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ELECTRICAL MATERIALS SCIENCE

MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

DNIPRO UNIVERSITY OF TECHNOLOGY

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The regularities of processes and phenomena that occur in dielectric, conductive, semiconductor and magnetic materials used in electrical and electronic devices under the influence of energy of electric, magnetic and thermal fields are considered. The main feature of the textbook is detailed structuring of educational material, focusing largely on the distance form of learning, as well as demonstration of the close relationship of properties of various electrical materials and the basics of electrical engineering on specific examples.

The manual is intended for students of 141 "Power Engineering, Electrical Engineering and Electromechanics" speciality, as well as students of other specialties.

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INTRODUCTION

The course "Electrical Materials Science" is mandatory (normative) in the curriculum of the specialty 141 "Electrical Power Engineering, Electrical Engineering and Electromechanics", which requires sufficient attention to the teaching of the course. This is especially important for those students who focus on the specialization "Non-traditional and renewable energy sources" of this specialty [1]. The very name of this specialization indicates the relevance of a deep understanding of processes in electrical materials. An important condition for quality training of students in the course is their prior and fairly thorough training in fundamental disciplines - Physics, Basics of Electrical Engineering and Higher Mathematics. This means knowledge of the most important physical phenomena that occur in electrical materials as components of electrical or electronic equipment, the laws of these phenomena and the mathematical formulation of these laws.

Many years of experience in teaching this course and other related fundamental disciplines (Theoretical Foundations of Electrical Engineering, Theory of Electric and Magnetic Circuits, Electric Machines, Basics of Electronics and Microprocessor Technology) for students of the National Technical University "Dnipro Polytechnic" allows summarizing the difficulties of courses mastering. These difficulties arise due to the contradictions between the requirements for basic training and the actual educational level of students. In most cases, students have not yet completed the study of Physics and Electrical Engineering, are insufficiently aware of the priority of understanding the laws of natural phenomena. In particular, most students already know that electric current is the ordered motion of charged particles, but do not understand the terms "order", "motion" and "charged particles" deeply enough, limiting themselves to the mathematical formulation of Ohm's law in relation to a particular section of an electric circuit.

Electrical materials can be thoroughly studied provided a deep understanding of the various factors of energy fields influencing them (electric, magnetic and thermal fields). But most students at this stage have not even begun to study these fields. Most of the published textbooks and manuals devoted to the study of electrical materials are based on the fact that students are already prepared sufficiently on these issues, and therefore do not pay enough attention to the fundamental features of the impact of energy fields on electrical materials. Therefore, there is an urgent need for a textbook that could fill in the gap between the need for in-depth knowledge of electrical engineering students in the most important properties of electrical materials and their rather limited prior training in basic disciplines.

This textbook pays maximum attention to the patterns of processes and phenomena that occur in electrical materials as a part of electrical and electronic devices, in dielectric, conductive, magnetic, and semiconductor materials. First of all, attention is paid to the force nature of the influence of electric and magnetic fields on charged particles: on the Coulomb, Ampere, Faraday, and Lorentz forces. It is the forces to be the main factors influencing the electrical materials essentially in the working electrical device. In particular, the dielectric material is characterized by the displacement of the bound charges in the electric field under the influence of Coulomb forces, which cause the polarization of the dielectric and its heating. The conductive material is characterized by the motion of free charges (electric current) under the influence of electromotive force (analogue of Coulomb force) in accordance with Ohm's law, which causes a magnetic field and heating of the conductor. The magnetic material has the ability to concentrate the magnetic field, the energy and force of which is widely used in technology.

The main feature of the manual is the detailed structuring of the educational material to provide more convenient links in the electronic version of the manual, focusing on distance learning, as well as demonstrating specific examples of the close relationship of various electrical materials with the basics of electrical engineering.

This textbook helps students to acquire knowledge and provides opportunities to determine the basics of operation of elements and principles of construction of electrical, electrical and electromechanical systems and systems, taking into account the properties of electrical materials used in these systems.

1 MAIN PHENOMENA IN ELECTRICAL ENGINEERING AND THEIR REGULARITIES

To study the basic properties of electrical materials, it is first necessary to understand the force nature of impact of electric and magnetic fields on these materials to formulate the basic patterns of processes associated with these fields.

1.1 Electric field

If a test charge q is placed at a certain distance from the charged bodies, then forces act on this charge. The space of existence of these forces is called electric field. The forces and energy of the electric field are usually used to store and move electric charges.

1.1.1 Atom model

A simplified model of the atom of a substance is shown in Fig. 1.1.

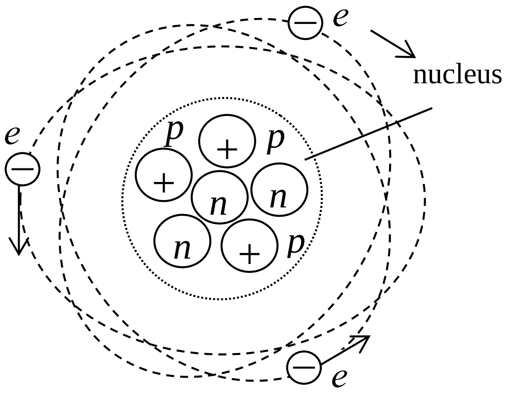

Figure 1.1 – Simplified model of the atom

According to this model the atom contains interconnected charged particles negatively charged electrons e with a mass of 9.11×10^{-31} kg and a positively charged nucleus (Fig. 1.1). The electrons are attracted by the Coulomb forces to the nucleus and rotate around it very quickly. The nucleus consists of nucleons weighing approximately 1.673×10^{-27} kg: positively charged protons p and uncharged (neutral) neutrons n. The mass of the neutron exceeds the mass of the proton by 0.138% because it is split into a proton, an electron and an antineutrino during its beta decay in the nucleus. The mass of the electron is 1836 times less than the mass of the nucleon. Therefore, the mass of an atom, and hence its energy according to Einstein's formula, is concentrated in its nucleus. The numerical values of the charges of the electron and proton are the same and comprise q_e=1.602×10^{-19} C. The diameter of an atom is ~ 2x10^{-10} m, and the diameter of its nucleus is hundreds of thousands of times smaller, about 10-15 m. The most important properties of a chemical element are determined by the number of protons in the nucleus of its atom. The number of neutrons in the nucleus can change, creating the appropriate isotopes of the chemical element, including unstable (radioactive) isotopes.

1.1.2 Electric charges

In the neutral state the total number of electrons in the atom (Fig. 1.1) or in their combination into molecules or domains is equal to the total number of protons. Therefore, neutral atoms or molecules with zero total charge practically do not interact with distant charged bodies. Some interaction can occur when the average electron center does not coincide with the average proton center, i.e. when the molecule has a dipole structure.

If the number of electrons differs from the number of protons, then such a molecule loses its electrical neutrality and becomes an ion. This may be due to the molecule’s temporary loss of an electron under the influence of external factors (positive ion) or the addition of an extra electron (negative ion).

The charge Q of the body is estimated in coulombs (C). If the charge Q is estimated by the number of elementary charges q_e=1.602×10^{-19} C (electrons or protons), then one-coulomb charge consists, respectively, of 6.24×10^{20} elementary charges.

1.1.3 The force nature of the electric field

Coulomb force

The main property of the electric field is the force of mutual attraction and repulsion between differently and identically charged bodies respectively. This force is called the Coulomb force. The presence of an electric field is determined by the force *f* acting on the test charge *q* from one or more charged bodies (Fig. 1.2). Coulomb force is able to move free charges *q* in space or to shift charges *q* by some distance, if they are connected.

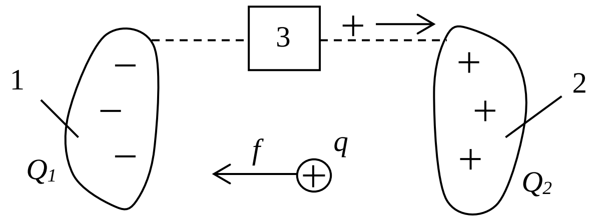

Figure 1.2 – The force influence of the electric field

Electric field strength

The quantitative characteristic of the force of the electric field at each of its points on the test charge *q* is the field strength *E* as a vector quantity:

$$E = \frac{f}{q}, \tag{1.1}$$

where *f* – is the force of the electric field in Newtons (N) on the test charge;

q – is the magnitude of the test point electric charge in the coulombs (C).

Transmission of electric field force

If the charge *Q* of a body or its position in space changes in time *t*, then the force *f* and the strength *E* at the location of the test charge *q* also change, but with some delay in time *Δt*. This delay is due to the distance *l* between the electric charge *Q* of the body and the test charge *q* and the final rate of transmission of the force interaction, which does not exceed the velocity of light *c*:

$$\Delta t \geq \frac{l}{c}. \tag{1.2}$$

The time delay Δt is usually neglected. But in cases of large distance l, very fast changes or high frequency of charge changes Q, taking into account the delay Δt can be fundamentally important.

1.1.4 Homogeneous electric field

Creating a homogeneous electric field

In a homogeneous electric field, the field strength E is the same at any point. Such a field can be created by two differently charged flat and parallel metal plates or covers 1 and 2 (Fig. 1.3). Covers 1 and 2 can accumulate (condense) charges due to their connection to an electric source 3 with an electromotive force e and electric voltage u at the output of the source. The electromotive force e or voltage u can be constant or variable over time.

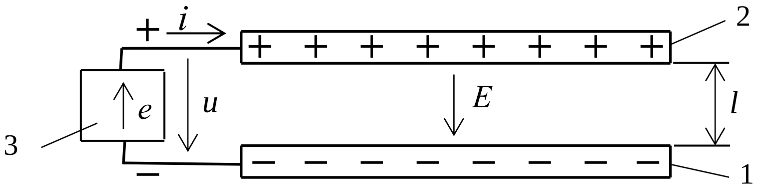

Figure 1.3 – Homogeneous electric field of a flat capacitor

Strength of a homogeneous electric field

The numerical value of the voltage E of a homogeneous electric field of a flat capacitor (Fig. 1.3) can be determined using the formula:

$$E = \frac{u}{l}, \text{ V/m,} \qquad (1.3)$$

where u is the voltage of the electric source (potential difference) in volts, due to which the electric charge Q can be accumulated on plates 1 and 2 (voltage of one volt corresponds to the energy of one joule, which must be spent to move the 1 coulomb charge in space (1V = 1J/1C);

l is the distance between the metal plates 1 and 2 in meters (m).

Flat capacitor capacitance

The capacitance of the capacitor C characterizes the ability of the capacitor to accumulate charges Q and is measured in farads (F). One farad corresponds to the charge of the capacitor in one coulomb, which creates electric voltage of one volt between the covers of the capacitor (1F = 1C/1V). The capacity of a flat capacitor is proportional to the area S of its covers, increases with increasing interaction between its covers, and therefore is inversely proportional to the distance l (Fig. 1.3), and depends on the properties of the medium:

$$C = \frac{Q}{u} = \frac{S\varepsilon_a}{l}, \tag{1.4}$$

where $\varepsilon_a = \varepsilon_r \cdot \varepsilon_0$ – is absolute dielectric constant of the medium between the covers of the capacitor, F/m;

$\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m – is absolute dielectric constant of vacuum (air has almost the same value of absolute dielectric constant);

$\varepsilon_r = \varepsilon_a / \varepsilon_0$ – the relative dielectric constant of the medium between the covers of the capacitor.

Elementary charges can be accumulated (condensed) not only due to the voltage u of the electric source 3, but also under the influence of other phenomena, for example, due to friction of dielectric materials. In such cases, the voltage u should be considered as a result of the process of charges accumulation.

1.1.5 Electric field energy

Energy of electric field of two charged bodies

The system of charged bodies due to the forceful nature of the electric field of this system is able to perform some work on the motion of charges in space (to create electric current). Therefore, it has energy W_e, which is called the energy of the electric field and is measured in joules (J). In particular, in the case of a system of two charged bodies 1 and 2 (Fig. 1.2 or 1.3), this energy can be determined through the integral of the elementary work *dA* to generate electric current in the process of complete discharge of this system from the initial charge *Q* to zero:

$$W_e = -\int_Q^0 dA = -\int_Q^0 uidt = -\int_Q^0 \frac{q}{C}dq = \frac{Q^2}{2C} = \frac{Qu}{2} = \frac{Cu^2}{2}, \qquad (1.5)$$

where $u=q/C$ – is instantaneous value of the electric voltage between the covers of the capacitor, which decreases in the process of its discharge from the initial value $u=Q/C$ to zero;

i – is instantaneous value of electric current in the process of discharge, A;

q – is instantaneous value of the accumulated charge, which decreases during the discharge of the capacitor from the initial value of Q to zero;

$dq=idt$ – is elementary change of charges due to their motion.

Energy volumetric density of an electric field

In the analysis of the electric field energy volumetric density of the electric field W_e (J/m^3) is often used. The value of w_e for a flat capacitor can be determined using the following formula:

$$w_e = \frac{W_e}{V} = \frac{1}{V}\frac{Cu^2}{2} = \frac{1}{V}\frac{\varepsilon_a S(El)^2}{2l} = \frac{\varepsilon_a E^2}{2}, \qquad (1.6)$$

where $V=S\cdot l$ – is the volume of space where there is a homogeneous field of a flat capacitor;

$E=u/l$ – is electric field strength, V/m (1.3).

Electric field energy gradient

The force of interaction of charged bodies f can be defined as the rate of change in space (as a gradient) of electric field energy:

$$f = -\frac{dW_e}{dx}, \qquad (1.7)$$

where dW_e – is elementary change in the electric field energy of a system of charged bodies due to the displacement of any component of this system by an elementary distance *dx*. The sign "minus" means the opposition of the force *f* to the cause of the change in energy, the reason for the displacement of the system components of these bodies by an elementary distance *dx*.

1.2 Electric current

There is a great variety of electric charges and their motion: the rotation of electrons around their axes and atomic nuclei (Fig. 1.1), the motion of charges during radioactive decay of nuclei, thermal oscillations of charges, motion of free charges under the influence of electromotive forces, displacement of bound charges, inertial displacement of released charges. Each of these types of motion in certain circumstances can be considered as ordered and called electric current.

1.2.1 Ordered motion of electric charges

In most cases, motion of free charges *q* in a closed electric circuit between plates 1 and 2 under the action of the electromotive force *e* of the electric source 3 in the conductors of electric current is considered as the ordered motion of charges (electric current) (Fig. 1.2). The electric current is usually created by electrons, which alternately leave their atoms and move to the vacated places of neighbouring atoms. If the circuit material has liquid or gaseous structure, then positive ions are also involved in the creation of electric current. The movement of ions essentially means the motion of the substance of such a conductor, and the ions and electrons move in opposite directions. If the material has solid structure, the motion of ions in this material is very limited.

The positive direction of electric current is the direction of motion of positive charges. If the current carriers are negative charges (electrons), which usually happens, then the direction of electron motion is opposite to the direction of the electric current. Quantitative characteristics of electric current are defined as the magnitude of charges *q* that have passed in a certain direction through the cross section of the conductor of electric current per unit time t, i.e. the rate of change of charges over time [4]:

$$i = \frac{dq}{dt}, \tag{1.8}$$

where i – is instantaneous value of electric current in amperes, A (1A=1C/1s);

q – is instantaneous value of electric charge in coulombs C.

1.2.2 Ohm's law

The process of moving electric charges, i.e. electric current, in the electrically conductive medium is resisted. In the simplest cases, when the resistance to electric current is created only by microparticles of the medium, there is a thermal field with energy W_T, which is dissipated in space. In such cases, the regularity of this process can be described by Ohm's law in its simplest form: in integral form for a separate section of the electrical circuit [4]:

$$i = \frac{u}{R}, \tag{1.9}$$

where i – is electric current of a separate section of the electrical circuit, A (1.8);

u – is electric voltage or difference of electric potentials on a separate section of the electric circuit in volts (V);

R – is active resistance to electric current from this section in ohms (Ohms), which affects the process of heat release.

The electric current i can be not only a consequence of the action of electromotive force e or electric voltage u (1.9), but also the cause of voltage ($u=i \cdot R$), as well as a factor influencing the electrical resistance ($R = u/i$). The value of R, in turn, can be considered as a process that interferes with the motion of charges, as a quantitative characteristic of this process, as well as an element of the electrical circuit. Sometimes the absence of an element

R in an electrical circuit or electrical schematic can be mistaken for a zero value of R, which leads to a paradoxical result according to (1.9).

1.2.3 Thermal energy of electric current

The thermal energy W_T, which for some time t is released due to electric current overcoming active resistance R and then transferred to the environment, is determined by means of formula [4]:

$$W_T = \int_t ui\,dt = \int_t i^2R\,dt = R\int_t i^2\,dt = I^2Rt. \tag{1.10}$$

If electric current i does not change over time $(i=I=const)$, then the formula (1.10) for calculating thermal energy is simplified accordingly.

1.2.4 The effective value of the electric current

If electric current i changes over time according to the periodic (sinusoidal) law $i = I_m \sin\omega t$, then the effective value of electric current is usually considered as the electric current I in formula (1.10):

$$I = \sqrt{\int_0^T i^2 dt} = \sqrt{\int_0^T (I_m \sin\omega\, t)^2 dt} = \frac{I_m}{\sqrt{2}}, \tag{1.11}$$

where I_m – is amplitude of sinusoidal current, A;

$\omega=2\pi f$ is angular frequency of electric current change, 1/s;

$f=1/T$ is cyclic frequency of electric current change in hertz (Hz);

T – is duration of the cycle of electric current change, s.

The effective value of the voltage u, which varies according to the sinusoidal law $u = U_m \sin\omega t$, can be calculated using a formula similar to formula (1.11).

1.2.5 The concept of reactive resistance

In situations where the energy of the electric or magnetic field changes over time, there is a reaction to this change in the form of reactive resistance to electric current without the release of thermal energy and the corresponding reactive voltage drop [4, 5]. For example, if the AC circuit has a section in the form of a capacitor with capacitance C, the voltage drop across this section according to (1.4) and (1.8) can be determined as follows:

$$u_c = \frac{1}{C}\int idt, \tag{1.12}$$

where i – is charge-discharge current, which occurs only when the charge time q of the capacitor (1.8) or voltage $u_c=q/C$ changes.

In particular, if the electric current changes over time according to the sinusoidal law $i=I_m\sin\omega t$, then formula (1.12) is converted to this form:

$$u_c = I_m X_c \, sin\left(\omega t - \frac{\pi}{2}\right) = U_{cm} \, sin\left(\omega t - \frac{\pi}{2}\right), \tag{1.13}$$

where I_m – the amplitude of the charging and discharging current of the capacitor, A;

$X_c=1/\omega C$ is reactive resistance of the capacitor (capacitive resistance) in ohms (Ohm);

$U_m=I_m \cdot X_c$ is amplitude of electric voltage on capacitor covers, V;

$\pi/2$ is phase shift of the voltage u_c with respect to the current i (the sign "minus" means the u_c lagging from i in phase by an angle $\pi/2$ or at time t by a quarter of the period T of the change of electric current).

A similar reaction occurs in the case of a change in the energy of magnetic field over time: there is a voltage drop u_L in the section of the AC circuit and the reactive resistance of this section.

1.3 Magnetic field

If a magnetic compass needle is placed near moving electric charges or electric current, forces act on it, which is confirmed by the corresponding rotation of the magnetic needle. These forces are mentioned as electrodynamic or magnetic, and the space of their existence is called magnetic field. Magnetic forces affect not only the magnetic needle, but also any moving charges. The magnetic field is represented by closed force magnetic field lines. The force nature of the magnetic field is often used in practice, especially in electric machines [2, 3].

1.3.1 Magnetic induction

Magnetic induction B determines the force of the magnetic field around the moving charges or around the conductor 1 with electric current i_1 (Fig. 1.4). The magnetic induction B is a vector quantity and causes the force action f on the moving charge q. The direction of the vector of magnetic induction B at some point of the closed circuit 2 is determined by the so-called right-hand thumb rule: perpendicular to the vector of electric current i_1 in the direction of rotation of thumb oriented in the direction of electric current i_1 (Fig.1.4).

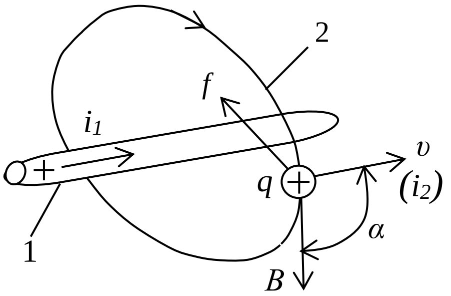

Figure 1.4 – Determination of vectors direction of magnetic induction *B* and force *f*

1.3.2 Lorentz force

The force of action f on a moving point charge q from the magnetic field is called the Lorentz force, which acts in addition to the Coulomb force (Fig. 1.4):

$$f = q \cdot \upsilon \cdot B \cdot sin\,\alpha, \tag{1.14}$$

where υ – is the speed of motion of the point charge q;

B – is numerical value of magnetic induction in Tesla (T) resulting from current i_1;

α – is the angle between the vector of magnetic induction B and the velocity vector υ (fig.1.4).

1.3.3 Ampere force

Instead of one charge q there can be many such charges moving in the same direction. If this direction is set by another current conductor i_2, it is better to use the concept of Ampere force:

$$f = i_2 \cdot l_2 \cdot B \cdot sin\, \alpha, \tag{1.15}$$

where l_2 – is the length of the part of the other conductor with current i_2, which is in a magnetic field with induction B;

α – is the angle between the induction vector B and the direction of the electric current i_2.

The direction of force f action on moving charges or current conductor is determined by the so-called rule of the left hand: the direction of force f will be shown by the stoked out thumb of the left hand if the magnetic induction vector B enters its palm, and other straightened fingers of the left hand show the direction of current i_2.

It is generally believed that the Ampere force acts on a conductor with a current that is placed in a magnetic field. But this occurs only in a homogeneous magnetic field. In fact, the Ampere force counteracts the cause of the change in magnetic energy in space, and therefore in some cases the Ampere force has almost no effect on such a conductor. In particular, in electric motors and generators, where the magnetic field is created in the magnetic circuit and the air gap with different properties, the Ampere force acts mainly on the magnetic circuit, in which the electrical conductors are fixed.

1.3.4 Magnetic flux

As an integral characteristic of magnetic field lines, the magnetic flux Φ in Weber (Wb) is used, which penetrates a surface with a limited area S. If all elements dS of this surface are perpendicular to the vector of magnetic induction B, then the magnetic flux is determined by the formula:

$$\Phi = \int_S BdS, \tag{1.16}$$

where B – is magnetic induction at some point of the magnetic field in Tesla (T);

S – is the total surface area permeated by the magnetic flux Φ.

The surface *S* mentioned above is preferably chosen to take into account the maximum number of magnetic field lines 2. This condition can be met if conductor 1 with current *i* is considered as part of a closed electrical circuit in the form of a closed conductor coil (Fig. 1.5). Therefore, the surface *S* must be limited by the loop of the conductor 1 with an electric current *i*. Under such conditions, it is assumed that the magnetic flux *Φ* penetrates the coil of the conductor with the electric current *i* or couplings with this coil (Fig. 1.5).

Dependence of magnetic flux on current

The dependence of the magnetic flux Φ_1 on the electric current *i* in the case of using one loop of the conductor with current (Fig.1.5):

$$\Phi_1 = L_1 \cdot i, \tag{1.17}$$

where L_1 – is inductance of one loop of the conductor in Henry (H).

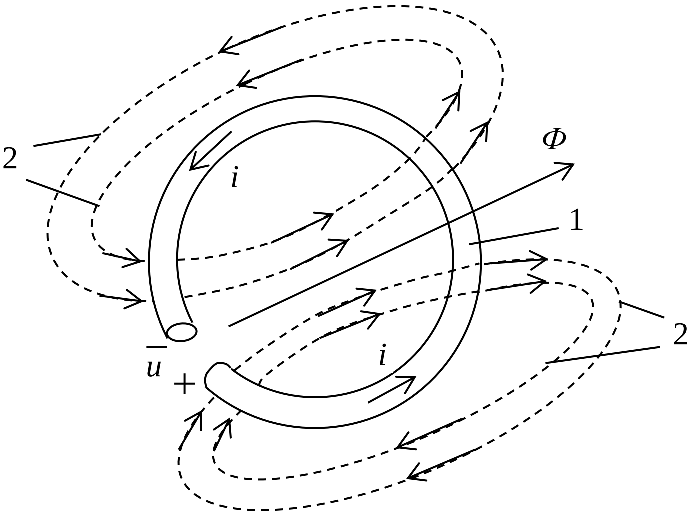

Figure 1.5 – Magnetic flux of one coil of a conductor with current

Flux coupling. Coil inductance

If the magnetic flux Φ is created by several loops of the conductor, then such a conductor is called an N-loop inductor. The magnetic flux Φ of such a coil, respectively, increases almost N times relative to Φ_1 and in addition is coupled with more loops of the coil. In such cases, it is better to use the term flux coupling Ψ, which is almost N times greater than the magnetic flux Φ_1 of one loop of the conductor with the same current i:

$$\Phi = \Psi = \sum_{i=1}^{N} \Phi_i \approx N\Phi_1 = Li, \qquad (1.18)$$

where $\Psi = \Phi$ is coupled flow F with N loops of the coil (flux coupling), Wb;

$L \approx N^2L_1$ is the inductance of the N-coil, which is greater relative to L_1 in N^2 times due to the increase in N times of the flux Φ relative to Φ_1 and due to the increase in the same number of couplings coupled with the flux Φ (1.24).

Magnetic field strength

Electric currents and magnetic field as a consequence of these currents usually operate in different environments with fundamentally different properties. Therefore, there is a need to use a convenient mediator between electric currents and magnetic induction. Such a mediator is the strength H of the magnetic field, which is considered both as a consequence of electric currents and as a cause of magnetic induction B, which coincides in direction with the strength H at each point of the magnetic field. The intensity H acts in a magnetic medium and does not depend on the properties of this medium in which the magnetic field acts. This approach allows you to use the analogy with electrical circuits and thus simplify the analysis of magnetic circuits with magnetic induction vector B.

Ampere's circuital law

The relationship between the magnetic field strength H and electric currents is determined by the Ampere's circuital law. According to this law, the linear integral of the closed circuit 2 (Fig. 1.4 or Fig. 1.5) of the magnetic field strength *H* is equal to the total current through the section, which is limited by this circuit:

$$\oint_l \bar{H} \cdot d\bar{l} = \sum_k i_k = F, \tag{1.19}$$

where $\bar{H} \cdot d\bar{l}$ – is scalar product of magnetic field strength vectors and closed-loop elementary circuit 2 (fig.1.4);

l – is the length of the closed circuit 2;

$\sum_k i_k$ – is the algebraic sum of the currents included in the closed circuit 2 (this sum is called the magnetizing or magnetomotive force *F* in amperes).

In practice, there is often a situation when the magnetic field strength is almost the same in numerical value at all points of the closed circuit 2 and coincides in direction with the elementary sections of this circuit. In such situations, the formula (1.19) of the Ampere's circuital law is simplified:

$$H \cdot l \approx \sum_k i_k = F.. \tag{1.20}$$

Dependence of magnetic induction on magnetic tension

The dependence of the magnetic induction *B* on the magnetic field strength *H* is determined by the properties of the medium in which the magnetic field is created. In the simplest case, when the medium is isotropic in its magnetic properties, and the rate of change of the magnetic field strength *H* is insignificant, the dependence *B (H*) is determined by the formula [6, 7, 8]:

$$B = \mu_a \cdot H, \tag{1.21}$$

where $\mu_a=\mu_r \cdot \mu_0$ – is absolute magnetic permeability of the medium in which the magnetic field is created, H/m;

$\mu_0 = \frac{1}{\varepsilon_0 c^2} = 4\pi \cdot 10^{-7}$ H/m – is absolute magnetic permeability of vacuum (air has almost the same value of absolute magnetic permeability);

$\mu_r = \mu_a / \mu_0$ – is relative magnetic permeability of the medium;

$\varepsilon_0 = 8.8542 \cdot 10^{-12}$ F/m – is absolute dielectric constant of vacuum;
$c \approx 300$ thousand km/s – is velocity of light in vacuum.

The absolute magnetic permeability of the μ_a medium is often a function of magnetic induction, and therefore the dependence (1.21) is usually nonlinear.

1.3.5 Electromagnetic induction

Faraday's law

Electromagnetic induction is the phenomenon of the occurrence of the electromotive force e (EMF) in a closed circuit due to a change in the time of the magnetic flux Φ that permeates this circuit. The regularity of this phenomenon is called the law of electromagnetic induction or Faraday's law:

$$e = -\frac{d\Phi}{dt}. \tag{1.22}$$

If a closed circuit is electrically conductive, then due to the action of EMF e electric current i occurs in it, which is called induction current. This current can be conditionally called the secondary current i_2, if the electric current i_1 is considered to be primary as in cause of the magnetic flux Φ. The dependence of the magnetic flux Φ_1 on the primary current i_1 is determined by the above formulas (1.16), (1.21), and (1.19). Thus, Faraday's law determines the magnetic relationship between primary and secondary electric currents. However, there may be no electrical (galvanic) connection or contact between these currents. This feature is used in electrical and electromagnetic devices. The "minus" sign in the formula (1.22) means that the induction current counteracts the changes in the magnetic flux Φ.

Reactive resistance of inductor coil

If the alternating magnetic flux $\Phi_1(t)$ is caused by alternating current $i(t)$ in one loop of the conductor, then this counteraction is manifested by the occurrence of a voltage drop u_L in this conductor:

$$u_{L1} = -e = \frac{d\Phi_1}{dt} = \frac{d(L_1 i)}{dt} = L_1\frac{di}{dt}, \tag{1.23}$$

where e – is electromotive force (EMF) of self-induction in volts (V);

L_1 – is inductance of one loop of the conductor; H.;

$\Phi_1 = L_1 i$ – is magnetic flux of one loop of the AC conductor, (Wb).

The voltage drop u_L on the N-loop coil with the same current i will increase N^2 times compared to a single-coil:

$$u_L = -e = \frac{d\psi}{dt} \approx N\frac{d\Phi}{dt} \approx N\frac{d(N\Phi_1)}{dt} \approx N^2\frac{d(L_1 i)}{dt} = L\frac{di}{dt}, \qquad (1.24)$$

where $\Psi \approx N\cdot\Phi$ – is flux coupling of the magnetic flux Φ with N loops of the coil, Wb;

$\Phi \approx N\cdot\Phi_1$ – is alternating magnetic flux of the N-loop coil, which increased almost N times relative to the flux Φ_1 of single-coil of conductor;

$L \approx N^2\cdot L_1$ – is the inductance of the N-loop coil.

In particular, if the electric current changes in time according to the periodic (sinusoidal) law $i = I_m \sin\omega t$, then the formula (1.24) will obtain the form

$$u_L = I_m X_L \sin\left(\omega t + \frac{\pi}{2}\right) = U_{Lm} \sin\left(\omega t + \frac{\pi}{2}\right), \qquad (1.25)$$

where I_m – is the amplitude of the electric current in the inductor coil, A;

$X_L = \omega L$ – is reactive resistance of the inductor coil in ohms (Ohm);

$U_m = I_m\cdot X_L$ – is amplitude of electric voltage on the inductor coil, V;

$\pi/2$ – is phase advance of the voltage u_L relative to the current i, which essentially means the advance of the voltage u_L relative to the current i at time t by a quarter of the period.

1.3.6 Magnetic field energy

The magnetic field is able to perform certain work due its force on moving charges (electric current) and therefore has a magnetic energy $W_м$ in joules (J). Consider the magnetic energy $W_м$, which is accumulated in an N-

loop coil with inductance L in the presence of electric current i. If such a coil is closed by a conductor and disconnected from an electric source, the electric current in it will rapidly reach zero point, which means that for a certain time all the accumulated energy $W_{м}$ will be spent. This energy can be determined through the integral of the elementary work dA on the movement of charges:

$$W_{м} = -\int_I^0 dA = -\int_I^0 u_L i dt = -\int_I^0 L\frac{di}{dt} i dt = \frac{LI^2}{2} = \frac{\Phi NI}{2}, \quad (1.26)$$

where u_L – is electric voltage in the coil, which occurs due to the EMF self-induction during the change of electric current in it, V (1.24);

$L=N^2L_1=N^2\Phi_1/i=N\Phi/i$ – is the inductance of the N-loop coil, H (1.24);

Φ – *is* the initial value of the magnetic flux generated by the electric current i in the N-loop coil.

Energy volumetric density of the magnetic field

In the analysis of the magnetic field quite often there is a need to determine the energy volumetric density of the magnetic field $w_{м}$ (J/m^3) at its separate points:

$$w_{м} = \frac{dW_{м}}{dV} = \frac{d}{dV}\left(\frac{\Phi NI}{2}\right) = \frac{1}{2}\frac{d}{ds}\left[\frac{d}{dl}\left(\int_S BdS \cdot \oint_l Hdl\right)\right] = \frac{B\cdot H}{2}, \quad (1.27)$$

where $dV = dS \cdot dl$ – is elementary volume of space where the magnetic field exists, m^3;

$\Phi = \int BdS$ – magnetic flux (1.16);

$NL = F = \oint Hdl$ – is magnetizing force, A (1.19).

From formula (1.27) it follows that magnetic field can exist and be characterized by a certain energy $W_{м}$ or $w_{м}$ even in the absence of electric current in the usual sense of the term, if a residual magnetic induction $B=B_r$ is created in a magnetic material (e.g a permanent magnet).

Magnetic field energy gradient

The force f of the interaction of moving charges as the basis for the existence of a magnetic field can be determined by the rate of change in space (through a gradient) of the magnetic field energy similar to the definition of the electric field strength (1.7):

$$f = -\frac{dW_М}{dx}, \tag{1.28}$$

where $dW_М$ is elementary change in the energy of the magnetic field due to the displacement of any element of the system of moving charges or magnetic circuit by the elementary distance dx. The sign "minus" means the opposition of the force f to the cause of the change of magnetic energy, for example, the cause of the displacement of the system of moving charges by the elementary distance dx.

In the same way, the force effect of the magnetic field of a pre-magnetized permanent magnet on materials that are capable of being magnetized can be determined, for example, the pulling force of iron elements by a magnet.

1.4 Exemplary tasks on the basics of electrical engineering

1.4.1 Calculation of electric field forces

Task 1. Calculate the electrostatic forces of interaction between the charged covers of a flat capacitor. Its covers have the shape of a square with an area of $S = 2$ m^2, isolated by a dielectric with a relative dielectric constant $\varepsilon_r = 5$ and a thickness of $l = 0.2$ mm, they are mutually offset along the dielectric by 10% relative to the area S (Fig. 1.6) and have a residual charge $Q = 200$ μC.

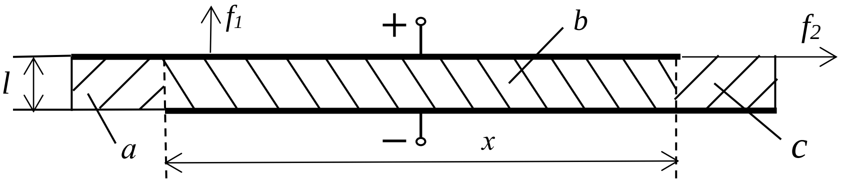

Figure 1.6 – To the task 1.4.1

Solution. The electrostatic force *f* of the interaction between the covers of the capacitor can be defined as the energy gradient of the electric field of the capacitor (1.7). The force *f* can have two components: force f_1 due to the distance of the upper cover of the capacitor from the lower cover (due to increasing the distance *l*) by the elementary distance *dl* and force f_2 due to the shift of the upper cover of the capacitor to the right (resulting from distance *x* increasing) by the elementary distance *dx* (Fig. 1.6).

Considering a quite small thickness of the dielectric compared to other dimensions of the capacitor, we can assume that the electric field is concentrated mainly in the zone "b". Therefore, the electric field energy can be taken into account only in zone *"b"*, neglecting the energy of the electric field in zones *"a"* and *"c"*.

Using formulae (1.4) ... (1.7), we obtain the following value of the force f_1 (Fig.1.6) in the direction of increasing the distance *l* by the elementary distance *dl*:

$$f_1 = -\frac{dW_e}{dl} = -\frac{d}{dl}\left(\frac{Cu^2}{2}\right) = \frac{d}{dl}\left(\frac{Q^2}{2C}\right) = -\frac{Q^2}{2}\frac{d}{dl}\left(\frac{l}{S_b\varepsilon_r\varepsilon_0}\right) =$$

$$= -\frac{Q^2}{2S_b\varepsilon_r\varepsilon_0} = -\frac{\left(200\cdot10^{-6}\right)^2}{2\cdot1{,}8\cdot5\cdot8{,}85\cdot10^{-12}} = -251{,}1\ (N),$$

where $S_b = S\cdot0.9 = 2\cdot0.9 = 1.8$ m^2 – is the area of the covers of the capacitor in the area "*b*", which under the condition of the task is 10% less than the area S;

$C = \frac{S_b\cdot\varepsilon_r\varepsilon_0}{l} = \frac{1{,}8\cdot5\cdot8{,}85\cdot10^{-12}}{0{,}2\cdot10^{-3}} = 398{,}25\cdot10^{-9}F$ – is capacitor capacity;

$u = Q/C = 200\cdot10^{-6}/398.25\cdot10^{-9} = 502$ V – is voltage between the covers of capacitor.

A negative value of the force f_1 means that this force is actually directed in the opposite direction: in the direction of decreasing the distance *l*, i.e. the upper cover of the capacitor is actually attracted to the lower cover.

To calculate the force f_2 it is necessary to take into account that the zone "*b*" has the shape of a rectangle with area $S_b = S\cdot0.9 = 2\cdot0.9 = 1.8\ m^2$

with sides $y = \sqrt{S} = \sqrt{2} = 1.414\ m$ and $x = \frac{S_b}{y} = \frac{1.8}{1.414} = 1.273\ \ m$. Using formulas (1.4) ... (1.7) we obtain the following value of the force f_2 in the direction of increasing x by the elementary distance dx:

$$f_2 = -\frac{dW_e}{dx} = -\frac{d}{dx}\left(\frac{Cu^2}{2}\right) = -\frac{d}{dx}\left(\frac{Q^2}{2C}\right) = -\frac{Q^2}{2}\frac{d}{dx}\left(\frac{l}{S_b\varepsilon_r\varepsilon_0}\right) =$$

$$= -\frac{Q^2 l}{2y\varepsilon_r\varepsilon_0}\frac{d}{dx}\left(\frac{1}{x}\right) = \frac{Q^2 l}{2yx^2\varepsilon_r\varepsilon_0} = \frac{(200 \cdot 10^{-6})^2 \cdot 0{,}2 \cdot 10^{-3}}{2 \cdot 1{,}414 \cdot 1{,}273^2 \cdot 5 \cdot 8{,}85 \cdot 10^{-12}} =$$
$$= 0{,}0394\ (N)$$

A positive value of the force f_2 means that this force acts on the upper cover of the capacitor in the direction of increasing the distance x.

1.4.2 Calculation of magnetic field forces

Task: Calculate the force of interaction between two parallel conductors with length l = 1 m and diameter d = 2 mm with direct or low-frequency currents $i_1=i_2$=50A of different directions, which are placed in a dielectric medium at a distance a=20 mm between their axes.

The simplest solution may be under the following assumptions: $a >> d$, $l >> a$, the current density is the same at all points of intersection of conductors. Under the following conditions, the force of interaction (Ampere force) between parallel conductors can be calculated using formula (1.15):

$$f = i_2 \cdot l \cdot B_1 \cdot \sin\alpha = i_2 \cdot l \cdot \mu_0 H_1 = i_2 \cdot l \cdot i_1 \frac{\mu_0}{2\pi \cdot a} =$$
$$= 50 \cdot 1 \cdot 50 \frac{4\pi \cdot 10^{-7}}{2\pi \cdot 0{,}02} = 0{,}025(N)\ ,$$

where $B_1=\mu_a \cdot H_1$ – is induction of the magnetic field created by the current i_1 of the first conductor at the locations of the second conductor, T (1.21);

$H_1=i_1/2\pi a$ is – the magnetic field strength from the current i_1 of the first conductor at the location of the second conductor, A/m (1.20).

$\alpha=\pi/2$ – is the angle between the induction vector B and the direction of the electric current i_2.

$\mu_a \approx \mu_0 = 4\pi \cdot 10^{-7}$ H/m – is absolute magnetic permeability of the dielectric medium.

Under the action of this force, conductors with electric currents of different directions repel each other according to the rule of the left hand.

1.5 Test questions on the basics of electrical engineering

1. Explain the electric charge and its unit of measurement. What is elementary charge?

2. On what basis can we establish the existence of a charged particle or body?

3. Determine the conditions under which a charged particle can become neutral.

4. Name the causes and conditions of accumulation or condensation of electric charges.

5. Formulate the connection between the electric charge of a capacitor and its electric voltage and capacitance.

6. Define the concept of electric field. Name the causes and conditions of the electric field.

7.On what grounds can the existence of an electric field be established?

8. Define the concept of electric field strength and explain its unit of measurement.

9. What is the difference between a homogeneous electric field and an inhomogeneous electric field?

10. What is the relationship between the electric field strength and the electric charge and the force of the field on this charge?

11. Formulate the dependence of the electric field strength of a flat capacitor on the electric voltage and the distance between its covers.

12. Explain the energy of an electric field and its unit of measurement.

13. How can the energy of the electric field manifest itself?

14. What is the energy gradient of electric field?

15. Formulate a relationship between the energy of an electric field and the force of its action on charged particles.

16. Formulate the dependence of the electric energy of a capacitor on its electric voltage and capacitance.

17. Explain electric current and its unit of measurement.

18. Formulate the dependence of the electric current in a separate section of the electrical circuit on the voltage and electrical resistance of this section.

19. What is the relationship between electric current and electric charge?

20. What are the phenomena when moving electric charges?

21. Explain the energy of the thermal field and its unit of measurement.

22. What can be the reasons for the release of thermal energy in an electrical circuit?

23. How can the energy of the thermal field manifest itself?

24. By what formula can you calculate the energy of the thermal field in a particular section of the electrical circuit?

25. Define the concept of magnetic field.

24. By what feature can the existence of a magnetic field be established?

26. Name the causes and conditions of the magnetic field.

27. Explain the induction of a magnetic field and its relationship to magnetic flux.

28. Explain the strength of the magnetic field and its relationship to magnetic induction.

29. Formulate the dependence of the magnetic field strength on the electric currents that cause the magnetic field.

30. How to determine the magnitude and direction of the force with which the magnetic field acts on a conductor with an electric current and on individual moving charged particles?

31. Determine the phenomenon of electromagnetic induction.

32. What is the relationship between alternating magnetic flux and electromotive force in a closed conductive circuit?

33. Explain the causes and conditions of induction current.

34. Explain the inductance of the coil and its unit of measurement.

35. What is flux coupling and how does it relate to magnetic flux and coil inductance?

36. Explain the energy of the magnetic field and its unit of measurement.

37. How can the energy of the magnetic field manifest itself?

38. What is the energy gradient of the magnetic field? Formulate a relationship between the energy of a magnetic field and the force of its action on moving charged particles.

39. What is the difference between the energy of the magnetic field and its volume density?

40. Formulate the dependence of the magnetic field energy on the electric current of the inductor coli and its inductance.

41. What are the consequences of changing the energy of the magnetic field?

2 DIELECTRIC MATERIALS

The main feature of dielectric materials is the small number of free charges that can generate electric current. This allows the use of dielectrics as electrical insulating materials. Virtually all charged dielectric particles are connected and are therefore only able to move under the influence of electric field forces near charged bodies. This process of displacement of bound charges is called dielectric polarization. Thus, electrical insulation and the ability to polarize are the most important properties of dielectrics [6...8].

2.1 Polarization of dielectrics

Polarization is the process of displacing the bound electric charges of a dielectric under the influence of electric field forces (Coulomb forces), which is sometimes called the electric bias current.

2.1.1 The main types of polarization

Electron polarization is an elastic displacement of the orbits of electrons relative to the nuclei of dielectric atoms under the influence of an electric field in a very short time of about 10^{-15} s. Electronic polarization occurs in any dielectric, regardless of the presence of other types of polarization. The loss of energy of the electric field during the full cycle of the field usually does not occur.

Ionic polarization is the elastic displacement of dielectric ions under the influence of an electric field. It is peculiar to solids with an ionic structure and proceeds more slowly due to a larger mass of ions for $\approx 10^{-13}$ s. Ionic polarization can also occur without loss of electric field energy. In some cases, however, there may be loss of electrical energy and heating of the dielectric. This polarization is called ion-relaxation.

Dipole polarization is the rotation or reorientation of dipole dielectric molecules by electric field forces. It is peculiar to polar dielectrics and belongs to the slow types of polarization. The polarization time is from 10^{-10} s to 10^{-2} s. The rotation of dipole molecules under the action of an electric field requires overcoming the forces of internal "friction" in the substance, which causes the loss of electrical energy in the dielectric by means of dielectric heating.

Migratory polarization is peculiar to dielectrics that have impurities in the form of fine powder of conductive materials. During the action of an electric field, free electrons and ions of electrically conductive inclusions begin to move (migrate) within these inclusions, accumulate and thus create polarized regions. This process is quite slow, can last seconds or even minutes, accompanied by significant energy losses even at low frequencies of electric field change.

Spontaneous polarization occurs in solid nonlinear dielectrics with a domain structure. Such materials have their own internal fields, which create macroscopic polarized regions (domains). The action of the external field contributes to the predominant orientation of these domains in the direction of the field, which creates the effect of very strong polarization. Spontaneous polarization of the dielectric is accompanied by its significant heating. The dielectric constant ε_r depends nonlinearly on the electric field strength and the dielectric temperature (with a maximum) and can exceed the value of 100,000. Materials with this type of polarization are called ferroelectrics.

2.1.2 The main characteristics of the polarization process

The characteristic features of the process of dielectrics polarization are the accumulation of electric charges due to the displacement of the bound electric charges under the influence of electric field forces (1.4), as well as some energy losses in the dielectric. These characteristics of dielectrics depend on the dielectric constant and the tangent of the angle of dielectric loss.

Dielectric constant of the dielectric is a characteristic of the polarization process and is determined by the dielectric constant ε_r relative to the absolute dielectric constant of the vacuum ε_0 (1.4). To determine the relative dielectric constant ε_r the dielectric is placed in an alternating homogeneous electric field of a capacitor with flat parallel charged plates (Fig. 2.1).

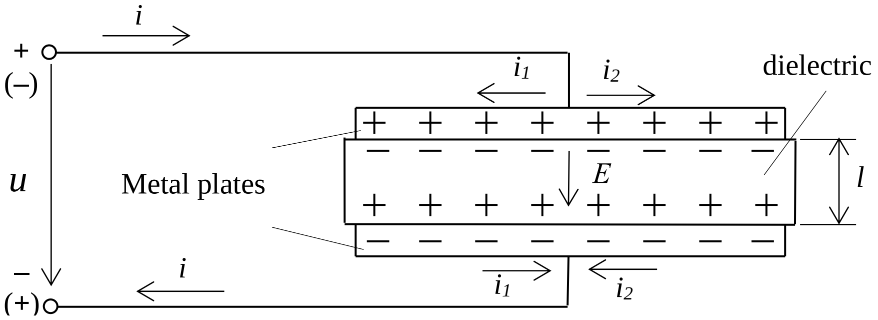

Figure 2.1 – Dielectric in a homogeneous electric field

The principle of measuring of the relative dielectric constant ε_r of the dielectric is based on the direct dependence of the capacitance of the capacitor C on the absolute dielectric constant ε_a of its dielectric (1.4):

$$\varepsilon_r = \frac{\varepsilon_a}{\varepsilon_0} = \frac{C}{C_0}, \qquad (2.1)$$

where $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m – is absolute dielectric constant of vacuum or air;

$C_0 = \varepsilon_0 \cdot S/l$ – is the calculated capacity of this capacitor in farads (F) using vacuum instead of the investigated dielectric (1.4);

C – is the capacitance of the capacitor with the investigated dielectric, which can be measured using an AC measuring bridge (Fig. 2.2);

S – is area of metal covers of the capacitor, m^2;

l – is dielectric thickness, m (Fig. 2.1).

In most cases, the value of $\varepsilon_r = \varepsilon_a/\varepsilon_0$ is about 2 ... 10. But for the manufacture of small capacitors with large capacity special dielectrics with a very high value of dielectric constant ε_r: from several hundred to several hundred thousand are created [9].

The displaced charges of a polarized dielectric can be considered as additional charges due to their ability to induce free charges of the opposite sign on the metal plates of the capacitor by Coulomb forces. These charges, in turn, can move freely in the conductors outside the capacitor. In some dielectrics, the polarization and its disappearance can be quite slow. For example, to discharge reliably a high-voltage cable disconnected from an electric source it is necessary to lock its cores for a long time: for about a minute.

Dielectric losses – is the power P of energy that is lost under the influence of an alternating electric field and leads to the heating of the dielectric:

$$P = U \cdot I \cdot cos\,\phi = U^2 \cdot \omega \cdot C\,\frac{tg\delta}{1+tg^2\delta} \approx U^2 \cdot \omega \cdot C \cdot tg\delta, \quad (2.2)$$

where U – is the effective value of the alternating (sinusoidal) voltage applied to the covers of the capacitor with a dielectric, V (1.11);

I – is the effective value of the alternating (sinusoidal) current outside the capacitor due to the process of cyclic recharging of the capacitor, A (1.11);

φ – is the angle of phase advance of the current I relative to the voltage U, which is less than 900 by the value of δ ($\varphi=90^0-\delta$) due to dielectric losses;

δ – is dielectric loss angle;

$tg\delta$ – is the tangent of the dielectric loss angle, which is measured using an AC measuring bridge (Fig. 2.2);

$\omega = 2\pi f$ – is the angular frequency of the voltage change on the covers of the capacitor, s^{-1};

f – is cyclic frequency of voltage change on the capacitor covers, Hz;

$C = \varepsilon_r \cdot C_0$ – is capacitance of the capacitor with the investigated dielectric, which can be measured using an AC measuring bridge (Fig. 2.2).

Specific dielectric losses:

$$p = \frac{P}{V} = E^2 \omega \varepsilon_r \varepsilon_0 tg\delta, \text{(W)}, \qquad (2.3)$$

where $V=S \cdot l$ – stands for dielectric volume, m^3;

$E=U/l$ – is homogeneous electric field strength (1.3).

From formula (2.3) it is seen that the value of $tg\delta$ depends on the dielectric losses that make the dielectric heat, especially at large values of voltage U and frequency ω. Therefore, dielectrics with a small value of $tg\delta$ (less than 5×10^{-4}) are sometimes called high-frequency. If the frequency f or voltage U is small, then you can use low-frequency dielectrics with relatively large values of $tg\delta$. The main advantage of such dielectrics may be the large value of the dielectric constant ε_r and the small size of the capacitors. The value of $tg\delta$ depends on various external factors, primarily on temperature, voltage, and its frequency. If the voltage U is constant over time, then the heating of the dielectric is determined only by the movement of free charges, the number of which is extremely small in the dielectric. In such cases, dielectric losses are neglected.

Measurement of dielectric constant and dielectric loss

The dielectric constant ε_r and the tangent of the dielectric loss angle $tg\delta$ are measured using an AC measuring bridge when connecting a flat capacitor with the investigated dielectric to the AC voltage source u (Fig. 2.2).

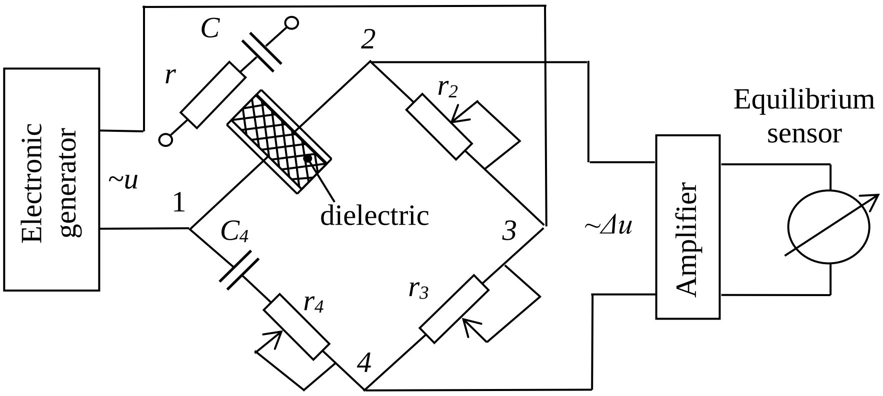

Figure 2.2 – Scheme for determining the relative dielectric constant ε_r and the tangent of the angle of dielectric loss $tg\delta$

The measuring bridge of alternating current contains four electric arms, one of which is a flat capacitor with the investigated dielectric and unknown parameters (r, C at their series connection or R, C_p at their parallel connection), and three others: resistors and the capacitor (r_2, r_3, r_4, C_4) with known parameters. In the first diagonal of the bridge (between nodes 1 and 3) from the electronic generator voltage u is supplied, which varies with frequency ω according to the sinusoidal law. The voltage on the second diagonal of the bridge Δu (between nodes 2 and 4) is amplified and controlled by the bridge equilibrium sensor. During the measurement, resistors r_2, r_3, r_4 are adjusted in order to establish the electrical equilibrium of the bridge ($\Delta u \approx 0$). In the case of equilibrium of the bridge, the following equation is valid:

$$\left(r - j\frac{1}{\omega \cdot C}\right) \cdot r_3 = \left(r_4 - j\frac{1}{\omega \cdot C_4}\right) \cdot r_2, \tag{2.4}$$

where r, C – are equivalent parameters of the capacitor with the investigated dielectric (resistance r takes into account the presence of dielectric losses).

Equation (2.4) is valid if its real and image parts are equal:

$$C = C_4\frac{r_3}{r_2}; r = r_4\frac{r_2}{r_3}. \tag{2.5}$$

The value of the relative dielectric constant ε_r can be determined by formulas (2.1) and (2.5), and the value of the tangent of the dielectric loss angle $tg\delta$, by the following formula, which follows from (2.5):

$$tg\delta = \omega \cdot r \cdot C = \omega \cdot r_4 \cdot C_4. \tag{2.6}$$

The design of the AC measuring bridge provides for the automatic use of the above formulae and thus allows to obtain the final measurement result C and $tg\delta$ provided that the equilibrium of this bridge is obtained.

For dielectrics with large values of $tg\delta$ in the measuring bridge there is a second measuring range $tg\delta$, which uses a different scheme of replacement of the capacitor with the investigated dielectric: in the form of a parallel connection of other values of the elements R and C_p. Switching the bridge to the second range does not affect the $tg\delta$ measurement results, but somewhat affects the measurement results of the capacitance $C_p=C/(1+tg^2\delta)$, and hence the determination of the dielectric constant ε_r [6].

Equivalent dielectric circuit, which is under the influence of an alternating electric field, is shown in Fig. 2.3 [6, 7, 8].

This scheme uses the following elements that take into account the most important features of the processes occurring in the dielectric:

C_0 is capacitance of a capacitor without a dielectric, to the covers of which an alternating electric voltage u is applied to create an alternating electric field in the dielectric. The accumulation or recharging of C_0 is carried out by an electric current i_0 almost instantly and without dielectric losses. This capacity can be determined using the formula (1.4);

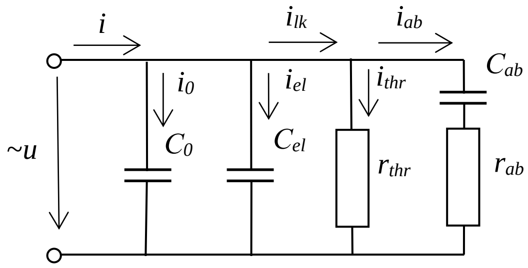

Figure 2.3 – Equivalent dielectric circuit

C_{el} – is additional capacitor capacity, which results from the elastic types of dielectric polarization: electronic and ionic polarization. The accumulation or recharging of the C_{el} is carried out by the electric current i_{np} also almost instantly and without dielectric losses. This capacity is several times larger than C_0;

C_{ab} – is additional capacitor capacity, which results from slow (relaxation) types of dielectric polarization: dipole, migration and spontaneous polarization. Charging or recharging of C_{ab} is carried out by the absorption current i_{ab} very slowly (in some cases for several minutes) and with a fairly large dielectric loss. This capacity can be many times greater than C_0 and C_{el};

r_{ab} – is electrical resistance, which takes into account the presence of dielectric losses due to delayed (relaxation) types of dielectric polarization;

r_{thr} – is electrical resistance, which takes into account a number of free charges in the inside and on the surface of the dielectric. These charges cause a through electric current i_{thr}, which together with the absorption current i_{ab} create a leakage current i_{lk}. Usually the i_{thr} current is neglected, i.e. $i_{thr} \approx 0$ is taken.

Electric currents in the process of dielectric polarization

The process of polarization of the dielectric under the influence of the electric field of the capacitor (Coulomb forces) is accompanied not only by the displacement of the bound electric charges, but also by the directing and corresponding movement of free charges, i.e. electric current, outside the dielectric. If this process is repeated frequently, the electric current outside the dielectric of the capacitor increases in proportion to this frequency. This process of directing and moving free charges is maintained even in cases where there are virtually no charged particles in the space between the capacitor covers, i.e. there is vacuum or air.

Charging and discharging current during dielectric polarization

In most cases, the covers of the capacitor are supplied with alternating voltage u, which usually varies according to the sinusoidal law $u=U_m\sin\omega t$. This is accompanied by a charging and discharging current, the effective value of which can be calculated according to Ohm's law

$$I = \frac{U}{X_C}, \tag{2.7}$$

where U – is current value of alternating voltage (1.11) on capacitor covers, V;

$X_c=1/\omega C$ – is reactance of the capacitor, Ohm (1.13);

Formula (2.7) may give the erroneous impression of the dielectric's ability to transmit a fairly large current I, although it has virtually no free charges, and of the violation of Kirchhoff's first law. For example, if at some point in time the charges enter the cover of the capacitor from the conductive part of the closed circuit, then according to this law at the same time the charges must seem to come out of it towards the dielectric. But this cannot be due to the lack of free charges in the dielectric. In fact, the charges do not move in the direction of the dielectric, but in different directions of the same cover, which is not always noticed [10]. The fig. 2.1 shows the currents i_1, i_2 as components of the current i according to Kirchhoff's first law.

2.1.3 Transmission of electric field force in space

Consider the process of periodic recharging of the capacitor (Fig.2.1), in which the distance l between the covers can be very large. Even in a very remote metal cover of such a "capacitor" charging-discharging current occurs when you turn on the AC source and disappears when you turn off this source [10]. It is clear that this current is very small at large distances l, but under certain circumstances it can be controlled. This means the possibility to transmit controlled electrical signals or information over long distances in air or space without electrical conductors (Fig. 2.4).

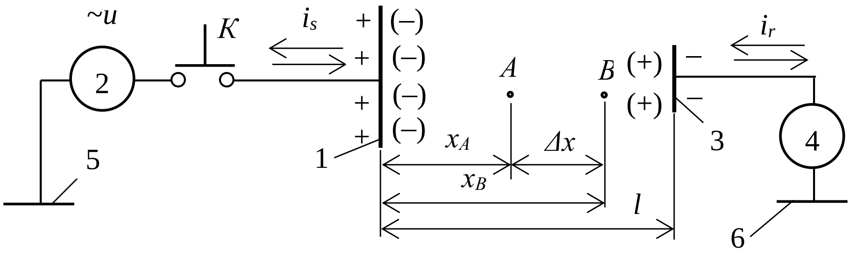

Figure 2.4 – Scheme of information transmission in space by an alternating electric field

One of the metal covers 1 of the "capacitor" acts as an antenna of the signal transmitter from the AC source 2 i_s, and the other metal cover 3 plays the role of the receiving antenna. If you close the key K, the cover 1 is charged from the source 2 with a current i_s, for example, initially with positive charges. These charges interact with the charges of other material bodies, including the charges of the receiving antenna 3, and attract negative charges according to Coulomb's law. It is assumed that this force acts in a straight line that connects antennas 1 and 3. As a result, the antenna 3 is charged with negative charges, accompanied by the corresponding electric current i_r of signals receiver 4. The process of interaction of charges of antennas 1 and 3 during their recharging are similar. The disappearance of the current i_r may indicate the opening of the key K. This is the principle of transmitting information over long distances in the form of alternating electrical signals. This transmission of information is called the transmission of radio signals. Grounding 5 and 6 in this scheme (Fig. 2.4) is not mandatory, but only allows one to get a higher level of the receiver signal i_r.

The main condition for recharging such a "capacitor", and hence the transmission of information over a distance, is a change in the time of the current in both magnitude and direction. The most natural law of current change i_s is the sinusoidal law.

Wave nature of an alternating electric field

If the Coulomb force is controlled at two points A and B at a distance x_A and x_B from the primary source of alternating charges (from antenna 1), then in the case of a sinusoidal law of current i_s the Coulomb force f_B at point B will change with some time of delay Δt compared to the Coulomb force f_A at point A (Fig.2.4):

$$f_A = F_{mA}\, sin(\omega t)\,;$$
$$f_B = F_{mB}\, sin(\omega t - \phi), \tag{2.8}$$

where $\omega=2\pi f$ – is angular frequency of electric current i_s and Coulomb force, s^{-1};

$f=1/T$ – is cyclic frequency of electric current i_s and Coulomb force, Hz;

$T=\lambda/v$ – is duration of the cycle or period of oscillations of electric current i_s and Coulomb force, s;

v – is the speed of propagation in space of the electric field force, which cannot exceed the speed of light in vacuum $c\approx 3\cdot 10^8$ m/s;

λ – is the distance to which the force is applied during one period of oscillations $t = T$ (the value of λ is called the wavelength);

$\varphi=\omega\Delta t$ – is phase shift of the Coulomb sinusoidal forces;

$\Delta t=\Delta x/v=(x_B-x_A)/v$ – is time delay in the process of transmission of the electric field force in space (1.2), which is due to the difference in the distance Δx between points A and B and the speed limit v.

The law of change of charging-discharging current i_s can be of any type, not necessarily sinusoidal. If desired, the non-sinusoidal current i_s can be represented as the sum of sinusoidal currents (harmonics) and each of these harmonics can be considered separately.

The process of propagation of the electric field force is for convenience represented (simulated) in the form of movement of radio waves of length $\lambda = T \cdot v$ with a speed v close to the speed of light c in vacuum. In fact, it is not the waves that move in space, but the effect of the Coulomb force on the charges of material particles, which are encountered in the propagation of this force and which fluctuate with the periodicity of the Coulomb force.

2.1.4 The notion of electromagnetic field

Recharging the covers of a capacitor or antenna is accompanied by an electric current, and hence a magnetic field. The magnetic field also has the force of influencing the electric charges of material particles. The force of magnetic field is due to the electromotive force (EMF) according to the Faraday's law of electromagnetic induction (1.22) and the Lorentz (1.14) or Ampere (1.15) force. The EMF acts on the alternating magnetic field of antenna 1 on any charges of antenna 3, while the Lorentz or Ampere force acts only on the moving charges of antenna 3. The force of the magnetic field propagates in space similar to the force of the electric field.

The alternating electric and magnetic fields are so closely interconnected that they are usually considered as a single electromagnetic field. The oscillations of the electromagnetic forces of this field propagate in any space with limited velocity, including vacuum. Material particles of space can only interfere with the process of propagation of electromagnetic oscillations or change the direction of their propagation.

Electromagnetic oscillations occur due to oscillations or changes in the position of charged particles in electrical circuits or in the composition of atoms or nuclei. Even the disappearance of charged particles, such as electrons, due to their annihilation is a very rapid change in charge, and therefore is accompanied by high-frequency oscillations of electromagnetic forces, annihilation gamma rays. Electromagnetic oscillations, which are usually called electromagnetic waves, are divided into several frequency ranges f or wavelength λ depending on the nature of their interaction with the environment:

– radio waves (f<3...3·10^{11} Hz, λ=10^4...10^{-3} m);
– infrared rays (f=3·10^{11}...3.85·10^{14} Hz, λ=10^{-3}...7.8·10^{-7} m);
– visible light (f=3.85·10^{14}...7.89·10^{14} Hz, λ=7.8·10^{-7}...3.8·10^{-7} m);
– ultraviolet rays (f=7.89·10^{14}...3·10^{16} Hz, λ=3.8·10^{-7}...10^{-8} m);
– x-rays (f=3·10^{16}...6·10^{19} Hz, λ=10^{-8}...5·10^{-12} m);
– gamma rays (f>6·10^{19} Hz, λ<5·10^{-12} m).

If there is a material object in the path of propagation of the force of the electromagnetic field, then there is a partial absorption of energy of the electromagnetic field and the movement of charged particles similar to the movement of charges in the antenna 3 of the receiver (Fig. 2.4). Therefore, this object can become a source of secondary or reflected electromagnetic waves, which can be controlled by the receiving antenna 3 and the receiver 4 (Fig. 2.4). Reception of secondary electromagnetic waves can be used to control the location of a material object (for example, in the radar of an aircraft), in controlling the surface temperature by infrared radiation or in gamma location. Reception of partially absorbed direct electromagnetic waves can be used to determine the location of the aircraft by controlling the partially absorbed gamma rays of cosmic origin, as well as gamma control of the level of materials in the process tank.

2.2 Electrical conductivity of dielectrics

The electrical conductivity of the dielectric is manifested by a through electric current i_{thr} (Fig. 2.3) and is due to the presence of free electric charges. To determine the electrical conductivity the dielectric is placed in an electric field between the metal conductors and the magnitude of the electric leakage current i_{lk} is measured. The electrical conductivity of the dielectric is determined using a constant electric voltage u due to the possible influence of charging-discharging currents i_0, i_{el}, i_{ab}. From the moment of application of this voltage, the currents i_0, i_{el} disappear almost instantly, and the absorption current i_{ab} decreases gradually in time t (Fig. 2.5). Therefore, when determining the electrical conductivity of the dielectric, it is necessary to wait for some time t_n (about a minute) after applying the voltage u, when the absorption current i_{ab} decreases to almost zero, and the output current $i_{lk}=i_{ab}+i_{htr}$ decreases to i_{thr}.

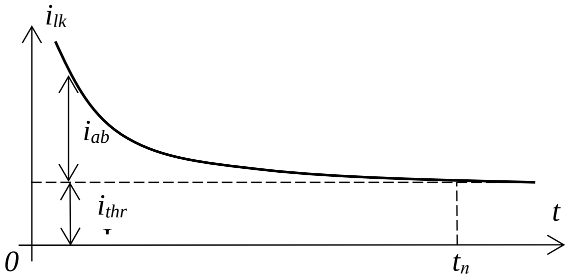

Figure 2.5 – Dependence on the time of the output current through the dielectric

2.2.1 Electrical conductivity of gaseous dielectrics

The electrical conductivity of gaseous dielectrics may occur due to electrical breakdown or ionization of neutral molecules, i.e. splitting of molecules into free ions and electrons. Ionization may occur under the influence of external factors (due to significant heating of gas, ultraviolet, X-ray, radioactive, cosmic or gamma radiation) or due to shock ionization.

The fig. 2.6 shows the dependence of the through current i_{thr} on the electric voltage u applied to the metal electrodes or capacitor plates.

Figure 2.6 – Dependence of through electric current *i_{thr}* of gaseous dielectric on electric voltage *u*

In the initial section of the given graph at $u<u_1$ there is an almost linear dependence of the claim on u due to some stock of free ions and electrons that did not have time to recombine. At $u_1<u<u_2$ almost all free charges are involved in the electric current i_{thr} , and therefore this current reaches the saturation current $I_σ$. In particular, the current i_{thr} in the air under the normal

conditions reaches the value of I_σ at a distance between the electrodes $l = 10$ mm and an electric field strength of 0.6 V/m. The density of this current is approximately 10-15 A/m^2 [6]. Only at $u>u_2$ the further increase of current i_{thr} under the influence of shock ionization and emission of electrons from the surface of metal electrodes occurs. At very high values of voltage u there is an electric breakdown of the dielectric (see section 2.3).

The graph in fig. 2.6 demonstrates the possibility of practical use of the electrical conductivity of gaseous dielectrics to control the intensity of ionizing radiation of radioactive substances by measuring the electric saturation current I_σ at voltage $u_1<u<u_2$. Another example of the widespread use of air conductivity is an electric arc, the high temperature of which allows one to cut, melt or weld metal.

The ability of air to conduct electric current in most cases should be considered as its negative property. In particular, the break of an electric current circuit in the air causes electrical discharges that can lead to a gas explosion or fire. Therefore, appropriate precautions must be taken in potentially explosive atmospheres or areas. As such measures technical devices to prevent sparking can be used, which operate on the principle of biased and forced exclusion of electric current.

Considering the vacuum as a very rarefied gaseous dielectric can give contradictory impressions. On the one hand, the vacuum due to the lack of material particles in it can be considered as an ideal electrical insulator. On the other hand, the absence of these particles means the inability of the vacuum to resist moving charges, i.e. the superconducting properties of the vacuum. Examples of the use of "superconducting" properties of vacuum are electrovacuum devices in electronics, television cathode ray tubes, and particle accelerators. In nature, the most common phenomenon of movement of charges in a vacuum is the so-called solar wind, the flow of high-energy ionized particles of the Sun at a speed of 300 ... 1200 km/s. This flow of charges can cause magnetic storms on Earth, ionize the upper atmosphere and even carry atmospheric molecules into outer space.

2.2.2 Electrical conductivity of liquid dielectrics

The electrical conductivity of liquid dielectrics is closely related to the molecular structure of the liquid and the presence of impurities [6]. The electric current is generated mainly by ions and charged colloidal particles. Particularly high electrical conductivity occurs in those dielectrics that contain many molecules of polar (dipole) structure. The most common way to clean a liquid dielectric is to remove moisture, i.e. to dry it. With prolonged action of the electric field, the ions can settle on the electrodes, which leads to some purification of the dielectric from impurities. The electrical conductivity of a liquid dielectric increases with increasing temperature due to a decrease in its viscosity and an increase in the mobility of ions.

The dependence of the through electric current on the voltage u in a liquid dielectric is nonlinear, as in gaseous dielectrics (Fig. 2.6), but without a clearly determined area of current saturation.

The most common liquid dielectric is transformer oil. Its resistivity at a temperature of $+20^0$C is $\rho \approx 10^{10}...10^{13}$ Ohm m, and the relative dielectric constant is $\varepsilon_r \approx 2{,}2$ [6…9].

2.2.3 Electrical conductivity of solid dielectrics

The electrical conductivity of solid dielectrics is due to the movement of mainly weakly fixed ions of random impurities and ions of the dielectric itself, especially at high temperatures. In some dielectrics there is an electronic conductivity, especially in strong electric fields. A characteristic feature of ionic conductivity is the electric current transfer of a certain amount of a substance that is deposited on the electrodes. Free charges can occur not only inside the dielectric (in its volume), but also in a thin layer of moisture and dirt on its surface. Therefore, for solid dielectrics between the volume and surface conductivity are distinguish.

Surface conductivity occurs due to the ability of the dielectric to adsorb moisture and dust on its surface. The smooth surface of the dielectric adsorbs less moisture and contaminants, especially if the dielectric is nonpolar. As the temperature of the dielectric increases, the mobility of its free ions and their concentration increases due to the thermal dissociation of molecules, which causes an increase in electrical conductivity.

According to the values of specific volume ρ_V and specific surface ρ_S resistance (or specific volume γ_V and specific surface γ_S electrical conductivity), dielectrics are conventionally divided into three main groups:

– high-quality (ρ_v=10^{13}...10^{16} Ohm ·m, ρ_s=10^{14}...10^{16} Ohm);
– quality (ρ_v=10^{9}...10^{12} Ohm ·m, ρ_s =10^{10}...10^{13} Ohm);
– satisfactory (ρ_v=10^{6}...10^{8} Ohm ·m, ρ_s=10^{8}...10^{9} Ohm).

2.2.4 Measurement of electrical resistance of solid dielectrics

Measurement of volume R_v and surface R_s dielectric resistances should be performed at constant voltage and with some time delay (of about one minute) until the charging-discharging current in the electrodes disappears. To measure R_v and R_s, three cylindrical electrodes are usually used, which divide the total electric leakage current i_{lk} into its two components: volume i_v and surface i_s currents (Fig. 2.7).

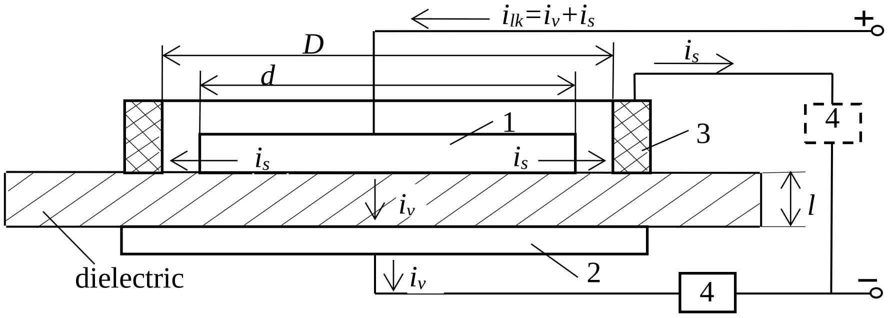

Figure 2.7 – The scheme of separation of volume and surface dielectric currents

The leakage current i_{lk} from the source terminal "+" branches from the electrode 1 to the volume current i_v to the electrode 2 and the surface current i_s to the electrode 3. The currents i_v, i_s converge in the terminal "-" of the source, passing through the sensor 4. Resistances R_v, R_s are measured by alternately connecting the sensor 4 to the branches with currents i_v and i_s, leaving the jumper in place of the sensor. The values of these currents are so small that to measure R_v, R_s with a fairly high gain DC amplifier is used.

According to the results of measurement based on the scheme of fig. 2.7 of volume R_v and surface R_s resistances the volume resistivity ρ_v (Ohm · m) and the surface resistivity ρ_s (Ohm) can be determined, respectively using the following formulas [6]:

$$\rho_v = R_v \frac{S}{l}; \rho_s = R_s \frac{L}{g}, \tag{2.9}$$

where $S = \pi \cdot d^2/4$ – is the area of the contact surface of the electrode 1;

d – is electrode diameter 1;

l – is the distance between electrodes 1 and 2, which is overcome by volume charges;

$L=\pi \cdot (D+d)/2$ – is the effective perimeter of the electrode 1, from which the free surface charges flow;

D – is the inner diameter of the electrode 3;

$g = (D-d)/2$ – is the distance between electrodes 1 and 3, which is overcome by surface charges.

Determination of free charge concentration

The specific conductivity γ_v of a substance is proportional to the concentration of free charges n_0 in the volume of the dielectric, their mobility u_q and the magnitude of the charge q of the ion or electron [6]. Therefore, the concentration of free charges can be calculated by knowing the value of the specific volume resistivity ρ_v of the dielectric (2.9):

$$n_0 = \frac{1}{\rho_v u_q q}, \text{ m}^{-3}, \tag{2.10}$$

where $q = 1{,}602 \cdot 10^{-19}$ C – is charge of an ion or an electron;

$u_q=\upsilon/E$ – is average mobility of free charges, $\text{m}^2/(\text{V}\cdot\text{s})$;

υ – is the average speed of free charges, m/s;

E – is electric field strength, V/m (1.3).

The mobility of ions and electrons is $u_q \approx 10^{-13}...10^{-16}$ $\text{m}^2/(\text{V}\times\text{s})$ and $u_q \approx 3{,}5\cdot 10^{-3}...10^{-4}$ $\text{m}^2/(\text{V}\times\text{s})$ respectively [6]. In the approximate calculations n_0 can be taken $u_q \approx 10^{-9}$ $\text{m}^2/(\text{V}\times\text{s})$ considering the presence of both types of current carriers in the dielectrics.

2.3 Electric breakdown of dielectrics

Electric breakdown is a phenomenon when a dielectric loses its electrical insulating properties under the influence of an electric field. The field strength E_{br} at which this occurs is called the electrical strength [6]:

$$E_{br} = \frac{U_{br}}{l}, \text{ V/m}, \qquad (2.11)$$

where U_{br} – is electric voltage at which there the electric breakdown occurs, V;

l – is distance between electrodes (dielectric thickness), m.

2.3.1 Electric breakdown of gaseous dielectrics

The breakdown of a gaseous dielectric is due to shock and photon ionization, i.e. purely electrical and very fast processes. Therefore, when determining the electrical strength E_{br} (2.11) of such dielectrics the maximum (amplitude) voltage values U_{br} are used.

Shock ionization occurs due to collisions with neutral molecules of free electrons as the most mobile charges, which under the influence of an electric field received a high velocity (about 1000 km/s), and therefore high kinetic energy, which is sufficient for ionization of molecules. If the ionization process develops as avalanche, then there is a breakdown of the dielectric. This process is accelerated if photons are additionally produced as a result of shock ionization, the energy of which is sufficient for ionization of other gas molecules [6]. Gas breakdown occurs within $10^{-7}...10^{-8}$ s at l = 1 cm.

Influence of distance between electrodes on electric breakdown is shown in Fig. 2.8 on the example of air [6]

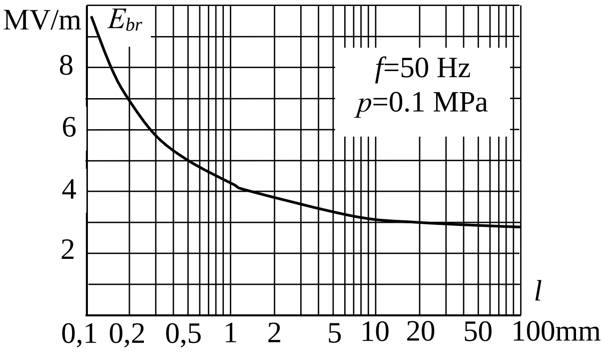

Figure 2.8 – Dependence of electrical strength of air on the distance between the electrodes

In particular, the electrical strength of air increases from 3 MW/m at l = 20mm to 7 MV/m at l = 0.2 mm. Due to this dependence, the tests of dielectrics for their electrical strength are carried out at a standard dielectric thickness (or distance between electrodes) l_{st} = 2.5 mm.

Influence of gas pressure on its electric breakdown

As the pressure increases, the gas density increases, the free path length of electrons and their ability to perform shock ionization decrease. Therefore, under the normal conditions, the electrical strength of the gas E_{br} depends proportionally on its pressure p (right part of the graph in Fig. 2.9).

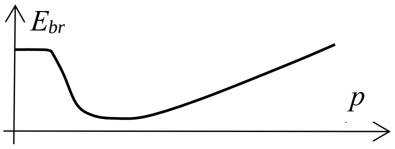

Figure 2.9 – Dependence of electrical strength of gas on its pressure

In a very rarefied gas, the probability of electron collisions with molecules decreases, and therefore the dependence of E_{br} on p becomes inversely proportional (left part of the graph in Fig. 2.9). In the state of almost vacuum ($p \approx 0$) the influence of cold emission, i.e. extraction of electrons from electrodes by Coulomb forces, dominates. In such cases, the value of E_{br} depends only on the material of the electrodes.

In an inhomogeneous electric field before the breakdown a partial breakdown of the gas in the form of a corona near the electrodes with small dimensions may occur, i.e. in places of high strength E. The electrical strength of the gas decreases especially if the small electrode is connected to the positive terminal of the DC source. A cloud of slow positive ions appears near such an electrode, which reduces the effective distance between the electrodes and reduces the electrical strength of the gas [6].

2.3.2 Electrical breakdown of liquid dielectrics

Liquid dielectrics (usually petroleum or transformer oil) differ from gaseous ones in greater density, which means shorter electron free path length and higher electrical strength. Electrical breakdown (loss of electrical insulating properties) occurs due to ionization of thermal processes. The main factors of negative impact on the electrical strength of transformer oil E_{br} (2.11) are the temperature and water that gets into the oil from moist air and is in it in an emulsion state.

Influence of moisture on electric breakdown of oil becomes especially significant if the water content exceeds 0.01% (Fig.2.10)

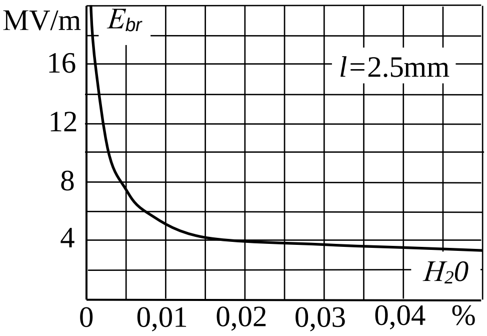

Figure 2.10 – Dependence of electrical strength of transformer oil on water

The negative effect of moisture is enhanced by fibrous impurities that intensively absorb water. The breakdown of liquid dielectrics is explained by the fact that polar impurities (emulsion water, fibers, and solid particles) are oriented in an electric field along its lines of force, forming chains. Current flows through such circuits causing intense local heating [6, 13].

Influence of temperature on electric breakdown of oil is shown in Fig.2.11. Electrical strength E_{br} transformer oil begins to decrease significantly at temperatures above 80 ° C, when light fractions of oil begin to boil with the formation of many gas bubbles.

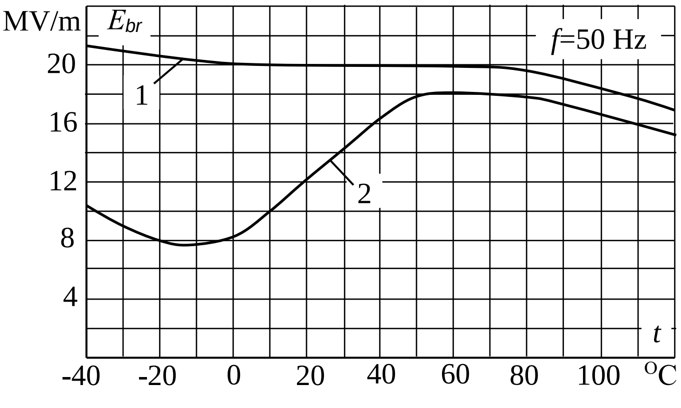

Figure 2.11 – Dependence of electrical strength of transformer oil on temperature at *l* = 2.5 mm (1 for dried oil, 2 for operating oil)

The presence of water impurities in the operating oil significantly reduces its electrical strength E_{br}. The increase in E_{br} of operating oil in the temperature range 0 ... 60^{O}C is explained by the transition of water impurities from the state of emulsion to the state of molecular solution. The increase in E_{br} during the cooling of the oil in the temperature range -10 ...-40^{O}C is due to the increase in oil viscosity and freezing of water drops [12, 13].

2.3.3 Electrical breakdown of solid dielectrics

Solid dielectrics, unlike gaseous and liquid dielectrics, do not restore their electrical insulating properties after electrical breakdown. The electric breakdown of a solid dielectric can be of the following four types.

The breakdown of a homogeneous dielectric is a purely electric breakdown due to shock ionization in the almost complete absence of electrical conductivity and dielectric losses, which is peculiar to gaseous and liquid dielectrics under the influence of a homogeneous electric field. The breakdown process is of very rapid development: within $10^{-7}…10^{-8}$ s. The electrical strength of some homogeneous dielectrics in a homogeneous electric field can exceed the electrical strength of transformer oil several times [9]. For example, the electrical strength of glass, mica and liquid-impregnated paper reaches 100 ... 300 MV/m, i.e. an order of magnitude higher than that of transformer oil [6…9, 13].

The heterogeneity of solid dielectrics is often caused by gas inclusions in them and porosity. Heterogeneous solid dielectrics include paper and wood not impregnated with a liquid dielectric, and porous ceramics. Their electrical strength is slightly higher than the electrical strength of air. If the density of these materials is increased or if the gas inclusions are displaced by a liquid dielectric, then their electrical strength increases.

Thermal breakdown is caused by heating the dielectric through its direct contact with the conductor of electric current (1.10), due to the presence of an external heat source, as well as through electric current and dielectric losses directly into the dielectric, especially at high values of electric field strength *E,* field frequency ω, dielectric constant ε_r and the tangent of the dielectric loss angle $tg\delta$ of the dielectric (2.3). In turn the heating of the dielectric significantly increases ε_r and $tg\delta$, which contributes to the further heating of the dielectric. If in some dielectric zones the heat release exceeds the heat transfer, then the process of these zones heating to critical temperatures for this dielectric (about 100 ... 150 ° C, sometimes 200 ... 300 ° C) is developed avalanche-like.

Electrochemical breakdown occurs due to electrolytic processes in the dielectric, which cause its gradual chemical destruction, irreversible deterioration of electrical insulating properties and reduced electrical strength. This phenomenon is called dielectric aging, which occurs slowly, accompanied by the formation of a small amount of chemically active substances or semiconductor compounds. Dielectric aging is accelerated under the influence of high temperature and humidity.

2.4 Thermal properties of dielectrics

Among the thermal properties of dielectrics, the most important are heat resistance and thermal conductivity.

2.4.1 Heat resistance of dielectrics

Heat resistance is the ability of electrical insulating materials to perform their basic functions without damage and unacceptable deterioration of properties under the influence of high temperature. The ability to increase the operating temperature of the insulation is extremely important. It allows us to get more power while maintaining the size or reduce the size and cost of products while maintaining power. Size reduction is especially important for mobile equipment. Electrical insulating materials used in electrical machines, transformers and devices are divided into 7 main classes of heat resistance depending on the permissible operating temperature [6…9]:

Class Y (up to 90° C) – includes fibrous materials based on cellulose, cotton, silk and polyamides, which are not impregnated and not immersed in liquid electrical insulating material (yarn, fabrics, tapes, paper, cardboard, wood), polyvinyl chloride, natural rubber, polyethylene, polystyrene.

Class A (up to 105° C) – includes the same fibrous materials, but impregnated with oil, oil-resin and other varnishes or immersed in a liquid dielectric, as well as polyamide film, insulation of enamelled conductors with polyvinyl acetate varnishes.

Class E (up to 120° C) – includes plastics with organic filler and thermosetting binder (getinax, textolite), epoxy and polyurethane resins and compounds, polycarbonate films, insulation of enamelled conductors on polyurethane and epoxy varnishes.

Class B (up to 130° C) – includes materials based on mica, asbestos, and fiberglass with organic binders and impregnating materials and on organic substrates (micanites, fiberglass, and fiberglass fabrics), polyurethane varnishes, and epoxy compounds with inorganic filler.

Class F (up to 155° C) – includes micanites without substrates or with inorganic substrates using organic binders of high heat resistance, epoxy and organosilicon resins.

Class H (up to 180° C) – includes materials based on mica, asbestos, fiberglass in combination with organosilicon resins of high heat resistance, organosilicon elastopolymers, fluoroplastic-4.

Class C (up to 200° C) – includes inorganic materials without organic binders and impregnating materials (mica, ceramic materials, glass, quartz, asbestos, heat-resistant mycanites).

Classes 220 and 250 **(operating temperatures 220 and 250° C) –** have been introduced for materials that are to operate at higher temperatures. These include some types of mica, ceramic materials, glass. For higher operating temperatures, classes 275, 300 ... (every 25° C) are allowed.

Materials belong to a certain class of heat resistance on the basis of experience of operation or tests. The analysis of data of long-term operation of electric machines revealed that the service life of their insulation, and hence machines, is sharply reduced when the winding temperature is exceeded to the maximum permissible value (corresponding to the heat resistance class of insulation). Thus, for the insulation of classes A and B when the temperature is exceeded for about every 10° C, the service life is halved.

2.4.2 Thermal conductivity of dielectrics

The importance of thermal conductivity of dielectrics is due to the need for constant transfer of thermal energy through the dielectric from the operating electrical equipment to the environment. The main sources of thermal energy are electrical losses in conductors with electric current (1.10), dielectric losses (2.3), and magnetic losses. Dielectrics have low thermal conductivity due to the extremely small number of free electrons, which play an important role in heat transfer. Among the commonly used dielectrics low specific thermal conductivity γ_m is peculiar to the following: air (γ_mt = 0.05 W/m·K), paper (γ_m = 0.1 W/m·K), lightweight fabric (γ_m = 0.13 W/m·K). Getinax (γ_m = 0.35 W/m·K), porcelain (γ_mt = 1.6 W/m·K), and crystalline quartz (γ_m = 12.5 W/m·K) have relatively high thermal conductivity.

2.5 Some dielectric materials

2.5.1 Gaseous dielectric materials

Air in many cases remains the main dielectric, despite a number of its disadvantages. We mean first of all its low values of dielectric constant ε_r, electrical strength E_{br}, and thermal conductivity γ_m (Fig. 2.8, 2.9, and 2.12).

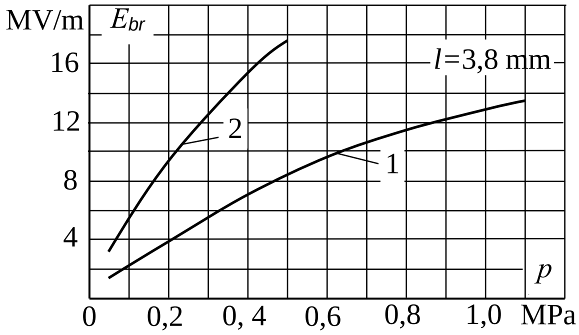

Figure 2.12 – Dependence of electrical strength of air (1) and electronegative gas (2) on pressure

Electronegative gas is sulphur hexafluoride (sulphur hexafluoride) SF_6 having high electrical insulating properties. Relative to air, the electrical strength of electronegative gas is 2.5 times higher; the density is 6.1 times higher. Electronegative gas is transparent, non-toxic and chemically stable.

Electronegative gas has especially great advantages over air at high pressure (Fig. 2.12). At higher temperatures, in particular in the electric arc zone, electronegative gas molecules split into fluorine and sulphur during the opening of an electric current conductor, absorbing significant part of electrical energy and helping to extinguish the arc. The removed energy is then gradually returned due to the electronegative gas renewal. Electronegative gas is successfully used in high voltage and power circuit breakers, as well as in capacitors and electrical cables.

Hydrogen has a high specific thermal conductivity and heat capacity, as well as a very low density at normal pressure. These properties allow the efficient use of hydrogen to cool the moving parts of very powerful electric machines, in particular, synchronous turbogenerators and compensators. The efficiency of hydrogen utilization is manifested in a significant improvement of machine cooling, reduction of machine power losses due to friction and ventilation, in increasing machine power and its efficiency, improving the operation of electric brushes, slowing down the aging of electrical insulation. Hydrogen due to the small size of atoms is easily soluble in metals, especially in lithium *Li*, which allows convenient and safe storage and transportation of hydrogen. For example, one kilogram of lithium hydride *LiH* may contain 2.8 m^3 of hydrogen. These advantages compensate the main disadvantage of hydrogen: its high explosiveness in an environment where there is oxygen. This disadvantage forces the use of a number of technical means to prevent a possible explosion of hydrogen as an insulating and cooling gas.

Inert gases include helium *He*, neon *Ne*, argon *Ar*, krypton *Kr*, xenon *Xe*, and radon *Rn*. These gases are very inert chemically, have a low density and are easily ionized due to the low electrical strength of E_{br}. Each of the inert gases has its own special and even unique properties that allow them to be used in very specific conditions.

Helium has the lowest liquefaction temperature, which allows it to be used as an effective low-temperature cooler, including conditions creating for superconductivity of electrical conductors. In particular, the liquefaction temperature of the main helium isotope ^4He is 4.216 K at atmospheric pressure, the viscosity of liquid helium is almost zero, and the thermal conductivity is very high.

Neon has a relatively low liquefaction temperature (27.1 K) at a much higher heat of vaporization than helium, and is therefore sometimes used as a low-temperature cooler. Neon fills bright red gas-discharge and signal lamps, which are used in advertising, radio equipment, as well as at lighthouses and airfields due to the weak scattering of red rays in the fog. A mixture of neon and helium is used as a working medium in gas lasers. The widespread use of neon is hampered by its high cost, which is several hundred times higher than the cost of helium.

Argon is liquefied at a temperature of 87.1 K. It is obtained as a by-product in the separation of air to oxygen and nitrogen on an industrial scale, and therefore it has a relatively low cost. Argon is used in violet-blue gas discharge tubes, argon lasers, to fill conventional incandescent lamps, to create a protective (oxygen-free) environment when welding some metals, such as aluminium.

Krypton is liquefied at a temperature of 119.8 K. It is obtained from the air in the form of a krypton-xenon mixture and is used for filling greenish gas discharge tubes and X-ray tubes, as well as for the manufacture of high-power ultraviolet gas lasers.

Xenon is liquefied at a temperature of 112 K, which is very close to the liquefaction temperature of krypton. It is obtained from a krypton-xenon mixture and is used for the manufacture of powerful gas-discharge and pulsed light sources, as a working medium for lasers, as well as a working fluid in ion jet engines.

2.5.2 Liquid dielectric materials

Liquid dielectrics organically combine two very important functions: providing high electrical insulation strength and heat dissipation from the windings and magnetic circuits of existing electrical equipment [13]. The first function is based on the much higher electrical strength of liquid dielectrics compared to gaseous dielectrics and on the ability of liquid dielectrics to displace gas cavities from fibrous dielectrics, i.e. to impregnate fibrous dielectrics. The second function is based on a much higher heat capacity and thermal conductivity of liquid dielectrics compared to gaseous dielectrics and on the possibility of physical movement and transfer of heat, i.e. convection, which is not peculiar to solid dielectrics. In addition to these functions, liquid dielectrics are able to effectively dampen the energy of the electric arc in electrical switches. This energy is accumulated in the magnetic field around the conductors of electric current and then is almost completely released in the break point of the electric current in accordance with the law of conservation of energy. Liquid dielectrics used in electrical equipment can be divided into three main groups: petroleum insulating oils, vegetable oils and synthetic liquid dielectrics.

Petroleum electrical insulating oils

Transformer oil is a mixture of various hydrocarbons obtained from petroleum by step distillation with the release of the desired fractions of oil and their subsequent thorough purification from impurities. The most important property of transformer oil is its electrical strength, which depends on the moisture content (Fig. 2.10), gas inclusions and temperature (Fig. 2.11). The electrical strength is determined experimentally using metal disk electrodes with a diameter of 25 mm with rounded edges at a distance between these electrodes l = 2.5 mm. The table. 2.1 shows the norms of the minimum permissible values of electrical strength of two types of oil: "fresh" (clean and dry) oil, prepared for pouring into a transformer or other device and "operational", which is in operation [6].

Table 2.1 – Norms of electrical strength of transformer oil

Nominal voltage of the device filled with oil, kV	Electrical strength of oil E_{br} (not less), MV/m	
	for "fresh"	For "operational"
Up to 15 inclusive	10	8
From 15 to 35 inclusive	12	10
From 60 to 220 inclusive	16	14
From 330 and above	20	18

Capacitor oil is used to impregnate paper electrical insulation of capacitors. Oil-impregnated paper has a higher dielectric constant ε_r and greater electrical strength E_{br}, which reduces the size, weight and cost of capacitors at a given operating voltage, frequency and capacitance. Capacitor oil is similar to transformer oil in manufacturing technology, but requires more thorough purification. The electrical strength of the dried condenser oil must be at least 20 MW/m.

Cable oil is used to impregnate paper electrical insulation of electrical power cables. There are several types of cable oil depending on the operating voltage, with different viscosity. High-voltage cables with a voltage of 110 ... 500 kV use especially carefully purified and degassed oil and create an additional pressure of ≈0.3 ... 0.4 MPa during cable operation.

Vegetable insulating oils are viscous liquids obtained from the seeds of various plants. Among these oils, drying oils are the most important. Drying occurs due to chemical processes based on oxidative polymerization. When heated, the film of dried vegetable oil does not dissolve. Examples of vegetable insulating oil are hemp, tung, and castor oil.

Synthetic liquid insulating dielectrics in some respects are superior to petroleum oils, we can note chlorinated hydrocarbons, organosilicon and organofluorine liquids [6…9].

Chlorinated hydrocarbon is a chlorinated product of biphenyl $C_{12}H_{10}$ with different degrees of chlorination. Chlorinated hydrocarbon $C_{12}H_5Cl_5$ (sovol) is used more often. In comparison with petroleum oils, sovol has better properties: $\varepsilon_r \approx 5$; $tg\delta \approx 0.005 ... 0.01$; $\rho \approx 10^{11}$ Ohm · m; $E_{br} \approx 15$ MV/m. The disadvantage of sovol is the toxicity of gas emissions under the influence of electric arc.

Organosilicon liquids are substances whose molecules consist of silicon and oxygen atoms and have a linear structure. In comparison with petroleum oils, organosilicon liquids have better properties, especially in terms of heat resistance (up to 250° C): $\varepsilon_r = 2.4 ... 2.8$; $tg\delta = 0.0001 ... 0.0003$; $\rho = 10^{11}...10^{12}$ Ohm m; $E_{br} \approx 14 ... 18$ MV/m). These fluids have a high cost and are therefore are only used at high operating temperatures.

Organofluorine liquids are substances whose molecules consist of carbon and fluorine atoms, have the form of C_mF_n, and a linear structure, can be in liquid, gaseous or solid state. The main advantages of organofluorine liquids are high heat resistance (up to 300° C), non-flammability and the ability to intensive heat dissipation. Other characteristics of organofluorine liquids are as follows: $\varepsilon_r = 2.2 ... 2.5$; $tg\delta = 0.0001 ... 0.0002$; $\rho = 10^{12}...10^{14}$ Ohm · m; $E_{br} \approx 12 ... 19$ MV/m.

2.5.3 Solid dielectric materials

The common difference between most solid dielectrics and gaseous and liquid dielectrics is the ability to withstand mechanical loads in addition to the basic electrical insulating functions.

Resins and polymers

Resins is the main starting material or important component for the manufacture of many solid dielectrics. At normal temperatures, resins are amorphous vitreous substances, and when heated, they become plastic and then liquid with adhesive properties. By their origin, resins are natural and synthetic. The most practical are synthetic resins, which are obtained by polymerization or polycondensation. Therefore, in some cases, synthetic resins are called polymers. Polymers can be formed from monomers by polymerization or polycondensation. The polymerization process takes place with the participation of one substance (monomer) under the action of heating, high pressure, ultraviolet rays, catalysts without the release of by-products. As a result of polymerization, linear polymers are formed, the molecules of which have the form of chains or threads. Linear polymers are flexible and elastic; most of them soften and melt at moderate temperatures, and are therefore often referred to as thermoplastics. The process of polycondensation takes place with the participation of at least two different chemicals with the release of by-products (water, ammonia ...). As a result of polycondensation, spatial polymers or resins are formed, the molecules of which are developed in different directions of space. Spatial polymers and resins are usually hard, brittle; difficult to melt and dissolve, and therefore are often called thermosetting.

Resins and polymers can be divided into three main groups: natural resins, thermoplastic and thermosetting synthetic resins and polymers.

Natural resins are the product of the activity of some insects or resinous plants. They are obtained almost in a ready form only at simple operations of clearing and remelting.

Shellac – is a resin that is released on trees by insects in tropics. When heated to 60 ° C it becomes flexible, when> 60 ° C it melts, and when heated for a long time it is baked and acquires thermosetting properties. Electrical insulating properties are : $\rho_v=10^{13}...10^{15}$ Ohm · m; $\varepsilon r\approx 3.5$, tgδ≈0.01, E_{br}= 20 ... 30 MV/m.

Rosin – is a brittle resin, consisting mainly of organic acids, soluble in liquid hydrocarbons, softens at a temperature of +50 ... 70 ^{O}C. Rosin is obtained from natural pine resin. A solution of rosin in petroleum oil is used in the manufacture of oil varnishes and cable compounds. Electrical insulating properties are $\rho_v=10^{12}...10^{13}$ Ohm · m; $\varepsilon_r\approx 3$, tgδ≈0.03, E_{br}= 10 ... 15 MV/m.

Copals – are refractory, solid and insoluble resins. They are extracted as fossil decomposition products of resin-bearing trees, for example, in the form of amber. Copals are used as an additive to oil varnishes. Electrical insulating properties of copals are $\rho_v=10^{15}...10^{17}$Ohm·m; $\varepsilon_r\approx 2.8$, tgδ≈0.001.

Thermoplastic polymers with a linear structure of molecules include polyethylene, polyvinyl chloride, fluoroplastic-4, polystyrene, polyimide resins.

Polyethylene is a product of polymerization of gaseous ethylene C_2H_4, colourless, transparent, solid, greasy to the touch, non-polar, resistant to acids and radiation; melts and burns in the flame, has quite high electrical insulating properties: $\rho_v=10^{13}...10^{15}$Ohm · m; ε_r= 2.3 ... 2.4; tgδ = 0.0001 ... 0.0005; E_{br}= 15 ... 20 MV/m. Films, hoses, tubes for cable insulation, coil frames are made of polyethylene.

Polyvinyl chloride (PVC) is a product of polymerization of gaseous vinyl chloride C_2H_3Cl in the presence of hydrogen peroxide. PVC has a yellowish colour, is hard, brittle, flammable, resistant to water, acids, alcohol, kerosene, gasoline, ozone, radiation. PVC is a polar dielectric and therefore has reduced dielectric properties compared to non-polar polymers: $\rho_v=10^{13}...10^{14}$= 1013 ... 1014 Ohm·m; ε_r= 3.2 ... 3.6; tgδ = 0.03 ... 0.08; E_{br} = 15 ... 20 MV/m. PVC is used for insulation of low voltage wires and cables, tubes for auxiliary insulation, adhesive insulating tapes, and films.

Polytetrafluoroethylene (fluoroplastic-4) is a polymerization product of gaseous tetrafluoroethylene C_2F_4. Fluoroplastic-4 is an organofluorine polymer, a white or greyish-looking material that is relatively soft and non-polar. In terms of electrical insulating properties, fluoroplastic-4 is one of the best dielectrics: $\rho_v=10^{15}...10^{16}$ Ohm · m; ε_r = 1.9 ... 2.1; tgδ = 0.0001 ... 0.0003; E_{br} = 20 ... 30 MV/m. Fluoroplastic-4 has extremely high heat resistance (+ 250 ° C), retains flexibility at temperatures below minus 80 ° C, is extremely chemically stable, non-flammable, does not get wet with liquids, has low radiation resistance. Fluoroplastic-4 is used in critical cases with simultaneous action on the insulation of high or low temperatures and chemically active media.

Polystyrene is a polymerization product of liquid styrene C_8H_8. The electrical insulating properties of polystyrene are approximately the same as those of polyethylene. Polystyrene is widely used in the technique of high and ultrahigh frequencies. Its disadvantage is the fragility at low temperatures and the tendency to surface cracks.

Polyimide resins contain an imide group of atoms ... $–CO – N – CO –$ ... They are very high-quality dielectric materials, are the most heat-resistant among polymers (not less than + 220^{O} C), have considerable frost resistance (to minus 269^{O}C), steady to organic solvents, oils and dilute acids, as well as to the action of ionizing radiation. Electrical insulating properties of polyimides are ρ_v=10^{15}...10^{16} Ohm·m; ε_r = 3.5; tgδ = 0.0006 ... 0.0016; E_{br} = 160 ... 200 MV/m. Polyimides are used to make films that are used in capacitors, heat-resistant cable products, insulation of electrical machines, as well as for the manufacture of some plastics and varnishes for coating conductors and impregnating small coils.

Thermosetting synthetic resins and polymers include phenol-formaldehyde resins, solid epoxy resins, and organosilicon resins.

Phenol-formaldehyde (bakelite) resins are products of polycondensation of aqueous solutions of phenol C_6H_5OH and formaldehyde H_2CO with a catalyst. In the case of formaldehyde excess using an alkaline catalyst (ammonia) thermosetting resin (bakelite) with good dielectric characteristics: ρ_v=10^{11}...10^{12}Ohm · m; ε_r = 5 ... 6.5; tgδ = 0.01 ... 0.1; E_{br} = 10 ... 20 MV/m is obtained. Bakelite is resistant to water, alcohol, acetone, gasoline, oils, sulphuric and hydrochloric acids. Bakelite resin is used for the manufacture of getinax, textolite, paper-bakelite cylinders, tubes, insulating sleeves. Bakelite is used to make powders for hot pressing of mass products: switches, sockets, buttons, and plugs.

Epoxy resin in the normal state is a thermoplastic material. But after adding the hardener, the epoxy resin becomes thermosetting due to polymerization within a few hours. Epoxy resins are used in the manufacture of adhesives, varnishes, compounds. Most epoxy resins make toxic effect on the human body in the process of their polymerization.

Organosilicon resins have siloxane groups of cyclically repeating silicon and oxygen atoms. They may be both thermoplastic with a linear structure of molecules and thermosetting with a spatial structure of molecules. Organosilicon resins are used in the manufacture of varnishes, compounds, plastics. Their high electrical insulating properties are maintained even at elevated temperatures. The disadvantage of these resins is their relatively high price, as well as low mechanical strength.

Electrical insulating varnishes and compounds are multicomponent materials, which in the stage of storage and manufacture of insulation are in a liquid state, and in the final stage they harden [6…9]. Their main components are resins, polymers, bitumens and vegetable oils, which are able to dry. Varnishes are divided into impregnating, coating and adhesive ones.

Impregnating varnishes impregnate porous insulation to increase electrical strength, heat resistance, and dielectric constant.

Coating varnishes form a smooth and moisture-resistant film on the surface of dielectrics. Some topcoats (so-called enamel varnishes) are applied directly to the surface of the conductive metal, forming an insulating layer.

Adhesive varnishes are used to glue together sheets of solid dielectric materials, for example, in the manufacture of micanites.

Compounds are electrically insulating impregnating and filling substances which consist of a mix of various resins, bitumens and oils. At the time of use the compounds are in a liquid state. The compounds are then cured by cooling or chemical processes. To improve the mechanical properties they are filled with fillers, plasticizers and hardeners. Compounds are used for impregnation of windings of electric machines and transformers, for casting of radio devices, for sealing of electrotechnical nodes.

Fibrous materials consist of elongated particles. Air voids between these particles significantly impair the dielectric properties of fibrous materials. Therefore, they are usually impregnated with liquid dielectrics, oils, varnishes or resins. Fibrous materials include wood, paper, fiber, fabric and other fibrous materials of natural, artificial or synthetic origin.

Wood has good mechanical properties. The dielectric properties of wood are improved by drying and subsequent impregnation with paraffin, hemp oil, and various resins.

Electrical paper and cardboard are sheet or roll materials that are made mainly of wood pulp. Sawdust is boiled in a solution of sodium hydroxide NaOH to remove harmful impurities, washed, dried and rolled, trying to minimize the volume of air gaps. Cardboard differs from paper only in thickness (up to 3 mm).

Cable paper is used for insulation (wrapping) of conductors of high-voltage power cables with voltage up to 500 kV. It is impregnated with oil-rosin compound.

Capacitor paper is the thinnest and highest quality fibrous electrical insulating material. It is impregnated with petroleum condenser oil to increase ε_r and E_{br} and reduce $tg\delta$.

Textile electrical insulating materials are cotton, silk, synthetic fabrics or fiberglass fabrics that are impregnated with electrical insulating oils and varnishes to improve their electrical insulating properties. If varnishes are used for impregnation, these materials are called varnish fabrics or varnished tapes.

Plastics are multi-component materials that consist of a binder, filler and some additional components. A binder is an organic macromolecular compound (organic resin or polymer) that has an adhesive ability as well as the ability to plastic deformation under pressure and heat.

Filler is a substance that is adhered to the binder under the action of pressure and high temperature, and is formed. The filler significantly reduces the cost of plastic and at the same time can improve its mechanical properties, especially if the filler is a sheet of fibrous material, such as paper (getinax) or fabric (textolite or fiberglass). As additional components plasticizers can be used which increases plasticity and reduces fragility of materials, as well as hardeners, lubricants, dyes.

Rubbers are vulcanized multicomponent systems based on natural or synthetic rubber. Rubbers due to their high elasticity are elastomers. In the manufacture of rubber, sulphur or thiuram, accelerators of the vulcanization process, fillers (chalk, talc, kaolin) are added to improve the mechanical properties and reduce the cost of rubber, softeners (stearin, paraffin) are added to improve the technological properties [7]. Depending on the amount of sulphur, there are soft rubber (1...3% sulphur) and hard rubber, which is called ebonite (30 ... 35% sulphur). Free sulphur is able to react chemically with copper. Therefore, if it is necessary to insulate copper conductors, rubber with the addition of thiuram is used instead of sulphur. Rubber is widely used in the manufacture of conductors and cables, dielectric gloves and galoshes. A significant disadvantage of rubber is its low resistance to oxygen, light, heat and electrical discharges.

Ceramic dielectrics are obtained by sintering very shattered and thoroughly mixed minerals and metal oxides. They have a higher resistance to electrical and thermal aging and to long-term mechanical stress compared to organic dielectrics.

Among ceramic dielectrics the most famous is ***electrical porcelain***, which is used at low frequency. It consists of ~ 50% kaolin, ~ 25% quartz SiO2, and ~ 25% feldspar. Electrical porcelain has the following dielectric characteristics: $\rho_v=10^{11}...10^{12}$ Ohm·m; $\varepsilon_r= 5 ... 7$; tgδ = 0.025 ... 0.035; E_{br} = 25 ... 30 MV/m. Low-frequency capacitor ceramics, which is obtained by synthesis of pure oxides of strontium, bismuth, titanium, tin, oxides of zinc and manganese, are also used for operation at low frequency.

High-frequency ceramics include steatite (based on clinoenstatite $MgO{\cdot}SiO_2$), forsterite (based on forsterite $2MgO{\cdot}SiO_2$), spinel-forsterite (based on spinel $MgO{\cdot}Al_2O_3$ and forsterite $2MgO{\cdot}SiO_2$), vilemite (based on vilemite $2ZnO{\cdot}SiO_2$), aluminous (based on alumina Al_2O_3) and corundum ceramics [7]. Corundum ceramics has the highest heat resistance (high values of electrical characteristics are maintained at temperatures up to 400° C, and mechanical characteristics are maintained at temperatures up to 1600° C). Corundum ceramics has the following dielectric characteristics at a frequency of 1 MHz: $\rho_v=10^{14}...10^{15}$ Ohm · m; ε_r = 9.3 ... 10.5; tgδ = 0.0001 ... 0.0005; E_{br} = 28 ... 50 MV/m.

Mica materials

Mica as the basis of mica materials is a natural dielectric that has very high dielectric properties. Mica occurs in nature in the form of crystals of different shades. Their characteristic feature is the ability to delaminate easily into very thin plates. Mica occurs in two types: muscovite and phlogopite. Their chemical formulas are approximately as follows: $K_2O{\cdot}3Al_2O_3{\cdot}6SiO_2{\cdot}2H_2O$ for ***muscovite****;* $K_2O{\cdot}6MgO{\cdot}Al_2O_3{\cdot}6SiO_2{\cdot}2H_2O$ for ***phlogopite***. Mica may also contain compounds of iron, sodium and calcium.

In terms of dielectric properties, muscovite is better: ρ_v=10^{12}...10^{16}Ohm · m; ε_r= 6.8 ... 7.2; tgδ = 0.0003 at a frequency of 1 MHz and 0.015 at a frequency of 50 Hz; E_{br} ≈200 MV/m. Dielectric properties of phlogopite are as follows: ρ_v=10^{12}Ohm · m; ε_r= 6 ... 6.2; tgδ = 0.0015 at a frequency of 1 MHz and 0.05 at a frequency of 50 Hz; E_{br} ≈100 MV/m.

Mica belongs to the materials with high heat resistance (550 ... 900 ^{O}C), has sufficient mechanical strength and moisture resistance. Mica is used in mica capacitors, in the manufacture of glued electrical insulating materials (micanites, micalexes, mica tapes, mycofolia, and mica) and insulating gaskets. Organosilicon and phenol-formaldehyde resins or varnishes based on these resins are used for bonding mica plates.

In addition to natural mica ***fluorophlogopite***, synthetic mica is produced for electrical insulation. It differs from phlogopite by hydroxyl groups of *OH* that are replaced by fluorine ions *F* in its crystal lattice. Fluorophlogopite has a higher heat resistance (up to + 1000 ° C).

Oxide dielectric films are formed on the surface of a metal in the form of a chemical compound of this metal with oxygen and is called oxide insulation. The best Al_2O_3 oxide film is created on the aluminum surface. Under normal conditions, aluminum is always covered with a very thin oxide film, which as a dielectric can withstand only a small voltage of about 1 V. Therefore, to ensure acceptable dielectric properties a much thicker oxide film (about 0.01 ... 0.07 mm) is created by means of special treatment of aluminium, which is able to withstand a voltage of 100 ... 300 V [6]. To do this, electrochemical anodic treatment of the aluminium surface is used.

An oxide film is also used to make resistors of high-resistance alloys for electric heaters, which is created by thermal oxidation of a conductive alloy in air at temperatures up to 900 ° C. The conductor with such a coating can be wound in a coil with coils close to each other.

Oxide insulation is also used to cover electrical steel plates, from which most magnetic conductors of electrical machines, transformers and other types of AC electrical equipment are assembled. Such insulation is sufficient to limit eddy currents in magnetic conductors, despite the low electrical insulating properties of the iron oxide film [6].

2.6 Active dielectrics

The properties of active dielectrics can be controlled by external energy influence: electric or magnetic field strength, mechanical force, temperature or light flux [7, 15]. Active dielectrics can have ferroelectric, piezoelectric, pyroelectric, electro-optical, or electret effects.

2.6.1 Ferroelectrics

Ferroelectrics are characterized by spontaneous polarization, which is due to the presence of relatively large regions (domains) with a strong intrinsic electric field (with a dipole moment of spontaneous polarization $P_s=\Sigma p_0$, where p_0 is the dipole moment of the elementary domain) and which can be controlled by electric voltage E of external electric field [7]. The external electric field contributes to the predominant orientation of the dipole moments of the domains in one direction, which results in the effect of strong polarization P with a corresponding increase in the dielectric constant ε_r to a maximum ε_{rm} at $E=E_s$ (Fig. 2.19). When almost all domains are reoriented, further amplification of the external electric field is no longer able to increase the polarization more than P_σ. Therefore, ferroelectrics are characterized by a very high dielectric constant ε_r (up to tens of thousands) and a nonlinear dependence of the polarization P and the dielectric constant ε_r on the external electric field strength (Fig. 2.13).

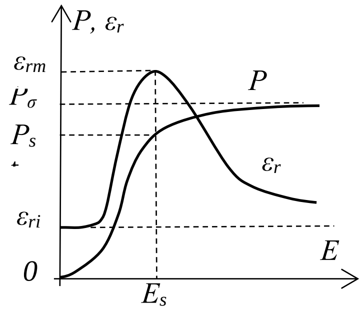

Figure 2.13 – Dependence of polarization *P* and dielectric constant ε_r of ferroelectric on the electric field strength *E*

The ferroelectric effect disappears when the dielectric temperature T is higher than the temperature of the Curie point T_c, regardless of the electric field applied from the outside.

The process of reorientation of electric moments of domains when changing the polarity of the electric field strength E is accompanied by significant energy losses, i.e. there is a dielectric hysteresis similar to magnetic hysteresis (Fig. 2.14), where P_{res} is the residual polarization; E_c is coercive force.

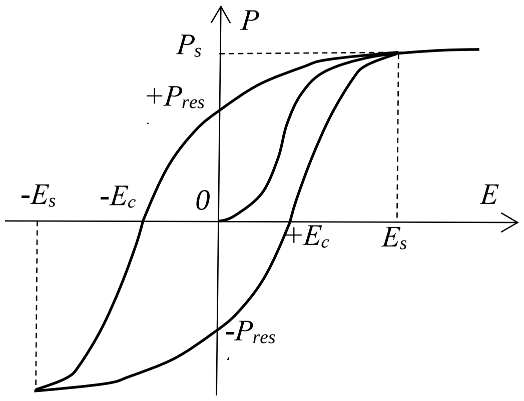

Figure 2.14 – Dependence of polarization *P* (C/m^2) and dielectric constant ε_r of ferroelectric on the electric field strength *E*

The area of the hysteresis loop is proportional to the specific energy losses for one cycle of reorientation of dielectric domains. Therefore, ferroelectrics are used for the manufacture of small low-frequency capacitors varicons, the capacity of which can be changed by changing the electric field strength E. Ferroelectrics are chosen so as to obtain the maximum possible value of the dielectric constant ε_r with the minimum possible dependence of ε_r on temperature and the minimum value of the rectangle of the hysteresis loop $K_{rhl}=P_0/P_н$. If K_{rhl}>0.9, then the ferroelectric can be used to make storage elements for computers. Depending on the mechanism of spontaneous polarization, there are ionic and dipole ferroelectrics.

Ionic ferroelectrics are crystals with predominantly ionic bonds. These include barium titanate $BaTiO_3$ (T_c=120^{O}C), lead titanate $PbTiO_3$ (T_c=490^{O}C), cadmium titanate $CdTiO_3$ (T_c=223^{O}C), lead methaniobate $PbNb_2O_6$ (T_c=570^{O}C), potassium iodate KJO_3 (T_c=210 ^{O}C) [7].

Dipole ferroelectrics are substances whose atoms are bonded together by a chemical (covalent) bond. These substances include the ferric salt $NaKC_4H_4O_6\cdot 4H_2O$ (T_c=24^{O}C), triglycine sulphate $NH_2CH_2COOH)_3\cdot H_2SO_4$ (T_c=49^{O}C), sodium nitrate $NaNO_2\cdot 4H_2O$ (T_c=163^{O}C), dihydrogen phosphate-potassium KH_2PO_4 (T_c=151^{O}C) [7]. Dipole ferroelectrics in an elementary cell contain an atom (ion) or a group of atoms (ions) that have two equilibrium positions. At a temperature T below T_c one of the equilibrium positions becomes better: there is a spontaneous polarization, in the elementary cell a dipole moment occurs. The result is a phase transition of the dielectric from the paraelectric state to the ferroelectric state [15].

2.6.2 Piezoelectrics

When polarized under the influence of an electric field, all dielectrics change their geometric dimensions. This phenomenon is called electrostriction. In most dielectrics, this phenomenon is irreversible, i.e. under the influence of mechanical forces the dielectric is usually not polarized. But there are solid anisotropic crystalline asymmetric dielectrics, which are polarized by mechanical stress in the absence of an external electric field: electric charges occur on their surface. This phenomenon is called the "direct piezoelectric effect", and dielectrics with this effect are piezoelectrics [7]. The resulting polarization of the piezoelectric P (C/m^2) and surface electric charges with a density of σ (C/m^2) are directly proportional to the mechanical stress G (N/m^2) taking into account the polarity (direction of action) of the mechanical stress:

$$P = \sigma = \pm d \cdot G \tag{2.12}$$

where d = $10^{-10}...10^{-12}$ C/N is proportionality factor, called as the piezomodule.

The direct piezoelectric effect is used to convert mechanical stresses or strains into electrical signals for the manufacture of pickups, strain sensors, ultrasound receivers.

With the ***inverse piezoelectric effect***, there is a mechanical deformation of the crystal $\Delta l/l$ in proportion to the intensity E of the applied electric field:

$$\frac{\Delta l}{l} = \pm d \cdot E. \tag{2.13}$$

The reverse piezoelectric effect is used to convert electrical signals into mechanical vibrations for the manufacture of acoustic emitters, ultrasonic generators. Piezoelectrics used in practice can be divided into three groups: monocrystalline piezoelectrics, piezoceramics, and polymer piezoelectrics.

Monocrystalline piezoelectrics. The most commonly used single-crystal piezoelectric is quartz. Plates are cut out of quartz single crystal, their surfaces are ground, metal electrodes are sprayed on them and thus an electromechanical resonator with a high mechanical quality factor and a small value of $tg\delta \approx 10^{-4}$ is formed [7]. If an alternating voltage is applied to such a resonator, the frequency of which coincides with the frequency of natural mechanical oscillations, then strong mechanical oscillations of the resonant frequency occur, i.e. the inverse piezoelectric effect is manifested. Such plates are used as frequency stabilizers. Under a mechanical load on such a quartz plate with a pressure of 10^4 Pa, a potential difference of 6 mV occurs, i.e. a direct piezoelectric effect is manifested. In addition to monocrystalline quartz, single crystals of lithium sulphate, niobate and tantalate and ferric salt are also used, which have even better characteristics than that of quartz.

Piezoceramics – is polarized ferroceramics [7]. To provide ferroceramics with piezoelectric properties it is kept in a strong direct electric field with a voltage of 2 ... 4 MV/m at a temperature of 100 ... 150 ° C for about an hour [7]. After removing the field, the ceramic retains residual polarization and turns into the anisotropic state. Piezoceramics is mainly made of polycrystalline ferroelectric lead zirconate titanate $PbZrO_3$-$PbTiO_3$. Its main advantage over single crystals is the possibility to produce active elements of complex shape and any size. The disadvantage of piezoceramics is that the values of ε_r, $tg\delta$, and mechanical losses are too high, which makes it almost impossible to use it at high frequencies.

Polymer piezoelectrics. Piezoelectric effects can occur in films of some polymeric materials textured by drawing and polarized in a constant electric field. Polyvinylidene fluoride or fluoroplastic-2 is of practical interest among such materials [7]. When the film of this material is extracted by 300 ... 400%, a special conformation of polymer chains is formed, which acquire a piezoelectric effect in a strong electric field. Polymer piezoceramics is similar in properties to piezoceramics, but have the advantage of having about 4 times less density. This advantage and high flexibility make polymer piezoceramics a more promising material in the production of piezoelectric transducers.

2.6.3 Pyroelectrics

The pyroelectric effect is the ability of a material to change the spontaneous polarization ΔP_s when the temperature ΔT changes in the absence of an external electric field:

$$\Delta P_s \approx p \cdot \Delta T, \tag{2.14}$$

where p – is pyrocoefficient in C/(m^{2}K), which depends on the temperature T, reaches its maximum at $T \approx T_c$ and drops to zero at $T > T_c$.

This effect occurs in all ferroelectrics due to the dependence of the spontaneous polarization P_s on the temperature T at $T < T_c$, especially near the Curie point T_c. The pyroelectric effect is most manifested in the monocrystalline state of the ferroelectric, when the intrinsic electric fields of monodomain crystals are oriented mainly in one direction almost independently of the external electric field [7]. Unlike a conventional ferroelectric, the spontaneous polarization vector of a “perfect” pyroelectric cannot be changed by an external electric field until an electric breakdown state. Pyroelectrics are used in thermal detectors, including sensitive detectors of infrared radiation.

To obtain monodomain crystals the finished detector or grown single crystal is polarized by a constant electric field at a temperature of $T \ll T_c$ and the polarized state is fixed by irradiation, the introduction of certain volatile additives or the use of a pair of electrodes of different metals [7]. Doped or irradiated crystals of triglycine sulphate $(NH_2CH_2COOH)_3 \cdot H_2SO_4$ (p=360 μC/(m^{2}K), ε_r = 25) are used for the production of low-frequency detectors. The most stable pyroelectric properties are lithium niobate $LiNbO_3$ (p=51 μC/(m^{2}K), ε_r= 29) and lithium tantalate (p= 176 μC/(m^{2}K), ε_r = 43). The maximum pyroelectric coefficient p is peculiar to ferroelectrics with T_c values close to room temperature, for example, a solid solution of strontium-barium niobate (SBN) (p = 2800 μC/(m^{2}K), ε_r = 8200, T_c = 49 ^{O}C) or materials based on solid solutions of lead titanate and lead zirconate, which are doped with lanthanum to reduce T_c to room temperature (p = 1760 μC/(m^{2}K), ε_r= 3980).

Electrocaloric effect is the reverse pyroelectric effect, i.e. the ability of the material to change the temperature ΔT due to changes in the intensity ΔE of the external electric field:

$$\Delta T \approx q \cdot \Delta E, \tag{2.15}$$

where q – is coefficient of electrocaloric effect, which is proportional to the pyroelectric coefficient p and opposite in sign [7].

All pyroelectrics can show electrocaloric effect. When the external electric field strength ΔE changes, the spontaneous polarization ΔPs changes, which due to the electrocaloric effect leads to cooling or heating of the crystal in the conditions of the adiabatic process (in the absence of heat supply or removal). The crystal is heated if the sign q is positive and the electric field strength vector E coincides with the spontaneous polarization vector P_s, and is cooled if the vector E does not coincide with the vector P_s. The electrocaloric effect will be manifested to the maximum extent in the phase transition of the ferroelectric (at the temperature $T \approx T_c$), especially if T_c is room temperature.

2.6.4 Electro-optical materials

The electro-optical effect is a change in the dielectric constant ε_r, the refractive index *n*, and the scattering of light by the material under the action of an external electric field, thermal field, and pressure. Electro-optical materials are used in the production of active elements (modulators) designed to change the basic parameters of radiation in the optical range using an external electric field. As a technical characteristic of the electro-optical effect of materials a half-wave voltage $U_{\lambda/2}$ is used, at which the phase of light emanating from the crystal changes by 180^O [7]. Depending on the type of electro-optical effect there are electro-optical materials with linear, quadratic, and dynamic electro-optical effects.

Materials with a linear electro-optical effect have a linear dependence of ε_r and *n* on the electric field strength *E*. These include crystals of piezoelectrics and ferroelectrics that do not have a centre of symmetry [7]: crystals of potassium dihydrogen phosphate KH_2PO_4 (transparency region λ = 0.2 ... 1.35 μm, $U_{\lambda/2}$= 10 kV at λ = 0.546 μm), lithium niobate $LiNbO_3$(transparency region λ = 0.4 ... 0.5 μm, $U_{\lambda/2}$= 3 kV at λ = 0.546 μm), lithium tantalate $LiTaO_3$ (transparency region λ = 0.3 ... 0, 6 μm, $U_{\lambda/2}$= 1.5 kV at λ = 0.546 μm). In addition to the listed ferroelectric crystals, some crystals with a cubic structure similar to the diamond structure are also used: cadmium telluride *CdTe* (transparency region λ = 2 ... 28 μm, $U_{\lambda/2}$= 53 kV at λ = 0.546 μm), zinc sulphide *ZnS* (transparency region λ = 0.4 ... 12 μm, $U_{\lambda/2}$= 12 kV at λ = 0.546 μm), copper chloride *CuCl* (transparency region λ = 0.4 ... 20 μm, $U_{\lambda/2}$= 6 kV at λ = 0.546 μm). Such crystals are widely used as modulators of laser radiation.

Materials with a quadratic electro-optical effect do not depend on the sign of the applied voltage, but depend on the square of the electric field strength. These include crystals that have a centre of symmetry as well as some isotropic liquid media [7]: barium titanate $Ba\ TiO_3$ (transparency region λ = 0.4 ... 4.5 μm, $U_{\lambda/2}$= 0.5 kV at λ = 0.546 μm).

Materials with a dynamic electro-optical effect have a continuous chaotic change in the refractive index of light in dielectrics under the influence of an external electric field, and in some cases under the influence of thermal field and pressure. These materials include liquid crystals, which are in the intermediate state between solid crystalline and liquid isotropic states [7]. Liquid crystals, as well as ferroelectrics, have a domain structure. Therefore, a loop of dielectric hysteresis is manifested in an alternating electric field. At the point of phase transition, the dielectric constant ε_r has a maximum that disappears with increasing frequency. In liquid crystals, the reorientation of dipoles is slow compared to ferroelectrics, and therefore the maximum ε_r occurs at very low frequencies (less than 1 Hz). The structure of liquid crystals is very mobile, is easily changed under the influence of external energy (electric or magnetic field, temperature, pressure), which leads to changes in electrical and optical properties. This feature is the basis of some devices. The control electric field can be constant or variable at a frequency of 100 ... 10000 Hz. Since liquid crystals have a high resistivity ($\rho=10^6...10^{10}$ Ohm · m), their power consumption does not exceed 1 W/m^2, which is several orders of magnitude less than the power consumption of gas-discharge and phosphor indicators. Therefore, such materials are promising for use, especially in small computers.

2.6.5 Electrets

Electrets are solid dielectrics that are able to maintain a polarized state for a long time (residual polarization) and form an electrostatic field in the environment; similar to permanent magnets, which form a constant magnetic field in the environment [7]. An important characteristic of electrets is the surface charge density σ. The value of σ changes markedly in the first hours and even a few days after making the electret. Therefore, in practice, a constant value of σ is used, which is called the surface density of the stabilized charge. This characteristic is $10^{-6}...10^{-4}$ C/m^2 in different dielectrics.

The charge of the electret decreases over time, in particular due to electrical conductivity. The discharge time of an electret with a very high resistivity can be many years and even hundreds of years. The discharge rate of the electret increases with increasing ambient temperature and humidity.

If an electret plate of l_e thickness is placed between the covers of a flat capacitor, in which an air gap of l_a thickness is provided, the electric field strength in the air gap will be equal to [7]:

$$E = \frac{\sigma}{\varepsilon_0\left(1+\varepsilon_r\frac{l_a}{l_e}\right)}, \qquad (2.16)$$

where σ – is density of residual electric charges, C/m^2;

l_e, l_a – are the thickness of the plate of the electret and the air gap, m;

ε_0=8.85·10^{-12} F/m – is absolute dielectric constant of vacuum;

ε_r – is relative dielectric constant of the electret.

Natural dielectrics (wax, paraffin, rosin, amber, shellac, mica), synthetic polymers (polytetrafluoroethylene, polystyrene, polypropylene, polycarbonates, polyvinyl chloride), inorganic materials (sulphur, cadmium sulphide CdS, zinc sulphide ZnS, glass-ceramic materials), organic compounds (naphthalene $C_{10}H_8$), and ceramic titanium-containing materials can be used as electrets. For example, $CaTiO_3$-based ceramics can have the most stable residual charge [7]: σ = 80 ... 250 μC/m^2, ε_r= 150, ρ_v=10^{11} Ohm·m.

Depending on the method of manufacture, the following categories are known: thermoelectrets (heating before melting of crystalline or softening of amorphous substances followed by cooling in a strong electric field), electroelectrets (action of a strong electric field for several hours), coronaelectrets (action of corona discharge in the gas gap between dielectric surface and electrode, the most common industrial method), photoelectrets (the action of light and a constant electric field). Electrets are used as signal sensors or transducers: electret condenser microphones, pressure sensors, vibration sensors, tachometers, penetrating radiation dosimeters, barometers.

2.7 Exemplary tasks on dielectric materials study

2.7.1 Determination of dielectric polarization parameters

Task: To determine the electric field strength and energy, as well as dielectric losses in two different dielectrics that insulate the covers of a flat capacitor with an area of S = 1.6 m^2. The capacitor is connected to a sinusoidal current source with an operating voltage U = 100 V and a frequency f = 1 kHz. One of these dielectrics has a thickness l_1= 3 mm, the relative dielectric constant ε_1= 2 and the tangent of the dielectric loss angle $tg\delta_1$=10^{-3}, and the other dielectric is an air layer l_2= 1 mm thick.

Solution. The placement of dielectrics in series with the direction of electric field forces is two series-connected capacitors C_1 and C_2 (1.4):

$$C_1 = \frac{S\cdot\varepsilon_1\varepsilon_0}{l_1} = \frac{1{,}6\cdot 2\cdot 8{,}85\cdot 10^{-12}}{3\cdot 10^{-3}} = 9{,}44\cdot 10^{-9}(F);$$
$$C_2 = \frac{S\cdot\varepsilon_2\varepsilon_0}{l_2\cdot} = \frac{1{,}6\cdot 1\cdot 8{,}85\cdot 10^{-12}}{10^{-3}} = 14{,}16\cdot 10^{-6}(F).$$

The electric voltage U is distributed between the two sections U_1 and U_2 of the electrical insulation in direct proportion to the reactance of the two capacitors $X_1=1/\omega C_1$ and $X_2=1/\omega C_2$ (1.13), based on the Kirchhoff's second law $U \approx U_1+U_2$, $X \approx X_1+X_2$ and considering the very small value $tg\delta$:

$$U_1 = \frac{X_1 U}{X_1+X_2} = \frac{C_2\cdot U}{C_1+C_2} = \frac{14{,}16\cdot 10^{-9}\cdot 100}{9{,}44\cdot 10^{-9}+14{,}16\cdot 10^{-9}} = 60(V);$$
$$U_2 = \frac{X_2 U}{X_1+X_2} = \frac{C_1\cdot U}{C_1+C_2} = \frac{9{,}44\cdot 10^{-9}\cdot 100}{9{,}44\cdot 10^{-9}+14{,}16\cdot 10^{-9}} = 40(V).$$

The effective value of the electric field strength in each dielectric (1.3):

$$E_1 = \frac{U_1}{l_1} = \frac{60}{3\cdot 10^{-3}} = 20\cdot 10^3(V/\text{м});$$
$$E_2 = \frac{U_2}{l_2} = \frac{40}{10^{-3}} = 40\cdot 10^3(V/\text{м}).$$

The energy of the electric field between the covers of the capacitor (1.5):

$$W_e = C\frac{U^2}{2} = \frac{C_1\cdot C_2}{C_1+C_2}\cdot\frac{U^2}{2} = \frac{9{,}44\cdot 10^{-9}\cdot 14{,}16\cdot 10^{-9}}{9{,}44\cdot 10^{-9}+14{,}16\cdot 10^{-9}}\cdot\frac{100^2}{2} =$$
$$= 2{,}832\cdot 10^{-5}(J)..$$

Dielectric losses in the first dielectric (2.2):

$$P_1 = U_1^2\cdot 2\pi\cdot f\cdot C_1\cdot tg\delta_1 =$$

$$= 60^2 \cdot 2\pi \cdot 10^3 \cdot 9{,}44 \cdot 10^{-9} \cdot 10^{-3} = 0{,}21 \cdot 10^{-3} (W).$$

Dielectric losses in the air are very small and therefore can be neglected.

2.7.2 Determination of electrical conductivity parameters of dielectrics

Task: Determine the electric current consumed by a flat capacitor with covers 10x1000 mm, which are isolated from each other by a solid dielectric with a thickness of l = 0.1 mm. The dielectric has a relative dielectric constant ε_r= 3, a dielectric loss tangent $tg\delta$=10^{-3}, a specific volume resistivity ρ_v=10^8 Ohm·m, and specific surface resistivity ρ_s =10^{10} Ohm. Determine the electric current when connecting the capacitor to an electric source: a) of direct current with voltage U = 100 V; b) of sinusoidal current with an operating voltage U = 100 V and a frequency f = 400 Hz.

Solution.

a) In the case of connecting a capacitor to an electric source of direct current, the capacitor consumes only the volume I_v and surface I_s electric currents, which are determined, respectively, by the volume R_v and surface R_s resistances (2.9):

$$I_v = \frac{U}{R_v} = \frac{U}{\rho_v \frac{l}{S}} = \frac{100}{10^8 \frac{10^{-4}}{10^{-2}}} = 10^{-4} (A);$$

$$I_s = \frac{U}{R_s} = \frac{U}{\rho_s \frac{l}{L}} = \frac{100}{10^{10} \frac{10^{-4}}{(0{,}01 + 1) \cdot 2}} = 2{,}02 \cdot 10^{-4} (A).$$

Total electric current consumed by the capacitor at constant voltage (output current):

$$I_o = I_v + I_s = 10^{-4} + 2{,}02 \cdot 10^{-4} = 0{,}302 \cdot 10^{-3} (A).$$

b) In the case of connecting a capacitor to an electric source of sinusoidal current of the same voltage U = 100 V, the effective value of the output current I_o is the same as in previous calculations, i.e. I_o=3.02·10^{-4} A. This current coincides in phase with the sinusoidal voltage U, i.e. is active.

In addition to this current, the capacitor will consume the charging-discharging current I_c in accordance with the value of the reactive resistance $X=1/\omega C$ of the capacitor (1.13):

$$I_c = \frac{U}{X_c} = U\omega C = U\omega \frac{S \cdot \varepsilon_r \varepsilon_0}{l} =$$

$$= 100 \cdot 2\pi \cdot 400 \frac{10^{-2} \cdot 3 \cdot 8{,}85 \cdot 10^{-12}}{0{,}1 \cdot 10^{-3}} = 0{,}667 \cdot 10^{-3} (A).$$

The charging-discharging current I_c is ahead of the phase sinusoidal voltage U at an angle $\varphi=\pi/2-\delta = \pi/2-10^{-3} \approx \pi/2$, i.e. is essentially purely reactive. The total effective value of the sinusoidal current consumed by the capacitor (1.11):

$$I = \sqrt{I_o^2 + I_c^2} = \sqrt{(0{,}302 \cdot 10^{-3})^2 + (0{,}667 \cdot 10^{-3})^2} = 0{,}732 \cdot 10^{-3} (A).$$

2.7.3 Determination of electric breakdown parameters of dielectrics

Task: The covers of the flat capacitor are insulated by two dielectrics. One of these dielectrics has a thickness l_1= 1 mm, relative dielectric constant ε_{r1}= 15 and electrical strength E_{br1}= 20 MV/m, and the other dielectric is an air layer with a thickness of l_2= 0.5 mm, the electrical strength of which at this thickness is E_{br2}= 5 MV/m [6]. Determine two values of the electrical voltage u_{br} between the covers of such a capacitor, at which there will be a) partial breakdown and b) complete breakdown of its electrical insulation.

***Solution*.** At a given arrangement of two dielectrics (in series with the direction of electric field forces), the capacitor can be represented as two series-connected capacitors with capacitance C_1 and C_2 with different values of dielectric thickness, voltage, and electric field strength (see task 2.7.1).

The capacitances of these capacitors can be determined using the following formulae (1.4):

$$C_1 = \frac{\varepsilon_{r1}\varepsilon_0}{l_1} S; C_2 = \frac{\varepsilon_{r2}\varepsilon_0}{l_2} S; C = \frac{C_1 \cdot C_2}{C_1 + C_2} = \frac{\varepsilon_{r1}\varepsilon_{r2}\varepsilon_0}{\varepsilon_{r1} l_2 + \varepsilon_{r2} l_1} S.$$

The electric voltage u of the capacitor is distributed between the two parts of the dielectric is inversely proportional to the capacitance of the capacitors, based on the conditions $Q_1=Q_2$, $C_1u_1=C_2u_2$ and $u_1+u_2=u$:

$$u_1=\frac{C_2u}{C_1+C_2}=\frac{\varepsilon_{r2}l_1u}{\varepsilon_{r1}l_2+\varepsilon_{r2}l_1};u_2=\frac{C_1u}{C_1+C_2}=\frac{\varepsilon_{r1}l_2u}{\varepsilon_{r1}l_2+\varepsilon_{r2}l_1}.$$

The electric field strength in each of the dielectrics (1.3):

$$E_1=\frac{u_1}{l_1}=\frac{\varepsilon_{r2}l_1u}{(\varepsilon_{r1}l_2+\varepsilon_{r2}l_1)\cdot l_1}=\frac{\varepsilon_{r2}u}{\varepsilon_{r1}l_2+\varepsilon_{r2}l_1};.E_2=\frac{u_2}{l_2}=\frac{\varepsilon_{r1}l_2u}{(\varepsilon_{r1}l_2+\varepsilon_{r2}l_1)\cdot l_2}=\frac{\varepsilon_{r1}u}{\varepsilon_{r1}l_2+\varepsilon_{r2}l_1}.$$

From the given formulas and numerical data it is seen that the breakdown of the dielectric will occur primarily in the air layer, in which there is a greater electric field strength E_2 and which has a lower electrical strength E_{br2}. This breakdown can be called partial because it does not lead to a complete breakdown of the capacitor insulation. A partial breakdown will occur at a voltage between the covers of the capacitor $u \geq u_a$ provided $E_2 \geq E_{br2}$:

$$u \geq u_a = E_{br2}\frac{\varepsilon_{r1}l_2+\varepsilon_{r2}l_1}{\varepsilon_{r1}} =$$
$$= 5\cdot 10^6\frac{15\cdot 0{,}5\cdot 10^{-3}+1\cdot 1\cdot 10^{-3}}{15}=2833(V).$$

Due to the partial breakdown of the air layer at $u>u_a$, the entire voltage u will be applied to the first dielectric, and therefore the electric field strength in the first dielectric will be determined by another formula ($E_1=u/l_1$). A complete breakdown will occur at a voltage between the covers of the capacitor $u \geq u_b$ provided $E_1 \geq E_{br1}$:

$$u \geq u_b = E_{br1}l_1 = 20\cdot 10^6\cdot 1\cdot 10^{-3}=20000(V).$$

Thus, at a voltage between the covers of the capacitor u≥2833 V there will be a partial breakdown, and at u≥20000 V, a complete breakdown of its insulation.

2.7.4 Determination of parameters of active dielectrics

Task: An electret plate with a thickness of l_1 = 20 mm based on a titanium material $CaTiO_3$ with a dielectric constant ε_r = 150 received the residual electric charge with a density of σ = 200 μC/m^2 due to prolonged exposure to a strong electric field. This plate was placed between the metal parallel plates of a flat capacitor with some air layer of l_2 thickness in order to create an electrostatic field with a voltage of E_2= 1 MV/m. It is necessary to determine the thickness l_2 of the air layer.

Solution. To determine the thickness l_2 of the air layer of the condenser, we can use the formula (2.16):

$$E_2 = \frac{\sigma}{\varepsilon_0\left(1 + \varepsilon_r \frac{l_2}{l_1}\right)};$$

$$l_2 = \left(\frac{\sigma}{\varepsilon_0 E_2} - 1\right)\frac{l_1}{\varepsilon_r} = \left(\frac{200 \cdot 10^{-6}}{8{,}85 \cdot 10^{-12} \cdot 1 \cdot 10^6} - 1\right)\frac{20 \cdot 10^{-3}}{150}$$
$$= 2{,}9 \cdot 10^{-3} (m).$$

Thus, the thickness of the air layer should be 2.9 mm to obtain an electrostatic field with a voltage of 1 MV/m using a given plate of the electret.

2.8 Test questions on dielectric materials

1. What are the main properties of dielectric materials?
2. Identify the main differences between the dielectric and the conductor of electric current.
3. What physical laws regulate the process of dielectric polarization?
4. What is the dielectric constant of a dielectric?

5. In which cases does a dielectric with high dieectric constant have advantages?

6. What is the relationship between capacitor capacitance and dielectric constant?

7. Explain the scheme of experimental determination of dielectric constant.

8. Explain the influence of an alternating electric field on the behaviour of a dielectric. What is the electric bias current in the dielectric?

9. Explain the difference between the electric bias current in the dielectric of the capacitor and its charging-discharging current. How is the electric field force transmitted in space?

10. What causes the electrical conductivity of the dielectric?

11. What electric charges can create an electric current in a gaseous dielectric?

12. How to use the electrical conductivity of gaseous dielectrics?

13. How is the electrical conductivity of a gaseous dielectric related to the emission of electrons from the surface of the electrodes?

14. What is the difference between the electrical conductivity of liquid and gaseous dielectrics?

15. Explain the ability of very rarefied air or vacuum to perform the function of a dielectric and a superconductor simultaneously.

16. What is the difference between the electrical conductivity of solid dielectrics and the electrical conductivity of liquid and gaseous dielectrics?

17. What is the volume and surface conductivity of a dielectric?

18. Explain the principle of determining the volume and surface resistance of a solid dielectric.

19. At what voltage (constant or alternating) is it necessary to measure the resistance of dielectrics?

20. How can the polarization of a dielectric affect the results of measuring its resistance?

21. What is the dielectric loss?

22. What does the tangent of the dielectric loss angle characterize?

23. Which formulae can be used to determine dielectric losses?

24. How do frequency and electric field strength and dielectric constant affect the dielectric losses?

25. Explain the scheme of experimental determination of the tangent of the dielectric loss angle.

26. Explain the phenomenon of electric breakdown of the dielectric.

27. What is the electrical strength of a dielectric?

28. Explain the dependence of the electrical strength of the dielectric on its thickness.

29. Why is the electrical strength of gaseous dielectrics much less than the electrical strength of liquid and solid dielectrics?

30. Explain the dependence of the electrical strength of a liquid dielectric on its temperature and the content of water and other impurities.

31. Explain the scheme of experimental determination of the electrical strength of dielectrics.

32. What is the heat resistance of dielectrics?

33. Give examples of the distribution of electrical insulating materials for individual classes of heat resistance.

34. What is the practical significance of heat resistance of electrical insulating materials?

35. How does the temperature of the dielectric affect its basic functions?

36. Name the most important causes of dielectric heating.

37. What is the difference between the heat resistance of dielectrics and their thermal conductivity?

38. What is the practical significance of the thermal conductivity of dielectrics?

39. What is convection and what does it have to do with the thermal conductivity of a dielectric?

40. Name the most commonly used gaseous dielectrics.

41. What are the advantages of hydrogen as a dielectric over air?

42. Name the main advantages of electronegative gas in comparison with air.

43. Name the main advantages of liquid dielectrics over gaseous and solid dielectrics.

44. What materials are used to make liquid dielectrics?

45. Name the main advantages of solid dielectrics over gaseous and liquid dielectrics.

46. Why air cavities in solid dielectrics degrade the quality of dielectrics?

47. What is the benefit of impregnating solid dielectrics with liquid dielectrics?

48. Name the main components of plastics.

49. What is the difference between thermoplastic and thermosetting resins and polymers?

50. In what cases can oxide films be used as electrical insulation?

3 CONDUCTIVE MATERIALS

Conductive materials include metals and their alloys, carbon materials, solutions, electrolyte melts and ionized gases, which are used as conductors of electric current in combination with electrical insulating materials. The most widely used are hard metals and their alloys. High-conductivity metals with a resistivity of not more than 0.05 μOhm·m are used to make electric wires, cores of electric cables, windings of transformers and electric machines. Resistors and electric heating devices are made of high-resistance metals and alloys with a resistivity of at least 0.3 μOhm·m.

Some other materials and chemical compounds are also capable of performing electrically conductive functions if special conditions are created. We mean superconductors and cryoconductors in conditions of ultralow temperatures, as well as semiconductors under the influence of additional physical factors. Superconductors do not create resistance to electric current at all, and cryoconductors hardly create it. They have limited use due to the difficulty of creating conditions of ultralow (cryogenic) temperatures. Semiconductors are rapidly expanding their use in electrical engineering and especially in electronics due to their specific and controlled conductive properties.

3.1 Physical processes and phenomena in conductive materials

The main physical process in conductive materials is the movement of free charges (electrons and sometimes ions) under the action of electromotive forces. The electric current in metals in their solid and liquid state is due to the movement of only electrons, and therefore metals are conductors of the first kind. This current is accompanied by thermal, electric and magnetic fields, as well as emission and contact phenomena. The exception is superconductors, which do not emit thermal energy in the state of superconductivity.

In conductive materials of the second kind, not only electrons but also ions move as carriers of matter. Therefore, the electric current in the conductor of the second kind is additionally accompanied by the movement of the substance, the deposition of this substance on the supplied electrodes, and the change in the chemical composition of this conductor. Conductors of the second kind or electrolytes include aqueous, acidic and alkaline solutions of various substances and melts of crystalline substances with an ionic structure. Conductors of the second kind also include vapours of liquids and metals and highly ionized gas (plasma), provided that the electric field strength exceeds the intensity of shock or photon ionization.

In semiconductor materials there are two types of electrical conductivity: electronic *(n*) and electron-hole (*p*). This allows semiconductors to create a variety of electronic products with control *p-n* junctions.

3.1.1 Active resistance of conductive materials

The electrical resistance, which is due to the change in time of the thermal field energy, is referred as the active resistance *R*, and the corresponding voltage drop is called the active voltage drop u_a (see section 1.2). The active resistance *R* of the conductor occurs at both direct and alternating electric current. It is due to the resistance of microparticles of this conductor and takes into account the process of allocation (change in time *t*) of thermal energy

$$W_T=f(t)=Pt=I^2Rt.$$

Measurement of active resistance *R* is usually carried out at direct current *I* by the method of ammeter and voltmeter, followed by its calculation $R=U/I$ (1.9). If one need to determine the resistivity of the conductor wire ρ by the value of *R* (2.9), then to measure *R* it is necessary to exclude the influence of the transient resistance in the contacts and create the same electric current density at all points of the wire within its length *l* (Fig. 3.1).

The transient resistance in the power terminals 1 and 2 of the conductor connection to the current source and the uneven distribution of the current density almost does not affect the results of measuring the resistance *R* if potential terminals 3 and 4 for voltage *U* measuring are at a sufficient distance Δl from terminals 1 and 2. The conductor must have a constant

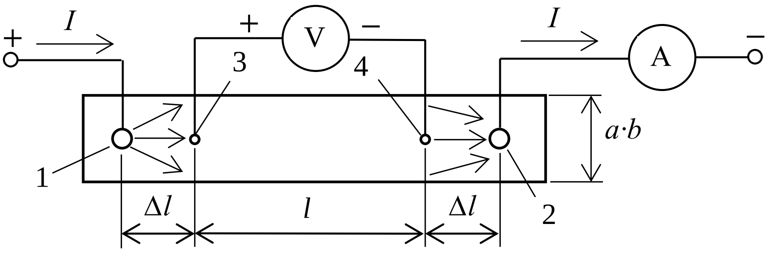

Figure 3. 1– Diagram of measuring the active resistance *R* of a conductor at direct current

cross-sectional area *S* in the area between the potential terminals 3 and 4 to ensure the consistency of the electric current density. The resistivity ρ (Ohm · m) can be determined by the following formula (2.9):

$$\rho = R\frac{S}{l}, \quad (3.1)$$

where S – is cross-sectional area of the sample of conductive material, m^2;

l – is the distance between the potential terminals 3 and 4 for measuring the voltage *U*, m;

$R=U/I$ – is active resistance of the sample of conductive material as a result of measurement by the method of ammeter and voltmeter (Fig. 3.1).

With four terminals (Fig. 3.1) the special measuring shunts are also made. They measure the electric current by measuring voltage drop *U* at the terminals 3 and 4 with a sufficiently sensitive voltmeter followed by current determination using the formula $I=U/R$. Some ammeters have built-in measuring shunts.

Influence of temperature on resistivity ρ of most conductive materials is quite significant and has the proportional nature (Fig. 3.2).

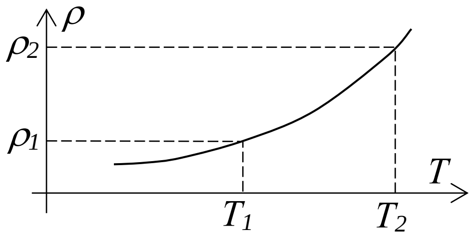

Figure 3.2 – Influence of temperature *T* on resistivity ρ of conductive material

When the temperature T changes slightly, a piecewise linear approximation of the nonlinear dependence ρ on T is allowed:

$$\rho_2 \approx \rho_1[1 + \alpha_\rho(T_2 - T_1)], \tag{3.2}$$

where ρ_1, ρ_2 – is resistivity of conductive material (Ohm·m) at a temperature of T_1 and T_2, respectively; (in Kelvin ^{O}K or Celsius ^{O}C degrees);

α_ρ – is the average temperature coefficient of resistivity (K^{-1}) in the temperature range $T_1 \ldots T_2$ (table. 3.1).

In most metals during the transition from solid to liquid state the resistivity increases significantly due to a decrease in the density of the molten metal. For example, the coefficient of resistivity increase at melting makes 2.4 for copper and 1.64 for aluminium [6]. Exceptions are gallium *Ga* and bismuth *Bi,* in which the transition from solid to liquid state the resistivity is increased significantly due to density decrease of the molten metal.

Table 3.1 –The main conductive properties of some metals at 20^{O}C [9]

Metal	Density d, g/sm^3	ρ, μOhm·m	α_ρ, K^{-1}	$T_{melting}$, ^{O}C	The work A of the electron output, eV	Absolute specific thermo-EMF ψ, μV/K
Silver, *Ag*	10.49	0.015	0.0041	961	4.3	+1.5
Copper, *Cu*	8.92	0.0170	0.0043	1083	4.4	+1.8
Aluminium, *Al*	2.70	0.026	0.0041	660	4.25	-1.3
Tungsten, *W*	19.3	0.055	0.0050	3400	4.54	+2.0
Cobalt, *Co*	8.85	0.064	0.0060	1500	4.41	-20.1
Nickel, *Ni*	8.96	0.068	0.0067	1453	4.5	-19.3
Iron, *Fe*	7.87	0.097	0.0062	1540	4.31	+16.6
Platinum, *Pt*	21.45	0.098	0.0039	1770	5.32	-5.1
Tin, *Sn*	7.29	0.113	0.0045	232	4.38	-1.1
Chrome, *Cr*	7.19	0.13	0.0024	1900	4.58	+18
Lead, *Pb*	11.34	0.19	0.0042	327	4.0	-1.2
Mercury, *Hg*	13.5	0.958	0.0009	–39	4.52	+8.1
Bismuth, *Bi*	9.80	1.16	0.0042	271	4.4	-75

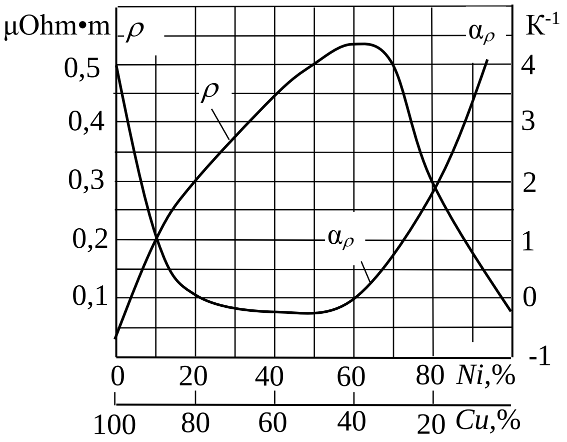

Figure 3.3 – Dependence of ρ and α_{ρ} of copper-nickel alloy on its composition [6]

Resistivity of alloys depends not only on the concentration of their components, but also on the formation of the structure of the cooling alloy. If two metals are fused in the form of a joint solution, then when it hardens, a common crystal lattice is created. In such cases, the resistivity can increase significantly with the formation of the extreme dependence of ρ and α_{ρ} on the content of one of the components of the alloy. Fig. 3.3 shows the following dependence demonstrating the example of an alloy of copper Cu and nickel *Ni*.

If separate crystal lattices are created during solidification of an alloy of two metals, the specific resistance depends on the content of one of the components of the alloy approximately linearly [6].

Influence of current frequency on active resistance of conductor due to the effect of displacement of alternating electric current to the conductor surface (skin effect). Figure 3.4 shows a diagram that explains this effect in the case when there are no closed magnetic circuits around the conductor.

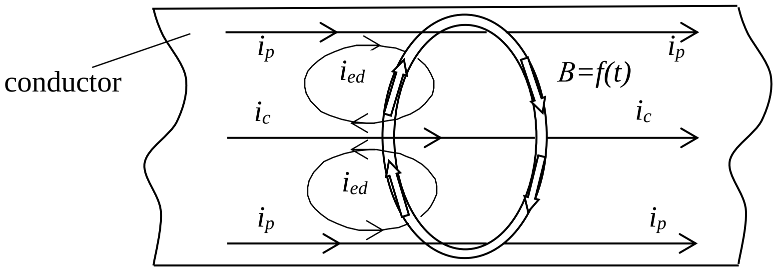

Figure 3.4 – The scheme of displacement of alternating current on the surface of the conductor

To explain this effect we consider alternating (sinusoidal) currents in the central i_c and peripheral i_p parts of the electrical conductor, which are represented by vectors. These currents cause closed lines of alternating magnetic induction $B = f(t)$ according to the right-hand Ampere's rule in a plane perpendicular to the current vectors (see section 1.2). Magnetic induction $B = f(t)$, in turn, according to the law of electromagnetic induction (1.22), causes electromotive forces and eddy currents i_{ed} in planes perpendicular to the vector of magnetic induction. These currents are proportional to dB/dt, and therefore proportional to the frequency of the current.

In fig. 3.4 we can see that the eddy currents i_{ed} are directed towards the current i_c in the central part of the conductor and coincide in direction with the currents i_p in the peripheral part of the conductor. Thus, conditions are created for displacing the current from the central part of the conductor i_c to its surface, which leads to an increase in the active resistance of the conductor in proportion to the frequency of the electric current. Therefore, at a very high frequency due to the skin effect, it is advantageous to use conductors of tubular (coaxial) type or multicore conductors with very thin insulated cores.

In electric machines with closed magnetic circuits around the conductors with alternating current, the skin effect is manifested in a slightly different way. This is due to the fact that the lines of magnetic induction $B = f(t)$ are closed mainly in magnetic circuits due to their high magnetic permeability. A typical example of the use of this effect is an induction motor with a short-circuited rotor, in the conductors of which the current is displaced towards the outer surface of the rotor during the start of the motor. This improves the starting conditions of such a motor.

3.1.3 Reactive resistance of conductive materials

The electrical resistance, which is due to the sinusoidal current and the corresponding change in time of the energy of the electric or magnetic field is called reactive resistance (see sections 1.2 and 1.3). The reactive resistance that is associated with a change in the energy of the electric field is called the capacitive resistance $X_c=1/\omega C$, and the corresponding voltage drop is called the capacitive voltage drop u_c (1.13). Reactive resistance, which is associated with a change in the energy of the magnetic field, is called the inductive resistance $X_L=\omega L$, and the corresponding voltage drop is called the inductive voltage drop u_L (1.25).

Reactive resistance is not directly related to the properties of the conductor material and its insulation, and is determined only by the geometric parameters of the electrical conductor and its individual parts. Reactive resistance can only indirectly affect the results of determining the properties of the conductor material in the case of using alternating current or voltage. For example, if there is a need to determine the active and reactive resistance of the conductor under the action of sinusoidal current, it is necessary to take into account the dependence of electric current not only on active resistance R (Fig. 3.1), but also on inductive resistance X_L and capacitive resistance X_c. To do this in addition to the ammeter and voltmeter an additional device wattmeter is required (Fig. 3.5).

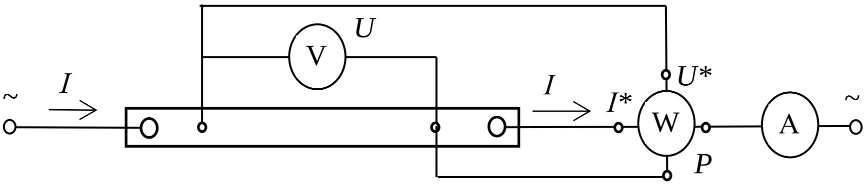

Figure 3.5 – The scheme of measurement of active and reactive resistance at alternating current

According to the measurement results according using the scheme 3.5, you can determine the active resistance R and reactive resistance X using the following formula (1.10):

$$R = \frac{P}{I^2} = \frac{U^2}{P}; X = \sqrt{\frac{U^2}{I^2} - R^2}, \qquad (3.3)$$

where I, U – are effective (rms) values of sinusoidal current and voltage (1.11);

P – is active power (wattmeter readings).

If the current changes according to a non-periodic law, then the concept of reactive resistance becomes incorrect, because the it is relevant only for the sinusoidal law of change of current and voltage.

3.1.3 Equivalent circuits of electrical conductors

There are several equivalent circuits of the conductor of electric current depending on its geometrical parameters, frequency of electric current, and some other circumstances. The equivalent circuit of the conductor has the simplest form if the electric current does not change over time or if its changes are not accompanied by significant changes in the energy of the magnetic or electric field (Fig. 3.6, *a*). In this case, only the energy of the thermal field is manifested, which in the equivalent circuit is taken into account by the active resistance *R*.

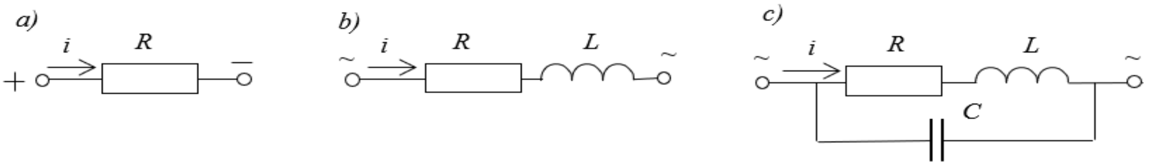

Figure 3.6 – Equivalent circuits of an electrical conductor

If there is an alternating electric current in the conductor, then the energy of the magnetic field is additionally manifested due to its changes. To take into account the manifestations of the magnetic field in the equivalent circuit of the conductor inductance *L* is introduced (Fig. 3.6, *b*). This circuit is commonly used in the manufacture of an inductor coil or a low-frequency electric choke from a conductive wire. Sometimes it is necessary to use this circuit even at a direct current if the conductor opens or closes. If there is a high frequency current in the conductor of the inductor coil or when the current has significant high-frequency components, it is necessary to take into account the electric field. For this purpose capacity *C* is used in the equivalent circuit of the conductor (fig. 3.6, *c*).

If the electrical conductor systems are used that are closely related through magnetic and electric fields, special equivalent electrical circuits are used. Long overhead and especially cable power lines, transformers, electric machines, switching electronic systems, and high-frequency lines with parameters distributed in space are the examples of such systems.

3.1.4 Emission and contact phenomena in metals

Electron emission is a phenomenon of electrons coming out of the metal surface. There are a lot of practically free electrons in the metal. It takes almost no energy to move them. But to go beyond the metal each electron still needs to do some work A to overcome the potential barrier (potential difference φ) at the metal-vacuum boundary:

$$A = q_e \cdot \varphi = W_{vac} - W_F, \tag{3.4}$$

where q_e=1.602×10^{-19} C – is modulus of charge of the electron (its sign is negative);

W_{vac} – is electron energy in vacuum;

W_F – is electron energy in the highest filled level of solid metal at a temperature of absolute zero on the Kelvin scale (Fermi level).

The potential barrier φ is due to the forces of attraction of an electron to an atom or molecule, which at the exit of the electron becomes a positive ion ("hole"), as well as the forces of repulsion of those electrons that have already left the metal and formed an electron cloud near the surface. The work A of the electron leaving the surface of most pure metals at a temperature of + 20 ° C is about 4 eV (electron volts) (Table 3.1). The emission of electrons at such a low temperature is called cold (autoelectronic) emission. For some alloys and metal oxides, the value of A can be much smaller, which allows them to be used to cover pure metal and thus create more favourable conditions for the practical use of electron emission. For example, if a layer of alkaline earth metal oxide (gallium Ga, strontium Sr, barium Ba) is applied to the surface of tungsten W, the work for leaving A will decrease from 4.54 eV to 1.2 ... 2 eV, and the emission electron flux density will increase by several orders [7].

Electron emission into vacuum is used in various vacuum electronic devices (see section 2.2). In these devices, the air is almost completely pumped out so that it does not interfere with the movement of emission electrons. Hot (thermoelectronic) emission is used to reduce the electric field strength and increase the flux density of emission electrons to acceptable values. To do this the metal surface (emitter or cathode) is heated to a temperature of 1700 ... 2200 ^{O}C.

Contact potential difference occurs when two different metals come into contact with each other. Therefore, an electric field is formed in the space surrounding the metals. The reason for this phenomenon is the different value of the work A of the electron leaving and the different concentration of conduction electrons in different metals. When different metals come into contact, part of the conduction electrons passes from the metal with less work A charging it positively, to another metal charging it negatively. The contact potential difference φ_{12} of two contacting metals according to the classical electronic theory can be calculated using the formula:

$$\varphi_{12} = \varphi_2 - \varphi_1 + \frac{kT}{q_e} ln \frac{n_1}{n_2}, \tag{3.5}$$

where φ_1, φ_2 – is the potential barrier for the electron to go beyond the first and second metals, respectively (3.4);

n_1, n_2 – is the concentration of conduction electrons in the first and second metals respectively (2.10);

$k = 1.3806488 \cdot 10^{-23}$ J/K – is the Boltzmann physical constant, which determines the relationship between temperature and energy;

T – is the temperature of the two metals at the point of contact (in Kelvin degrees).

Thermoelectric force. Seebeck effect

To measure the contact potential difference φ_{12} (3.5) another contact is required to create a closed measuring circuit, i.e. at least a pair of soldered contacts (junctions) is required. If the temperatures of these junctions T_1 and T_2 are the same ($T_1=T_2=T$), then the sum of the two contact potential differences U_{12} in this circuit according to (3.5) will be zero ($U_{12}=\varphi_{12}+\varphi_{21}=0$). If $T_1 \neq T_2$, then the sum of the two contact potential differences U_{12} in this circuit (thermoelectric force) according to (3.5) will be different from zero (Fig. 3.7) [6]:

$$U_{12} = \varphi_2 - \varphi_1 + \frac{kT_1}{q_e} ln\frac{n_1}{n_2} - \varphi_2 + \varphi_1 + \frac{kT_2}{q_e} ln\frac{n_2}{n_1} =$$
$$= \frac{k}{q_e} ln\frac{n_1}{n_2}(T_1 - T_2) \approx \psi_{12} \cdot (T_1 - T_2), \qquad (3.6)$$

where $\psi_{12}=k/q_e \cdot \ln(n_1/n_2)$ – is the relative specific thermoelectric force (thermo-EMF) for the selected pair of conductors or semiconductors (thermo-EMF coefficient or Seebeck coefficient), V/K;

T_1–T_2=ΔT – is the temperature difference between the two joints, K.

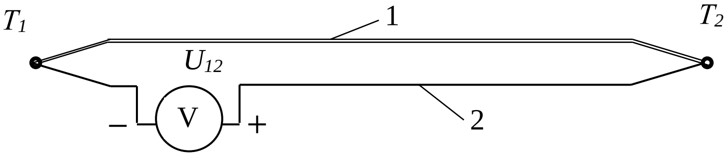

Figure 3.7 Thermoelectromotive force in a thermocouple

The sign of approximate equality in formula (3.6) is due to the fact that it does not take into account the electrothermal effect of Thomson. A more accurate formula for determining the thermoelectric force is [9]:

$$U_{12} = \int_T^{T+\Delta T} \psi_{12} dT \approx \psi_{12} \Delta T. \qquad (3.7)$$

Considering the feasibility of an absolute reference frame of the specific thermoelectromotive force, the coefficient ψ_{12} can be represented as follows:

$$\psi_{12} = \psi_1 - \psi_2 = \psi_{13} - \psi_{23}, \qquad (3.8)$$

where ψ_1 and ψ_2 are absolute specific thermo-EMF separately for the first and second conductors or semiconductors of the selected pair.

The final part of formula (3.8) means that the thermo-EMF of one substance relative to another one can be determined not only by the absolute specific thermo-EMF given in the reference books, but also by the relative specific thermo-EMF relative to the third substance. Reference data on the absolute specific thermo-EMF should be used as follows. If you need to determine the value of the specific thermo-EMF, for example, nickel relative to copper (Table 3.1), you need to subtract from the absolute specific thermo-EMF of Nickel (–19,3) the absolute specific thermo-EMF of copper (+1,8) and get ψ_{12} = (–19.3) - (+1.8) = –21.1 (μV/K).

The Seebeck effect, discovered in 1826, is often used to control temperature using a so-called thermocouple, a specially selected and insulated pair of metal conductive wires. Using a thermocouple you can determine the temperature T_2 of the second junction by measuring the voltage U and knowing the Seebeck coefficient ψ_{12}, and the temperature T_1 (3.6). Thermocouples are also used to increase the safety of household gas stoves: to turn off automatically the gas valve in the case of uncontrolled extinguishing of the gas burner flame, which is accompanied by the lack of thermo-EMF and electric current in the thermocouple.

The Seebeck effect is also used for direct (machine-free) conversion of thermal energy into electricity using thermoelectric generators. For constant operation of the thermoelectric generator under load R it is necessary to provide good thermal contact of joints of conductors of the first 1 and second 2 types with two environments with the sufficient difference of temperatures T_1-T_2 (fig. 3.8).

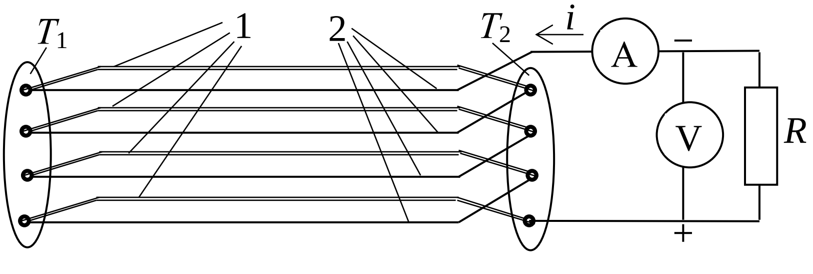

Figure 3.8 – Scheme of a thermoelectric generator

Various heat sources are used to supply heat to hot junctions and maintain the required temperature difference T_1-T_2: solar concentrators, fossil fuels, radioactive isotopes, and even nuclear reactors.

The Seebeck effect as a natural phenomenon can manifest itself on a planetary scale. The temperature and structural inhomogeneity of the Earth according to this effect causes thermo-EMF and the corresponding electric current in the Earth. This current results in the Earth's protective magnetic field, which deflects the flow of fast and high-energy charged particles of the Sun (solar wind of speed of 300 ... 1200 km/s) as they approach the Earth's atmosphere by means of the Lorentz force, and thus saves air, water, and life on Earth.

Peltier electrothermal effect – is a phenomenon of heat release or absorption by contacts of two different conductors or semiconductors when a direct electric current passes through them. The Peltier effect was discovered in 1834. This phenomenon is the opposite of the phenomenon of thermoelectromotive force (Peltier effect is inverse to the Seebeck effect). Therefore, the effect of the Peltier effect can be demonstrated similarly to the demonstration of the Seebeck effect (Fig. 3.7 and 3.8) with the only difference that electrical energy is not obtained from thermocouples, but on the contrary is supplied to them from the source.

The Peltier effect can be explained by the existence of a contact potential difference at the contact of two different conductors or semiconductors, i.e. an electric contact field (3.5). If the electric current flows against the direction of the contact field, the external current source must spend the additional energy. This energy will be spent on heating the contact. If the electric current flows in the direction of the contact field, then this field maintains the electric current, i.e. performs the work of charges moving. The energy required for this will be taken from the conductor and cools the contact. Thus, the electric current transfers heat from one side of the Peltier element to the opposite side creating a temperature difference.

The amount of heat Q that is released or absorbed in contact during the passage of current I, is proportional to the value of the current and the time t of its flow:

$$Q = \Pi \cdot I \cdot t, \tag{3.9}$$

where $\Pi = \psi T$ – is Peltier coefficient, which is easier to determine using the coefficient ψ of thermoelectromotive force (3.6) according to the second Thomson ratio (3.12).

The Peltier effect is more noticeable in semiconductors and is therefore more often used in semiconductor elements (in Peltier elements). Despite their low efficiency, Peltier elements are used for cooling refrigerator freezers, infrared sensors, diode lasers and a variety of electronic and computer devices. An example of improving the efficiency of Peltier elements is the combination of a refrigerator and an electric stove in a single device, in which cold contacts are placed in the freezer, and hot contacts, next to the heating elements of the electric stove. Peltier elements consist of several pairs of semiconductor parallelepipeds with electronic *(n)* and electron-hole *(p)* electrical conductivity, usually bismuth telluride Bi_2Te_3 and germanium-silicon compounds.

Thomson's electrothermal effect – is the phenomenon of heat release or absorption when electric current passes through an in homogeneously heated conductor. If along the conductor with an electric current *I* there is a temperature difference ($\Delta T=T_1-T_2$), then in addition to the Joule thermal energy $W=I^2Rt$ (1.10) additional heat Q_T, called Thomson heat, is released or absorbed in the volume of the conductor for some time *t*:

$$Q_T = \sigma \cdot I \cdot \Delta T \cdot t, \tag{3.10}$$

where σ – is Thomson coefficient, which depends on the nature of the conductor.

In the differential form the amount of heat dQ_T emitted during time *dt* on the segment *dx* of the conductor of *dV* volume is determined by the ratio:

$$dQ_T = -\sigma \cdot \nabla T \cdot J \cdot dt \cdot dV, \tag{3.11}$$

where $\nabla T = \frac{dT}{dx}$ – is the temperature gradient of the conductor along its length *dx*;

$J=dI/dS$ – is electric current density;

$dV=dS\cdot dx$ – is elementary volume of the conductor.

When charge carriers (conduction electrons) pass through a segment of inhomogeneously heated conductor or semiconductor, for example, from the region of high temperature T_1 with higher energy of electrons to the region of low temperature T_2 ($\Delta T=T_1-T_2>0$) electrons transfer excess energy and heat this segment additionally. In the opposite direction of electron transfer from the region of low temperature T_2 to the region of high temperature T_1, the electrons replenish their energy due to the surrounding atoms and therefore cool this segment of the conductor.

Thomson phenomenon was discovered in 1856. It is an absolute phenomenon by its nature, because it does not require contact of different materials (unlike other electrothermal phenomena). This allowed Thomson, based on the first and second principles of thermodynamics, to relate three electrothermal effects (to link the coefficients of Seebeck ψ, Peltier Π, and Thomson σ) and to introduce an absolute frame of reference for the specific thermoelectromotive force ψ (Table 3.1) for each conductor or semiconductor separately:

$$\sigma = T\frac{d\psi}{dT}; \Pi = T \cdot \psi = \int_0^T \frac{\sigma}{T} dT, \tag{3.12}$$

where T – is the absolute temperature of the conductor or semiconductor at the point of contact in Kelvin degrees, K.

The Thomson effect in comparison with the Peltier effect and Joule's law is manifested to a small extent due to the relatively small values of the Thomson coefficient σ under the normal conditions. For example, for bismuth at room temperature, the coefficient σ reaches only ~10^{-5} V/K. Therefore, the result of the Thomson effect is taken into account only with increased requirements for the accuracy of measurements or calculations.

3.1.5 Stray currents

Stray currents are usually called those currents that occur in the ground. Among the causes of these currents we consider only those that occur as a result of electrical contact with metal conductors with electric current and are associated with human activities.

Stray currents are caused by electrical contact of conductors with electric current and the ground. Contact of conductors with the earth is allowed usually when it is necessary for safety reasons of the electric equipment operation: for protective grounding of the electric equipment and equalization of electric potential of its external case with electric potential of the earth. This grounding must be sufficiently reliable (with the minimum possible transient resistance) to exclude accidental electric shock. The stray currents arising in such cases are certainly useful, because due to these currents the potentials of the hull and ground are equalized. A fairly common source of stray currents is rail electric transport, in which rail tracks are used as conductors of electric current and are in direct electrical contact with the ground. When an electric current I flows in a rail track that has an electrical resistance R_r, a voltage drop $\Delta U = I_r \cdot R_r$ occurs according to Ohm's law (1.9). In turn, the rail track due to the presence of voltage drop ΔU is a source of stray currents I_{st} in the ground.

The most negative consequences of stray currents occur on rail electric vehicles, where direct or rectified current is used. Under the influence of these currents the electrochemical corrosion of those areas of above-ground and underground metal structures that are in moist soil and from which stray currents I_{st} emanate is significantly accelerated. Such areas are called anode zones. The matter of fact is that in moist soil being the electrolyte not only negative electrons are the carriers of electric charges, but also positive ions. Moreover, ions are also carriers of a substance that is part of the mentioned metal structures. Therefore, the participation of ions in stray currents means the gradual movement of matter in the anode zones of metal structures into the ground, i.e. their accelerated corrosion and destruction and a significant reduction of their service life. The most expensive and important industrial facilities that are negatively affected by stray currents include tunnels, main metal pipelines, rails and supports on railways, cable power lines, and underground structures in large cities. Stray currents can also create a difference in electrical potentials between individual parts of metal structures in any place, including places far from the rail electric vehicles, and cause explosive sparks when accidentally closing and opening these parts. Explosive gas, gasoline, oil, coal and textile dust, explosives, and other flammable and explosive substances may be found in such places. Therefore, gas, oil refining, coal, chemical and other similar explosive enterprises need not only to reduce the average annual level of stray currents, but also to prevent dangerous potentials of stray currents at any time.

Limitation of stray currents and their potentials. The active methods of limiting stray currents, which involve the use of additional controlled DC sources to compensate the voltage drops on certain sections of the railway or in additional parallel cables, are the most effective. To protect tunnels, as the most important structures, from the corrosive effects of stray currents, the so-called tunnel protection is used. It provides for the inclusion of track current sources into the electrical break of the railway track in accordance with the current in the tunnel section. To protect all sections of the track and reduce stray currents and their electrical potentials to a safe level, an additional electrical cable is used, which connects these sections with the "minus" of the traction substation through additional controlled current sources.

3.2 Metals of high electrical conductivity

3.2.1 Copper and its alloys

Copper Cu is obtained by processing sulphide ores. In terms of electrical conductivity, copper is second only to silver (Table 3.1). Copper has high mechanical strength and corrosion resistance, is easily drawn into a wire of small diameter, well soldered. Copper is more often used in the soft state, which is obtained after annealing at a temperature of + 270 ° C, followed by cooling. Soft copper has 3 ... 5% higher electrical conductivity than hard copper. Standard copper in the annealed state has resistivity ρ= 0.017241 μOhm·m. Impurities reduce the electrical conductivity of copper significantly. Therefore, for use in electrical engineering, it must be subjected to electrolytic purification. Copper of M1 grade has no more than 0.1% of impurities; and grade M0, no more than 0.05%. The purest is M006 copper, which has no more than 0.01% of impurities and is smelted in vacuum induction furnaces.

Various copper alloys are used to obtain special or additional properties. Among these alloys, the most well-known and commonly used are bronze and brass.

Bronze – is an alloy of copper with impurities in small quantities. Tin Sn, phosphorus P, zinc Zn, lead Pb, nickel Ni, aluminium Al, manganese Mn, iron Fe, beryllium Be, titanium Ti, silicon Si, magnesium Mg, cadmium Cd can be used as these impurities. Bronzes are marked with the letters C, followed by letters and numbers that indicate the alloying elements and their content in per cent. Beryllium bronze ($CuBe_2$) contains 2% beryllium, it is used to make membranes and elastic contacts in electrical devices. Cadmium bronze (*CuCd1*) contains 1% cadmium, it is used to make contact wires on electric vehicles and collector plates. Phosphor bronze (*CuSnP6.5-0.15*) contains 6.5% of tin and 0.15% of phosphorus, is used for production of current-carrying springs in electric devices.

Brass – is a copper alloy in which the main alloying element is zinc Zn in the amount of up to 45%. It is much more ductile and cheaper than copper, and therefore is widely used in electrical engineering for the manufacture of live parts by stamping. To improve certain properties a small amount of other elements: tin, lead, manganese, nickel or aluminium is introduced in some grades of brass. Brass is marked with the letter Л and a number indicating the percentage of copper. For example, Л63 brass contains 63% copper and the rest is zinc. By the way, brass of this grade has the maximum plasticity. In brass of complex composition, the marking indicates the alloying element.

3.2.2 Aluminium and its alloys

In terms of electrical conductivity, aluminium ranks third after silver and copper being only 1.53 times worse than copper (Table 3.1), and in terms of density it is in the first place (3.3 times lighter than copper). Aluminium conductor is twice as light as copper one with the same resistance. Therefore, aluminium has significant advantages over other conductive materials, especially considering the relatively low cost of aluminium. The low mechanical properties of aluminium are sometimes compensated by the additional steel conductors. In particular, high-voltage power lines steel-aluminium conductors are used.

Aluminium is obtained by dissolving pure alumina Al_2O_3 in molten cryolite and at a temperature of ~ 950^{O}C by electrolysis: aluminium is isolated from it. Primary purification of aluminium by blowing chlorine through its melt can reduce the amount of impurities in aluminium to 0.3%. Further reduction of impurities to 0.01% is possible with electrolytic refining of aluminium. Technically pure aluminium grades A85, A8, A7, A6, A5, and A0 contains at least 99.85%, 99.8%, 99.7%, 99.6%, 99.5% and 99.0% of aluminium, respectively. Chemically pure aluminium branded A995, A99, A97, and A95 contains at least 99.995%, 99.99%, 99.97% and 99.95

of aluminium, respectively. Especially pure A999 aluminium contains at least 99.999% of aluminium. Ultrapure aluminium with a purity of 99.9999% (up to 0.0001% of impurities) is produced using the method of zone melting for semiconductor technology. Especially pure and ultrapure aluminium is used as a cryoconductor with very low resistivity. For example, at 20^{O}K its resistivity decreases in 2000 ... 6000 times [6].

Aluminium is a very active metal that is rapidly oxidized in air and is covered with a thin and dense Al_2O_3 oxide film. This film normally protects the inner layers of aluminium from further oxidation (corrosion) and can even perform electrical insulating functions. In the case of this film destroying, for example, under the influence of an electric arc when the conductor is opened, the process of oxidation of aluminium energetically supports the combustion of the arc. Therefore, aluminium must not be used in case of fire or explosion threat. The ability of aluminium to active oxidation and strong heating is used in metallurgy in the form of iron-aluminium termite: a powdered mixture of aluminium (25%) and iron oxide Fe_2O_3 (75%).

Aluminium has a negative absolute specific thermoelectric force (Table 3.1). Therefore, aluminium wire in contact with copper or steel wire creates galvanic vapour. In this pair, aluminium is the anode and therefore in the presence of moisture is prone to accelerated electrochemical corrosion, especially in the presence of electric current.

Among the electrotechnical aluminium alloys, the most well-known is aldrey, which in addition to aluminium contains magnesium Mg (0.3 ... 0.5%), silicon Si (0.4 ... 0.7%) and iron Fe (0.2..0.3%). This alloy is almost not inferior to pure aluminium in terms of electrical conductivity, and in terms of mechanical properties it is close to copper [6].

3.3 Superconductors

Superconductors differ from conventional electrical conductors by extremely low resistivity at low (cryogenic) temperatures. Superconductivity was discovered by the Dutch scientist Kammerling-Onnes in 1911.

3.3.1 The nature of superconductivity

Superconductivity as a phenomenon is the transition of some conductors of electric current from the normal state to the state of superconductivity at very low temperature $T<T_c$ and magnetic induction $B<B_c$, where T_c and B_c are called critical temperature and critical magnetic induction. Conductive materials with this property are called superconductors. Their specific electrical resistivity in the superconducting state has an extremely small value $\rho<5\cdot 10^{-24}$ Ohm · m, which cannot be measured and is therefore considered as zero. The state of superconductivity disappears if the temperature T of the superconductor or if the magnetic induction on its surface B exceeds the critical value ($T>T_c$ or $B>B_c$).

The temperature of superconductor T does not depend on the electric current I in it due to the zero value of the resistivity ρ (1.10). Therefore, the condition for the existence of superconductivity ($T<T_c$) does not limit the electric current. But the magnetic induction B on the surface of the superconductor is a consequence of the electric current in it (see subsection 1.2.3.1), and therefore the second condition for the existence of superconductivity ($B<B_c$) limits the electric current. The connection of magnetic induction B on the surface of the superconductor with the current I can be established using formulas (1.20) and (1.21):

$$B = \mu_a \cdot H = \frac{\mu_a}{\pi D} I = \frac{\mu_a D}{4} J, \tag{3.13}$$

where μ_a – is the absolute magnetic permeability of the superconductor on its surface, which can be equated to μ_0 (to the absolute magnetic permeability of vacuum $\mu_0=4\pi\cdot 10^{-7}$ H/m);

H – is magnetic field strength on the surface of the superconductor, A/m;

I – is electric current in the superconductor, A;

D – is diameter of the superconductor, m;

$J = I/(\pi D^2/4)$ – is average current density in the superconductor, A/m^2.

The most recognized theory, which at the microscopic level explains the physical nature of superconductivity, is the so-called BCS theory, the quantum theory of superconductivity of American scientists Bardin, Cooper and Schriffer. Unfortunately, this theory is not able to fully explain all the phenomena associated with superconductivity. This is especially true for explaining the root causes of high-temperature superconductivity. Therefore, scientists from different countries, considering the prospects for the practical use of superconductivity, are constantly and intensively working to improve the theory of superconductivity.

The BCS theory is based on the idea that conduction electrons with antiparallel spins (with opposite directions of electron rotation around their axes) can be combined into so-called Cooper pairs. They can be represented as pairs of miniature magnets with opposite magnetic poles, which through crystal lattices are attracted to each other with a force exceeding the Coulomb force of mutual repulsion (Fig. 3.9).

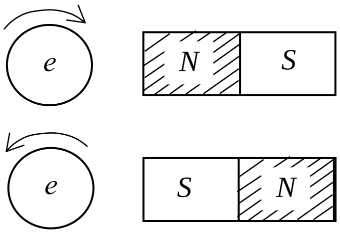

Figure 3.9 – Cooper electronic pairs

Cooper pairs have a total zero spin, and therefore are able to move freely (without electrical resistance) in the superconductor. Superconductivity disappears if Cooper pairs are separated by the force of Brownian motion of microparticles (with excessive temperature rise), the magnetic field (with excessive increase in magnetic induction), and under the influence of high frequency of electromagnetic field.

In the strict sense, the resistance of a superconductor at alternating current is slightly different from zero and increases with increasing frequency. This is due to the presence of a small number of ordinary electrons among the superconducting electrons (Cooper electron pairs), which participate in the creation of alternating electric current and therefore cause some thermal (Joule) losses. This effect is especially manifested at the frequency of the electromagnetic field $f > 3 \cdot 10^{11}$ Hz, when the energy of the quanta of the electromagnetic field $h \cdot f$ becomes sufficient to separate the

Cooper pairs, where $h=6.626176\cdot 10^{-34}$ J·s is Planck's constant or quantum action. This frequency is the initial in the infrared range. Therefore, superconductors in the light frequency range of electromagnetic waves are not different from ordinary conductors.

3.3.2 Meissner effect

From the formula (3.13) it is seen that you can use not only the limitations on magnetic induction on the surface of the superconductor ($B<B_c$), but also limitations on the magnetic field strength ($H<H_c$) as a condition for the existence of superconductivity. But the use of the density J of electric current to determine the conditions for the existence of superconductivity ($J<J_c$) is not entirely correct for two reasons. First, the magnetic induction B as a fundamental factor of superconductivity depends not only on the electric current density J, but also on the geometrical parameters (3.13). Second, the electric current density in the superconductor is extremely unevenly distributed due to the Meissner effect.

The Meissner effect is the displacement of the magnetic field into the surface and very thin layer of the superconductor. This effect is the second fundamental difference between superconductors and ordinary electric conductors. The thickness of this layer, according to studies of German physicists Fritz and Heinz London, is about 10^{-2} microns. In this case, it does not matter which electric currents caused the magnetic field: external currents or internal currents of the superconductor. This means that the electric current of the superconductor as the primary cause of the magnetic field in accordance with the law of total current (1.19) is also displaced into the surface and very thin layer of the superconductor. This feature makes us use cables with a large number of thin superconducting cores or films placed in its external thin layer as superconductors.

The conditions for the existence of the Meissner effect coincide with the conditions for the existence of superconductivity if a superconductor of the 1st kind is used and do not coincide if the superconductor of the 2nd kind is used. Therefore, depending on the behaviour of superconductors in a magnetic field, there are two main groups: superconductors of the 1st and 2nd kind.

3.3.3 Superconductors of the 1st kind

Superconductors of the 1st kind have the following characteristic features (Fig. 3.10, *a*): existence of one zone of the superconducting state with one value of critical magnetic induction B_{c0} at $T_c≈0$, abrupt transition from normal to superconducting state, and complete displacement of the external magnetic field from the superconductor volume in the state of superconductivity (Meissner effect).

Superconductors of the 1st kind are sometimes called "soft" superconductors. Superconductors of the 1st kind include some pure (elementary) metals [6]:

- titanium *Ti* (T_{c0}= 0.39 K; B_{c0}= 0.006 T);
- cadmium *Cd* (T_{c0}= 0.52 K; B_{c0} = 0.0028 T);
- zinc *Zn* (T_{c0}= 0.85 K; B_{c0}= 0.0055 T);
- gallium *Ga* (T_{c0}= 1.08 K; B_{c0}= 0.0059 T);
- aluminium *Al* (T_{c0}= 1.2 K; B_{c0}= 0.01 T);
- thallium *Tl* (T_{c0}= 2.37 K; B_{c0}= 0.018 T);
- indium *In* (T_{c0}= 3.41 K; B_{c0}= 0.028 T);
- tin *Sn* (T_{c0}= 3.7 K; B_{c0}= 0.031 T);
- mercury *Hg* (T_{c0}= 4.2 K; B_{c0}= 0.046 T);
- tantalum *Ta* (T_{c0}= 4.5 K; B_{c0}= 0.083 T);
- lead *Pb* (T_{c0}= 7.2 K; B_{c0}= 0.08 T).

At such small critical values of temperature T_{c0} and magnetic induction B_{c0}, superconductors of the 1st kind are of no practical interest.

3.3.4 Superconductors of the 2nd kind

Superconductors of the 2nd kind have the following characteristic features (Fig. 3.10, *b*): in addition to the usual superconducting state zone for superconductors of the 1st kind, there is a zone of mixed superconducting state with two values of critical magnetic induction: B_{c01} and B_{c02}; the transition from the normal state to the superconducting state is not abrupt, but gradual in some temperature range; the Meissner effect is fully manifested only in the zone of the superconducting state, and only partially in the zone of the mixed state. The mixed state in terms of resistivity ρ does not differ from the superconducting state, i.e. ρ=0.

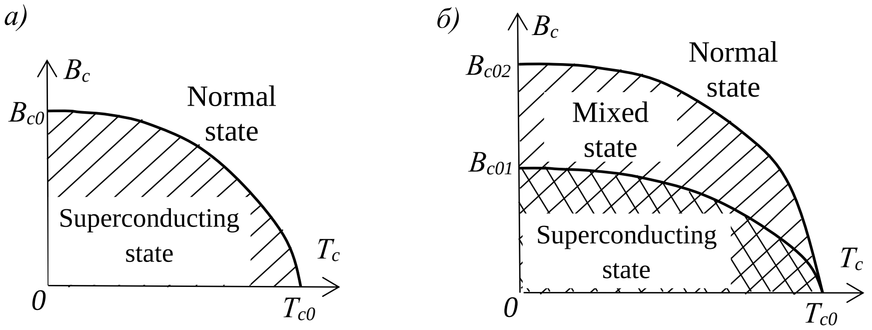

Figure 3.10 – Diagrams of superconductors of the 1st kind (*a*) and 2nd kind (*b*)

Among pure metals, only niobium *Nb* (T_{c0}= 9.22 K; B_{c02}= 0.195 T), vanadium *V* (T_{c0}= 5.43 K; B_{c02}= 0.137 T), and technetium *Tc* (T_{c0}= 7.8 K; B_{c02}= 0.141 T) belong to superconductors of the 2nd kind. Other superconductors of the 2nd kind are alloys and various chemical compounds. They are usually subjected to plastic deformation in the cold state in order to increase the concentration of defects in the crystal lattices and the critical magnetic induction $B_к$ [7]. Such superconductors are sometimes called "solid" superconductors.

The "solid" superconductors include: a) alloys of niobium *Nb* and titanium *Ti* (T_{c0}=10 K; B_{c02}=12 T); niobium *Nb* and zirconium *Zr* (T_{c0}=9.5 K; B_{c02}=11 T); vanadium *V* and gallium *Ga* (T_{c0}=14.2 K; B_{c02}=22.6 T); niobium *Nb*, aluminium *Al*, and germanium *Ge* (T_{c0}=21 K; B_{c02}=41 T); b) chemical compounds of niobium *Nb* with nitrogen *N*; niobium with germanium Nb_3Ge (T_{c0}=23.2 K; B_{c02}=22.6 T); niobium with tin Nb_3Sn (T_{c0}=18 K; B_{c02}=22 T); lead with molybdenum and sulphur $Pb_1Mo_{5,1}S_6$ (T_{c0}=14.4 K; B_{c02}=60 T).

Fundamentally new are ceramic high-temperature superconductors (HTSC) based on copper oxide with a critical temperature $T_к$ above 30 K. Such superconductors were first obtained in 1986 by Swiss scientists K. Müller and J. Bednorz. Ceramic HTSCs include lanthanum ceramics: a compound of lanthanum *La* with strontium *Sr*, copper *Cu*, and oxygen *O* (T_c= 56 K) or with barium, copper and oxygen $La_{1,8}Ba_{0,2}CuO$ (T_c=85 K); yttrium ceramics: a combination of yttrium with barium, copper and oxygen $YBa_2Cu_3O_7$ (T_{c0}=90 K; B_{c02}=100 T); bismuth ceramics: a combination of bismuth with strontium, calcium, copper and oxygen $Bi_2Sr_2CaCu_2O_8$ (T_c=95 K); thallium ceramics: a compound of thallium with barium, calcium, copper and oxygen $Tl_2Ba_2CaCu_2O_8$ (T_c=110 K); mercury ceramics: a compound of mercury with barium, calcium, copper and oxygen $HgBa_2Ca_2Cu_2O_8$ (T_c=125 K). The main advantage of ceramic HTSCs is the ability to cool them with relatively cheap liquefied nitrogen. This paves the way for the widespread use of superconductors in industry.

3.4 Metals of high electrical resistance

3.4.1 Resistive alloys

Resistive alloys are used for the manufacture of measuring instruments and sample resistors. Therefore, these alloys must have not only a high electrical resistivity ρ, but also a high stability ρ: a small temperature coefficient of resistivity α_ρ (see subsection 3.1.1.2).

Manganine – is the most typical alloy for the manufacture of sample resistors. It contains copper *Cu* (85%), manganese *Mn* (12%) and nickel *Ni* (3%) [11]. Its main electrical properties are: a sufficiently high resistivity ρ=0.42 ... 0.48 μOhm · m, a fairly small value of the temperature coefficient of resistivity $\alpha_\rho=(6...50)\cdot10^{-6}$ K^{-1}, and quite small coefficient of thermoelectromotive force paired with copper ψ_{12}=1...2 μV/K (see subsection 3.1.4.3). To obtain a small value of the coefficient α_ρ the manganese wire is subjected to a special heat treatment: annealing in vacuum at a temperature of +550 ... 600^{O}C. Maximum operating temperature of manganine is +200^{O}C.

Constantan – is an alloy containing copper *Cu* (58.5%), nickel *Ni* (40%), and manganese (1.5%) [11]. Its average temperature coefficient of resistivity $\alpha_\rho=(-5...-50)\cdot10^{-6}$ K^{-1} at ρ= 0.48 ... 0.52 μOhm·m (Fig. 3.3). Maximum operating temperature of constant is +450 ^{O}C. Strain-sensitive sensors for measuring mechanical forces and deformations of metal structures are also made of constantan. As a disadvantage of the constantan in comparison with manganese, it should be noted a rather large coefficient of thermoelectromotive force paired with copper ψ_{12}= 45 ... 55 μV/K, which can negatively affect the accuracy of measurements (especially when using measuring bridges). In addition, constantan contains a lot of relatively expensive nickel.

3.4.2 Alloys for electric heating elements

Alloys for electric heating elements must be cheap enough and work in contact with air at fairly high temperatures, sometimes up to 1000 °C. These requirements are met by a variety of iron-based alloys. The high heat resistance of such alloys is explained by the formation of a continuous film due to the introduction of nickel Ni, chromium Cr and aluminium Al. The service life of the heating elements can be significantly increased by excluding the access of oxygen to the surface of the heating wire. To do this the wire is placed in the middle of a tube of oxidation-resistant metal, and the tube is filled with a dielectric with high thermal conductivity (magnesium MgO). The most widely used iron-based alloys are nichrome and chromal.

Nichrome – is an alloy of iron with nickel Ni (55 ... 78%), chromium Cr (15 ... 23%) and manganese Mn (1.5%). The main electrical properties of nichrome are: resistivity ρ=1 ... 1.2 μOhm · m, temperature coefficient of resistivity $\alpha_\rho=(1...2)\cdot10^{-4}$ K^{-1}, maximum operating temperature 1000 ... 1100^{O}C. Nichrome can be easily pulled into a relatively thin wire or tape. The main disadvantage of nichrome is the high content of expensive nickel. If the nickel content is reduced by increasing the iron, the maximum operating temperature and service life of the alloy is reduced. This alloy is called ferronichrome.

Chromal – is an alloy of iron with chromium Cr (12 ... 27%), aluminium Al (3.5 ... 6.5%) and manganese Mn (0.7%) with some silicon Si content (0.6 ...1.2%), and carbon C (0.6 ... 0.15%). The main electrical properties of chromal are: resistivity ρ=1.26 ... 1.4 μOhm · m, temperature coefficient of resistivity $\alpha_\rho=(0,5...1,5)\cdot10^{-4}$ K^{-1}, maximum operating temperature 750 ... 1400^{O}C. Chromal is much cheaper than nichrome, but due to its hardness and fragility it is difficult to make thin wires or tapes of it. If the chromium content is reduced by increasing the iron, the maximum operating temperature and service life of the alloy is reduced. This alloy is called fechral.

3.5 Metals for various purposes

3.5.1 Refractory metals

Tungsten W – is a very dense (d = 19.3 g/cm^3) and refractory ($T_{melting}$=3400^{O}C) metal. An intermediate product of its production from tungsten $FeWO_4$+$MnWO_4$ and scheelite $CaWO_4$ is tungstic acid H_2WO_4, from which hydrogen is extracted at +900°C and to get a fine tungsten powder. This powder is pressed and sintered at a pressure of up to 200 MPa to get tungsten rods by powder metallurgy technique. After difficult thermal and mechanical processing in the hydrogen atmosphere a wire with a diameter up to 0.01 mm is obtained from them. Due to its high refractoriness tungsten can operate at temperatures up to + 2300 °C without access to oxygen (in vacuum or in the inert gas atmosphere). The electrical resistivity of tungsten ρ significantly depends on the temperature: it increases approximately according to the linear law from 0.055 μOhm· m at 20 ^{O}C to 1.05 μOhm· m at 3000 ° C. Due to this property tungsten wires are sometimes used as a current stabilizer (as a barretter). Tungsten is relatively expensive, difficult to process, and therefore it is used only where a very high operating temperature and thermoelectron emission is required: in the manufacture of incandescent lamps for lighting and electronic lamps, in X-ray, electron-beam and discharge tubes [7]. To reduce the work function and increase the emission of electrons 1...2% of thorium oxide ThO_2 is added to tungsten. Tungsten is weakly prone to the formation of an electric arc, so it has long been used to make bursting contacts.

Tantalum Ta – is a refractory metal with a melting point $T_{melting}$=3000^{O}C, has a density d = 16.6 g/cm^3 and a resistivity ρ= 0.124 μOhm · m, tungsten is better subjected to plastic deformation, including at low temperatures. Tantalum blanks are sintered by powder metallurgy in vacuum because of its ability to absorb inert gases and become very brittle. Tantalum is obtained from uncommon tantalum by electrolysis. Tantalum is mainly used in the electrovacuum industry for the manufacture of anodes and grids of generator lamps, in the manufacture of electrolytic capacitors, and as a superconductor.

Molybdenum Mo – is a refractory metal with a melting point $T_{melting}$=2620^{O}C with the lowest resistivity among refractory metals (ρ= 0.05

μOhm · m), has similar properties to tungsten at a much lower density (*d* = 10.2 g/cm^3) and significantly greater plasticity. It begins to oxidize at 400 ° C, and in a humid atmosphere, even at 250 ° C. Therefore, molybdenum parts can only operate in a vacuum or in inert gas environment. Molybdenum is obtained from molybdenite ore MoS_2. Due to its high strength, hardness and ductility, molybdenum is one of the best materials for the manufacture of parts of complex configuration, operating in high temperatures. Molybdenum, like tungsten, is used as electrodes in radio lamps and for the manufacture of breaking electrical contacts. Paired with tungsten, molybdenum is used to make high-temperature thermocouples that are capable of operating at temperatures up to 2000 ° C in inert media or vacuum.

Niobium Nb – is a refractory metal with a melting point $T_{melting}$=2470^{O}C with a resistivity ρ= 0.15 μOhm · m and a density *d* = 8.57 g/cm^3. In terms of chemical properties and processing methods, niobium is similar to tantalum. Niobium blanks are also made by powder metallurgy. Niobium and some of its alloys are superconductors with a relatively high critical temperature in the superconducting state (for pure niobium $T_к$ = 9.2 K, and for alloys $T_к$ = 23.2 K). Therefore, it is used for the manufacture of superconducting electromagnets, as well as in electrovacuum technology.

3.5.2 Fusible metals

Lead Pb – is a very malleable metal with a melting point $T_{melting}$ = 327 ^{O}C and resistivity ρ= 0.19 μOhm·m. In the cold state, it is easily rolled on foil. Lead is resistant to corrosion under the action of water, sulphuric and hydrochloric acids, and therefore is used for the manufacture of cable protective sheaths, plates of lead acid batteries, fuses. Lead absorbs X-rays and gamma rays very effectively (an order of magnitude better than steel and two orders of magnitude better than bricks), and is therefore used in protection against these rays. Water-soluble lead compounds are poisonous.

Tin Sn – is a soft and ductile metal of silver color with a low melting point ($T_{melting}$= 332^{O}C) and a relatively high resistivity (ρ= 0.113 μOhm·m), when bent it cracks characteristically. Tin is resistant to oxidation at temperatures up to 150 ° C and is not exposed to water, which allows you to use it for protective anti-corrosion coating of metal (steel) products. Cold tin is easily rolled on foil. Additives of lead (up to 15%) and antimony (up to 1%) are added to the tin to facilitate rolling. Thin tin foil is used in the manufacture of capacitors. Tin is widely used in most soft (low temperature) solders. Alloys based on or with the addition of tin are widely used in the manufacture of semiconductor devices of silicon, germanium and gallium arsenide due to the fact that tin is almost the only carrier of donor elements, especially phosphorus.

Zinc Zn – is a light metal that is obtained by metallurgy and then purified by electrolytic method. It is melted at $T_{melting}$= 419^{O}C, has a relatively low resistivity ρ= 0.0592 μOhm · m, is brittle at normal temperatures, but when heated to 100^{O}C it becomes plastic. Upon further heating to 200 °C, zinc becomes very brittle again (is even ground into a powder). Zinc is well forged and rolled into thin sheets. In air it is covered with a thin protective oxide film ZnO, and in the presence of moisture and carbon dioxide, with a film of zinc carbonate $Zn_2(OH)_2CO_3$. Due to this property zinc is used as an anti-corrosion coating of metal (steel) products. Zinc is also used to metallize condenser paper by applying zinc vapour to the paper in a vacuum at a temperature of about 600 °C.

Cadmium Cd – is a malleable and viscous metal of silvery-white colour with a melting point $T_{melting}$= 321^{O}C and a resistivity ρ= 0.074 μOhm · m. In a humid atmosphere it is covered with a thin film of oxide, which protects the metal from further corrosion. Cadmium is used in the production of alkaline cadmium-nickel batteries, and as a protective (anti-corrosion) coating is part of some types of bronze and low-temperature solders. Soluble cadmium compounds are toxic.

Mercury Hg – is the only metal that is in a liquid state at normal temperatures ($T_{melting}$= -39^{O}C). Mercury has a fairly large resistivity ρ= 0.958 μOhm · m. It is used in gas discharge lamps due to its low ionization potential compared to conventional and even inert gases. Many metals (gold, silver, platinum, magnesium, aluminium, zinc, tin, lead, cadmium) are dissolved in mercury to form amalgams. Tungsten, iron and tantalum are insoluble in mercury. Mercury, its compounds and especially vapours are poisonous

3.5.3 Precious metals

In electrical engineering, precious metals include gold *Au*, silver *Ag*, platinum *Pt* and palladium *Pd*. These metals and their alloys have high chemical resistance.

Gold Au has a very high ductility (you can get a foil up to 0.01 μm thick), does not interact with acids and alkalis, is dissolved only in a mixture of nitric and hydrochloric acids (in "aqua regia"), is melted at $T_{melting}$= 1063°C, has a resistivity ρ= 0.0225 μOhm · m. In electronic technology, gold is used in the manufacture of semiconductor photoresistors and photocells, precision contact elements in particularly critical cases. In less critical cases alloys of gold with silver, nickel and zirconium, which have increased hardness, are used.

Silver Ag – is a white shiny plastic metal with a very high electrical conductivity (ρ = 0.015 μOhm · m), is melted at $T_{melting}$ = 961°C, is easily machined, at temperatures above 200°C begins to oxidize with the formation of AgO_2 and AgO. At normal temperatures, silver combines with sulphur (Ag_2S), and therefore it is not recommended to use it near substances that contain sulphur, for example, near vulcanized rubber or ebonite. Silver is used as a contact material in switching devices, as part of some solders, in the production of silver-zinc and silver-cadmium batteries. Alloys of silver with platinum (3.6 ... 12.6% *Pt*), palladium (19.6 ... 40.5% *Pd*), copper (2.7 ... 50.5% *Cu*), magnesium, nickel, magnesium and zirconium are successfully used as conductive materials in the manufacture of capacitors, galvanic coatings of high-frequency devices, conductive films.

Platinum Pt – is a shiny refractory ($T_{melting}$ = 1770°C), very dense (*d* = 21.45 g/cm^3), plastic, and chemically very stable metal, has a resistivity ρ= 0.098 μOhm · m. Platinum is slowly dissolved only in "aqua regia". Due to its high cost platinum is rarely used: in the manufacture of high-temperature thermocouples paired with platinum-rhodium, as well as in the creation of alloys with palladium, silver, gold, iridium, rhodium, ruthenium, copper, nickel, and their subsequent use as contact materials and solders.

Palladium Pd – is a silvery-white metal with a resistivity ρ= 0.108 μOhm · m, is melted at 1550 ° C, reacts with chlorine and bromine at room temperature. In air, when heated to 600 ... 700 °C, palladium is oxidized. 900 volumes of hydrogen can be dissolved in one volume of palladium, which is then released at 350 ... 500 ° C. Palladium is 4-5 times cheaper than platinum, is close in properties to platinum, and therefore replaces it in some cases.

3.6 Non-metallic conductive materials and products

Among non-metallic conductive materials, electrical coal materials are of the greatest importance. They have a fairly high electrical and thermal conductivity, very low coefficient of friction, high chemical resistance and heat resistance. Graphite, soot and anthracite are used as primary raw materials for obtaining such materials.

Natural graphite – is a soft crystalline substance of dark grey colour, has a layered structure. The individual layers of graphite are separated from each other and easily peeled off, which is important for the operation of sliding contacts. This property is used in dry oils.

Soot – is a coal powder of a high degree of dispersion with admixtures of resinous substances. The graphite structure of soot is not fully formed. Soot is obtained by incomplete combustion of various organic substances.

Anthracite – is a shiny black fossil coal with the highest degree of structure change among other types of coal.

Electrodes for electric arc furnaces and electrolytic baths, electric brushes for electric machines and autotransformers, carbon powders for microphones and resistors are made of coal materials.

3.6.1 Carbon electrodes

Carbon electrodes are made of crushed carbon mass together with a binder. This mass is used to make blanks by pushing it through a nozzle or pressing in moulds. Coal resin (a by-product of coking coal) and sometimes liquid glass are used as binders. Coal billets undergo a firing process at a temperature of about 800^{O}C and then, if products improvement is necessary, the process of graphitization at a temperature of 2200 ... 2500^{O}C. Graphitization allows significant reduction of the resistivity of carbon electrodes: from ρ= 50 μOhm · m to 15 μOhm · m, reduction of the hardness and increase the allowable electric current density in them from J_{al}= 1.5 A/mm^2 to J_{al} = 2.0 A/mm^2 [6]. For carbon electrodes, which must operate at high temperatures, the graphitization process is carried out at an even higher temperature, at 3000 ° C.

3.6.2 Electric brushes

Electric brushes are designed to provide a sliding electrical contact between the moving part of the electric machine (collector) and the fixed part, with the expectation that between the brush and the collector may be sparks and even electric arcs due to switching processes. Hence the special requirements for electric brushes taking into account the resistivity ρ, the allowable current density J_{al}, the allowable linear sliding speed υ_{al}, the coefficient of friction, the transient resistance of the contacts and other features are needed. Taking into account these requirements a variety of electric brushes is produced, which differ in the composition of components, manufacturing process and their electromechanical characteristics [6]:

– carbon-graphite (ρ = 18...60 μOhm·m, J_{al}= 6...8 A/mm^2, υ_{al} = 10 ... 15 m/s);

– graphite (ρ = 10 ... 46 μOhm · m, J_{al} = 7 ... 11 A/mm^2, υ_{al} = 12 ... 25 m/s);

– electrograted (ρ =10...45 μOhm·m, J_{al} =9...11 A/mm^2, υ_{al} = 25 ... 45 m/s);

– copper-graphite (ρ=0.05...1.2 μOhm· m, J_{al}=12...20 A/mm^2, υ_{al}=2...25 m/s);

3.6.3 Coal powders for microphones and resistors

Coal powders are often made of anthracite (rarely graphite) by crushing them into powder. The resistivity of the powder depends on the size of the grains, the density of their backfill, pressure and heat treatment. It can vary in a very wide range (ρ= 0.01 ... 400 Ohm · m). Fine-grained powders are obtained after sieving through a sieve with 52 holes, and coarse-grained ones, with 45 holes for every 1 cm^2 of the sieve surface. In the process of powder firing at a temperature of 600 ... 800^{O}C its electrical resistance increases. Powders should not clump over time and stick together under the influence of high humidity. Carbon resistors have advantages over wirewound resistors: they are smaller, have a high upper limit of nominal resistance, low dependence of resistance on voltage, temperature and humidity. Soot, pyrolytic carbon and borocarbon films are also used as the primary material for the manufacture of carbon resistors [6].

3.7 Semiconductors

Semiconductor materials in their resistivity ((ρ=10^{-6}...10^{8} Ohm·m) occupy an intermediate position between conductors ((ρ=10^{-8}...10^{-5} Ohm·m) and dielectrics (ρ=10^{7}...10^{16} Ohm·m). Their resistivity ρ can be significantly reduced under the influence of impurities and various energy factors: temperature, light, electric field, magnetic field, ionizing radiation, and mechanical force.

Semiconductors have a completely filled valence band, which is separated from the conduction band by a narrow band gap ΔW (in semiconductors ΔW<3 eV). This zone is significantly narrowed (up to ΔW = 0.05 eV) due to specially selected impurities that are easily ionized, giving electrons to the conduction band or taking them from the valence band. Therefore, with increasing influence of energy factors, the probability of excitation of electrons and their transition to the conduction band increases.

Thus, semiconductors are similar in their properties to conductors, in most cases used for the manufacture of control semiconductor elements and are rarely used as dielectrics [14, 15]. Semiconductors include some simple chemical elements and a huge number of alloys and chemical compounds.

3.7.1 Physical processes in semiconductors and their application

The operation of most semiconductor devices is based on impurity conductivity. To obtain this semiconductor materials are doped with a predetermined and precisely dosed chemical element (impurity). Before doping the semiconductor is thoroughly cleaned of accidental and harmful impurities using special technologies. Depending on the concentration and type of impurities, semiconductors are divided into a) intrinsic (without impurities); b) n-type (donors whose atoms donate electrons to the conduction band at the energy of thermal fluctuations more than the activation energy of the donor electrons ΔW_d); c) p-type (acceptors, the atoms of which take electrons from the conduction band at the energy of thermal fluctuations more than the activation energy of the "holes" of the acceptor ΔW_a); d) compensated (donor concentration balances the concentration of acceptors, as a result of which the semiconductor behaves as proper). At very high concentrations of impurities, the semiconductor becomes degenerate and behaves like a metal.

The main advantage of semiconductor devices is their controllability or significant dependence on thermal energy (thermistors), light (photoresistors), mechanical force (strain gages), electrical voltage (varistors). Of particular interest are the unique properties of the so-called *p-n* junctions (contacts of *n*-type and *p*-type semiconductors). The ability of *p-n* junctions to transmit electric current in only one direction is widely used in the manufacture of diodes, transistors, thyristors and a wide variety of integrated circuits and microchips.

Electrical conductivity of intrinsic semiconductors

Intrinsic semiconductors do not contain an alloying impurity. These include very pure simple semiconductors (there are only nine of them: silicon *Si*, germanium *Ge*, selenium *Se*, etc.), as well as many semiconductor chemical compounds (gallium arsenide *GaAs*, indium antimonide *InSb*, indium arsenide *InAs*, etc.). In intrinsic semiconductors electrical conductivity is ensured by the transition of electrons from the valence band to the conduction band if the energy of their thermal fluctuations exceeds the band gap ΔW. With the departure of the electron into the conduction band the valence band becomes not completely filled. In the former place of the electron there is a shortage of electrons: there is a so-called hole, which is considered a positively charged particle. Thus, a pair of free charge carriers (an electron in the conduction band and a hole in the valence band) is formed in the semiconductor crystal, which creates the semiconductors' own electrical conductivity or electron-hole conductivity [7].

In the absence of an external electric field the electron and the hole perform thermal chaotic motions within the crystal. In the presence of an external electric field the movement of the electron against the electric field and the hole in the direction of the electric field will be directed, i.e. the electric current occurs. In this case the hole as a positive particle of a solid semiconductor cannot move physically. In fact, the electron of the neighbouring atom captured by the hole moves, which creates a hole in its former place and the illusion of moving the hole. It should be noted that free electrons have greater mobility than holes. Therefore, at the same concentration of free electrons and holes the intrinsic conductivity of semiconductors is mainly of the electron type.

Electrical conductivity of n-type semiconductors

Doping of intrinsic semiconductors with donors allows obtaining n-type semiconductors. For semiconductors of group 4 of the periodic table, for example, for silicon, donors may be impurities of elements of group 5 of the table (phosphorus, arsenic, antimony). These atoms have one electron more on the valence shell than the atoms of the semiconductor, i.e. the "extra" electron. At the energy of thermal fluctuations of atoms more than the activation energy of the electron of donor ΔW_d "extra" electrons with a high probability pass into the conduction band, and therefore can participate in the electric current in the presence of an external electric field. In n-type semiconductors, electrons are considered as the main charge carriers, and electrical conductivity is considered to be electronic. The number of electrons in the conduction band depends on the concentration of donors, the energy of the donor levels, the width of the band gap of the semiconductor, and the temperature. Doping with donors is carried out to the level of $10^{13}...10^{19}$ atoms per cm^3. If the concentration of donors is too high, the semiconductor can degenerate into a conductor.

Electrical conductivity of p-type semiconductors

Doping of own semiconductors with acceptors allows to obtain *p*-type semiconductors. For semiconductors of group 4 of the periodic table, for example, for silicon the impurities of elements of group 3 of table (boron, aluminium, indium) can be acceptors. If silicon is doped with trivalent indium, the indium atom lacks one electron to form bonds with silicon. As a result, the electron deficiency is formed in the valence band, which is commonly called a hole. At the energy of thermal fluctuations of atoms more than the activation energy of the holes of the acceptor ΔW_a "extra" holes with a high probability pass into the conduction band, and therefore can participate in the electric current in the presence of an external electric field. In *p*-type semiconductors holes are considered as the main charge carriers, and electrical conductivity is considered to be of a hole type.

Determination of the type of electrical conductivity of semiconductors

The existence of "extra" electrons and the electrical conductivity of an *n*-type semiconductor can be confirmed by a very simple experiment: to heat one end of the semiconductor and determine the polarity of the electric potentials of its hot and cold ends. Under the influence of heat, the "extra" electrons will begin to pass in greater numbers into the conduction band and then move to the cold end, where they are much less in the free state. As a result of such displacement, the cold end of an *n*-type semiconductor with a temperature T_c will be charged negatively, and its hot end with a temperature T_h will be charged positively (Fig. 3.11, a).

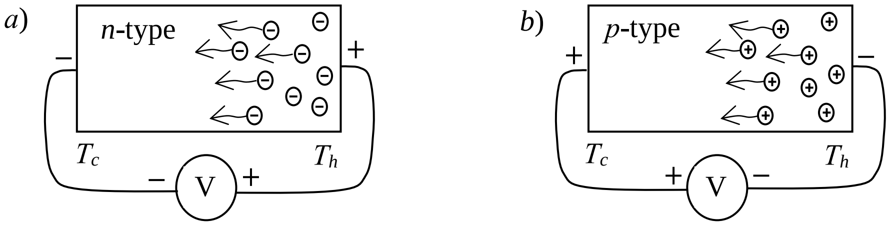

Figure 3.11 – Determination of *n*-type (a) and *p*-type (b) semiconductors by heating one of its ends and measuring the difference of potential

Similarly, the existence of "extra" holes and the electrical conductivity of the *p*-type semiconductor can be confirmed. Under the influence of heat, "extra" holes will begin to pass into the conduction band in greater numbers and then migrate to the cold end, where they are much less in the free state (Fig. 3.11, b). As a result, the cold end of the *p*-type semiconductor will be charged positively, and its hot end negatively.

The type of electrical conductivity of semiconductors can also be determined based on the Hall effect. To do this place the semiconductor plate in an external transverse magnetic field (place the first pair of its faces perpendicular to the magnetic induction vector *B*), apply the electric potential difference between the second pair of its faces creating an electric field of strength *E* along the semiconductor, and determine the polarity of the electric field on the third pair of semiconductor faces (Fig.3.12).

Under the influence of electric field forces, “extra” electrons in a *n*-type semiconductor will move against the electric field vector *E* and thus create an electric current along the semiconductor (Fig. 3.12, a). At the same time, these electrons will shift to the left under the influence of Ampere or Lorentz forces according to the rule of the left hand at the directions of vectors *E* and

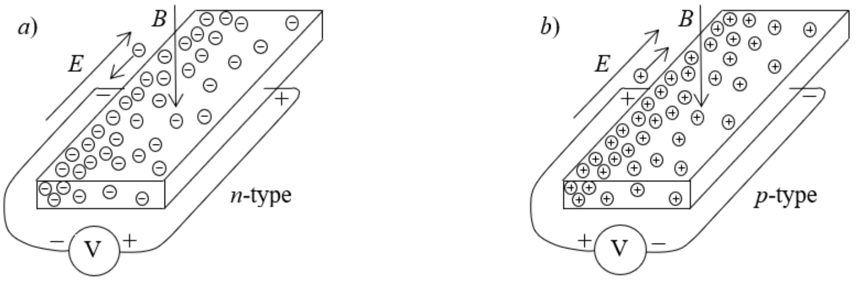

Figure 3.12 – Determining *n*-type (a) and *p*-type (b) semiconductor using the Hall effect

B (see sections 1.2) selected in Fig. 3.12. As a result of this displacement the left face of the *n*-type semiconductor plate will be negatively charged, and the right, positively.

If a *p*-type semiconductor is in the same conditions, then its “extra” holes will move in the direction of the strength vector *E* of the electric field (Fig. 3.12, b). The positive holes will be shifted to the left according to the same laws and rules. As a result, the left face of the plate of the *p*-type semiconductor will be charged positively, and the right one will be charged negatively.

The Hall effect is of interest not only for the type of electrical conductivity of the conductor, but also as the basis for the development of the semiconductor appliances for measuring the magnetic field strength or multiplying the two analogue values for electric power measuring.

Influence of temperature on electrical conductivity of impurity semiconductors is associated with the energy of thermal fluctuations of atoms. If this energy exceeds the activation energy of the electron donor ΔW_d (for *n*-type semiconductors) or the activation energy of the acceptor holes ΔW_a (for *p*-type semiconductors), then the probability of transition of charge carriers into the conduction band, and hence electrical conductivity, increases sharply with increasing temperature. This feature is used in thermistors, semiconductor resistors, which significantly change their electrical resistance when the temperature changes. The main characteristics of thermistors include the nominal resistance *R* and its temperature dependence $R = f(T)$. If this dependence is inversely proportional (if *R* decreases with increasing T), then such thermistors are called thermistors. They are usually made of semiconductor ceramics based on oxides of titanium, vanadium, chromium, manganese, iron, cobalt, copper or zinc. If the dependence $R = f(T)$ is proportional (if R increases with increasing T), then such thermistors are called posistors. They are usually made of semiconductor ceramics based on barium titanate $BaTiO_3$ (ferroelectric) and used at temperatures above the Curie point T_c (see section 2.6). When such a posistor is heated, its electrical resistance can increase thousands and even tens of thousands times [7].

Photoconductivity – is the ability of semiconductors to increase the electrical conductivity from the effects of electromagnetic radiation in the light range due to the small width of the band gap ΔW. Semiconductor devices that have photoconductivity are called photoresistors. The quantum nature of light is manifested in photoconductivity. Due to the absorption of the energy of light quanta, the energy of thermal fluctuations of the semiconductor atoms increases, which means that the probability of the transition of more charge carriers from the valence band to the conduction band increases. This leads to an increase in the electric current in the semiconductor in the presence of an electric field (applied electric voltage). The difference between the electric current in a semiconductor under the influence of electromagnetic radiation (light current) and the electric current in the dark (dark current) at constant voltage is called photocurrent $i_{ph}=\gamma_{ph}\cdot u$, where u is the electric voltage applied to the semiconductor, γ_{ph} is photoconductivity depending nonlinearly on the properties of the semiconductor, illuminance (luminous flux density), and the frequency or wavelength of electromagnetic oscillations in the light range (energy of light photons). The dependence of γ_{ph} semiconductors on light is used to manufacture photoresistors and create a variety of photosensitive devices in the desired range of electromagnetic oscillations: from infrared to ultraviolet waves. Sulphides, selenides, and tellurides of cadmium (CdS, $CdSe$, $CdTe$), lead (PbS, $PbSe$, $PbTe$), and bismuth (Bi_2S_3, Bi_2Se_3, Bi_2Te_3), as well as crystals of silicon Si and germanium Ge are widely used for this purpose.

Influence of electric field on electrical conductivity of semiconductors is significantly manifested only in strong electric fields, when the electric field strength exceeds a certain critical value E_{cr}, which depends on the characteristics of the semiconductor, its temperature and impurity concentration, and is about 10^6 V/m. There are four types of the mechanism of influence of the electric field on the electrical conductivity of semiconductors: thermoelectronic ionization, tunnelling effect, shock ionization and thermal breakdown.

Thermoelectronic ionization occurs under the influence of a strong electric field (at $E>E_{cr}$) and relatively low temperatures. The electric field increases the kinetic energy of the charge carriers during their thermal motions, which facilitates thermal activation (thermoelectronic ionization), reduces the activation energy ΔW needed for thermal transfer of charge carriers from impurity levels (from the valence band) to the conduction band, and thus to increase the specific conductivity γ of the semiconductor. In weak electric fields (at $E<E_{cr}$) the specific electrical conductivity γ does not depend on the electric field strength E.

The tunnel effect (electrostatic ionization) occurs at a much higher electric field strength (at $E>10^7$ V/m) almost regardless of temperature, and somewhat resembles the cold emission of electrons from metals (see section 3.1). At the intensity $E\approx E_{cr}$ there is a process of gradual infiltration of the charge carrier from the valence and impurity zones into the conduction band. This process is called tunnel impregnation. With increasing electric field strength (at $E> 10^7$ V/m) and decreasing the width of the band gap ΔW, the probability of tunnel impregnation of charge carriers increases sharply, and thus sharply increases the tunnel current density.

Shock ionization – is a process of avalanche-like increase in the concentration of free charge carriers at an electric field strength $E = 10^7 \ldots 10^8$ V/m, which somewhat resembles the process of electric breakdown of a gaseous dielectric. At such high electric field strength, the free electrons at the length λ of their free path have time to "heat up" (accelerate) that they are able to throw the associated electrons into the conduction band when they collide with impurity or semiconductor atoms. At $E > E_{br}$ electric breakdown occurs. Unlike the electrical breakdown of solid dielectrics (see section 2.3), the electrical breakdown of a semiconductor does not lead to its electrical failure and is the normal mode of operation of some semiconductor devices, such as zener diodes.

Thermal breakdown of a semiconductor occurs when the balance between the process of heat release in the semiconductor and the process of its transfer to the environment is disturbed. Thermal breakdown leads to the destruction of the semiconductor, i.e. is an irreversible process.

3.7.2 Technologies for the production of semiconductor materials

In the production of semiconductors there are extremely high requirements for their purity. The cleaning quality must be enough for the electrical conductivity of the cleaned semiconductor not to be greater than its own electrical conductivity. For example, the content of random impurities should not exceed 10^{-11}% in silicon Si, $5\cdot 10^{-90}$% in germanium Ge, $8 \cdot 10^{-30}$% in selenium Se. Particularly pure single-crystal ingots are obtained according the following approximate scheme [7]: a) production of technically pure simple semiconductor; b) pre-cleaning of the semiconductor; c) preparation of polycrystalline ingots; d) deep purification of polycrystalline ingots by methods of zone melting or cultivation of crystals. In the process of obtaining a single crystal ingot the semiconductor is doped if required by the production technology.

Simple semiconductors at 20 ^{O}C have band gaps ΔW=0.36...2.5 eV in width. Simple semiconductors include 9 chemical elements [6]: borium B (ΔW = 1.1 eV), silicon Si (ΔW = 1.12 eV), germanium Ge (ΔW = 0.72 eV), phosphorus P (ΔW = 1.5 eV), arsenic As (ΔW = 1.2 eV), sulphur S (ΔW = 2.5 eV), selenium Se (ΔW = 1.7 eV), tellurium Te (ΔW = 0.36 eV) and iodine J (ΔW = 1.25 eV). Silicon and germanium are the most commonly used among simple semiconductors.

Silicon is the second most common chemical element in nature after oxygen, not found in free form in nature, mainly in the form of silicon dioxide SiO_2. Silicon is crystallized with the formation of cubic spatial lattices of the diamond type with sides of 0.542 nm. Each silicon atom in these lattices is equidistant from four adjacent atoms. Silicon melts at a temperature of 1417 °C, is intensively oxidized at temperatures above 900 °C. At the temperatures below 6.7 K and pressures above 12 GPa silicon transfers to the superconducting state. The relatively wide forbidden band gap of silicon (ΔW = 1.12 eV) allows to make semiconductor devices with high operating temperature (up to 120 ... 200^{O}C) of it. The degree of purification of silicon is determined by measuring its electrical resistivity: the greater the electrical resistivity, the purer the silicon. Specific resistance of especially pure silicon at its own electrical conductivity is ρ=2.3·10^{3} Ohm · m.

Germanium is one of the first semiconductor materials to be widely used in the manufacture of semiconductor devices. Its content in the earth's crust is very small and has no significant accumulations. Germanium is crystallized with the formation of cubic spatial lattices of the diamond type with sides of 0.566 nm. Germanium atoms are held in lattice nodes by equivalent covalent bonds in the same way as silicon. Germanium is melted at a temperature of 936 ^{O}C. At temperatures below 5.4 K and pressures above 11 GPa germanium transfers to the superconducting state. The relatively narrow band gap of germanium (ΔW = 0.72 eV) allows to use it to make semiconductor devices with a much lower operating temperature compared to silicon (up to 70 ° C). The degree of purification of germanium is determined the same as for silicon, based on the electrical resistivity ρ=0.68 Ohm · m of particularly pure germanium at its own electrical conductivity. Germanium does not interact with silicon when heated to 1500 ^{O}C, which allows the widespread use of quartz crucibles in obtaining particularly pure polycrystalline ingots of germanium.

Semiconductor chemical compounds have different properties, which in many cases surpass simple semiconductors. Some of them have a fairly wide band gap, which allows you to increase the operating temperature to + 300 ° C (gallium arsenide $GaAs$), up to + 400 °C (gallium phosphide GaP) and even up to + 600 °C (silicon carbide SiC). Binary compounds of the type $A^{IV}B^{IV}$, $A^{III}B^{V}$, $A^{II}B^{VI}$ are the most widely used chemical compounds. These compounds have a crystalline structure that is similar to diamond lattices and differs only in the nature and size of the constituent particles. In addition, oxide semiconductors are widely used as semiconductor chemical compounds.

The only semiconductor binary ***chemical compound of elements of group IV of the periodic table (compound of $A^{IV}B^{IV}$ type) is silicon carbide SiC***.

Silicon carbide has high hardness (almost not inferior to diamond), a very high operating temperature (+ 600°C). In the production of silicon carbide monocrystals the sublimation method is used: the cultivation of crystals from the gas phase in graphite crucibles in the inert gas atmosphere at a temperature of 2500 ... 2600 °C. Monocrystalline silicon carbide is used in the manufacture of LEDs, high-temperature power semiconductor devices, field-effect transistors, tunnel diodes, thermistors, photoresistors, varistors and solar cells.

Borium *B,* aluminium *Al,* gallium *Ga,* and indium *In* are used to form semiconductor ***chemical compounds of $A^{III}B^{V}$ type*** as an element of A^{III} of group III of the periodic table. Phosphorus *P*, arsenic *As*, antimony *Sb,* nitrogen *N* are used as an element of the B^{V} of V group of the periodic table. These compounds have a crystalline structure. The most widely used and studied compounds of the $A^{III}B^{V}$ type are phosphides (gallium phosphide *GaP*), arsenides (gallium arsenide *GaAs*, indium arsenide *InAs*), antimonides (indium antimonide *InSb*, gallium antimonide *GaSb*), nitrides (aluminium nitride *AlN*, gallium nitride *GaN*, indium nitride *InN*). Compounds of the $A^{III}B^{V}$ type are chemically stable and have high electron mobility. The most important properties of compounds of $A^{III}B^{V}$ type are determined mainly by the properties and concentration of impurities. Doping with these impurities is usually carried out simultaneously with the cultivation of single crystals.

Chemical compounds of $A^{II}B^{VI}$ type include the so-called chalcogenides: binary chemical compounds of metals of group II of the periodic table with chalcogens (sulphur *S*, selenium *Se* and tellurium *Te*). An excess of A^{II} metal in these compounds determines the electronic conductivity, and an excess of chalcogen B^{VI} determines the hole conductivity. Chalcogenides are characterized by increased sensitivity to electromagnetic radiation in a wide range of frequencies, from infrared to

X-rays. Therefore, they are widely used in the manufacture of photoresistors and phosphors. Among the chalcogenides the most widely used are sulphides, selenide and tellurides of zinc (*ZnS, ZnSe, ZnTe*), cadmium (*CdS, CdSe, CdTe*) and mercury (*HgS, HgSe, HgTe).*

Binary chemical compounds with oxygen of metals of the transition group of the periodic table are called ***oxide semiconductors***. These compounds include oxides of titanium *Ti*, vanadium *V*, chromium *Cr*, manganese *Mn*, iron *Fe*, cobalt *Co*, nickel *Ni*, copper *Cu*, zinc *Zn* (MnO, Mn_3O_4, Cu_2O, ZnO, $ZnFeO_4$, $MnCr_2O_4$). In oxide semiconductors electronic conductivity is the main type of electrical conductivity. Thermistors, voristors and other devices are made of these materials by methods of ceramic technologies.

3.7.3 Basic properties of p-n junctions

The *p-n* junction properties that occur at the contacts of *n*-type and *p*-type semiconductors result from the unique features of the transition contact between the *n*-type semiconductor, in which electrons are the main charge carriers due to the donor impurity, and the p-type semiconductor, in which holes are the main charge carriers due to the acceptor impurity. Such a transient contact cannot be formed by simply touching the plates of these two semiconductors because of contamination of their surface (even with ideal purification technology), as well as due to the violation of the crystal structure. Therefore, the transition contact is obtained by diffusion or by melting the appropriate impurities in the plate of a single crystal semiconductor.

Consider the phenomena that occur during electrical contact between *p*-type and *n*-type semiconductor plates for three variants of applying the u_{ex} voltage from an external power supply to a single crystal of semiconductors of two types with a *p-n* junction.

According to ***option "a"***, the voltage of the external source is absent ($u_{ex}= 0$). Electrons in the *n*-region and holes in the *p*-region are the main charge carriers that arise due to the ionization of the atoms of the donor and acceptor impurities. At not very low temperatures almost all atoms of these impurities are ionized. Therefore, the concentration of electrons in the *n*-region is almost equal to the concentration of donor atoms, and the concentration of holes in the *p*-region is the concentration of acceptor atoms [7]. At the boundary of these regions there is a concentration gradient of charge carriers and mutual thermal diffusion. Part of the electrons from the *n*-region passes into the *p*-region and recombines with the holes of the *p*-region in the boundary zone. As a result, practically no free electrons remain in the boundary zone of the *n*-region of δ_n width. Therefore, a stationary bulk positive charge of ionized donor atoms is formed in the δ_n band (Fig. 3.13, *a*).

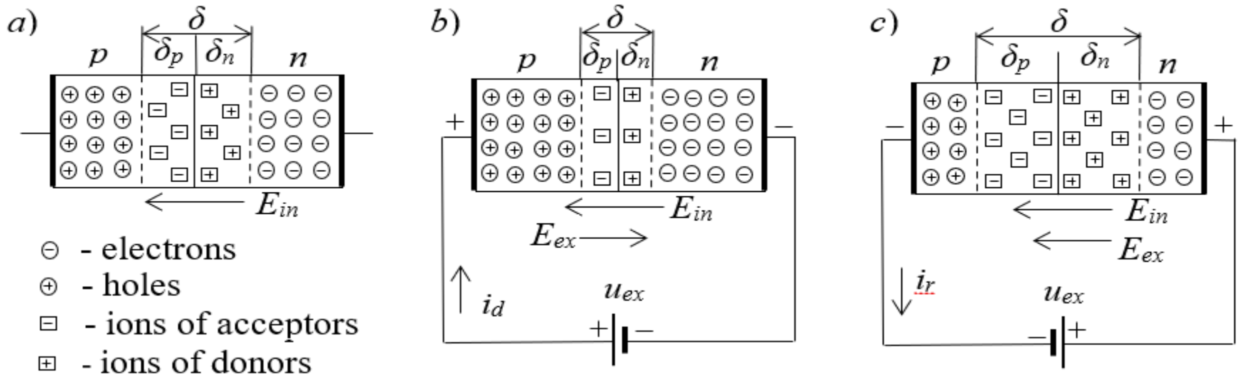

Figure 3.13 – The main properties of the *p-n* junction at $u_{ex} = 0$ (a), at $u_{ex}>\varphi_c$, when the *p-n* junction is open (b) and when $u_{ex}<\varphi_c$, when the *p-n* junction is closed (c)

Similarly, part of the holes from the *p*-region passes into the *n*-region and recombines with the electrons of the *n*-region in the boundary zone. As a result, practically no free holes remain in the boundary zone of the *p*-region with a δ_p width. Therefore, a stationary bulk negative charge of ionized acceptor atoms is formed in the δ_p zone. Between these volume charges there is an internal electric field of E_{in} voltage. This field is inhibitory for the main charge carriers and accelerated for the non-main charge carriers. At a certain value of $E_{in}>\varphi_c$, where φ_c is a potential barrier, the internal electric field prevents further diffusion of the main charge carriers. Under this condition, thermodynamic equilibrium occurs at constant temperature and in the absence of an external electric field. A double locking layer with a thickness of $\delta=\delta_n+\delta_p\approx 1$ µm (*p-n* junction) with high resistance is formed due to the very low concentration of free electrons and holes in this layer. For germanium the potential barrier is φ_c = 0.2 ... 0.4 V, and for silicon φ_c = 0.5 ... 0.75 V.

According to ***variant "b"***, the external source of electric power with its electric field of E_{ex} voltage acts towards the internal electric field of E_{in} (Fig. 3.13, *b*). Therefore, the resulting field strength in the *p-n* junction $E_{res}=E_{in}-E_{ex}$ decreases, which leads to a decrease in its potential barrier $\varphi_{res}=\varphi_c-u_{ex}$ and a decrease in the distance δ. This option is called direct activation of the *p-n* junction. In this embodiment, the barrier layer δ is filled with charge carriers and is narrowed, and at a certain value of the voltage u_{ex} of the external source *p-n,* the transition becomes open to the so-called direct electric current i_d. This current results from the movement of the main charge carriers with a relatively high energy sufficient to overcome the potential barrier φ_{res} of the barrier layer and penetrate into neighbouring areas. The electrons penetrate from the *n*-region into the *p*-region, and the holes from the *p*-region into the *n*-region, where they recombine. The voltage drop at the *p-n* junction in this case is called the direct voltage drop U_d and is considered positive.

According to ***variant "c",*** the external source of electric supply with its electric field E_{ex} coincides in its direction of action with the internal electric field E_{in} (Fig. 3.13, *c*). Therefore, the resulting field strength in the *p-n* junction $E_{res}=E_{in}+E_{ex}$ is increased, which leads to the increase in its potential barrier $\varphi_{res}=\varphi_c+u_{ex}$ and an increase in δ. This option is called the reverse switching of the *p-n* junction. In this variant, under the action of an external voltage u_{ex} electrons and holes as the main charge carriers are shifted in different directions from the *p-n* junction, the barrier layer δ expands, and the *p-n* junction becomes closed to electric current. The main charge carriers are unable to overcome the potential barrier φ_{res} of *p-n* junction, and move to neighbouring areas. The voltage drop at the *p-n* junction in this case is called the reverse voltage u_r and is considered negative. When $/u_r/>/u_{br}/$ there is a breakdown of the *p-n* junction due to an avalanche-like increase in the concentration of free charge carriers, where u_{br} is the voltage of the electric breakdown.

Real semiconductors, in addition to the main charge carriers (electrons in the *n*-region and holes in the *p*-region), contain a very small number of non-basic charge carriers (electrons in the *p*-region and holes in the *n*-

region), for which the potential barrier of *p-n* junction is completely absent. Therefore, there is a very small reverse current i_r when the *p-n* junction of semiconductors is switched on in reverse.

3.7.4 Using the properties of p-n junctions

The properties of *p-n* junctions, which occur during electrical contacts of *n*-type and *p*-type semiconductors, are related to their ability to transmit electric current in only one direction (valve properties), as well as the controllability of this process. These properties are the basis of the operation principle of a large number of semiconductor devices: diodes, transistors, thyristors, zener diodes, varicaps, integrated circuits, and microchips. Such semiconductor devices are able to operate only at a moderate temperature, at which the impurity conductivity dominates over the intrinsic conductivity of the semiconductor. The appearance of its own electrical conductivity at too high temperature leads to a violation of normal operation and controllability of the *p-n* junction.

Varicap – is a semiconductor capacitor of controlled capacity. Its operation is based on the dielectric property of the potential barrier of the *p-n* junction to vary in proportion to the reverse voltage u_r of the external source (Fig. 3.13, c). The capacity of the flat varicap C_{var} is determined in principle by the same formula as the capacity of a conventional flat capacitor (1.4), but you need to consider the width δ of the barrier layer *p-n* junction as the distance between the covers of the varicap. The dependence of varicap capacitance C_{var} on the absolute value of the reverse voltage u_r is inversely proportional and resembles a hyperbola, taking into account formula (1.4) and the direct dependence of the width δ of the barrier layer *p-n* junction on u_r. (Fig. 3.14, *a*).

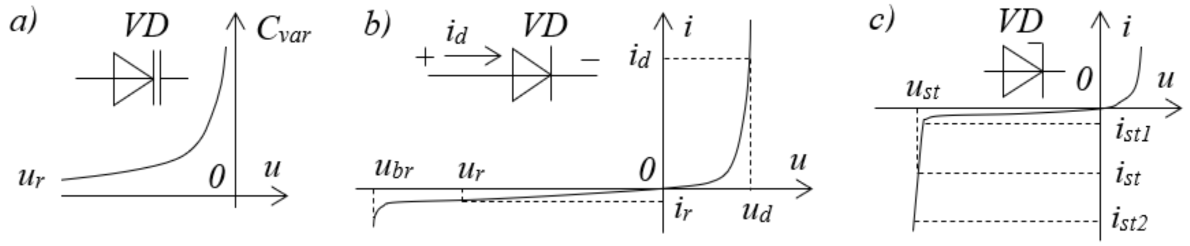

Figure 3.14 – The main characteristics of varicap (*a*), diode (*b*) and zener diode (*c*)

Diode – is a semiconductor device that uses the valve properties of the *p-n* junction of semiconductors. Diodes are commonly used to rectify alternating electric current. The dependence of the electric current of the diode $i(u)$ on the applied voltage (volt-ampere characteristic) is significantly nonlinear (Fig. 3.14, *b*). At direct connection of the diode (at $u > 0$) there is a direct electric current i_d and direct voltage drop u_d, which can reach 0.2 ... 1.1 V, and in normal conditions is the main cause of heating of the diode because of losses $\Delta P = u_d \cdot i_d$, in it. When the diode is switched on again (at $u < 0$) the diode usually almost does not pass the reverse current i_r. Therefore, this current and losses $\Delta P = u_r \cdot i_r$ are often neglected. But when using diodes in high-frequency devices, especially when the diode is supplied with alternating voltage in the form of rectangular pulses with very steep fronts, reverse current and losses from it cannot be neglected. In such cases we even have to consider the operation of the diode in a mode close to the short-circuit mode, at the time of switching the diode from the conductive state to the non-conductive state. At high frequencies it is also necessary to take into account the electrical capacitance of the *p-n* junction, which depends on the voltage and can significantly slow down the process of diodes switching. At the inadmissibly large value of the reverse voltage (at $/u_r/ > /u_{br}/$) there is a breakdown of the *p-n* junction and the loss of semiconductor properties.

Zener diode – is a semiconductor diode in which the breakdown of the *p-n* junction of the reverse voltage is used as the operating mode. Zener diodes are used to stabilize the reverse voltage at the level of u_{st} in a fairly wide range of values of the stabilization current $i_{st} = i_{st1} ... i_{st2}$, which flows through the zener diode in the opposite direction (Fig. 3.14, c).

Transistor – is a three-electrode controlled semiconductor device. Bipolar transistors are the most widely used among the various types of transistors. In such transistors electric current is generated by two types of charge carriers: electrons and holes. The bipolar transistor contains a central semiconductor region of one type of conductivity (base *B*) and two extreme semiconductor regions of another type of conductivity (emitter *E* and collector *C*). The transition contacts between them (two *p-n* junctions) are created, as in semiconductor diodes, by diffusion or by fusing the corresponding impurities into the plate of the single crystal semiconductor. In a bipolar transistor two variants of semiconductor alternation are possible: *npn* and *pnp*. Each of these options, including the valve properties of the *p-n* junctions can be represented as two oppositely connected semiconductor diodes (Fig. 3.15).

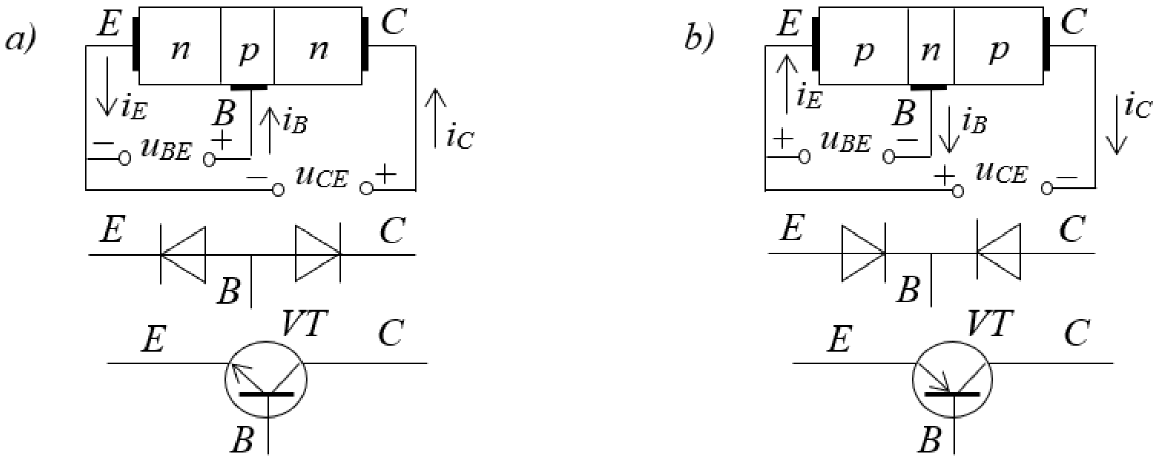

Figure 3.15 – Control of bipolar transistors of *p-n-p* (*a*) and *n-p-n* (*b*) types

Collector *C* differs from emitter *E* by a much larger *p-n* junction area and a much lower concentration of alloying impurities. In addition, to control the operation of the low current transistor i_B, its base *B* must have small thickness and a medium degree of doping of impurities.

If a voltage u_{BE} is created between the base *B* and the emitter *E* in the forward direction, then the *p-n* junction between the base and the emitter becomes open for the movement of the main charge carriers (for direct current i_B). These charge carriers are not the main carriers in the base, and therefore easily penetrate through the *p-n* junction between base *B* and collector C. The base is made thin enough that the main charge carriers of the emitter do not have time to recombine and create a significant base current. If the voltage u_{BE} between the base and the emitter is small or has the opposite polarity, then the current i_B, and hence the current i_C through the collector-emitter section will not occur. Thus, insignificant changes in the base current Δi_B are able to lead to significant changes in the current Δi_C in the collector circuit due to the change in the electrical resistance R_{CE} in the collector-emitter section. This means the amplifying and control capabilities of the transistor, i.e. $\Delta i_C/\Delta i_B >> 1$.

In the control mode of analogue signals there can be large power losses $\Delta P=(i_C)^2R_{CE}$ in the transistor. Therefore, modern electronic devices try to use transistors in the key mode, when the power losses ΔP are insignificant due to the minimum value of i_C in the closed state of the transistor or the minimum value of R_{CE} in the open state of the transistor.

Thyristor – is a three-electrode partially controlled semiconductor device, which structurally consists of four semiconductor regions of different conductivity *(pnpn)* with three *p-n* junctions. The extreme *p*-region, to which the positive pole of the power supply u_{AC} is connected, is called the anode *A*, the other extreme *n*-region, to which the negative pole is connected, is referred as the cathode *C*, and the intermediate *p*-region, to which the positive control signals i_{ce}, u_{ce} are supplied, is mentioned as the control electrode *CE* (Fig. 3.16, a). Sometimes, for convenience, the thyristor is represented as two interconnected transistors of the *pnp* and *npn* types (Fig. 3.16, b). As it can be seen from Fig. 3.16, the transition T_2 is a common collector transition of two transistors in the thyristor substitution circuit, and transitions T_1 and T_3 are emitter transitions.

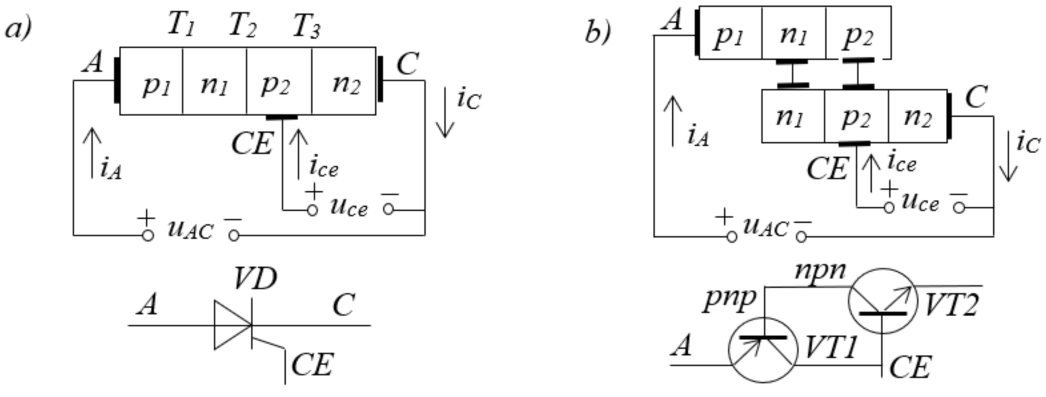

Figure 3.16 – The structure of thyristor (*a*) and the scheme of its replacement by transistors (*b*)

In the absence of control signals i_{ce} on the control electrode *CE* thyristor almost does not pass electric current in any direction, i.e. is in the off state.

When the direct voltage u_{AC} increases, the current i_A of the thyristor does not increase significantly until the voltage u_{AC} approaches the critical value: to the voltage u_{on}, the voltage of turning on. When $u_{AC}>u_{on}$ under the influence of an increasing electric field, a sharp increase in the number of charge carriers due to shock ionization in the collision of charge carriers with atoms occurs in the transition T_2. Electrons from the region n_2 and holes from the region p_1 are directed into the region p_2 and n_1, and saturate them with non-basic charge carriers. Because of this, the current in the transition T_2, and hence the current i_A of the thyristor increases sharply to the maximum possible value, which is determined by Ohm's law and almost the vertical section of the volt-ampere characteristic of the open thyristor (Fig. 3.17).

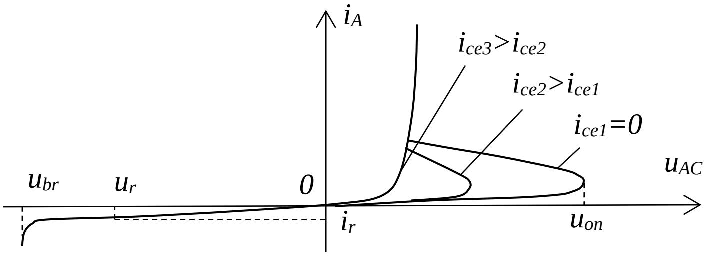

Figure 3.17 – Volt-ampere characteristic of a thyristor

The thyristor returns to the off (open) state within 1...100 μs if the direct current i_A of the thyristor becomes less than the holding current i_h. If you need to speed up the process of forced shutdown of the thyristor, then create short-term conditions for the reverse current of the thyristor. The thyristor, like the diode, does not pass current i_r in the reverse direction (at the reverse voltage u_r).

At an unacceptably high value of the reverse voltage (at $/u_r/>/u_{br}/$) there is a breakdown of the thyristor and the loss of its semiconductor properties. The switching voltage u_{on}, at which the avalanche-like increase in current i_A begins, can be reduced significantly. To do this (Fig. 3.16, a) it is necessary to introduce non-basic charge carriers in the region T_2, which will increase the ionization intensity in the *p-n* junction. This is done by applying pulse control current i_{ce} to the control electrode *CE*. At a sufficiently high value of this current, the thyristor is close to a semiconductor diode in its volt-ampere characteristic (Fig. 3.17).

3.8 Exemplary tasks on the conductive materials study

3.8.1 Determination of electrical conductivity parameters of conductors

Task: Determine the mass of copper wire with a diameter of $D = 1$ mm, from which the coil of the electromagnet is made, and its inductance L. The coil consumes alternating electric current $I = 1.7$ A of industrial frequency at a voltage $U = 220$ V and is heated to a temperature $T = 70\ ^{O}$C with power $P = 9$ W.

Solution. The mass of the wire can be determined through its length l, using formulae (3.1), (3.2), (3.3) and reference data of table. 3.1:

$$m = V \cdot d = S \cdot l \cdot d = 0.785 \cdot 10^{-6} \cdot 118.4 \cdot 8920 = 0.829(kg),$$

where $V = S{\cdot}l$ – is the amount of copper used to make the wire;

$S = \pi D^2/4 = \pi{\cdot}(10^{-3})^2/4 = 0.785{\cdot}10^{-6}$ (m^2) – is the cross-sectional area of the wire;

$l \approx R\frac{S}{\rho} = 3.1142\frac{0.785 \cdot 10^{-6}}{0.020655 \cdot 10^{-6}} = 118.4(m)$ – is wire length (3.1);

$R = P/I^2 = 9/1.7^2 = 3.1142$ (Ohm) – is electrical resistance of the coil at temperature $T = 70\ ^{O}$C (3.3);

$\rho \approx \rho_0[1 + \alpha_\rho(T - T_0)] = 0.017 \cdot 10^{-6} \cdot [1 + 0.0043 \cdot (70 - 20)] = 0.020655 \cdot 10^{-6}(Ohm \cdot m)$ – is resistivity of copper at temperature $T = 70\ ^{O}$C;

$\rho_0 = 0.017{\cdot}10^{-6}$ Ohm·m – is resistivity of copper at temperature $T = 20^{O}$C (table. 3.1);

$\alpha_\rho = 0.0043$ K^{-1} – is the average temperature coefficient of resistivity in the temperature range $T...T_0$ (table. 3.1);

$d = 8.920$ kg/m^3 is density of copper (table. 3.1).

The inductance of the coil of the electromagnet is determined using the formula 3.3:

$$L = \frac{X_L}{\omega} = \frac{1}{2\pi f}\sqrt{Z^2 - R^2} = \frac{1}{2\pi \cdot 50}\sqrt{129.41^2 - 3.1142^2} = 0.412(H).,$$

where Z=U/I=220/1.7=129.41 (Ohm) – is the impedance of the coil (3.3);

$\omega=2\pi f$ – is angular industrial frequency, s^{-1};

f = 50 Hz – is industrial frequency.

3.8.2 Determination of thermoelectric generator parameters

Task: Determine the number of series-connected electrical iron-cobalt circuits in the thermoelectric generator to obtain a voltage U = 9 V at its output at a temperature difference of the joints ΔT = 80 ^{O}C. Determine the amount of heat energy transferred from the hot junction of this heat generator to the cold junction every hour (for t = 3600 s) when the heat generator is loaded with a current I_l = 1 A.

Solution. The number of electrical circuits N of the heat generator is determined by its voltage U and the potential difference U_{12} (thermoelectric force), which is characteristic of the selected pair of conductors (iron and cobalt) at the temperature difference of the joints ΔT=80 ^{O}C (3.6):

$$N=\frac{U}{U_{12}}=\frac{U}{\psi_{12}\cdot\Delta T}=\frac{9}{36.7\cdot10^{-6}\cdot80}=3065.,$$

where $\psi_{12}=\psi_1-\psi_2=16.6\cdot10^{-6}-(-20.1\cdot10^{-6})=36.7\cdot10^{-6}$ (V/К) – is relative specific thermoelectric force for the selected pair of conductors or Seebeck coefficient (3.8);

$\psi_1=16.6\cdot10^{-6}$ V/К – is absolute specific thermoelectromotive force of iron (table. 3.1);

$\psi_2=-20.1\cdot10^{-6}$ V/К – is absolute specific thermoelectromotive force of cobalt (table. 3.1).

The amount of thermal energy transferred from the hot junction of the heat generator to the cold junction can be determined using the formula (1.10):

$$W_T=I_l\cdot U\cdot t=1\cdot9\cdot3600=32400J=7739\,\text{kcal}.$$

The same heat energy will be transferred by this heat generator by lowering the temperature of the cold junction in the freezer if you create a current I_l=1 A in the opposite direction using another source of electrical energy. This follows from the Peltier electrothermal effect (3.9) and its reversibility to the Seebeck effect (see Section 3.1).

3.8.3 Determining the parameters of the electric heating element

Task: Determine the power of the electric heating element, which is made of chromal wire with a length of l = 3 m and a diameter of D = 0.5 mm. This element is connected to an electric source with a voltage U = 220 V and in a stable thermal mode has a temperature of T = 300 ^{O}C

Solution. The thermal power of the electric heating element P depends on its electric current I (or voltage U) and resistance R (1.10), the geometric parameters of the wire (3.1), the resistivity of chromal, and its temperature T (3.2):

$$P = \frac{W_T}{t} = I^2 R = \frac{U^2}{R} = \frac{220^2}{21} = 2305(W),$$

where $R = \rho \frac{l}{S} = 1.37 \cdot 10^{-6} \frac{3}{0.196 \cdot 10^{-6}} = 21(Ohm)$ – is electrical resistance of chromal wire at operating temperature T=300^{O}C (3.1);

$\rho \approx \rho_0[1 + \alpha_\rho(T - T_0)] = 1.33 \cdot 10^{-6} \cdot [1 + 10^{-4} \cdot (300 - 20)] = 1.37 \cdot 10^{-6}(Ohm \cdot m)$ – is resistivity of chromal at operating temperature T=300 ^{O}C (3.2);

$\rho_0 \approx 1.33 \cdot 10^{-6}$ Ohm·m – is resistivity of chromal at temperature T_0=20 ^{O}C (see section 3.4);

$\alpha_\rho \approx 10^{-4}$ K^{-1} – is the average temperature coefficient of resistivity of chromal in the temperature range $T_0 ... T$ (see section 3.4);

$S = \pi D^2/4 = \pi \cdot (0.5 \cdot 10^{-3})^2/4 = 0.196 \cdot 10^{-6}$ (m^2) is the cross-sectional area of the chromal wire.

3.8.4 Determining the capabilities of the superconductor

Task: Determine the maximum possible value of the direct electric current I_{max} in a superconductor made of niobium stanidum Nb_3Sn in the absence of an external magnetic field and the operating temperature T = 10 K, assuming a 40% margin for the critical values of temperature T_c and magnetic induction B_c. The diameter of the electrically conductive part of the superconducting cable, which may consist of thin wires or films of niobium stanidum, is limited by the value D_{cab}=5 mm.

Solution. The superconductivity band of the niobium stanidum Nb_3Sn is known to be bounded by the axes of the critical values of the temperature T_c and the magnetic induction B_c and the curve $B_c=f(T_c)$. This curve in relative units ($\underline{B}_c=B_{\text{к}}/B_{\text{к}0}$, $\underline{T}_c=T_c/T_{\text{к}0}$) is very close to a circle with a unit radius, where B_{c0}=22T, T_{c0}=18K (see section 3.3 and Fig. 3.12, b). The curve of operating values of magnetic induction and temperature in relative units, in which according to the task, a 40% margin ($\underline{B}=B/0.6B_{c0}$, $\underline{T}=T/0.6T_{c0}$), must be provided is also close to a circle with a unit radius:

$$\left(\frac{B}{0{,}6\cdot B_{c0}}\right)^2+\left(\frac{T}{0{,}6\cdot T_{c0}}\right)^2=1,$$

where T=10 K – is operating temperature of the superconductor (set under the conditions of the task);

$$B=0.6\cdot B_{c0}\cdot\sqrt{1-\left(\frac{T}{0.6\cdot T_{c0}}\right)^2}=0.6\cdot 22\cdot\sqrt{1-\left(\frac{10}{0.6\cdot 18}\right)^2}=$$

$4.986(T)$ – is working magnetic induction as a result of solving this equation

When determining the maximum possible value of the electric current I_{max} in the cable one must be based on its most critical place, where the magnetic induction is maximum. Such a place in a superconducting cable is a very thin layer of the outer cylindrical surface of its electrically conductive part, where the current is displaced according to the Meissner effect (see section 3.3) and where the operating magnetic induction B reaches its maximum according to the law of total current (see sections 1.2):

$$I\kappa\,\frac{B}{\mu_0}_{cab}\;\frac{B}{4\pi\cdot 10^{-7}}_{cab}\;\frac{4{,}986}{4\cdot 10^{-7}}_{max},$$

where H – is operating magnetic field strength on the cylindrical surface of the superconductor, which is directly proportional to the current I_{max} (1.20) and the operating magnetic induction B (1.21);

3.9 Test questions on conductive materials

1. What are the main functions of an electric conductor?
2. Identify the main difference between an electric conductor and a dielectric.
3. What factors affect the resistivity of the conductor?
4. Name the main properties of conductive materials.
5. How can you measure the resistivity of a conductor?
6. What are the physical laws to determine the electric current in a conductor?
7. What determines the electrical conductivity of the conductor?
8. Name the main causes of active and reactive resistance. In which cases can the term "reactive resistance" be used?
9. How does the frequency of electric current affect the active and reactive resistance of the conductor?
10. Propose a scheme for replacing the inductor coil at high frequency electric current.
11. Explain the phenomenon of electron emission from the metal surface.
12. What is the contact difference of potential?
13. What is the relationship between the contact difference of potential and the Seebeck effect?
14. In which cases can a thermoelectric force occur in a closed electric circuit?
15. Name the difference between the Seebeck and Peltier effects. How can the Seebeck and Peltier effects be used in practice?
16. Explain the causes of stray currents. What are the negative consequences of stray currents? Name the means of reducing stray currents and their potentials.
17. What materials are called high conductivity conductors?
18. Name the main electrically conductive alloys based on copper.
19. 19.What are the advantages and disadvantages of aluminium as a conductor of electric current compared to copper?
20. Name the main electrically conductive alloys based on aluminium.
21. What are the requirements for aluminium to be used as a cryoconductor?

22. What are superconductors and what are their main differences from conventional conductors?

23. Explain the essence of the Meissner effect in superconductors.

24. What is the physical nature of superconductivity?

25. Explain the difference between superconductors of the 1st and 2nd kind.

26. Explain the practical value of superconductors?

27. What materials are called conductors of high electrical resistance?

28. Name the conductive alloys of high electrical resistance based on copper.

29. What metals do alloys contain for the manufacture of electric heating elements?

30. In what cases it is expedient to use precious metals as conductors of electric current?

31. Name fusible metals and their area of use.

32. What non-metallic materials should be used as conductors of electric current?

33. Name the main advantages and disadvantages of non-metallic conductors compared to metallic conductors.

34. What are electric brushes and in what cases are they used?

35. What is the fundamental difference between semiconductors and conductors and dielectrics?

36. What are the reasons for the significant dependence of the electrical conductivity of semiconductors on the influence of energy factors (temperature, light, electric field)?

37. What is the difference between *n*-type and *p*-type semiconductors?

38. Explain the role of donors and acceptors in the manufacture of semiconductor elements.

39. What is the hole electrical conductivity of semiconductors?

40. What properties of *p-n* junctions between semiconductors are most useful for the manufacture of semiconductor devices?

41. Name the main differences between the diode, varicap and zener diode.

42. How is the controllability of *p-n* junctions manifested in the transistor?

43. Name the main difference between a transistor and a thyristor.

4 MAGNETIC MATERIALS

All materials in a magnetic field (see section 1.2) necessarily interact with it by force and therefore exhibit their magnetic properties, since any materials contain moving charged particles (see section 1.1). The force of this interaction can be called the Lorentz force (see section 1.2). As a result of this interaction, charged particles can change their motion and thus affect the resulting magnetic field. Materials that enhance the magnetic field and the concentration of magnetic field lines in a certain area are called magnetic materials. These properties are most useful when it is necessary to connect electric circuits or circuits with a magnetic field in order to create Faraday electromotive forces and Lorentz and Ampere forces (see sections 1.2): in transformers, generators, motors, inductors, inductor coils, and other electromagnetic devices [2...3]. Magnetic materials include ferromagnetic crystalline substances (ferromagnets) and ferrimagnetic chemical compounds (ferrites).

4.1. Physical processes and phenomena in magnetic materials

4.4.1 General information about magnetic properties

The magnetic properties of materials are due to elementary circular currents at the microscopic level, which are able to create their own magnetic fields (magnetic moments M), be changed under the influence of an external magnetic field and thus affect the resulting magnetic field. The elementary currents include, first of all, the rotation of electrons around their own axes (electron spins) and the rotation of electrons in atoms (Fig. 1.1). The magnetic moments of nuclei are three orders of magnitude smaller than the magnetic moments of the electronic shells of atoms, and therefore the magnetic moments of nuclei are usually neglected.

The magnetized material, which is in the external magnetic field, creates its own magnetic field, which in isotropic materials is directed parallel or antiparallel to the external field. Therefore, the magnetic induction B of the resulting magnetic field in the material is determined by the algebraic sum of the induction of the external field B_0 and the internal field $B_{вн}$ (1.21):

$$B = B_0 + B_{in} = \mu_0 H + \mu_0 J_M = \mu_0(H + J_M) = \mu_0(1 + k_M)H =$$
$$= \mu_0 \mu_r H = \mu_a H, \tag{4.1}$$

where B_0 – is magnetic induction of external magnetic field in vacuum (excluding the influence of magnetic material), T;

B_{in} – is magnetic induction of the internal field, which is due to the internal magnetic moments (magnetization of J_M) of the magnetic material, T;

$H \approx \frac{1}{l}\sum_k i_k = \frac{F}{l}$ – is magnetic field strength generated by external electric currents i_k according to the law of total current (1.20), A/m;

F – is magnetizing (magnetomotive) force, A;

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m – is absolute magnetic permeability of vacuum (magnetic constant);

$J_M = M/V = k_M \cdot H$ – is magnetization of the magnetic material under the influence of the magnetic field (vector sum of magnetic moments M of all atoms in the unit volume V of the magnetic material), A/m [7];

$k_M = \mu_r - 1$ – is magnetic susceptibility, which characterizes the ability of a material to change its magnetic moment under the influence of an external magnetic field;

$\mu_r = \mu_a / \mu_0$ – is relative magnetic permeability of the material;

$\mu_a = \mu_r \cdot \mu_0$ – is absolute magnetic permeability of the material, H/m.

4.1.2 Classification of materials according to their ability to be magnetized

According to the ability to magnetize and affect the resulting magnetic field, all materials are divided into 5 groups: diamagnets, paramagnetics, ferromagnets, antiferromagnets and ferrimagnets [7].

Diamagnets are materials in which atoms or molecules do not have their own magnetic moment. They can have only a small induced magnetic moment of opposite orientation with respect to the external magnetic field, and therefore can only slightly weaken it (k_M=–10^{-6}...10^{-7}<0; 0<μ_r<1). A negative value of the magnetic susceptibility k_M leads to the ejection of diamagnets from the magnetic field. Diamagnets include most dielectrics and semiconductors, a number of metals (copper *Cu*, silver *Ag*, gold *Au*, zinc *Zn*, mercury *Hg*, gallium *Ga*) and metalloids (phosphorus *P*, sulphur *S*, silicon *Si*, etc.), as well as substances in the superconducting state.

Paramagnetics are materials, in which atoms or molecules in the absence of an external magnetic field have a small intrinsic magnetic moment, which occurs due to some uncompensated spin magnetic moments of electrons. These moments practically do not interact with each other, are oriented chaotically, and therefore the resulting magnetic moment M = 0. Under the influence of an external field, the magnetic moments of atoms are oriented in the direction of this field and therefore somewhat amplify it (k_M=10^{-3}...10^{-6}; μ_r>1). Paramagnetism is manifested in alkali metals (sodium *Na*, potassium *K*) and in some transition metals with an unfinished electronic shell (titanium *Ti*, vanadium *V*, chromium *Cr*, manganese *Mn*).

Ferromagnets are similar to paramagnets, but the spin magnetic moments of their electrons interact closely with each other and form magnetic domains with a volume of 0.001 ... 10 mm^3. Domains are in a state of magnetic saturation due to the same orientation of the magnetic moments of all its atoms. The domain structure is formed in the absence of an external magnetic field due to spontaneous (spontaneous) magnetization at temperatures below T_c (Curie point). For example, for pure iron T_c=768 ^{O}C, for nickel T_c=358 ^{O}C, for cobalt T_c=1131 ^{O}C. In the absence of an external magnetic field, the magnetic moments of the domains are oriented almost chaotically, and therefore their resulting magnetic moment is almost zero. But under the influence of an external magnetic field the magnetic moments of domains are easily oriented in the direction of this field and amplify it many times, being strongly dependent on the strength of the external magnetic field (k_M≈μ_r=10^2...10^6). At the same time domains are additionally magnetized, increasing in the sizes. Ferromagnets include three transition metals with an unfinished electronic shell and alloys based on them (iron *Fe*, nickel *Ni*, and cobalt *Co*), as well as some rare earth elements that have not been used as ferromagnets due to very low values of T_c.

Antiferromagnets are materials in which atoms, like paramagnetics and ferromagnets, have their own magnetic moment. But under the influence of an external magnetic field and due to the exchange interaction the magnetic moments acquire the opposite orientation and compensate each other (k_M=10^{-3}...10^{-5}) almost completely. Antiferromagnets include a fairly large number of compounds based on manganese *Mn*, chromium *Cr*, Nickel *Ni*, and vanadium *V*.

Ferrimagnets (ferrites) are crystalline materials with a domain structure. Their domains consist of two or more different magnetic sublattices, which are interconnected antiparallel (antiferromagnetic). The result is a nonzero difference in the magnetic moments of the sublattices, which leads to spontaneous magnetization of the crystals. Thus, ferrites can be considered as uncompensated antiferromagnets. In terms of their magnetic properties ferrites are inferior to ferromagnets in the magnetic induction of saturation, but have a much higher resistivity ρ, which can reach 10^{11}Ohm·m. The high resistivity virtually eliminates eddy currents in ferrites, which allows their use in high-frequency magnetic fields. Ferrites are a complex system of metal oxides with the general chemical formula $MeO \cdot Fe_2O_3$, where *MeO* is a divalent metal oxide.

4.1.3 Magnetization of magnetic materials

The process of magnetization of magnetic materials (ferromagnets and ferrites) under the influence of external magnetic field is accompanied by a shift of domain boundaries, rotation of their magnetic moments in the direction of external magnetic field and increase of some domains due to other domains; up to full magnetic saturation [6]. In this state almost all single crystals become single-domain, constant in their linear dimensions, and oriented in the direction of the external magnetic field.

Magnetostriction – the phenomenon of changing the linear dimensions of ferromagnetic single crystals in the process of magnetization of magnetic material. This phenomenon is characterized by the magnetostriction constant $\lambda_s = \Delta l / l$, a change in the length of the sample of magnetic material in relation to the length *l* of this sample. If the material sample is elongated in the direction of the magnetic field due to the reduction perpendicular to the direction of the magnetic field, then the sign of the value of λ_s is positive, and if vice versa, negative. The value of λ_s and even its sign depends on the strength H of the magnetic field. Of the three main ferromagnets the largest magnetostriction occurs in nickel (λ_s=–3,7·10^{-5}). Very high magnetostriction occurs in rare earth elements: in terbium *Tb*, dysprosium *Dy*, holmium *Ho*, erbium *Er*, thulium *Tm*. For example, polycrystalline terbium has $\lambda_s=3\ 10^{-3}$, and monocrystalline terbium has $\lambda_s=2\ 10^{-2}$ [7]. Magnetostriction is used in magnetostrictive ultrasonic transducers, in which the energy of an alternating magnetic field is converted into the energy of mechanical vibrations (or vice versa).

The phenomenon of magnetostriction, like many other phenomena, can be reversed, i.e. mechanical deformation of the ferromagnet changes its magnetization. This phenomenon is called the magnetoelastic effect or the Villari effect. This effect is the basis of magnetoelastic transducers (strain gages). They use the dependence of the change in magnetic permeability $\Delta\mu_r$ or magnetic induction ΔB on mechanical stresses and forces. The sensitivity of the magnetoelastic material is characterized by the strain sensitivity coefficient $K_S=(\Delta\mu_r/\mu_r)/\lambda_s$, where $\lambda_s=\Delta l/l$ is the magnetostriction constant. The coefficient of strain sensitivity can reach the values of K_S=300.

Magnetic anisotropy – is the dependence of properties of the magnetic material on the selected direction. Its reason is the anisotropic nature of the magnetic interaction between the atomic carriers of the magnetic moment. Especially large magnetic anisotropy occurs in single crystals of ferromagnets. It is manifested in the presence of the axes of the lightest magnetization, which are characterized by the maximum values of magnetic susceptibility k_M (4.1) and the minimum consumption of electrical energy for the magnetization process. In the absence of an external magnetic field, the magnetic moments of the domains are spontaneously oriented along one of the axes of light magnetization. With increasing temperature, the effect of magnetic anisotropy is weak, and at temperatures above the Curie point T_c it disappears completely. The anisotropy effect is used in the manufacture of thin sheets of electrical steel by cold rolling technology. In such sheets, the axis of light magnetization coincides with the direction of rolling. The use of cold-rolled sheets of electrical steel in the magnetic circuits of the transformer significantly reduces the cost of electrical energy to create a working magnetic induction.

The main magnetization curve of magnetic materials

The process of magnetization of magnetic materials is characterized by the main (static) magnetization curve $B=f(H)=\mu_a \cdot H$ (1.21), where $B=\Phi/S$ is the magnetic induction or magnetic flux density Φ (1.16); S is the cross-sectional area of the magnetic field lines; μ_a is the absolute magnetic permeability of the magnetic material; H is the magnetic field strength at a certain point of the magnetic material (see subsection 1.2.4), which depends on the magnetizing (magnetomotive) force F of the external currents i_k (1.19) and is used as an intermediary between the magnetic induction B and the magnetomotive force F of the currents i_k (1.17).

The magnetization curves $B = f (H)$ are similar for all magnetic materials and have a nonlinear character (Fig. 4.1), where B_s is the magnetic induction of saturation; B_m is the maximum (operating) magnetic induction, which is usually selected to be by ≈35% less than the saturation induction ($B_m \approx 0.65 \cdot B_s$) to reduce the negative impact of the nonlinear nature of the curve $B = f (H)$.

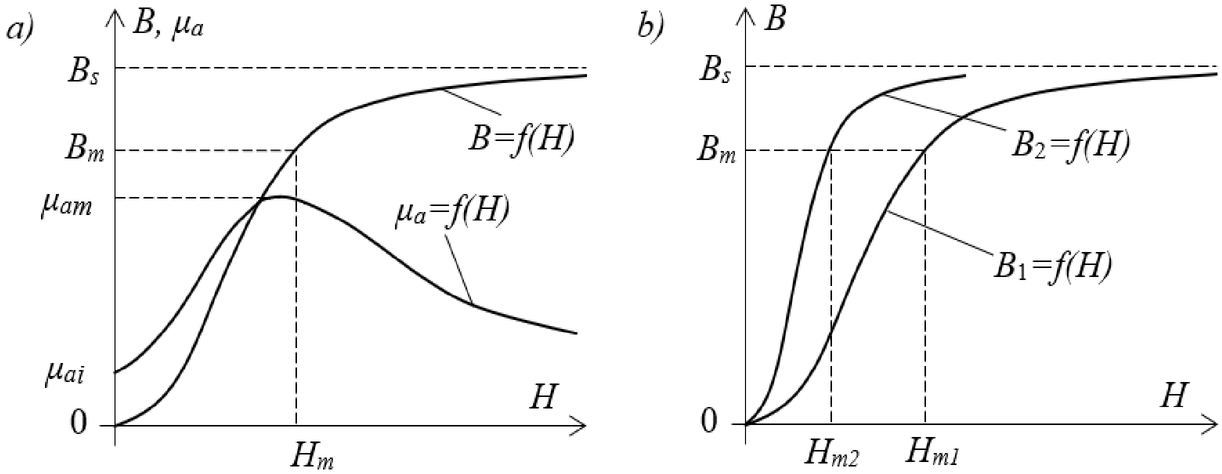

Figure 4.1 – Magnetic induction *$B=f(H)$* and absolute magnetic permeability *$\mu_a=f(H)$*

The main magnetization curve $B = f (H)$ can be determined experimentally if the magnetization process begins from a completely demagnetized state of the magnetic material and the intensity H is gradually increased to a state of saturation of the magnetic material. The dependence of the absolute magnetic permeability on the magnetic field strength $\mu_a=B/H=f(H)$ is also nonlinear (Fig. 4.1, a), where μ_{ai} is the initial absolute magnetic permeability at H=0; μ_{am} is the maximum value of magnetic permeability. To understand the importance of magnetic permeability we can compare two magnetization curves $B_1=f(H)$ and $B_2=f(H)$ (Fig. 4.1, b). The curve $B_2=f(H)$ with a larger value of μ_a has an advantage over the curve $B_1=f(H)$ because it requires less magnetic field strength ($H_{m2}<H_{m1}$), and therefore less power consumption to obtain the operating induction B_m other things being equal.

The absolute magnetic permeability μ_a decreases with increasing frequency of the alternating magnetic field due to the inertia of magnetic processes [6]. In strong magnetic fields (at very large values of H) μ_a decreases significantly and may even approach the magnetic permeability of the vacuum μ_0. As the temperature of the ferromagnet rises above the Curie point T_c, there is an abrupt decrease in μ_a to μ_0.

An important characteristic of ferromagnets when used in alternating magnetic fields is the dynamic magnetic permeability $\mu_{a\sim}$:

$$\mu_{a\sim} = \frac{B_m}{H_m} \approx const, \tag{4.2}$$

where B_m, H_m – amplitude values of induction and magnetic field strength.

When analysing the operation and design of electrical devices of alternating electric current, the dynamic magnetic permeability $\mu_{a\sim}$ is often taken as constant ($\mu_{a\sim}$=const) and independent of H, especially if the amplitude value of the magnetic induction B_m is chosen significantly lower than the saturation induction B_s [12].

4.1.4 Reversal magnetization of magnetic materials

Magnetic hysteresis

If you magnetize the ferromagnet slowly, and then reduce the magnetic field strength H from any point of the main magnetization curve (Fig. 4.1), the induction B will decrease not along the main magnetization curve, but with some lag. This phenomenon is called magnetic hysteresis. As a result of this phenomenon the dependence graph $B = f(H)$ after the end of the complete reversal cycle takes the form of a static hysteresis loop. By changing the magnetic field strength you can get a number of hysteresis loops, as shown in Fig. 4.2.

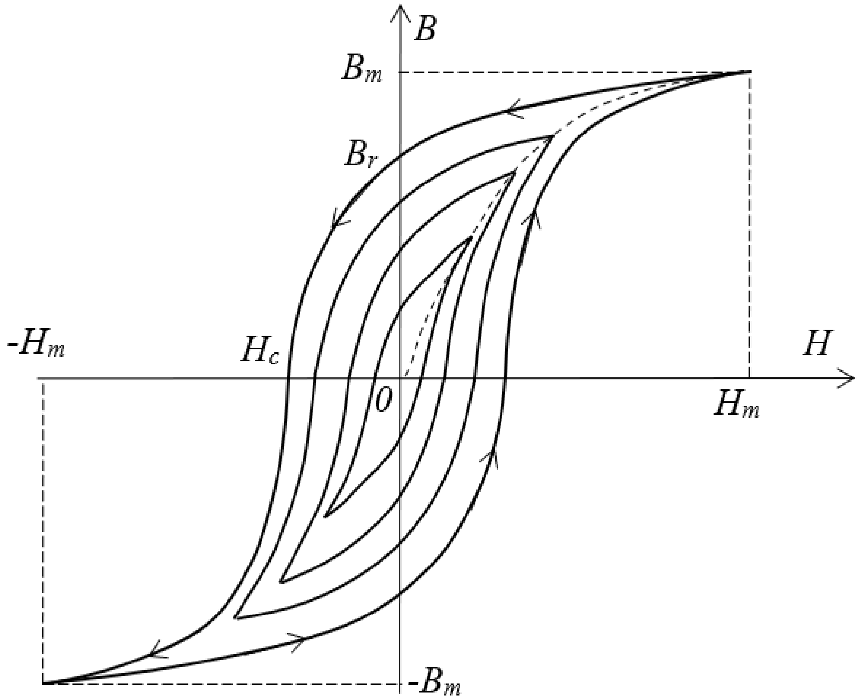

Figure 4.2 – Static loops of magnetic hysteresis in ferromagnets

The hysteresis loop at maximum induction $B=B_m$ close to the saturation induction B_s is called the limit hysteresis loop. The value of B that remains at $H = = 0$ in the process of demagnetization of the material from the saturation state is called the residual induction B_r. To bring the induction from the value of B_r to zero it is necessary to create the strength H_c of inverse direction, which is called the coercive force. Hysteresis loops are symmetric with respect to the origin if there are no constant components of the magnetic field strength H_0 or the magnetizing current I_0.

Sometimes magnetic materials are used in an alternating magnetic field while simultaneously magnetizing with a constant magnetic field of intensity H_0. In these cases, the remagnetization process is characterized by a partial hysteresis cycle (Fig. 4.3) with amplitude values of the intensity $H_{\sim}$ and magnetic induction $B_{\sim}$, and the properties of ferromagnets are characterize by differential magnetic permeability μ_{ad}, which depends on H_0:

$$\mu_{ad} = \frac{B_{\sim}}{H_{\sim}} = f(H_0). \tag{4.3}$$

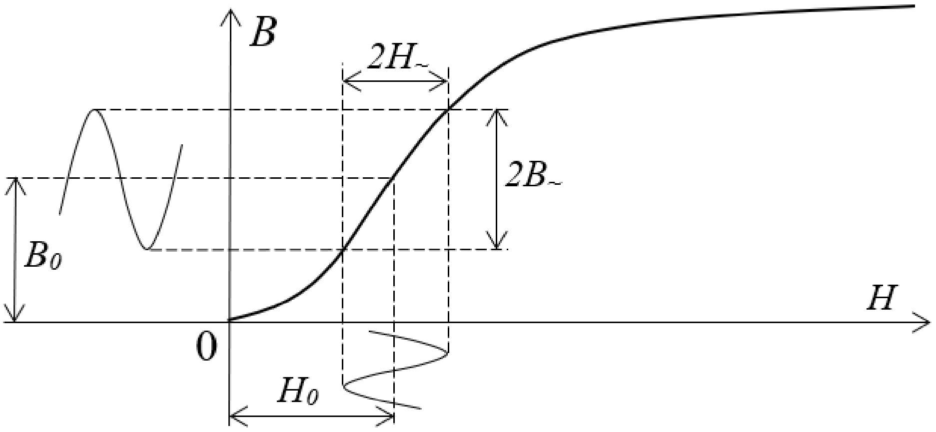

Figure 4.3 – Magnetization of ferromagnets by a constant magnetic field

Magnetic amplifiers work on the basis of the dependence $\mu_{ad}=f(H_0)$. In some cases, for example, when the magnetizing winding is powered by an electronic inverter, a constant voltage component H_0 can occur spontaneously.

Magnetic losses

The presence of the coercive force H_c in the hysteresis loop (Fig. 4.2) means the loss of energy for each cycle of static reversal of the ferromagnet, which is proportional to the area of this loop S_h. Power loss P_h due to hysteresis can be determined by the empirical formula [6]:

$$P_h = \eta \cdot f \cdot B_m^n \cdot V, \tag{4.4}$$

where η – is a factor that depends on the material;

B_m – is amplitude of magnetic induction;

n = 1.6...2.0 – is degree indicator;

f – is cyclic current frequency;

V – is the volume of the ferromagnet sample.

With an alternating magnetic field, in addition to losses due to hysteresis, there are additional losses from eddy currents in the ferromagnet, as well as due to the so-called magnetic aftereffect or magnetic viscosity of the material. Therefore, in the experimental determination of magnetic losses it is better to use dynamic hysteresis loops, which are the dependence of the instantaneous values of magnetic induction B on the instantaneous values of the magnetic field H. Dynamic hysteresis loops are slightly wider (have a higher value of H_c) compared to static loops of magnetic hysteresis (Fig. 4.2). The losses of electric power on the eddy currents P_f are significantly dependent on the frequency of the magnetic field and the electrical conductivity of the ferromagnet. These losses can be determined by the empirical formula [6]:

$$P_f = \xi \cdot f^2 \cdot B_m^2 \cdot V, \tag{4.5}$$

where ξ – is coefficient that depends on the type and shape of the ferromagnet, as well as its electrical resistivity ρ (3.1).

Dependence of magnetic induction on the voltage of the source

Consider the process of reversal magnetization of ferromagnets on the example of reversal magnetization of the magnetic circuit of an unloaded single-phase transformer. Its primary winding with N_1 number of turns is connected to the AC voltage source u_1, which in normal situations varies according to the sinusoidal law $u_1=U_m \cdot \sin\omega t$ (Fig. 4.4).

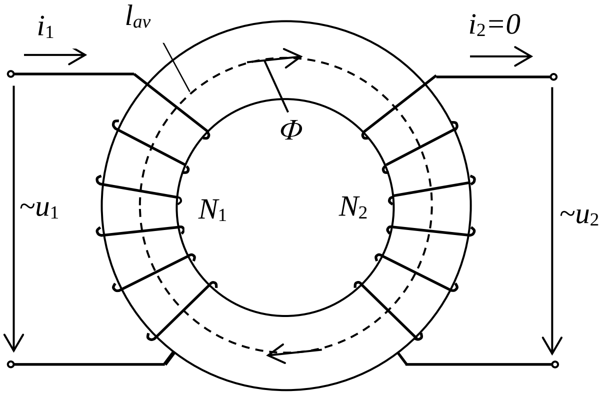

Figure 4.4 – Unloaded single-phase transformer

The winding N_1 with current i_1 together with the magnetic circuit becomes an inductor with a ferromagnetic core (choke), considering the lack of load current i_2 in its secondary winding N_2

Assume that the electric current i_1, the magnetic flux Φ, and the magnetic induction B vary according to the sinusoidal law, as does the voltage u_1. Assume also that the dynamic magnetic permeability $\mu_{a\sim}$ of the ferromagnet (4.2) is constant ($\mu_{a\sim}$=const) and essentially high, so almost all magnetic lines of force are concentrated in the magnetic circuit, i.e. the magnetic scattering flux Φ_σ outside the magnetic circuit is absent ($\Phi_\sigma \approx 0$). Then, according to Faraday's law of electromagnetic induction (1.22), the electromotive force (EMF) in the primary winding of the transformer:

$$e_1 = -N_1 \frac{d\Phi}{dt} = -N_1 \frac{d}{dt}(B_m S \cdot sin\,\omega\, t) =$$
$$= -B_m 2\pi f N_1 S \cdot cos\,\omega\, t = -E_{m1}\, cos\,\omega\, t, \qquad (4.6)$$

where $\Phi \approx \Phi_m \cdot \sin\omega t = B_m S \cdot \sin\omega t$ – is magnetic flux in the magnetic circuit, which penetrates the turns of the windings N_1 and N_2 of the transformer and varies almost according to the sinusoidal law, W;

$B_m = \Phi_m/S$ – is amplitude of magnetic induction, T;

S – is the cross-sectional area of the magnetic circuit, m^2;

$\omega = 2\pi f$ – is angular frequency of change of electric current and magnetic flux, s^{-1};

f – is cyclic frequency of change of electric current and magnetic flux, Hz;

$E_{m1} = B_m 2\pi f N_1 S$ – is the amplitude of the EMF in the primary winding of the transformer, V.

If we neglect the voltage drop across the active resistance of the primary winding, then from (4.6) the following formula for calculating the current (effective) voltage values in the transformer windings (see section 1.2):

$$\begin{cases} U_1 \approx \frac{E_{m1}}{\sqrt{2}} = 4.44 B_m f N_1 S; \\ U_2 \approx \frac{E_{m2}}{\sqrt{2}} = U_1 \frac{N_2}{N_1} = 4.44 B_m f N_2 S. \end{cases} \qquad (4.7)$$

It is important to note that the voltage U_1 (4.7) is given by an alternating current source and cannot depend on the magnetic induction B, the current i_1 or the magnetic field strength H. Therefore, the intensity H in the magnetization curve $B = f\ (H)$ (Fig. 4.1) must be considered as a consequence of the magnetic induction B, which is given by the voltage U_1 and is directly proportional to this voltage (4.7). Significantly nonlinear interdependence of B and H becomes fundamentally important in the area of saturation of ferromagnets (Fig. 4.1). In this section a slight increase in the voltage ΔU_1, and hence the magnetic induction ΔB, corresponds to a significant (sometimes multiple) increase in the magnetic field strength ΔH and the electric current ΔI_1 in the magnetizing winding. This means the risk of failure of the transformer.

4.2 Measurement of basic parameters of magnetic materials

The main parameters of ferromagnets mean magnetic permeability, magnetic losses and magnetic resistance. The simplest variant of the scheme of measurement of these parameters is given in fig. 4.5.

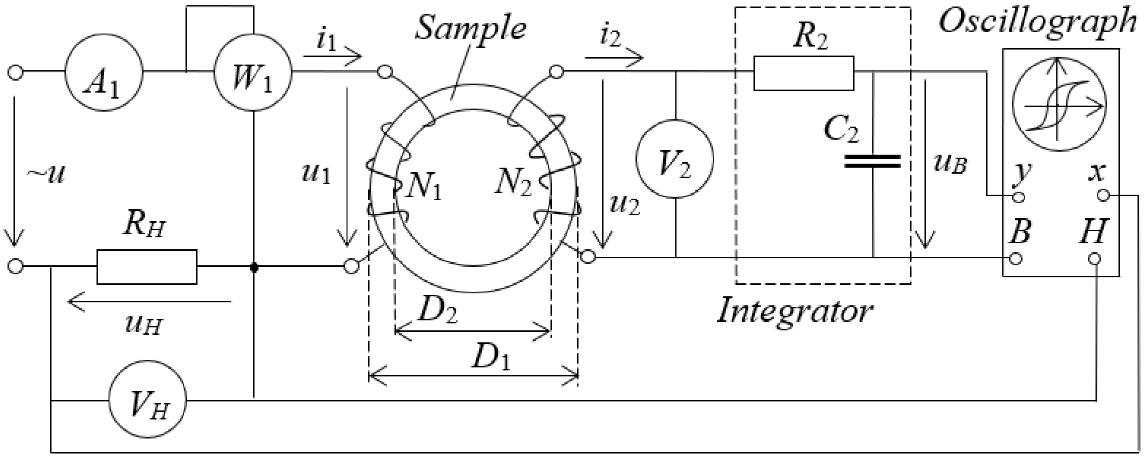

Figure 4.5 – Scheme of measuring the main parameters of ferromagnets

The magnetic flux Φ and the induction B in the ferromagnet sample are generated by an alternating electric current i_1 in the primary (magnetizing) winding N_1, which is connected to a sinusoidal voltage source $u=U_m\sin\omega t$.

With the help of a shunt with a small resistance R_H a voltage drop u_H is created, which is directly proportional to the current i_1 and the magnetic field strength H, and is fed to the input *“x”* of the oscillograph. The active power consumed by the primary winding N_1 is measured by a wattmeter W_1. The current value i_1 is measured by an ammeter A_1. The law of change of this current deviates from the sinusoidal law due to the nonlinearity of the magnetization curve of the ferromagnet $B\ (H)$. Therefore, to determine the amplitude of this current I_{m1} and the magnetic field strength H_m in the scheme of Fig. 4.5 an amplitude voltmeter V_H is used. It is connected to the R_H shunt.

The secondary winding N_2 is used to obtain the voltage u_2, which is proportional to the rate of change (derivative) of the magnetic induction according to (1.24):

$$u_2 = -e_2 = N_2 \frac{d\Phi}{dt} = N_2 S \frac{dB}{dt}, \tag{4.8}$$

where $S=0.5\cdot(D1\text{–}D2)\cdot h$ – is cross-sectional area of the ferromagnet sample, m^2;

h – is the thickness of the ferromagnet sample, m;

N_2 – is the number of turns of the secondary winding.

The effective value of this voltage is measured by voltmeter V_2. The voltage u_2 is integrated by the *RC*-integrator to form a voltage u_B directly proportional to the instantaneous value of the magnetic induction B (4.8), and then fed to the input *"y"* of the oscillograph.

Thus, electric voltages u_H and u_B, directly proportional to the instantaneous value of the magnetic field strength H and magnetic induction B are formed at the inputs *"x"* and *"y"* of the oscilloscope. This allows you to get dynamic loop of magnetic hysteresis $B\ (H)$ on the oscillograph screen and determine the basic properties or parameters of the ferromagnet using the loop.

4.2.1 Determination of magnetic permeability according to instrument readings

According to the readings of electrical meters of the scheme of fig. 4.5 it is possible to determine the amplitude values of the magnetic field strength H_m and the magnetic induction B_m in the investigated sample of the ferromagnet for further calculation of the dynamic magnetic permeability $\mu_{a\sim}$ (4.2).

The amplitude of the voltage H_m is determined in accordance to the Ampere's circuital law (1.20) according to the readings of the voltmeter V_H, which responds to the amplitude of the voltage on the shunt R_H:

$$H_m = \frac{I_{m1} \cdot N_1}{l} = \frac{U_{mH} \cdot N_1}{R_H l}, \tag{4.9}$$

where I_{m1} – is the amplitude of the alternating current i_1 in the magnetizing (primary) N_1;

N_1 – is the number of turns of the primary winding;

$l = \pi(D_1+D_2)/2$ – is the average length of the magnetic field lines of a ferromagnet sample made in the form of a ring;

D_1, D_2 are outer and inner diameters of the ferromagnet sample;

$U_{mH}=I_{m1} \cdot R_H$ – is voltage amplitude on shunt R_H (voltmeter readings V_H).

The amplitude of the magnetic induction B_m is determined according to the law of electromagnetic induction (1.22) on the basis of formula (4.7) according to the readings of the voltmeter V_2, which responds to the effective value of the voltage U_2 on the secondary winding:

$$B_m = \frac{U_2}{4.44 f N_2 S}. \tag{4.10}$$

The results of calculations of H_m and B_m using formulae (4.9) and (4.10) allow to determine the dynamic magnetic permeability

$$\mu_{a\sim}=B_m/H_m\ . \tag{4.2}$$

4.2.2 <u>Determination of magnetic losses by the area of the hysteresis loop</u>

The area of the dynamic loop of hysteresis S_H obtained with the help of an oscillograph, characterizes the lost energy per unit volume V of the ferromagnet for each cycle of its reversal. Therefore, the power of magnetic losses P_M (W) can be determined using the following formula:

$$P_M = P_H + P_f = S_H \cdot f \cdot m_B \cdot m_H \cdot V, \tag{4.11}$$

where S_H – is the area of the dynamic hysteresis loop on the oscillograph screen, mm^2;

f – is cyclic frequency of reversal magnetization of the ferromagnet, Hz;

$m_B = B_m/l_{ym}$ – is scale on the y-axis (scale of magnetic induction), T/mm;

l_{ym} – is the deviation of the oscillograph beam along the y-axis according to the amplitude of the magnetic induction B_m (4.10), mm;

$m_H = H_m/l_{xm}$ – is the scale along the x-axis of the oscilloscope (the scale of the magnetic field strength), A/m/mm;

l_{xm} – is the deviation of the oscillograph beam along the x-axis according to the amplitude of the magnetic field strength H_m (4.9), mm;

$V = 0.25 \cdot \pi \cdot (D_1^2 - D_2^2) \cdot h$ is the volume of ferromagnet sample, m^3.

Specific magnetic losses p_M (W/kg):

$$p_M = \frac{P_M}{m} = \frac{S_H \cdot f \cdot m_B \cdot m_H \cdot V}{m} = \frac{S_H \cdot f \cdot m_B \cdot m_H}{d}, \tag{4.2}$$

where $m = d \cdot V$ – is the mass of the sample ferromagnet, kg;

d – is the density of the ferromagnet, kg/m^3.

By adjusting the voltage u on the winding N_1 (Fig. 4.5) you can get a range of hysteresis loops (Fig. 4.2) and build the main magnetization curve using them, which is shown in Fig. 4.2 by dashed line, as well as the dependence of magnetic permeability on the magnetic field strength $\mu_a=f(H)$, as shown in Fig.4.1, a. Further, with the help of the dependence $\mu_a=f(H)$, if necessary, it is possible to determine other values of magnetic permeability: the initial μ_{ai}, the maximum μ_{am}, and the differential μ_{ad} (4.3).

4.2.3 Determination of magnetic losses according to the readings of the devices

The scheme at fig. 4.5 allows to determine the same properties of the ferromagnet for comparison, but without the use of an oscillograph. In particular, the magnetic losses of the P_M (W) can be determined by the readings of the wattmeter P_{W1} and ammeter A_1:

$$P_M = P_H + P_f = P_{W1} - I_1^2 R_1.. \qquad (4.13)$$

where R_1 is active resistance of primary winding N_1.

Specific magnetic losses p_M (W/kg):

$$p_M = \frac{P_M}{m} = \frac{P_M}{d \cdot V}. \qquad (4.14)$$

4.2.4 Measurement of complex magnetic resistance

For calculations of magnetic conductors the methods similar to methods of calculations of electric circuits of sinusoidal current are often used. In particular, the symbolic method of calculation using complex numbers is used, which is based on the sinusoidal law of voltage change $u=U_m\sin\omega t$ of power source and characteristic values of ferromagnets. To do this the concept of complex magnetic resistance of the magnetic circuit is introduced, replacing the magnetic induction B and the magnetic field strength H by equivalent sinusoidal functions of time t ($B=B_{me}\sin\omega t$ and $H=H_{me}\sin\omega t$).

Equivalent hysteresis loop

At a sinusoidal voltage $u_1=U_{1m}\sin\omega t$ (Fig. 4.5), when the magnetic induction in the magnetic circuit is also practically sinusoidal, the real amplitude B_m ($B_{me}=B_m$) is chosen as the amplitude B_{me} of its equivalent sinusoidal wave $B=B_{me}\sin\omega t$. The amplitude H_{me} of the equivalent sinusoidal wave $H=H_{me}\sin\omega t$ of magnetic field strength should be chosen based on the equality of magnetic losses. To do this the dynamic hysteresis loop *B (H)* is replaced by an equivalent ellipse with the same area (Fig. 4.6).

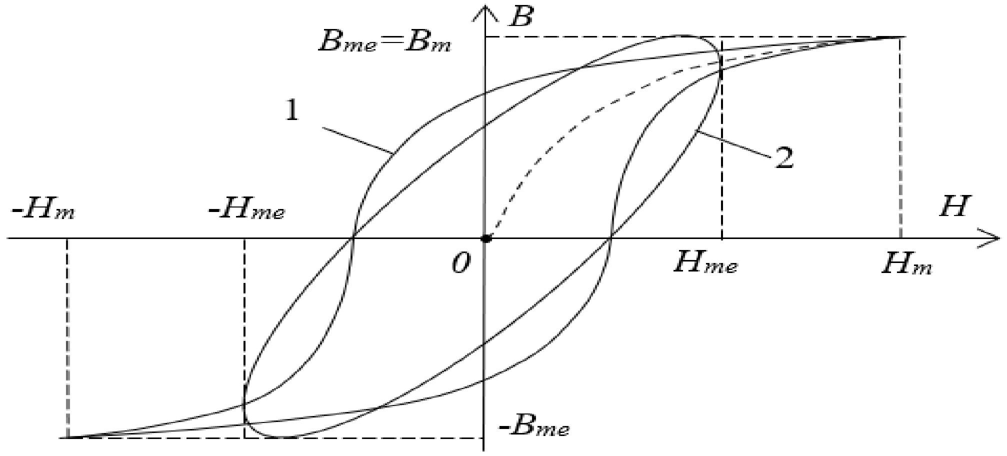

Figure 4.6 – Dynamic hysteresis loop (1) and equivalent ellipse (2)

The amplitude H_{me} of the equivalent sinusoidal wave of the magnetic field strength and the magnetomotive force (MMF) F_m can be determined through the current value I_1 of the equivalent sinusoidal wave of the magnetizing current i_1 (the readings of the ammeter A_1 in the scheme of Fig. 4.5):

$$H_{me} = \frac{\sqrt{2} I_1 N_1}{l}; F_m = \sqrt{2} I_1 N_1. \tag{4.15}$$

Equivalent circuit of the coil with a ferromagnetic core

After the introduction of equivalent sinusoidal waves the inductor with a ferromagnetic core (Fig. 4.5) may be considered as linear element for a specific constant voltage, a vector diagram of the coil may be built, and a equivalent circuit may be provided (fig. 4.7).

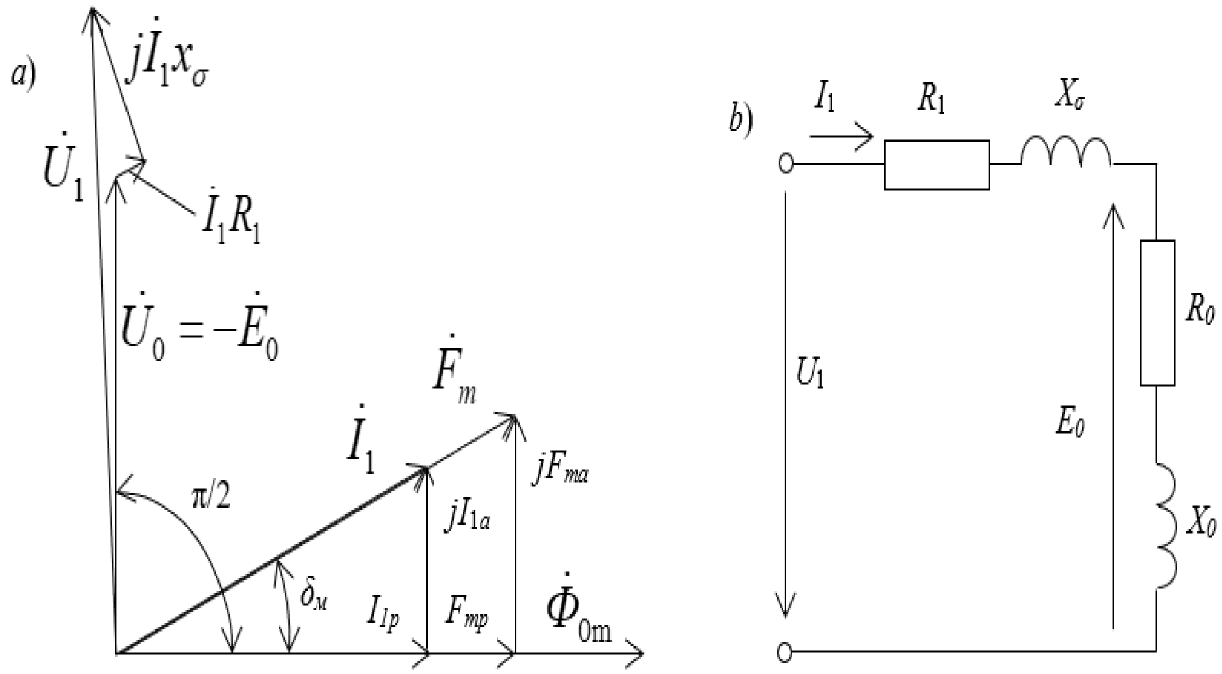

Figure 4.7 – Vector diagram (*a*) and equivalent circuit (*b*) of the coil with the core

In the equivalent circuit of the coil with a ferromagnetic core and the vector diagram of the coil the following designations are used:

R_1 – is active resistance of the coil or magnetizing winding N_1, which takes into account the heating of this winding by electric current I_1, Ohm (fig. 4.5);

$R_0 = \frac{P_M}{I_1^2} = \frac{U_0 \cdot I_{1a}}{I_1^2}$ – is active resistance (Ohm) with respect to magnetic losses P_M in the ferromagnetic core of the coil (4.13);

I_1 – is the effective value of the magnetizing current (readings of the ammeter A_1 in the scheme of Fig. 4.5), which causes the magnetic field strength of the amplitude H_{me} and the magnetomotive force (MMF) of F_m amplitude (4.15);

$U_0 = U_2 \cdot N_1 / N_2$ – is the main component of the voltage U_1 (4.6) applied to the coil, which balances the EMF E_0, is in antiphase with it, and precedes the vector of the main magnetic flux Φ_{0m} in phase by the angle π/2 (fig. 4.7);

N_1, N_2 is the number of turns of the primary and secondary windings (fig. 4.5);

I_1R_1, I_1x_σ – is other voltage– components U_1 (fig. 4.7);

$I_{1a}=P_M/U_0$ – is the active component of the current I_1, which is due to the magnetic loss of P_M and causes the active component of MMF $F_{ma}=F_m\cdot\sin\delta_M$ (fig. 4.7,a);

$I_{1p}=\sqrt{I_1^2-I_{1a}^2}$ – is reactive component of current I_1, which causes the reactive component of MMF $F_p=F_m\cdot\cos\delta_M$ and the main magnetic flux Φ_{0m} (fig. 4.7,a);

U_2 – is operating voltage on the secondary winding N_2 (voltmeter V_2 readings);

δ_M – is phase angle of lag of magnetic flux Φ_{0m} from current I_1 and MMF F_m (angle of magnetic losses), which is caused by magnetic losses P_M.

$\Phi_{0m}=B_mS$ – is the amplitude of the main part of the magnetic flux (W), which is closed by a ferromagnetic core and causes electromotive force (EMF) in the magnetizing winding E_0 (its complex amplitude is indicated on the vector diagram as $\dot{\Phi}_{0\mathrm{m}}$);

$B_m = U_2/(4.44fN_2S)$ – is the amplitude of the magnetic induction in the core (4.7), T;

S – is cross-sectional area of the ferromagnetic core, m^2;

F – is cyclic frequency of magnetic flux change, Hz;

$X_0=\sqrt{Z_0^2-R_0^2}$, $z_0=U_0/I_1$ – is inductive and impedance of the coil (Ohm), which is due to the main magnetic flux Φ_{0m} (without R_1);

$X_\sigma=-X_0+\sqrt{Z^2-(R_1+R_0)^2}$ – is inductive resistance of the coil (Ohm), which is due to the magnetic flux scattering Φ_σ;

$z=U_1/I_1$ – is impedance of the coil with a ferromagnetic core.

Determination of complex specific magnetic resistance

To determine the magnetic resistance, we use Ohm's law for a magnetic circuit, which is similar to Ohm's law for electric circuits:

$$Z_M=\frac{\dot{F}_m}{\dot{\Phi}_{0m}}=\frac{\dot{H}_{me}\cdot l}{\dot{B}_m\cdot S}=|Z_M|e^{j\delta_M}=\dot{\rho}_Z\frac{l}{S}=(\rho_R+j\rho_X)\frac{l}{S}=R_M+jX_M, \quad (4.16)$$

where Z_M – is complex magnetic resistance (H^{-1});

$|Z_M|=F_m/\Phi_{0m}$ – is module of complex magnetic resistance (H^{-1});

$\dot{F}_m$ is complex amplitude of the magnetomotive force (A), the modulus of which according to the law of total current is $F_m=\sqrt{2}I_1\cdot N_1=H_{me}\cdot l$ (4.15);

$\dot{\Phi}_{0\mathrm{m}}$ is complex amplitude of the main part of the magnetic flux (W);

$l=\pi(D_1+D_2)/2$ – is the average length of the magnetic field lines of a sample of a ferromagnet made in the shape of a ring (Fig. 4.5);

$I_{1a}=P_M/U_0$ – is active component of current I_1, which is caused by magnetic losses of P_M and causes the active component of MMF $F_{ma} = F_{ma}\sin\delta_{\text{м}} = \sqrt{2}\cdot I_{1a}\cdot N_1$;

$P_M = P_{W1} - I_1^2R_1$ – is magnetic losses (4.13), W;

P_{W1} – is active power consumed by the coil with a ferromagnetic core (readings of the wattmeter W_1 in the scheme of fig. 4.5);

$X_{\text{м}} = \frac{F_{ma}}{\Phi_{0m}} = \frac{\sqrt{2}\cdot I_{1a}\cdot N_1}{\Phi_{0m}} = \frac{\sqrt{2}\cdot P_M\cdot N_1}{\Phi_{0m}\cdot U_0} = \frac{P_M}{\Phi_{0m}^2\pi\cdot f} = |Z_{\text{м}}|\sin\delta_{\text{м}}$ – is imaginary component of magnetic resistance (H^{-1});

$R_{\text{м}} = \frac{F_{mp}}{\Phi_{0m}} = \frac{\sqrt{2}\cdot I_{1p}\cdot N_1}{\Phi_{0m}} = \sqrt{|Z_{\text{м}}|^2 - X_{\text{м}}^2} = |Z_{\text{м}}|\cos\delta_{\text{м}}$ – is the real component of magnetic resistance (H^{-1});

$\dot{\rho}_Z = Z_{M}\frac{S}{l} = \frac{\dot{H}_{me}}{\dot{B}_m} = \frac{1}{\dot{\mu}_{a\sim}} = \rho_Z\cdot e^{j\delta_{\text{м}}}$ – is complex specific magnetic resistance;

$\dot{\mu}_{a\sim}$ – is complex dynamic magnetic permeability of ferromagnet, H/m;

$\rho_Z = \frac{H_{me}}{B_m} = \frac{\sqrt{2}I_1N_1}{lB_m} = \sqrt{\rho_R^2 + \rho_X^2}$ – is modulus of magnetic resistivity, m/H;

$\rho_X = X_{\text{м}}\frac{S}{l} = \frac{P_MS}{\Phi_{0m}^2 l\pi\cdot f} = \rho_Z\sin\delta_{\text{м}}, \rho_R = R_{\text{м}}\frac{S}{l} = \sqrt{\rho_Z^2 - \rho_X^2} = \rho_Z\cos\delta_{\text{м}}$ – is imaginary and real components of the magnetic resistivity, m/H.

4.3 Some magnetic materials

Magnetic materials can be divided into three main groups: low-frequency magnetic soft, high-frequency magnetic soft and magnetic hard materials.

4.3.1 Low frequency magnetic soft materials

Magnetic materials with a small value of the coercive force H_c<<800 A/m, high magnetic permeability μ_a, relatively high resistivity ρ and low reversal magnetizing losses are called magnetic soft materials. Low-frequency soft magnetic materials are used to make magnetic circuits for electrical machines, transformers, and other devices that use alternating magnetic flux with a frequency from zero (constant magnetic flux) to several thousand hertz.

Technically pure iron contains a small amount (less than 0.1%) of impurities of carbon, sulphur, manganese, silicon and other elements that degrade its magnetic properties. Due to the low resistivity (ρ= 0.1 μO · m) technically pure iron is usually used in a constant magnetic field: for the manufacture of magnetic conductors of DC electric machines, pole pieces of electromagnets and electrical measuring instruments. The table 4.1 shows the main properties of several types of iron.

Table 4.1 – The main magnetic properties of iron [6]

A kind of iron	The content of impurities, %		Magnetic properties		
			Relative magnetic permeability		Coercive force H_c, A/m
	carbon	oxygen	initial μ_{rn}	maximum μ_{rm}	
Technically pure iron	0.02	0.06	250	7000	64
Electrolytic iron	0.02	0.01	600	15000	28
Carbonyl iron	0.005	0.005	3300	21000	6.4
Electrolytic iron, which is remelted in vacuum	0.01	-	-	61000	7.2
Iron, which is annealed in hydrogen	0.005	0.003	6000	200000	3.2

Siliceous electrical steel – is an alloy of iron with silicon. The presence of silicon increases the electrical resistivity, which reduces losses to eddy currents. In addition, silicon promotes the release of carbon in the form of graphite, as well as almost complete deoxidation of steel, i.e. the conversion of oxygen to slag (silica). This leads to an increase in μ_{rn} and a decrease in H_c. On the other hand, the presence of silicon leads to a decrease in the induction of saturation B_s and deterioration of mechanical properties (increased hardness and brittleness). Therefore, the concentration of silicon in steel should not exceed 4.8%.

Silica steel sheets are made by rolling blanks in hot or cold condition. Therefore, there are hot-rolled and cold-rolled siliceous steels. In the process of cold rolling (with high compression and special heat treatment) textured steel of large crystal structure is obtained, in the sheets of which the crystals are oriented by the axes of light magnetization in the rolling direction. The magnetic properties of such steel in the rolling direction are much better compared to hot-rolled. The use of cold-rolled textured steels requires a design of the magnetic circuit, in which the magnetic flux passes in the direction of the best magnetic properties, i.e. in the direction of rolling.

Electrotechnical thin-sheet steel (0…1 mm thick) is produced in the form of sheets or rolls, marked with four figures [9]. The first figure means the class, i.e. the structural state and type of rolling (1 - hot-rolled isotropic; 2 - cold-rolled isotropic; 3 - cold-rolled anisotropic with rib texture; 5 - cold-rolled isotropic with planar cubic texture). *The second figure* means the approximate concentration of silicon (0 - up to 0.4%; 1 - 0.4… 0.8%; 2 - 0.8… 1.8%; 3 - 1.8… 2.8%; 4 - 2.8… 3.8%; 5 - 3.8… 4.8%). *The third figure* means the group according to the main normalized (guaranteed) characteristics (0 - specific magnetic losses on reversal magnetizing $p_{1,7/50}$ at magnetic induction B_m=1.7 T and frequency f = 50 Hz; 1 - $p_{1,5/50}$ at B_m=1.5 T and f = 50 Hz, 2 - $p_{1,0/400}$ at B_m=1.0 T and f = 400 Hz, 4 - $p_{0,5/3000}$ at B_m = 0.5 T and f = 3000 Hz; 6 - magnetic induction $B_{0,4}$ in weak magnetic fields at a field strength of H= 0.4 A/m; 7 - magnetic induction of B_{10} in medium magnetic fields at a field strength of H = 10 A/m). The fourth figure determines the ordinal number of the steel type (with the improvement of magnetic properties as this number increases from 1 to 8).

The maximum relative magnetic permeability μ_{rm} of hot-rolled steels (class 1) is μ_{rm} = 3000 ... 10000, cold-rolled (class 3) μ_{rm}> 40000. Specific magnetic losses in steel with a thickness of 0.35 mm: class 1 (steel 1513) $p_{1,5/50}$= 2.5 W/kg; class 2 (steel 2411) $p_{1,5/50}$= 3.0 W/kg; class 3 (steel 3414)

$p_{1,5/50}$= 1.1 W/kg. Electrical steel is used in electrical machines, apparatus and devices that operate at medium and strong magnetic fields at alternating current of industrial frequency (50 Hz) and at high frequency (400 Hz, 800 Hz).

Permalloy – is an alloy of iron with nickel, which is characterized by high magnetic permeability (especially in weak magnetic fields) and low coercive force. High-nickel permalloys have a nickel content of 70 ... 80%, and low-nickel ones have 40 ... 50%. Permalloy, along with good magnetic properties, have disadvantages: they contain scarce nickel, require complex heat treatment, under mechanical stress the magnetic properties deteriorate markedly, have lower values of magnetic induction saturation B_s and specific electrical resistance ρ compared to electrical steel. Alloys are made in the form of cold-rolled strips with a thickness of 0.02 ... 2.5 mm, hot-rolled and forged rods with a diameter of 8 ... 10 mm. Permalloys is used for the manufacture of cores of small transformers, inductors, pulse transformers, magnetic amplifiers, and magnetic screens.

Alsifer – is alloy of iron *Fe* (84.9%) with silicon *Si* (9.5%) and aluminium *Al* (5.6%). According to its main properties, alsifer is almost not inferior to high-nickel permalloys: μ_{rn} = 35000; μ_{rm}= 120,000; H_c = 1.8 A/m; B_m = 1.8 T; ρ= 0.8 μO·m. But due to the difficulty of obtaining the exact composition of the components, industrial alsifer has much worse performance. Resulting from its increased hardness and fragility, alsifer products are made by casting with a wall thickness of at least 2 mm.

Amorphous alloys contain one or more transition metals (iron *Fe*, nickel *Ni*, cobalt *Co*) in the amount of 75 ... 85% as the main component and metalloid - glass former (borium *B*, carbon *C*, silicon *Si*, phosphorus *P*) in the amount of 15...20%. Amorphous alloys contain alloying metals (chromium *Cr*, tantalum *Ta*, vanadium *V*, manganese *Mn*), which give them specific properties. Amorphous alloys are formed at very rapid cooling, when the particles do not have time to line up in the crystal structure. The properties of amorphous alloys are close to permalloys, but less susceptible to mechanical stress, have high corrosion resistance and strength while maintaining ductility. The electrical resistivity of amorphous alloys is 2 ...

3 times higher than that of permalloys, which significantly reduces eddy current losses. Due to the relative simplicity of manufacturing technology amorphous alloys are widely used.

4.3.2 High frequency magnetic soft materials

Magnetodielectric – is a plastic mass that is pressed using a dielectric as a binder (phenol-formaldehyde resin, polystyrene, bakelite, nitrovarnishes, glass) and a soft magnetic ferromagnet powder as a filler (alsifer, permalloy, carbonyl iron). Magnetodielectrics have a very high electrical resistivity, and therefore they are used at high frequencies (f = 0.1 ... 100 MHz). On the other hand, the presence of gaps between ferromagnetic particles significantly reduces the magnetic permeability of the material (μ_r = 10 ... 250) and the magnetic induction of saturation (B_s = 0.3 ... 0.4 T). Ring, cylindrical, and armour cores are made of magnetodielectrics for operation in weak high-frequency magnetic fields.

Magnetically soft ferrites – re chemical compounds of iron oxide Fe_2O_3 with oxides of some metals according to the formula $MeO{\cdot}Fe_2O_3$, where *Me* is a symbol of divalent metals (manganese *Mn*, nickel *Ni,* zinc *Zn,* cobalt *Co).* Ferrites combine good magnetic properties with extremely high specific electrical resistance, which is $10^6...10^{11}$ times higher than that of metal ferromagnets. In the manufacture of ferrite products a powder of finely ground, mixed and pre-fired oxides of the corresponding metals is obtained. A plasticizer is added to the powder, and from the obtained mass the products of the desired shape are pressed under high pressure, and fired at 1100 ... 1400^{O}C.

The initial magnetic permeability of magnetically soft ferrites μ_{rn} ranges from a few units to 20,000, the maximum magnetic permeability μ_{rm} ≈35000, the coercive force H_c = 8 ... 2240 A/m, the saturation induction B_s = 0.08 ... 0.5 T, the tangent of the angle of magnetic loss $tg\delta_m$ = 0.005 ... 0.1. The electrical resistivity of ferrites is high ((ρ=0,001...10^{10}0hm · m), and therefore the magnetic losses from eddy currents are very low. Most ferrites have small hysteresis losses.

The most commonly used ferrites include manganese-zinc, nickel-zinc, and lithium-zinc.

Magnetic soft ferrites are used to make the cores of high-frequency inductors, transformers, magnetic antennae, parts of the deflection systems of television tubes and many other devices of high-frequency (more than 1000 Hz) and pulsed equipment.

4.3.3 Magnetically hard materials

Materials with a very large coercive force H_c are called magnetically hard materials. They are magnetized or re-magnetized in very strong magnetic fields, and are used mainly for the manufacture of permanent magnets. Materials in which H_c>4 kA/m are conditionally considered as magnetic-solid. In the best magnetically hard materials H_c> 500 kA/m. Magnetically hard materials are divided into alloyed martensitic steels, cast magnetically hard alloys, metal-powder magnets and magnetically hard ferrites.

Curve of demagnetization and density of magnetic energy

The main characteristics of magnetically solid materials are the coercive force H_c, the residual magnetic induction B_r, as well as the demagnetization curve $B (H)$ as part of the boundary hysteresis loop (Fig. 4.2), and the magnetic field energy density curve $w_m=B\cdot H/2$ in the air gap l (in the working space) of a permanent magnet (Fig. 4.8).

The energy density of the magnetic field w_m in the air gap significantly depends on the magnitude of this gap l. In the closed state of the magnetic circuit of the permanent magnet, when $l = 0$ and $B=B_r$, the magnetic energy in the gap is zero due to zero H. At a very large gap, when $l = max$ and $H=H_c$, the magnetic energy in the gap is also almost zero due to almost zero value B.

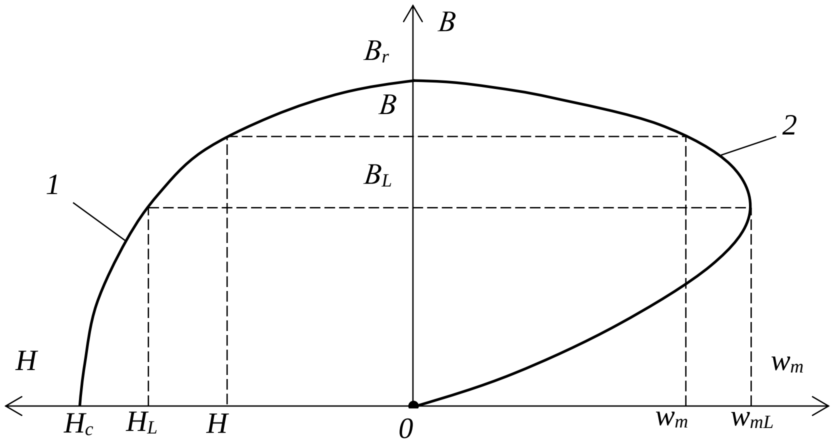

Figure 4.8 – Demagnetization curve (1) and magnetic field energy density (2)

Hence, at some (optimal) gap value $l = L$, when $B = B_L$ and $H=H_L$, the density of magnetic energy in the working space reaches its maximum ($w_m=w_{mL}=max$). To characterize magnetically-hard materials we use $B_L{\cdot}H_L$ or the coefficient of convexity γ of the demagnetization curve

$$\gamma = \frac{B_L{\cdot}H_L}{2B_r{\cdot}H_c}. \qquad (4.7)$$

Alloyed martensitic steel – is the simplest and most affordable material for making permanent magnets. This steel is alloyed with the addition of chromium *Cr* (1.3 ... 10%), tungsten *W* (0 ... 6.2%), cobalt *Co* (0 ... 16.5%), and molybdenum *Mo* (0 ... 1.7%). Its main magnetic properties are: H_c = 4.6 ... 13.6 kA/m, B_r = 0.8 ... 1.0 T, w_{mL} = 1 ... 4 kJ/m^3. These properties are guaranteed after heat treatment of martensitic steel and 5-hour structural stabilization in boiling water [6]. Alloyed martensitic steels have limited use due to their low magnetic properties. The main advantage of martensitic steels is low price and ease of machining.

Cast magnetic hard alloys are alloys of iron *Fe* with aluminium *Al* and nickel *Ni* (alni alloys) with the addition of silicon *Si* (alnisi) or cobalt *Co* (alnico or magnico). After special treatment these alloys obtain the following properties [6]: H_c = 40 ... 87 kA/m, B_r = 0.5 ... 1.33 T, w_{mL} = 3.6 ... 26.4 kJ/m^3, γ = 0.34 ... 0.74. Cast magnetic hard alloys are several times better than alloyed martensitic steels in terms of their magnetic properties.

Their main disadvantage is the difficulty of products with accurate dimensions manufacturing due to increased hardness and fragility.

Metal-powder magnets are made using methods of powder metallurgy. There are two types of these magnets: metal-ceramic and metal-plastic. Metal-ceramic magnets are made by pressing a fine powder of a cast magnetic-hard alloy followed by sintering at high temperatures similar to the process of annealing ceramics. Metal-plastic magnets are made of grains of cast magnetic-hard alloy, fastened with a binder, similar to the manufacture of plastic parts. Metal-powder magnets are used in the mass production of parts with sufficiently accurate dimensions that do not require further machining.

The mechanical strength of metal-ceramic magnets are several times higher than that of cast magnetically hard alloys, but metal-ceramic magnets have 10 ... 20% worse magnetic properties. For example, magnico powder (8% Al + 15% Ni + 24% Co + 3% Cu) is used to produce metal-ceramic magnets with the following properties [6]: H_c = 50 kA/m, B_r = 1.0 T, w_{mL} = 11.7 kJ/m^3, $\gamma = 0.47$. Metal-ceramic magnets based on cobalt alloys Co (61.5 ... 64%) with rare earth metals (36 ... 38.5%): with samarium Sm and praseodymium Pr have a very large coercive force H_c [6]: H_c = 500 ... 560 kA/m, B_r = 0.77 ... 0.9 T, w_{mL}= 55 ... 72 kJ/m^3.

Metal-plastic magnets in their magnetic properties are significantly inferior to cast magnetic-hard alloys due to the large quantity of non-magnetic binder. For example, alni grains (15% Al + 24% Ni + 4% Cu) are used to produce metal-plastic magnets with the following properties [6]: H_c=38 kA/m, B_r=0.3 T, w_{mL}=1.62 kJ/m^3, γ=0.28.

Magnetically solid ferrites – are usually barium ferrites ($BaO{\cdot}6Fe_2O_3$). There are two brands of barium magnets: isotropic and anisotropic. Barium isotropic magnets, the production of which is similar to the production of magnetically soft ferrites, have the following properties [6]: H_c=114...144 kA/m, B_r=0.18...0.22 T, w_{mL}=2.8...4.4 kJ/m^3. Barium anisotropic magnets, the production of which involves pressing in a constant magnetic field with a voltage of up to 800 kA/m, have the following properties [6]: H_c=128...240 kA/m, B_r=0.3...0.4 T, w_{mL}=8.0...14.0 kJ/m^3. Barium magnets are made in the form of washers or thin disks, have high stability under the influence of external magnetic fields. The disadvantage of barium magnets is the low mechanical strength, fragility and strong dependence of magnetic properties on temperature.

4.4 Exemplary tasks on the study of magnetic materials

4.4.1 Calculation of the force of the magnetic field on a current-carrying conductor

Task. Determine the force f of the magnetic field on a conductor with a current I = 20A in the air gap of the electromagnet, as well as the magnetic energy W_m of the electromagnet. A direct electric current I_c= 2A is created in the magnetizing coil of the electromagnet. The number of turns of the coil N = 500. The ferromagnetic core of the coil has the shape of an open ring with an air gap δ = 2 mm (Fig. 4.9). The outer diameter of the ferromagnetic ring D_1= 20 cm, the inner diameter D_2= 16 cm, the thickness h = 2 cm. The relative magnetic permeability of the ferromagnetic core μ_r = 1000.

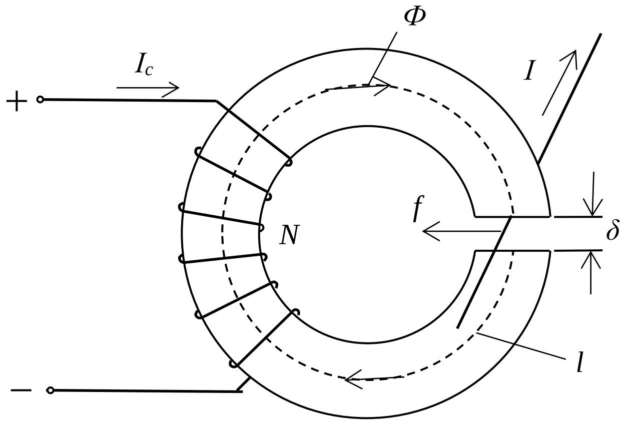

Figure 4.9 – **Scheme of a coil with an open annular core**

Solution. According to the law of full current (1.20):

$$H \cdot l + H_{\delta} \cdot \delta = I_c \cdot N,$$

where $H=B/\mu_a$ – is magnetic strength in the ring, A/m;

$\mu_a=\mu_r\cdot\mu_0$ – is absolute magnetic permeability of the ferromagnetic core;

$\mu_0 = 4\pi\cdot10^{-7}$ H/ m – is the absolute magnetic permeability of air;

B – is magnetic induction in the ferromagnetic ring and the air gap, T;

$l=\pi\cdot(D_1+D_2)/2-\delta=\pi\cdot(0.2+0.16)/2-0.002=0.5632$ (m) – is the average length of the magnetic field lines of the annular ferromagnetic core;

$H_\delta=B/\mu_0$ – is magnetic strength in the air gap, A/m;

Magnetic induction B in the air gap:

$$B = \frac{I_C N \mu_0}{\frac{l}{\mu_r}+\delta} = \frac{2\cdot500\cdot4\pi\cdot10^{-7}}{\frac{0.5632}{1000}+0.002} = 0.49(T).$$

The force of the magnetic field on a conductor with a current in the air gap of the electromagnet can be determined by the Ampere formula (1.15):

$$f = I\cdot h\cdot B\cdot \sin\alpha = 20\cdot0.02\cdot0.49\cdot1 = 0.196(N).$$

The energy W_m of the electromagnet can be determined by formulae (1.26) or (1.27):

$$W_m = \frac{\Phi N I_C}{2} = \frac{BSNI_C}{2} = \frac{0.49\cdot0.0004\cdot500\cdot2}{2} = 0.098(J);$$

$$W_m = \frac{B\cdot H}{2}V + \frac{B\cdot H_\delta}{2}V_\delta = \frac{B^2 S}{2\mu_0}\left(\frac{l}{\mu_r}+\delta\right) = \frac{0.49^2\cdot0.0004}{2\cdot4\pi\cdot10^{-7}}\left(\frac{0.5632}{1000}+0.002\right) = 0.098(J),$$

where $S=0.5\cdot(D1-D2)\cdot b=0.5\cdot(0.2-0.16)\cdot0.02=0.0004$ (m^2) is the cross-sectional area of the ferromagnetic ring;

$\Phi = B\cdot S$ is magnetic flux, W.

$V=l\cdot S$ is the volume of the ferromagnetic core of the electromagnet coil;

$V_\delta=\delta\cdot S$ is the air gap volume of the ferromagnetic core.

4.4.2 Determination of ferromagnet parameters

Task. Study of a ring-shaped sample of a ferromagnet according to the scheme on fig. 4.5 provided the following readings of electrical measuring instruments: the current value I_1 (ammeter readings A_1) and active power P (wattmeter readings W_1), which are consumed by the magnetizing winding with the number of turns N_1= 900 at a frequency of 50 Hz, are I_1= 0.2 A and P = 10 W; the current voltage U_2 on the secondary winding with the number of turns N_2= 300 (voltmeter reading V_2) is U_2= 25 V. The active resistance of the magnetizing winding R_1= 200 Ohms. The ferromagnet sample has an outer diameter D_1= 20 cm, an inner diameter D_2= 16 cm, a thickness h=2 cm and a density d = 7800 kg/m^3. Determine the dynamic magnetic permeability $\mu_{a\sim}$, the magnetic losses P_M, the specific magnetic losses p_M, and the tangent of the angle of magnetic losses $tg\delta_M$ of the ferromagnet.

Solution. Amplitude of magnetic induction B_m in ferromagnet (4.10):

$$B_m = \frac{U_2}{4.44 f N_2 S} = \frac{25}{4.44\cdot 50\cdot 300\cdot 0.0004} = 0.938(T),$$

where $S=0.5\cdot(D_1-D_2)\cdot h=0.5\cdot(0.2-0.16)\cdot 0.02=0.0004$ (m^2) – is the cross-sectional area of the ferromagnetic ring.

The amplitude H_{me} of the equivalent sine wave of the magnetic field strength (4.15):

$$H_{me} = \frac{\sqrt{2} I_1 N_1}{l} = \frac{\sqrt{2}\cdot 0.2\cdot 900}{0.565} = 450\ (A/m),$$

where $l=\pi\cdot(D_1+D_2)/2=\pi\cdot(0.2+0.16)/2=0.565$ (m) – is the average length of the magnetic field lines of the annular ferromagnetic sample.

Dynamic magnetic permeability of a ferromagnet (4.2):

$$\mu_{a\sim} = \frac{B_m}{H_{me}} = \frac{0.938}{450} = 0.002084\ (H/m).$$

Magnetic losses in ferromagnet (4.13):

$$P_M = P_{W1} - I_1^2 R_1 = 10 - 0.2^2 \cdot 200 = 2\ (W).$$

Specific magnetic losses (4.14):

$$p_M = \frac{P_M}{m} = \frac{P_M}{d \cdot V} = \frac{2}{7800 \cdot 0.0002261} = 1.134(W/\mathrm{kg}).$$

where $V = \frac{\pi}{4}(D_1^2 - D_2^2) \cdot h = \frac{\pi}{4}(0.2^2 - 0.16^2) \cdot 0.02 = 0.0002261(m^3)$ – is the volume of the ferromagnetic ring sample.

The tangent of the angle of magnetic loss $tg\delta_{м}$ (fig. 4.7,a):

$$tg\delta_{м} = \frac{I_{1a}}{I_{1p}} = \frac{0.02667}{0.1982} = 0.1346.$$

where $I_{1a}=P_M/U_0$ =2/75=0.02667 (A) – is the active component of the current I_1, which is due to the magnetic loss of P_M and causes the active component of the magnetomotive force;

$U_0 = U_2 \cdot N_1/N_2 = 25 \cdot 900/300=75$ (W) – is the main component of the voltage applied to the coil;

$I_{1p} = \sqrt{I_1^2 - I_{1a}^2} = \sqrt{0.2^2 - 0.02667^2} = 0.1982(A)$ – is reactive component of current I_1, which causes the reactive component of the magnetomotive force.

4.5 Test questions on magnetic materials

1. Explain the process of magnetization of the material.
2. What physical laws regulate the process of magnetization of material?
3. How is a magnetic field created in a ferromagnet?
4. Name the main difference between ferromagnets and ferrites from other materials.
5. What are the main functions of a ferromagnet?
6. Explain the phenomenon of magnetostriction.

7. What are the characteristics of the magnetization process of the material?
8. Explain the phenomenon of magnetic anisotropy.
9. Explain the dependence of the ferromagnet magnetization process on temperature.
10. Explain the relationship between magnetic induction and the magnetic field strength of a ferromagnet.
11. What is the basic magnetization curve?
12. Explain the dependence of magnetic flux and magnetic induction on the electric current in the magnetizing winding.
13. What is the process of magnetic saturation of a ferromagnet?
14. Explain the practical value of ferromagnets.
15. In what situations is it more profitable to use air or vacuum compared to magnetic materials to create a magnetic field?
16. What is absolute and relative magnetic permeability?
17. To what extent can the magnetic permeability of a ferromagnet differ from the magnetic permeability of a dielectric or vacuum?
18. What causes the increased magnetic permeability of ferromagnets?
19. What is the initial and maximum magnetic permeability?
20. Explain the technical and economic advantages of ferromagnets with high magnetic permeability.
21. In which cases is there a need to re-magnetize magnetic materials?
22. Explain the concept of magnetic hysteresis.
23. What are hysteresis losses and how can these losses be reduced?
24. Explain the concepts of coercive force and residual magnetic induction.
25. What are eddy current losses and how can these losses be reduced?
26. Explain the differences between the dynamic hysteresis loop and the static loop.
27. What is dynamic magnetic permeability?
28. How do the magnetic losses of a ferromagnet differ from the losses of hysteresis and eddy currents?
29. How does the frequency of reversal magnetizing of the ferromagnet affect the magnetic loss?

30. In which cases are ferromagnets magnetized with a constant component of current or magnetic field strength?

31. What is the relationship between AC voltage and magnetic induction?

32. Explain the reason for the dependence of the magnetic field strength and electric current in the magnetizing winding on the voltage of the power supply.

33. In which cases can the electric current in the magnetizing winding increase significantly with a slight increase in the voltage applied to this winding?

34. Explain the scheme of measuring the main magnetic characteristics of ferromagnets. How to generate electrical signals to obtain an oscillogram of the dynamic hysteresis loop?

35. Explain the possibility of determining the magnetic losses on the oscillogram of the dynamic hysteresis loop.

36. How can the magnetic loss be determined from the readings of an ammeter and wattmeter?

37. Explain the possibility of measuring the magnetic permeability of a ferromagnet using conventional electrical measuring instruments.

38. Explain the concept of equivalent hysteresis loop.

39. How can the amplitude of the equivalent sine wave of the magnetic field strength and the magnetizing force be determined from the readings of the ammeter in the circuit of the magnetizing winding?

40. What is the complex magnetic resistance and the specific magnetic resistance, and how can they be determined?

41. Explain the concepts of real and imaginary components of magnetic resistance and specific magnetic resistance.

42. What is the relationship between the imaginary component of magnetic resistivity and magnetic loss?

43. Explain the scheme of replacement of the coil with a ferromagnetic core.

44. How can you determine the parameters of the replacement circuit of the coil with a ferromagnetic core?

45. What is the magnetic flux scattering and how does it affect the parameters of the coil replacement circuit?

46. Explain the vector diagram of a coil with a ferromagnetic core.

47. How do magnetic losses affect the phase shift between the magnetizing current and the main magnetic flux?

48. Explain the concept of the angle of magnetic loss and the method of determining its magnitude.

49. What magnetic characteristics are the most important for soft magnetic materials?

50. Name the most common and well-known magnetic-soft low-frequency materials.

51. What is the difference between electrical steel and ordinary (structural) steel?

52. Name the main components of permalloy.

53. What are amorphous alloys and what are their advantages over permalloy?

54. Name the main components of alsifer, the technology of its production and scope.

55. In which frequency bands are low-frequency and high-frequency magnetic-soft materials used?

56. What is the main feature of magnetic-soft high-frequency materials?

57. Name the main difference between magnetodielectrics and ordinary dielectrics.

58. Name the main components of ferrites, technology for their production and scope.

59. What magnetic characteristics are most important for magnetically hard materials?

60. Explain the demagnetization curve of magnetically hard materials.

61. What is the energy density of the magnetic field in the working space and how it is important for magnetically hard materials?

62. What is the order of values of coercive force and residual magnetic induction of magnetically hard materials?

63. Why it is impossible to use magnetically hard materials in an alternating magnetic field.

64. How can one create an alternating magnetic field with a permanent magnet?

65. What are the advantages of cast powder magnets over cast magnetically hard alloys?

66. Name the main components of magnetically hard ferrites, the technology of their production and scope.

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