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Кафедра фізики

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ДО ЛАБОРАТОРНОГО ПРАКТИКУМУ З ФІЗИКИ
РОЗДІЛ „ФІЗИКА ТВЕРДОГО ТІЛА”
(англійською мовою)

Для студентів інженерно-технічних спеціальностей
денної форми навчання

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CONTENT

INTRODUCTION

Basic goal of the laboratory work manual on Physics is to enable students to learn important physical phenomena by experience. Laboratory work description does not try to give students a complete picture of the studied phenomena. Such presentation can only be achieved as a result of study of lectures and textbooks.

Large attention in the laboratory work manual on Physics for the students of technical professions is devoted to the handling of the measured results. Prior independent preparation, above all theoretical, is needed for successful completion of the work.

Every laboratory work is supposed to take two academic hours. Before the class a student must prepare a protocol of laboratory work and learn appropriate theoretical material.

During the class students do the necessary measurements, execute calculations and take the report to the conclusion. Measured results are discussed with a teacher and confirmed.

Fully designed report on laboratory work should be given to the teacher before the end of the class. It must include: title sheet, laboratory work number and name, list of devices and installations, purpose of work, drawing of the setting, calculation formulae, table of the measurement results and calculations, conclusions, as the result of the work. Graphs must be done on a millimeter`s paper.

If a student does not have time to support the laboratory work before the end of the class, he/she is allowed to design a report (graph) with the use of the computer programs (Excel, Origin) for the next class.

Laboratory work is considered done after the successful speech in support in front of a teacher (report explanation + mark for theoretical material).

Support of report: purpose of work + experimental method + conclusions.

Theoretical material: knowledge of the physical phenomena, which was studied in this laboratory work (laws, formulas).

1. LABORATORY WORK № 80
STUDY OF THE CRYSTAL STRUCTURE

The aim: to determine of the crystal lattice parameters.
The task: to determine the indexes of the sites, the directions and the planes, the density packing of atoms, the coordination number and interatomic distance given crystal lattice.
Instrumentation and appliances: models of crystals.

1.1 Introduction

Crystals are formed from atoms, sometimes in simple and sometimes in complicated ways. Many crystals built up of ions bearing positive and negative charges: rock salt is composed of Na^+ and Cl^- ions. Crystals of the alkali metals are made up of small positive ion cores immersed in a negatively charged sea of conduction electrons. Some crystals are made up of neutral atoms having slightly overlapping electron clouds forming electron bridges or covalent bands between neighboring atoms.

The differences among these varieties of crystal line binding forces are closely connected with differences in the mechanical, electrical and magnetic properties of crystals. In all crystals the actual interaction which causes the binding is almost entirely the ordinary Coulomb electrostatic interaction between charges - the attraction between the negative charges of the electrons and the positive charges of the nuclei. The differences in the types of crystalline binding thus are not differences in the nature of the interaction, but are qualitative differences in the distribution of electronic charge. One of the questions in the physics solid state is "Where are the nuclei and the electrons in the solid?" This problem is called the determination of the structure of the solid.

All atoms are constructed of various elementary particles and a complete descriptions of a solid would simultaneously specify the condition of all these particles. However, such a description is unnecessarily complex for most purposes. An approximation sufficiently accurate for the study of the geometrical arrangement of entire atoms in crystals is to suppose the atoms to be round, hard balls. These balls rest against each other in various geometrical arrangement. Solids have own mode of atom placement.

The solids of primary interest for us have an arrangement of atoms in which the atoms are arranged on some regular repetitions pattern in three dimensions. Such solids are called crystals, and the arrangement of atoms is termed the crystal structure.

The internal regularity of atom placement in solids often leads to symmetry of their external shapes.

Suppose that are some atoms in the neighborhood of our origin *O*. The translational invariance insists that there must be exactly similar atoms, placed similarly about each lattice site.

It is obvious that we can define the physical arrangement of the whole crystal if we specify the content of a single unit cell.

The whole crystal is made up of endless repetitions of this object stacked like bricks in a wall. Suppose that there is some central symmetry about some point in the structure. This would be a convenient point to choose as the center of a cell, itself with central symmetry. One can do this systematically by constructing a Wigner-Seitz cell, that is, by drawing the perpendicular bisector planes of the translation vectors from the chosen center to the nearest equivalent lattice sites. The volume inside all the bisector planes is obviously a unit cell - it is the region whose elements lie nearer to the chosen center that to any other lattice site.

The unit cell can contain one or more atoms. Naturally, if it contains only one atom, we put that on the lattice site, and say that we have a Bravais lattice. If there are several atoms per unit cell, then we have a lattice with a basis.

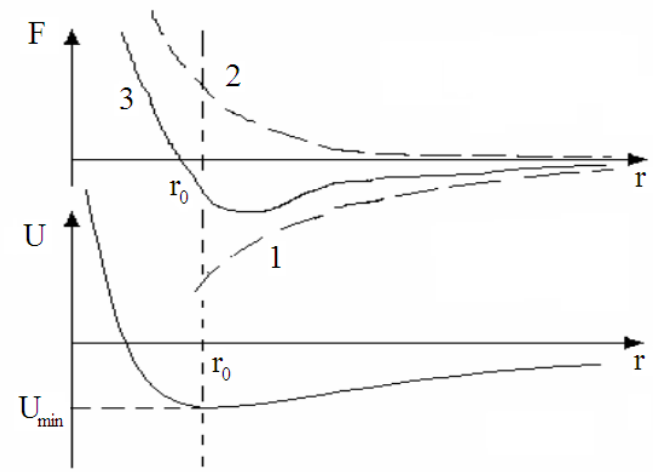
Structures are classified according to their symmetry properties, such as invariance under rotation about an axis, reflection in a plane.

1.2 Crystal lattice

When the atoms draw near, between atoms exist the forces of the interaction. Figure 2.1 shows the dependence of the energy of the interaction and the dependence between them.

It means, that the atoms in crystal lattice must be in equilibrium state, when r near to r.

Then we may to make the conclusion that the atoms must construct in the strict order under influence the forces of the interaction. In result it formed a body with regularity or periodically structure. So bodies are crystals. For describing crystal structure we use the idea of the crystal lattice.



Curve 1: When $r > r_0$ between the atoms there are the forces of the attraction.
Curve 2: When r tends r_0 ($r \Rightarrow r_0$) between the atoms began to act the repellent forces.
Curve 3: When $r = r_0$, then $F_{att} = F_{rep}$, and so the energy of the interaction reaches minimum U_{min} how it shows "*b*".

Figure 1.1

The crystallization process of a substance occurs due to the forces of attraction acting between its particles. At small his dances disappear and the forces of repulsion appear, preventing the further binding of particles. These forces strive to arrange the particles of substance as closer to each other as possible. In the first approximation we may to compare molecules with solid particles, in particular, with balls of definite radius witch may be brought only into contact by the forces of attraction.

When ball-type particles are packed tightly, each of them is surrounded by a certain number of adjoining (neighboring) particles arranged at equal distances from the first. This number is called a coordination number with values 12, 8, 6, 4 and 2.

The orderly distribution of particles within the volume of a crystal forms co called space crystal lattice. Geometrically the entire pattern of a lattice can be obtained if we draw three systems of planes intersecting between themselves at angles and. The planes in each system are parallel to each other and are spaced at equal distances *a*, *b* and *c*. These planes divide the crystal by unit cells constituting kind of bricks of witch the whole crys-

tal is built. Depending on the ratio between the cell ribs *a*, *b* and *c* as well as the angles we distinguish seven crystallographic systems:

a) $a = b = c$; $\alpha = \beta = \gamma = 90^0$ – cubic system;
b) $a = b \neq c$; $\alpha = \beta = 90^0$, $\gamma = 120^0$ – hexagonal system;
c) $a = b \neq c$; $\alpha = \beta = \gamma = 90^0$ – tetragonal system;
d) $a \neq b \neq c$; $\alpha = \beta = \gamma = 90^0$ – trigonal system;
e) $a \neq b \neq c$; $\alpha = \beta = 90^0 \neq \gamma$ – monoclinic system;
f) $a \neq b \neq c$; $\alpha \neq \beta \neq \gamma \neq 90^0$ – triclinic system;
g) $a = b = c$; $\alpha = \beta = \gamma \neq 90^0$ – rhombohedral system.

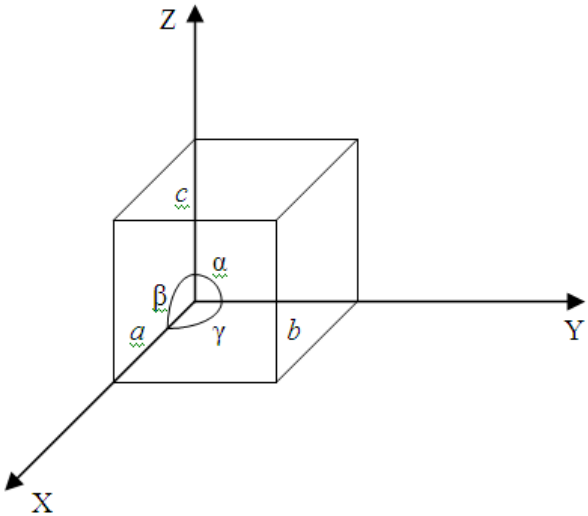


Figure 1.2

1.3 Mean of sites, directions and plains

Figure 1.3 shows us the simple crystal lattice in the system coordinate *X*, *Y*, *Z*.

The position of the particles define by vector $r = ma + nb + pc$, where *m*, *n*, *p* is whole numbers; *a*, *b*, *c* is basis vectors of the translation.

In our case $|a|=|b|=|c|$ and it is the lattice constant. If the unit of the length is the lattice constant, then the site coordinates is *m*, *n*, *p*. The index of the sites defined how their coordinate.

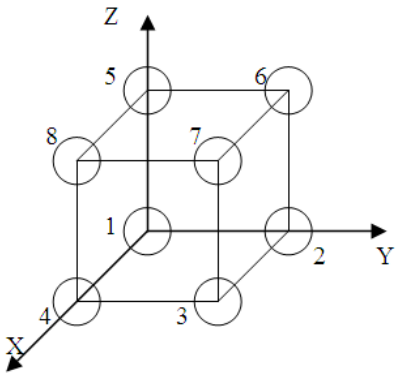


Figure 1.3

For example: Site *N*6 *x*=0; *y*=1; *z*=1, then the index of the site *N*6 is [[011]].

We take the length of the parallelepiped edges as a unit.

1.4 The index of the direction

The first way. If we must to define any direction, we must to know coordinates of two points which belong to this direction. For example, we must to determine the direction 5 – 6. Origin of coordinates is the point 1 on fig. 2.2. At first we change this origin on the point number 5 or 6. Let 5 be. Then we will have the new system coordinate *X*', *Y*', *Z*'. In touching system coordinate the direction 5 – 6 cross the origin and then the index of the direction 5 – 6 is the index of the site 6: [[010]]. The mean of the direction 5 – 6 is [010].The second way. In the common case the index of the direction defined by analytical method. For it we use the equation of the straight line

$$\frac{x-m_1}{m_2-m_1}=\frac{y-n_1}{n_2-n_1}=\frac{z-p_1}{p_2-p_1}, \qquad (1.1)$$

where m_1, n_1, p_1 and m_2, n_2, p_2 are the coordinates of two sites lay in this direction. Then the indexes of this direction are the quantities of the denominators:

5: [[001]] 6: [[011]]

$[m_2-m_1 \quad n_2-n_1 \quad p_2-p_1]$

5 – 6 : [0 – 0 0 – 1 1 – 1] => [010] or [010].

1.5 The index of the planes. Miller index

The first way. If the plane cuts on the coordinate axis segments x, y, z in the units of the lattice constants, then there is a number S such that
$h = S/x$; $k = S/y$; $l = S/z$.

In result we have h, k, l how minimum whole numbers.

The numbers h, k, l are the index of the plane or Miller index of the plane – ($h\ k\ l$).

The second way. In the common case we must to decide 3-th order determinant

$$\begin{vmatrix} m - m_1 & n - n_1 & p - p_1 \\ m_2 - m_1 & n_2 - n_1 & p_2 - p_1 \\ m_3 - m_1 & n_3 - n_1 & p_3 - p_1 \end{vmatrix} = 0 , \qquad (1.2)$$

where [[m_1 n_1 p_1]], [[m_2 n_2 p_2]], [[m_3 n_3 p_3]] are coordinates of three point, which belong this plane. When we had decided this determinant in result we have

$$hm + kn + lp = 0 . \qquad (1.3)$$

Thus we have ($h\ k\ l$).

For the cubic system:

a) normal to the plane with index ($h\ k\ l$) lies in the direction [$h\ k\ l$];

b) distance d between neighbor planes with index ($h\ k\ l$) is

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}} , \qquad (1.4)$$

where a is the length of the cubic edge. The distance between planes with large index is little compare with distance between planes with little index.

The planes with little index have more high atoms density. The density packing of atoms is the quantity of atoms per unit an area.

At first we must to sketching all possible planes with different indexes. For instance

After that we determine the quantity of the atoms belonged to these planes:

a) $N = 1$ b) $N = 2$ c) $N = 1/2$.

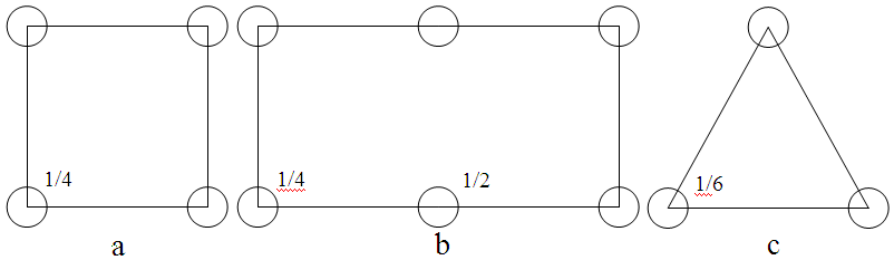


Figure 1.4

Then we calculate the area of these planes S and density n

$$n = \frac{N}{S} . \qquad (1.5)$$

Compare different n_i it is possible to find n_{max}. For description crystal structure we must determine the coordination number. It is the number of the nearest neighbors.

And also the interatomic distance is the shortest distance between two atoms in a crystal.

Control questions

1. What is crystal structure?
2. What is unit sell?
3. What is coordination number?
4. What is the density packing of atoms?
5. What is interatomic distance?

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Reviewer: Lushchin S.P., the reader, candidate of physical and mathematical sciences.

2. LABORATORY WORK № 81
THE ELEMENTS OF PHYSICAL STATISTICAL DISTRIBUTION

The aim: determine what is statistical distribution is described thermoelectron gas and what is temperature of thermoelectron gas.
The task: plot the graph of distribution of thermoelectrons over energies and compare it with Maxwell-Boltzmann's function.
Instrumentation and aooliances: electron tube, milliampermeter, microampermeter, voltmeter, potentialmeter, variable resistor, power source.

2.1 Theory

1. Numerous events occur that cannot be predicted. These are called ***random events***. The results obtained by observing numerous events of a single type, for example, analyzing the number of winning tickets for a large number of loan lotteries, may be summarized on the form of a so-called distribution curve. In the case of the analysis of the prize list, the distribution curve may be constructed on the basis of the date for the number of series of one hundred bonds for which there was one winner, two winner, etc.

If we construct a graph, plotting the random quantity along the horizontal axis and the number of random events along the vertical axis, the obtained curve is ***a distribution curve***. An example of such a curve is shown in Figure 4.1. The curve is drawn through the mid-points of the tops of the rectangles. Each rectangle has an area equal to the number of times a random event occurred for the quantity lying in the given interval.

We call the distribution law of one or another quantity ***a statistical law***. It is more accurately given the greater the number of events used to determine each ordinate of the curve.

Naturally, knowing the distribution curve does not enable us to predict the number of a bond that will win in the lottery. However, we can say, for example, what portion of the series consisting of one hundred numbers each will have one winner. The greater the number of bonds used in the analysis, the greater the accuracy of this prediction.

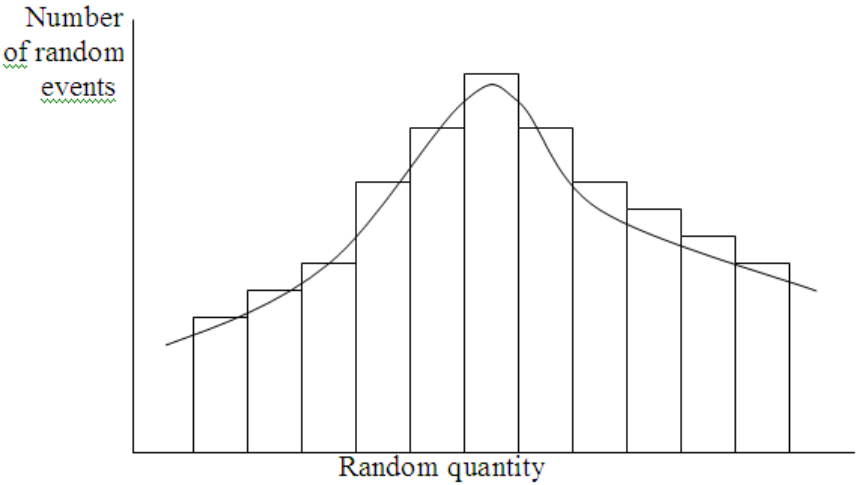


Figure 2.1

Certain ideas about the distribution of particles follow immediately from the chaotic nature of thermal motion.

Let us consider a small volume of space – a cube at point x, y, z whose sides are Δx, Δy, Δz.

Assume a considerable number of particles to be contained in this cube. We shall consider these particles having velocity components in the ranges from v_x to $v_x + \Delta v_x$, v_y to $v_y + \Delta v_y$ and v_z to $v_z + \Delta v_z$. The magnitudes of Δv_x , Δv_y and Δv_z are such that a large number of particles are contained in the indicated interval of velocities. The kinetic energy of a particle is determined by the value of the velocity and the potential energy of a particle in an external field depends on the coordinates of the particle in space, all the particles segregated by us have, practically, one and the same energy e.

Boltzmann's law gives a general expression for the number of particles whose coordinates are in the neighborhood of x, y, z and velocities in the neighborhood of v_x, v_y, v_z. This number is

$$n = A \cdot e^{-\frac{\varepsilon}{kT}} \cdot \Delta x \cdot \Delta y \cdot \Delta z \cdot \Delta v_x \cdot \Delta v_y \cdot \Delta v_z , \qquad (2.1)$$

where A is a constant, T is the absolute temperature and k is Boltzmann's constant.

The energy in to exponent is equal

$$\varepsilon = \frac{mV^2}{2} + U\,. \tag{2.2}$$

Hence

$$\Delta n = A \cdot e^{-\frac{\frac{mV^2}{2}+U}{kT}} \cdot \Delta x \cdot \Delta y \cdot \Delta z \cdot \Delta v_x \cdot \Delta v_y \cdot \Delta v_z\,. \tag{2.3}$$

Boltzmann's law or ***Boltzmann's distribution*** shows that the largest energy corresponds to the lowest number of particles whose velocities and coordinates lie in the given interval.

The velocity distribution of molecules, first determinated theoretically by Maxwell, may be considered to be a consequence of Boltzmann's law. We are interested in the number of molecules having a speed from v to $v + \Delta v$, where

$$v = \sqrt{v_x^2 + v_y^2 + v_z^2}\,. \tag{2.4}$$

The number of molecules is the same for all cubes of volume Δv_x, Δv_y, Δv_z located within a spherical shell of radius v to $v + \Delta v$. The number of molecules having velocities in the range from v to $v + \Delta v$ is proportional to the volume of the spherical shell, i.e. $4\pi v^2 \Delta v$. Thus, if the number of molecules contained in one cube is equal to

$$A \cdot e^{-\frac{mv^2}{2 \cdot k \cdot T}} \cdot \Delta v_x \cdot \Delta v_y \cdot \Delta v_z\,. \tag{2.5}$$

The number of molecules contained in the spherical shell is represented by the formula:

$$dn = A \cdot e^{-\frac{mV^2}{2k \cdot T}} \cdot 4\pi \cdot v^2 \cdot dv\,. \tag{2.6}$$

If n is the all number of molecules, then

$$\frac{dn}{n} = f(v)dv\,, \tag{2.7}$$

where $f(v)$ is the function of velocity distribution.

The number of particles having energy in the ranges from ε to $\varepsilon + d\varepsilon$ is:

$$dn = \frac{2n}{\sqrt{\pi} \cdot kT\sqrt{kT}} \cdot \sqrt{\varepsilon} \cdot e^{-\frac{\varepsilon}{k \cdot T}} \cdot d\varepsilon \,. \qquad (2.8)$$

From this formula following that the function of energy distribution is

$$f(\varepsilon) = \frac{dn}{n \cdot d\varepsilon} = \frac{2}{\sqrt{\pi} \cdot kT \cdot \sqrt{kT}} \cdot \sqrt{\varepsilon} \cdot e^{-\frac{\varepsilon}{kT}} \,. \qquad (2.9)$$

An example of such function of energy distribution is shown in Figure 2.2.

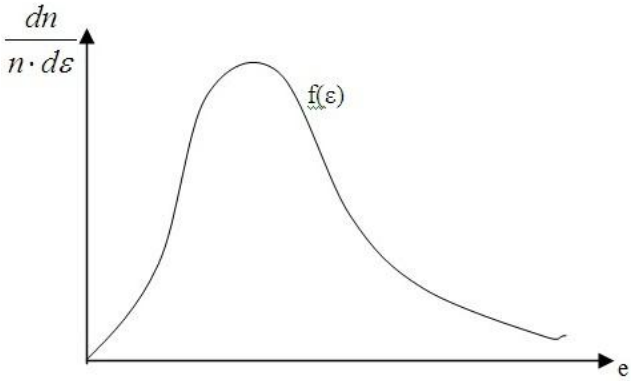


Figure 2.2

The square between the curve $f(\varepsilon)$ and the horizontal axis ε is equal unit. For it following that

$$\int_0^\infty f(\varepsilon) d\varepsilon = 1 \,. \qquad (2.10)$$

This formula is normalization function of energy distribution. By normalization constant A may be written in the form

$$A = 2\pi^{-\frac{1}{2}} \cdot (kT)^{-\frac{3}{2}} \,. \qquad (2.11)$$

2. Electrons at lower level practically do not take part in interactions between atoms. We must to understand the behavior of upper band electrons. Since we are dealing with a very large number of electrons, it is natu-

ral to use statistical physics methods and consider an aggregate of such electrons as a kind of gas.

The state of each electron of such a gas may be represented by a point (p_x, p_y, p_z) in momentum space. The energy of an electron depends on its momentum. Let us assume that the electrons behave like free particles.

If the electrons are free, the relationship between their energy and momentum is given by the formula

$$\varepsilon = \frac{p^2}{2m}, \tag{2.12}$$

where p is determined by

$$p = \sqrt{p_x^2 + p_y^2 + p_z^2}\ . \tag{2.13}$$

This means that in momentum space a surface of equal energy is a sphere. It is customary to call such a sphere a Fermi sphere. We can say, that the states of an electron gas are contained in a sphere of radius

$$p_{\max} = \sqrt{2m \cdot \varepsilon_{\max}} \tag{2.14}$$

According to the principle of uncertainly, the projection of the momentum of a particle in a metal body of linear dimension L cannot determinates with greater accuracy than h/L, where h is Plank's constant. Therefore, in momentum space, the concept of a point should be replaced by the concept of a cell of volume h^3/V, where V is the volume of the metal body under consideration. One of the basic postulates of the theory is that such as cell represents a quantum start and that it can contain no more than two electrons of opposite spins.

If there electrons in a volume V in the under consideration, then $N/2$ cells are occupied, i.e., the volume

$$\frac{N}{2} \cdot \frac{h^3}{V}. \tag{2.15}$$

This is the volume of a Fermi sphere of radius $p_{\max}$.

Thus,

$$\frac{4}{3} \cdot \pi \cdot (2\pi \cdot \varepsilon_{\max})^{3/2} = \frac{N}{2} \cdot \frac{h^3}{V}. \tag{2.16}$$

The above discussion assumed that the temperature is at absolute zero. At a higher temperature, electrons may pass over into momentum-space cells which correspond to higher energy.

The distribution of electrons according to energy at a given temperature may be calculated.

On the basic of the Pauli exclusion principle, we can construct a ***Fermi-Dirac statistics***, in which the function $e^{-\frac{\varepsilon}{kT}}$ is replaced by the expression:

$$f_{F-D} = \frac{1}{e^{\frac{\varepsilon-\varepsilon_{MAX}}{kT}}+1}. \qquad (2.17)$$

where ε_{max} is the maximum possible energy of the electrons at absolute zero. Figure 4.3 shows the dependence of the Fermi-Dirac function on ε when T>0 K

3. The escape of electrons from a metal upon heating is known as thermoionic emission. When the temperature is raised, electrons are excited, some of them acquiring a sufficient velocity in the direction perpendicular to the surface of the material to surmount the potential barrier ε.

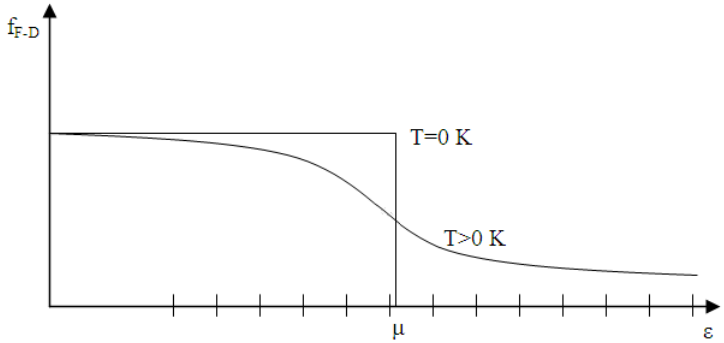


Figure 2.3

An electron gas obeys Fermi-Dirac statistics, according to which the number of electrons having an energy ε is proportional to the expression

$$\frac{1}{e^{\frac{e-\mu}{kT}}+1}. \qquad (2.18)$$

But we are interested in the energies, which considerably greater than the zero-level energy μ. At absolute zero, electrons have a limiting

energy μ. In the model of an electron gas, μ corresponds to a Fermi surface. Therefore it is accurate enough to reduce the above expression to

$$e^{-\frac{\mu-\varepsilon}{kT}} = e^{-\frac{e\cdot\phi}{kT}}, \qquad (2.19)$$

where ϕ – work function is stopping potential. Thus, we may determine the number of electrons having energy equal to the height of the potential well. It may be rigorously proved that the thermionic emission current is proportional to this expression.

The circuit shown is Figure 4.4 may be used to measure the thermionic current.

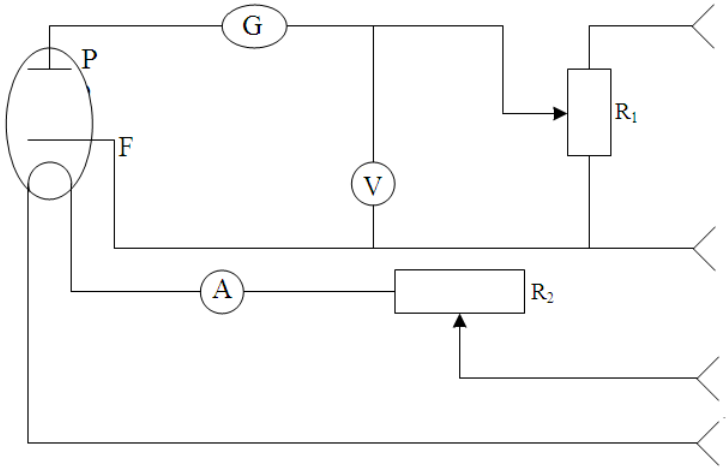


Figure 2.4

The diode D which is shown diagrammatically consist of a filament F and a metallic plate P, both seated in a vacuum tube. The filament is heated by electric current from a battery A. Another battery B and galvanometer G are connected in series between the plate and one side of the filament. When the positive terminal of B is connected no current flows through the circuit; the galvanometer which registers the current reads zero.

The explanation of this behavior is that the filament when heated gives off negative electrons; hence, each time the plate is positive in relation to the filament, the electrons become attracted to the plate and flow through the circuit to the filament. When, however, the plate is negative in

relation to the filament, the plate repels the electrons with the result that no current flow in the circuit.

If the filament is heated to a given temperature *T*, some of the free electrons of the metal evaporate from the filament into the space surrounding it. These from an electron gas around the filament. A state of equilibrium results when as many electrons leave the filament as re-enter it from the electron gas around it.

When a difference of potential exist between the filament and the plate, so that "+" on the plate and "-" on the filament, we have accelerating potential and electrons are attracted to the plate and other electrons evaporate from the filament to replace them. If a difference of potential between the filament and the plate so that “-“on the plate “+” on the filament then we have counter potential and electrons are repulsed from plate.

The number of electrons which create electronic current between the filament and the plate given the following expression:

$$N = B \cdot A_e^{1/2} \cdot \exp(-\frac{A_e}{kT}), \qquad (2.20)$$

where *B* is coefficient; A_e is work function.

Then a current is measured by galvanometer G is determined by formula

$$I = C \cdot A_e^{1/2} \cdot \exp(-\frac{A_e}{kT}), \qquad (2.21)$$

where *C* is new coefficient.

If on the plate negative potential exist relatively of the filament (counter potential) then it is equivalent of a rise of the work function. In this case for plates current we have

$$I = C \cdot \sqrt{A_e + e \cdot U_{count}} \cdot \exp(-\frac{A_e + e \cdot U_{count}}{kT}). \qquad (2.22)$$

After to take a logarithm

$$\ln I = \ln(C \cdot \sqrt{A_e + e \cdot U_{count}} \cdot e^{-\frac{A_e}{kT}}) - \frac{e \cdot U_{count}}{kT}, \qquad (2.23)$$

or

$$\ln I = \ln I_0 - \frac{e \cdot U_{count}}{kT}. \qquad (2.24)$$

Those formulas give us a possible to determine the absolute temperature T of the filament if we draw the graph of ln$I$ against U_{count}, how it shown from Figure 4.5.

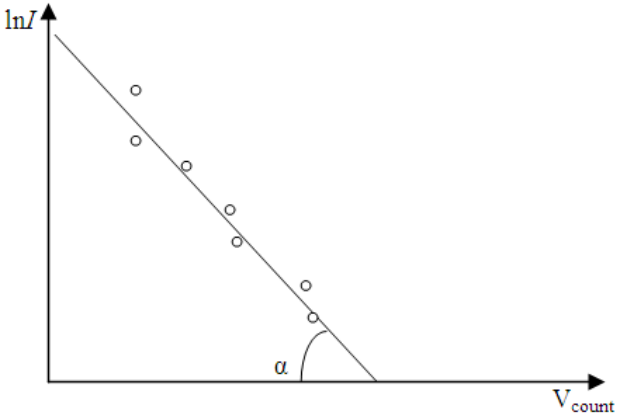


Figure 2.5

2.2 Experimental part

1. Measure the plates current on versus a counter potential. Put down the date of measurements in table 4.1.

Table 2.1

N	Counter potential U_{count}, V	Plates current I, μA	$\Delta I = I_n - I_{n+1}$	ln I
1				
…				
12				

2. Put ΔI versus U_{count} on the graph. Make a comparison between experimental curve and Maxwell-Boltzmann's distribution over the energy.
3. Put ln I versus U_{count} on the graph. Determine the absolute temperature T of the electronic gas by formula

$$T = \frac{e \cdot \Delta U_{count}}{k \Delta(\ln I)}, \qquad (2.25)$$

where e=1.6·10^{-19} C ; k=1.36·10^{-23} J/grad.

4. Make analysis of the experimental results.

Control questions

1. What is Maxwell-Boltzmann's statistical distribution?
2. What is Fermi-Dirac's statistical distribution?
3. What is normalization function of energy distribution?

References

1. Епифанов Г.И. Физика твердого тела. – М. Высшая школа, 1977. – С. 67-89.
2. Gevorkjan R.G., Shepel V.V. A Course of General Physics. – Moscow: Higher School, 1967. – 550 p.

Translator: Lushchin S.P., the reader, candidate of physical and mathematical sciences.
Reviewer: Loskutov S.V., professor, doctor of physical and mathematical sciences.

3. LABORATORY WORK №82.1 RESEARCH ON ELECTRIC CONDUCTIVITY OF SEMICONDUCTORS

The aim: to study phenomenon of solids electric conductivity.

3.1 Introduction

The phenomenon of electric conductivity in solids is related to the movement of the free charges under the action of an electric field. Such kind of charge movement leads to changes in their energy. Possible values of electron energy in solids create the energy lines that are called an **energy bands**. Since electric conductivity is created by the movement of valence electrons, so then it's features are caused by the principles of filling the quantum states of an electrical band, called **valence band,** by the valence electrons. With the temperature T close to zero there are two possible states:

a) The quantum states of the valence band are completely filled with electrons. The solid body with such a valence band will not conduct electrical current because valence electrons cannot move under the action of external electric field. This movement would lead to the change of their energy, and that should be followed by passing of electrons to other quantum states. But all states are fullfield and there is no way to pass to. These solids are called dielectrics.

b) If quantum states of the valence band are partly filled with electrons then there is no mentioned above limits of their movement under the action of external eclectic field. The solids with such filled valence bands can conduct electric current well. They are good conductors. The experiments show that metals have high electric conductivity. So quantum states of valence band in metals are partly filled.

It is established that electric conductivity of semiconductors sharply grows with increase of temperature unlike in metals where it decreases monotonically. Growth of semiconductors electric conductivity with increase of temperature is explained by band's theory of solids as follows: the band of excited states is situated above the valence energetic band, this band is separated from valence band by forbidden energy line i.e. such values of energy that free electron cannot have. This energy create a forbidden

band. Energy width of forbidden band is denoted as $\Delta \boldsymbol{E_g}$. This parameter is an important characteristic for optical and electrical properties of semiconductors.

With increase of temperature some electrons from valence band pass to the band of exited states. The band of exited states in this case will be partly filled with electrons moving under the action of external electric field like electrons in metals. For this reason, this band is called the conduction band. The possibility of electrons' transition from valence to conduction band is defined in accordance with Maxwell-Boltzmann's statistics by the expression:

$$W = A\exp\left(-\frac{\Delta E_g}{2kT}\right), \tag{3.1}$$

where k is a Boltzmann's constant, A is a normalizing factor.

So the concentration of free electrons in the conduction band changes with the temperature T by the expression:

$$n = n_0 \exp\left(-\frac{\Delta E_g}{2kT}\right), \tag{3.2}$$

where n is the concentration of free electrons at temperature T. According to the electron's conduction theory the expression for specific resistance has the form:

$$\sigma = en\mu \ , \tag{3.3}$$

where e is the electron charge, n and μ are the concentration and the mobility of the electrons.

The experiment shows that the mobility of electrons decreases in metals with the increase of temperature. The similar relationship $\mu(T)$ is observed in semiconductors and dielectrics at moderate temperatures. But for semiconductors the temperature relationship of the concentration is stronger than mobility and it's assumed that:

$$\sigma = \sigma_0 e^{-\frac{\Delta E_g}{2kT}}, \tag{3.4}$$

where σ_o is a constant.

From the last equation follows, that the principal difference in relationship $\sigma(T)$ between semiconductors and metals exist. In metals σ decreases while temperature is increasing and in semiconductors – increases stably. The difference between the semiconductors and dielectrics has a conditional

nature. If the width of forbidden band is lower than 3eV it means that the material is semiconductor, if greater - dielectric.
In semiconductors the conductivity is realized not only by free electrons from conduction band but also by movement of valence electron's vacancies passing to the conduction band. Vacancies have the positive charge. Concentration of vacancies in semiconductors equals to the concentration of the free electrons. These vacancies are called holes. Mobility of the holes is rather lower than mobility of electrons. The expression for specific conductivity of semiconductor is:

$$\sigma = en(\mu_n + \mu_p), \tag{3.5}$$

where μ_n and μ_p is mobility of electrons and holes.

3.2 Experimental Part

To determine the width of forbidden band $\Delta \boldsymbol{E_g}$ the relationship of germanium diode reverse saturation current with temperature is used. The current density is $j=\sigma E$. Where E is the intensity of the electric field in the conductor. For the part of conductor with length L, $E=U/L$, where U is the voltage in this part of the conductor. The current is $I=jS$, where S is the cross section area of the conductor. We obtain:

$$\frac{I}{S} = \sigma \frac{U}{L} \Rightarrow I = \sigma \cdot S \frac{U}{L}.$$

The value $S\frac{U}{L}$ we may be considered as a constant, and $\sigma = \sigma_0 \exp(-\frac{\Delta E_g}{2kT})$.

So at constant voltage, applied to the semiconductor sample the relationship of current from temperature is:

$$I = \sigma_0 S \frac{U}{L} \exp\left(-\frac{\Delta Eg}{2kT}\right) \tag{3.6}$$

If to take the natural logarithm from (5.6) we obtain:

$$\ln I = \ln\left(\sigma_0 S \frac{U}{L}\right) - \frac{\Delta Eg}{2kT} \tag{3.7}$$

The graph of the function $\ln(I) = f(1/T)$ looks like a straight line, as it is shown at the fig.3.1.

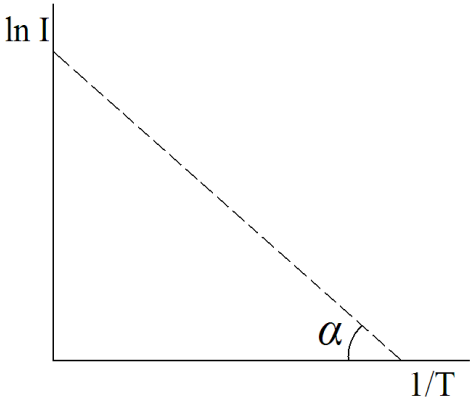


Figure 3.1

From the expression (5.7) it is seen that tangent of the slope of line $\ln(I) = f(1/T)$ equals:

$$tg\alpha = \frac{\Delta Eg}{2k} \Rightarrow \Delta Eg = 2k \cdot tg\alpha \,. \qquad (3.8)$$

To determine $\tan\alpha$ and ΔE_g respectively we need to plot the graph $\ln(I) = f(1/T)$, and so this we need experimentally establish the value of the current trough semiconductor at different temperatures. The experiment and the theory of p-n junction (diodes) made from germanium shows that reverse current of saturation I_s grows with increase of temperature according to the expression (3.6). At the fig.3.2 the volt-ampere characteristic of germanium p-n junction for reverse direction at different temperatures is shown.

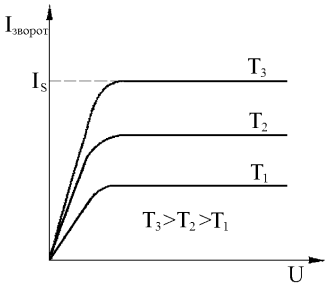


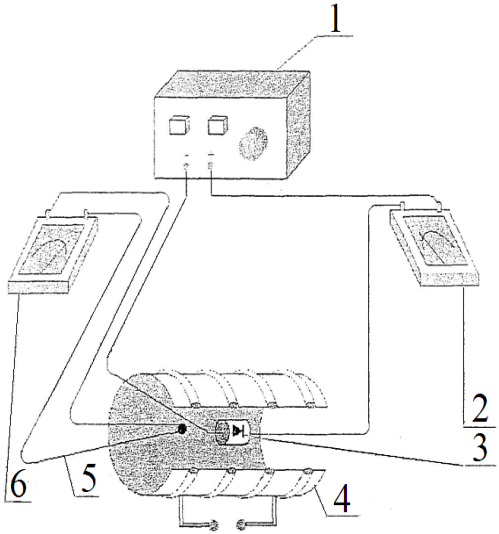
Fig. 3.2.

3.3 Problem №1

1. To obtaine the relationship between current *I* and temperature *T*.
2. To determine the width of forbidden band $\Delta \boldsymbol{E_g}$ of germanium with a help of obtained graph.
3. To compare the obtained values with the table ones.

Devices and equipment

1. DC source B-24M (or other).
2. Germanium diode made from (for example Д7Ж).
3. Voltmeters- amperemeters M-2018.
4. Thermoelectric couple.
5. Electric oven.
6. Conductors.



1). DC source B-24M (or other). 2). Device for measuring the reverse current of the diode (device M-2018, scale for 1.5 mA). 3). Investigated diode 4).Thermoelectric couple for measuring the temperature *T* inside the oven. 5). Electric oven for heating the diode. 6). Device for measuring the electromotive force (EMF) of the thermoelectric couple.(appliance M-2018 or other, scale 15 mA)

Figure 3.3

Order of Work Performance

1. To learn the wiring diagram at the fig.3.3.
2. To connect the oven (5) and source (1) to the AC 220 V network.
3. To apply voltage *U*=10V to the diode from the source (1). The voltage is controlled by voltmeter which is placed at the front source panel.
4. To write down the instruments values (2) and (6) to the table 3.1.
5. EMF of thermocouple convert to ^{o}C using such kind of data for thermoelectric couple, for example:

$$\Delta t^{o}\mathrm{C} \approx 14{,}4^{o}\mathrm{C}\,, \qquad (3.9)$$

It means that themperature inside the oven is greater than room one on 14.4 ^{o}C

6. To calculate the absolute temperature T of the diode using the expression $T = 273 + t_R + \Delta t$, where t_R is the room temperature. Calculate the value of $1/T$ and write down it to the table 3.1.

<u>Caution! It is necessary to monitor attentively the temperature in the oven and not to overheat the diode more than 120÷130°C.</u> The instrument values should be written down during cooling the diode in the oven. As a result of thermal inertia, more reliable data will take place during slower cooling, i.e. at the end of cooling.

№	EMF of the thermoelectric couple, mV	The difference Δt between the temperature of the diode and room one, °C	Absolute temperature T of the diode, K	$1/T$, K^{-1}	The reverse current I in the scale point M-2018	ln$I$ in the scale point
1						
2						
….						
10						

7. To calculate ln(I) and plot the graph of relationship $\ln(I) = f(1/T)$. To define the tanα from the graph and calculate ΔE_g using the formula (3.3).
8. To compare the obtained values with table ones(0.7eV). $1eV = 1.6 \cdot 10^{-19} J$.
9. To make the conclusion.

3.4 Problem №2

To determine the width of forbidden band ΔE_g of germanium.

<u>Device and equipment.</u>

1. The digital multimeter DT-838 with the thermoelectric couple - 1 item.
2. The digital multimeter DT-838B - 1 item.
3. Investigated germanium diode D-9 – 1item.
4. Wiring oven – 1 thing.
5. DC source AC-DC with the output voltage 6V – 1 item.
6. Connecting wires.

Performance of the Work

1. To connect the scheme according to the wiring diagram, fig.3.4.
2. To place the thermoelectric couple and investigate diode soldered together into the cylindrical cavity of the wiring oven.
3. To set limits on the measuring devices: DT-838(device № 1) – "TEMP ^{o}C" for temperature measuring; DT-838B(device №2) – "Ω2000" for measuring of the diode resistance switched in the stop direction.
4. To connect the DC source to the network.
5. After heating the oven with the diode and thermoelectric couple up to 85°C to disconnect the DC source from the network.
6. After every 5 ^{o}C to measure resistance of the cooling diode using the ohmmeter DT-830B(device №2) and to set the values into the table 3.2. If it is needed set another network measurement on the ohmmeter.

№	Δt, ^{o}C	T, K	$1/T$, K^{-1}	R, Ω	ln R	ΔE_g, eV
1	80					
2	75					
…	…					
12	25					

7. Using the results of the experiment plot the graph of the relationship $\ln R = f(1/T)$.
8. Using the expression $\Delta E_g = 2k \cdot \tan\alpha$, where $\tan\alpha$ is a tangent of the slope at the graph, $k = 1.38 \cdot 10^{23}\ J/K$ is a Boltzmann's

constant, calculate the width of forbidden band ΔE_g of the germanium.

9. To compare the obtained values with table ones (0.7eV).
10. To make the conclusion.

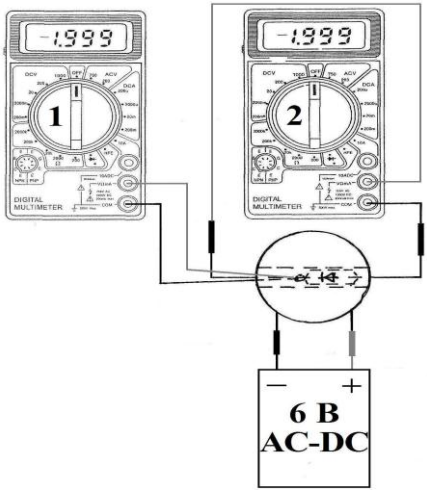


Figure 3.4

Control Questions

1. What is the valance band, conduction band and forbidden one?
2. What is the difference between conductors and semiconductors?
3. How does the resistance of the semiconductor depend upon the temperature?
4. What is thermo EMF?
5. What is the mobility of the charge?
6. How to calculate the specific resistance of the intrinsic semiconductor?
7. In how many times the current will change through the germanium sample, if the temperature will be increased from 27 ^{o}C up to 87 ^{o}C?

References

1. Епифанов Г.И. Физика твердого тела. – М. Высшая школа, 1977. – С. 164-183.
2. Gevorkjan R.G., Shepel V.V. A Course of General Physics. – Moscow: Higher School, 1967. – 287-294 p.

Translator: Lushchin S.P., the reader, candidate of physical and mathematical sciences.
Reviewer: Loskutov S.V., professor, doctor of physical and mathematical sciences.

4. LABORATORY WORK № 84.1 PHOTORESISTIVE EFFECT IN SEMICONDUCTORS

The aim: investigation of photoresistive effect in semiconductors.
The task: plot the volt-ampere graphs of photoconductivity at different values of illumination; plot the light graphs of photoconductivity at different values of voltages.
Instrumentation and appliances: device for measuring photoconductivity in semiconductors.

4.1 Introduction

As it is known radiation and absorption of electrical energy occur in packets or quanta. The magnitude of a quantum energy depends only its radiation frequency and is equal to $h\nu$, where h is a universal Planck's constant equals to h=6.62·10^{-34} J·s.

The corpuscular properties of electromagnetic radiation are manifested when losses and transformations of electromagnetic energy occur. The shorter the wave length is, the more distinct the effects. These properties, on the other hand, are not manifested during propagation, scattering and diffraction of electromagnetic waves if these processes are not accompanied by energy losses.

A corpuscule of an electromagnetic field is called ***a photon***. Its energy

$$E = h\nu . \tag{4.1}$$

Using the law of equivalence of mass and energy, we are entailed to ascribe to a photon the mass

$$m = \frac{E}{c^2} = \frac{h\nu}{c^2} . \tag{4.2}$$

Assuming the concept of momentum applicable to a photon, we obtain

$$p = mc = \frac{h\nu}{c} . \tag{4.3}$$

Some parameters of electromagnetic radiations you can see in table 4.1.

Table 4.1

	Λ	E, eV	m, kg	p, kg·m/s
Radio wave	2.000 m	$0.62 \cdot 10^{-9}$	$1.1 \cdot 10^{-45}$	$3.3 \cdot 10^{-37}$
Visible light	6.000 Å	2	$3.6 \cdot 10^{-36}$	$1.1 \cdot 10^{-27}$
X-ray	1 Å	12.4	$2.2 \cdot 10^{-32}$	$6.6 \cdot 10^{-24}$

4.2 Photoelectric effect

The term ***photoelectric effect*** is applied to electrical phenomena occurring when a substance is illuminated with light. There are three types of photoelectric phenomena: 1) ***external photoeffect***, when the absorption of light leads to the liberation of electrons beyond the irradiated body; 2) ***internal photoeffect***, when the number of free electrons increases inside the matter, but they do not escape outside; 3) ***photovoltaic effect***, when under action of radiation an electromotive force originates at the border of two semiconductors.

Striking out of electrons under the action of electromagnetic waves define important confirmation of the indispensability of the corpuscular viewpoint. Since the escape energy of an electron from a metal is not least than 2.2 eV, the photoelectric effect becomes possible when

$$h\nu > 3.5 \cdot 10^{-19} J, \tag{4.4}$$

i.e., for frequencies of the order of

$$\nu = 0.5 \cdot 10^{15} Hz \ (\lambda = 6.000 \text{ Å}). \tag{4.5}$$

Einstein proposed that the photoelectric effect be viewed as an effect of collision between a photon and an electron. If A represents the work function of electron, i.e. the work required to overcome the binding free between the electron and the substance, the low of conservation of energy has the form

$$h\nu = A + \frac{mV^2}{2}, \tag{4.6}$$

where $\frac{mV^2}{2}$ is the kinetic energy of the photoelectron, the electron dislodged from the substance.

The variation of the electrical resistance of a semiconductor sample due to illumination is termed ***photoresistive effect***, or ***internal photoeffect***. The variation of the resistance or the conductance is caused by the variation of charge carrier concentration. The photoresistive effect may be described with the aid of photoconductivity σ_{pc}

$$\sigma_{pc} = e_n \mu_n \delta_n + e_p \mu_p \delta_p , \qquad (4.7)$$

where δ_n, δ_p are excess electron and hole concentration produced by illumination. The conductivity $\sigma_0 = \sigma_d$ due to equilibrium carriers is termed dark-current conductivity:

$$\sigma_0 = e_n \mu_n n_0 + e_p \mu_p p_0 . \qquad (4.8)$$

The total conductivity may be represented in the form of a sum of dark and light conductivities:

$$\sigma = e_n \mu_n (n_0 + \delta_n) + e_p \mu_p (p_0 + \delta_p) = \sigma_d + \sigma_{pc} . \qquad (4.9)$$

The electric circuit shown in fig. 10.1 may be used to measure the dependence of current of photoconductivity versus a different of voltage or a value of illumination on the photoresistor R_0.

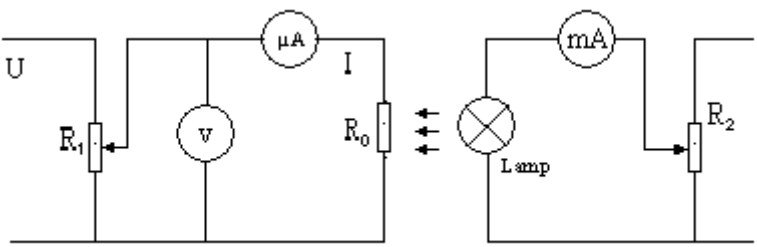


Figure 4.1

4.3 Experimental part

1. Measure the current of photoconductivity versus a difference of voltage on the photoresistor when values of illumination are different. Put down the data of measurements in table 4.2.

Table 4.2

Difference of voltage U, V	Current of photoconductivity I, μA		
	E_1=…, lx	E_1=…, lx	E_1=…, lx

2. Plot the graph of dependence I from difference of voltage U for E_1, E_2 and E_3.
3. Measure the current of photoconductivity versus a value of illumination of the photoresistor when potentials on the photoresistor are different. Put down the date of measurements in table 10.3.

Table 4.3

Illumination of photoresistor E, lx	Current of photoconductivity I, μA		
	U_1=…, V	U_2=…, V	U_3=…, V

4. Plot the graph of dependence current of photoconductivity I from a values of illumination E for U_1, U_2 and U_3.
5. Make analysis of the experimental results.

Control questions

1. What is photoelectric effect?
2. What kinds of photoelectric effect do you know?
3. What is photoresister?
4. What is intrinsic photoconductivity?

References

1. Gevorkjan R.G., Shepel V.V. A Course Of General Physics. – Moscow: Higher School, 1967. – 550p.
2. Koshkin N.I., Shirkevich M.G. Handbook Of Elementary Physics. – Moscow: Mir Publishers, 1977. – 272p.
3. Kireev P.S. Semiconductor Physics.-Moscow: Mir publishers, 1974. – 672p.

Translator: Lushchin S.P., the reader, candidate of physical and mathematical sciences.
Reviewer: Loskutov S.V., professor, doctor of physical and mathematical sciences.

5. LABORATORY WORK №84.2 DETERMINATION OF THE SEMICONDUCTOR FORBIDDEN BAND BY THE OPTICAL METHOD

The aim: examine the characteristics of light absorption by semiconductors and its explanation on the basis of band theory.

Tasks: 1) construct a spectral dependence of absorption coefficient on versus wavelength $\alpha=f(\lambda)$;

2) determine the forbidden band of CdS and compare it with tabular values.

Instruments and equipment: An experimental setup is shown on the picture 11.1, it consists of: 1 - monochromator UM-2; 2 - researched sample (CdS film); 3- optical source; 4 - microammeter; 5 - power source; 6 - photocell (resistance photocell FCK-G1)

5.1. Theory

In case of falling beam of light with density J_0 on the surface of crystal part J_ρ reflects, part J_α absorbed and part J_τ is skipped. It is clear that, $Jo= J_\rho+ J_\alpha+ J_\tau$. Ration of appropriate intensities to the intensity of incoming beam gives coefficients $\rho=\frac{J_\rho}{J_0}$, absorption $\alpha=\frac{J_\alpha}{J_0}$, and transmission $\tau=\frac{J_\tau}{J_0}$. All this coefficients depends on the wavelength.

For semiconductors relationship of absorption coefficient α from wavelength λ in frames of band theory is simply explained by energy considerations. When the light is absorbed by the electron, the quantum energy is transferred to it fully. Electron energy rises and that is shown on the band diagram by the transitions 1- 3 to the higher energetical levels. Transition 1 - is absorption itself, 2,3 - impurity absorption (appropriately donor and acceptor-type absorption). Such transitions can exist just when photon

energy $E_F = h \cdot v = \frac{h \cdot c}{\lambda}$ is not less than appropriate energetic interval :ΔE_g, E_D, E_A. Under other conditions absorption would not happen. So, the important condition of absorption is correlation $\frac{h \cdot c}{\lambda} \geq E_g$ for fundamental absorption or $\frac{h \cdot c}{\lambda} \geq E_A$ for impurity absorption. Such spectral relationship of absorption coefficient for semiconductor is shown on picture 11.3.

Here $\lambda_F = \frac{h \cdot c}{\Delta E_g}$ - double wave limit of fundamental absopion, $\lambda_D = \frac{h \cdot c}{\Delta E_D}$ or $\lambda_A = \frac{h \cdot c}{\Delta E_A}$ double wave of impurity absorption.

Long-wave limit of absorption is such a wavelength? Wherein the radiation with larger value of the wave-length than the given one isn't already absorbed. Thus, experimentally defining the wavelength of the fundamental absorption, it's possible to find the width of the forbidden band:

$$\Delta E_g = \frac{h \cdot c}{\lambda_f}.$$

Where λ_f is the maximum wavelength in the absorption spectrum, in other words the radiation with the wavelength of more than λ_f isn't absorbed.
You have to note, that the impurity absorption is possible only at the relatively low temperatures, when the atoms of the impurity aren't ionized yet at the expense of the thermal energy.

5.2. The order of performance of the work

1. Provide the photodetector with the voltage and write down the value of the dark current.
2. Fix the clean glass plate on the body of the illuminator before the lamp ans switch on the lamp.
3. Reach the maximum current of photoresistor within the boundaries of 90-100 mcA by means of rotation of the drum Б

of the monochromator. In the case of reading off scale of the microammeter, decrease the width of the entrance S1 and exits S2 slits, increase their width in the case of the low signal in maximum. In such cases it's desirable to set up approximately equal values of the width of both slits.

4. Take away the dependence of the intensity J_0 of the incident light flux (microammeter indication) on the angle of the rotation of the drum (wavelength). The dependence is removed in the interval of angles from 1000° to 3000° through 100°.
5. Replace the glass plate with the researched sheet, spread on the glass underlay.
6. Take away the dependence of intensity J, that went through the sheet, from the angle of rotation of the drum, similarly to the 4.
7. Fill in results of the measurements and calculations in the table 5.1.

The table 5.1

φ, degree	J_0, μA	J, μA	λ, nm	α
1000				
…..				
3000				

8. Using the data of the of the table 5.2., constract the auxiliary graded graph, and with its help transfer the values of the angles φ of the rotation of the drum into the wavelength λ.

The table 5.2.

φ, degree	1000	1500	2000	2500	3000
λ, nm	418	465	515	582	665

9. For each wavelength calculate and write down the absorption coefficient α with the help of the equation

$$\alpha = \frac{J_0 - J}{J_0 - J_T}. \qquad (8.2)$$

10. Constract the relationship graph α=*f*(λ) and define λf according to the decay (see the picture 11.1).
11. Calculate the width of the forbidden band with the help of the equation (11.2) and compare the found value with the table one (ΔEg.table=2.4 eV).
12. Make the conclusion.

Control questions

1. Give the definitions of the absorption, transmission and reflection coefficients.
2. Explain the spectral dependence of the absorption coefficient within the theory.
3. Suppose the reflection coefficient is equal to zero. Draw the spectral dependence of the transmission coefficient of the semiconductor.
4. Why is the impurity absorption possible at the law temperatures?
5. What is the long-wave limit of absorption and how can you explain its existence?

6. LABORATORY WORK № 85
CONTACTS PHENOMENA ON P-N JUNCTION

The aim: to study the electrical conductivity of p-n junction.
The task: plot the volt-ampere characteristic of p-n junction.
Instrumentation and appliances: voltmeter, milliampermeter, source of current, diode.

6.1 Introduction

The classification of materials according to their conductivity materials are characterized by different conductivities, table 6.1:

Table 6.1

Material	σ, $s \cdot m^{-1}$
Aluminium	$3.12 \cdot 10^{7}$
Gold	$4.13 \cdot 10^{7}$
Copper, drawn	$5.62 \cdot 10^{7}$
Copper, annealed	$6.30 \cdot 10^{7}$
Silver	$6.03 \cdot 10^{7}$
Nichrome	$9.00 \cdot 10^{5}$
Diamond	$10.00 \cdot 10^{-10}$
Ebonite	$5.00 \cdot 10^{-14}$
Pyrex	$1.00 \cdot 10^{-12}$
Micx	$1.10 \cdot 10^{-11}$
Paraffinized wax	$3.30 \cdot 10^{-17}$
Quartz	$5.10 \cdot 10^{-13}$

Materials with conductivities $\sigma=(10^{7} \div 10^{6})$ $S \cdot m^{-1}$ are usually termed ***conductors***, or ***metals***.

Isolators or ***dielectrics*** are those with conductivities $\sigma=(10^{-8} \div 10^{-16})$ $S \cdot m^{-1}$.

Materials with intermediate conductivities $\sigma=(10^{-8} \div 10^{6})$ $S \cdot m^{-1}$, were termed ***semiconductors***.

The temperature dependence of conductivity of metals is the resistance increases with temperature:

$$R = R_0(1 + \alpha t)\,, \tag{6.1}$$

where R_0 is the resistance at t = 0° C; α is the thermal resistance coefficient equal about 1/273.

In case of semiconductors the resistance rapidly decreases with the increase of temperature. The empirical formula connecting the resistance and absolute temperature T valid within a limited temperature range is given below:

$$R(T) = R_0 e^{B/T}\,, \tag{6.2}$$

where B is constant. This formula may be rewritten for conductivity

$$\sigma = \sigma_0 e^{\frac{E_a}{kT}}\,, \tag{6.3}$$

where k is Boltzmann's constant. The quantity E_a characteristic of the given semiconductor is called its ***activation energy***.

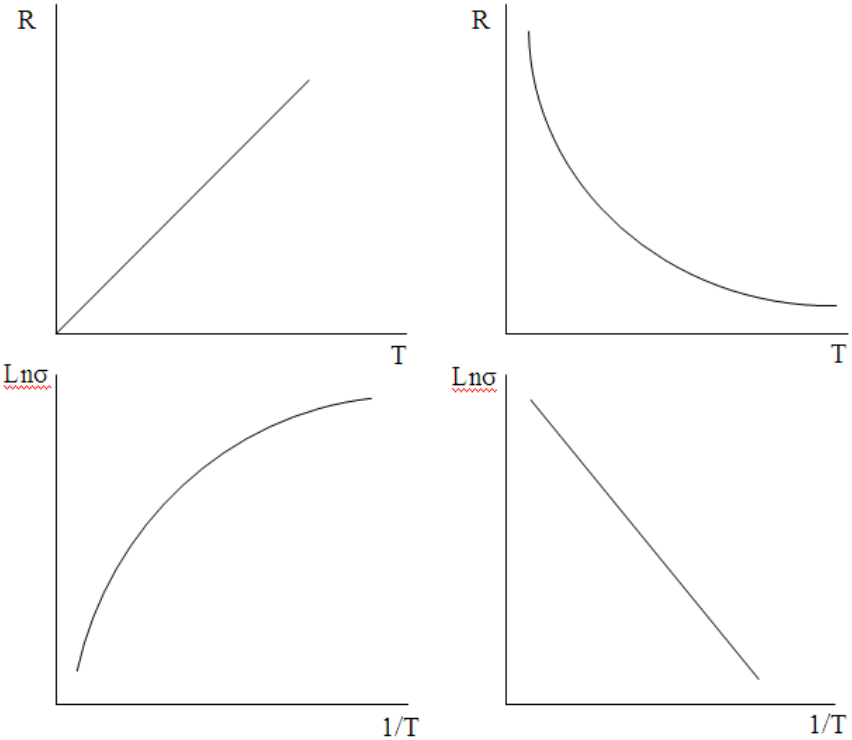


Figure 6.1

The semiconductors are materials the conductivity of which at room temperature ranger between 10^{-8} and 10^{6} $S \cdot m^{-1}$ and depends strongly on the nature and amount of impurities, on the structure of the material and on the ambient: temperature, illumination, electric and magnetic fields, etc.

There are two kinds of semiconductive materials: ionic and electronic. In ionic semiconductors the current is carried by the ions of the substance.

The current in electronic semiconductors is carried by electrons only. A crystal lattice is a result of atomic interaction. The nature of this interaction is determined by the atoms costituting the crystal. Main part in this interaction is played by the so-called exchange effect in the course of which two atoms exchange electrons and there by establish forces of attraction between them.

Let us discuss the model of conduction in semiconductors using silicon as an example.

The silicon atom has 14 electrons, which are divided among the electron shells in the following way: $(1s^2)(2s^2)(2p^6)(3s^2)\ 3p^2$. The incomplete outer shell contains four electrons. The lattice type of the silicon crystal is the diamond type. The diamond-type lattice is cubic. Every atom is bound to four nearest silicon atoms by covalent bonds, and all of its four valence electrons take part in these bonds. In the ideal lattice all electrons are bound, there are no free carriers, and, correspondingly, the application of an electric field does not result in an electric current. To produce current some electrons must be freed from their bond. To tear an electron away from its bond energy must be expanded. This energy may be supplied to the crystal in the form of the energy of photons, or of particles, or in the form of the energy of thermal lattice vibrations. At room temperature the energy needed to free one electron in silicon is 1.08 eV. Note that the freeing of one electron produces one incomplete bond.

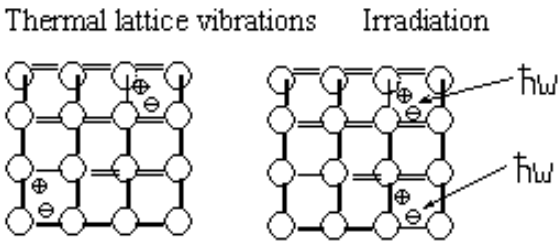


Figure 6.2

The process of bonding a free electron is termed ***recombination***. It is the opposite of the process of freeing a bonded electron. The number of free electrons and vacant (incomplete) bonds are equal.

If electric field $\vec{E}$ is applied to the crystal, free electrons taking part in random thermal motion will be acted upon by the force $\ln \vec{E}$ and will begin to drift against the field. If we denote electron concentration by *n*, their mobility by μ_n, we will be able to write for the electron current density.

$$\overrightarrow{J_n} = \ln \mu_n n \vec{E} = \sigma_n \vec{E} . \qquad (6.4)$$

The incomplete bond can, in fact, move from atom to atom as a result of electron motion. When external electric field $\vec{E}$ is applied the bound electrons will be acted upon by the force $e_n \vec{E}$ and will be moving against the field and occupy vacant bonds. The availability of vacant bonds enables valence electrons to move against the field. This means that their mobility depends on the number of vacant bonds usually called ***holes***. In this way the mass of the valence electrons, too, contributes to semiconductor conductivity.

If the concentration of bound electrons is *N* and their mobility μ_n, their current density is

$$\vec{J} = e_n \mu_n N \vec{E} . \qquad (6.5)$$

Thus, in semiconductors there are ***two kinds of charge carriers***: free electrons and bound electrons.

Therefore

$$j = j_n + j_N = (e_n \mu_n n + e_n \mu_N N) E . \qquad (6.6)$$

The motion of the hole in the direction of the field is equivalent to the motion of a positive charge e^+. Denoting the hole concentration by *p* and their mobility by μ_p, we can write the current density of the mass of bound electrons in the form

$$\vec{J} = e_n \mu_n N \vec{E} = e_p \mu_p p \vec{E} = \vec{J}_p . \qquad (6.7)$$

Holes with the charge $e_p = e^+$ are regarded as ***quasiparticles*** the motion of which is quite equivalent to the motion of valence electrons.

A semiconductor with equal concentrations of electrons and holes ($n = p$) is termed ***intrinsic***. The current density in it is

$$\vec{J} = \sigma\vec{E} = (e_n\mu_n n + e_p\mu_p p)\vec{E}\ . \qquad (6.8)$$

Difference of concentrations of electrons and holes is produced by introducing impurities, also called ***doping***. This leads to extrinsic (impurity) conductivity. To understand the essence of extrinsic conductivity let us consider silicon doped with elements of the fifth and the third groups. Suppose an arsenic atom replace silicon atom in the crystal lattice. The outer shell of the arsenic atom has five electrons. Four of them will take part in forming covalent bonds with nearest silicon atoms. The fifth electron is unable to take part in bonding since all the bonds are filled. At the same time it is acted upon by the neighboring silicon atoms hence the decrease if its bonding energy to the arsenic atom.

For this reason impurities are easily ionized, and a large number of free electrons appear in the crystal – much larger than in pure silicon.

Impurities, which supply electrons, are termed ***donors***. The donor impurity acts only as a source of free electrons.

The concentration of electrons in a donor-doped semiconductor will be much greater than the concentration of holes. Current in such a crystal is carried mainly by electrons by reason of which they are termed majority carriers, while the holes are termed minority carriers. Such a semiconductor bears the name of ***electron***, or ***n-type semiconductor***. The conductivity of an electron-type semiconductor may by written in the form

$$\sigma = \sigma_n + \sigma_p \approx \sigma_n = e_n\mu_n n\,, \qquad (6.9)$$

since $p << n$ and $\sigma_p << \sigma_n$.

Consider now another case. Suppose an atom of indium, or any other group III element, is introduced into silicon. The indium atom has three valence electrons by reason of which one of its bonds with silicon atoms will remain incomplete. To fill this bond it is necessary to transfer to the indium atom one electron belonging to some silicon atom.

An impurity atom, which accepts an electron, is termed ***acceptor***. In a semiconductor, doped with acceptors the hole concentration greatly surpasses the free electron concentration, and because of this its conductivity is mainly of the hole type:

$$\sigma = \sigma_n + \sigma_p \approx \sigma_p = e_p\mu_p p\,, \qquad (6.10)$$

since $n << p$ and $\sigma_n << \sigma_p$. In this case holes are majority carriers and the electrons-minority carriers. An acceptor-doped semiconductor is termed ***hole***, or ***p-type semiconductor***.

5.2 Inhomogeneous semiconductor, p-n junction

We may consider the contact between an electron and hole-type sample of the same semiconductor.

Suppose we have a semiconductor sample with donor $N(r)$ and acceptor $N(r)$ impurities arbitrarily distributed in it. This results in electron and hole concentrations being dependent on the coordinate.

The diffusion current $\overrightarrow{j_D}$ results in charge separation leading to the creation of a space charge and of the accompanying electric field, which bends the energy bands. In thermodynamical equilibrium the Fermi level is independent of the coordinate:

$$F = F_0 . \tag{6.11}$$

The diffusion current $\overrightarrow{j_D}$ is compensated by the drift current $\overrightarrow{j_E}$ therefore

$$\vec{j} = \overrightarrow{j_D} + \overrightarrow{j_E} = 0 . \tag{6.12}$$

Some electrons from *n*-region will go over to the *p*-region, and some of the holes from the *p*-region will go over to the *n*-region, charging the *n*-region positively, and the *p*-region negatively.

An electric field will be established in the *p*-*n* junction area directed from the n-region to the *p*-region.

The resistance of a semiconductor with built-in-fields and space charges measured for opposite current directions will be different. An external voltage applied to a *p*-*n* junction drops almost entirely on the space charge region. Let the external field be directed against the contact field E_c. The external electric field lowers the potential barrier U^c with the result that the electron flow from the n-region increases almost exponentially with the applied voltage. When the direction of the applied voltage is reversed, the electric field raises the potential barrier with result that majority carriers are drawn away from the junction region, and the width of the space charge layer is increased. The current through the junction consists only of minority carriers whose concentration is small, and for this reason the current termed reverse current is also small.

Even though the boundary between two bodies in close contact (welded or fused) is very narrow, nevertheless it is of finite width; hence the designation barrier layer. Investigations indicate that a barrier layer between two semiconductors is formed when one of the semiconductors is a

p-type conductor and the other an *n*-type. Such barrier layer is called ***p-n junctions***, fig. 6.3.

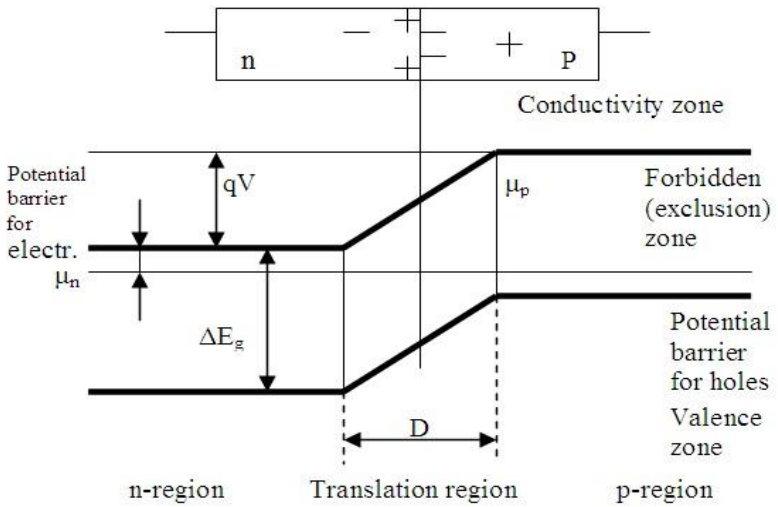


Figure 6.3

Figure 6.4 illustrate the rectification provided by barrier layers. The figure shows a typical current-voltage curve. The left branch of the curve is the characteristic for the reverse current. The forward current increases rapidly with increasing voltage, but the reverse current remains almost constant and has vary low value.

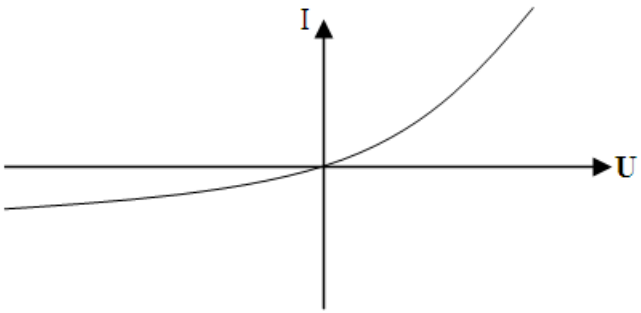


Figure 6.4

6.3 Experimental part

1. Measure the current over a difference of potential applied to *p-n* junction in two cases:
a) for the forward current;
b) for the reverse current.
Put down the data of measurements in table 6.2:

Table6.2

№	Forward current		Reverse current	
	U_a, V	I_a, A	U_b, V	I_b, A
1				
...				
10				

2. Put *I* versus *U* on the graph for the forward and the reverse current.
3. Make analysis of the experimental results.

Control questions

1. Classification of materials according to their conductivity.
2. What is extrinsic conductivity?
3. What is intrinsic conductivity?
4. Draw the energy diagrams for forward and reverse currents of *p-n* junction.

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1. Gevorkjan R.G., Shepel V.V. A Course of General Physics. – Moscow: Higher School, 1967. – 550 p.
2. Koshkin N.I., Shirkevich M.G. Handbook of Elementary Physics. – Moscow: Mir Publishers, 1977. – 272 p.
3. Kireev P.S. Semiconductor Physics. – Moscow: Mir publishers, 1974. – 672 p.

Translator: Lushchin S.P., the reader, candidate of physical and mathematical sciences.
Reviewer: Loskutov S.V., professor, doctor of physical and mathematical sciences.

7. LABORATORY WORK № 86
REGISTRATION OF RADIATION

The aim: measurement of activity of the preparation KCl.
The task: measure the activity of the preparation; determine the mass of radioactive isotope.
Instrumentation and appliances: impulse counter, power source, photoelectron multiplier, lead house.

7.1 Introduction

Radioactivity is called the transformation of unstable isotopes of one chemical element into another isotope of the element.

This process is accompanied with emanation of elementary particles or nuclei.

The main types of radioactive transformations include:
a) α – decay;
b) β – decay (including *K*-catch);
c) spontaneous fission of radioactive nuclei;
d) proton radioactivity.

Number of atoms that are not disintegrated in the radioactive preparation decreases over time, according to ***the law of radioactive decay***.

$$N = N_0 e^{-\lambda T}, \tag{7.1}$$

where N_0 – number of atoms that were in the initial time $t = 0$; N – number of atoms that are not disintegrated in time t; λ – ***the collapse*** was appropriate to the size of the radioactive substance that shows how much of the available atoms disintegrating per unit time.

The time T is the time during which the initial number of atoms decreases twofold. It is called ***the half-life***.

Size T easily identify with the subject:

$$\frac{1}{2} N_0 = N_0 e^{-\lambda T}, \text{ hence } T = \frac{\ln 2}{\lambda} = \frac{0{,}693}{\lambda}. \tag{7.2}$$

Half-life of radioactive substances is in range from $3 \cdot 10^{-7}$ s to $5 \cdot 10^{15}$ years.

7.2 Activity of the preparation and measuring unit

The number of decomposition nuclei of atoms, which is occurred per unit of time called ***the activity of the preparation***. In the international system of units (SI) activity is measured by the number of decay per second. The unit of activity in this system is one disintegration/s Bq (Becquerel). Unsystematic units are also used: decay/min and Curie. Activity unit, called the Curie is defined as the activity of this preparation, which is occurred $3.7 \cdot 10^{10}$ acts of decay per second. Derivatives of Curie unit activity: millicurie (10^{-3} Curie) and microcurie (10^{-6} Curie). To measure the activity of powerful radioactive preparations are used multiples of the Curie units: kilocurie (10^{3} Curie) and mehacurie (10^{6} Curie).

6.3 Connection of the activity of the preparation with a mass of active isotope in it

Radioactive isotopes can be used not only in pure form, but with non-radioactive substances. Therefore the amount of radioactive substance is judged not by weight of the preparation and of its activity.

From the definition of activity of the preparation implies that it is derivative *dN*/*dt*, using the law of radioactive decay, we get:

$$n = \left| \frac{dN}{dt} \right| = \lambda N_0 e^{-\lambda t} = \lambda N \quad . \tag{7.3}$$

The number of atoms of radioactive isotopes in the preparation at any given time is equal to:

$$N = \frac{M}{m} \quad , \tag{7.4}$$

where M – mass of radioactive isotope in the products; m – mass of the radioactive atom.

Mass of one atom can be determined from the ratio:

$$m = \frac{A}{N_A} \quad , \tag{7.5}$$

where A – atomic mass of radioactive isotope, N_A – Avogadro's number.

In view of relations (16.4) and (16.5) equality (16.3) can be written as:

$$n = \frac{\lambda M N_A}{A} \quad . \tag{7.6}$$

Equality (6.6) defines the communication activity of the preparation with a mass of radioactive isotope in it.

6.4 Measurement of the activity of the preparation by absolute method

Method for determining the activity of the source based on the direct account of particles emitted by the preparation, called ***absolute method***.

The number of radioactive particles released into the source of all parties (i.e. the solid angle 4π per unit time) is equal to the number of particles that fall on the counter for two reasons.

At first, in working volume of counter can fall only particles produced by radioactive sources in the direction of the counter window.

At second, the path of the radioactive layer working volume of counter meter flow of radioactive particles partially absorbed in a layer of air between the preparation and counter and also in the material of the counter window.

Let the unknown activity of the preparation through the n and introduce the coefficient K, which shows that the fate of particles released preparation, gets to the counter.

Then

$$n = \frac{n_1}{K} \quad , \tag{7.7}$$

where n_1 – the number of particles that actually got to working volume of counter meter per unit time.

The number of particles n_1 is determined experimentally using radiometric settings. The number of pulses n'' registered in installing per unit of time will be differ from the number of n_1 particles that get into working volume of counter from the preparation. It is related to the fact that the counter possesses tome intervals that are complete unsensitive. This time τ is called ***"dead time" counter***. On the other hand the number of pulses n_1 is some number of pulses n_b, which is caused by various outsider the influence (e.g. cosmic radiation). It is so-called ***counter background***.

On account of "dead time" speed meter account is

$$n' = \frac{n''}{1 - n''\tau} \ . \qquad (7.8)$$

The number of shares registered in the light meter "dead time" and background will be equal

$$n_1 = n' - n_{\phi} \ . \qquad (7.9)$$

Activity meter is calculated by (7.7) subject to (7.8) and (7.9).

6.5 Scintillation counter. Scintillator

Scintillation method for registration of shares is one of the oldest methods. Prevalence after he received a photoelectron multiplier – devices that have the capability to record weak light flashes. ***Scintillation counter*** is a ***scintillator*** and ***photoelectron multiplier (PEM)***.

Scintillators are called such substances under the influence of charged particles emit photons in the visible part of the spectrum. In scintillator flashes of light appear not only under the influence of charged particles, but also under the influence of gamma radiation and neutrons.

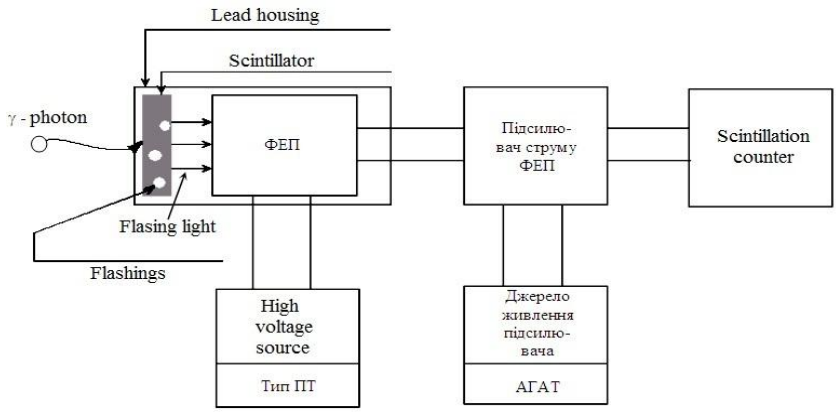

Figure 7.1

The second component of the scintillation counter is ***PEM***. Photons of light get to the photocathode PEM, beat our electrons as a result of photoeffect. Under the influence of external electric field the electrons are di-

rected to dynode PEM, where the secondary electron emission takes place, which resulted in the anode PEM comes in dozens and hundreds of thousands of times more electrons. Thus was born an electrical impulse, which then registers the appropriate electronic circuits.

Work performed at the installation, which consists of scintillation counter, a power source, a lead box. Block diagram of the installation shown in the picture.

7.6 Experimental part

1. Enable the installation.
2. To measure the background count. This should apply to PEM voltage 1250 V. Clear counters in the absence of evidence of radiation source close to the lead box.
3. To measure the speed account. To do next:
a) put the source of radiation lead to an open window box;
b) make the speed dimension account similar measure background counter in a closed box, lead box;
c) results of measurements recorded in the table on account of "dead time" and background. ("Dead time" counter equate $\tau = 5 \cdot 10^{-6}$ s);
d) duration of measurement taken in the mean.

Table 7.1

Duration of measurement t, s	Number of registreited impujses		Background counter $n_{\phi} = \frac{N_{\phi}}{t}$	Rate account of preparation $n'' = \frac{N_{np}}{t}$	Rate accounts due to "dead time" $n' = \frac{n''}{1 - n'\tau}$	Rate account due to background $n = n' - n_{\phi}$	Preparetion activity n
	Without preparation N_{ϕ}	With preparation $N_{\text{пр}}$					

4. Calculated by (6.7) activity of the preparation. (Consider the coefficient K = 0.1, A = 40, $\lambda = 1.3 \cdot 10^{9}$ years).
5. Using (7.6) define the mass M of radioactive isotope in the products.

Control questions

1. What is the physical meaning of radioactivity phenomenon?
2. What processes belong to the main types of radioactive transformations?
3. How does the law of radioactive decay express in mathematical way?
4. What is the physical content of a permanent collapse of λ.
5. What is called the half-life?
6. In what units measure preparation activity?
7. How to determine the activity of the preparation using the law of radioactive decay?
8. What is the connection of activity of the preparation with the number of radioactive isotopes in it?
9. What is the essence of absolute measurement of activity of the preparation method?
10. Why do not all shares issued in the fall to counter preparation?
11. How to calculate the rate accounts including:
a) The "dead time", b) the background count?
12. What is the content ratio *"K"*, included in the formula (16.7) to calculate the activity of the preparation?
13. How to determine the mass of radioisotopes in preparation on its activity?

References

1. Gevorkjan R.G., Shepel V.V. A Course of General Physics. – Moscow: Higher School, 1967. – 550 p.
2. Koshkin N.I., Shirkevich M.G. Handbook of Elementary Physics. – Moscow: Mir Publishers, 1977. – 272 p.

Translator: Loskutov S.V., professor, doctor of physical and mathematical sciences.
Reviewer: Lushchin S.P., the reader, candidate of physical and mathematical sciences.

8. LABORATORY WORK 87.1 DETERMINATION OF CURIE POINT OF FERROMAGNETICS

Purpose of work: determine Curie point of ferromagnetic.
Equipment and supplies: under study sample of ferromagnetic; nichrom electric furnace; multimeter DT-830B-2pieces; multimeter DT-838-1piece; thermocouple XK; power supply AC-DC-4pieces; the primary winding with core

r_1=222 Om, $w_{1=}$2000 coils; secondary winding with core r_2=2000 Om, w_2=17250 coils.

8.1 Shot theory

All substances have magnetic properties. If you put any body in a magnetic field, it will be magnetized. This phenomenon is called magnetization and the bodies are able to magnetize under the influence of an external magnetic field, called the magnet. One of the most important characteristics of magnetization is a vector quantity - magnetization. Magnetization $\vec{j}$ is equal to magnetic moment, per unit volume of a magnet:

$$\vec{j} = \frac{\sum_i \vec{p}_{mai}}{V},$$

where $\vec{p}_{mai}$ is a magnetic moment of the i-th atom (molecule).

For many isotropic magnets vector $\vec{j}$ is directly proportional to the external magnetic field $\vec{H}$:

$$\vec{j} = \chi\vec{H},$$

where χ is a magnetic susceptibility of magnetic substance.

Magnetic induction $\vec{B}$ in the substance, which is located an external magnetic field $\vec{H}$ consists of a magnetic induction of the external magnetic field and of the magnetic induction $\vec{B}$ of own magnetic field of the substance:

$$\vec{B} = \vec{B}_0 + \vec{B}_i = \mu_0 \vec{H} + \mu_0 \vec{j} = \mu_0 \vec{H} + \mu_0 \chi \vec{H} = \mu_0 (1+\chi)\vec{H} = \mu_0 \mu \vec{H}$$

,

where $\mu = 1 + \chi$ is a magnetic permeability of substance.

All substances have certain magnetic properties, which are caused by the movement of electrons in their atoms. Magnetism of substances has different forms: diamagnetism, paramagnetism and ferromagnetism.

Ferromagnetics are materials that have spontaneous magnetization in the absence of external magnetic field. Its magnetic permeability depends on the external magnetic field intensity and it is a large value $\mu >> 1$. Ferromagnetic increase an external magnetic field in hundreds and thousands times and they are related to highly magnetic materials. This phenomenon is called ferromagnetism. Magnetic susceptibility χ of ferromagnetic can achieve values up to:

$$\chi \sim 10^4 \div 10^5 .$$

Experimental investigation of ferromagnetic features was initiated by A.G. Stoletov (1839-1896) in 1878. He obtained the dependence between a magnetization of iron and an intensity of a magnetic field (Fig8.1).

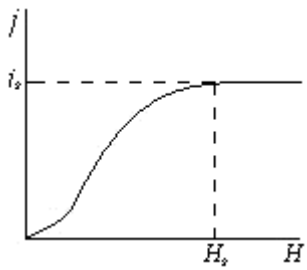

Figure 8.1

When H_s has a given value a magnetization reaches saturation and remains constant. This phenomenon Stoletov had called a magnetic saturation.

Magnetic permeability of ferromagnetic depends on the external magnetic field intensity (Fig.8.2).

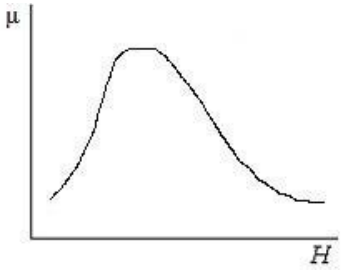

Figure 8.2

The value of μ increases fast with a growth of *H*, reaches a maximum and then decreases, tending to unit. This phenomenon is explained by

$$\mu = \frac{B}{\mu_0 H} = \frac{\mu_0 H + j}{\mu_0 H} = 1 + \frac{j}{\mu_0 H}$$

and when magnetic saturation is reached (*j*=*const*) with increasing of *H* the ratio $\frac{j}{H} \to 0$ and $\mu \to 1$. Maximum value of μ for paramagnetic reaches very large values. For example, for iron $\mu_{max} = 5000$, for permalloy (Fe and Ni alloy) $\mu_{max} = 100000$.

A characteristic feature of ferromagnetic is dependence between magnetization $\vec{j}$ and the previous way of magnetizing of a sample. Magnetization curve for its does not retrace themselves with increase and then decrease of an external magnetic field (Fig. 8.3). This phenomenon is called a <u>magnetic hysteresis</u>.

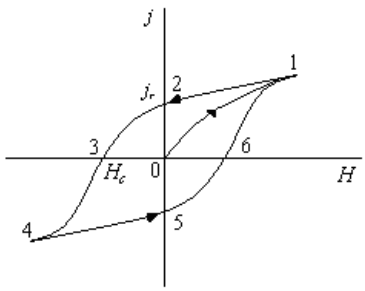

Figure 8.3

In Fig.8.3 a dependence curve of j and H has the form of the loop and is called the hysteresis loop. The segment 0-1 is the magnetization curve of the demagnetized ferromagnetic at the initial state (j = 0). This curve is called the initial magnetization curve. If the magnetic field $\vec{H}$ is reduced from a certain value (point 1) to zero the magnetization $\vec{j}$ falls to a value j_r . This magnetization is called residual. Ferromagnetics in this state are called permanent magnets. To demagnetize completely the ferromagnetic it is necessary to apply the reverse field H_c . This magnetic field intensity H_c is called the coercive force of ferromagnetics. Further increasing of magnetic field intensity in the reverse direction leads to demagnetization of ferromagnetic (3-4). Point 4 corresponds to the saturation magnetization. Segments (4-5-6) correspond to demagnetization and (6-1) corresponds to further remagnetization to saturation of magnetization in the point 1. Thus the obtained closed curve is the hysteresis loop. The area of hysteresis loop denotes the work done by the external magnetic field during one magnetization cycle of a ferromagnetic.

Residual magnetizaton j_r, coercive force H_c, maximum permeability μ_{max} and Curie temperature T_C are the main characteristics of ferromagnetics. These characteristics are different for ferromagnetic materials in a wide range. All ferromagnetics can be presented as two groups.

1. Soft magnetic materials which have small coercive force

$$H_C \sim (0{,}8 \div 8)\ \frac{\text{A}}{\text{M}},$$

a high permeability, narrow hysteresis loop and very small loses of energy at demagnetization. They can be easily magnetized and demagnetized.

2. Hard magnetic materials which have large coercive force

$$H_C \sim (10^4 \div 10^5)\ \frac{\text{A}}{\text{M}},$$

a relatively low permeability, wide hysteresis loop and large loses of energy at demagnetization. They are difficult to magnetized and demagnetized.

Typical soft magnetic materials are silicon steel Fe-Si and soft iron. These materials are mainly used in electric engineering as cores of transformers.

Typical hard magnetic materials are cobalt, steels and various alloys of Fe, Ni, Al, Co. They are used for making permanent magnets.

With increasing temperature the spontaneous magnetization of ferromagnets is reduced. When the temperature reaches a certain critical point T_c, which is called Curie temperature or Curie point, loses its ferromagnetic properties and converted into paramagnetic. Curie's law:

$$\chi = c(T_k - T)^{\gamma},$$

where $\gamma \neq 1$ and takes on different meanings in different temperature ranges.

Ferromagnetic placed in magnetic field change its size during magnetization and demagnetization. This phenomenon is called magnetostriction. It is used to produce supersonic waves.

The classic theory of ferromagnetism was found by French physicist P.Weiss in 1907. According to this theory ferromagnetic material is split into small regions which in the absence of the external magnetic field are spontaneously magnetized to saturation. These regions are called domains.

The total magnetization of the ferromagnetic sample is found to be equal to zero. Consequently the ferromagnetic material is not magnetized in the whole. If a ferromagnetic is placed in an external magnetic field domains whose magnetization is not oriented in the field direction turns its magnetization direction into the magnetizing field. As the result the growth in domain size occurs and ferromagnetic material becomes magnetized (Fig.8.4).

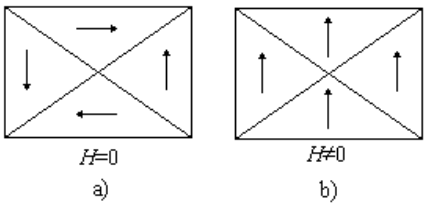

Figure 8.4

At first Einstein and Haas (1915) experimentally proved that ferromagnetism is caused by orientation of own magnetic moment of electrons, i.e. by the electron spins. The ferromagnetism is observed in crystal

materials whose atoms have unfilled inner electron shells with uncompensated spins.

The modern interpretation of ferromagnetism by quantum theory of Frenkel and Heisenberg (1928) is to assume the existence of strong interatomic forces in crystal. These forces are known as exchange forces and have quantum nature. By means of exchange forces the spin magnetic moments of electron are oriented parallel to each other that causes the existence of spontaneous magnetizing regions – domains in the absence of the external magnetic field. Under the influence of the external magnetic field magnetic moments of atoms of neighboring domains tend to be aligned in the direction of the field.

Nowadays semiconductors ferromagnetic are widely used in engineering. These materials are called ferrites. The general formula of ferrites is $MeO \bullet Fe_2O_3$, where Me is the twice-valiant metal (Mn, Co, Ni, Cu, Mg, Zn, Fe, Cd). Ferrites have large magnetic susceptibility and permeability, small coercive forces, small heat loses during magnetization and very high electric resistance (up to ~ 10^4 Ω•m). Ferrite cores are used in radioelectronics, in computers (as cells of memory) etc. The Curie temperature for various ferrites is in the range of 300-600 ˚C.

8.2 Procedure of the laboratory work

1. Connect electrical circuit according to wiring diagram (Fig. 8.5) and fix the junction of the thermocouple in the sample.

2. Set the gauge:

«200V» to multimeter DT-830V; “temperature ^{0}C” on multimeter DT-838.

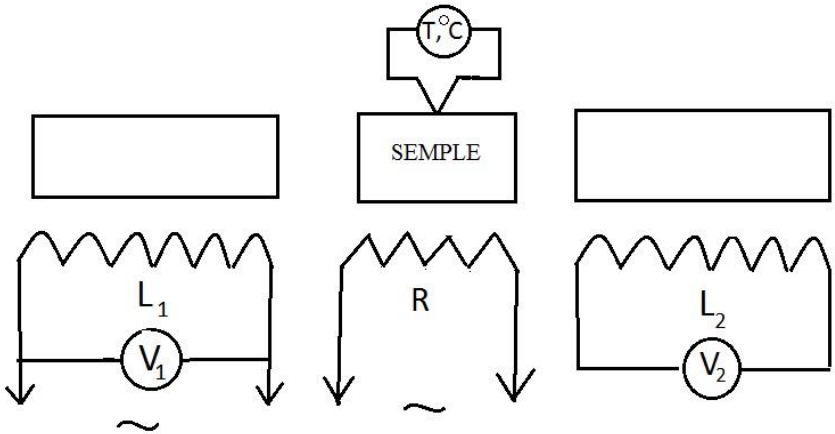

Figure 8.5

3. Turn on the power AC-DC to 220V and install them switch to the provisions of «12V».

4. The heating of sample monitored using indicators of multimeter DT-838. The voltage on the primary and secondary windings monitored by using multimeters DT-830B (V_1 and V_2 respectively).

5. Fixed minimum reading of multimeter V_2 and assign temperature. Turn off the heating of the sample and to measure voltage V_1 and V_2 on the primary and secondary windings and corresponding values of the temperature of the sample until it complete cooling. Enter up these measurements in the table:

Table:

№	T, °C	V_1,V	V_2,V
1 2 3 …..			

6. Plot the graph $U_2 = f(T)$.

7. To hold a tangent to the graph at the falling site of graph and on the intersection it with the axis of abscissa determine the temperature that will correspond the Curie point.

8. To analyze results and make up the conclusion.

Control questions

1. What types of magnetic you know?
2. What are ferromagnetic materials?
3. What is called the Curie point?
4. What's the physical nature of properties in ferromagnetic?
5. What substances do you know with ferromagnetic properties?
6. Wherefore are used ferromagnetic?

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9. LABOR SAFETY REGULATION №62 DURING WORKING IN PHYSICS LABORATORY

9.1 General provisions

9.1.1 People who are allowed to work in the lab:
- members of the department who know their functional responsibilities and have an access to the independent work;
- students who have learnt behavior rules in the lab, who know methods of the performance of the laboratory work and who are well instructed.

9.1.2 Briefing is performed by the member of the department. Every student must confirm his knowledge of the briefing with his personal signature in journal 'Labor safety regulation of students'

9.1.3 Teacher permits students to work in the lab after checking of their knowledge level of the methods of laboratory works performing.

9.2 Safety requirements before starting work

9.2.1 Only instruments in good working condition are used.

9.2.2 Before starting work teacher must check the working condition of the devices and then permit to work.

9.2.3 People who don't take part in the laboratory work don't have an access to the lab.

9.3 Safety requirements during laboratory work

9.3.1 It's not allowed to turn on or turn off the sources of the electrical or light energy without permission of the teacher.

9.3.2 It's not allowed to turn different screws, press any buttons, switches without permission of the teacher.

9.3.3 Students must immediately inform the teacher about all shortcomings of the devices

9.4 Safety requirements after finishing the work

9.4.1Before finishing the work student must consecutively turn off all devices.

9.4.2 Student must check by sight serviceability of the devices. It's necessary to remember that student is responsible for the broken-down devices.

9.5 Safety requirements in case of emergencies

9.5.1 Student must:
- stop working;
- turn all devices off;
- inform teacher about what has happened in the lab.

9.5.2 In case of the fire student must begin to extinguish a fire with available means.
9.5.3 Teacher must call the number 9-101 and notify about accident.