieces** (2), made of soft magnetic material for directing and concentrating the field lines in the **air gap** (3) of the circuit.



Fig. 5.37. Magnetic circuit with permanent magnet and air gap.

In order to use the hard magnetic material as a permanent magnet, the former **is first formed**. The states through which a hard magnetic material passed until it is used as a permanent magnet are shown in figure 5.38:

- P_s state corresponds to the magnetization state at saturation, that is obtained by placing the magnet in a magnetizer where a magnetizing current passes, which leads to the formation of the magnet;
- P₀ state corresponds to the rest state, when the magnet is placed in a closed magnetic circuit;
- P_m state is the operating state, when the magnet is introduced in the working state, provided with air gap.



Fig.5.38. Forming the magnet and establishing the operating point on B=f(H) curve.

The hard magnetic material is first introduced in a magnetizer circuit (with solenoids, electromagnets, in pulses, etc.). This step is described in figure 5.38 by the circuit corresponding to P_s state. When a current *I* passes through coil 3 of the magnetization circuit, the magnetic field in the magnet will be H_s . On the magnetization curve in figure 5.38, this state corresponds to the displacement of the operating point on the first magnetization curve, from the demagnetization state (point 0) in the magnetic saturation state (point P_s). It has to be mentioned that in the magnetizer, a high intensity magnetic field is established, $H_s >> (3\div5) H_c$.

After the magnetization at saturation, the magnetization current is interrupted, the hard magnetic material is placed in a closed magnetic circuit, corresponding to P_0 **state**. On the magnetization curve in figure 5.38, this state corresponds to the displacement of the operating point from P_s to P_0 . The permanent magnet is short-circuited by the soft ferromagnetic armatures, so that it constantly maintains a remanence state (if ageing processes do not intervene).

When the magnet is placed in the working circuit (with air gap), that corresponds to P_m point, the energy accumulated by the magnet will be used to produce a magnetic flux in the air gap. As the magnetic field in the magnet has an opposite direction to the field in the air gap, the operating point P_m will be established on the portion from quadrant II of the B=f(H) curve, according to the magnetic material nature and the circuit geometry.

Some relations lead to the important remarks for establishing the operating point:

> For the P_m state, the magnetic circuit law can be written:

$$\oint_{\Gamma} \overline{H} \cdot d\overline{I} = 0.$$
(5.85)

By computing the integral on the Γ contour, formed by the soft core portion (the magnetic voltage across the soft ferromagnetic armatures is neglected), the length of the magnet I_m , the air gap length I_{δ} , there results:

$$\int_{I_m} \overline{H}_m \cdot d\overline{I} + \int_{I_\delta} \overline{H}_\delta \cdot d\overline{I} = 0.$$
(5.86)

By considering uniform fields, the expression of the magnetic field intensity in the magnet is obtained:

$$\overline{H}_{m} = -\frac{I_{\delta}}{I_{m}} \cdot \overline{H}_{\delta} \,. \tag{5.87}$$

Relation (5.87) underlines that the magnetic field strength in the magnet has an opposite direction relative to the field strength in the air gap H_{δ} . This field is therefore called **demagnetizing field**.

For the magnetic circuit corresponding to P_m state, the magnetic flux law can be written. Considering that there are no leakages:

$$B_{\delta} = B_m \frac{S_m}{S_{\delta}}, \qquad (5.88)$$

where B_m and B_δ represent the magnetic inductions in the magnet and the air gap, respectively, and S_m and S_δ are the areas of the cross sections of the magnet and air gap, respectively.

> The analytic expression of the **load line** Δ is obtained with relations (5.87) and (5.88):

$$B_m = -\frac{I_m}{I_\delta} \cdot \frac{S_\delta}{S_m} \cdot \mu_0 H_m.$$
(5.89)

This relation can also be written as:

$$B_{\rm m} = -\pi_{\rm m} \mu_0 \mathcal{H}_{\rm m} \,, \tag{5.90}$$

where $\pi_{\rm m}$, defined by relation:

$$\pi_{\rm m} = \frac{I_{\rm m}}{I_{\delta}} \cdot \frac{S_{\delta}}{S_{\rm m}} , \qquad (5.91)$$

is called **magnetic circuit permeance**. The inverse of this magnitude represent the **demagnetisation factor** Δ_m .

> The operating point P_m is obtained by intersecting the load line Δ with the B = f(H) characteristic of the magnet (Fig. 5.39).



Fig. 5.39. The influence of the air gap length on the operating point.

Notes:

- Relation (5.88) underlines that to a larger air gap corresponds a lower slope of the load line Δ, so that the functioning point is displaced towards greater values of the demagnetizing field.
- A lower air gap corresponds to a higher slope of the charge line (Fig. 5.39).
- For a small air gap (closed circuit, $I_{\delta} \cong 0$) the functioning point reaches the remanence point.
- For a large air gap (open circuit, I_δ ≅ ∞), the functioning point tends to the coercivity point.
- When the air gap increases the operating point is displaced towards the coercivity point, and the magnetic induction reduces.

5.7.3. Operation Regimes for Magnets

According to the air gap type, permanent magnets operate in static or dynamic regime.

a) Static operating regime. This is the case of the magnets used for the manufacture of measuring devices, acoustic diffusers, when the equivalent magnetic circuit has constant air gap. According to relation (5.89), for a constant air gap, the slope of the load line remains unchanged and the operating points remains in the same position P_m . This is the static operating point.

b) Dynamic functioning regime. This is the case of the magnets used for the manufacture of the electric devices with permanent magnets of the transducers with variable reluctance, etc., where the equivalent magnetic circuit has variable air gap. For a magnetic circuit having variable reluctance, the position of the dynamic operating point will be displaced on the magnetization characteristic according to the position of the air gap. For example, the magnetic circuit in figure 5.40a is made of a mobile piece 2 that rotates in the air gap of the polar pieces 1, that are intended to concentrate the magnetic flux generated by magnet 3.



Fig. 5.40. Dynamic operating regime of permanent magnets: a) magnetic circuit with variable air gap; b) demagnetization curve of the magnet and the load lines.

When the mobile pieces rotate, the magnetic flux that crosses this piece varies with time. For the case in figure 5.40a, when the air gap is obscured by the mobile piece 2 (position A), it may be assumed that the magnet provides magnetic flux corresponding to P₁ operating point, of induction B_1 , this point being given by the intersection of B = f(H) curve with Δ_1 operating (load) line (Fig 5.40b). This line corresponds to a maximum of the permeance, for the case when the core is completely introduced in the circuit.

5. Magnetic Materials

During the rotation of the piece and fixing it in B position (in figure 5.40a), the air gap increases and the slope of the load line diminishes. Thus, if the core is rotated with 90^{\circ}, the air gap permeance reaches the minimum value, and the reluctance is maximum, the operating point of the magnet reaches the P₂ position, corresponding to the load line Δ_2 .

If the rotation continues, the air gap permeance tends again to a maximum value corresponding to recoil line Δ_1 , but the working point and the recovery, respectively are not made at the initial position, the magnetic induction reaching only B_2 value.

By continuing the rotation, the operating point describes a new branch of the magnetizing cycle. After several rotations, the described cycle stabilizes, the variation of the magnet induction being between B_2 and B'_2 . For this magnetic circuit, according to the position of the air gap, the dynamic operating point will displace between the Δ_1 and Δ_2 load lines. Thus, working with variable air gap, the operating point does not displace on the fundamental demagnetization curve, but on a minor cycle.

As the minor cycle is sufficiently narrow, it is usually approximated by a line, called recovery line. This is defined as a line having the slope equal to the slope of the tangent at the demagnetization fundamental curve in a given point. The slope of the recovery line has a physical meaning of return or recoil permeability, defined by relation:

$$\mu_{rrev} = \frac{1}{\mu_o} \frac{\Delta B}{\Delta H}.$$
(5.92)

The usual values for the recoil permeability are 1.2÷9. An ideal magnet is a magnet that has μ_{rrev} as close to 1 as possible.

If the mobile armature is removed, the operating point is determined by Δ_3 line. When the core is completely introduced or removed, the operating point moves between Δ_3 and Δ_1 lines.

The temperature has a great influence on the position of the operating point; the permanent magnet no longer operates on the fundamental demagnetization curve, but on the corresponding recovery lines.

W 5.7.4. Designing and Selection Criteria for Permanent Magnets

There are numerous methods for dimensioning magnets from circuits with permanent magnets for which various optimisation criteria are applied.

An efficient optimisation criterion is the **energetic criterion**. The magnetic circuit is dimensioned so that the operating point P of the magnet to coincide with the maximum specific energy point. This criterion, also called **Evershed criterion**, correspond to a minimum volume necessary for the magnet.

For a simple magnetic circuit, as the one in figure 5.32, a relation is established between length I_m and section S_m , and length I_{δ} and section S_{δ} :

$$I_m = I_\delta \frac{H_\delta}{H_m}, \qquad (5.93)$$

$$S_m = S_\delta \frac{B_\delta}{B_m}.$$
(5.94)

Using these relations, it can be obtained the necessary volume of the magnet according to the air gap volume and the magnitudes corresponding to the magnetic field in the magnet and in the air gap:

$$V_m = V_\delta \cdot \frac{H_\delta B_\delta}{H_m B_m}.$$
(5.95)

Therefore, the volume of magnetic material necessary for obtaining a certain magnetic field in the air gap decreases as the product $(H_m B_m)$ increases.

When the magnet operate in a point characterised by maximum energy density $(B_m H_m)_{max}$, relation (5.95) becomes:

$$V_{mmin} = V_{\delta} \cdot \frac{\mu_0 H_{\delta}^2}{(B_m H_m)_{max}} \,.$$
(5.96)

Thus, an optimal magnetic circuit dimensioning corresponds to a correct choice of the magnet and to establishing of air gap permeance value such that the operating point is placed on the B = f(H) curve, corresponding to quality index $(B_m H_m)_{max}$.

Note:

For the same value of the specific energy, thus, for the same operating point, there are infinite possibilities for choosing length I_m and section S_m of the magnet, according to length I_{δ} and section S_{δ} of the air gap.

In order to facilitate the dimensioning calculus of the circuits with magnets, the manufacturers give data relative to the energy provided by the magnets as parabola network, each corresponding to a specific energy given by product, and as a load lines network having the slope:

$$\rho = \frac{B_m}{\mu_0 \cdot H_m}.$$
(5.97)

In the catalogues from the magnets manufacturer companies, the demagnetization curves are given for different values of the recoil line slope (Fig 5.41).



Fig. 5.41. Demagnetization curve for the barium ferrite at different demagnetization factors and different magnetic energy densities.

It has to be noticed that not only the quality of the used magnet and the magnetic circuit dimensions, but also the position of the magnet relative to the polar pieces dictate the optimal functioning of the devices with magnets.

Thus, two Alnico 5 magnets, disposed in a magnetic circuit in several manners, will produce different inductions in the air gap (Fig. 5.42).





Г

b)

N

S-N-S

Fig. 5.42. The influence of the magnet disposal on the magnetic induction existent in the magnetic circuit air gap: a) the magnet disposed in front of the air gap; b) the magnet disposed between the ferromagnetic armatures.

A simple calculus of the magnetic circuit leads to the conclusion that the positioning of the magnets in front of the air gap (case a, figure 5.41) determines higher magnetic induction in the air gap, while the demagnetizing field is stronger.

Δ

5.7.5. Material Production Evolution for Permanent Magnets

Hard magnetic materials are used in the permanent magnets manufacture, having multiple applications in electronic and electrotechnic industry, aviation and automotive, medicine. The large use of permanent magnets in automotive makes 20% of world magnets production to be addressed to this domain, the distribution being:

20% - for electric motors and generators,

- 20% for automotive board electronic devices,
- 15% for audiovisual devices (speakers, antennae, etc.),
- 10% for electrical motors from auxiliary equipment,
- 8% for informatics,
- 7% for other applications.

Great magnet manufacturers, such as: UGIMAG, RTC, VAKUUMSCHMELZE, KRUPP WIDIA, MAGNET FABRIK, HITACHI METALS, SUMIMOTO, pursue to increase the performances and to guarantee the properties of various types of materials used in the magnet's manufacturing process.

The evolution of the main types of hard magnetic materials is shown in Table 5.16 and figure 5.43.

Period / year	(<i>BH</i>) _{max} [kJ/m ³]	Material	Types
1880-1917	1-4	Carbon steel (1-1.2%)	-
1917-1930	4-10	Cobalt steel	01 MK, K5
1940-1950	1940-1950 10-40		Alnico 5
1950-1955	20-40	Hard ferrites	Spinal 1
1960	40-80	Alnico	Alnico 9
1970	150-200	Cobalt-Rare earths	SmCo₅
1980	200-250	Cobalt-Rare earths	Sm ₂ Co ₁₇
1980-1996	250-320	Iron-Neodymium -Boron	NdFeB

Table 5.16. Development of permanent magnet types.

The table shows that the maximum value of the specific magnetic energy provided by the magnets have constantly increased, as new types of magnets have been obtained. The quality index increased from 2 kJ/m^3 in 1917 to 300 kJ/m³ in the beginning of 21 century. This means the increase of coercive field from 5 kA/m in the case of martensitic steels to more than 1000 kA/m for present magnetic materials.



Fig. 5.43. Evolution of production of permanent magnetic materials.

5. Magnetic Materials

In present, Alnico alloys, hard ferrites and composites of transitional metals with rare earths are used in the manufacture of permanent magnets. Practically, martensitic steels, the only ones used until 1930, have been abandoned, being now used only in applications where special mechanical properties are required.

During the past decades, the quantity of produced hard magnetic materials changed according to manufacture price and request on the market (Table 5.17).

Estimation year	Hard ferrite	Alnico	Cobalt-Rare earths	Rare Iron- Rare earths	
1970, %	20	60	-	-	20
1984, %	62	18	15	-	5
1994, %	59	10	11	16	4

Table 5.17. Diversification of hard magnetic materials

The price for different types of materials also modified, the evolution for 1996 being the one shown in Table 5.18.

Price	SmCo₅	Sm ₂ Co ₁₇	NdFeB	Hard Ferrites
Raw materials Price/kg, %	120	110	75	5
Price/kg, %	90	100	80	5
Price/m ³ , %	90	100	72	3

Table 5.18. Price evolution for hard magnetic materials.

Certain aspects related to the specific properties of various types of hard magnetic materials are presented in the following chapters.

5.7.6. Alloyed and Martensitic Steels

Martensitic steels and **alloyed steels** have the carbon content of $1\div1.2$ %, being the only materials used until the first decade of the 20th century as materials for permanent magnets. By adding 6% W or Cr, there ameliorates their properties. Remanent induction of 1 T, coercive fields of $4\div4.5$ kA/m and a quality index that does not exceed 1.7 kJ/m³ are obtained.

The martensitic structure is obtained by rapid quenching of the steel at a high temperature (900°C), when cementite remains in the material and forms together with ∞ -iron a supersaturated solution. The cementite excess produces important internal tensions (the crystalline lattice deforms) that give the material a relatively high coercive field (4 kA/m).

Having a low quality index and being extremely susceptible to shocks, vibration and temperature variations, martensitic steels have been replaced with alloyed steels, especially with wolfram based ones (Table 5.19). Materials in Electrical Engineering

Table 5.19. Magnetic performances of martensitic-steels and alloyed steels comparative to other hard magnetic materials.

Material	B _r ,	<i>H</i> _c ,	(<i>BH</i>) _{max} ,	B _m ,	<i>Н</i> _{<i>m</i>} ,
(chemical composition: Fe	т	kA/m	kJ/m ³	Т	kA/m
and % other elements)					
Carbon steel (0.5 Mn)	0.9	4.0	1.60	0.62	2.56
Steel with W (0.7 C; 0.5 Cr; 6 W; 0.3 Si)	1.03	5.6	2.40	0.63	4.6
Steel with Cr (0.9 C; 3.5 Cr; 0.3 Mn)	0.98	5.6	2.32	0.63	4.6
Steel with Co (0.9 C; 3-6 Cr; 5-6 W; 35 Co)	0.9	20	7.40	0.58	12.7
Vicalloy II - anisotropic (42 Co; 13 V)	1.0	42	21	-	-
Koerflex 200 (50 Co; 15 V)	1.6	6	11.9	1.2	4
Cunife I (60 Cu; 20 Ni)	0.57	48	15	0.42	33
Alloy Pt-Co (77 Pt; 23 Co)	0.68	344	74	-	-
Alni 22 (21.5 Ni; 11 Al; 4,5 Cu)	0.63	20	5.57	0.4	13.9
Alni 23 (23 Ni; 11 Al; 4 Cu)	0.59	24	6.36	0.37	13.7
Alni 24 (24 Ni; 12 Al; 4 Cu)	0.55	32	7.16	0.35	20.7
Alni 25 (24.5 Ni; 13 Al; 3.5 Cu)	0.52	34	7.55	0.35	21.5
Alni 28 (28 Ni; 10 Al; 5.0 Cu)	0.50	35	7.96	0.34	23.5
Barium isotropic ferrite	0.2	132	6.4	0.1	64
Barium anisotropic ferrite	0.37	200	25	0.24	120
Flexible ferrite (10% binder)	0.14	94	3.4	0.08	44
Lodex 32 (oblong particles)	0.73	76	27.2	0.53	52

By reducing the carbon content (below 1%) and adding W, Co, Cr in certain proportions, **alloyed steels** having superior magnetic characteristics to martensitic-steels are obtained. By alloying with wolfram carbide in which the internal tensions increase, the coercive field increases (6.4 kA/m). The quality index also increases, but the remanent induction decreases. By alloying with chromium, the same results are obtained, but the cost of this procedure is more reduced.

By introducing cobalt, alloys having $H_c = 20$ kA/m and (*BH*)_{max} = 8 kJ/m³ are obtained. The demagnetization characteristics for unalloyed carbon steel (curve 1) and a 36% cobalt alloyed carbon steel (curve 2) are illustrated in figure 5.44.



Fig. 5.44. Demagnetisation characteristics for unalloyed carbon steel magnets (curve 1) and 36% cobalt alloyed carbon steel magnets (curve 2).

The benefit effect of the cobalt addition can be noticed: the coercive field increases significantly and the quality index, accordingly.

<u>Applications</u>: hysteresis motor rotors, where a higher permeability and a lower coercive field are favourite. But, as they have a meta-stable structure, alloyed steels are successfully replaced by certain types of Alnico magnets, that have a better stability of the properties.

5.7.7. Alni and Alnico Alloys

In this group are included alloyed based on **Alni** and **Alnico**, cheaper materials, with remarkable properties: $H_c = 20 \div 90$ kA, $Br = 0.6 \div 1.15$ T and $(BH)_{max} = 6 \div 40$ kJ/m³.

The good magnetic properties of cold-hardening alloys are caused by a specific treatment:

- In melted state, these alloys form a homogeneous solution that, if it is slowly quenched, tends to transform into a heterogeneous mixture of different crystals. In order to avoid this phenomenon, a sudden quenching of the alloy is applied, starting with (1100÷1300)°C, obtaining a supersaturated solution of Fe₃NiAI in Fe.
- Then, a annealing is applied, at a temperature inferior to the one at which the separation of crystals from the solution could be produced, followed by a slow quenching. During the annealing, the composite from the (Fe₃NiAI) solution is precipitate in the entire volume of the material as very fine particles. Deformations of the basic crystalline lattice are thus produced, and local internal tensions appear, determining the increase of the coercive field. But, as the dispersion of the Fe₃NiAI is made in the entire volume of the material, the coercive field takes values much greater than in the case of steel cooling (when the hardening is made only in a reduced area on the bodies surface).

The magnetic characteristics of these alloys depend on the percentage of each constituting element, on the impurities and added elements content, on the applied thermal, mechanical or thermo-magnetic treatments.

By applying some thermo-magnetic treatments (quenching in a magnetic field) alloys having pronounced anisotropy and superior magnetic characteristics are obtained. Resembling characteristics are encountered at alloys having columnar structure (their crystals are directed during the casting process).

Alni alloys – have remanent inductions between 0.5 \div 1.2 T, coercive fields between 20 \div 90 kA/m and quality indexes between 5.5 \div 24 kJ/m³. The alloys having low Ni content have low H_c and high B_r , being used in high section magnets manufacture.

Alnico alloys – are alloys based on the Fe, Ni, Al, elaborated for the first time by Mishima company in 1931. Due to cobalt content, these alloys have the Curie temperature and remanent induction superior to Alni alloys.

According to the cobalt content and the applied treatments during the technological processes, there are:

- > High coercitive field alloys (Alnico 32, Alnico 34, Alnico 38, Ticonol 1500),
- > High quality index and high coercitive field alloys (Alnico 900, Magnico),
- > Alloys with oriented crystals (Alnico 24),
- > **Isotropic alloys** (Alnico 12, Alnico 15),
- > Semi-columnar or columnar structure alloys, etc.

The cobalt addition reduces the influence of the cooling speed during the thermal treatments. The paramagnetic matrix rich in Ni and Al is completed with 50-60% of the volume with single-domain particles of Fe-Co, which provide special properties.

The isotropic types have spherical or elongate grains, that are chaotically oriented in the paramagnetic matrix. The increase of the cobalt content from 13% to 30% leads to an increase of the coercive field from 50 kA/m to 80 kA/m, to a moderate decrease of the magnetic induction (0.7 T) and to a sensitive increase in the quality index from 13 to 18 kJ/m³.

Anisotropic types, called Ticonal or Alnico 5, 8, 8C, with a columnar or semicolumnar structure, exhibit special values for the remanent induction $(1\div1,40)$ T, coercive field (50÷60) kA/m and a quality index of 40÷80 kJ/m³.

The main properties of the Alnico magnets are shown in Table 5.20.

5. Magnetic Materials

Туре	(<i>BH</i>) _{max} [kJ/m ⁻³]	<i>B</i> _r [T]	_в Н _с [kA/m]	μ _{r rev}	<i>B_m</i> [T]	<i>H_m</i> [kA/m]	Remark
A1	12	0.65	54	4	0.38	32	isotr.
A2	18	0.60	9	3.5	0.38	48	isotr.
A3	40	1.26	50	3.5	1	40	anis.
A4	32	1.10	64	4	0.70	46	anis
A5	46	1.30	53	3	1.05	45	anis.
A6	56	1.90	56	2	1.15	50	anis.
A7	45	0.90	125	2	0.55	80	anis.
A 8	80	1.05	125	1.3	0.80	100	anis.
A9	50	0.80	160	2	0.48	105	anis.

Table 5 20	Magnetic	norformancos	of	Alnico	magnete
Table 5.20.	wayneuc	penomances	0I	AILICO	maynets

In certain countries, the Alnico magnets types are standardised by quality indexes and coercive fields. In Germany, starting with 1940, the notation for Alnico magnets was established as Alnico *m/n*, where:

m is the specific energy in kJ/m⁻³,

n is the value of the polarization coercive field in kA/m.

Example:

AlNiCo 52/6 corresponds to a quality index $(BH)_{max} = 56 \text{ kJ/m}^3$ and a polarization coercive field $_{M}H_{c} = 6$ kA/m.

Alnico and Alni magnets are obtained by casting or sintering. Sintering determines the obtaining of magnets having homogeneous structure and exact structure, resistant to shocks and vibrations, with superior guality indexes.

5.7.8. Hard Magnetic Ferrites

Hard magnetic ferrites are composites of metallic oxides of Sr, Ba, Pb, Ca with Fe₂O₃. The commercialisation as Ferroxdur even since 1952, exhibit a demagnetisation characteristic very close to the ideal one.

Hard magnetic ferrites have a spinel (cobalt ferrites CoFe₂O₄) or hexagonal structure (barium, strontium or lead ferrites). Among these ones, due to good magnetic characteristics and low price, the most used is barium ferrite; having the chemical structure BaO.6Fe₂O₃, this structure is characterised by a spinel blocks sequence.

The recoil permeability is $\mu_{rrev} = 1.04 \div 1.08$ for the anisotropic types and $\mu_{rrev} = 1.20$ for the isotropic types. Thus, the B = f(H) characteristic is in the II-nd quadrant, as a line. This fact allows the operating in strong demagnetizing fields, without the alteration of the returning work induction values.

Isotropic ferrites obtained by sintering have a coercive field of remanent induction $_{B}H_{c}$ of 150 kA/m and polarization $_{M}H_{c}$ in the range of 280 kA/m, and remanent induction of 0.22 T, for which the quality index is 7.5 kJ/m³ (Table 5.20).

According to the sintering temperature and to the grains dimensions, inductions of $0.30\div0.40$ T, with coercive fields of $180\div200$ kA/m and corresponding specific energies of $25\div30$ kJ/m³ are obtained in the case of anisotropic types of barium ferrites.

High values of the H_c correspond to lower values for B_r . The temperature dependence is significant. Some characteristics for barium ferrites (FB) and strontium ferrites (FS) are shown in Table 5.21.

Material	FB-1	FB-2	FB-3	FS-4	FS-5
Remanent magnetic induction, min. [T]	min 0,2	min 0,35	min 0,135	min 0,36	min 0,21
Coercive field, min. [kA/m]	116	131	91	223	
Saturation field, min. [kA/m]	800	650	800	1150	800
Maximum energy (<i>BH</i>) _{max} [kJ/m ³]	min 5,6	min 22,3	min 3	min 23,9	min 6,7
Curie Temperature [ºC]	450	450	450	450	450
Composition	Isotropic barium ferrite	Anisotropic barium ferrite	Barium ferrite (plasto- ferrite)	Anisotropic strontium ferrite	Isotropic strontium ferrite

Table 5.21. Performances of some hard magnetic ferrites.

Permanent magnets made of ferrites are cheaper, have high electric resistivity and coercive field up to 800 kA/m. However, they have reduced remanent induction (0.2÷0.4) T. These magnets are usually obtained by sintering, the pressing being made in a magnetic field. By adding some organic binders, flexible magnets are obtained, that have reduced performances of magnetic characteristics.

By introducing the ferritic powder in a thermoplastic resin or rubber, the **plastic** ferrites are obtained, with coercive field of values $160 \div 170 \text{ kA/m}$.

Hard magnetic ferrites are used in a very wide applications domain, especially where the stabilization of the B_r with temperature is not requested.

5.7.9. Composites of the Rare Earths with Co and Fe

Rare earths RE are considered the elements belonging to the lanthanum group (lanthanides), starting with lanthanum (Z = 57) and ending with lutetium (Z = 71), to which yttrium is added (Z = 39), all having resembling properties.

RE composites with cobalt used in the permanent magnets manufacture are **PR-** Co_5 and **PR-Co**₁₇ type, being noticed for their high Curie temperature and for the high anisotropy coefficients.

SmCo₅ **composites** have saturation inductions of 0.97 T, intrinsic coercive fields of 1500÷2000 kA/m, their characteristics being linear. SmCo₅ variants with remanent inductions of 0.6÷0.8 T, with $_BH_c$ of 800÷950 kA/m and quality indexes of 140÷150 kJ/m³.

By casting the samarium-cobalt powder in a thermoplastic resin and sintering magnets, types resembling to the most performing Alnico magnets are obtained. Their properties are strongly dependent with temperature. Sm₂Co₁₇ variants with a mass content of 5% Sm, 48÷50% Co, 10÷15% Fe and almost 8% Cu and Zr have superior properties.

Although they have lower coercive field compared with the $SmCo_5$ variants, these magnets have inductions comparable with the Alnico magnets inductions, the quality indexes taking values up to 240 kJ/m³.

Rare earths composites with iron

Ternary composites with boron, iron and rare earths RE were commercialised starting with 1983 by companies like General Motors and Sumimoto, having the structural formula: **PR**_{1-x}(**Fe**_{1-x}**B**_y)_x.

The magnet products manufactured nowadays use, from the rare earths, the **neodymium**, element wider spread than **samarium**, the structural formula being **Nd**₂**Fe**₁₄**B**. If **dysprosium** and **praseodymium** are added, remarkable characteristics are obtained: remanent inductions of 1.10÷1.30 T, with $_BH_c$ de 800÷950 kA/m, recoil permeability of 1.05 and quality indexes of 330 kJ/m³ (Table 5.22).

Туре	(<i>BH</i>) _{max} [kJ.m ⁻³]	<i>В</i> , [T]	<i>_BH_c</i> [kA/m]	<i>jHc</i> [kA/m]	<i>H_k</i> [kA/m]	μr rev	Remark
RC1	150	0.90	700	1800	800	1.03	anis.
RC2	80	0.63	470	1500	950	1.05	isotr.
RC3	210	1.10	550	1200	450	1.05	anis.
RF1	280	1.20	900	1200	800	1.05	anis.
RF2	320	1.25	950	1200	1000	1.05	anis.

Table 5.22. Performances of magnets made of rare earths composites.

RE type magnets are composites of the rare earths with cobalt; RF type magnets are **neodymium-iron-boron** composites. Newer types of materials for magnets require properties as stable as possible with temperature. The inconvenient in the case of these materials is that they have low Curie temperature, about 310°C and an important induction variation with temperature coefficient (from -0.9 to -0.12% /°C). This fact limits the utilisation of NdFeB composites at temperatures of (100÷150)°C.

The magnetic properties of some permanent magnets at different temperatures are comparatively illustrated in the Table 5.23.

Properties	Sm ₂ Co ₁₇	NdFe B
<i>B</i> _r at 22 ^e C [T]	1.10	1.16
<i>B</i> _r at 150ºC [T]	1.05	0.98
Temp. coef. α _B [%/K]	- 0.035	- 0.12
<i>_JH_c</i> at 22ºC [kA/m]	2000	2500
<i>_JH_c</i> at 150ºC [kA/m]	1600	800
(<i>BH</i>) _{max} at 22ºC [kJ/m ³]	220	255
(<i>BH</i>) _{max} at 150ºC [kJ/m ³]	200	175

Table 5.23. Thermal stability of magnets made of rare earths composites.

<u>Applications</u>: acoustic reception devices, auxiliary motors, inductors for starters, film for magnetic recording, etc.

General view of permanent magnets materials properties is shown in Table 5.24.

Alloy	<i>B</i> r [T]	H _{cM} [kA/m]	H _{cB} [kA/m]	(BH) _{max} [kJ/m ³]	<i>Т</i> _с [°С]	α _B [%/°C]	Price
Fe-Co-Al-Ni (Alnico 5)	1.05	50	43	44	880	-0.025	moderate
Fe-Co-Al-Ni (Alnico 8)	1.06	130	100	42	860	-0.06	moderate
Fe-Cr-Co	1.4	60	44	42	650		moderate
Ferrite BaFe ₁₂ O ₁₀	0.42	247	150	34	469	-0.2	low
Ferrite BaFe ₁₂ O19	0.39	275	240	28	450	-0.01	low
SmCo₅	0.8- 0.9	1100 - 1500	500-760	130-180	720	-0.03	very high
Sm ₂ Co ₁₇	0.95- 1.15	600- 1300	500-820	200-240	800	-0.1	very high
Nd ₂ Fe ₁₄ B	1.0- 1.4	750- 1500	600- 1000	200-380	310		high
$Sm_2Fe_{12}N_3$	1.0	2400	750	160	477		
Nd-Fe- B/αFe	1.2	280	200	80-160	316		

Table 5.24. Comparative data for permanent magnetic materials

5.7.10. General Physical Properties of Hard Magnetic Materials

In the case of hard magnetic materials, besides the magnetic properties, the general physical and technological properties are important. These properties determine, together with the magnetic properties, the quality and the price of electronic and electrical equipment (Table 5.25).

Material	Density [kg/m ³]	Specific heat [J/(kg.K)]	Thermal conductivity [W/(m.K)]	Dilation coefficient [10 ⁻⁶ K ⁻¹]	Resistivity [10 ⁻⁸ Ω.m]
Alnico molten	7.3	450	25	12	45-65
Alnico sintered	7-7.2	450	25	2	45-65
Alnico agglomerated	5.2	550	12	10	0.1
Sintered ferrites	4.6-4.9	700-800	4-5	2-13	0.1
Plastic ferrites	2.4-3.9	800	1.5-2	15-25	55
Co-PR 1/5	8.3	370	10	2-13	90
Co-PR 1/17	8.4	350	12	2-8	150
Co-PR with binders	6-6.5	450	5.8	10	
Fe-Nd-B	7.4-7.5	450	9	2-4	150
Fe-Cr-Co	7.6	450	15	10	70-80
Pt-Co	15.9	250	40	9	30

Table 5.25. General physical properties of hard magnetic materials.

Some of these characteristic particularities are presented in the next paragraphs:

- **Resistance at mechanical stresses**. Sintered materials do not resist at stresses, at traction and shocks, so they are protected and stiffed by covering;
- **Electric resistivity**. Sintered or agglomerated materials have high resistivity, which is an advantage in the case of dynamic regimes, where high frequency fields, that generate losses, are superposed over constant fields;
- Thermal conductivity. Low conductive materials are disadvantageous: for example, collector closed devices, the thermal flux passes through the inductor. A thermal flux of 1 W/cm² passing through a ferrite of 10 mm length produces a temperature drop of 20÷25°C, unlike the case of a cobalt-rare earth magnet, whose thickness can be reduced to 4 mm and that determines a temperature drop of only 3.5÷4°C;

312 Materials in Electrical Engineering

- Mass density influences the total mass of the equipment, ferrites are advantageous relative to Alnico magnets, and NdFeB relative to SmCo;
- Workability. In the case of tachometers, measuring devices, and of synchronic micromotors, FeCrCo alloys magnets are used, ductile and with good cold workability properties;
- Assembling and fixing methods must allow the positioning of the magnet and of the other components so that the parasite air gaps to be eliminated;
- Magnetization methods with unassembled magnet or in the final construction must ensure the application of sufficiently high magnetic field in order to attain the area of magnetic saturation and of alignment of the magnetic moments in the material.

ASSESSMENT QUESTIONS



Assessment Questions – Chapter 1

What is a material parameter?			
	A material property	а	
§ 1.1.1 1	A physical quantity that can be associated to each material property	b	
	A chemical property	С	

	Which of the quantities is a material parameter?	
	Electrical conductivity	а
§ 1.1.1 2	Electrical susceptibility	b
	Thermal elongation	С

	What is the electrical conductivity measured by?	
	1/Ωm	а
§ 1.1.1 3	Ωm	b
	N/m ²	С

	What is the thermal conductivity measured in?	
	Ωm	а
§ 1.1.1 4	W/m K	b
	W/m ²	С

	What is the linear dilation coefficient measured in?	
	N/m ²	а
§ 1.1.1 5	W/k	b
	1/K	С

What is the classification criterion of gaseous, liquid and solid materials?			
	State of aggregation	а	
§ 1.1.2 6	A specific property	b	
	The domain in which they are used	С	

	According to electrical conductibility materials are divided into:	
	Conductive materials, Semiconductive materials, Electroinsulating materials	а
§ 1.1.2 7	Ferromagnetic materials, Ferrimagnetic materials	b
	Crystalline materials, Amorphous materials, Mezomorphous materials	С

	What material parameter contains the law of elasticity?	
	The friction coefficient	а
§ 1.2.1 8	The Young module	b
	The specific heat	С

The law of electrical conductivity is mathematically expressed by:		
	E=f(<i>I</i>)	а
§ 1.2.2 9	P=f(E)	b
	J=f(E)	С

Quantity J represents :		
	The intensity of the electrostatic field	а
§ 1.2.2 10	The electric current density	b
	Electrical resistivity	С

The law of electrical conduction in the case of isotropic materials, linear and with no imprinted fields is:		
	$\overline{P} = \varepsilon_0 \cdot \chi_e \cdot \overline{E}$	а
§ 1.2.2 11	$\mathbf{Q} = \mathbf{m} \cdot \mathbf{c} \cdot \Delta \mathbf{\theta}$	b
	$\overline{J} = \sigma \cdot \overline{E}$	С

The law of electrical conduction in the case of linear materials with physical-chemical non-homogeneities or submitted to acceleration is mathematically expressed by:		
	$\overline{J} = \sigma \cdot \left(\overline{E} + \overline{E_i}\right)$	а
§ 1.2.2 12	$F_f = \mu \cdot N$	b
	$\overline{M} = \chi, \cdot \overline{H}$	С

The materials that permit easy the passing of electric current are:		
	Semiconductive materials	а
§ 1.2.2 13	Electroinsulating materials	b
	Electrically conductive materials	С

Which is the correct order of the following materials if they are ordered increasingly according to the electrical resistivity values?		
	Gallium arsenic, amber, paper, silver, manganese	а
§ 1.2.2 14	Silver, manganese, gallium arsenic, paper, amber	b
	Amber, gallium arsenic, silver, manganese, paper	С

The law of the electrical conductivity for anisotropic, linear materials with no imprinted fields is $\overline{J} = \overline{\overline{\sigma}E}$ where $\overline{\overline{\sigma}}$ is:		
	A constant	а
§ 1.2.2 15	A tensor with 6 components	b
	A tensor with 9 components	С

316

In which materials takes place the ionic conductivity?		
§ 1.2.2 16	Conductive materials, semiconductive materials, electroinsulating materials	а
	Conductive materials, electroinsulating materials	b
	Semiconductive materials, electro-insulating materials	С

Decide to which category of materials belongs, if its electrical resistivity is 10 Ω m.		
	Semiconductive materials	а
§ 1.2.2 17	Electroinsulating materials	b
	Electrically conductive materials	С

The temporary electrical polarization law is mathematically expressed by:		
	$\overline{P}_t = f(\overline{E})$	а
§ 1.2.3 18	$\frac{\mathrm{d}m}{\mathrm{d}t} = \frac{1}{F} \cdot \frac{A}{n}$	b
	$\overline{J} = \sigma \cdot \overline{E}$	С

	The temporary electrical polarization is measured in:	
	V/m	а
§ 1.2.3 19	Ωm	b
	C/m ²	С

What is the correct order of the following materials if they are ordered increasingly according to their relative electrical permittivity?		
	Barium titanate, paper, transformer oil, water, air	а
§ 1.2.3 20	Air, water, paper, barium titanate, transformer oil	b
	Air, transformer oil, paper, water, barium titanate	С

The temporary electrical polarization law in the case of isotropic and linear dielectrics, with no permanent polarization is mathematically expressed by:		
	$\overline{\boldsymbol{P}} = \boldsymbol{\varepsilon}_{0} \cdot \boldsymbol{\chi}_{\boldsymbol{e}} \cdot \overline{\boldsymbol{E}}$	а
§ 1.2.3 21	$Q = m \cdot c \cdot \Delta \theta$	b
	$F_f = \mu \cdot N$	С

	The quantity marked by the χ_e symbol represents:	
	Electrical permittivity	а
§ 1.2.3 22	Electrical susceptivity	b
	Magnetic permeability	С

Law of temporary magnetization is mathematically expressed by:		
	$\mu = \mu_0 \cdot \mu_r$	а
§ 1.2.4 23	$\overline{M}_t = f(\overline{B})$	b
	$\overline{M}_t = f(\overline{H})$	С

	The temporary magnetization M_t is measured in:	
	A/m	а
§ 1.2.4 24	H/m	b
	F/m	с

The law of temporary magnetization in the case of isotropic and linear materials, with no permanent magnetization is mathematically expressed by:		
	$J = \frac{l}{S}$	а
§ 1.2.4 25	$\overline{M_t} = \chi_m \cdot \overline{H}$	b
	$\overline{M_t} = \mu_0 \cdot \chi_m \cdot \overline{H}$	С

	The quantity marked by the μ symbol represents:	
	Magnetic susceptibility	а
§ 1.2.4 26	Absolute electrical permittivity	b
	Absolute magnetic permeability	С

Decide to which category of materials belongs a material, if its electrical resistivity is $10^{-8} \Omega m$.		
	Electroinsulating materials	а
§ 1.2.2 27	Electrically conductive materials	b
	Semi-conductive materials	С

	Decide to which category of materials the bakelite belongs?	
	Electrically conductive materials	а
§ 1.2.2 28	Semi-conductive materials	b
	Electroinsulating materials	С

Decide to which category of dielectrics the transformer oil belongs if its relative permittivity is $\epsilon_r=2$:		
	Polar non-linear	а
§ 1.2.3 29	Non-polar	b
	Polar linear	С

Decide to which category of dielectrics the epoxy resin belongs if its relative permittivity is ε_r =10:		
	Polar non-linear	а
§ 1.2.3 30	Non-polar	b
	Polar linear	С

Assessment Questions – Chapter 2

	What is the electric current?	
	The ordered movement of the charge carriers (electrons or/and ions) submitted to an electric field	а
§ 2.1.1 1	The chaotic movement of the charge carriers (electrons or/and ions) submitted to an electric field.	b
	The ordered movement of the charge carriers (electrons or/and ions) submitted to an thermal field	С

What is the mathematical expression of the medium square velocity of the electrons in the absence of an electric field?		
	$V_{T} = \sqrt{\frac{m_{0}}{3 kT}}$	а
§ 2.1.3 2	$v_{\tau} = \sqrt{\frac{3kT}{m_0}}$	b
	$v_{\tau} = \sqrt{\frac{kT}{m_0}}$	С

What is the mathematical expression of the total velocity of the electron in the presence of an electric field?		
	$\overline{V} = \overline{V}_T + 2 \overline{V}_e$	а
§ 2.1.3 3	$\overline{V} = \overline{V}_{T} - \overline{V}_{e}$	b
	$\overline{V} = \overline{V}_T + \overline{V}_e$	С

	How can electrical current density be expressed?	
	$J = q_0 \cdot v_d$	а
§ 2.1.3 4	$J = \frac{N}{V} \cdot V_d$	b
	$J = \frac{N}{V} \cdot \boldsymbol{q}_0 \cdot \boldsymbol{v}_d$	С

How can the electron acceleration be expressed in an electrical field?		
	$\overline{a} = -\frac{q_0}{m_0} \cdot \overline{E}$	а
§ 2.1.3 5	$\overline{a} = \frac{q_0}{m_0} \cdot \overline{E}$	b
	$\overline{a} = \frac{q_0}{2m_0} \cdot \overline{E}$.	С

The drift velocity of conduction electron depends on time as follows:		
	Linear	а
§ 2.1.3 6	Saw-tooth output	b
	Parabolic	С

How is mathematically expressed the mobility of the electron?		
	$\mu_{o} = \left \overline{E} \right \left \overline{V}_{d} \right $	а
§ 2.1.3 7	$\mu_{0} = \frac{\left \overline{E}\right }{\left \overline{V}_{d}\right }$	b
	$\mu_{o} = \frac{\left \overline{V}_{d} \right }{\left \overline{E} \right }$	С

	The relation for the mobility of the electron is:	
	$\mu_0 = \frac{q_0 t_c}{2m_0}$	а
§ 2.1.3 8	$\mu_0 = \frac{q_0 t_c}{m_0}$	b
	$\mu_0 = \frac{2q_0 t_c}{m_0}$	С

	Mobility is measured in:	
	$\frac{V s}{m^2}$	а
§ 2.1.3 9	$\frac{m^2}{Vs}$	b
	V s m	С

How is mathematically expressed the electrical conductivity of metals?		
	$\sigma = \frac{q_0 n_0}{\mu_0}$	а
§ 2.1.3 10	$\sigma = q_0 n_0 \mu_0$	b
	$\sigma = \frac{q_0}{n_0 \mu_0}$	С

How is the drift velocity of the electrons in comparison with the average thermal agitation velocity:		
	Higher	а
§ 2.1.3 11	Lower	b
	Equal	С

In Mathiessen's law $\rho = \rho_{imp} + \rho_{def} + \rho_T$, the ρ_{def} symbol represents a component of the resistivity due to:		
	Plastic deformation	а
§ 2.1.4 12	Lattice defects	b
	Other intrinsic factors	С

At a rising temperature, the electrical resistivity of the metals increases linearly in the field of:		
	High temperatures	а
§ 2.2.2 13	Low temperatures	b
	Room temperatures	С

How it is mathematically expressed the temperature coefficient of resistivity:		
	$\alpha_{\rho} = \frac{1}{\rho_{0}} \cdot \frac{\rho_{\theta} - \rho_{0}}{\theta - \theta_{0}}$	а
§ 2.2.2 14	$\alpha_{\rho} = \frac{\rho_{\theta} - \rho_{0}}{\theta}$	b
	$\alpha_{\rho} = \frac{1}{\rho_{0}} \frac{\Delta \rho}{\rho_{0}}$	С

	The unit of the temperature coefficient of resistivity is:	
	$\frac{1}{K}$	а
§ 2.2.2 15	$\frac{1}{\Omega K}$	b
	$\frac{\Omega}{K}$	С

The order of magnitude of the temperature coefficient of resistivity in the case of the conductive materials is:		
	10 ⁻¹	а
§ 2.2.2 16	10 ⁻³	b
	10 ⁻²	С
	The modification of the electrical resistivity is produced by:	
---------------	--	---
	Lattice defects, impurities, temperature	а
§ 2.2.3 17	Dislocations	b
	Lattice vibrations	С

There is the relation $J_{ad} = exp(3.30107 - 0.58825 \cdot d)$ where J_{ad} is the admissible			
conductive current density and <i>d</i> is the diameter of the conductor. What is the admissible conductive current density if the diameter of the conductor is 2.5 mm?			
§ 2.3.1 18	3.55321 A/mm ²	а	
	8.25063 A/mm ²	b	
	6.55340 A/mm ²	С	

An electric line of 200 km is made up of 20 mm diameter of conductors. The electric current which flow on it is of 800 A. The resistivity of the material is 30 n Ω m. Calculate the electrical resistance and the Joule losses through the conductors.			
	<i>R</i> =19.1 Ω	<i>P</i> _J =12.224 W	а
§ 2.3.1 19	<i>R</i> =16.2 Ω	<i>P</i> J=36.554 W	b
	<i>R</i> =26.9 Ω	<i>P</i> J=64.351 W	С

A Cu-Ag alloy with $\rho_1 = 4.8 \cdot 10^{-8} \Omega m$ is used for making a $I_1 = 100 m$ long, and $d_1=2 mm$ diameter conductive wire. Calculate the resistance R_1 for this case, and the resistance R_2 for the case when the length of the wire is obtained with the same volume of material $(V_1=V_2)$ but with a diameter twice bigger $(d_2=2d_1)$.			
§ 2.3.1 20	<i>R</i> ₁ =1.5 Ω	<i>R</i> ₂ = 0.0958 Ω	а
	<i>R</i> ₁ =4.5 Ω	R ₂ = 0.2974 Ω	b
	<i>R</i> ₁ =6 Ω	R ₂ = 0.3932 Ω	С

The temperature coefficient of the resistivity for cooper is $\alpha_{Cu} = 3,9.10^{-3} \text{ 1/°C}$ and its resistivity at 0°C is $\rho_{Cu} = 1.72 \cdot 10^{-8} \Omega \text{m}$. Calculate the resistance R_0 at 0°C and resistance R_{760} at 760°C for a wire with 1 mm length and 1 mm ² area of cross section.			
	R_0 = 28 m Ω	R ₇₆₀ = 114.1	а
§ 2.3.1 21	<i>R</i> ₀ = 17.2 mΩ	<i>R</i> ₇₆₀ = 67.51 mΩ	b
	<i>R</i> ₀ = 108 mΩ	<i>R</i> ₇₆₀ = 3.82 mΩ	С

What is the formula of the calcopyrite?		
	Cu ₂ O	а
§ 2.3.1 22	Cu ₂ (CO ₃) ₂ (OH) ₂	b
	CuFeS₂	с

Which is the mass density of the copper?		
	8890 kg/m ³	а
§ 2.3.2 23	7800 kg/m ³	b
	5500 kg/m ³	С

The crystalline system of the metallic copper is:		
§ 2.3.2 24	Hexagonal	а
	Cubic with centered faces	b
	Cubic simple	С

The brass is an alloy that contains:		
	Cu – Zn	а
§ 2.3.2 25	Cu – Mn	b
	Cu – Sn	С

	The alloy of the aluminum, which contains also Mg, Si, Fe is:	
§ 2.3.3 26	Duraluminum	а
	Alduro	b
	Siluminum	С

Compare the melting temperatures $T_{\rm t}$ of the copper, silver and aluminum:		
§ 2.3.4 27	$T_{t(Cu)} < T_{t(Ag)}, < T_{t(Al)}$	а
	$T_{t(Ag)}, < T_{t(Al)} T_{t(Cu)}$	b
	$T_{t(AI)} < T_{t(Ag)} < T_{t(Cu)}$	С

If the relationship between the resistivity of the iron ρ _{Fe} and the percentage of the silicon impurities is linear and the appropriate resistivities for Fe-Si alloys are 15.269 Ωm, and 26.380 Ωm for the percentages of 0.1 and 0.5 % of silicon, calculate the resistivity of the iron with 1% silicon.			
§ 2.3.5 28	ρ _{Fe-Si} =35.227 Ωm	а	
	ρ _{Fe-Si} =41.649 Ωm	b	
	ρ _{Fe-Si} =62.346 Ωm	С	

Which of the metals are also called tungsten?		
	Nickel	а
§ 2.4.4 29	Molybdenum	b
	Wolfram	С

	For the improvement of the Mn-Cu alloys properties it is used:	
	Reheating, slow cooling and stripping	а
§ 2.4.5 30	Slow cooling, stripping	b
	Stripping	С

The constantan alloy contains:		
	60% Cu, 40% Ni	а
§ 2.4.6 31	50% Cu, 50% Ni	b
	40% Cu, 60% Ni	С

	Which are the main alloys used for coiled power resistors?	
	Feronichrom	а
§ 2.5.1 32	Chromel	b
	Mn-Cu alloys, nickeline	С

Which is the basis material used for the brushes of the electrical machines?		
	Silver	а
§ 2.5.2 33	Bronze with beryllium	b
	Graphite	С

For what types of contacts is the graphite used?		
	Fix contacts	а
§ 2.5.2 34	Gliding contacts	b
	Breaking circuit contacts	С

	The materials used for fuses must have their melting point:	
	As high as possible	а
§ 2.5.3 35	As low as possible	b
	It doesn't matter	С

The relation between the intensity of admissible electric conductive current and the conductor diameter is linear at constantan. Calculate the current intensity for 2 mm of conductor diameter if the admissible current on 2.4 mm conductor diameter is 50 A.		
§ 2.5.1 36	41.667 A	а
	60 A	b
	70 A	С

The electric conductive materials for off-on contacts must have a contact resistivity:		
6050	Very high	а
§ 2.5.2 37	Very low	b
	Doesn't matter	С

	Group correctly the materials with their melting temperatures:	
6004	Cu -1083°C, Ag - 960°C, Al - 658°C. Pb - 327°C	а
§ 2.3.1 38	Cu -960°C, Ag - 1083°C, Al - 327°C. Pb – 658°C	b
50	Cu -1083°C, Ag - 658°C, Al - 960°C. Pb - 327°C	С

The value of the thermo-electromotive force of a thermocouple depends on:		
	The temperature of the junction points	а
§ 2.5.4 39	The temperature of the junction points	b
	and materials which the circuit is made of	
	The materials which the circuit is made of	С

The strain gauge is an application of the phenomenon which shows the dependence of the electrical resistivity on:		
	Temperature	а
§ 2.5.5 40	Mechanical deformation	b
	Electric field	С

The materials for the active components of bimetals have a linear dilatation coefficient:		
	More than 5·10 ⁻⁶ 1/K	а
§ 2.5.6 41	Less than 5·10 ⁻⁶ 1/K	b
	Equal to 5·10 ⁻⁶ 1/K	С

Assessment Questions – Chapter 3

The semi-conductive materials are materials with a conductivity of:		
	(10 ⁵ -10 ¹²) 1/Ωm	а
§ 3.1.1 1	(10 ⁻⁵ -10 ⁶) 1/Ωm	b
	(10 ⁻⁸ -10 ⁻⁷) 1/Ωm	С

	The electrical conductivity for conductors can be explained by:	
	The theory of energy bands	а
§ 3.1.1 2	The theory of Drude-Lorentz	b
	The theory of Langevin	С

The Fermi level is:		
	The last possible level holding electrons	а
§ 3.1.1 3	The first possible level holding electrons	b
	An intermediate possible level holding electrons	С

	The forbidden Fermi energy band (ΔW_i) represents:	
5242	A forbidden band between the valence band and the conductive band	а
4	An unoccupied band also called conductive band	b
	A completely occupied band called also valence band	С

The forbidden Fermi interval has zero value in the case of the crystals that are:		
	Conductive	а
§ 3.1.2 5	Semiconductive	b
	Electroinsulating	С

	The Fermi level is situated in a band allowed for:	
	Conductors	а
§ 3.1.2 6	Semiconductors	b
	Electroinsulators	С

	The Fermi level is situated in a band forbidden for:	
	Semiconductive and electroinsulating crystals	а
§ 3.1.2 7	Conductive and electroinsulating crystals	b
	Conductive and semiconductive crystals	С

At the generation of the electric current participates the electrons:		
	From incompletely occupied bands	а
§ 3.1.3 8	Both completely and incompletely occupied bands	b
	From a completely occupied bands	С

The intrinsic electric conduction is specific for:		
	Pure semiconductive materials	а
§ 3.2.1 9	Metals	b
	Unpurified semiconductive materials	с

	The extrinsic electric conduction is specific for:	
	Unpurified semiconductive materials	а
§ 3.2.2 10	Metals	b
	Pure semiconductive materials	С

The electric current appears in semiconductive materials on the following conditions of temperature and electrical field:		
	T≠0 K, E=0	а
§ 3.2.1 11	T≠0 K, E≠0	b
	T=0 K, E=0	С

The electric current in intrinsic semiconductive crystals is generated by:		
	The ordered movements of the cvasi-free electrons	а
§ 3.2.1 12	The thermal agitation movement	b
	The ordered movements of cvasi-free electrons and of the incomplete bonds	С

The intrinsic electric conductivity is carried out (according to the energy band theory) by:		
	The electrons in the valence bands	а
§ 3.2.3 13	The holes in the valence band and the electrons in the conductive bands	b
	The holes in the valence band	С

Calculate the intrinsic resistivity at the temperature of 300K, knowing that $n_i=1.5 \times 10^{16}$ charge carriers/m ³ , $q_0=1.6 \times 10^{-19}$ C, $\mu_n=0.135$ m ² /(Vs), $\mu_p=0.048$ m ² /(Vs).		
	1.15×10⁵ 1/Ωm	а
§ 3.2.3 14	$7.32 \times 10^4 \Omega m$	b
	2.28×10 ³ Ωm	С

The resistivity of the Si is $2.3 \times 10^3 \Omega$ m at room temperature (300K). Calculate the electrical conductivity at 200°C (473K), knowing that ΔW_i =1.1eV and k=8.62×10 ⁻⁵ eV/K.		
	1.04 1/Ωm	а
§ 3.2.3 15	11.73 1/Ωm	b
	5.13 1/Ωm	С

The electrical conduction for semiconductive crystals is controllable and with stability in the case of:		
	Extrinsic semiconductors	а
§ 3.3.1 16	Both extrinsic and intrinsic semiconductors	b
	Intrinsic semiconductors	С

The electrical current in the process of extrinsic conduction for semiconductors of type <i>n</i> is generated by:		
	The ordered movement of the uncompensated bonds from the impurity atoms	а
§ 3.3.1 17	From both movements	b
	The ordered movement of the cvasi-free electrons generated by ionising the impurity atoms	С

The electrical current in the process of extrinsic conduction for semiconductors of type <i>p</i> is generated by:		
	The ordered movement of the uncompensated bonds generated by ionising the impurity atoms	а
§ 3.3.2 18	From both movements	b
	The ordered movement of the cvasi-free electrons generated by ionising impurity atoms	С

Semiconductive crystals of type <i>n</i> are obtained by the doping with:		
	Acceptor impurities	а
§ 3.3.2 19	Donor impurities	b
	Both solutions	с

Semiconductive crystals of type <i>p</i> are obtained by the doping with:		
	Acceptor impurities	а
§ 3.3.2 20	Both solutions	b
	Donor impurities	С

A sample of silicon is doped with 10 ²¹ atoms/cm ³ of phosphor. It is considered that the		
doped atom	s are completely ionized: n_i =1.5×10 ¹⁶ m ⁻³ ; μ_n =0.135m ² /(Vs);	
μ _p =0.048 m ²	/(Vs). Calculate:	
	the concentration of the majority charge carriers,	
	the concentration of the minority charge carriers,	
	the resistivity and the doping at room temperature (300K)	
	$n_n=10^7$ electrons/cm ³ $n_n=2.25 \times 10^{11}$ holes/cm ³	а
	ρ _n =0.03 Ωm	~
§ 3.3.2	$n_n=10^5$ electrons/cm ³ $n_p=2.25\times10^{11}$ holes/cm ³	b
21	ρ _n =0.07 Ωm	
	$n_n = 10^{21}$ electrons/cm ³	
	$n_p=2.25 \times 10^{11}$ holes/cm ³	С
	ρ _n =0.0463 Ωm	

The electrical conductivity of an intrinsic semiconductive material varies with the temperature in the following way:		
	Decreases	а
§ 3.4.1 22	Remains constant	b
	Increases	С

The electrical conductivity of the intrinsic silicon σ_i at T=300 K is:		
	4 10 ⁴ 1/(Ω m)	а
§ 3.2.3 23	4 10 ⁻⁵ 1/(Ω m)	b
	4 10 ⁻⁴ 1/(Ω m)	С

The concentration of the charge carriers in the intrinsic conductivity of the silicon at T=300K is:		
	$n_{\rm i}$ = 2.2 · 10 ²⁰ carriers/cm ³	а
§ 3.5.3 24	$n_{\rm i}$ = 3.2 ·10 ¹³ carriers/cm ³	b
	$n_{\rm i}$ = 1.2 ·10 ¹² carriers/cm ³	С

The electrical conductivity of the intrinsic germanium σ_i at T=300K is:		
	91 · 10 ⁻³ 1/(Ω m)	а
§ 3.2.3 25	9.1 · 10 ⁻⁵ 1/(Ω m)	b
	9.1 · 10 ⁻⁴ 1/(Ω m)	С

The concentration of the charge carriers in the intrinsic conductivity of the germanium at T=300K is:		
	$n_{\rm i}$ = 2.2 · 10 ²⁰ carriers/cm ³	а
§ 3.5.4 26	$n_{\rm i}$ = 3.2 ·10 ²² carriers/cm ³	b
	$n_{\rm i}$ = 4.5 ·10 ²⁶ carriers/cm ³	С

The electrical conductivity of an extrinsic semiconductive material varies with the decrease of the temperature in the following way:		
	Remains constant	а
§ 3.4.3 27	Increases	b
	Decreases	С

The electrical conductivity σ for an extrinsic semiconductive material of type <i>n</i> is expressed by:		
	$\sigma_{en} = n_{\rho} q_0 \mu_{\rho}$	а
§ 3.2.3 28	$\sigma_{en} = n_n q_0 \mu + n_p q_0 \mu_p$	b
	$\sigma_{en} = n_n q_0 \mu_n$	С

The characteristic of voltage-current for varistors is expressed by:		
	$I=AU^{lpha}$; $U=BI^{eta}$	а
§ 3.5.2 29	Other relation	b
	$U=BI^{\beta}; I=A\cdot exp(-rac{B}{T})$	С

Varistors are used for:		
§ 3.5.5 30	Over-voltage protection Frequency multipliers Current or voltage stabilizers	а
	Temperature measurement	b
	Other uses	С

The opto-electronic conversion is the phenomenon of transforming:		
	The electric signal in optic signal	а
§ 3.5.8 31	Both electric and optic signals	b
	The optic signal in electric signal	С

The incident optic radiation (electromagnetic radiation) is within the following wavelength:		
	$\lambda = 0.1 - 100 \text{ mm}$	а
§ 3.5.8 32	$\lambda = 0.1 - 100 \text{ cm}$	b
	λ = 0.1 - 100 μm	С

The absorption takes place only if the energy of the radiated photon W_r and the energy of the forbidden band ΔW_i of the semi-conductive are connected in the following way:		
	$W_r = \hbar \omega < \Delta W_i$	а
§ 3.5.9 33	$W_r = \hbar \omega = \Delta W_i$	b
	$W_r = \hbar \omega \geq \Delta W_i$	С

The phenomenon of radiative recombination consists in the transition of the electrons from different energy levels, in the following way:		
	W_1 on levels $W_2 > W_1$, with energy liberation	а
§ 3.5.9 34	W_1 on levels $W_2 < W_1$, with energy liberation	b
	W_1 on levels $W_2 > W_1$, with energy absorption	С

A semi-conductive can be used as electro-luminescent material in the following conditions:		
с о г о	The stimulated recombination is weaker than light absorption	а
§ 3.5.9 35	The stimulated recombination is equal to light absorption	b
	The stimulated recombination is stronger than light absorption	С

Electro-optic devices that emit radiations of different colors are called:		
\$ 2 5 0	LED-s (Light Emitting Diodes)	а
§ 3.5.9 36	Opto-couplings	b
	Fotoresistors	С

The thermoresistors with a negative coefficient of temperature are based on the phenomenon of:		
§ 3.5.7 37	The increasing resistivity of the semi-conductives at an increasing temperature	а
	The decreasing resistivity of the semi-conductives at an increasing temperature	b
	Liniar dependency on temperature	С

A thermistor with a negative coefficient of temperature has R_0 =100 Ω at T=300K. Calculate the <i>R</i> resistivity at T=350K, if the thermic sensibility of the material is β =2000.		
§ 3.5.3 38	38.6 Ω	а
	110 Ω	b
	56.6 Ω	С

The thermistors with a negative coefficient of temperature are used for:		
§ 3.5.4	- Measuring the temperature - Resistivity increase compensation of diverse circuit elements	а
39	 Modifying the temperature of the circuit elements 	b
	- Limitation of the current and reducing the over-voltages	С

The thermistors with a positive coefficient of temperature are used for:		
§ 3.5.7	 Measuring the temperature Compensating the increase of the electrical resistivity of the diverse elements in the electrical circuit 	а
40	 Modifying the temperature of the circuit elements 	b
	- For temperature transducers, current limiters, short-circuit and over-voltage protection	С

Assessment Questions – Chapter 4

The polarization phenomenon means:		
§ 4.1.1 1	The microscopic deformation and displacement of the free electric charge system of the structural units of the dielectric under the electric field.	а
	The microscopic deformation and displacement of the free and bonded electric charge system of the structural units of the dielectric under the electric field.	b
	The microscopic deformation and/or displacement of the bonded electric charge system of the structural units of the dielectric under the electric field.	С

The electrical materials that contain only bonded electrical charges are:		
	Real dielectrics	а
§ 4.1.1 2	Conductors	b
	Ideal dielectrics	С

	An electro-insulating material must have a resistivity:	
	As high as possible	а
§ 4.1.2 3	As low as possible	b
	It does not matter	С

What operating regimes are taken into account when designing insulation?		
	Anomalous operating regimes	а
§ 4.1.3 4	Continuous operating regimes	b
	Overcharged operating regimes	С

What is the admissible temperature for the oil saturated paper in short-circuit regime?		
	250°C	а
§ 4.1.3 5	150°C	b
	180°C	С

The volume resistivity of the electroinsulating material can be expressed by:		
	$\rho_V = \frac{R_V \cdot S_{ef}}{2d}$	а
§ 4.2.2 6	$\rho_{V} = \frac{R_{V} \cdot S_{ef}}{d}$	b
	$\rho_{V} = \frac{R_{V} \cdot d}{S_{ef}}$	с

The surface resistivity can be expressed by:		
	$\rho_{s} = \frac{R_{s} \cdot \pi \cdot D_{av}}{\frac{D_{2} - D_{1}}{2}}$	а
§ 4.2.2 7	$\rho_{S} = \frac{R_{S} \cdot \pi \cdot D_{av}}{D_{2} - D_{1}}$	b
	$\rho_{s} = \frac{R_{s} \cdot D_{av}}{\frac{D_{2} - D_{1}}{2}}$	С

	The unit for the surface resistivity is:	
	1/Ω	а
§ 4.2.2 8	Ω	b
	Ω·m	С

The conductivity due to the ordered displacement of the positive and negative ions under the electric field is called:		
	Electronic conductivity	а
§ 4.2.3 9	Molionic conductivity	b
	Ionic conductivity	С

Which of the following agents are intrinsic agents that influence conductivity in electroinsulating materials?		
	Humidity	а
§ 4.2.3 10	The nature of the dielectric	b
	Temperature	С

	What type of conductivity increases in the Pool domain?	
	Ionic conductivity	а
§ 4.2.3 11	Ionic conductivity and electronic conductivity	b
	Electronic conductivity	С

What is the minimum value of the electric field intensity when in all dielectrics an important increase of the electronic conductivity is produced?		
	10 ¹⁰ V/m	а
§ 4.2.3 12	10 ⁶ V/m	b
	10 ⁸ V/m	С

In the case of ionic crystal, at low temperatures, conductivity is due to:		
	Void generations	а
§ 4.2.3 13	Impurities of interstitial ions	b
	Impurities of interstitial ions and void generations	С

The change of the conductivity mechanism is expressed in $\ln \sigma_{ion} = f(1/T)$ by:		
	The decreasing feature of the characteristics	а
§ 4.2.3 14	The decreasing feature of the characteristics and the change of the characteristics slope	b
	The change of the characteristics slope	С

In the mathematical expression $\sigma(E,T) = \sigma_0 \exp\left[-\frac{W-\beta E}{kT}\right]$ of the electrical conductivity of the electroinsulating materials, β factor reflects the influence of:		
	Impurities	а
§ 4.2.4 15	Electric field	b
	Temperature	С

The Pool-Frenkel law of the electrical conductivity of the electroinsulating materials is valid in the case of:		
	Constant temperature	а
§ 4.2.4 16	Constant electric field	b
	Constant activating energy	С

The conductivity dependence on the electric field in the case of the polymers is:		
	Parabolical	а
§ 4.2.4 17	Linear	b
	Exponential	С

In the relation expressing the dependency on temperature of the electrical conductivity in constant electrical fields <i>a</i> parameter reflects:		
	The constant of the crystalline network	а
§ 4.2.4 18	Dependency on the impurities of the electrical conductivity	b
	The medium coefficient of thermal sensibility	С

Which is that material where the resistivity varies the least with humidity:		
	Alcaline glass	а
§ 4.2.4 19	Cerezine	b
	Bakelite	С

The dependency on humidity of the surface resistivity in the case of the bakelite (<i>u</i> expressed in percents) is given by: $\rho_s = \exp(32.67539 - 0.13723 u)$. Give the surface resistivity at 70% humidity		
	1.042·10 ⁺⁶ Ω	а
§ 4.2.4 20	1.042·10 ¹¹ Ω	b
	$1.042 \cdot 10^{12} \Omega$	С

What concur in producing electrical current at higher temperatures than 200°C in glasses?		
	Monovalent ions	а
§ 4.2.5 21	Bivalent ions	b
	Trivalent ions	С

The electrical conductivity in ceramic materials is mainly of type:		
	Electronic	а
§ 4.2.5 22	Ionic	b
	Electronic and ionic	С

At what temperature of the alumina (AI2O3) predominate the mixed conductivity?		
	1500°C	а
§ 4.2.5 23	1800°C	b
	1300°C	С

	The metal-dielectric transition is the transition of a material:	
	From the dielectric state to the conductive characteristic state	а
§ 4.2.6 24	From the dielectric state to the conductive characteristic state or from the conductive state to the dielectric characteristic state	b
	From the conductive state to the conductive characteristic state	С

The unit of measurement of the dynamic coefficient of viscosity is:		
	Pa / s	а
§ 4.2.7 25	Pa·s	b
	Pa / s ²	С

	The ionic conductivity of liquids is expressed by:	
	$\sigma_{ion} = \frac{n_i q_i^2}{\pi r \eta}$	а
§ 4.2.7 26	$\sigma_{ion} = \frac{n_i q_i^2}{6 \pi r}$	b
	$\sigma_{ion} = \frac{n_i q_i^2}{6\pi r \eta}$	С

	The Pisarevski-Valden law is expressed by:	
\$ 4 2 7	$\frac{\sigma}{\eta} \cdot = \text{const}$	а
27	$\sigma \cdot \eta = const$	b
	$\sigma \cdot \eta^2 = const$	С

Where do the molecules dissociate easier?		
	In polar liquids	а
§ 4.2.7 28	The same degree, in polar and non-polar liquids	b
	In non-polar liquids	С

	Where can molionic conductivity be met?	
	In non-polar liquids	а
§ 4.2.7 29	In polar liquids	b
	In colloidal systems	С

Which dielectrics cannot be used as electro-insulators at high temperatures?		
	Dielectrics with electronic conductivity	а
§ 4.3.1 30	Dielectrics with electronic and ionic conductivity	b
	Dielectrics with ionic conductivity	С

What is the name of the materials composed by non-polar molecules?		
	Diaelectrical materials	а
§ 4.3.1 31	Dielectrical materials	b
	Feroelectrical materials	С

	The electric moment is expressed by:	
	$\overline{oldsymbol{ ho}}=oldsymbol{q}_{_{lib}}\overline{oldsymbol{h}}$	а
§ 4.3.1 32	$\overline{p} = 2q_{leg}\overline{h}$	b
	$\overline{p} = q_{leg} \overline{h}$	С

Which materials have an electric moment even in the absence of external electric fields?		
	Polar	а
§ 4.3.1 33	Non-polar	b
	Polar and non-polar	С

What is the relation of the electric moment for diaelectrical materials?		
	$\overline{p} = 0$	а
§ 4.3.1 34	$\overline{p} > 0$	b
	$\overline{p} \neq 0$	С

	What is the angle between the electric moments of water?	
	90 °	а
§ 4.3.2 35	104.5°	b
	30°	С

	What does the phenomenon of electric polarization consist of?	
	The apparition of electric dipoles	а
§ 4.3.2 36	The reorientation of the electric dipoles	b
	The apparition or reorientation of the electric dipoles	С

	The electric polarizability of the atom depends on:	
	The nature and the structure of the dielectric	а
§ 4.3.2 37	The nature of the dielectric	b
	The structure of the dielectric	С

What kind of average of the microscopic electric field \overline{E}_{micro} is the macroscopic electric field?		
	Spatial	а
§ 4.3.2 38	Spatial-temporal	b
	Temporal	С

The relation between the intensity E_0 of the effective electric field and the intensity \overline{E} of the applied electrical field is:		
	$\overline{E} = \overline{E}_0 + \frac{\gamma}{\varepsilon_r} \overline{P}$	а
§ 4.3.2 39	$\overline{E}_{0} = \overline{E} + \frac{\gamma}{\varepsilon_{0}} \overline{P}$	b
	$\overline{E}_{0} = \overline{E} + \frac{\varepsilon_{0}}{\gamma} \overline{P}$	С

Which of the following definitions of the relative electrical permittivity is correct?		
	The relative electrical permittivity ε_r of a material is the ratio between the <i>C</i> capacity of a capacitor having as dielectric the studied material and the <i>C</i> ₀ capacity of a capacitor, with the same geometry, having as dielectric the vacuum	а
§ 4.3.3 40	The relative electrical permittivity ε_r of a material is the ratio between the C_0 capacity of a capacitor having as dielectric the vacuum and the <i>C</i> capacity for the same system, with the same geometry of a capacitor having as dielectric the studied material	b
	The relative electrical permittivity ε_r of a material is the ratio between the <i>C</i> capacity of a capacitor having as dielectric the studied material and the <i>C</i> ₀ capacity for the same system, with the same geometry having as dielectric the air	С

The angle of losses δ is defined as:		
§ 4.3.3 41	The supplement of the phase angle between the applied voltage <i>u</i> and the intensity of the current <i>i</i> passing through the capacitor, having as dielectric the studied electro-insulating material	а
	The complementation of the phase angle between the current <i>i</i> passing through the capacitor, having as dielectric the studied electro-insulating material and the applied voltage <i>u</i>	b
	The complementation of the phase angle between the applied voltage <i>u</i> and the current <i>i</i> passing through the capacitor, having as dielectric the studied electroinsulating material	С

The loss factor of series connection for the equivalent condenser is:		
	$tg_s = \frac{C_s}{\omega G_s}$	а
§ 4.3.3 42	$tg\delta_{s} = \frac{U_{R}}{U_{C}} = \frac{R_{s}}{X_{s}} = \frac{\omega C_{s}}{G_{s}}$	b
	$tg\delta_{s} = \frac{U_{c}}{U_{R}} = \frac{X_{s}}{R_{s}} = \frac{C_{s}}{\omega G_{s}}$	С

The induced electric moments are considered to be parallel with the effective electric field for dielectrics:		
	Isotropic dielectrics	а
§ 4.3.3 43	Isotropic and linear dielectrics	b
	Linear dielectrics	С

	The electronic polarizability is expressed by:	
	$\alpha_e = \pi \varepsilon_0 r^3$	а
§ 4.3.4 44	$\alpha_e = 4\pi\epsilon_0 r^2$	b
	$\alpha_e = 4\pi\epsilon_0 r^3$	С

	The measurement unit of the electronic polarizability is:	
	F·m ²	а
§ 4.3.4 45	F·m ³	b
	F∙m	С

The potential energy of electrostatic nature of the dipole in the effective electric field is expressed by:		
	$W_{p} = \vec{p}_{p} \cdot \vec{E}_{0} = -p_{p} E_{0} \cos \theta$	а
§ 4.3.6 46	$W_{\rho} = -\vec{p}_{\rho}\cdot\vec{E}_{0} = -p_{\rho}E_{0}\cos\theta$	b
	$W_{p} = -\vec{p}_{p}\cdot\vec{E}_{0} = -p_{p}E_{0}\sin\theta$	С

For what values of $a = \frac{p_p E_0}{kT}$ parameter, the Langevin function take value of 1/3?		
	a <<1	а
§ 4.3.6 47	a >> 1	b
	a >1	с

The electrical susceptivity of dielectrics with orientation polarization is expressed by:		
	$\chi_{e} = \frac{\frac{p_{p}^{2}}{3k\varepsilon_{0}T}}{1 - \gamma \frac{p_{p}^{2}}{3k\varepsilon_{0}T}}$	а
§ 4.3.6 48	$\chi_{e} = \frac{\frac{p_{p}^{2}}{k\varepsilon_{0}T}}{1 - \gamma \cdot \frac{p_{p}^{2}}{k\varepsilon_{0}T}}$	b
	$\chi_{e} = \frac{\frac{p_{p}^{2}}{3k\varepsilon_{0}T}}{1 + \gamma \frac{p_{p}^{2}}{3k\varepsilon_{0}T}}$	С

What expression can be used in order to calculate the average of relative permittivity ϵ_m for perfectly homogeneous mixtures?		
	Langevin	а
§ 4.3.9 49	Clausius-Mosotti	b
	Pisarevski-Valden	С

The average of relative permittivity for stratified materials is expressed by $\frac{1}{\varepsilon} = \sum_{i=1}^{n} \frac{v_i}{\varepsilon_i}$ and		
	it is valid to the equivalent capacity of a connection:	
	Serial connection	а
§ 4.3.9 50	Paralel connexion	b
	Mixed connexion	С

	The expression of the electric strength $E_{str} = \frac{U_{str}}{d}$ is valid:	
	In non-homogenous fields	а
§ 4.4.1 51	In homogenise and non- homogenous fields	b
	In homogenous fields	С

What causes the losses through electrical conduction in dielectrics?		
	The non-null resistivity of the dielectrics	а
§ 4.4.2 52	The non-null conductivity of the dielectrics	b
	The finite electrical conductivity of the dielectrics	С

The volume density of the active power losses in a dielectric is expressed by:		
	$p_{\sigma} = \rho_{tot} E_{ef}^2$	а
§ 4.4.2 53	$p_{\sigma} = \sigma_{tot} E_{ef}^2$	b
	$p_{\sigma} = \sigma_{tot} E_{ef}$	С

What is the name of those power losses that appear in a dielectric due to the fact that the quantity of electric polarisation \overline{P} is not in phase to the quantity of the electric field intensity \overline{E} ?		
	Losses through electric polarisation	а
§ 4.4.3 54	Losses through electrical conduction	b
	Losses through magnetic hysteresis	С

	Losses through electric polarization appear in:	
	Linear and non-linear dielectrics	а
§ 4.4.3 55	Linear dielectrics	b
	Non-linear dielectrics	С

When ∮PdE≠0 ? _{Γciclu}		
	Relaxation time is comparable with the period	а
§ 4.4.3 56	Relaxation time is much shorter than the period	b
	Relaxation time is much longer than the period	С

The quantity $J_D = dD/dt$ is:		
	The density of the conduction electrical current	а
§ 4.4.4 57	The density of the convection electrical current	b
	The density of the displacement electrical current	С

Breakdown through partial discharges is due to:		
	Presence of the cavities filled with gas in solid dielectrics	а
§ 4.4.4 58	Lattice defects	b
	Impurities	С

The electric breakdown of gases in homogenous electric fields is produced in a time interval of the order of:		
	10 ⁶ ÷10 ⁴ s	а
§ 4.4.5 59	10 ⁻⁸ ÷10 ⁻⁶ s	b
	10 ⁻¹⁰ ÷10 ⁻⁸ s	С

	Paschen curves are expressed by:	
	$U_{str} = f(d)$	а
§ 4.4.5 60	$U_{str} = f(p)$	b
	$U_{str} = f(p \cdot d)$	С

The material parameter that globally characterises the thermal inertia of the material is:		
	Thermal conductivity	а
§ 4.4.5 61	Thermal transmission coefficient	b
	Thermal diffusivity	С

The division into stability classes of the electroinsulating materials has been made according to:		
	Electrical and thermal stability	а
§ 4.5.6 62	Thermal stability	b
	Mechanical stability	С

Assessment Questions – Chapter 5

The state of magnetization is temporary if it maintains		
§ 5.1.1 1	If it does not depend on the existence of an exterior magnetic field	а
	If it is depend on the existence of an exterior magnetic field	b
	Other solution	С

The state of magnetization can be permanent if:		
§ 5.1.1 2	It doesn't depend on the existence of an exterior magnetic field	а
	While the body is introduced in an exterior magnetic field	b
	Other solution	С

The state of magnetization of the bodies is characterized through:		
	Through the quantities \overline{m} and \overline{M}	а
§ 5.1.1 3	The nature of material	b
	Structure of material	С

The quantity of the amperian magnetic moment is expressed by:		
	$\overline{m} = i \cdot \overline{S}$	а
§ 5.1.1 4	$\overline{M} = \frac{\Delta \overline{m}}{\Delta V}$	b
	$\Delta \overline{m} = \frac{\overline{M}}{\Delta V}$	С

The state of magnetization of a material can also be described through:		
	The law between \overline{B} , \overline{H} and \overline{M}	а
§ 5.1.1 5	$\mu = \mu_0 \mu_r$	b
	The magnetic polarization law	С

	The absolute magnetic permeability of the vacuum is:	
	μ₀=4π.10 ⁻⁷ H/m	а
§ 5.1.1 6	$\mu_0 = 4\pi . 10^7 \text{ H/m}$	b
	μ₀=1/4π.10 ⁻⁷ H/m	С

	The absolute permeability of the material μ is measured by:	
	H/m	а
§ 5.1.1 7	Н	b
	m/H	С

	The magnetic susceptivity χ_{m} of the diamagnetic materials is:	
	χ _m < 0	а
§ 5.1.2 8	$\chi_{m} = 0$	b
	χ _m > 0	С

	The magnetic susceptivity χ_{m} of the paramagnetic materials is:	
	χ _m > 0	а
§ 5.1.2 9	$\chi_{m} = 0$	b
	χ _m < 0	с

	The magnetic susceptivity χ_{m} of the ferromagnetic materials is:	
	χ _m >> 0	а
§ 5.1.2 10	χ _m > 0	b
	χ _m < 0	С

What is the name of the materials with a homoparallel order of the atomic magnetic moments?		
	Ferromagnetic materials	а
§ 5.1.2 11	Ferrimagnetic materials	b
	Diamagnetic materials	С

What is the name of the materials with an anti-parallel order of the atomic magnetic moments?		
	Ferrimagnetic materials	а
§ 5.1.2 12	Diamagnetic materials	b
	Ferromagnetic materials	С

The orbital magnetic moment, determined by the movement of the electron on the orbit, is expressed by:		
	$\overline{m}_{orb} = i \cdot \overline{S}$	а
§ 5.1.3 13	$\overline{K}_{orb} = \overline{r} \times m_0 \overline{v}$	b
	K _{orb} =rm ₀ v	С

The spin magnetic moment, determined by the movement of the electron around its own axis, is expressed by:		
	$g_{spin} = \frac{m_{spin}}{K_{spin}} = \frac{q_0}{m_0}$	а
§ 5.1.3 14	$K_{spin} = \sqrt{s(s+1)}\hbar$	b
	$\overline{m}_{spin} = -\frac{q_0}{m_0} \cdot \overline{K}_{spin}$	С

The total magnetic moment of the single-electron atom is expressed by:		
	$\overline{m}_{atom} = \overline{m}_{orb} + \overline{m}_{spin}$	а
§ 5.1.3 15	$\overline{m}_{atom} = \overline{m}_{orb} \pm \overline{m}_{spin}$	b
	$\overline{m}_{atom} = \overline{m}_{orb} - \overline{m}_{spin}$	С

The total magnetic moment of the atom with more electrons is expressed by:		
	$\overline{m}_{atom} = \sum_{i,k} \left[\overline{m}_{orb} + \overline{m}_{spin} \right]$	а
§ 5.1.3 16	$\overline{m}_{atom} = \overline{m}_{orb} - \overline{m}_{spin}$	b
	$\overline{m}_{atom} = \overline{m}_{orb} + \overline{m}_{spin}$	С

The polar magnetic materials are characterized by:		
	The existence of atomic magnetic moments	а
§ 5.1.3 17	The magnetic moments reciprocally compensate each other	b
	There are no atomic magnetic moments	С

	Which of the presented elements are magnetic polar:	
	Cr, Fe, Co	а
§ 5.1.3 18	Al, Cu, Sn	b
	Ne, Ar, Kr	С

Which of the following elements belong to the ferromagnetic materials?		
	Fe, Co, Ni, Gd	а
§ 5.1.3 19	Ne, Ar, Kr, Ni	b
	Fe, Al, Cu, Sn	С

The phenomenon of diamagnetism determines the modification of the total magnetic field by:		
	Decreasing the magnetic field	а
§ 5.2.1 20	Increasing the magnetic field	b
	Maintaining it constant	С

The phenomenon of paramagnetism causes the modification of total magnetic field by:		
	Increasing the magnetic field	а
§ 5.2.3 21	Decreasing the magnetic field	b
	Maintaining it constant	С

The classical theory of the diamagnetism of the bonded electrons in a free atom was elaborated by:		
	Langevin	а
§ 5.2.1 22	Larmor	b
	Lorentz	С

When an external magnetic field is applied to a diamagnetic material, the variation of the rotation frequency of the electron is called:		
	Larmor frequency	а
§ 5.2.1 23	Langevin frequency	b
	Thomson frequency	С

The magnetic susceptivity of the diamagnetic materials depends on:		
8521	Volume concentration <i>n</i> of the forming atoms and the Z number of the electrons in the atom	а
9 5.2.1 24	Intensity of the magnetic field	b
	Temperature and the intensity of the exterior magnetic field	С

How is the magnetic susceptivity $\chi_{\tiny md}$ for a diamagnetic material?		
	$\chi_{md} = -10^{-5}$	а
§ 5.2.2 25	$\chi_{md} = -10^{-8}$	b
	$\chi_{md} = -10^3$	С

The phenomenon of paramagnetism can be met in the case of the magnetic substances where \overline{m}_{atom} is:		
	$\overline{m}_{atom} \neq 0$	а
§ 5.2.3 26	$\overline{m}_{atom}=0$	b
	$\overline{m}_{atom} \ll 0$	С

The paramagnetic phenomenon is generated by:		
	Electrons bonded to the atom and the conduction electrons	а
§ 5.2.3 27	Electrons bonded to the atom	b
	Number of atoms	С

	The susceptivity of the paramagnetic materials has a value of:	
	$\chi_{\textit{mp}} \approx 10^{-5} \div 10^{-4}$	а
§ 5.2.3 28	$\chi_{\textit{mp}} \approx 10^{-1} \div 10^{-2}$	b
	$\chi_{mp} \approx 10^2 \div 10^3$	С

	The magnetic susceptivity depends on temperature:	
	Inversely proportional	а
§ 5.2.4 29	Doesn't depend on temperature	b
	Directly proportional	С

The electrical steel sheets are materials with crystalline structure in which the alloy elements are:		
	Fe, Ni, Co	а
§ 5.3.1 30	Fe, Si	b
	Ni, Co, Si	С

The alloy elements that have a positive influence on the magnetic properties of the electrical Fe-Si sheets are:		
	Ni, Co, Al	а
§ 5.3.1 31	O ₂ , N ₂ , S	b
	Mn, H ₂ , C	С

The magnetic characteristics of the electrical Fe-Si sheets depend on:		
§ 5.3.1 32	Mostly on alloy elements, presence of impurities and non- metal inclusions, size of the crystalline grains	а
	Mainly the magnetization regime	b
	Mainly the pressure and the operating temperature	С

What indicators are used in order to estimate the quality of the electrical Fe-Si sheets?		
§ 5.3.1 33	The specific magnetic losses, the values of magnetic induction for different values of field intensity	а
	The content of the alloy, the resistivity of the material	b
	Mechanical parameters	С

The characteristic properties of the soft magnetic materials are:		
8532	Magnetic saturation, hysteresis cycle, remanence, coercivity, temperature dependency of magnetic properties	а
9 5.3.2 34	The state of magnetization and dependency on temperature	b
	The intensity of the magnetic field and magnetic induction	С

The magnetization characteristic represents:		
§ 5.3.2 35	Dependence of the magnetic induction \overline{B} on the intensity of the applied magnetic field \overline{H}	а
	Dependence of magnetic losses on the magnetic induction	b
	Geometrical place of the peaks of the hysteresis cycles	С

What does the characteristics of the re-magnetization losses represent?		
	Dependence of the total losses on magnetic induction	а
§ 5.3.2 36	Dependence of the hysteresis losses on magnetic induction	b
	Dependence of losses on the intensity of the magnetic field	С

The measurement method with the Epstein frame allows to study electrical Fe-Si sheets in:		
	Sinusoidal magnetization regime	а
§ 5.3.3 37	Impulse magnetization regime	b
	Magnetization regime in continuous current	С

The dynamic characteristic of magnetization refers to the dependence:		
	$B_m = f(H_m)$	а
§ 5.3.3 38	$p = f(B_m)$	b
	$\mu_{ef} = f(H_{ef})$	С

The curve of the effective magnetic permeability refers to the dependence:		
	$\mu_{\it ef}=f(H_{\it ef})$	а
§ 5.3.3 39	$\mu_{ef} = f(B_{ef})$	b
	$B_m = f(H_m)$	С

According to which law can the intensity of the magnetic field be determined in the magnetic core of the Epstein frame?		
	The law of the magnetic circuit	а
§ 5.3.3 40	The dependency law between <i>B</i> , <i>H</i> and <i>M</i>	b
	The law of the electromotive force	С

According to which law can the magnetic induction be determined in the magnetic core of the Epstein frame?		
	The law of the electromotive force	а
§ 5.3.3 41	The law of the magnetic circuit	b
	The dependency law between <i>B</i> , <i>H</i> and <i>M</i>	С

What characteristics can be determined with the Epstein frame?			
	$B_m = f(H_{ef}); \ p_{Fe} = f(B_m); \ \mu_{efr} = f(H_{ef})$	а	
§ 5.3.3 42	$p_{Fe} = f(H)$, $R=f(U)$	b	
	$B_{ef} = f(H_m)$	С	

How are the ferromagnetic materials characterized by?			
§ 5.4.1 43	Homoparallel ordered atomic magnetic moments	а	
	Crystalline structure	b	
	Antiparallel ordered atomic magnetic moments	С	

The permeability of the ferromagnetic materials μ_r reaches values of the order of:			
	$10^2 \div 10^6$	а	
§ 5.4.1 44	10 ⁻² ÷ 10 ⁻⁴	b	
	$10^{-2} \div 10^{2}$	с	
The static magnetic permeability is expressed by:			
---	--	---	
	$\mu_{rst} = \frac{B}{\mu_0 H}$	а	
§ 5.4.1 45	$\mu_{rrev} = \lim_{\Delta H' \to 0} \left(\frac{\Delta B'}{\mu_0 \Delta H'} \right)$	b	
	$\mu_{r\Delta} = \lim_{\Delta H \to 0} \left(\frac{\Delta B}{\Delta H} \right)$	С	

By representing the dependence of magnetic induction <i>B</i> on the intensity of the magnetic field <i>H</i> , the following can be obtained in the case of the cyclical variation of <i>H</i> :		
	The hysteresis cycle	а
§ 5.4.1 46	The characteristic of demagnetization	b
	The curve of first magnetization	С

-	The soft magnetic materials have the following hysteresis cycle:	
	Narrow - less than 1 kA/m	а
§ 5.4.1 47	Narrow – less than 1 A/m	b
	Wide - more than 1 kA/m	С

The hard magnetic materials have the following hysteresis cycle:		
	Wide - more than 1 kA/m	а
§ 5.4.1 48	Wide - more than 1 A/m	b
	Narrow - less than 1 kA/m	С

The Curie temperature $T_{\rm C}$ represents the value after the material becomes:		
	Paramagnetic	а
§ 5.4.2 49	Ferrimagnetic	b
	Diamagnetic	С

The ferrimagnetic substances are characterized by spontaneous magnetic moments that are:		
	Unequal and anti-parallel ordered	а
§ 5.4.3 50	Un-ordered	b
	Equal and anti-parallel ordered	С

What are the ferrites?		
	Ceramic materials with ferrimagnetic properties	а
§ 5.4.3 51	Crystalline or amorphous materials	b
	Metallic material with ferromagnetic properties	С

How the temperature influences the properties of ferrimagnetic materials?		
	More accentuated than on ferromagnetic materials	а
§ 5.4.3 52	In almost the same degree as on ferromagnetic materials	b
	In almost the same degree as on the conductive materials	С

In the Weiss theory, the specific properties of ferromagnetic materials are determined by:		
	The structure of the magnetic domains	а
§ 5.5.1 53	The working temperature	b
	The value and the direction of the magnetic field	С

The magnetic non-isotropy is a characteristic of ferromagnetic substances that refer to:		
	The existence of the preferential directions of magnetization	а
§ 5.4.3 54	High-valued re-magnetization losses	b
	The non-existent preferential directions of magnetization	С

The most stable configuration of magnetic domains can be obtained when:		
	Sum of internal energies is minimum	а
§ 5.4.3 55	Sum of internal energies is constant	b
	Sum of internal energies is maximum	С

The magnetostriction appears when the magnetic field acts upon a material and it is characterized by:		
	Reversible elastic deformation	а
§ 5.4.3 56	Reversible magnetization	b
	Irreversible magnetization	С

	The Rayleigh domain refers to magnetic field intensity of:	
	Low values	а
§ 5.5.1 57	Medium values	b
	High values	С

	In the Rayleigh domain, the magnetization processes are:	
	Reversible	а
§ 5.5.4 58	Saturated	b
	Irreversible	С

	The integral $\int_{ciclu} B dH$ represents:	
	The dissipated energy in a cycle	а
§ 5.4.6 59	The losses through eddy currents	b
	The losses through hysteresis	С

How are the magnetic losses through eddy currents reduced in Fe-Si sheets?		
	Thermal treatment will be applied	а
§ 5.1.1 60	The thickness will be reduced and there will be insulated between	b
	There are magnetized in c.c.	С

Which of the insulating processes of steel sheets is characterized by a high filling coefficient?		
	Insulation with ceramic oxides	а
§ 5.6.4 61	Insulation with lacquers	b
	Insulation with papers	С

The commercialized materials Permalloy and Supermalloy are alloys of:		
	Fe-Ni	а
§ 5.6.5 62	Fe-Si	b
	Fe-Co	с

Which alloys have high values of saturation magnetic induction?		
	Fe-Co	а
§ 5.6.6 63	Ni-Fe-Cr	b
	Ni-Cu	С

The advantages of ferrites compared to other ferromagnetic materials are:		
	Higher resistivity	а
§ 5.6.6 64	Higher Curie temperature	b
	Higher magnetic saturation induction	С

363

	The quality index of the materials for permanent magnets is:	
	(BH) _{max}	а
§ 5.7.1 65	The value of <i>H</i> _c	b
	(<i>BH</i>) _{min}	С

In the catalogues of the magnets producing companies, the following information are given for the magnets:		
8571	The magnetization curves for different values of the slope load line	а
9 5.7.4 66	The operating point	b
	The magnetization curve for different values of the current	С

In the case of Alnico magnets of sorts A, the maximum value of the coercive field has its sort:		
	A9	а
§ 5.7.7 67	A8	b
	A6	С

Which type of hard magnetic ferrite is characterized by the maximum value of the index $(BH)_{max}$?		
	FS-4	а
§ 5.7.8 68	FS-5	b
	FS-3	С

ASSESSMENT ANSWERS



Answers – Chapter 1

§ 1.1.1 1	b
§ 1.1.1 2	а
§ 1.1.1 3	а
§ 1.1.1 4	b
§ 1.1.1 5	С
§ 1.1.2 6	а
§ 1.1.2 7	а
§ 1.2.1 8	b
§ 1.2.2 9	с
§ 1.2.2 10	b

§ 1.2.2 11	С
§ 1.2.2 12	а
§ 1.2.2 13	С
§ 1.2.2 14	b
§ 1.2.2 15	С
§ 1.2.2 16	b
§ 1.2.2 17	а
§ 1.2.3 18	а
§ 1.2.3 19	С
§ 1.2.3 20	С

§ 1.2.3 21	а
§ 1.2.3 22	b
§ 1.2.4 23	С
§ 1.2.4 24	а
§ 1.2.4 25	b
§ 1.2.4 26	С
§ 1.2.2 27	b
§ 1.2.2 28	С
§ 1.2.3 29	b
§ 1.2.3 30	С

Answers – Chapter 2

§ 2.1.1 1	а
§ 2.1.3 2	а
§ 2.1.3 3	С
§ 2.1.3 4	С
§ 2.1.3 5	а
§ 2.1.3 6	b
§ 2.1.3 7	С
§ 2.1.3 8	а
§ 2.1.3 9	b
§ 2.1.3 10	b

§ 2.1.3 11	b
§ 2.1.4 12	b
§ 2.2.2 13	С
§ 2.2.2 14	а
§ 2.2.2 15	а
§ 2.2.2 16	b
§ 2.2.3 17	а
§ 2.3.1 18	b
§ 2.3.1 19	а
§ 2.3.1 20	а

§ 2.3.1 21	b
§ 2.3.1 22	С
§ 2.3.2 23	а
§ 2.3.2 24	b
§ 2.3.2 25	а
§ 2.3.3 26	b
§ 2.3.4 27	С
§ 2.3.5 28	b
§ 2.4.4 29	С
§ 2.4.5 30	а

а

§ 2.5.6 41

§ 2.4.6 31	а
§ 2.5.1 32	С
§ 2.5.2 33	С
§ 2.5.2 34	b
§ 2.5.3 35	b
§ 2.5.1 36	а
§ 2.5.2 37	b
§ 2.3.1 38	а
§ 2.5.4 39	b
§ 2.5.5 40	b

Answers – Chapter 3

§ 3.1.1 1	b
§ 3.1.1 2	а
§ 3.1.1 3	а
§ 3.1.2 4	а
§ 3.1.2 5	а
§ 3.1.2 6	а
§ 3.1.2 7	а
§ 3.1.3 8	а
§ 3.2.1 9	а
§ 3.2.2 10	а

b
С
b
С
а
а
С
а
b
а

§ 3.3.2 21	С
§ 3.4.1 22	С
§ 3.2.3 23	С
§ 3.5.3 24	а
§ 3.2.3 25	С
§ 3.5.4 26	С
§ 3.4.3 27	С
§ 3.2.3 28	С
§ 3.5.2 29	а
§ 3.5.5 30	а

§ 3.5.8 31	С
§ 3.5.8 32	С
§ 3.5.9 33	С
§ 3.5.9 34	b
§ 3.5.9 35	С
§ 3.5.9 36	а
§ 3.5.7 37	b
§ 3.5.3 38	а
§ 3.5.4 39	а
§ 3.5.7 40	С

Answers – Chapter 4

§ 4.1.1 1	С
§ 4.1.1 2	С
§ 4.1.2 3	а
§ 4.1.3 4	b
§ 4.1.3 5	а
§ 4.2.2 6	b
§ 4.2.2 7	а
§ 4.2.2 8	b
§ 4.2.3 9	С
§ 4.2.3 10	b

§ 4.2.3 11	b
§ 4.2.3 12	С
§ 4.2.3 13	b
§ 4.2.3 14	С
§ 4.2.4 15	b
§ 4.2.4 16	а
§ 4.2.4 17	b
§ 4.2.4 18	С
§ 4.2.4 19	b
§ 4.2.4 20	а

§ 4.2.5 21	b
§ 4.2.5 22	b
§ 4.2.5 23	С
§ 4.2.6 24	b
§ 4.2.7 25	b
§ 4.2.7 26	С
§ 4.2.7 27	b
§ 4.2.7 28	а
§ 4.2.7 29	С
§ 4.3.1 30	С

§ 4.3.1 31	а
§ 4.3.1 32	С
§ 4.3.1 33	а
§ 4.3.1 34	а
§ 4.3.2 35	b
§ 4.3.2 36	С
§ 4.3.2 37	а
§ 4.3.2 38	b
§ 4.3.2 39	b
§ 4.3.3 40	а
§ 4.4.5	С

§ 4.3.3 41	С
§ 4.3.3 42	b
§ 4.3.3 43	b
§ 4.3.4 44	С
§ 4.3.4 45	а
§ 4.3.6 46	b
§ 4.3.6 47	а
§ 4.3.6 48	а
§ 4.3.9 49	b
§ 4.3.9 50	а

Assessment Answers

§ 4.4.1 51	С
§ 4.4.2 52	b
§ 4.4.2 53	b
§ 4.4.3 54	а
§ 4.4.3 55	а
§ 4.4.3 56	а
§ 4.4.4 57	С
§ 4.4.4 58	а
§ 4.4.5 59	b
§ 4.4.5 60	С

§ 4.4.5 61	С
§ 4.5.6 62	b

Answers – Chapter 5

§ 5.1.1 1	b
§ 5.1.1 2	а
§ 5.1.1 3	a
§ 5.1.1 4	а
§ 5.1.1 5	а
§ 5.1.1 6	а
§ 5.1.1 7	a
§ 5.1.2 8	а
§ 5.1.2 9	а
§ 5.1.2 10	а

§ 5.1.2 11	а
§ 5.1.2 12	а
§ 5.1.3 13	а
§ 5.1.3 14	С
§ 5.1.3 15	а
§ 5.1.3 16	а
§ 5.1.3 17	а
§ 5.1.3 18	а
§ 5.1.3 19	а
§ 5.2.1 20	а

§ 5.2.3 21	а
§ 5.2.1 22	а
§ 5.2.1 23	а
§ 5.2.1 24	а
§ 5.2.2 25	а
§ 5.2.3 26	а
§ 5.2.3 27	а
§ 5.2.3 28	а
§ 5.2.4 29	а
§ 5.3.1 30	b

369

§ 5.3.1 31	а
§ 5.3.1 32	а
§ 5.3.1 33	а
§ 5.3.2 34	а
§ 5.3.2 35	а
§ 5.3.2 36	а
§ 5.3.3 37	а
§ 5.3.3 38	а
§ 5.3.3 39	а
§ 5.3.3 40	а

§ 5.3.3 41	а
§ 5.3.3 42	а
§ 5.4.1 43	а
§ 5.4.1 44	а
§ 5.4.1 45	а
§ 5.4.1 46	а
§ 5.4.1 47	а
§ 5.4.1 48	а
§ 5.4.2 49	а
§ 5.4.3 50	а

§ 5.4.3 51	а
§ 5.4.3 52	а
§ 5.5.1 53	a
§ 5.4.3 54	а
§ 5.4.3 55	a
§ 5.4.3 56	а
§ 5.5.1 57	a
§ 5.5.4 58	а
§ 5.4.6 59	а
§ 5.1.1 60	b

§ 5.6.4 61	а
§ 5.6.5 62	а
§ 5.6.6 63	а
§ 5.6.6 64	а
§ 5.7.1 65	а
§ 5.7.4 66	а
§ 5.7.7 67	а
§ 5.7.8 68	а

BIBLIOGRAPHY

- 1. BOGORODIŢKII N.P., etc.: *Elektrotehniceskie materialî*. Leningrad, 1985.
- 2. BOZORTH R.: Ferromagnetism, IEEE Press, p.968, 1978.
- 3. BRAITHWAITE N., etc.: *Electronic Materials*. Milton Keynes, London, 1990.
- 4. BUCHANAN R.C.: Ceramic Materials for Electronics. Processing, Properties, and Applications. Ilinois, New York, 1986.
- 5. BURZO E.: *Fizica fenomenelor magnetice*. Ed. Academiei, Bucureşti, Vol. 1 (1979), Vol. 2 (1981).
- 6. BURZO E: Magneți permanenți, Ed. Academiei, București, Vol. I (1986), Vol. II (1987).
- 7. CĂTUNEANU V., IANCU O., DRAGULINESCU M.: *Materiale şi componente electronice*. Editura Didactică și Pedagogică, București, 1981.
- 8. CHUNG D.: Applied Materials Science. Applications of Engineering Materials in Structural, Electronics, Thermal and other Industries. CRC Press, London, 2001.
- 9. CULLITY B.D., GRAHAM C.D.: *Introduction to Magnetic Materials*. 2nd ed., IEEE Press, John Wiley & Sons, Inc., Hoboken, New Jersey, p.544, 2009.
- 10. DELLA TORRE E.: Magnetic Hysteresis. IEEE Press, p.215, 1999.
- 11. DRÅGÅNESCU M.: *Electronica corpului solid.* Editura Tehnică, București, 1972.
- 12. ELLIOTT R.: *Electromagnetics: History, Theory and Applications*. IEEE Press Series on Electromagnetic Waves, p.630, 1993.
- 13. FEYNMAN R., LEIGHTON R., SANDS M.: *Lectures on Physics Mainly Electromagnetism and Matter*. Addison-Wesley Publishing Company, p.536, 1964.
- 14. GERU N.: Teoria structurală a proprietăților metalelor. E. D. P., București, 1980.
- 15. HELEREA E., etc.: Materiale electrotehnice, Universitatea din Braşov, 1984.
- 16. HELEREA E., OLTEAN I., MUNTEANU A., *Materiale pentru electrotehnică şi electronică*. Îndrumar laborator, Universitatea "Transilvania" din Braşov, 1991.
- 17. HELEREA E.: *Materiale electrotehnice. Dielectrici*. Editura Universității "Transilvania", Braşov, 1998.
- 18. HELEREA E., ACIU L., OLTEAN I., MUNTEANU A.: *Materials for Electrical Engineering. Applications.* Univ. Transilvania din Braşov, p.85, 2002.
- 19. HELEREA E., MUNTEANU A.: *Materiale electrotehnice. Aplicații*. Universitatea Transilvania din Braşov, 2002.
- 20. HELEREA E.: *Materiale pentru electrotehnică și electronică*, Editura Matrix Rom, București, p.298, 2003.
- 21. HELEREA E., ȚICĂ R., DUMITRESCU L.: *Materiale electroconductoare, Materiale electroizolante Interferențe cu mediul,* Univ. Transilvania din Braşov, p.250, 2003.

- 22. IFRIM A., NOŢINGHER P.: *Materiale electrotehnice.* Editura Didactică şi Pedagogică, Bucureşti, 1980/1992.
- 23. KEITHLEY J.: The Story of Electrical and Magnetic Measurements: From 500 BC to the 1940s. IEEE Press, p.240, 1999.
- 24. KIREEV S.S.: *Fizica semiconductorilor.* Editura Științifică și Enciclopedică, București, 1977.
- 25. KITTEL C.: Introduction to Solid State Physics. John Wiley & Sons, Inc., 1986.
- 26. LACROUX G: *Les aimants permanents*. Techniques et Documentation Lavoisier, Paris, 1989.
- 27. MORRISH A.: The Physical Principles of Magnetism. IEEE Press, p.680, 2001.
- 28. MÜNCH W.: Werkstoffe der Elektrotechnik. Editura Teubner, Stuttgart, 1978/1992.
- 29. MURRAY I. (ed.): *Handbook of Materials Selection for engineering applications.* Marcel Derek Inc., New York, 1997.
- 30. NEWMAN T.E.: *Electricity and Electronics.* The Neville Press Inc., Mc Grow-Hill, 1995.
- NICOLAIDE A.: Bazele fizice ale electrotehnicii. Editura Scrisul Românesc, Craiova, Vol. I (1983), Vol. II (1986).
- 32. NICOLAIDE A.: *Magnetism and Magnetic Materials*. Editura Universității Transilvania Braşov, 2001.
- 33. PHILIPPE R.: *Matériaux de l'electrotehnique*. Presses Polytechniques Romandes, Lausanne, 1989.
- 34. POPESCU C., IFRIM A., LEFTER C.: Materiale electrotehnice. Proprietăți și utilizări. Editura Tehnică, București, 1976.
- 35. SHACKELFORD J.F.: Introduction to Materials Science for Engineering. University of California, Davis Prentice Hall, Uper Saddle Riever, New Jersey, 1996.
- 36. SHUGG W.: Handbook of Electrical and Electronic Insulating Materials. IEEE Press, p.578, 1995.
- 37. SMITH W.F.: *Principles of Materials Science and Engineering.* Engineering Series, Mc Graw Internat, Edition 1990, New York, Univ. of Central Florida, 1986/1990.
- 38. TAREEV B.M.: Cpravocinik po electrotehniceskim materialam. Energoatomizdat, Leningrad, 1988.
- 39. TIMMINGS RL: Engineering Materials. Longman Lt., Essex, 1998.
- 40. VONZOVSKI S.V.: Magnetismul. Editura Şt. şi Enciclopedică, Bucureşti, 1981.
- 41. WAYNE-BEAUTY J.: *Electrical Engineering. Materials Reference Guide*. McGraw-Hill Publishing Company, 1990.

CONTENTS

1. F	PARAMETERS AND MATERIAL LAWS IN ELECTRICAL ENGINEERING	3
	1.1. Definitions and Classifications	4
Δ	1.1.1. Definitions. Material Parameters	4
Δ	1.1.2. Classification of Materials	5
	1.2. Material Laws in Electrotechnics	6
Δ	1.2.1. Laws and Material Parameters	6
Δ	1.2.2. Electric Conduction Law	8
M	1.2.3. Temporary Electric Polarization Law	10
M	1.2.4. Temporary Magnetization Law	12
	1.3. Material Laws in Any Medium	14
M	1.3.1. Electric Conduction Law in Any Medium	14
M	1.3.2. Temporary Electric Polarization Law in Any Medium	15
M	1.3.3. Temporary Magnetization Law in Any Medium	16
2. (CONDUCTIVE MATERIALS	17
2	2.1. Electric Conduction in Metals	18
Δ	2.1.1. General Presentation of the Electric Conduction	18
Δ	2.1.2. Experimental Determination of the Resistivity	19
M	2.1.3. Establishing the Electric Conductivity Expression	21
M	🗴 2.1.4. The Mathiessen Law	27
2	2.2. Metal Electric Conductivity Dependence of Various Factors	28
Δ	2.2.1. Intrinsic and Extrinsic Factors	28
M	2.2.2. Temperature Dependence	29
M	2.2.3. The Influence of Plastic Deformation and Pressure	32
M	2.2.4. The Influence of Electric Current Frequency	33
2	2.3. Materials with High Electric Conductivity	34
Δ	2.3.1. Requirements for Materials with High Conductivity	34
M	2.3.2. Copper and Alloys of Copper	35
M	2.3.3. Aluminum and Alloys of Aluminum	37
M	2.3.4. Silver	39
M	2.3.5. Iron and Alloys of Iron	41
2	2.4. Materials with High Resistivity	44
Δ	2.4.1. Requirements for Materials with High Resistivity	44
M	2.4.2. Nickel	45
M	2.4.3. Molybdenum	47
M	2.4.4. Wolfram	48
M	2.4.5. Manganese Alloys	49
M	2.4.6. Nickelines	50

374	Materials in Electrical Engineering	
M	2.4.7. Resistive Alloys Based on Precious Metals	. 51
M	2.4.8. Iron and Alloys of Iron	. 52
2.5	Applications of Conductive Materials	. 54
Δ	2.5.1. Resistors	. 54
M	2.5.2. Electric Contacts and Brushes	. 56
M	2.5.3. Fuse Wires	. 60
M	2.5.4. Thermocouples	. 61
M	2.5.5. Strain Gauges	. 65
M	2.5.6. Thermo-Bimetals	. 68
2.6	Superconductive Materials	. 71
M	2.6.1. Characteristics of the Superconductive State	. 71
M	2.6.2. Justification of the Super-Conduction State	. 74
M	2.6.3. Applications of the Super-Conduction State	. 77
2.7	. Re-Valorization of the Metals	. 79
3 SF	MICONDUCTIVE MATERIALS	83
0.0L 31	Electric Conduction in Semiconductors	. 00 84
Δ	3.1.1. General Presentation	. 84
M	3.1.2. Energy States in Crystals	. 86
M	3.1.3. Conduction Mechanism in Energy Bands Theory	. 90
3.2	Intrinsic Electric Conduction	. 92
Δ	3.2.1. Intrinsic Conduction – Physical Model	. 92
M	3.2.2. Intrinsic Conduction – Energy Bands Model	. 94
M	3.2.3. Electric Conductivity in Intrinsic Semiconductors	. 96
3.3	. Extrinsic Electric Conduction	. 99
Δ	3.3.1. <i>n</i> -Type Extrinsic Conduction – Physical Model	. 99
Δ	3.3.2. <i>p</i> -Type Extrinsic Conduction – Physical Model	101
M	3.3.3. <i>n</i> -Type Extrinsic Conduction – Energy Bands Model	102
Δ	3.3.4. <i>p</i> -Type Extrinsic Conduction – Energy Bands Model	104
////	3.3.5. Electric Conductivity in Extrinsic Semiconductors	105
3.4	. Factors that Influence the Conductivity of the Semiconductors	106
	3.4.1. Temperature – An Important Factor of Influence	106
	3.4.2. The Dependency of Intrinsic Conductivity on Temperature	107
	3.4.3. The Dependency of Extrinsic Conductivity on Temperature	108
	3.4.4. Magneto-Electric Effects	112
	3.4.5. Hall Effect in Metals and Semiconductors	113
	3.4.6. Magneto-Resistive Effect in Semiconductors	118
3.5	5. Properties and Use of the Semiconductive Materials	120
	3.5.1. Performances and Fields of Use	120
	3.5.2. Semiconductive Materials Used for Voltage Control Conduction	121

	Contents	375
M	3.5.3. Silicon	122
M	3.5.4. Germanium	125
Δ	3.5.5. Varistors	127
M	3.5.6. Materials for Thermo-Electric Conversion	128
Δ	3.5.7. Thermistors	129
M	3.5.8. Semiconductive Materials for Optic-Electric Conversion	133
M	3.5.9. Semiconductive Materials for Electric-Optic Conversion	135
M	3.5.10. Semiconductive Materials for Magneto-Electric Conversion	138
M	3.5.11. Semiconductive Materials for Mechano-Electric Conversion	140
M	3.5.12. Usual Structures for Semiconductive Devices	141
4. DI		145
4.1	. General Characteristics	146
Δ	4.1.1. Electroinsulating Materials and Dielectrics	146
M	4.1.2. Requirements for Electroinsulating Materials	147
M	4.1.3. Durability of the Electrical Insulation	147
4.2	2. Electrical Conduction in Dielectrics	151
Δ	4.2.1. General Characteristics of Electrical Conduction	151
Δ	4.2.2. Determining the Volume and Surface Resistivity	153
M	4.2.3. Electrical Conduction Mechanisms	155
Δ	4.2.4. Influencing Factors on the Electric Conductivity	158
M	4.2.5. Electric Conduction in Glasses, Ceramics and Cermets	163
M	4.2.6. Metal-Dielectric Interfaces	167
	4.2.7. Electric Conduction in Electroinsulating Liquids	170
4.3	3. Electrical Polarization in Dielectrics	174
Δ	4.3.1. Polar and Non-Polar Dielectrics	174
Δ	4.3.2. A General Approach to the Polarization Phenomena	178
	4.3.3. Electronic Polarization	181
	4.3.4. Ionic Polarization	185
	4.3.5. Orientation Polarization	188
	4.3.6. Temperature Influence on the Polarization State	191
	4.3.7. The Clausius - Mosotti Equation	193
	4.3.8. Dielectric Permittivity of Composite Materials	194
4.4	. Dielectrics in Alternative Electric Fields	197
Δ	4.4.1. Complex Permittivity	197
	4.4.2. Electric Polarization Losses	200
	4.4.3. Total Losses in Dielectrics	203
4.5	b. Electric Breakdown Phenomena	206
	4.5.1. High Voltage Testing	206
	4.5.2. Electrical Breakdown Models	208

376	Materials in Electrical Engineering	
M	4.5.3. Electric Breakdown Prevention	211
4.6	6. General Properties of Dielectrics	213
Δ	4.6.1. Electric Properties	213
Δ	4.6.2. Mechanic Properties	215
Δ	4.6.3. Chemical and Physical Properties	216
M	4.6.4. Thermal Properties	218
M	4.6.5. Influence of the Frequency on Dielectric Properties	221
M	4.6.6. Thermal Stability of Dielectrics	223
5. MA	AGNETIC MATERIALS	225
5.1	. Magnetization States	226
Δ	5.1.1. Characteristic Quantities	226
Δ	5.1.2. Classifications	227
M	5.1.3. Uni-Electronic Atom Magnetism	228
M	5.1.4. Multi-Electronic Atom Magnetism	233
M	5.1.5. Polar or Non-Polar Magnetic Materials	234
5.2	2. Material Behavior in External Magnetic Field	236
M	5.2.1. Material Diamagnetism	236
M	5.2.2. Diamagnetic Materials Classes	240
M	5.2.3. Material Paramagnetism	242
M	5.2.4. Paramagnetic Materials Classes	246
5.3	3. Interpreting the Ferri- and Ferro-Magnetic States	247
M	5.3.1. Characteristics of Ferromagnetic Materials	247
M	5.3.2. Temperature Dependence of Magnetic Properties	252
M	5.3.3. Ferrimagnetic Materials	254
M	5.3.4. Magnetic Domains Theory	258
M	5.3.5. Explanation for the Magnetization Curves	263
5.4	Losses in Ferromagnetic Materials	266
M	5.4.1. Losses Due to the Hysteresis Loop	266
M	5.4.2. Losses Due to the Eddy Currents	268
M	5.4.3. Additional Magnetic Losses	269
M	5.4.4.Total Losses in Magnetic Materials	269
5.5	5. Experimental Study of Fe-Si Sheets	271
Δ	5.5.1. What are the Fe-Si Sheets	271
Δ	5.5.2. Characteristic Parameters	273
Δ	5.5.3. The Principle of the Measurement Method with Epstein Frame	274
M	5.5.4. Automated Measurements and Results	277
5.6	. Properties and Fields of Use of the Soft Magnetic Materials	280
Δ	5.6.1. Performances and Development Trends	280
Δ	5.6.2. Iron as a Soft Ferromagnetic Material	282

	Contents	377
Δ	5.6.3. Steel and Soft Magnetic Cast Iron	283
Δ	5.6.4. Fe-Si Alloys	285
M	5.6.5. Fe-Ni Alloys	. 288
M	5.6.6. Soft Magnetic Ferrites	291
M	5.6.7. Magneto-Dielectric Materials	. 292
5.7	. Properties and Fields of Use of the Hard Magnetic Materials	. 293
Δ	5.7.1. Characteristic Parameters of the Materials Used for Permanent Magnets	. 293
M	5.7.2. Establishment of the Operation Point for Magnets	. 294
M	5.7.3. Operation Regimes for Magnets	. 298
M	5.7.4. Designing and Selection Criteria for Permanent Magnets	. 299
Δ	5.7.5. Material Production Evolution for Permanent Magnets	301
M	5.7.6. Alloyed and Martensitic Steels	. 303
M	5.7.7. Alni and Alnico Alloys	305
M	5.7.8. Hard Magnetic Ferrites	307
M	5.7.9. Composites of the Rare Earths with Co and Fe	. 309
M	5.7.10. General Physical Properties of Hard Magnetic Materials	. 311
ASSE	SMENT QUESTIONS	313
Ch	apter 1	. 314
Ch	apter 2	. 320
Ch	apter 3	. 329
Ch	apter 4	. 337
Ch	apter 5	. 351
ASSE	SMENT ANSWERS	365
Biblic	ography	371
Conte	ents	. 373