Ministry of Science and Higher Education of the Republic of Kazakhstan

Non-profit joint-stock company "Toraigyrov University"

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RESEARCH OF PHYSICOMECHANICAL PROPERTIES IN MATERIALS SCIENCE AND THEIR APPLICATION

Monograph

Pavlodar Toraighyrov University 2025

Recommended for publishing by the Academic Board of the Toraighyrov University

(Protocol No7 dated 26.02.2025)

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Zh78 Research of physicomechanical properties in materials science and their application / A.Zh. Zhumabekov. - Pavlodar: "Toraighyrov University", 2025. - 109 pages.

ISBN 978-601-345-624-9

The monograph uses the issues of materials science from the point of view of physics and mechanics for research.

This work will be helpful for students, undergraduates, and doctoral students specialising in physics, mechanics, and technical specialities, as well as research institutes in metallurgy, when solving issues related to the physical and mechanical properties of metals and semiconductor materials.

UDC 53:531/534(035.3) LBC 22.3

ISBN 978-601-345-624-9

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Introduction

In electronic and radio engineering production, an increase in product quality and parameters is impossible without using high-quality materials. High requirements are imposed on materials used in electrical engineering, especially in electronics and microelectronics. To correctly choose the material and its processing methods, it is necessary to know the structure of the material, its physical nature, various external influences that contribute to these properties, and the conditions of use. Structural materials used in the manufacture of electronic equipment are divided into the following main groups according to their properties and function: conductivity, semiconductor, and dielectric.

The quality of products made from these materials should be monitored. The control is carried out at all stages of the manufacture of the item because only in this case will the quality of the manufactured product have the highest percentage, and confidence in its correct operation will increase. To do this, you need to know what material the products are made of. Materials science is an interdisciplinary branch of knowledge that studies changes in the properties of materials in liquid and solid states, depending on various factors. The properties under study include the substance structure and electronic, thermal, chemical, magnetic, and optical properties of these substances. In addition, this science uses many methods that allow us to study the structure of materials. When working with micro- and nano-sized objects, it is necessary to know the structure and properties of materials and all their characteristics. Materials science will help to solve this problem. Knowledge of the properties and construction of materials leads to the creation of new industries in production and fundamentally new products. However, in classical sectors, the knowledge gained by materials science is widely used in innovation, error correction, increasing the range of products, reducing production and product prices, and increasing safety.

The task of the discipline "materials science" is to get acquainted with the dependence of the process of passing current in the material and their classification, the reliance of their parameters on the conditions of the external environment, and the parameters of external influence and processing of structural materials. In the monograph, structural materials are considered to be electronic equipment materials. This monograph is intended for theoretical, practical, and independent work on the subjects "materials science" taught to students of the educational program "Electronic and electrical engineering" and "Technical Physics" of Toraigyrov University, and is offered as an additional tool for other technical specialities.

1 Basic Concepts and Formulas

1.1 The structure of materials and conductive materials

A material is a substance that can be used to prepare consumer products. It consists of interconnected atoms and ions, or molecules.

Structural materials are necessary for manufacturing various machine parts, engineering structures, and electronic equipment.

Structure of solids

An atom can form various bonds that depend on the structure of the outer electronic layer.

Covalent bonds are achieved by sharing two adjacent atoms and electrons. They can be present in molecules (in three aggregate states of matter) or between crystal lattice-forming Atoms (for example, Diamond, Silicon, and Germanium).

The second type of bond – the ionic bond – is determined by the gravitational force between positive and negative ions. Solids with an ionic structure are characterised by high mechanical strength and a relatively high melting point. An example of such ionic crystals is the alkali metal halide NaCl.

The third type of bond is a metallic bond, which also leads to the formation of solid crystal bodies. Metals can be considered a system formed by positively charged ions, the free electrons in the medium at the lattice node.

The fourth type of bond is the molecular bond (Van der Waals bond). Such a bond exists in some substances with covalent internal molecular bonds between molecules. In this case, the intermolecular bond is conditioned by the coordinated movement of valence electrons in neighbouring molecules. The van der Waals bond is not strong and is observed between molecules of some substances with a low melting point, such as paraffin.

Hydrogen bond. The Bond type is observed in organic molecules that form electrically damaging molecules, such as oxygen, nitrogen, and hydrogen, in their compositions. Let's take a water molecule of hydrogen and oxygen as an example. The electrons that form the valence bond between hydrogen and oxygen are displaced towards the oxygen atom. The water molecule is a strong dipole. Therefore, the negative pole is the fraction of oxygen, and the positive pole is the fraction of a hydrogen atom. When a water molecule is brought closer, the oxygen and hydrogen atoms are subjected to a strong electrostatic interaction and form a hydrogen bond. The binding energy of this bond is 0.1 EV per molecule.

Organic compounds with hydrogen bonds form the basis of materials widely used in life and engineering.

According to the degree of regulation, materials are divided into monocrystalline, polycrystalline, and amorphous. The property of anisotropy characterises monocrystals, hence the dependence of physical properties on the direction; the property of polycrystalline and amorphous materials is isotropic. Mono- and polycrystalline bodies have a specific melting point. By this sign, they can be easily distinguished from amorphous bodies. Amorphous bodies do not have a particular point of melting, and when heated, they gradually go into a liquid state and soften as the temperature increases.

Amorphous bodies include glass and many non-metallic materials, including polycrystals and metals. Examples of monocrystals are quartz, diamond, and specially grown semiconductors.

Defects of crystals

Genuine crystals always have defects. Defects of a solid include any periodic disturbances in the electrostatic field of the crystal lattice: violations of the stoichiometric composition, the presence of other impurities, additional crystallographic planes (dislocations, holes), etc. The size of at least one of the defects must be the same as the interatomic distance. Defects are divided into static, constant in time, and dynamic (atom oscillations in the crystal lattice node).

Point defects are vacancies, the entanglement and substitution of doped atoms, and interstitial atoms. A vacancy is an unfilled node in a grid. If the Crystal has many voids, diffusion will pass quickly. The size of the vacancy increases with temperature. Atoms of impurities can be located between nodes if their size is less than the size of the lattice–forming atom; these are atoms of impurity embedding. If the additive atom is close in size to the lattice atom, it replaces the atom of the central element in the lattice node, which is the additive substitution atom. Atoms of the primary substance can be located between nodes and inter-node atoms. Point defects are always present in crystals.

Linear defects – dislocations – are common when there are displacements in the grid. If the displacement is incomplete and does not reach the end of the crystal, the dislocation can be considered a region of a moving and non-moving boundary. In it, an excess unfinished plane is formed inside the crystal, and its Edge is the line of extreme dislocation. The dislocation extends from one crystal border to another or is closed in the Crystal. A characteristic of the size of the dislocation in a crystal is the density of the dislocation or the length of all dislocation lines per unit volume of the Crystal. Dislocations occur when crystals grow or when the crystal material solidifies. As a result of cold plastic deformation, they begin to grow rapidly in size.

A bürgers vector is a vector that is passed through a crystal lattice node where the contour is closed in the absence of dislocations and contains grouping, closing the contour. In crystals, along with linear dislocations, there are defects such as volumetric cavities and cracks, and cracks of a size that is more significant than the interval between atoms. These defects have a substantial impact on the destruction of the Crystal. The study and observation of crystal defects are not only theoretically important. It also determines the levels of physical and mechanical properties of solids. For example, point defects significantly impact solids' electrical, magnetic, and optical properties, while linear defects affect the plastic properties, and microcracks affect the mechanical strength.

Properties of materials

All the properties and characteristics inherent in materials can be divided into functional (performing work) and technological (capable of processing).

Functional properties refer to the determination of materials' usefulness for the manufacture of high-quality products. These include electrical, mechanical, thermophysical, optical, magnetic, and chemical properties.

The change in the material's characteristics during processing is called a technological property. Depending on the processing method (mechanical, thermal, chemical, etc.), it has many meanings, such as hardness, plasticity, melting, weldability, adhesion ability, etc. If the complex of these properties is suitable for processing the material, then the material is said to be technological.

The structure and composition of material properties can be classified according to the degree of dependence. Two groups are defined: structuresensitive and structure-stable.

Conductor refers to a substance that has electrical conductivity properties.

Specific electrical resistance refers to the characteristic of the electrical property of a material, which is determined by the ratio of the cross-sectional area of a cylindrical conductor made of a given material to the resistance.

Temperature coefficient of specific electrical resistance at shortinterval temperatures, TK ρ or α_{ρ}

$$\alpha_{\rho} = \frac{1}{\rho} \cdot \frac{\Delta \rho}{\Delta T} \tag{1.1}$$

The Fermi function determines the probability of filling the levels with electrons (one level corresponds to two states).

$$F(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$
(1.2)

where E - is the energy of the filling probability of the determinable level, eV;

 E_F – Fermi level energy, eV;

k – Boltzmann constant;

T – Temperature in Kelvin, K.

The Fermi level depends on the N concentration of electrons in the metal, i.e.

$$n = \frac{8\pi}{3} \left(\frac{2m^*}{h^2}\right)^{3/2} E_F^{3/2}$$
(1.3)

where m^* – an effective mass of an electron, a dimensional quantity, characterising the dynamic properties of an electron, kg; h – Planck constant.

Specific electrical conductivity – the inverse of the specific electrical resistance.

According to quantum theory, the γ -specific electrical conductivity of a metal is determined by the following expression.

$$\gamma = \frac{e^2 n}{m^* V_F} \lambda \quad \text{or} \quad \gamma = \left(\frac{8\pi}{3}\right)^{1/3} \frac{e^2 n^{2/3}}{h} \lambda$$
 (1.4)

where e – charge of an electron;

 V_F – the thermal velocity of electrons, which is close to the Fermi energy E_F , m/s;

 λ – the length of the electron's free path (the distance an electron travels between two collisions), m.

At a given temperature, the ratio of specific thermal conductivity to the specific conductivity of a metal is a constant value (*Wiedemann-Franz law*)

$$\frac{\lambda_T}{\gamma} = L_0 T \tag{1.5}$$

Where $L_0 = 2,45 \cdot 10^{-8} V^2 K^{-2}$ – Lorentz number.

The resistivity of a metal can be defined as the sum (Matthysen's rule)

$$\rho = \rho_{therm} + \rho_{mixt} + \rho_{def} \text{ or } \rho = \rho_{therm} + \rho_{res}$$
(1.6)

where ρ_{herm} , ρ_{mixt} , ρ_{def} – specific resistances of electrons conditioned by scattering in thermal oscillations, mixtures, and defects, Om·m; ρ_{res} – temperature independent connector or residual resistance, Om·m.

The *density of electric current* is a vector directed in the direction of movement of positive electric charges, the magnitude of which is determined by the ratio of the current flowing through the elementary area perpendicular to the direction of movement of charges to the location of this area.

The current density *j* decreases with depth *z* by the following law.

$$j(z) = j_0 \exp(-z/\Delta) \tag{1.7}$$

where j_0 – current density on the surface, A/m;

 Δ - depth of penetration of the field into the conductor, m.

$$\Delta = \sqrt{\frac{\rho}{\pi f \mu_0 \mu}} \tag{1.8}$$

where ρ -conductor resistivity, Om·m;

f – frequency of the supplied voltage, Hz;

 μ_0 – magnetic constant;

 μ – magnetic permeability of the conductor.

The equivalent cross-section area of the conductor during the passage of high-frequency current, or for a conductor in a circular cross-section

$$S_{hf} = \pi D \Delta \tag{1.9}$$

Where D – conductor diameter, m.

1.2 Magnetic materials

Magnetic is a term used when we consider all substances' magnetic properties.

Magnetism is the interaction between electric currents, current, and magnets.

Five types of magnetism are distinguished:

1) diamagnetism $-k_m \approx -10^{-6}$, $\mu \approx 1$;

2) paramagnetism $-k_m \approx 10^{-4}$, $\mu \approx 1$;

3) ferromagnetism $-k_m \approx 10^4 - 10^5$, $\mu \approx 10^4 - 10^5$;

4) antiferromagnetism $-k_m \approx 10^{-4}$,

5) ferrimagnetism $-k_m \approx 10^3 \cdot 10^4$, $\mu \approx 10^3 \cdot 10^4$.

Diamagnetism is the property of a poorly magnetised substance against an external magnetic field. Diamagnets are the only class of materials in which the final magnetic moments of atoms are equal to zero in the absence of an external magnetic field. Diamagnetism is conditioned by changes in the movement of electrons caused by the force of the captured field. Additional induced currents, conditioned by changes in the movement of electrons, lead to the formation of local magnetic moments directed against the captured field according to Lenz's law. Diamagnetism is inherent in all substances but is poorly observed and often hidden by other effects. (For example, copper and gold.)

 $\mu \approx 1;$

Paramagnetism – properties of magnetisation of substances directed by an external field. Paramagnetism is characteristic of substances in which the sum of the magnetic moments of atoms is not equal to zero. In the absence of an external field, the direction of the magnetic moments of atoms has an unregulated character due to thermal motion, and magnetisation is equal to zero. When capturing a field, the orientation of some of the magnetic dipoles in the direction of the field. The magnetic acuity of paramagnets depends on temperature because the thermal movement of atoms disrupts the orientation of their magnetic moments. (For example, aluminium and platinum.)

Ferromagnetism is the property of substances that super-magnetize in an external magnetic field and maintain magnetisation after removing the field. Ferromagnets differ from paramagnets in the presence of domains, that is, spontaneous (spontaneously) magnetised regions. Inside the domains, the ferromagnet is magnetised to self-saturation without the action of an external field, and the magnetic moments of the atoms are parallel.

When temperature increases, the orientation of the magnetic moments of atoms inside the domain is gradually disrupted, leading to a corresponding decrease in magnetisation. When the temperature T_{κ} is reached, the substance loses its ferromagnetic properties and becomes a paramagnet. Km = 0, the condition determines the Curie point when thermal motion breaks the domain structure, and the ferromagnet is transferred to the paramagnet structure. (For example: iron, nickel, cobalt.)

Antiferromagnetism is characterised by an antiparallel arrangement of unconnected magnetic moments of neighbouring atoms. The domain structure is not formed because the magnetic fields of neighbouring atoms are mutually destroyed. Magnetically, antiferromagnets are similar to poor paramagnets but differ because with increasing temperature, their acuity increases, reaching the maximum value at the Neel point and then decreasing, as in paramagnets. (Example: Chrome.)

Ferrimagnetism (magnetism of ferrites) – this is antiferromagnetism in the case when the uncompensated moments of neighbouring atoms, where the antiparallel is located, are not equal in magnitude or the number of atoms with oppositely directed moments is not equal. Therefore, ferrimagnetism is acquired only by compounds of elements. Ferrites are $MeO \cdot Fe_2O_3$, where Me - metal (*Ni*, *Mn*, *Mg*, *Fe*, *Co*, *Cu* et al.), Fe2O3 is called iron oxide, type two oxide. Ferrites, like ferromagnets, have a domain structure.

Ferrites resistivity on the electrical side $\rho = 10^{-1} - 10^3$ Om·m, belongs to the class of semiconductors.

Domains – the magnetic field that self-magnetizes before saturation.

Curie temperature – phase transition temperature of the ferromagnet to the paramagnet.

Neel temperature – phase transition temperature of the antiferromagnet to the paramagnet.

Magnetic soft material – a ferromagnet that magnetises until saturated and re-magnetizes in a relatively weak magnetic field.

Magnetic solid material – a ferromagnet that magnetises until saturated and re-magnetizes in a relatively strong magnetic field.

Magnetostriction – change in the position and size of the body when magnetised.

Thermostriction – magnetostriction deformation of ferromagnets, ferrimagnets, and antiferromagnets when heated without a magnetic field.

The magnetoresistive effect occurs when a magnetic field influences the electrical resistance of solid conductors.

Magnetic thermal phenomenon – changes in the thermal state of a body due to changes in its magnetic state.

The magnetosphere effect is the deformation effect on the magnetisation of a ferromagnet.

Piezomagnetism is the formation of magnetisation in a substance under the influence of external pressure, and the substance observing piezo magnetisation is called a piezo magnet.

The particle's magnetic moment is a vector quantity in the form of a magnetic dipole describing the magnetic property of a particle.

The vector sum of the magnetic moments of atoms in a unit volume is called residual magnetisation J_m .

$$\vec{J}_{m} = \frac{\sum_{i=1}^{N} \vec{M}_{A}}{V},$$
(1.10)

$$\vec{J}_m = k_m \vec{H} \tag{1.11}$$

where k_m - magnetic susceptibility – description of a magnetic showing its ability to magnetise in a magnetic field;

H – magnetic field strength – an additional characteristic of the magnetic field, whose circulation along a closed loop is determined only by the algebraic cosine of the conduction currents pierce the loop, A/m.

The final field along the material consists of the sum of the external and self-fields and their *induction*.

$$\vec{B} = \mu_0 \left(\vec{H} + \vec{J}_m \right) = \mu_0 \left(1 + k_m \right) \vec{H} = \mu_0 \mu \vec{H}$$
(1.12)

Where $\mu = 1 + k_m$.

Power conditioned by hysteresis expenditure per unit volume P_h

$$P_h = \eta f B_m^n \tag{1.13}$$

where B_m – maximum induction in the sample, Tl;

n – degree indicator, it is equal to 1.6-2;

f – variable field frequency, Hz;

 η - coefficient proportional to the static area of hysteresis (that is, to a trap obtained when the magnetic field voltage is slowly changed).

Eddy currents (Foucault currents) – induction currents generated in massive conductors.

The power spent on the passage of Eddy Current in a unit volume is equal to $P_{\rm C}$

$$P_{C} = \xi f^2 B_m^2 \tag{1.14}$$

Where – coefficient is proportional to the specific liquidity of the material.

Magnetic losses (the cost of hysteresis) – energy converted to heat when re-magnetizing the sample.

Magnetic flow angle tangent to describe losses in magnetic material, $tg\delta_m$, деп аталатын параметрді қолданған қолайлы. It is acceptable to use a parameter called. It can calculate the power P_A produced by a rod mounted inside the inductive winding.

$$P_A = I^2 \omega L \cdot tg \delta_m \tag{1.15}$$

where I – current passed through the winding, A;

 ω – AC cycle frequency, Hz;

L – inductance of core winding, Hz;

 $tg \delta_{m}$, the inverse of the value is the quality of the rod it is called.

Solenoid – a conductor twisted into a spinner in many windings, along which an electric current passes.

Inductance – description of the magnetic property of an electric circuit, determined by the proportional coefficient between the electric current flowing in the circuit and the full magnetic flux piercing the circuit.

The inductance of a solenoid is much more significant in length than its diameter.

$$L = \mu_0 \mu \frac{n^2 S}{l} \tag{1.16}$$

where n – number of Rolls;

l – solenoid length, m;

S – cross-sectional area, m².

Magnetic field strength is born in a medium through which current *I* passes along the winding.

$$H = \frac{nI}{l} \tag{1.17}$$

If the winding is ring-shaped, then the length of the midline of this ring is taken as l.

According to exponent's law, magnetic induction decreases with increased distance z from the surface area.

$$B(z) = B_0 \exp(-z/\Delta)$$
(1.18)

1.3 Dielectrics

Dielectric – a substance that conducts electricity poorly.

Dielectric polarisation – description of the electric state of a dielectric, determined by the ratio of the sum of the dipole electrical moment of a particle in some volume of material to the value of this volume.

In a dielectric in an electric field with a vanity E, there is a polarization P; with the separation of positive and negative charges, there is a native electric moment.

$$\vec{P} = \varepsilon_0 (\varepsilon - 1)\vec{E} = \varepsilon_0 \chi \vec{E} \tag{1.19}$$

where ε_0 – electrical constant;

 ϵ – dielectric constant;

 χ – dielectric permittivity.

Dielectric permittivity – description of a dielectric indicating its ability to polarise in an electric field.

Electrical induction (electrical shear) within the dielectric

$$\vec{D} = \varepsilon_0 \vec{E} + \vec{P} = \varepsilon_0 \varepsilon \vec{E} \tag{1.20}$$

Each dielectric connected to an electrical circuit and coated with electrodes can be considered a known capacitance capacitor.

$$C = \frac{Q}{U} \tag{1.21}$$

where C – capacitor capacity, μF ; Q – capacitor charge, Kl; U – supplied voltage, V.

Electrical capacity – characteristic of the ability of a conductor to have an electric charge equal to the ratio of the magnitude of the charge in the conductor to the potential of the conductor.

We denote the charge value on the capacitor substrates together with the dielectric as Q_{sub} . Then, during homogenisation, bound charges are formed on the surface of the dielectric, reducing the field strength inside the dielectric. The density of the bound charges, σd , is equal to the Homecoming, and the density of the charges in the capacitor substrates (inside which the dielectric is located) is equal to the electric shift.

$$\sigma_d = \vec{P}, \ \sigma_{el} = \vec{D}$$

One of the most essential properties of a dielectric is its relative dielectric constant. This value shows how many times the capacitance of the capacitor and the charge increase when the dielectric is introduced into the space between the substrates compared to a vacuum. In addition, it shows how many times the electric field strength decreases inside the dielectric compared to a vacuum. The more strongly polarised a material is in an electric field, the higher the material's dielectric constant.

The polarization mechanism is divided into two main types:

1) instantaneous, that is, passing in a very short time without heat dissipation (electronic, Ionic);

2) reduced or relaxed-long in time and designed for dielectric heating (dipole, migration, electron-relaxation, ion-relaxation).

Electronic polarisation is the elastic displacement and deformation of the electronic shells of atoms and ions. The formation time of such a homecoming is 10-15 s. The displacement and deformation of the Electronic orbits are independent of temperature, but with an increase in temperature associated with an increase in the heat of the dielectric and a decrease in the number of particles per unit volume, the electronic homecoming decreases. Electronic election is observed in all types of dielectrics, and it is not associated with energy loss.

Ion polarisation is observed in bodies with an ionic structure. It is conditioned by the displacement of ions from the distances between the nodes of the crystal lattice to minimal distances. The formation time of Ionic Homecoming is about 10⁻¹³ seconds. When the temperature increases, this homogeneity rises due to the weakening of the bonds of ions located in the nodes of the crystal lattice.

Dipole relaxation, or simply dipole polarisation - is caused by the partial orientation of the dipoles under the influence of an electric field. With increasing temperature, dipole polarisation initially increases, then decreases.

The time the dipole reduces by 2.7 times compared to the initial value due to thermal motion during the adjustment of field-oriented dipoles is called the relaxation time.

$$P(t) = P(0) \exp\left(-\frac{t}{\tau_0}\right)$$
(1.22)

Ion-relaxation polarisation is found in inorganic glass and some Ioniccrystalline inorganic substances in which ions are in a non-dense layer. In this case, poorly bound ions are shifted in the direction of the field under the influence of an external electric field.

Electronic relaxation polarisation occurs when excited by the heat energy of defective electrons. Electron-relational polarisation is designed for dielectrics with an extensive refractive index, internal field, and electronic and electrical conductivity, such as alloy titanium dioxide. The high value of the dielectric liquidity under electron relaxation polarisation and the maximum values in temperature dependence should be noted.

Migration polarisation macroscopic is expressed in inhomogeneities and impurities in solids with an inhomogeneous structure. This evocation is observed at low frequencies and occurs due to the scattering of electricity. Conductivity and semiconductor inclusions in a technical dielectric will cause such polarization. Slowly moving ions accumulate in layered materials at the boundaries of layer parts and electrode layers.

If a dielectric is formed from two different components or a mixture of them, then it ε electrical fluidity.

When connecting in a series

$$\frac{1}{\varepsilon} = \frac{\theta_1}{\varepsilon_1} + \frac{\theta_2}{\varepsilon_2} \tag{1.23}$$

when connecting in parallel

$$\varepsilon = \theta_1 \varepsilon_1 + \theta_2 \varepsilon_2 \tag{1.24}$$

Lichtenecker formula in the chaotic distribution of components

$$\ln \varepsilon = \theta_1 \ln \varepsilon_1 + \theta_2 \ln \varepsilon_2, \qquad (1.25)$$

$$\alpha_{\varepsilon} = \theta_1 \alpha_{\varepsilon 1} + \theta_2 \alpha_{\varepsilon 2} \tag{1.26}$$

when ε_1 , ε_2 – dielectric constants of the first and second material; θ_1, θ_2 – their volumetric contributions;

 $\alpha_{\varepsilon 1}, \alpha_{\varepsilon 2}$ – temperature coefficients of dielectric constant, K⁻¹.

$$\alpha_{\varepsilon} = \frac{\Delta \varepsilon}{\Delta T} \cdot \frac{1}{\varepsilon}$$

For a two-component dielectric

$$\theta_1 + \theta_2 = 1$$

Electrical conductivity – the ability of a body to conduct electric current under the influence of an electric field.

When supplying a constant voltage, all-dielectric materials conduct a negligible conduction current, conditioned by the displacement to which the free carriers of the electric charge are directed. Electronic or Ionic electrical conductivity is observed in the dielectric depending on the type of charge carriers. In solid dielectrics, ionic conductivity is usually observed.

Conductivity current density

$$\vec{j} = en\vec{V} \tag{1.27}$$

when n – concentration of free charge carriers,

V – average drift speed of charged particle motion in the direction of the field, m/s.



Figure 1.1 – Change in current in the dielectric after the constant voltage is applied

As the DC voltage supply time changes, the current in the dielectric decreases (Figure 1.1). In Area 1, the current of the dielectric consists of two components: the absorption and the piercing current. The cause of the absorption current (or shear current) will be slow-forming evocations (relaxation, migration). If the shear currents of elastic bound charges in electronic and Ionic evaporation pass quickly, they cannot be measured with an instrument.

The low number of free charges in the dielectric and weak breakdown currents cause the formation of currents. The leakage current of the dielectric is equal to the sum of the puncture current and the absorption current:

$$I_{ym} = I_{a\delta} + I_{c\kappa} \tag{1.28}$$

At constant voltage, the absorption currents, changing their direction, pass at the moments of switching on and off of the voltage; at alternating voltage, these currents pass during the material's stay in the electric field.

As the figure shows, only a puncture current passes through the dielectric after completing the homecoming processes.

When measuring shear currents, the fluidity of Dielectrics is worth considering. Separating charges on the electrodes and the neutral puncture current determines a dielectric's conductivity. At alternating voltage, the active conductivity of the dielectric is determined not only by the breakdown current but also by the active constituents of the absorption current.

With prolonged work with voltage, the current through solid and liquid dielectrics decreases or increases over time. A decrease in current over time indicates that the material's electrical conductivity has reduced, although it is conditioned by ions of foreign impurities and due to the sample's electrical purification. An increase in current over time indicates that charges, structural elements of the material, are involved.

In a dielectric, current can travel in two parallel ways: with the dielectric's volume and with the dielectric's surface. The volumetric v and surface s electric liquidity are distinguished in this regard. The technique often uses inverse quantities – own-volumetric ρ_v and own surface resistance ρ_s

$$\rho_{\rm V} = R_{\rm V} \frac{S}{h}, \quad \rho_{\rm S} = R_{\rm S} \frac{d}{l} \tag{1.29}$$

when S – cross-sectional area of the dielectric through which current flows, m²;

h – dielectric thickness (distance between electrodes), m;

d – the width of the surface area of the dielectric through which the current flows is equal to the length of the electrodes), m; l – the distance between the electrodes m

l – the distance between the electrodes, m.

If the surface resistance is measured in the sample with circular and ring-shaped electrodes, then the surface resistance ρ_s is

$$\rho_s = R_s \frac{2\pi}{\ln D_d} \tag{1.30}$$

When D and d – the diameters of the outer and inner electrodes, respectively, m.

Surface electrical conductivity is conditioned by the presence of moisture or turbidity on the surface of the dielectric. Water will have a high specific conductivity. For high conductivity to be observed, which is determined by the thickness of the layer, a thin layer of moisture must be present on the surface of the dielectric. But, since the moisture content of the adsorbed shell is related to the nature of the material, surface electrical conductivity is considered an intrinsic property of the dielectric.

The adsorption of moisture on the surface of the dielectric will depend on the environment's relative humidity. Therefore, relative humidity is essential in determining the value of a dielectric's specific surface conductivity.

The less homogeneity of the substance and the cleaner the dielectric surface, the lower the specific surface fluidity. Volumetric-porous materials will also have surface resistance.

High values of specific surface resistance are obtained by non-polar dielectrics, the surfaces of which are not water-permeable.

Various surface cleaning methods increase surface resistance: washing with water or solvents, heating at 600-700°C and painting the product with organosilicon varnishes.

Specific conductivity

$$\gamma = q N_T \,\mu_T \tag{1.31}$$

when q – charge carrier charge, Ql;

 N_T , μ_T – concentration and mobility of carriers, m⁻³, m²/(V·s).

The electrical conductivity of solids is caused by the displacement of dielectric ions and, in some materials - by the presence of free electrons.

The mobility of an electron will be much greater than the mobility of ions. For example, the electron mobility in titanium dioxide is about 10^{-4} m²/(V·s), and the ion mobility in aluminosilicate ceramics is only 10^{-13} - 10^{-16} m²/(V·s). So, in a dielectric with electronic electrical conductivity, the concentration of electrons is 10^9 - 10^{12} times less than in the dielectric

concentration with Ion electrical conductivity when the value of its specific conductivity and the charges of carriers are the same.

In ionic conductivity, the type of electrical conductor is experimentally determined, considering the substance's transport to the electrodes. This phenomenon is not observed in electronic conductivity. In solid dielectrics with an ionic structure, the electrical conductivity is primarily ionic, and the number of dissociated ions is exponentially dependent on temperature.

An exponential dependence expresses the mobility of ions.

$$N_T = N \exp\left(-\frac{E_d}{kT}\right), \mu_T = \mu \exp\left(-\frac{E_{sec}}{kT}\right)_{max}$$
(1.32)

when N - 1 m³ total number of ions per volume;

 E_d – the energy of dissociation, eV;

 $\mu_{\rm max}$ – ion limit mobility, m²/(V·s);

 E_{sec} – the energy of an ion jump from one place to another, eV; k – Boltzmann constant;

T – temperature, K.

The dependence of the specific volumetric conductivity of the dielectric from temperature varies according to the exponential law.

$$\gamma_{\rm v} = A \cdot \exp\left(-\frac{E}{kT}\right) \tag{1.33}$$

when $E_A = E_d + E_{vol}$

 E_A – the activation energy of the conductor is approximatively equal to the dissociation energy, $E_d >> E_{sec}$.

The dielectrics' lower electrical conductivity ensures that the charge and potential difference are maintained for some time after the capacitor substrates are disconnected from the current source. The zero is characterised by the capacitor's charging and discharging time, also known as the capacitor time constant.

$$\tau_0 = R_{\mu_3} C = \rho \varepsilon_0 \varepsilon \tag{1.34}$$

when R_{u_3} – insulation resistance of capacitor dielectricity, Ohms;

C – capacitor capacity, μ F;

 ρ – dielectric resistivity, Ohms ·m.

There are three main types of punctures:

1) *Electrical punching* is associated with electronic processes in a dielectric that occur in a strong electric field and cause a sudden sharp increase in electric current density during punching.

2) *Thermal puncture* is a consequence of a decrease in the dielectric's active resistance under the influence of heating in the electric field, which leads to an increase in the active current, an increase in the heating of the dielectric, and even thermal destruction.

3. *Electrochemical puncture*. Electrochemical processes can cause punctures under prolonged stress, passing under the influence of an electric field in a dielectric.

Puncture is the phenomenon of forming a passage channel in a dielectric through the action of an electric field. At this point, a short-circuit current will flow through the dielectric. The voltage under this condition is called the breakdown voltage U_{punc} , and the magnitude corresponding to the electric field strength is called the *electrical strength* $E_{str.}$

$$E_{str} = \frac{U_{punc}}{h} \tag{1.35}$$

For starting devices and installations, the operating voltage of the U_w is used, which is 2-4 times less than the breakdown voltage.

$$U_w = \frac{punc}{\kappa} \tag{1.36}$$

Where K is the fund coefficient.

Dielectric losses are the part of the alternating electric field energy in a dielectric that passes into heat.

Dielectric losses tg δ The tangent angle is active and reactive. I_c It is equal to the ratio of the current components, and PA separated from the dielectric is used to calculate the power.

$$tg\delta = \frac{I_A}{I_C} = \frac{R_C}{R_A} = \frac{1}{\omega C R_A},$$
(1.37)

$$P_A = UI_A = U^2 \varpi C \ tg\delta \tag{1.38}$$

where R_A , R_C – active and reactive resistance of Dielectrics, Ohms; ω – angular frequency of a given voltage ($\omega = 2\pi f$), Hz;

U – supplied voltage, V; C – capacitor capacity, μ F.

If in dielectrics, losses are often observed in electrical conductors, then $tg\delta$

$$tg\delta = \frac{1}{2\pi f\varepsilon_0 \varepsilon\rho} \tag{1.39}$$

Segnetoelectric - a crystal dielectric in which there is a selforientation of the dipole electric moments of the particles that compose it in the absence of an external electric field.

The static dielectric constant is determined by the basic evection curve of segnetoelectrics

$$\varepsilon_{st} = \frac{D}{\varepsilon_0 E} \approx \frac{P}{\varepsilon_0 E} \tag{1.40}$$

Piezoelectric effect – the formation of electrical charges due to the deformation of some crystals, and the substance that observes the piezoelectric phenomenon is called a *piezoelectric*.

Direct piezoelectric effect: the charge generated at the surface of the dielectric is linearly dependent on mechanical actions.

$$Q = d \cdot F$$
 or $q_s = d \cdot \sigma$ (1.41)

where Q – charge, Ql;

d – piezo module, Ql/N; F – force, N; q_s – charge surface density, Ql/m²; σ – mechanical stress, N/m².

In the *reverse piezoelectric effect*, the change in the dielectric's linear dimensions depends on the electric field strength and follows the linear law.

$$\frac{\Delta l}{l} = d \cdot E \tag{1.42}$$

where $\frac{\Delta l}{l}$ – relative change in dimensions;

E – electric field strength, V/m.

A *pyroelectric* is a crystalline dielectric that has self-induced homecoming.

The *pyroelectric effect* is called the spontaneous change inhomogeneity during temperature changes. At a constant temperature, the spontaneous electric moment is compensated by opposite-character Free charges. The change in temperature is accompanied by a shift in self-homogeneity, as well as the flow of electric current *I*

$$i = -S \cdot p \cdot \frac{dT}{dt} \tag{1.43}$$

where S – surface of pyroelectrics, m²;

p – pyroelectric coefficient, Ql/(m²·K); $\frac{dT}{dt}$ – temperature change rate, K/s.

Liquid dielectrics – liquids with high specific electrical resistance ($\approx 10^{10}$ Ohm/cm).

Liquid crystals are liquids with anisotropic properties linked by a sequence in the molecule's direction.

According to the manifestations of general symmetry, all liquid crystals are divided into three types: smectics, nematics and cholesterol.

Smectic is a liquid crystal characterised by an ordered arrangement of the Centers of mass of a molecule in the marked direction of its long axes.

Nematics is a liquid crystal characterised by the fixed orientation of their long axes during the chaotic arrangement of the Centers of gravity of molecules.

Cholesterol is a type of liquid crystal that differs from nematics in that it additionally twists the molecule in the direction perpendicular to its long axis.

Electret – a dielectric in which the polarisation maintains the state for a long time after stopping the external influence that causes polarization.

1.4 Semiconductor and Electronic Engineering Materials Research Methods

A *semiconductor* is a substance whose electrical conductivity increases when the temperature increases and is characterised by an intermediate electrical conductivity value between conductors and dielectrics. Semiconductor materials are used for the manufacture of electronic tools and devices.

The probability of an electron being at a level with energy E is subject to Fermi-Dirac statistics.

$$F_n(E) = \left[1 + exp\left(\frac{E - E_F}{kT}\right) \right]^{-1}$$
(1.44)

where E_F – Fermi energy

The *Fermi level* is an electron-filled top of the energy at absolute zero temperature.

Usually, in semiconductor $E - E_F > 3kT$ (1.44), the number one in the expression can be ignored, and the probability is described by Maxwell-Boltzmann statistics.

For electrons
$$F_n(E) \approx \exp\left(-\frac{E - E_F}{kT}\right)$$
, (1.45)

For holes
$$F_p(E) \approx \exp\left(-\frac{E_F - E}{kT}\right)$$
 (1.46)

The Fermi level in its semiconductor (chemically pure semiconductor) is in the middle of the *Forbidden Valley*.

Zone theory is a quantum theory of the energy spectrum of electrons in crystals.

The *valence field* is the allowable field of electrons' energy value, filled with valence electrons when the temperature is zero.

A *Forbidden zone* is an energy valley that cannot have electrons in an ideal Crystal.

A *conduction zone* is a valence valley in which not all energy levels are covered by electrons.

Impurity conductivity is electrical conductivity conditioned by an acceptor or donor impurity in a semiconductor.

The specific concentration of charge carriers in an impurity semiconductor

$$n_i = p_i = \sqrt{N_C N_V} \exp\left(-\frac{\Delta E}{2kT}\right)$$
(1.47)

where ΔE – width of the forbidden valley, eV;

 N_C and N_V – effective densities of Valence and conductive States, m⁻³;

 m_C and m_{V-} valence zone and conductive zone effervescent mass densities.

 N_C and N_V values are determined using the following formulas:

$$N_C = \frac{2(2\pi m_C kT)^{3/2}}{h^3},$$
 (1.48)

$$N_V = \frac{2(2\pi m_V kT)^{3/2}}{h^3}$$
(1.49)

A *donor* is a defect in a semiconductor's crystal lattice's ability to transfer electrons to the conduction band conditioned by a mixture or dislocation.

A *donor additive* is an electron-carrying additive to the conduction band of a semiconductor.

Donor level- the energy level in a semiconductor conditioned by the presence of a donor mixture.

Holes are an energy state in the valence zone of a semiconductor in which the electron is not located.

Hole conduction is an electrical conductivity caused by the movement of ledges in a semiconductor.

Electronic conductivity – electrical conductivity conditioned by the movement of electrons.

An n-type semiconductor is a semiconductor with electronic conductivity properties.

P-type semiconductor – a semiconductor with low conductivity properties.

The concentration of electrons and holes in an alloy semiconductor (artificially introduced alloy semiconductor)

$$n_0 = \sqrt{N_C N_D} \exp\left(-\frac{E_C - E_D}{2kT}\right),\tag{1.50}$$

$$p_0 = \sqrt{N_C N_A} \exp\left(-\frac{E_A - E_V}{2kT}\right) \tag{1.51}$$

where N_D , N_A – concentration of donors and acceptors, m⁻³; E_D , E_A – the energy of levels of donor and acceptor impurities, eV;

 $\Delta E_D = E_C - E_D$ – ionisation energy of donor mixture, eV; $\Delta E_A = E_A - E_V$ – ionisation energy of acceptor mixture, eV.

The mixture's ionisation energy differs between the mixture level and the nearest field.

For the concentration of charge carriers

$$n_0 p_0 = n_i^2 \tag{1.52}$$

where n_0 and p_0 – Concentration of electrons and electrons in a mixed semiconductor, m⁻³;

 n_i – concentration of own carriers, m⁻³.

So, the product does not depend on the composition of the mixture. Fermi level in alloy semiconductor

$$E_F = \frac{E_C + E_D}{2} + \frac{kT}{2} \ln \frac{N_D}{N_C}$$
(1.53)

The ratio of the average speed to the field strength in directed motion is called the mobility of carriers.

$$\mu = \frac{v}{E} \tag{1.54}$$

As a rule, defects' mobility is less than electrons' mobility. Specific conductivity of intrinsic semiconductors

$$\gamma = \gamma_0 \cdot exp\left(-\frac{\Delta E}{2kT}\right) \tag{1.55}$$

Where γ_0 - constant value for a given semiconductor.

Specific conductivity of an impurity semiconductor γ

$$\gamma = en_0\mu_n + ep_0\mu_p \tag{1.56}$$

where e – charge of an electron;

 n_0 and p_0 – equilibrium concentrations of electrons and electrons, m⁻³;

 μ_n and μ_p – electron and hole motions, m²/(V·s).

Potential differences or Thermo-EDF are formed in semiconductors due to temperature differences. Thermo-EDF for an N-type alloy Semiconductor at a temperature difference of 1 K

$$\alpha_{T} = \frac{kn\mu_{n}}{\gamma} \left(2 + \ln \frac{2(2\pi m_{n}^{*}kT)^{\frac{3}{2}}}{nh^{3}} \right)$$
(1.57)

Thermocouple – the effect of a thermoelectric temperature sensor based on the presence of a shielding force.

Laser material – the asset is the substance used to create the medium in the laser.

The thermoelectric driving force (Thermo-EDF) is an electromotive force generated in an electrical circuit. The contact between them comprises conductors of different origins at different temperatures.

Superconductivity – the phenomenon of a jump in the electrical resistance of some substances to zero at a lower temperature.

The current flowing through the ring generates a magnetic field that can be measured. The conductor made in the form of a ring has a resistance; the current passing through time decreases according to the following law.

$$I = I_0 \exp(-Rt/L) \tag{1.58}$$

where L - ring inductance, Hn; R - his resistance, Ohm;

 I_0 – primary current, A.

The time required to turn off the current in the ring from the superconductor is at least 100,000 years.

Radiography is a set of approaches to studying a substance's phase composition and structure based on analysing the scattering of X-ray radiation.

X-ray electron spectroscopy is an approach to studying the structure of matter based on measuring the energy spectra of electrons excited by X-ray radiation in the matter, which fly out during photoelectronic emission.

X-ray spectral analysis-determination of its chemical composition by the characteristic X-ray spectrum of atoms of a substance.

The Oge effect fills the void created by an electron at the internal level of atomic energy, transfers the energy released by not emitting radiation at this point to another higher-level electron, and leaves and passes this electron from the atom.

Ion mass spectrometry (IMS) is a way of studying a substance by determining the mass of ions of this substance or by the ratio of the mass of ions to their electric charge.

2 Theoretical foundations of the analysis of loads and stresses

2.1 Types of Loads Affecting Mechanical Structures

The theoretical foundations of analysing loads and stresses in mechanical structures underlie many mechanics and materials science disciplines. These foundations allow engineers and researchers to understand how structures behave under the influence of different forces and what changes can occur in the material under the influence of these forces. The main aspects of the theoretical foundations of the analysis of loads and stresses:

1) Fundamentals of solid medium mechanics – studies the behaviour of materials that assume that they are solid; that is, there are no gaps and breaks at the micro level. This makes it possible to model the behaviour of materials under load using equations of state that describe the relationship between deformation and stress;

2) elasticity theory – describes the behaviour of materials that return to their original shape after removing the load. The Basic Laws of this theory, such as Hooke's law, explain the linear relationship between stress and deformation for elastic bodies;

3) theory of plasticity – studies the behaviour of materials subject to irreversible deformation under the influence of loads. It is essential to understand how and under what conditions materials can leave the elastic zone and go to the plastic stage, which can lead to permanent deformations;

4) stresses and deformations – stress describes the internal forces distributed in the material, and deformation describes changes in the shape or size of the object in response to these stresses. Analysis of stresses and deformations allows you to determine which areas of the structure are at the highest risk of destruction;

5) Finite element methods are numerical for solving solid mechanics problems. This method allows you to simulate complex structures and load conditions, divide the object into many small elements, and solve equilibrium equations for each.

Understanding the theoretical foundations of load and stress analysis allows engineers and designers to create more reliable and safe designs. These foundations are the basis for predicting the behaviour of materials and structures in various situations, which are key to engineering and technological innovation.

Mechanical structures are subjected to various loads that can cause stresses, deformations and eventually destruction. Understanding these loads is very important for the design of reliable and safe structures. The main types of loads affecting mechanical structures:

1) static loads are loads that do not change over time. Examples include the weight of the structure, the load of equipment placed on the structure, and the pressure of stationary objects on the structure;

2) dynamic loads – change over time. They can be unpredictable and cause tremors, leading to fatigue. Examples of dynamic loads include wind load, transport load, and seismic activity;

3) temporary loads – affect the structure for a limited time. Examples include snow loads, construction loads, and loads of temporarily deployed equipment;

4) distributed loads – evenly distributed in a particular area of the structure. An example is the pressure of a liquid or gas on the walls of a container or container;

5) Concentrated loads are applied to a tiny area of the structure. An example is the pressure of a post or post on a beam;

6) shock loads – applied suddenly and with great force, often in a very short time. Examples include a hammer hitting a steel plate or hitting a heavy object on the surface;

7) cyclic loads – repeated at a specific frequency and can lead to material fatigue due to constant stress changes. Examples include loads of rotating machines or fluctuations in traffic;

8) Temperature loads—Temperature changes can cause temperature stresses due to the expansion or compression of the material. Although there is no load in the traditional sense, the effects can be similar, causing deformations and stresses in the structure.

As is known from practice, when using structural elements, they undergo the following main changes:

1) compression is a load directed to the axis of the structure, reducing its length;

2) stretching is a load directed from the axis of the structure, which tends to increase in length;

3) bending-a load that causes deformation of the structure depending on the moment applied to the cross-section;

4) shear-a load that acts parallel to the plane of the cross-section and tries to move one part of the structure relative to another;

5) torsion is a load that tries to rotate the structure around its axis.

When designing mechanical structures, all possible loads must be considered to ensure their reliability and safety. Modern analysis methods, such as the method of final elements, make it possible to accurately predict structures' behaviour under various loads' influence.

2.2 Classification of stresses in mechanical structures

Mechanical properties characterise the ability of the metal to resist the effects of external forces. Therefore, when choosing a metal to manufacture machine parts, you must know its mechanical properties: strength, elasticity, ductility, hardness and durability. These properties are determined based on mechanical tests in which metals are subjected to external forces (loads). External forces can be static, dynamic or cyclical (variable).

Mechanical properties can be divided into three main groups.

The first group includes a set of characteristics determined under one short-term load. These include elastic properties: modulus of regular elasticity E, modulus of transition and Poisson's coefficient μ .

Resistance to small elastic-plastic deformations is determined by the limits of elasticity $-\sigma_{el}$, proportionality $-\sigma_{pr}$ and fluidity $-\sigma_{0.2}$.

Tensile strength - σ_{str} , cut resistance - τ_{ag} and transition- τ_{tr} , hardness (according to Brinell) HV and scratching (on the Moos scale), and break length L_p are characteristics of a material in an area of large deformations to fracture.

Ductility is characterised by relative elongation δ and relative narrowing ψ after the break, and the break prolongs the deformation capacity δp of a series of non-metallic materials.

In addition, the impact bend KCU (KCV, KCT) determines the strength of the cut pattern.

The second group includes parameters that assess the resistance of materials to variable and prolonged static loads. The endurance limit is determined when rebooted in a multi-cycle fatigue zone based on $10^7 - 2 \times 10^7$ on the cycle. Multi-cycle fatigue is determined from a conditionally selected multi-cycle test base ($N \ge 5 \cdot 10^4$ cycles) and is characterised by a decrease in the load frequency (f=0.1-5 Hz).

Low cyclic fatigue resistance is rated for strength within low cyclic fatigue at a given repeated voltage level or in a selected test base.

Resistance to prolonged static loads is usually determined at temperatures above 20°C.

The criteria for the resistance of materials to long-term exposure to constant stresses $\sigma_{0.2}$ and σ_{τ} temperatures and long-term strength limits are. The extended tensile strength limit is determined in a given test base (usually 100 and 1000 hours), and the crawling limit is determined according to the residual resistance (usually 0.2%) or total deformation given in the established test base.

The third group is extinction characteristics. In engineering practice, these characteristics have been used relatively recently.

The fracture characteristics are determined in samples with pre-grown primary cracks. They are estimated by the following main parameters: the fracture's viscosity, the critical coefficient of voltage intensity at Flat deformation, the conditional critical coefficient of voltage intensity at Flat voltage state, the specific work of the sample with KST crack, and the growth rate of the site fatigue crack in a given K voltage intensity range.

Of the mechanical properties, only the elastic properties of metallic materials are structurally insensitive characteristics associated with the parameters of the crystal lattice and do not depend on thermomechanical processing modes if the latter does not cause polymorphic transformations. In practice, the elastic constants are associated with the ratio $E = G (1+\mu)$ for isotropic polycrystalline metal materials. Elastic properties are determined by the resonant frequency of vibrations of a thin core of uniform crosssection under the influence of small stresses in static tests (E_{CT} , G_{CT}) or by the dynamic method (E_{dyn} , G_{dyn}). At a temperature of 20°C and close to it, the values of the elastic constants determined by both methods are practically the same. In static tests, with an increase in temperature, the effect of bulk deformation is affected, as a result of which this method gives a progressive decrease in the values of elastic constants relative to the data obtained by the dynamic process.

All other mechanical properties are structurally more or less sensitive and anisotropic. Sharp anisotropy of elastic and other mechanical characteristics is characteristic of many non-metallic materials, determined by their oriented structure. Some anisotropy is also characteristic of many metal materials. The strength, flexibility, endurance and fracture performance of the material grains in the longitudinal direction relative to the deformation axis is usually higher than that of the transverse. However, for some, titanium alloys are characterised by "reverse" anisotropy. Most magnesium deformable alloys ($\sigma_{0,2 CZ} \ll \sigma_{0,2}$) have a significant fluid difference in tensile and compression.

Among some characteristics of mechanical properties, dependencies are experimentally established that make it possible to judge the strength limit of materials with sufficient accuracy by hardness values and cutting resistance by the strength limit. Correlations also exist between the tolerance and strength limits and different fracture characteristics.

Tension measures internal forces in material under external influences (loads, temperature changes, etc.). To study the stresses through an arbitrary point of the body, a cross-section is mentally made (figure 2.1), and one of

the halves of the body is thrown. Internal forces replace the effect of the thrown half on the other half.



Figure 2.1 – Scheme for switching external forces to internal stresses

In the slight element of section dS, an arbitrarily directed internal force of dF acts in the vicinity of an arbitrary point A. The ratio P = dF/dS is the voltage vector at point A in the dS square. The components of the voltage vector generally acting on the square are denoted σ and are called everyday stresses, and those acting along the square are called tangent stresses τ at point A in the square dS, $\sigma^2 + \tau^2 = p^2$.

In the general case, the stress state of a body at point A is characterised by the set of all stress vectors for all cross-sections (squares passing through point A) and, therefore, for any direction. A voltage tensor can determine the voltage state at point A and is characterised by nine components along three coordinate axes (three standard and six tangents). The tangent stresses are equal to even ($\tau_{xy} = \tau_{yx}, \tau_{xz} = \tau_{zx}, \tau_{yz} = \tau_{zy}$), that is, only six components remain. Voltages are expressed as Pa (Pascal).

$$\mathbf{T}_{str} = \begin{vmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{vmatrix}.$$
(2.1)

The characteristic of a tensor is the law by which its components are transformed when the coordinate axes are rotated. When turning the coordinate system, you can find its position when the tangent stresses are zero. These areas are called the main ones.

The condition determines the main directions of voltage Tensor *I*1, *I*2, *I*3 because it is invariant.

The voltage Tensor I_{1} , the first invariant, is the sum of the standard voltages:

$$I_1 = \sigma_x + \sigma_y + \sigma_z = 3_{\sigma 0}. \tag{2.2}$$

The mean value of the three normal voltages is called hydrostatic pressure:

$$\sigma_0 = (\sigma_x + \sigma_y + \sigma_z)/3. \tag{2.3}$$

Гидростатикалық қысым кернеу тензорына сәйкес келеді, оның қалыпты компоненттері σ_0 , ал тангенстері нөлге тең. Гидростатикалық қысым металда пластикалық деформацияны тудырмайтындықтан, ол кернеу жүйелерінен шығарылады. Тензордың қалған бөлігі S_{σ} кернеу девиаторы деп аталады:

The hydrostatic pressure corresponds to the voltage Tensor, the standard components of which are σ_0 , and the tangents are zero. Since hydrostatic pressure does not cause plastic deformation in the metal, it is removed from tension systems. The rest of the tensor is called the S_{σ} voltage deviator.

$$S_{\sigma} = \begin{cases} S_{x} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & S_{y} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & S_{z} \end{cases}.$$
 (2.4)

Voltage Tensor I_2 the following expression defines the second invariant:

$$I_2 = \sigma_x \sigma_y + \sigma_x \sigma_z + \sigma_y \sigma_z - \tau_{xy}^2 - \tau_{yz}^2 - \tau_{zx}^2.$$

$$(2.5)$$

Кернеу девиаторының екінші инвариантының квадрат түбіріне пропорционалды шамалар тангенс кернеулерінің қарқындылығы τ_j және қалыпты кернеулердің қарқындылығы σ_j деп аталады.

The values proportional to the square root of the second invariant of the voltage deviator are called the intensity of tangent stresses τ_j and the intensity of everyday stresses σ_j

$$\tau_j = \sqrt{I_2(S_\sigma)}, \sigma_j = \sqrt{3I_2(S_\sigma)}.$$
(2.6)

where τ_i – the intensity of stresses;

 σ_i – intensity of standard voltages;

 S_{σ} – voltage deviators;

I_2 – second invariant of the voltage Tensor.

Stresses in the material can occur due to phase changes in physicochemical processes and uneven temperature distribution (when heating and cooling the metal) and during heat treatment. In this case, the voltages that occur in the volume of the entire body are called macronutrients (or Type I voltages), and the voltages that occur in the volume of a single grain are called micronutrients (or type II voltages). Voltages that occur in ordinal volumes of several crystal lattice parameters are called submicroscopic (or type III voltages). Deformations are called changes in the shape or dimensions of the body (or part of the body) under the influence of external forces, as well as during heating or cooling and other effects that lead to changes in the relative position of body parts (figure 2.2).



a) linear deformation; 6) angular deformation

Figure 2.2 – Deformation scheme

Geometrically, the deformed state at a point is characterised by a deformation Tensor:

$$\varepsilon_{ij} = \begin{vmatrix} \varepsilon_x & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_y & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_z \end{vmatrix}.$$
(2.7)

 ε_x , ε_y , ε_z components *x*, *y*, *z* describes the linear deformations of fibres located on their axes: relative extensions (or relative abbreviations), εxy , εxz , εyz components – angles of rotation to deformation (or transition deformation) of two perpendicular fibres.

For the component of the transition deformation, the equality is fair:

$$\varepsilon_{xy} = \varepsilon_{yx} = \frac{1}{2}\gamma_{xy}, \ \varepsilon_{xz} = \varepsilon_{zx} = \frac{1}{2}\gamma_{zx}, \ \varepsilon_{zy} = \varepsilon_{yz} = \frac{1}{2}\gamma_{yz}.$$
(2.8)

When the coordinate system is rotated, all components of the deformation tensor are transformed along certain linear relationships concerning the guide cosines. In the theory of deformation and linear transformation, it is proved that among all possible directions of the coordinate axes, there is a triad of mutually perpendicular directions (main directions), about which all transition components of the deformation are equal to zero. The main directions of deformations are determined by three scalar approximations independent of the location of the coordinate system, so-called invariants.

First, invariant $I_1 = \varepsilon_x + \varepsilon_y + \varepsilon_z$ geused to record the stability conditions of the volume of the metal to be formed:

$$I_1 = \varepsilon_x + \varepsilon_y + \varepsilon_z = 0 \tag{2.9}$$

The second invariant of the deformation tensor is as follows:

$$I_2 = (\varepsilon_x - \varepsilon_y)^2 + (\varepsilon_y - \varepsilon_z)^2 + (\varepsilon_z - \varepsilon_x)^2 + \frac{3}{2}(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)(2.10)$$

The value proportional to the square root of the second invariant is called the deformation intensity. It describes the deformation in the general case of the deformed state.

$$\varepsilon_{i} = \frac{\sqrt{2}}{3} \sqrt{(\varepsilon_{x} - \varepsilon_{y})^{2} + (\varepsilon_{y} - \varepsilon_{z})^{2} + (\varepsilon_{z} - \varepsilon_{x})^{2} + \frac{3}{2}(\gamma_{xy}^{2} + \gamma_{yz}^{2} + \gamma_{zx}^{2})}.$$
(2.11)

Simple deformation schemes: stretching, compression, shifting, twisting, and bending. The first two circuits (tensile and compression) can be characterised only by linear components, and the second (transition, torsion, bending)—transition (angular).

Stresses in mechanical structures can occur under various external and internal loads. They are classified according to several criteria, including the direction of action, the nature of distribution, and the cause of occurrence. The main types of stresses encountered by engineers in the design and analysis of mechanical structures:

1) Normal and tangent stresses. Everyday stresses occur when the force is applied perpendicular to the cross-sectional area of the element. They can

be stretched or compressed depending on the direction of the force applied. Tangent stresses occur when a force acts parallel to the cross-sectional area, causing friction or torsion;

2) Main and additional stresses. The principal stresses are caused by external loads applied directly to the construction element. Restrictions on deformation such as temperature changes, pre-stress, or support deposition cause additional stresses;

3) uniform and uneven stresses. Uniform stresses are equally distributed over the entire section of the element. Uneven stresses vary in magnitude at different points in the section;

4) temporary and permanent stresses. Temporary stresses occur under the influence of temporarily applied or time-varying loads. Constant or longterm operating loads cause constant voltages;

5) fatigue stress occurs under the influence of cyclically changing loads and can lead to fatigue damage of the material even at stresses significantly less than the strength limit of the material under static load;

6) temperature stresses occur due to differences in temperature expansion or compression of materials, which can lead to additional internal stresses in the structure;

7) Hydrostatic stresses occur in liquids or gases under external pressure. They can also occur in solids when evenly compressed from all sides.

Understanding the different types of stresses and their effects on mechanical structures is essential for designing reliable and safe products. Engineers use various analysis methods, including the finite element method, to estimate stresses and optimise designs, considering their effects.

2.3 Overview of load and voltage analysis methods

Load and stress analysis is a key aspect of mechanics and engineering that ensures the reliability and safety of structures. There are several methods of analysis, each of which has its advantages and application areas. Here is an overview of the main techniques:

1) analytical methods – based on mathematical equations and the theory of elasticity for calculating stresses and deformations. These methods include elasticity theory-allows you to calculate stresses and deformations in materials that are entirely elastic and comply with Hooke's law; plasticity theory to analyse materials that can undergo plastic deformation; solving beam and slab problems equilibrium, deformation compatibility, and constitutional equations to analyse stresses in beams – slabs, and shells;

2) quantitative methods – uses computer modelling to analyse complex structures in which analytical solutions are impossible or too complex. The
most common numerical methods are the finite element method you to model and analyse very complex structures, divide them into more minor, more straightforward elements (finite elements) and calculate stresses and deformations of each component; the boundary element method, which solves static and dynamic analysis problems, focusing on the boundaries of the structure instead of the entire volume, as in MKE; discrete elemental methods-used to model systems consisting of many parts or blocks;

3) experimental methods – physically testing structures or scale models to measure stresses and deformations under load. These include: photoelastic-uses models of photoelastic materials to visualise stresses through polarised light; tensiometry-involves glueing tensometers to the surface of an object to measure deformation under load; digital image correlation is a modern optical method that allows you to obtain a deformation field on the surface of an object by analysing the changes registered in a series of images;

4) hybrid methods – combine elements of the above approaches to achieve more accurate or cost-effective analysis results.

The choice of the analysis method depends on many factors, including the complexity of the design, the type of material, the available resources and the accuracy of the desired results.

Load and stress analysis methods are necessary in various engineering fields to ensure the reliability, safety and durability of structures and materials. They allow:

1) predicting the behaviour of understanding how a structure responds to various loads (including weight, wind, vibration, temperature changes, etc.) allows engineers to design structures that can withstand these effects for life;

2) Design optimisation: Stress analysis helps determine where material can be removed without compromising safety or where material should be added to strengthen the structure.

Load and stress analysis methods are essential in engineering and structural design, providing the basis for designing, evaluating, and optimising mechanical structures and materials. These methods allow engineers to accurately predict how structures respond to various loads, including static, dynamic, thermal, and other effects. Based on these analyses, it is possible not only to guarantee the safety and reliability of structures but also to optimise their weight and cost and improve economic efficiency and productivity.

The results obtained from the load and voltage analysis provide essential data:

1) design of structures that can withstand the expected loads over the entire service life without excessive consumption of materials;

2) determination of critical points at which the probability of breakage or excessive deformations is maximum, which makes it possible to take measures to strengthen these sites;

3) predict and manage fatigue processes and wear, which is very important to ensure durability and reliability;

4) compliance with safety standards and standards, which is a prerequisite for many engineering projects;

5) Projects should be optimised in terms of economy and ecology, allowing the creation of light and low-cost structures in production.

Modern programs and methods, such as finite element analysis, provide powerful tools for performing these tasks, which makes it possible to simulate complex structures and their operating conditions with high accuracy. This accelerates development, shortens test cycles, and improves overall design efficiency.

Thus, load and voltage analysis methods are an integral part of modern engineering, which ensures the development of safe, economical and innovative solutions in various fields, from aviation development to construction and automotive engineering.

2.4 Methods and approaches to the analysis of specific structures

Methods and approaches to analysing mechanical structures are necessary to solve many problems related to designing, testing and operating various structures and mechanisms. These methods allow engineers and researchers to assess the behaviour of objects under the influence of multiple loads and determine their strength, stability, rigidity and other essential characteristics. The main aspects that require these methods are:

1) Strength Analysis. One of the main tasks is to determine the ability of the structure to withstand given loads without destruction. This includes the calculation of stresses, deformations and other factors that can affect the strength and durability of the structure;

2) dynamic analysis – dynamic performance analysis is necessary to assess the behaviour of structures when exposed to temporary loads, such as vibrations, shocks and moving loads. This is very important for structures that are exposed to dynamic influences in the process of work;

3) fatigue analysis – allows you to assess the ability of the structure to withstand repeated loads for a long time. This is especially important for parts and elements that are subject to cyclic loads;

4) thermal analysis – necessary to study the influence of temperature changes on the behaviour and characteristics of structures. Temperature effects can cause materials to expand or contract, which affects their strength and deformation;

5) Optimisation – analysis methods allow the evaluation of existing designs and their optimisation to achieve better performance at low cost and weight. This includes selecting materials, changing the geometry, and dividing the material into construction volumes;

6) service life prediction-the analysis of mechanical structures also helps to predict the service life of structures, which is very important for planning maintenance and repair and ensuring safety and reliability in the working process;

7) Compliance with standards and regulations—Analysis methods allow you to ensure that the structures being developed and used meet the current standards, norms, and safety requirements.

In general, methods and approaches to analysing mechanical structures are integral to engineering activities, making it possible to create more reliable, economical, and safe structures.

There are several methods and approaches to the analysis of specific mechanical structures, including:

1) the finite element method is a method of quantitative analysis that allows you to divide complex structures into simple elements to which the laws of mechanics can be applied. This method will enable you to simulate the behaviour of structures under various loads and conditions;

2) finite difference method – similar to the first method, this analysis method divides structures into finite differences to solve mechanics equations. It is used to analyse dynamic and static problems;

3) methods of analytical mechanics are classical methods based on equations of mechanics (for example, Newton's equations). They allow the analysis of structures through analytical calculations;

4) experimental methods – for example, wear and deformation tests, dynamic tests, etc. allow you to obtain data on the behaviour of the structure in actual conditions;

5) computer simulation—Virtual modelling and analysis of actual mechanical structures can be carried out using specialised software such as SolidWorks, Ansys, Abaqus, etc.

The choice of an approach to analysing specific mechanical structures depends on the study's goals and requirements as well as the available resources and data.

Thus, methods and approaches to analysing mechanical structures are necessary to solve many problems related to designing, testing, and operating various structures and mechanisms. These methods allow engineers and researchers to assess the behaviour of objects under the influence of multiple loads and determine their strength, stability, rigidity, and other essential characteristics.

2.5 The results of calculations and experimental studies

When choosing dimensions and materials for a particular structural element, it is necessary to provide a specific stock against the possibility of destruction or change in shape. The most significant stresses that occur when the element is operated must be designed so that, in any case, the material is less than the stresses that break or acquire residual deformations. The magnitude of the stresses that cause the material to break is called the tensile strength or time resistance; it is denoted by the same letters as the stresses but with the index "B". The amount of stress the deformation material exceeds is called the elastic limit. These values are the mechanical characteristics of the resistance of the material to decay and changes in the residual shape.

Stresses in its elements, which comprise only a part of the material's strength limit, must be allowed to ensure the structure's safety from destruction.

The magnitude of the permissible stresses is denoted by the same letter as the voltage but enclosed directly in parentheses; it is associated with equality with the strength limit p_b :

$$[p] = \frac{p_b}{k},\tag{2.12}$$

where k – safety factor;

 p_b – tensile strength; [p] – permissible voltage.

The safety factor indicates how often the permissible stress in the design is less than the strength limit of the material. The *k* coefficient is called the stock coefficient in the future. The value of this coefficient ranges from 1.7 - 1.8 to 8-10 and depends on the conditions under which the structure operates.

By denoting with the letter the most significant stresses p_{max} arising under the influence of external forces in the designed element, it is possible to express the primary requirement that the material and dimensions of this element satisfy inequalities.

$$p_{max} \le [p], \tag{2.13}$$

where p_{max} – maximum voltage; [p] – permissible voltage.

This is the so-called Strength condition: the actual stresses must not exceed the permissible ones.

Now, it will be possible to draw up a plan to solve the problems of material resistance.

Required:

1) determination of the magnitude and nature of all external forces applied to the projected element, including reactions;

2) Select the material that most corresponds to the purpose of the design and the nature of the action of external forces and establish the magnitude of the permissible stress;

3) give the dimensions of the cross-sectional area of the element in numerical or algebraic form and calculate the magnitude of the greatest real p_{max} stresses that occur in it;

4) $p_{max} \leq [p,]$ it is necessary to write down the strength condition and, using it, find and check the magnitude of the horizontal dimensions of the element.

This scheme for solving problems through the resistance of materials has been modified in some cases. There are structures in which the margin of safety for the entire structure is more significant than for the material in the tensest place, depleting the load-bearing capacity of the whole structure.

Strength condition for the material $p_{max} \leq [p]$ in these cases, it is replaced by a condition of strength for the entire structure:

$$P \le P_{per} = \frac{P_b}{k_1},\tag{2.14}$$

where P – load acting on the structure;

 P_{per} – its permissible value;

 $P_{\rm B}$ – a maximum load that destroys the entire structure.

Thus, the calculation by permissible voltages is replaced by the calculation by allowable loads.

Determination of permissible stresses requires knowledge of the strength of the material and its other mechanical characteristics, which can be obtained by experimental study of the material in special laboratories for testing materials. Finally, the calculation of real stresses requires the use of mathematical analysis methods and mechanics and the use of experienced data. Thus, theoretical mechanics and experimental procedures should be used to solve material resistance problems. When determining external forces should be based on static equations; in the case of statically indeterminate constructions, it is necessary to calculate the deformations of the material, as shown below, which involves two areas where the dependencies between deformations and forces or stresses are not possible only with the cash reliable results of laboratory experiments: one is analytical based on mechanics and mathematics, and the other is experimental. These two regions are closely related.

Although the problem of strength, when the resistance of materials arose, was posed due to purely practical tasks, in the future, the resistance of materials developed mainly in a theoretical direction, which sometimes caused a gap between the research results and their application in practice. The study of laboratory materials was carried out mainly along the lines of establishing norms for the reception of various materials. Currently, the resistance of materials is studied through extensive experimental and theoretical studies of authentic materials in terms of their work in structures, which allows us to solve several new practical problems. These are the tasks of studying the strength of new materials, the conditions of their destruction, and determining stresses within the limits and beyond elasticity.

Having drawn up a general plan for solving the problems of resistance of materials, you can now move on to certain types of tasks. They can be divided into several groups depending on the kind of deformation.

The main types of deformation (figure 2.3):

1) tensile or compression (A and B); examples – the work of chains, ropes, cables, stretched and compressed rods on trusses, columns; 2) cutting (C) – the work of bolts, rivets; 3) torsion – the work of shafts (D); 4) Bending – the work of any beams (e). These four types of deformation are called simple.



Figure 2.3 – The main types of deformation

In structures, the elements operate more complexly, experiencing two or more types of deformations simultaneously, such as bending or compressing, torsional bending, etc.; in these cases, the so-called complex deformation can be considered. For each deformation, stresses must be calculated, material and horizontal dimensions of structural elements must be selected, and methods must be established for calculating deformations.

For simplicity, you can first consider only the elements of structures and machines, the so-called Prismatic rods with a straight axis. This is called a body with all the identical cross-sections; the Centers of gravity of these sections lie in one straight line, called the axis of the rod. Rds with a variable cross-section and a curved axis will be considered.

The solution to the main problem of material resistance can be traced back to the simple case of stretching or compressing a prismatic Rod.

This is called the central elongation or contraction of the bar, the deformation of which occurs due to two equal and opposite forces applied to the terminal sections and directed along the axis of the bar. If these forces are directed outward from the end sections, there is a stretch (figure 2.4, A) and compression (figure 2.4, b).



Figure 2.4 – Stretching and crunching of the bar

According to the general plan for solving any resistance problem of materials, first of all, it is necessary to find the magnitude of these external forces that stretch the core. The magnitude of the forces P can usually be determined from the conditions under which the bar in question interacts with the rest of the structure.

As a simple example, we can consider the screw of the carriage connection (figure 2.5)



Figure 2.5 – Carriage connection screw

During the smooth movement of the train, the traction force of the steam locomotive P is balanced by the resistance to the movement of the rest of the train. The traction force of the steam locomotive (which sometimes reaches 25 T) is transmitted to the propeller using a screw cut so that the R forces are directed to the axis of the propeller. The core of the screw is subjected to stretching. The task here is to select the horizontal dimensions of the screw in such a way that its strength is ensured.

The external forces acting on the screw are equal to the pulling force. Next, you need to find the stresses caused by these forces, set the permissible value for them and select the cross-sectional dimensions of the rod so that the actual stresses do not exceed the permissible ones.

To calculate the stresses, select the sections separating the core and find the dangerous section where the most excellent voltage is applied. Formulas for calculating stresses are first set by sections perpendicular to the axis of the rod and, in the future, by inclined sections; thus, it is possible to find the most dangerous section.

Take a stretched stick and let it be divided into two parts with a crosssection of mn perpendicular to the axis. Let the second part be discarded; then replace the action of the thrown part with the forces transmitted through the section to the remaining part so that the balance of the first is not disturbed (figure 2.6).



Figure 2.6 – Stretched stick

The displacement forces equalise the external force P, so they must be equal to P^{H} , which is equal to p, in the opposite direction to the external force along the axis of the rod (figure 2.7). This result will be the force acting on the core P^{H} .



Figure 2.7 – Part of a stretched stick

Thus, the equilibrium conditions of the remaining part give only the magnitude of the resultant of the internal forces transmitted through the section mn, its direction and the point of application but cannot show how the stresses are distributed over the section area, that is, what forces are transported through the different Square units of this area. In addition, to assess the danger that threatens the strength of the material, it is necessary to find the most significant stress in the square unit of the area where the most critical force is transmitted.

Experiments with stretching rods in different materials have shown that if the tensile forces are precisely the same as on the axis of the rod, then the stretching of straight lines drawn parallel to its axis on the surface of the rod will be the same. Therefore, there is an assumption about the uniform distribution of stresses over the cross-section. Only at the ends of the core, where the P forces are directly transferred to the core, is the tension unevenly distributed between individual sections of the sectional area: the sections where the P force is directly applied are overloaded, but at a short distance from the ends, the work of the material is levelled. A uniform distribution of stresses along the cross-section perpendicular to the axis occurs. These stresses are directed parallel to The Force P, that is, to a standard section; therefore, they are called everyday stresses and denoted by the letter σ .

Since they are evenly distributed over the cross-sectional area, $P^H = \sigma F$ on the other hand, $P^H = P$; from here

$$\sigma = \frac{P}{H}, \qquad (2.15)$$

where σ – voltage;

P-force;

H – the value is the equalisation of the forces distributed over the section expressed by the voltage.

This formula allows you to calculate the voltage σ if the rod's tensile strength and cross-sectional dimensions are known.

On the other hand, if you determine the allowable value of the standard voltage, you can find the desired cross-sectional area from the same formula.

To determine what stresses are permissible during the operation of the rod from the selected material, it is necessary to experimentally establish the relationship between the strength of the rod and the stresses that occur in it. To do this, we make a pattern from this material(usually a round or rectangular cross-section) and put its ends on the machine's handles. This allows us to stretch the bar and gradually increase the forces.

Let the maximum load of the sample before the rupture be P_b . The magnitude of the everyday stresses caused by this load is called the tensile strength or time resistance of the material under test. It is usually expressed as kg/mm² or kg/cm².

$$\sigma_{tens} = \frac{P_b}{F},\tag{2.16}$$

where σ_{tens} – voltage tensile strength; P_b – tensile strength or temporary resistance; F – square.

In the cores of the structure, when stretching, everyday stresses should be allowed [σ] several times less than the strength limit σ_v ; the allowable stress is obtained by dividing the strength limit k by the stock coefficient σ_v . Several considerations determine the value of this coefficient. In any case, during the regular operation of this rod, there should be a break, and the remaining deformations should appear that can change the scheme of the structure. The stock ratio varies depending on the nature of the material used, the way forces influence the element of economic conditions, and several other factors.

Due to the importance of the correct choice of the stock coefficient and the amount of permissible stresses, these values are mandatory for the compilers of projects and calculations for many designs. Thus, for each case, the values of the allowable voltages $[\sigma]$ can be considered known. Then, the strength condition can be written using the formula (2.16) to determine the required amount of cross-sectional area of the stretched bar; this condition must mean that the real σ stress on the stretched bar under the action of forces; P must not exceed the stresses $[\sigma]$.

$$\sigma_{tens} = \frac{P}{F} \le [\sigma], \qquad (2.17)$$

where σ_{tens} – voltage tensile strength; P – force; F – square.

From this condition, the minimum required area of the bar is determined:

$$F \ge \frac{P}{[\sigma]},$$
 (2.18)
]- voltage;

where $[\sigma]$ -voltage; P-force; F-square.

(2.16) формуласын қолдана отырып, өзектің қимасын таңдауға болады.

Let's assume the cross-sectional area is given. Then, solving the formula (2.17) concerning P defines the allowable force.

$$P \le F[\tau], \tag{2.19}$$

where $F[\tau]$ – cross-sectional area; P – force.

2.6 Visualization of the stress and deformation applied to the key screw

So, as for the example from a practical point of view, you can study the key screw.

In modern engineering practice, numerical modelling is key in designing, analysing and optimising various structural elements. Comsol Multiphysics software provides powerful multi-parameter modelling tools that allow engineers to study the behaviour of objects in different physical conditions and at different loads. As part of our research, we will focus on analysing the mechanical behaviour of the standard fastener. This element is widely used in Mechanical Engineering and construction, and its reliability is essential for the safety and durability of the entire structure.

To carry out the analysis, we will develop a key screw model in Comsol Multiphysics, which allows you to visualise the distribution of stresses and deformations when applying external loads. We use the last elements method to get accurate results, help us identify weaknesses, and predict the order in which it works.

The purpose of this study is not only to test the strength and stability of the key screw to loads but also to optimise its design to improve its performance and reduce material capacity without loss of quality and reliability.



The geometry of the model is shown below.

Figure 2.8 – Key screw model

The cross-section shown below shows the bolt's fixed dependence. The load is applied to the box end of the combined key.



Figure 2.9 – Key and bolt interaction

In the images presented, schematic illustrations show the interaction between the key and the Bolt in the context of mechanical analysis. The first figure shows that the Bolt is constrained (fixed constraint), meaning it cannot move in space. The second figure shows the applied load attached to the bolt head, which simulates the process of tightening or loosening the bolt with a wrench.

In modelling Comsol Multiphysics, the perfect connection between the key and the Bolt does not slip, and the load is transmitted evenly on the contact surface. However, in this case, the contact between the surfaces is accompanied by friction, affecting the distribution of stresses and deformations.

Taking into account the specific contact conditions between the key and the Bolt, the expansion of the model may include the following aspects:

1) friction: introducing the coefficient of friction between the key and bolt surfaces allows you to simulate the tightening conditions more accurately. This is important to determine the exact force needed to tighten or loosen the Bolt;

2) Contact Pressure: accurate modelling of the contact pressure distribution between the key and the bolt allows you to understand better which areas of the Bolt are most loaded and how it affects its strength and durability;

3) Contact surface deformation: Considering the deformation of the contact surface under load allows one to assess the changes in contact that may be caused by the load and their impact on the hardening process.

4) wear: the long-term effects of friction can cause wear on both the key and the Bolt, which can also be considered in more advanced models.

Including these factors in the model increases its complexity and significantly increases the accuracy and realism of the simulation results. This makes it possible to design and use fasteners more efficiently in various engineering applications.

Algorithm of execution by the program Comsol Multiphysics:

1) from the" File "menu, select the" New " option;

2) in the" New "window, click "Model Wizard";

3) in the" Model Wizard "window, click" 3D";

4) in the" Select Physics "panel, select" Structural Mechanics > Solid Mechanics (solid)";

5) Click "Add";

6) click the" Study " button;

7) in the "Select Study "window, select" General Studies > Stationary";8) click" Done";

9) on the" Home "Panel, click" Import";

10) in the" Settings "window, find the" Import " section;

11) click" Browse";

12) go to the" Application Libraries folder "folder and select" wrench. Double click on the "mph in" file;

13) Click "Build all Objects";

14) on the" Graphics "panel, click" Zoom extensions";

15) on the" Home "Panel, click" Add Material";

16) go to the" Add Material " window;

17) in" Built-in", select" Structural steel";

18) click" Add to Component";



Figure 2.10 – Key screw model

19) drop the answer" Add Material";

20) in the" Model Builder "window, click" Parameters 1 "under" Global Definitions";

21) in the" Settings "panel, in the" Parameters "window, find the" Parameters " section;

22) enter the following parameters in the table;

Table 2.1-parameter table

* Name	Expression	Value	Description
F	150[N]	150 N	Applied force

23) in the" Model Builder "window, select" Solid Mechanics (solid) "under" Component 1 (comp 1)", right-click and select " Fixed Constraint;

24) on the" Graphics "panel, click" Wireframe Rendering";

25) select the border 35;

26) on the" Physics "panel, select "Boundaries" and click" Boundary Load";

27) select border 111;

28) select "Force" in the "Settings" window, "Boundary Load";

29) from the" Load type "list, select "Total force";

30) specify the vector "F_tot" as follows;

Tota	ll force			
Ftot	0	x		
	0	у	N	
	-F	z		

Figure 2.11 – Total strength given

The " - " sign indicates that the force will go down.

Use a smaller grid, as the geometry has small edges and surfaces.

31) in the" Model Builder "window, click" Mesh 1 "in" Component 1(comp 1)";

32) in the" Settings "window, in the" Mesh "section, click" Physics-Controlled Mesh";

33) from the" Element size "list, click" Finer";

34) click "Build All";

35) in the" Model Builder "window, select" Results > Stress(solid) "and select" Volume 1;

36) in the" Settings "window, select" Volume "and find the" Expression " section;

37) from the" Unit "list, select" MPa";

38) on the" Stress(solid) "panel, click "Plot";

39) on the" Graphics "panel, click" Zoom extensions";

40) In the" Model Builder "window, select" Stress(solid)", right-click on the mouse and click "Duplicate";

41) in the "Settings "window, in the "3D Plot Group "panel, enter" first Principal Strain "in the "Label " text box;

42) In the" Model Builder "window, select" first Principal Strain "and click" Volume 1 " below;

43) select" Volume "in the" Settings "window, click" Replace Expression "in the" Expression "section and select" Component 1(comp 1) > Solid Mechanics > Strain > Principal strains > solid.ep1 – First principal strain.»

44) in the" first Principal Strain "panel, click" Plot".



Figure 2.12 – Numerical simulation result of the key screw

The presented figure shows the result of numerical modelling in the Comsol Multiphysics program, which shows the distribution of the first key voltage on the key screw. In this case, stress and deformation are indicated by a colour scale on the model's right side.

Note that the maximum essential deformation is less than 2%, which satisfies the small deformation assumption.

The colour scale on the right shows the degree of deformation in different parts of the model. The most significant stress (shown in red) is concentrated in the area of the head of the key screw and the threaded end, indicating that these areas have undergone the most significant deformation. This may depend on the applied load acting in the direction of the Bolt axis, causing stretching or compression.

The least deformed areas (shown in blue) are located in the middle part of the key, which may indicate a low load on the area or that the Bolt material is resistant to deformation in this segment.

The figure also shows a coordinate system that helps determine the direction of the structure in space (with the X, y and z axes) and the object's dimensions (m), expressed in meters.

The benefits of the work done are as follows:

1) increasing the reliability of fasteners by accurately predicting their behaviour under load.

2) reduce the risk of mechanical failure and increase the safety of structures using these bolts.

3) saving materials and funds by optimising the structure of the Bolt without compromising its strength characteristics.

4) training and development of skills in working with advanced software for engineering analysis and modelling.

Thus, practical work with Comsol Multiphysics not only deepened the understanding of the mechanical properties of the key screw but also provided valuable data for its further improvement and application in various fields of engineering. This type of analysis is an essential tool in Mechanical Engineering and design development, allowing engineers to predict potential problems before the manufacture and use of products.

2.7 The effect of salt additives on the indicators in the technological process

The composition of electrolytes largely determines the technical and economic parameters of the electrolysis process. Since the first patents of Eru and Hall appeared in 1886, that is, for more than 100 years of the existence of the modern electrolytic method of aluminum production, noticeable changes have been made to the composition of the electrolyte of aluminum baths, although it still remains a cryolite–alumina melt.

In order to find an electrolyte more fusible, more electrically conductive, and cheaper, attempts were made to replace cryolite with other molten media for the electrolysis of alumina in them. Chlorides, carbonates, hydrates, sulfates, sulfides of various metals, aluminates, and borofluorides were tested, but no positive results were achieved. The reasons for this were either the insufficient solubility of alumina in such electrolytes, or their high volatility, or high hygroscopicity, or low stability at high temperatures, or, finally, the presence in their composition of elements more electropositive than aluminum.

Therefore, a different direction has emerged in the field of research related to the electrolyte of aluminum baths for a relatively long time – the introduction of salt additives into the cryolite melt, which would improve its properties and, consequently, the performance of aluminum baths.

The salts used should have cations more electronegative than Al^{3+} , and anions more electropositive than O^{2-} . Otherwise, the cations of salt additives on the cathode will be reduced with aluminum contamination, and the anions at the anode will be oxidized to produce undesirable products in the anode gases.

The industrial electrolyte currently used for the electrolytic production of aluminum consists mainly of cryolithoglinosum melt enriched with aluminum fluoride, the properties of which are improved by additives of various chemical compounds. The amount of these additives, as a rule, does not exceed 8-10%. The following compounds are most widely used as additives to industrial electrolytes: CaF_2 , LiF, NaCl, MgF₂. The main purpose of additives is to reduce the melting point of the electrolyte and increase its electrical conductivity. However, all additives except KF to one degree or another lead to a decrease in the solubility of alumina in the electrolyte, which limits their content in industrial electrolyte.

When using sodium chloride, the surface properties of electrolytes deteriorate. The surface tension of cryolite melts decreases both at the boundary with the gas phase and at the boundary with the solid phase (carbon). It also reduces the interfacial tension of cryolite melts at the interface with molten aluminum. Aluminum losses can decrease, and the current output increases only in electrolytes with a high content of sodium chloride. However, under these conditions, an interaction between cryolite (aluminum fluoride) and sodium chloride or aluminum and sodium chloride is more likely, leading to the formation of aluminum chloride, which partially persists in the electrolyte and partially volatilizes, decomposing by air moisture to form hydrogen chloride [6].

Magnesium fluoride reduces the electrical conductivity of cryolite melts to a greater extent than other additives under consideration. This is due to the appearance of complex MgF_3^- ions, which reduce the number of current carriers. The properties of MgF_2 are similar to those of calcium fluoride, but it should be noted that magnesium fluoride is more effective in melts with a cryolite ratio above 2.5 - 2.6, and calcium fluoride is more effective in melts with a cryolite ratio below 2.5 - 2.6 [6].

As for lithium fluoride, until recently it was a rather expensive salt, which limited its use in the process of electrolytic production of aluminum. The main property of LiF additives is a strong increase in the electrical conductivity of the electrolyte, which is due to the small radius of the Li⁺ ion, compared with Na⁺. Therefore, the addition of lithium salts can significantly intensify the electrolysis process.

Melting point of the electrolyte. The melting point determines the boundary of the existence of the liquid state of the system, therefore it is very important for practical purposes. Naturally, they tend to work with the lowest possible temperatures, as working conditions improve, equipment collapses less, and harmful side processes occur at a lower rate, which worsen the technical and economic performance of electrolysis. Knowing the temperatures of different systems helps you choose the right ratios of electrolyte components. According to the shape of the liquidus line, it is possible to predict a change in a number of physico–chemical properties of melts depending on changes in the composition of the system. It should be borne in mind that the electrolyte of industrial electrolyzers is usually

overheated by about 15-20 °C compared to the temperature of the beginning of crystallization.

Reducing the temperature of the liquidus opens up two possibilities for varying the parameters during the electrolysis process: reduce the operating temperature and set it at a level that preserves the previous overheating of the electrolyte relative to the crystallization temperature, or maintain the operating temperature at the same level, increasing the overheating of the electrolyte.

The positive consequences of the decrease in process temperature include:

- an increase in current output;

- a decrease in the solubility of aluminum and sodium;

- a decrease in the elasticity of the melt vapor, which leads to a decrease in the loss of valuable components, in particular, fluorine;

- reduction of sodium content in aluminum;

– reduction of heat losses.

All additives reduce the liquidus temperature of cryolite melts. The effect of lithium fluoride or magnesium fluoride additives on the melting point is most pronounced [6].

The effect of various additives on the melting point of the electrolyte is shown in Table 2.2.

Electrolyte density. The ratio of metal and electrolyte densities is determined by the behavior of the metal in the electrolyzer. The metal can be at the bottom of the electrolyzer or float to the surface of the electrolyte. The density of the electrolyte at the electrolysis temperature is usually 2.05-2.1 g/cm³, that is, the density of aluminum is about 10% higher than the density of the cryolithoglycemic melt. This is quite enough for the aluminum released during the electrolysis process to collect under the electrolyte layer on the bottom of the bath. Under certain conditions, the metal may be suspended. As the temperature decreases, the densities of the electrolyte and aluminum increase linearly, but not equally – the density of aluminum increases more slowly [6].

In general, the melt density needs to be reduced. The positive effects of reducing electrolyte density include:

- preventing mixing and maintaining good delamination between metal and electrolyte;

- increasing the rate of alumina dissolution, as well as reducing the likelihood of sediment formation on the hearth;

- obstructed movement of aluminum droplets into the ocean zone in case of their emulsification [6].

As follows from Table 2.2, additives of lithium, aluminum, and alumina fluorides reduce the density of the electrolyte, while calcium fluoride and magnesium fluoride have the opposite effect and increase the density of the melt.

Specific electrical conductivity of the electrolyte. Electrical conductivity is one of the most important physico–chemical properties of the melt, since the largest voltage drop occurs in the electrolyte layer, and this determines the cost of electricity for the aluminum produced.

The ohmic voltage drop in the electrolyte is about a third of the total voltage drop across the bath. It is desirable to have the highest possible electrical conductivity of the electrolyte in order to reduce the ohmic voltage drop in it. Although the design of the electrolyzer determines the amount of heat that must be generated to maintain thermal balance, reducing electrical resistance always provides advantages, as it allows for an optimal choice of current density in industrial electrolyzers (i.e. it is possible to increase the current strength, and, therefore, increase productivity, on the electrolyzer without disturbing the thermal equilibrium), or the interpolar distance (therefore, it is possible to increase the current output).

When aluminum fluoride is added to the cryolite melt, the electrical conductivity decreases [34]. Also, the electrical conductivity decreases slightly under the influence of calcium and magnesium fluorides. Additives of lithium fluoride and sodium chloride, on the contrary, significantly increase electrical conductivity.

In industrial electrolyzers, suspensions of carbon particles are always present, resulting from the shedding of anodes. In addition to carbon particles, there is a certain amount of insoluble alumina and aluminum carbides in the electrolyte. All mechanical impurities in molten salts reduce their electrical conductivity. It has been shown that industrial electrolytes have an electrical conductivity 5% lower than homogeneous media due to these impurities.

The specific electrical conductivity of an industrial electrolyte at a temperature of 950 – 960°C (K.O. = 2.7; 5% Al_2O_3 and 4-6% CaF_2) is 2.05×10^{-2} Sm/m [6].

Viscosity of electrolytes. The viscosity of an electrolyte is an important technological property that must be known in order to optimize hydrodynamic processes in an electrolyzer. The rate of diffusion of the electrolyte components, the rate of rise of gases, the separation of metal from the electrolyte, and the rate of alumina transfer in the electrolyte depend on it.

For some of these parameters, low viscosity is preferable, while others require its increased value. Therefore, it is quite difficult to identify the optimal viscosity or trends in optimal viscosity. It is most likely that an optimum exists for each electrolyzer design and operation (for example, an alumina supply system), and therefore, it remains important to know the trends. High viscosity is favorable for reducing diffusion and reducing the transport of dissolved metal to the anode [48]. However, as the viscosity increases, the electrical conductivity of the electrolyte decreases, the conditions for separating metal and electrolyte worsen, and the rate of rise of the anode gases decreases.

The addition of alumina, especially in the eutectic region, calcium fluoride, and magnesium fluoride increases the viscosity.

The addition of sodium fluoride and lithium fluoride reduces the viscosity (and its effect is more pronounced than for NaF).

Saturated steam pressure. The dependence of the saturated vapor pressure of substances on the composition of the melt provides important information about the thermodynamic properties of these substances. The steam pressure values are also of practical importance – they allow you to select electrolytes with lower volatility, which is important to reduce the loss of valuable electrolyte components and contamination of electrolysis workshops with harmful vapors of fluoride compounds and products of their hydrolysis.

The total saturated vapor pressure increases sharply with an increase in the concentration of aluminum fluoride in the $NaF - AlF_3$ system above its content in cryolite. This provision is important because there is a tendency to switch to more "acidic" industrial electrolytes.

Surface tension. Surface tension is an excess of free energy in the surface layer of a liquid at the interface of two phases, related to a unit surface area. If surface tension is measured as the tension force acting per unit length along a surface, then the measurement results are expressed in Newtons per meter (per centimeter). Knowledge of surface phenomena is important for the practice of electrolysis to understand the wetting of coal materials with electrolyte, the formation and behavior of a gas bubble on the surface of the anode, and the dissolution of metals in molten salts.

In the electrolysis of cryolithoglinosum melts, the surface tension at the melt–gas, metal–gas, and melt–metal boundaries is of interest, as well as the wettability of solid carbonaceous cryolithoglinosum materials with melt and metal.

A liquid particle is exposed to three forces of interfacial tension at the gas–solid, liquid-solid and liquid–gas phase interfaces.

The surface tension at the boundary with a solid surface is characterized by the wetting edge angle. Edge angles of less than 90° characterize a low, and more than 90° – a high surface tension.

Figure 2.13 schematically shows the forces acting on a gas bubble "sitting" on a solid surface and surrounded by liquid. Under equilibrium conditions, according to Young's equation, the marginal wetting angle of a solid by a liquid is:

$$\cos\theta = \frac{\sigma_{g,s} - \sigma_{l,s}}{\sigma_{g,l}} \tag{2.20}$$

where θ – is the edge angle of wetting,

 σ – is the interfacial tension, with a lower index, G – is a gas, S – is a solid, and 1 – is a liquid.



Figure 2.13 – Diagram of interfacial tension forces acting at the boundary of solid, liquid, and gaseous phases

A decrease in the interfacial tension at the electrolyte–gas – σ_{el-g} gas interface leads to faster removal of bubbles. Therefore, in order for the gas to separate well, it is necessary to reduce the σ_{e-g} gas.

The interfacial tension between the electrolyte and the coal σ_{el-c} affects the size of the gas bubbles; absorption of the electrolyte into the pores of the coal; and separation of the coal foam from the electrolyte.

The electrolyte moistens the surface of carbonaceous materials well. Wetting depends on the structure and porosity of the carbon materials. The greater the porosity, the better the wetting, and the equilibrium is not reached, and the melt is continuously absorbed into the carbon material.

The wetting of the coal surface with cryolithoglinosum melts improves dramatically when dissolved aluminum is introduced into the melt, which leads to increased absorption of the electrolyte into coal materials. Coal paticles in an electrolyte containing dissolved aluminum float poorly to the surface and remain in the electrolyte volume.

The interfacial tension between a metal and an electrolyte σ_{el-Al} is defined as the difference between the surface tensions of the metal and the

electrolyte. The surface tension of aluminum is three times greater than that of the electrolyte, so aluminum tends to take a spherical shape in the electrolyte.

Additives of aluminum fluoride, magnesium fluoride, and calcium fluoride increase the surface tension of the cryolite melt at the aluminum boundary. Alumina and sodium fluoride lower the surface tension (that is, they are surface–active substances).

Solubility of alumina in electrolyte. It is known that the concentration of alumina saturation of the melt strongly depends on the additives of various salts. The solubility of alumina at this temperature increases in alkaline electrolytes, that is, with an increase in the content of sodium fluoride, with the addition of other salts (except potassium fluoride), including calcium fluoride, the solubility of alumina decreases [46].

The effect of additives on the physicochemical properties of the electrolyte is shown in Table 2.2.

Comp	(weig	Al ₂ O	T ⁰ C	Metal	Elcond	Density	Vapo	Surfac	Visco
onent	ht %)	3	liqui	solubi	uctivity	(g/cm^3)	ur	e	sity
		Solu	dus	lity	(Sm)		pressu	tensio	(mPa
		bility		(wt%)			re	n	s)
		(wt%					(Pa)	(mN/	
)						m)	
Cryoli									
te (1)	100	12,4	1011	0,131	2,874	2,103	534	131,5	2,232
CaF ₂	4%	-1,5	-12	-0,013	-0,057	0,018	-2	0,3	0,130
	7%	-2,5	-20	-0,022	-0,099	0,033	-3	-2,6	0,228
AlF ₃	4%	-0,4	-1	-0,033	-0,171	-0,025	137	-4,0	-0,091
	12%	-1,4	-24	-0,078	-0,439	-0,060	596	-12,3	-0,399
LiF	1%	-0,5	-9	-0,018	0,047	-0,005	-11		-0,123
	3%	-1,3	-27	-0,021	0,142	-0,014	-33		-0,399
MgF ₂	1%	-0,5	-5	-0,004	-0,047	0,005	-10		0,041
	3%	-1,4	-15	-0,012	-0,139	1,013	-11		0,132
AI ₂ O ₃	3%		-16	-0,003	-0,145	-0,022	-90	-18,7	0,029
	5%		-28	-0,005	-0,282	-0,040	-130	-36,6	0,118
Temp	-25C	-1,5		-0,040	-0,090	0,023	-165	3,5	0,195
eratur	-50C	-2,8		-0,082	-0,182	0,047	-282	7,0	0,398
e (2)									

Table 2.2 – Effect of additives and temperature on melt properties

The first line shows the properties of the cryolite melt at 1011°C. Other lines show changes in properties under the influence of additives and temperature.

Overview of the proposed electrolyte compositions. An electrolyte for producing aluminum is known [14], consisting of, by mass%:

- calcium fluoride - 6-10;

- magnesium fluoride 0.5-1.5;
- sodium cryolite is the rest.

The disadvantage of this composition is the high content of calcium fluoride, which increases the density and viscosity of the electrolyte and reduces its electrical conductivity. For the above reasons, and primarily because of its low electrical conductivity, this electrolyte is unsuitable for electrolysis under increased current load.

The composition of $n \cdot NaF \cdot AlF_3 + LiF(6 \text{ wt. }\%)$ of a low– temperature electrolyte [14] with high electrical conductivity (2.5 Sm× cm⁻¹ at 750°C), but the solubility of alumina in it was 1.2 wt. %, which is completely unacceptable for the industrial use of this electrolyte.

An electrolyte for producing aluminum is known [14], consisting of a mixture of sodium cryolite, lithium cryolite, and potassium cryolite, mass%:

- lithium cryolite 17.5;
- potassium cryolite 5;
- Sodium cryolite is the rest.

The disadvantage of this composition is the presence of a large amount of lithium-containing compounds, since lithium, which passes into the commercial metal, is an undesirable impurity and there is a need for additional refining of the commercial metal from lithium. The high cost of lithium-containing compounds also increases production costs.

An electrolyte for the production of aluminum is known [14], consisting, by mass%:

- lithium fluoride 0.5 -1.5;
- magnesium fluoride 0-2;
- calcium fluoride -3-5;
- aluminum fluoride -8 12;
- alumina 1-6;
- Sodium cryolite is the rest.

The disadvantage of this electrolyte is its relatively low electrical conductivity (2.1 Cm \times cm -1) and the solubility of alumina in it (6.32%).

Description of the selected electrolyte. In this work, it is proposed to use the following electrolyte composition, % (by weight):

- potassium fluoride 4.0-7.0;
- lithium fluoride 1.0-3.0;
- calcium fluoride 4.0-5.0;
- magnesium fluoride 0.5-1.5;
- aluminum fluoride 4.0–6.0;
- alumina 2.0 4.0;
- Sodium cryolite is the rest.

The lower limit of aluminum content (4.0 wt. %) is due to the need to reduce the solubility of aluminum and sodium in the electrolyte and increase the interfacial tension at the metal–electrolyte interface for the stability of the metal surface. The upper limit of aluminum fluoride content is limited to 6.0 wt. % to maintain the high electrical conductivity of the electrolyte and the solubility of alumina in it.

The lower limit of potassium fluoride content (4.0 wt. %) is due to the need to maintain high solubility of alumina in the electrolyte. The upper limit of potassium fluoride content is limited to 7.0 wt. % in order to eliminate the negative effects of potassium on carbon-graphite hearth blocks.

The lower limit of lithium fluoride content (1.0 wt. %) is caused by the need to increase the electrical conductivity of the electrolyte. The upper limit of lithium fluoride content is limited to 3.0 wt. % due to the need to maintain the high solubility of alumina in the electrolyte and to maintain the purity of the aluminum produced.

The lower limit of calcium fluoride content (4.0 wt. %) is associated with the need to reduce the solubility of aluminum and sodium in the electrolyte, the elasticity of steam above the melt, and increase the efficiency of carbon foam burnout. The upper limit of the calcium fluoride content is limited to 4.0 wt. % to maintain the high electrical conductivity of the electrolyte and the solubility of alumina.

Lower limit of magnesium fluoride content (0.5 wt. %) is associated with the need to reduce the solubility of aluminum and sodium in the electrolyte and increase the efficiency of carbon foam burnout. The upper limit of magnesium fluoride content is limited to 1.5 wt. % to maintain the high electrical conductivity of the electrolyte and the solubility of alumina.

The lower limit of alumina content in the electrolyte (2.0 wt. %) is due to the need to maintain a sufficient concentration of Al_2O_3 for stable electrolysis of cryolithoglinosum melt (without the occurrence of anodic effects). The upper limit of alumina content in the electrolyte is limited to 4.0 wt. % to maintain a high rate of alumina dissolution in the electrolyte, that is, for greater manufacturability of the electrolysis process [14].

The proposed electrolyte composition has a liquidus temperature of -945 ° C, electrical conductivity (at T = 955°C and C_{Al.}=2.5 wt. %) is 2.6 Ohms⁻¹×cm⁻¹.

3 Examples of problem solving

3.1 The structure of materials and conductive materials

Example 1

If the resistivity of copper at a temperature of T=300 K is 0.017 μ Ohm*m, it is necessary to determine the length of the free travel of electrons in copper.

Resolution

According to quantum theory, the specific conductivity of metals is the length of the free path and is bound by a ratio of (1.4)

$$\gamma = \left(\frac{8\pi}{3}\right)^{1/3} \frac{e^2 n^{2/3}}{h} \lambda$$

And by definition $\rho = \frac{1}{\gamma}$.

The concentration of free electrons in copper equals the concentration of atoms.

$$n = d \, \frac{N_A}{M}$$

(d is the density of copper, – Avogadro number, M is the molar mass). From this

$$\lambda = \left(\frac{3}{8\pi}\right)^{1/3} \frac{h}{e^2 n^{2/3} \rho} = 3,89 \cdot 10^{-8} \,\mathrm{m}.$$

Example 2

It is known that in a cube with centred sides, aluminium's crystallisation period is a=0.4041 nm. Therefore, the concentration of free electrons, assuming that each atom of the crystal lattice has three electrons, must be determined.

Resolution

The sides come from four atoms per elemental cell in a grid of a centred Cube. Therefore, the number of atoms per unit volume

$$N = \frac{4}{a^3} = \frac{4}{(0,4041 \cdot 10^{-9})} = 6,06 \cdot 10^{28} \,\mathrm{m}^{-3}$$

From this, the concentration of electrons follows.

Is
$$n = 3N = 18,18 \cdot 10^{28} \,\mathrm{m}^{-3}$$
.

Example 3

Determination of how many times the specific thermal conductivity of copper changes when changing the temperature from 20 °C to 200 °C.

Resolution

According to the Wiedemann-Franz Law (1.5)

$$\frac{\lambda_T}{\gamma} = L_0 T$$

where γ – own capacity;

 L_0 – Lorentz number.

From the

$$\frac{\lambda_{T1}}{\lambda_{T2}} = \frac{\rho_2 T_1}{\rho_1 T_2} = \frac{(1 + \alpha_\rho \Delta T) T_1}{T_2} = 1,12$$

(for copper $\alpha_{a} = 4,3 \cdot 10^{-3} \text{ K}^{-1}$).

Example 4

The resistivity of copper with a tin content of 0.3 atomic per cent at a temperature of 300 K is 0.0258 μ Ohm*m. Determine the ratio β of the resistivity of copper at temperatures of 300 K and 4.2 K.

Resolution

According to the Mattison (1.6) rule

$$\rho = \rho_T + \rho_{\kappa}$$

where ρ_T – resistance of electrons scattered by thermal oscillations in the lattice;

 ρ_{resid} – residual resistance caused by electron scattering caused by the inhomogeneity of the structure.

For pure copper $\rho \approx \rho_T$. T=300 K when $\rho_T = 0,0168 \mu$ Ohm*m (See Appendix). At Absolute Zero, the total resistance of a real metallic conductor is equal to the residual resistance.

From the

$$\beta = \frac{\rho_{300}}{\rho_{4,2}} = \frac{\rho_{300}}{\rho_{ocm}} = \frac{\rho_{300}}{\rho_{300} - \rho_T} = \frac{0,0258}{0,0258 - 0,0168} = 2,87.$$

Example 5

The resistance of the light bulb's tungsten wire equals 35 Ohms at a temperature of 20 °C. When connecting to a network with a voltage of 220 V, it is necessary to determine the temperature of the lamp wire so that a current of 0.6 A flows in the wire in stable mode. The temperature coefficient of the specific resistance of tungsten at a temperature of 20 °C is equal to $5*10^{-3}$ K⁻¹.

Resolution

Taking into account the linear dependence of the resistance of a metal conductor from temperature

$$R_{2} = R_{1} [1 + \alpha_{R} (T_{2} - T_{1})]$$

Where $-T_1$ and T_2 Obstacles in temperature.

For tungsten, it can be assumed that. Resistance of the lamp wire in working mode

$$R_2 = \frac{U}{I} = \frac{200}{0.6} = 366 \text{ Om}.$$

Then

$$\Delta T = T_2 - T_1 = \frac{\left(R_2 - R_1\right)}{R_1 \alpha_R} = \frac{366, 7 - 35}{35 \cdot 5 \cdot 10^{-3}} = 1895 \,\mathrm{K}.$$

In finished $T_2 = 1895 + 293 = 2188$ K.

Explanation: in general terms $\alpha_{R} \neq \alpha_{\rho}$, because *l* and *S* values *T* - temperature dependent.

Example 6

It is necessary to determine how much the resistance R of a copper wire with a diameter of 1 mm in a circular section with a frequency of 10 MHz is greater than the resistance of a direct electric current in this particular wire.

Resolution

The formula determines the depth of transition of the electromagnetic field to the conductor (1.8).

$$\Delta = \sqrt{\frac{\rho}{\pi f \mu_0 \mu}}$$

Since copper is a diamagnetic substance, $\mu = 1$.

It has a frequency of 10 MHz for copper.

$$\Delta = \sqrt{\frac{0,017 \cdot 10^{-6}}{3,14 \cdot 10^7 \cdot 12,56 \cdot 10^{-7}}} = 2,07 \cdot 10^{-5} \text{ m}.$$

There is a noticeable surface effect from that. In this case, the coefficient of increase in the resistance of a circular area conductor is inversely proportional to the ratio of the areas through which the current flows.

$$K = \frac{R_{\sim}}{R} = \frac{\pi d^2}{4\pi d\Delta} = \frac{d}{4\Delta} = \frac{10^{-3}}{4 \cdot 2,07 \cdot 10^{-5}} = 12$$

Example 7

Determination of the resistance of a washer high-frequency resistor made of a carbon shell with a specific surface resistance ρ_s =300 ohms (figure 3.1). Dimensions of resistive elements: r_1 =3 mm, r_2 =7 mm.



Figure 3.1 – High-frequency resistor with washer made of carbon shell

Resolution

Through such a resistor (1 - ceramic disc with holes; 2 - junction areas; 3 - resistive shell), current flows radially through the resistive shell. Inside the resistive element with the dx coordinate, calculated from the centre, we distinguish the area of the thickness circle.

This is the resistance of the area.

$$dR_x = \frac{\rho dx}{2\pi x\delta}$$

where δ – shell thickness,

 $\frac{\rho}{\delta} = \rho_s$ – resistive Shell Square resistance.

Resistance of the dielectric disc /washer/ resistive element located on one side

$$R_{2} = \frac{\rho_{S}}{2\pi} \int_{r_{1}}^{r_{2}} \frac{dx}{x} = \frac{\rho_{S}}{2\pi} \ln \frac{r_{2}}{r_{1}} = \frac{300}{2 \cdot 3,14} \ln \frac{7}{3} = 40 \text{ Ohm.}$$

The resistor has two such elements connected in parallel, so $R = R_{_9}/2 = 20$ Ohm.

Example 8

Consider the potential difference at the ends of a copper conductor with a resistivity of 0.017 μ Ohm, which is 220 V, and determine when the electron will cover a distance of 1 km on the same wire.

Resolution

Specific conductivity according to Ohm's law

$$\gamma = env/E$$

The concentration of free electrons in copper

$$n = \rho' \frac{N_A}{M} = 8,45 \cdot 10^{28} \, \text{m}^{-3}$$

where $\rho' = 8920 \text{ kg/m}^3 - \text{density of copper};$

 $M = 63,54 \cdot 10^{-3}$ kg/mol – molar mass of copper; N_{A} – Avogadro number.

Then, the average electron velocity

$$v = E/(\rho en) = U/(\rho enl) = 9,6 \cdot 10^{-4} \text{ m/s}.$$

Magnetic materials Example 9 The magnetic induction of pure iron at saturation is 2.2 Tl. It is necessary to determine the magnetic moment per atom of Iron, considering that the wall of the elementary cell of the iron crystal lattice consists of a volumetric-centered a=0.286 nm/in boron magnetons/.

Resolution

The formula determines induction within a material (1.12)

$$B = \mu_0 (H + j_M)$$

In the magnetic saturation of ferromagnets $H \ll J_M$. Therefore, magnetisation $J_M \approx \frac{B}{\mu_0}$. On the other hand, The atomic number of iron per unit volume

$$N = \frac{K}{a^3}$$

Where K – multiple of an elementary cell, that is, the number of atoms per cell.

In the case of a volumetric-centered Cube K = 2. Magnetic moment per atom

$$M_{A} = \frac{J_{M}}{N} = \frac{Ba^{3}}{\mu_{0}K} = \frac{2.2 \cdot (0.286 \cdot 10^{-9})^{3}}{1.26 \cdot 10^{-6} \cdot 2} = 20.4 \cdot 10^{-24} \,\mathrm{J} \cdot \mathrm{T} \mathrm{I}^{-1},$$

The Bohr magneto is stable, and $\mu_E = 9,27 \cdot 10^{-24}$ J·Tl⁻¹ since it is an equal measure, the value of the magnetic moment in Bohr magnetons is equal to

$$M_{A} = \frac{20.4 \cdot 10^{-24}}{\mu_{E}} = 2,21$$

The number of non-compensated spins in iron crystal lattice magnetic moment shows that iron is one atom less than a free atom.

Example 10

In the transformer's core, the sum spent on hysteresis is 2 W/kg and 6 W/kg, respectively, at 1 kHz and 2 kHz and spent on eddy currents / at constant maximum induction in the core/. The rod's magnetic losses to eddy currents should be determined at 2 kHz.

Resolution

The sum losses of one cycle of re-magnetization are linearly dependent on the frequency, and we use the equation (1.13)

$$P_a = P_{\Gamma} + P_T = \eta B_m^n f + \xi B_m^2 f^2$$

Let's write for two frequencies.

$$\eta B_m^n f_1 + \xi B_m^2 f_1^2 = 2 \qquad \qquad \text{or} \qquad \eta B_m^n \cdot 10^3 + \xi B_m^2 10^6 = 2 \\ \eta B_m^n f_2 + \xi B_m^2 f_2^2 = 6 \qquad \qquad \text{or} \qquad \eta B_m^n \cdot 2 \cdot 10^3 + \xi B_m^2 \cdot 4 \cdot 10^6 = 6$$

According to the report condition, it should be determined that: $P_{T2} = \xi B_m^2 f_2^2$. It and ξB_m^2 You can quickly choose from a system of equations with two unknowns.

Example 11

Determination of the inductance of a solenoid consisting of 200 windings wrapped around a dielectric base of length l= 50 mm. The cross-sectional area of the base S = 50 mm². How will its inductance change if a cylindrical ferrite rod with magnetic fluidity $\mu = 400$ is inserted into the coil?

Resolution

Inductance of a solenoid whose length is more significant than its diameter

$$L_0 = \mu_0 \frac{n^2 S}{l} = 50.2 \ \mu \,\mathrm{Hn}$$

When the magnet introduces μ the rod, the inductance of the coil (1.16) increases by times according to the formula

$$L_1 = \mu_0 \mu \frac{n^2 S}{l} = 20 \text{ mHn.}$$

Dielectrics

Example 12

Without air space between the substrates of the flat capacitor, a sheet of dielectric thickness h=1 mm is clamped. A voltage of 200 V was applied to the capacitor, determining the surface density of the charge in the capacitor substrates and the dielectric σ_D . The dielectric constant is 6.

Resolution

An additional charge remains because the dielectric connected to a constant voltage source is evened out. On the capacitor substrates σ_{π} . Therefore

$$\sigma_1 = \sigma_{\mathcal{I}} + \sigma_0$$

Where – The surface density of charge is in capacitor substrates when there is no dielectric.

There

$$\sigma_{1} = \varepsilon_{0} \varepsilon E = \varepsilon_{0} \varepsilon U/h = 8,85 \cdot 10^{-12} \cdot 6 \cdot 200/10^{-3} \approx 10^{-5} \text{ Ql/m}^{2};$$

$$\sigma_{D} = P = \varepsilon_{0} \varepsilon E - \varepsilon_{0} E \approx 8,85 \cdot 10^{-12} \cdot 5 \cdot 200/10^{-3} \approx 8,85 \cdot 10^{-6} \text{ Ql/m}^{2}.$$

Example 13

Composite thermocompensated/i.e., a material with a temperature coefficient of dielectric constant equal to zero / a ceramic material made based on two dielectrics with dielectric constants $\varepsilon_1 = 40$; $\varepsilon_2 = 80$ and $\alpha_{\varepsilon_1} = 2 \cdot 10^{-4} \text{ K}^{-1}$; $\alpha_{\varepsilon_2} = -1,5 \cdot 10^{-3} \text{ K}^{-1}$ is given. It is necessary to determine ceramics' composition and dielectric constant, assuming that the components are distributed chaotically.

Resolution (1.26) We use the Lichtenecker formula.

$$\ln \varepsilon = \Theta_1 \ln \varepsilon_1 + \Theta_2 \ln \varepsilon_2$$

Where and Θ_2 -volumetric concentrations of components.

Differentiating the Lichtenecker formula can determine the temperature coefficient of the dielectric constant of a composite dielectric (1.26).

$$\alpha_{\varepsilon} = \Theta_1 \alpha_{\varepsilon 1} + \Theta_2 \alpha_{\varepsilon 2}$$

Since the material is thermoconpensated $\alpha_{\varepsilon} = 0$. Solving a system of equations

$$\Theta_1 \alpha_{\varepsilon_1} + \Theta_2 \alpha_{\varepsilon_2} = 0,$$

$$\Theta_1 + \Theta_2 = 1$$
,

We find that
$$\Theta_1 = \frac{\alpha_{\varepsilon 2}}{\alpha_{\varepsilon 2} - \alpha_{\varepsilon 1}} = 0,882 \ \Theta_2 = 0,112.$$

To the Lichtenecker formula and put, $\varepsilon = 43,4$. We'll figure it out.

Example 14

The specific volume resistance of one square is 1010 Ohm, and the specific surface resistance of one square is 1011 Ohm, with a wall thickness of 10 mm. The two opposite sides of the cube are coated with metal electrodes. At 2 kV at constant voltage, the current flowing through the facet of this cube must be determined.

Resolution

Electric current flows through the cube's volume and the four sides' surfaces. Therefore, we determine the resistance between the electrodes from the parallel connection of the volumetric resistance and the surface resistance of the four facets. (1.28) From the formulas, the volume resistance will be equal to

$$R_V = \rho_V \frac{l}{S}$$

The surface resistance is defined as

$$R_S = \rho_S \frac{l}{d}$$

Where l, d, S – length, width and cross-sectional area of the sample.

In our case

$$R_V = \frac{\rho_V a}{a^2} = \frac{\rho_V}{a} = \frac{10^{10}}{10 \cdot 10^{-3}} = 10^{12}$$
 Ohm,

$$R_{S1} = R_{S2} = R_{S3} = R_{S4} = \frac{\rho_S a}{a} = \rho_S = 10^{11} \text{ Ohm}$$

Full surface resistance and the complete resistance between the electrodes $R = \frac{R_V R_S}{R_V + R_S} = 2,44 \cdot 10^{10} \text{ Ohm.}$

Current between electrodes

$$I = \frac{U_0}{R} = 8,2 \cdot 10^{-8} \,\mathrm{A}.$$

Example 15

In a disc ceramic capacitor with a capacity of 100 pF, connected to an AC voltage of 100 V at a frequency of 1 MHz, $P_a = 10^{-3}$ W of power is sprayed. What will be the specific losses in a dielectric if the dielectric constant is 150, the electrical strength = 10 MW/m, and the reserve of electrical strength is equal?

Resolution

Specific costs are calculated for the volume of the capacitor's working dielectric.

$$p = \frac{P_a}{Sh}$$

Where S, h-the substrate's area and the dielectric's thickness, respectively.

We determine the thickness of the dielectric shell based on the condition to ensure electrical strength.

$$K = \frac{U_{mec}}{U} = \frac{E_{\delta ep}h}{U} - \text{ to constant voltage,}$$
$$K = \frac{E_{\delta ep}h}{U\sqrt{2}} - \text{ or to alternating voltage,}$$
$$h = \frac{U\sqrt{2}K}{E_{\delta ep}} = \frac{100\sqrt{2} \cdot 10}{10 \cdot 10^6} = 1,42 \cdot 10^{-4} \text{ m.}$$

The area of the substrates can be determined from the capacitance expression of a flat capacitor.

$$S = \frac{Ch}{\varepsilon_0 \varepsilon} = \frac{100 \cdot 10^{-12} \cdot 1,42 \cdot 10^{-4}}{8,85 \cdot 10^{-12} \cdot 150} = 1,07 \cdot 10^{-5} \,\mathrm{m}^2$$

From the $p = 6,58 \cdot 10^5 \,\text{W/m}^3$.

Example 16
A piezoelectric quartz mm thick plate is affected by mechanical stress. $\sigma_1 = 10^5 \text{ N/m}^2$ along the X-axis. It is necessary to determine the potential difference between the opposite planes of the plate if the piezo module of the horizontal piezoelectric effect along the X-axis is $d_{11} = 2,3 \cdot 10^{-12} \text{ Ql/N}$. The dielectric constant of quartz is 4.6.

Resolution

According to the equation of the direct piezoelectric effect (1.41)

$$P_1 = d_{11}\sigma_1$$

For a flat homogeneous dielectric, when a constant mechanical force is applied, the surface charge is equal to

Q = PS

We determine the potential difference between the plane facets by the dependencies of the capacitor's capacitance value on the area of its substrates and the possible difference in it.

$$C = \frac{Q}{U} \text{ and } C = \frac{\varepsilon_0 \varepsilon S}{h}$$
$$U = \frac{Q}{C} = \frac{d_{11}\sigma_1 Sh}{\varepsilon_0 \varepsilon S} = \frac{d_{11}\sigma_1 h}{\varepsilon_0 \varepsilon} = \frac{2,3 \cdot 10^{-12} \cdot 10^5 \cdot 10^{-3}}{8,85 \cdot 10^{-12} \cdot 4,5} = 5,77 \text{ V}.$$

Example 16

A capacitor with a capacity of 200 pF made of polystyrene shell is charged to 100 V and removed from the voltage source. Five days later, measurements showed that 10 V remained at the capacitor outputs. It is necessary to determine the capacitor insulation's resistance and the polystyrene's specific volumetric resistance without considering the surface dispersion. The dielectric constant of polystyrene is equal to 2.5.

Resolution

In the self-discharge process, the voltage change at the outputs of the capacitor is recorded using the following equation.

$$U_C(t) = U_C(0) \exp\left(-\frac{t}{\tau_C}\right)$$

where $U_{C}(0)$ – voltage value in a charged capacitor;

 $\tau_C = R_{u_3}C$ – capacitor time constant.

Logarithm the equation, and we get the following result

$$\ln U_C(t) = \ln U_C(0) - \frac{t}{\tau_C}$$

From this
$$R_{u_3} = \frac{t}{C \ln \left[\frac{U_C(0)}{U_C(t)} \right]} = \frac{5 \cdot 24 \cdot 3600}{200 \cdot 10^{-12} \ln \left(\frac{100}{10} \right)} = 9.4 \cdot 10^{14} \text{ Ohm.}$$

Because then $\rho = \frac{R_{u_3}C}{\varepsilon_0\varepsilon} = 8,4 \cdot 10^{15}$ Ohm·m.

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Example 16

If the width of the Forbidden Valley $\Delta E = 0,665 \text{ }{9}\text{B}$, and the effective masses of the density states for the electrons of the valence Valley and the conductor Valley, respectively $m_v = 0,388 m_0$; $m_c = 0,55 m_0$ Determining the location of the Fermi level in 300 K of the eigenvalue germanium, if equal to. Where m_0 - a mass of a free electron.

Resolution

The following expression determines the location of the specific Fermi level in a semiconductor.

$$E_{F} = \frac{E_{c} + E_{v}}{2} + \frac{kT}{2} \ln \frac{N_{v}}{N_{c}} = E_{i} + \frac{kT}{2} \ln \frac{N_{v}}{N_{c}}$$

where $-E_i$ the level corresponding to the middle of the Forbidden Valley;

 N_c , N_v – effective States densities for Valence Valley defects and conductor Valley electrons, respectively

$$N_{v} = \frac{2(2\pi m_{v} kT)^{3/2}}{h^{3}}, \quad N_{c} = \frac{2(2\pi m_{c} kT)^{3/2}}{h^{3}}$$

 k, h, m_0 We'll figure it out by setting the values of physical constants and temperature, m–3, m–3. From this

$$E_F - E_i = \frac{1,38 \cdot 10^{-23} \cdot 300}{2} \ln \frac{6,04 \cdot 10^{24}}{1,02 \cdot 10^{25}} = -1,08 \cdot 10^{-21} \text{J} = -6,78 \cdot 10^{-3} \text{ eV}.$$

Like Semiconductors, Energy is calculated by electron-volt since it has a small value: 1 eV = 1,610-19 J. For this reason, the Fermi level of specific germanium is located at 6.78 meV below the centre of the Forbidden Valley at room temperature.

Example 19

Let it be if the width of the Forbidden Valley is equal = 1,12 eV and the effective masses $m_c = 1,05m_0$, $m_v = 0,56m_0$ of the density of states. In Silicon T = 300 K, the specific concentration of charge carriers must be determined.

Resolution

The specific concentration of charge carriers

$$n_i = \sqrt{N_c N_v} \exp\left(-\frac{\Delta E}{2kT}\right)$$

Effective density of states for electrons in the conduction Valley and for faults in the valence Valley

$$N_{v} = \frac{2(2\pi m_{v}kT)^{3/2}}{h^{3}}, \quad N_{c} = \frac{2(2\pi m_{c}kT)^{3/2}}{h^{3}}$$

Hence, the specific concentration $n_i = 7 \cdot 10^{15} \,\mathrm{m}^{-3}$.

Example 20

It is necessary to determine the location of the Fermi level at 300 K of germanium, which contains $2 \cdot 10^{22}$ m⁻³ arsenic atoms and 10^{22} m⁻³ gallium atoms. The effective mass of the density of states in the conduction band $m_C = 0.55 m_0$.

Resolution

Gallium/element of the 3rd Group/ is a donor for Germanium. Well, arsenic/ element of the 5th Group/-acceptor for Germanium. As a result, it will have a semiconventional semiconductor-type electrical conductor. In this case, the excess concentration of donors $N'_{\mathcal{A}} = N_{\mathcal{A}} - N_A$. At room temperature, all impurities are ionised. Hence, the concentration of electrons in the conductor field is equal to the excess concentration of donors: We find the location of the Fermi level relative to the bottom of the conductor valley from the equation relating the electron concentration in the conductor Valley and the location of the Fermi level relative to the bottom of the conductor Valley.

$$n = N_c \exp\left(-\frac{E_c - E_F}{kT}\right)$$

where

$$N_c = \frac{2(2\pi m_c kT)^{3/2}}{h^3} = 1,02 \cdot 10^{25} \,\mathrm{m}^{-3},$$

$$\ln n = \ln N_c - \left(\frac{E_c - E_F}{kT}\right),$$

$$E_c - E_F = kT \ln \frac{N_c}{n} = 1,38 \cdot 10^{-23} \cdot 300 \ln \frac{1,02 \cdot 10^{25}}{10^{22}} = 2,86 \cdot 10^{-20} J = 0,179.$$

Example 21

Determine the concentration of electrons and defects in germanium of type at a temperature of 300 K with a resistivity of 0.05 Ohms*m. The specific concentration of charge carriers at room temperature $n_i = 2.1 \cdot 10^{19} \text{ m}^{-3}$, the mobility of electrons = 0.39 m²/(V·s), and the mobility of defects $\mu_p = 0.19 \text{ m}^2/(\text{V}\cdot\text{s})$.

Resolution

The resistivity is related to the concentration of electrons and defects by equations (1.56) and (1.52)

$$\gamma = \frac{1}{\rho} = e n_0 \mu_n + e p_0 \mu_p, \quad n_0 p_0 = n_i^2$$

For the concentration of defects, the following quadratic equation will be obtained.

$$p_0^2 - \frac{p_0}{e\mu_p\rho} + \frac{n_i^2\mu_n}{\mu_p} = 0$$

If we put the given values

$$p_0^2 - 6,58 \cdot 10^{20} p_0 + 9,03 \cdot 10^{38} = 0$$

Where

n-since the type corresponds to a semiconductor, we subtract the second solution of the quadratic equation, i.e.

$$n_0 = \frac{n_i^2}{p_0} = 6,72 \cdot 10^{17} \,\mathrm{m}^{-3}.$$

Example 22

In an ideal compensated Semiconductor, the concentration of electrons is equal to that of defects. Is it possible to determine that at all temperatures, the specific resistances of such a semiconductor are equal to the particular resistances?

Resolution

The perturbation of the periodic potential of the crystal lattice, which causes the scattering of charge carriers, is more significant in a compensated semiconductor than in a proprietary semiconductor. Such disorders include ionised acceptors and donors. Differences in the mobility of charge carriers and the specific resistances of the own and compensated Semiconductor - are most clearly observed in the zone of extremely low temperatures.

Example 23

When the Silicon sample was heated from $t_1 = 0$ ^oC to $t_2 = 18$ ^oC, its specific conductivity increased by 4.24 times. Determine the width of the Silicon Forbidden Valley.

Resolution

The formula determines the specific conductivity of intrinsic semiconductors (1.56)

$$\gamma = \gamma_0 \cdot \exp\left(-\frac{\Delta E}{2kT}\right)$$

where γ_0 - constant for a given semiconductor;

 ΔE - width of the Forbidden Valley.

Then

$$\frac{\gamma_1}{\gamma_2} = \frac{\exp\left(-\frac{\Delta E}{2kT_1}\right)}{\exp\left(-\frac{\Delta E}{2kT_2}\right)} = \exp\left(\frac{\Delta E}{2k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)$$

or when logarithmic

$$\ln \frac{\gamma_1}{\gamma_2} = \frac{\Delta E}{2k} \left(\frac{1}{T_1} - \frac{1}{T_2} \right)$$

hence the width of the Forbidden Valley

$$\Delta E = \frac{2kT_1T_2\ln(\gamma_1/\gamma_2)}{T_2 - T_1} = 1.1 \text{ eV}$$

Example 24

When photosetting a silicon wafer with monochromatic radiation scattering with an intensity of 10^{20} m⁻²·s⁻², it is necessary to determine the optical generation rate of heterogeneous charge carriers at a depth of 100 µm from the surface of the light. If the absorption rate of the material is $5 \cdot 10^4$ m⁻¹, and the coefficient of reflection of radiation from the surface is 0.3.

Resolution

The speed of optical generation and the number of charge carriers excited by light per unit of time per semiconductor volume depend on the intensity of radiation at a given depth X and the absorption indicator. Changes in radiation intensity obey the Buyer-Lambert Law.

$$I(x) = I_0 (1 - R) \exp(-\alpha x)$$

where $I_0 - x$ intensity in depth;

R – radiation reflection coefficient;

 α – material absorption indicator.

The number of Quanta absorbed in the area per unit thickness. dx

$$dI = I(x)\alpha dx$$

It is determined by equality. Optical generation speed

$$g(x) = \frac{dI}{dx} = \alpha I_0 (1 - R) \exp(-\alpha x) = 2,36 \cdot 10^{22} \text{ m}^{-3} \cdot \text{s}^{-1}.$$

3.2 Test questions and reports on the topics of material structure and conductive materials

1. How is the crystal lattice divided according to the size of the defects?

A) point, lattice, linear;

B) Point, Grid, volumetric;

C) point, linear, volumetric;

D) linear, volumetric, lattice;

E) point, linear, periodic.

2. The type of crystal in which the interaction between the Boles in the node of the crystal lattice occurs through a covalent bond:

A) metallic;

B) molecular;

C) atomic;

D) Ionic;

E) neutral.

3. The type of crystal in which the forces of interaction between the Boles in the node of the crystal lattice are Coulomb:

A) Ionic;

B) atomic;

C) metallic;

D) molecular;

E) neutral.

4. The type of crystal in which free electrons carry out the interaction between the Boles in the node of the crystal lattice:

A) Atomic;B) molecular;

C) Ionic;

D) metallic;

E) neutral.

5. The type of crystal in which the interaction between the Boles in the node of the crystal lattice occurs through the van der Waals forces:

A) Ionic;B) atomic;C) metallic;D) molecular;E) neutral.

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6. The elementary jacks were in the form of an oblique parallelepiped, i.e. $\alpha \neq \beta \neq \gamma \neq 90^{\circ}$, $a \neq B \neq c$ type of syngonia:

A) hexagonal;B) rhombicity;C) cubic;D) triclinic;E) tetragonal.

7. The elementary jacks are in the form of a fundamental parallelogram, a vertical prism, i.e. $\alpha = \gamma = 90^{\circ}, \beta \neq 90^{\circ}, a \neq B \neq c$ type of syngonia:

A) triclinic;B) rhombicity;C) monoclinic;D) hexagonal;E) tetragonal.

8. The elementary cell is in the form of a rectangular parallelepiped, i.e. $\alpha = \beta = \gamma = 90^{\circ}$, $a \neq b \neq c$ type of syngonia:

A) hexagonal;B) rhombicity;C) triclinic;D) monoclinic;E) tetragonal.

9. The main square of the elementary slot is in the form of a vertical prism, i.e. $\alpha = \beta = \gamma = 90^{\circ}$, $a = B \neq c$ type of syngonia:

A) triclinic;B) hexagonal;C) rhombicity;D) monoclinic;E) tetragonal.

10. The elementary cell is in the form of a Cube, which is deformed along the diagonal or stretched, i.e. $\alpha = \beta = \gamma \neq 90^{\circ}$, a = B = c type of syngonia:

- A) monoclinic;
- B) tetragonal;
- C) rhombicity;
- D) trigonal;
- E) hexagonal.

11. The elementary jacks form a right hexagonal prism, i.e. $\alpha = \beta = 90^{\circ}, \gamma = 120^{\circ}, a = B \neq c$ type of syngonia:

A) monoclinic;C) rhombicity;C) tetragonal;D) hexagonal;F) triclinic.

12. Elementary jacks are in the form of cubes, i.e. $\alpha = \beta = \gamma = 90^{\circ}$, a =

- B = c type of syngonia:
 - A) rhombic;
 - B) hexagonal;
 - C) cubic;
 - D) monoclinic;
 - E) tetragonal.

13. in which materials are the properties of anisotropy manifested:

- A) amorphous;
- B) monocrystalline;
- C) polycrystalline;
- D) in isotropic materials;
- E) amorphous and polycrystalline.

14. the number of electrons in the conductivity area of a dielectric and a semiconductor when the temperature increases:

A) depending on the width of the item;

B) depending on the temperature;

C) depending on the width and temperature of the substance;

D) does not depend on either the temperature or the width;

E) depends on the density of the substance.

15. What class does a substance at room temperature 10^5 Ohm·m belong

to:

A) conductivity;

B) semiconductor;

C) dielectric;

D) plasma;

E) belongs to all the listed classes.

16. What class does a substance at room temperature 10^{-7} Ohm·m belong

to:

A) conductivity;

B) semiconductor;

C) dielectric;

D) plasma;

E) belongs to all the listed classes.

17. Concentration of electrons in pure metals when temperature increases:

A) grow;

B) decreases;

C) increases and then decreases;

D) decreases growth after it;

E) does not depend on the temperature.

18. Dependence of specific thermal conductivity of metal on electrical conductivity:

A) directly proportional;

B) inversely proportional;

C) at the maximum level, the curve can be expressed as;

D) at the minimum level, the curve can be expressed as;

E) can be expressed as a curve at the maximum and minimum levels.

19. Based on what the resistivity of a metal depends on:

A) the distance between the crystal lattices;

B) to the concentration of free electrons;

C) the length of the free movement of electrons;

D) to the periods of crystal lattices;

E) to the number of electrons.

20. How does the temperature coefficient of resistivity change in most pure metals when the temperature increases:

A) does not change;

B) decreases;

C) grows;

D) grows and then decreases;

E) Kemi grows after it.

21. In the presence of an increase in the Atomic mixture in a metal, its resistivity:

A) grow;

B) decreases;

C) does not change;

D) depending on the material;

E) does not depend on the material.

22. The resistance of pure metals is greater than the resistance of alloys:

A) large;

B) low;

C) will be approximate;

D) will be equal to;

E) depending on the process, it can sometimes be large or small.

23. Two substances of the same size are made of pure metal but different in structure: amorphous, monocrystalline and polycrystalline. Which substance has a minimum resistivity:

A) amorphous;

B) monocrystalline;

C) polycrystalline;

D) in isotropic materials;

E) amorphous and polycrystalline.

24. Total resistance of the conductor when increasing the frequency from 50 Hz to 50 MHz of the supplied voltage:

A) does not change;

B) increases;

C) decreases;

D) increases and then decreases;

E) decreases and then increases.

25. Resistivity of metals at temperatures close to Absolute Zero:

A) close to zero;

B) equal to the constant power;

C) due to the constant degree or due to the structure and composition close to zero;

D) the variable is equal to the power;

E) equal to one.

26. Choose the material you need to make a low-resistance precision resistor:

A) copper;

B) manganin;

C) Chrome;

D) bronze;

E) iron.

27. Choose the material you need to make the heating element that will be used to heat the room:

- A) tantalum;
- B) tungsten;
- C) nichrome;
- D) constantan;
- E) bronze.

28. Choose the material that will be used to create a thermocouple that will work up to a temperature range of 500 $^{\circ}$ C:

A) Copel-alumel;

B) alumel-chromel;

C) platinum-tantalum;

D) manganine-constantane;

E) Copel-constantan.

29. Choose the material you need to make the transparent electrode:

A) niobium oxide;

B) alumina;

C) indium oxide;

D) tantalum oxide;

E) chromium oxide.

30. Specify the material required to make the high-speed resistor:

A) contact;

B) cermet;

C) indicator oxide;

D) heavy duty metal;

E) durable metal.

31. Considering that tungsten will have the composition of a volumetriccentered cube, it is necessary to determine the density of tungsten. It is known that the distance between neighbouring atoms is 0.2737 nm.

32. Determine the probability of filling the energy level inside the metal with electrons located 0.1 eV above the Fermi level.

33. Determine the temperature at which the probability of the presence of an electron with an energy of 0.5 eV higher than the Fermi level of the metal is equal to 1%.

34. It is necessary to determine the length of the free path of copper electrons at room temperature.

35. At 20 °C және 100 °C, the resistivity of pure copper is equal to 0.0168 μ Ohm·m and 0.0226 μ Ohm·m, respectively. Determine the temperature coefficient of resistivity and resistivity at zero °C.

36. Copper containing 0.5% indium has a resistivity equal to 0.0234 μ Ohm·m. Determine the concentration of indium atoms in a copper alloy with a resistivity of 0.0298 μ Ohm·m.

37. One outlet of the thermocouple is placed in a furnace at 200 °C, and the other is located at 20 °C. In this case, the voltmeter shows a thermoelectric of 1.8 mV. What is the term paper equal to if we put the second outlet of the thermocouple in a container with a) melting ice and b) boiling water?

38. Copper containing 0.3 atomic percent tin has a resistivity of 0.0258 μ Ohm·m at room temperature. Determine the resistivity of copper with 0.6 nuclear percent tin.

39. Determine the current density of molybdenum conductivity with a length of 100 m connected to a voltage of 1.2 V.

40. Graphite and copper rods with the same cross-sectional areas are connected in series. In what ratio of the rod lengths does the resistance of this composition not depend on the temperature? The specific resistances of copper and Graphite are equal to 0.017 and 8.0 μ Ohm·m, respectively, and the values of the temperature coefficient of resistivity are 4.3×10^{-3} K⁻¹ and 10^{-3} K⁻¹.

41. It is necessary to determine the resistance of a square on the surface of a brass flat conductor at a frequency of 10 MHz if the resistivity of brass at constant voltage is $0.08 \mu Ohm \cdot m$.

42. an electric mine operating from the mains with a voltage of 220 V is used to heat the room. The room loses 10^5 kJ of heat per day. Find the length of the nichrome wire that makes the heating element. The diameter of the wire is 0.7 mm, and the resistivity is one μ Ohm·m.

43. If it is known that the average rate of electron drift in a field with a voltage of 0.1 V/m is 5×10^{-4} m/s, it is necessary to determine the resistivity

of a metal conductor with a molar mass of 0.023 kg/mol and a density of 970 kg/m³. The Crystal has one electron per atom of the lattice.

44. It is necessary to determine the ratio of specific thermal conductors of silver at temperatures of 20 °C and 200 °C. The resistivity of silver at 20 °C is 0.015 μ Ohm·m, and the temperature coefficient of resistivity is 4.1×10^{-3} K⁻¹.

45. Nichrome and copper wires of the same length and diameter are connected in series to the Circuit. Determine the ratio of the heat these wires release and the voltage drop. The resistivity of copper and nichrome is 0.017 μ Ohm·m and one μ Ohm·m, respectively.

46. A shell resistor consists of three parts with specific surface resistances $\rho_{s_1}=10 \mu \text{Ohm}$; $\rho_{s_2}=20 \text{ Ohms}$; $\rho_{s_2}=30 \text{ Ohms}$. Determine the complete resistance of the resistor.



Figure 3.1 – Shell resistor

47. Determine the value of the specific thermal conductivity of copper at room temperature with its measured resistivity of $\rho = 0.017 \,\mu\text{Ohm}\cdot\text{m}$.

3.3 Test questions and reports on the topic of magnetic materials

48. Paramagnets are weakly magnetised because of the magnetic moments of atoms:

A) zero;

B) chaotically oriented;

C) directed in the opposite direction;

D) parallel direction;

E) directed perpendicularly.

49. Diamagnets are weakly magnetised because of the magnetic moments of atoms:

A) zero;

B) chaotically oriented;

C) directed in the opposite direction;

D) parallel direction;

E) directed perpendicularly.

50. Antiferromagnets are weakly magnetised because of the magnetic moments of atoms:

A) zero;

B) chaotically oriented;

C) directed in the opposite direction;

D) Not at all;

E) directed perpendicularly.

51. Magnetization of ferromagnets:

A) more significant than the magnetic field strength;

B) less than the magnetic field strength;

C) does not depend on magnetic field strength;

D) depends on the electric field strength;

E) depends on all the quantities mentioned.

52. Magnetic fluidity of a substance when the magnetic field strength increases:

A) grow;

B) decreases;

C) does not change;

D) grows and then decreases;

E) decreases and then increases.

53. At the Curie temperature:

A) the ferromagnet is transferred to the antiferromagnet position;

B) the ferromagnet moves to the diamagnetite position;

C) the ferromagnet is transferred to the paramagnet position;

D) the ferromagnet remains in its state;

E) ferromagnet, the ferrimagnet is transferred to the situation.

54. When the frequency of re-magnetization increases:

A) hysteresis costs increase rapidly;

B) costs for eddy currents increase rapidly;

C) both types of costs increase rapidly;

D) both types of costs do not increase;

E) the losses on eddy currents do not change.

55. Costs for eddy currents:

A) more in ferromagnetic materials than in ferrimagnetic ones;

B) more in ferrimagnetic materials than in ferromagnetic ones;

C) depends on specific parameters, not on the class of material;

D) does not depend on the actual parameters of the material;

E) all answers are correct.

56. Hysteresis costs:

A) magnetised materials have more magnetised materials;

B) magnetmaterials are more than magnetmaterials;

C) depends on the frequency of the magnet, not on the class of the material;

D) Not at all;

E) in magnetised materials, the magnetised will be equal to the magnetised.

57. Determine the magnetisation and magnetic induction of a copper wire exposed to a homogeneous magnetic field with a voltage of 1000 A/m.

58. Magnetic induction of nickel saturation 0.65 Tl, density 8960 kg/m^3 . Determine the magnetic moment per nickel atom.

59. Determine the magnetic strength of bismuth with magnetic induction equal to 12.5 mTl in a magnetic field with a voltage of 10^4 A/m.

60. for two magnetic materials, the following conditions are met: $\mu_{max1} > \mu_{max2}$; $B_{s1} < B_{s2}$. Max – maximum magnetic fluidity, B_s – saturation induction. Plotting the main magnetisation curves for these materials on one graph /dependence of magnetic induction on magnetic field strength/.

61. determine the magnetic losses in a coil with a rod magnetised by a magnetic field with a frequency of 0.1 MHz. The coil's inductance is 0.2 mHn, the current in the winding is 0.1 A, the tangent of the angle of magnetic losses is $tg\delta_m = 0.2$.

62. Determination of the coercive force of the ring ferromagnetic rod, if it is necessary to pass a current of 63 mA for its re-magnetization through the winding (equal to N=100), the average diameter of the ring of the rod is equal to 20 mm.

63. How many rolls need to be wound on a magnet rod with a length of 100 mm and a diameter of 8 mm to obtain an inductance of 10 mHn?

64. In a magnetic field with a voltage of 400 kA/m, the material has a magnetic induction of 1 Tl. Determine the material's magnetisation.

65. the homogeneous magnetic field strength in platinum is 5 A/m. Determine the magnetic induction caused by molecular currents if the magnetic resistance of platinum is $3.6*10^{-4}$.

66. Introduced into liquid oxygen, with a radius r = 40 cm, A current I=1 A flows along the circular contour. Determine the magnetisation of this contour at the centre. Magnetic acuity of liquid oxygen $k_m = 3.4 \times 10^{-3}$.

67. The length of a solenoid located in a diamagnetic medium is l=30 cm, the cross-sectional area is 10 cm^{2} , and the number of windings is N=1000. Determine inside the solenoid: 1) magnetic induction; 2) magnetisation

68. The length of the small section Of the iron rod is 1=0.5 m, and the number of windings is N=400. Determine the magnetic fluidity of iron when I=1 A is the current strength.

3.4 Test questions and reports on the topic of Dielectrics

69. Electric current is provided in Dielectrics:

A) mainly with electrons;

B) mainly with ions;

C) mainly with electrons and ions;

D) mainly with protons;

E) all answers are correct.

70. Electrical conductivity of a dielectric when the temperature increases:

A) can be said not to change;

B) slowly decreases;

C) decreases rapidly;

D) grow slowly;

E) grows quickly.

71. When the dielectric is evened out:

A) the electric field strength inside the dielectric increases;

B) the electric field strength inside the dielectric decreases;

C) depending on which of the instantaneous or slowed-down evocation prevails, the field strength can increase and decrease;

D) the electric field strength inside the dielectric does not change; E) Zero.

72. At constant voltage in the dielectric:

A) the absorption current is dominant;

B) the horizontal flowing current from which the dielectric flows is dominant;

C) the type of current depends on the parameterisation of the material;

D) the type of current depends on the purity of the material;

E) the absorption current is not dominant.

73. What composition of inorganic glass is represented by the minimum value of the specific volume resistance?

A) 100% SiO₂;

B) 90% SiO₂+10 % K₂O;

C) 90% SiO₂ + 10% Na₂O;

D) 70% SiO₂ + 30% Na₂O;

E) 60% SiO₂ + 40 % K₂O.

74. when working at high frequency, to reduce costs, it is necessary to choose the following dielectric:

A) polar;

B) nonpolar;

C) Ionic;

D) Ionic and polar;

E) all of the listed dielectrics.

75. what type of electrical breakdown prevails in Capacitor dielectrics?

A) electrical;

B) heat;

C) electrochemical;

D) mechanical;

E) the type of puncture is determined by its specific conditions.

76. the loss of power of a dielectric, which goes to electrical conductivity when increasing the frequency of a given voltage:

A) grow;

B) decreases;

C) grows and then decreases;

D) decreases and then increases;

E) does not depend on frequency.

77. Which of the plastics listed below is thermosetting:

A) vinyl plate;

B) Kapron;

C) textolite;

D) The Organist;

E) getinax.

78. Substances added to plastics to reduce their mechanical properties and price:

A) the filler is;

B) is a binder;

C) hardener;

D) is a plasticiser;

E) is a stabiliser.

79. The base material from which the hybrid microswitch is created is widely used:

A) fluoroplastic;B) stall;C) Quartz;

D) polychoric;

E) polyimide.

80. For a dielectric that acts as an insulator at constant voltage, the following parameters are most important:

A) electrical strength, resistivity;

B) dielectric losses, dielectric constant;

C) resistivity, dielectric losses;

D) mechanical strength and durability;

E) heat capacity and overall dimensions;

81. For a dielectric that acts as a capacitor in an alternating voltage circuit, the following parameters are most important:

A) electrical strength, resistivity;

B) dielectric losses, dielectric constant;

C) resistivity, dielectric losses;

D) mechanical strength and durability;

E) heat capacity and overall dimensions.

82. What is the name of the alloy of zinc with copper:

A) bronze;

B) brass;

C) silumin;

D) aviation;

E) duralumin.

83. We call piezoelectric the following material:

A) then the dependence of the evocation on the electric field strength has a hysteresis trap;

B) its homogeneity depends on temperature changes;

C) its homogeneity is associated with mechanical stress;

D) its homogeneity depends on the magnetic induction;

E) its homogeneity depends on the density of the material;

84. The following material is called pyroelectric:

A) its homogeneity depends on the change in temperature;

B) its homogeneity depends on the lighting;

C) its homogeneity is associated with mechanical stress;

D) its homogeneity depends on the magnetic induction;

E) its homogeneity depends on the density of the material;

85. the following material is used in pressure sensors:

A) quartz;

B) corundum;

C) segment salt;

D) rutile;

E) getinax.

86. U=80 V, d=0,1 mm, ϵ =4 given for the capacitor. Determine the charge density on the capacitor substrates and the dielectric surface.

87. The insulation resistance of a two-wire cable with a length of 2 m is 300 MOhm. What is the insulation resistance of such a cable with a length of 6 m? Insulation resistance is measured in the middle of two wires.

88. The capacitor has two layers of dielectrics in series. If the dielectric constant of the first and second dielectric is 2 and 4, respectively, the specific

conductivity is $1,5x10^{-14}$ S×cm⁻¹ and $3x10^{-14}$ ×cm⁻¹, and the thicknesses are 0.2 cm and 0.1 cm, the time constant of such a capacitor must be determined.

89. Ten minutes after switching off from an external electrical source, the voltage in the capacitor substrates decreases by 90%. Therefore, it is necessary to determine the resistivity of a dielectric with a dielectric constant equal to 4.

90. A flat capacitor with a dielectric constant 2.5 is 0.5 cm thick and has an area of 2 cm². The frequency of a given voltage is 1 kHz, and the tangent of the angle of dielectric losses is 5×10^{-3} . Determine the specific conductivity of the dielectric if it is known that its electrical conductivity explains the energy losses

91. On the surface of the dielectric, at a distance of 12 mm parallel to each other, there are two thin electrodes with a length of 20 mm. Determination of the specific surface resistance of the dielectric if the resistance between the electrodes is 5 MOhms.

92. If the resistivity of materials is 3×10^{15} Ohm*m, and the dielectric liquidity is 2.4, it is necessary to determine the tangent of the angle of dielectric losses in a nonpolar dielectric at a frequency of 1.5 MHz.

93. How will its capacitance change if a dielectric replaces a whole dielectric between the substrates of a capacitor with holes? A dielectric with holes is 50% lighter than an entire dielectric. The dielectric constant of dielectric as a whole is 2.8.

94. In the output filter of a constant voltage source of 1.5 kV, a series connection of three capacitors is used, designed for an operating voltage of 630 V. Is it possible to use a capacitor with insulation resistances of 600 MOhms, 1000 MOhms and 400 MOhms in this filter?

95. The electrical strength of the dielectric is $3 \cdot 10^7$ V/m, $\epsilon = 12,4$ determination of the thickness of the dielectric in the capacitor: C=150 pF, the operating voltage is 150 V, and the electrical strength reserve is equal to 3.

96. At a voltage of 20 V and a frequency of 1 MHz, the active scattering power in the dielectric is 200 μ W. What is the active power of scattering in this dielectric at a voltage of 10 V and a frequency of 2 MHz? It is necessary to assume that the losses in the dielectric are explained only by the electrical conductivity of the transverse hole.

97. Determine the total resistance of a dielectric plate with dimensions of 20 mm×10 mm×1 mm in the longitudinal direction; the specific volumetric and surface resistances are 10^{10} Ohms×m and 10^{10} Ohms, respectively.

98. A plate of piezoelectric quartz with a dielectric constant of 4.6 and a thickness of 0.5 mm is affected by a mechanical stress of 10^5 N/m^2 . Determination of the surface density of the charge on the opposite planes of the plate. The piezo module of the longitudinal piezoelectric effect equals $2 \times 10^{-12} \text{ Ql/N}$.

99. The heat sensor has a pyroelectric coefficient of 10^{-3} Ql/(m²×K) made of material and has a working surface of 10 cm^2 . What current is observed in the sensor circuit if the temperature increases by 1 K at 1 s?

3.5 Test questions and reports on the topic of semiconductor materials and methods of studying materials of electronic engineering

100. The energy level is located 10 kT above the Fermi level. If the temperature of the semiconductor is increased by 2 times, how will its probability of filling this level change?

A) increases by 2 times;

B) reduced by 2 times;

C) increases by 4 times;

D) reduced by 4 times;

E) does not change.

101. Resistivity of an alloy semiconductor:

A) more significant than the intrinsic semiconductor;

B) smaller than the intrinsic semiconductor;

C) does not differ from the intrinsic semiconductor;

D) zero;

E) all answers are correct.

102. Mobility of carriers when increasing temperature in an alloy semiconductor:

A) increases;

B) decreases;

C) remain stable;

D) first grows, then decreases;

E) First decreases, then increases.

103. Specific conductivity of a specific semiconductor when the temperature increases:

A) grows linearly;

B) decreases linearly;

C) does not change;

D) grows exponentially;

E) decreases exponentially.

104. Own semi-passerby:

A) the concentration of electrons is greater than the concentration of defects;

B) the concentration of electrons is less than the concentration of electrons;

C) the concentration of electrons is equal to the concentration of defects;

D) the concentrations of electrons and electrons are zero;

E) all answers are correct.

105. Donors are located in the valley where the impurity levels in the semiconductor are prohibited:

A) near the valent Valley Hill;

B) near the hill of the valley of the conductor;

C) near the bottom of the valent Valley;

D) near the bottom of the conductor Valley;

E) in the middle of the valent Valley.

106. Inverse temperature dependence of permittivity algorithm in Eigenvalue silicon compared to eigenvalue germanium:

A) less complex in all temperature slides;

B) less complex at low temperatures;

C) more complex in the entire temperature range;

D) more complex at low temperatures;

E) does not depend on temperature.

107. Unbalanced charge carriers appear in a semiconductor:

A) when heating;

B) when irradiated with light;

C) when most of the current flows;

D) when cooling;

E) when the current flows for a short time.

108. In a semiconductor, The Fermi level is 0.3 eV lower than the bottom of the conductor Valley. What is the probability of filling with electrons at an energy level 3 kT above the conduction band at room temperature?

109. Determination of the probability of electron filling of the energy level located above the Fermi level by 10 kT.

110. Determination of the location of the Fermi level at T=300 K in germanium crystals doped (doped) with arsenic to a concentration of 10^{23} m⁻³.

111. Determination of the specific concentration of charge carriers in Silicon at T=300 K if the width of its Forbidden Valley is 1.12 eV, and the effective masses of the density of states $m_C = 1,05m_o$, $m_V = 0,56m_o$.

112. Determination of the atomic number per unit volume in a silicon crystal at a temperature of 300 K if the crystal lattice period is 0.54307 nm.

113. Determination of the resistivity of an n-type semiconductor if the electron concentration of the conductor is equal to 10^{22} m⁻³, and their mobility is 0.5 m²/(V×s).

114. The 50 mm long rod made of gallium arsenide is supplied with a voltage of 50 V. When will the electron pass entirely through the sample if their mobility $\mu_n = 0.9 \text{ m}^2/(\text{V}\times\text{s})$?

115. Determination of the resistivity of germanium of the p-type and the ratio of electronic conductivity to low conductivity with a concentration of defects 4×10^{19} m⁻³. The specific concentration of charge carriers at room temperature is $n_i=2.1\times 10^{19}$ m⁻³, electron mobility mn = 0.39 m²/(V×s), defect mobility mp = 0.19 m²/(V×s).

116. A rectangular sample of an n-type semiconductor with dimensions a = 50 mm, b = 5 mm, $\delta = 1$ mm is set to a magnetic field with induction B = 0.5 Tl. A current of $I_a = 20$ mA flows under the influence of a voltage $U_a = 0.42$ V supplied along the sample, the magnetic induction vector of which is located perpendicular to the plane of the sample. Hall EMF $U_H = 6.25$ mV. Determine the specific conductivity, concentration and mobility of charge carriers for this semiconductor, assuming that either positive or negative carriers interpret electrical conductivity.

117. With a uniform distribution of the mixture, determine the amount of alloying (doped) arsenic required to add a silicon wafer with a volume of 100 mm² so that the resistivity of the crystal is equal to 0.01 Ohms×m. Electron mobility $\mu_n = 0.12 \text{ m}^2/(\text{V}\times\text{s})$.

118. Determination of what concentration of atoms of the acceptor mixture is required to obtain gallium arsenide at room temperature, with a specific conductivity of 10 mS/cm. The electrons and electrons have a mobility of 0.045 m²/(V×s) and 0.8 m²/(V×s), respectively.

119. The resistivity of indium antimonide with a Kemer concentration of $p = 10^{23} \text{ m}^{-3}$ at a temperature of 300 K is $3.5 \times 10^{-4} \text{ Ohms} \times \text{m}$. Electrons and holes determine mobility in their ratio. $\mu_n / \mu_p = 40$, and the specific concentration of charge carriers at this temperature $n_i = \text{is } 2 \cdot 10^{22} \text{ m}^{-3}$.

120. Under an optical microscope, objects with dimensions not less than:

A) 10 μm;

B) 5 μm;

C) 2 µm;

D) 0.2 µm;

E) 20 µm.

121. The allowable ability of an optical microscope in infrared rays:

A) approximate to simple lighting;

B) more significant than ordinary lighting;

C) smaller than simple lighting;

D) does not depend on lighting;

E) all answers are correct.

122. Under an electron microscope, the dimensions of objects can be viewed as follows:

A) Around 1 nm;

B) around 10 nm;

C) around 100 mm;

D) around 1 μ m;

E) around 0.1 nm.

123. What is used to study the internal structure of a material and product?

A) raster electron microscopy;

B) Oge – electron spectroscopy;

C) radiographic analysis;

D) second-order ion mass spectrometry;

E) Ionic mass spectrometry of the first order.

124. What can be used to determine the concentration of charge carriers in a semiconductor:

A) by the Quadrangular method;

B) by Thermo-EMF method;

C) through the Hall effect;

D) through the Peltier effect;

E) through Booger's law.

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Appendix A (recommended)

Name	Designation	Quantity
Universal Gas Constant	R	8.31 J·mol ⁻¹ ·K ⁻¹
Gravitational constant	G	$6.67 \cdot 10^{-11} \text{ N} \cdot \text{m}^2 \cdot \text{kg}^{-2}$
Avogadro number	N _A	6.02·10 ²³ mol ⁻¹
Boltzmann constant	k	$1.38 \cdot 10^{-23} \text{ J} \cdot \text{K}^{-1}$
Planck constant	h	6.63·10 ⁻³⁴ J·s
Magnetic constant	μ_{o}	$12.56 \cdot 10^{-7}$ Hn·m ⁻¹
Electrical constant	εο	8.85 \cdot 10 ⁻¹² F·m ⁻¹
Faraday constant	F	96484.56 Ql·mol ^{−1}
Stefan-Boltzmann constant	σ	$5.67 \cdot 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$
Atomic unit mass	u.m.a.	$1.66 \cdot 10^{-27} \text{ kg}$
Mass of an electron	m _e	9.1·10 ⁻³¹ kg
Charge of an electron	e	1.6·10 ⁻¹⁹ Ql
Boron Magneton	$\mu_{\rm b}$	$9.27 \cdot 10^{-24} \text{ J} \cdot \text{Tl}^{-1}$
Proton mass	m _p	$1.67 \cdot 10^{-27} \text{ kg}$

Table 1-physical constants

Table 2-Relations of physical quantities

$1 \stackrel{o}{A}$ (angstrem) = 10^{-10} m	$1 \text{ atm} = 1.01 \cdot 10^5 \text{ Pa}$
$1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$	1 mm Hg = 133 Pa

Appendix B (recommended)

	Designation		ľ		Designation		ų	
Suffix	Eng.	International	Multiplie	Suffix	Eng.	International	Multiplie	
tera	Т	Т	10 ¹²	deci	d	d	10 ⁻¹	
giga	G	G	109	santi	c	c	10 ⁻²	
mega	Μ	Μ	106	miles	m	m	10 ⁻³	
kilo	k	k	10 ³	micro	μ	μ	10 ⁻⁶	
hekto	h	h	10 ²	nano	n	n	10 ⁻⁹	
deck	da	da	10	pico	р	р	10 ⁻¹²	

Table 1-decimal suffixes for unit names

Table 2-Greek alphabet

Α	α	alpha	N	ν	Nju
В	β	beta	Ξ	ξ	Xi
Γ	γ	gamma	0	0	Omicron
Δ	δ	delta	Π	π	Pi
Ε	3	Epsilon	Р	ρ	Ro
Ζ	ζ	Zeta	Σ	σ	Sigma
Η	η	eta	Τ	τ	Tau
Θ	θ	theta	Y	υ	Ipsilon
Ι	l	iota	Φ	φ	Fi
K	κ	kappa	X	χ	Hi
Λ	λ	lambda	Ψ	Ψ	Dogs
М	μ	mu	Ω	ω	Omega

Appendix C (recommended)

Metal	densit y, ×10 ³ kg/m ³	Temp. meltin g, °C	Specifi c heat capacit y, J/(kg·K)	Specific thermal conductivit y, W/(m·K)	TCL I, ×10 ⁻⁶ K ⁻¹	Own resistanc e, µOhm∙m	TKρ , ×10 3 K ⁻¹	M P
aluminium	2.7	660	923	218	21.0	0.0265	4.1	Р
tungsten	19.3	3400	142	167	4.4	0.055	5.0	Р
iron	7.87	1540	453	73.3	10.7	0.097	6.25	F
gold	19.30	1063	134	312	14.0	0.0225	3.95	D
cobalt	8.85	1500	445	69.5	13.5	0.064	6.0	F
copper	8.92	1083	386	406	16.6	0.0168	4.33	D
molybdenu m	10.2	2620	272	150	5.3	0.05	4.33	Р
nickel	8.96	1453	440	75.5	13.2	0.068	6.7	F
niobium	8.85	2500	268	50	7.2	0.15	3.9	Р
tin	7.29	232	226	63.1	23.0	0.113	4.5	Р
platinum	21.45	1770	134	71.1	9.5	0.098	3.9	Р
rhenium	21.02	3180	138	52	6.7	0.214	3.2	Р
lead	11.34	327	130	35	28.3	0.190	4.2	D
Silver	10.49	961	235	453	18.6	0.0150	4.1	D
tantalum	16.6	3000	150	50	6.6	0.124	3.8	Р
Titan	4.52	1670	550	21.9	8.1	0.47	5.5	Р
Chrome	7.19	1900	462	88.6	6.2	0.13	2.4	А
zinc	7.14	419	336	113	30.0	0.0592	4.1	D

Table 1-Physical Properties of pure metals

Note

1 TCLI – temperature coefficient of linear increase;

2 ТК*р* – меншікті кедергінің температуралық коэффициенті;

 $3\ MP-magnetic properties, A-antiferromagnet, D-diamagnetic, P-paramagnet, F-ferromagnet;$

4 T = 300 K The resistivity is given for the temperature.

Appendix D (recommended)

Dielectric	Own resistance, Ом∙м	Dielectric liquidity, ε	ΤΚ <i>ε</i> , ×10 ⁻⁶ K ⁻¹	Angle tangent of dielectric losses, $tg\delta$	Electrical strength, MV/m
polyethylene	$10^{14} - 10^{15}$	2.3–2.4	-(200-300)	$(2-5) \cdot 10^{-4}$	40–150
polystyrene	$10^{14} - 10^{16}$	2.5–2.6	-(150-200)	$(2-4) \cdot 10^{-4}$	20–110
fluoroplast	$10^{14} - 10^{16}$	1.9–2.2	-(150-300)	$(2-3) \cdot 10^{-4}$	40–250
lavsan	$10^{14} - 10^{15}$	3.1–3.2	+(400-600)	$(3-10) \cdot 10^{-3}$	20–180
polyimide	1015-1016	3.5		$(1-2) \cdot 10^{-3}$	30–200
polyvinyl chloride	10 ⁹ -10 ¹³	3.1–3.4		0,015–0,018	35–45
getinax	$10^8 - 10^{10}$	3.0–6.0		0,04–0,08	15–30
glasstextol.	$10^8 - 10^{11}$	5.5-6.0		0,02–0,04	15–35
Mica	$10^{12} - 10^{14}$	6.0-8.0	+(10-20)	$(1-6) \cdot 10^{-4}$	100–250
quartz glass	10 ¹⁶	3.8–4.2		$(2-3) \cdot 10^{-4}$	40–400
alkaline glass	$10^{10} - 10^{15}$	5–10	+(30–500)	$(5-250) \cdot 10^{-4}$	40–400
sitals	$10^8 - 10^{12}$	5–10		$(1-80) \cdot 10^{-3}$	25-85
insulating porcelain	10 ⁹ -10 ¹¹	5–8		0,02–0,03	25–30
aliminoxide	$10^{14} - 10^{15}$	8.5–9.5	+(100–120)	$(1-2) \cdot 10^{-4}$	25–30
Polycor	1016	9	+(80–100)	$(1-2) \cdot 10^{-4}$	30–45
rutile ceramics	109-1012	40–300	-(80-2200)	$(2-10) \cdot 10^{-4}$	10–30
segnetkeram.	10 ⁹ -10 ¹¹	900– 20000		0.05–0.3	4–10

 Table 1-parameters of Dielectric Materials

Note

1 TK ϵ – temperature coefficient of dielectric constant;

2 For some dielectrics, the values of properties lie in the very ore range. Basically for ceramics and layering materials (Mica, textolite, getinax). The differences in the structure and chemical composition of materials explain this.

Appendix E (recommended)

Semi cond	Struc tural type	density, ×10 ³ kg/m ³	Temp. melting, °C	TCLI, ×10 ⁻⁶ K ⁻¹	Width of the Forbidden Zone, eV	EM, m²/V·s	Hole mobility, m ² /V·s	Е
Ge	Di	5.43	937	5.8	0.66	0.39	0.19	16.0
Si	Di	2.33	1415	2.3	1.12	0.14	0.08	12.5
α- SiC	He	3.22	2205		3.02	0.033	0.06	10.0
GaN	W	6.11	1700	5.7	3.40	0.03		12.2
GaP	S	4.07	1467	4.7	2.26	0.019	0.012	11.1
InP	S	4.78	1070	4.6	1.35	0.46	0.015	12.4
GaA	S	5.32	1238	5.4	1.43	0.95	0.045	13.1
InAs	S	5.67	942	4.7	0.36	3.3	0.046	14.6
GaSb	S	5.65	710	6.1	0.72	0.4	0.14	15.7
InSb	S	5.78	525	4.9	0.18	7.8	0.075	17.7
ZnS	S	4.09	1020		3.67			5.2
ZnS	W	4.10	1780	6.2	3.74	0.014	0.0005	5.2
CdS	W	4.82	1750	5.7	2.53	0.034	0.011	5.4
CdSe	W	5.81	1264		1.85	0.072	0.0075	10.0
HgT	W	8.09	670	4.8	0.08	2.5	0.02	
PbS	NaCl тип.	7.61	1114		0.39	0.06	0.07	17.0
PbSe	NaCl тип.	8.15	1076		0.27	0.12	0.10	

Table 1-Physical parameters of semiconductors

Note

1 EM – electron mobility;

2 Di – diamond. He – hexagonal. W – würzite. S – sphalerite;

3 ε – dielectric constant.

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A. Zh. Zhumabekov

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Monograph

Technical editor A. R. Omarova Responsible secretary Zh. K. Sapenova

Signet for printing 28.03.2025 г. Typeface Times. Size 29,7 x 42 ¼. Offset paper. Conv.pr.s.6.3 Circulation 500 pcs. Order №4354

Toraighyrov University 140008, Pavlodar, Lomov str., 64