FUNDAMENTALS OF THE ELECTRON THEORY OF SEMICONDUCTORS

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ARTİKEL AKADEMİ: 395

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ISBN 978-625-5674-35-7
1st Edition: December - 2025
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Publisher Certificate No: 19708

Cover and Book Design: Artikel Akademi

PRINTING: Uzunist Dijital Matbaa Anonim Şirketi
Akçaburgaz Mah.1584.Sk.No:21 / Esenyurt - İSTANBUL
Certification No.: 68922

KARADENİZ KİTAP LTD. ŞTİ.
Koşuyolu Mah. Mehmet Akfan Sok. No:67/3 Kadıköy-İstanbul
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CONTENTS

PREFACE

The rapid development of electronics, particularly the achievements in functional electronics, microelectronics, and nanoelectronics—an entirely new field of electronics—opens up new prospects for the future development of fundamentals and circuit design of electronic devices.

A large group of materials with electronic electrical conductivity, whose specific resistance at normal temperature lies between those of conductors and dielectrics, can be classified as semiconductors. The electrical conduction of semiconductors is highly dependent on external energy influences, as well as on extremely small amounts of various impurities present in the semiconductor composition. The control of semiconductor electrical conductivity under the influence of temperature, light, electric field, and mechanical forces forms the basis for the operating principles of thermistors, photoresistors, nonlinear resistors (varistors), strain gauges, and similar devices. The presence of two types of electrical conductivity in semiconductors—electron (n-type) and hole (p-type)—enables the fabrication of semiconductor devices with p-n junctions. These include various types of both high-power and low-power rectifiers, amplifiers, and generators. Semiconductor systems can be successfully employed to convert different forms of energy into electrical current energy. Examples of semiconductor converters include solar cells and thermoelectric generators. It is also possible to achieve cooling of several tens of degrees with the aid of semiconductors. In recent years, the recombination luminescence of electron-hole junctions at low DC voltages has acquired particular significance for the development of signal light sources and information display devices in computing machines. Semiconductors can also serve as heating elements (silicon carbide rods); they can be used to excite the cathode spot in ignitron rectifiers, to measure magnetic field intensity (Hall transducers), and can function as radioactive radiation indicators, among other applications.

The Author

SECTION 1. CLASSIFICATION OF MATERIALS BASED ON THE VALUE OF ELECTRICAL CONDUCTIVITY AND ITS DEPENDENCE ON TEMPERATURE

All substances that exist in nature differ sharply from each other due to their physical properties. These distinctive properties are characterized by certain physical quantities - density, thermal conductivity, heat capacity, heat absorption, etc. One of these characteristic quantities is the electrical conductivity of matter (special resistance). Each substance is characterized by the value of its electrical conductivity σ . The following table shows the value of the electrical conductivity of a number of substances. As can be seen from the table, the special electrical properties of metals such as gold, silver, and copper are 107 $Cm\cdot^{m-1}$, while for ebonite and amber this quantity is 10-14 $Cm\cdot^{m-1}$. Substances with $\sigma \approx \left(10^{7} \div 10^{6}\right)$ a conductivity of $Cm^{\cdot m-1}$ are called conductors or metals, and those with $\sigma \approx \left(10^{-8} - 10^{-17}\right)$ a composition of $Sm\cdot m^{-1}$ are called insulators or dielectrics.

Substances whose electrical conductivity lies within the range between that of metals and dielectrics are called semiconductors. The electrical conductivity of the semiconductors $\sigma \approx \left(10^{-8} \div 10^{6}\right)$ corresponds to the Sm˙m-1 interval.

Table 1

No	Substance	σ, *Siemens / m*	No	Substance	σ, *Siemens / m*
1	Copper (electrolytic)	$6{,}30 \cdot 10^7$	7	Diamond	10^{-10}
2	Silver	$6{,}03 \cdot 10^7$	8	Mica	$1{,}1 \cdot 10^{-11}$
3	Copper	$5{,}62 \cdot 10^7$	9	Pyrex	$1 \cdot 10^{-12}$
4	Gold	$4{,}13 \cdot 10^7$	10	Quartz	$5 \cdot 10^{-13}$
5	Aluminum	$3{,}12 \cdot 10^7$	11	Ebonite	$5 \cdot 10^{-14}$
6	Nichrome	$9 \cdot 10^5$	12	Paraffin	$3{,}3 \cdot 10^{-17}$

A typical comparison shows that the price of electrical conductivity of semiconductors differs significantly from that of metals and dielectrics. Such a designationdoes not provide much information about the specific characteristics of semiconductors. However, when comparing the temperature dependencies of the conductivity (resistance) of metal and semiconductor substances, it is observed that there is a sharp difference between the temperature dependencies of their conductivity (resistance).

When the temperature increases, the electrical resistance of the metals increases by law. For metals, this dependence is expressed as follows:

$$R(t) = R_0(1 + \alpha t), \quad (1)$$

where R0 is the resistance of the metal at a temperature of 0^0C, and Rt is the resistance of the metal at a certain temperature t. In the above expression (1), the quantity α- is the thermal coefficient of resistance, which is approximately equal to 1 for pure metals $\frac{1}{273K}$. Resistance for metals depends on the type of wire, its geometric size, and temperature. In the case of metals, the temperature dependence of the special resistance is also expressed as follows.

$$\rho = \rho_0 (1 + \alpha t) \tag{2}$$

Here ρ_0 is a special resistance of the metal at 0^0 C, ρ_t respectively, and at a certain *temperature t*. The thermal coefficient of resistance (special resistance) for metals is positive and is determined accordingly as follows:

$$\alpha = \frac{dR}{R_0 dt} \quad \text{or } \alpha = \frac{d\rho}{\rho_0 dt} \tag{3}$$

The temperature coefficient of resistance (special resistance) for metals is the relative change of resistance (special resistance) when the temperature of the metal changes one degree in the physical sense. In metals, electric charges are free electrons in an atom that are in weak bond with the nucleus. Semiconductors do not have free carriers.

In contrast to metals, the electrical resistance in semiconductors decreases sharply with the increase in temperature. An empirical relationship between the resistance of semiconductors and absolute temperature at certain temperature intervals is observed as follows: That is, with the increase in temperature, the resistance of the semiconductor decreases by exponential law. This dependence is expressed as follows:

$$R(T) = R_0 e^{\frac{\Delta E}{kT}} \tag{4}$$

where the R_0 quantity is resistance at a temperature of 00 C, *k* is the Bolsman constant, T is the absolute nemerate, and ΔE the quantity is the width of the forbidden zone of the semiconductor. For the special conductivity of the semiconductor (taking $\sigma = \frac{1}{\rho}$) into account that it is, then for the temperature dependence of the conductivity of the semiconductor, we take:

$$\sigma = \sigma_0 e^{-\frac{\Delta E}{kT}} \tag{5}$$

A semiconductor with ΔE_a a given characteristic quantity is also called **activation energy**. For different semiconductors, this quantity is different.

Activation energy is one of the core values that characterize a semiconductor. To determine it, the activation energy of the expression (5) is determined by electron volts from the angle of inclination of the suspension without logarising it.

$$\ln\sigma = \ln\sigma_0 - \frac{\Delta E}{kT}: \;\ln\frac{\sigma}{\sigma_0} = -\frac{\Delta E}{kT}: \;\ln\sigma \sim \frac{1}{T}$$

Figure 1 shows the tem-perature dependence of the resistance for metals and semiconductors, and Figure 2 shows the temperature dependence of the conductivity of the semiconductor (temperature suspension of the conductivity logarithm).

Figures 1 and 2 show the temperature dependence of the resistance for metals and semiconductors and $\ln\sigma -$ the inverse value of the temperature. The conductivity of semiconductors is explained by zone theory. The presence of activation energy for semiconductors ΔE – **indicates that a certain amount of energy must be supplied to the semiconductor in order to create conductivity.** This energy can be carried out by various methods, for example, by heating the semiconductor (giving thermal energy), illuminating matter, by radioactive radiation, by the influence of electric and magnetic fields, by creating high pressure, etc. All this shows that **semiconductors are substances whose electrical conductivity varies strongly under the influence of external factors such as temperature, pressure, external fields, lighting, and radioactive radiation.**

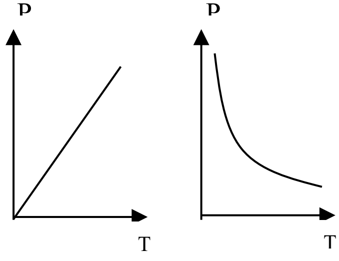


Figure 1. Temperature dependence of the resistance of metal and semiconductor.

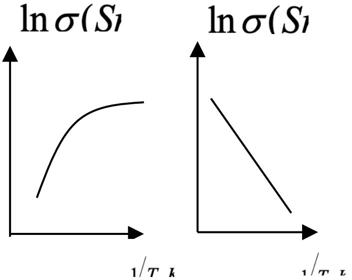


Figure 2 Dependence of the inverse value of temperature $\ln\sigma -$ *in metals and semiconductors.*

Since the conductivity of semiconductors is close to zero at an absolute temperature ($T \rightarrow 0$conditional) and when no additional energy is supplied from the outside in any way, **semiconductors are substances that have conductivity only when** excited. Although there is no difference in principle between semiconductors and dielectrics, the difference between them and metals is very noticeable.

The effect of various factors on the conductivity of semiconductors manifests itself in different ways, depending on the properties and structural properties of the substances. Under the same external influences, the same semiconductor has completely different conductivity, depending on the purity of the monocrystals, the perfection of the crystal, the defects in the crystal, the concentration of different adsorption atoms, etc.

There are two types of semiconductors: ionic and electron-type. In ion-type semiconductors, conductivity occurs with ions, and therefore the process of current passing through the ion-type semiconductor is accompanied by changes in composition and structure. Therefore, this type of semiconductor material is not used in the manufacture of the device. This is due to the fact that they are subject to disintegration (wear) during the current flow process, and the parameters of the device change. The following table shows some semiconductor elements in the table "Periodic System of Elements."

In electron-type semiconductors, the charge carriers are electrons, and therefore the process of transporting material does not occur when passing through an electric current, so the characteristics of devices made of electron-type semiconductors remain unchanged for a long time

Table **2**

Categories **Periods**	**II**	**III**	**IV**	**V**	**VI**	**VII**	
II	**Be**	**B**	**C**	**N**	**O**		
III		**Al**	**Si**	**P**	**S**	**Cl**	
IV		**Ga**	**Ge**	**As**	**Se**	**Br**	
V		**In**	**Sn**	**Sb**	**Te**	**J**	**Xe**
VI			**Pb**	**Bi**	**Po**	**At**	

In the modern era, along with simple semiconductors, semiconductor materials with highly diverse and complex compositions have also been developed. At present, this variety continues to expand. Simple semiconductor substances include 12 elements found in the Periodic Table: **B**-boron, **C**-carbon, **Si**-silicon, **P**-phosphorus, **S**-sulfur, **Ge**-germanium, **As**-arsenic, **Se**-selenium, **Sn**-gray tin (stannum), **Sb**-stibium, **Te**-tellurium, and **I**-iodine. Among the elemental semiconductors, germanium and silicon are the most widely used and the most abundant in nature. Based on these semiconductors, a large number of devices such as semiconductor diodes, transistors, thyristors, etc. are produced. There are numerous binary, ternary, quaternary, and other complex compounds that possess semiconductor properties. The general chemical formula of binary compounds is expressed as AXB8-X, where element A belongs to group x and element B belongs to group (8-x). For example: AI BVII, AIII BVI. Materials such as AgCl, CuBr, KBr, LiF, InSe, GaSe, and others belong to the class of binary semiconductors.

SECTION 2. TEMPERATURE DEPENDENCE OF THE CONDUCTIVITY OF METALS

The foundation of modern ideas about the electrical conductivity of metals and semiconductors was laid by Drude in 1900. This theory was later further developed by Lawrence. Zommerfeld further developed this theory by incorporating elements of quantum statistics. A further development of the theory of electrical conductivity is based on the quantum mechanical theory of a solid object. In the theory of semiconductors, the Drude and Lawrence approach retains its relevance today. To this end, let's take a general look at the basics of classical electron theory.

Many concepts of semiconductor physics are based on the electron theory of metals. On the basis of this theory, characteristic quantities such as the electron conductivity of semiconductors, the validity of freight carriers, etc., are also used for semiconductors in the appropriate order.

In the classical electron theory of metals, the free electron gas in metals is considered to be an ideal gas in molecular physics, similar to that of molecular physics, which is in thermal equilibrium with the ions of the crystal cage. In this case, the specific volume of the gas and the interaction of electrons with each other are not taken into account. The state of each particle is characterized by the sum of six numbers: *x, y, z* coordinates, and $\upsilon_x, \upsilon_y, \upsilon_z$ velocity (or also Px, Py, Pz momentum), or by two $\vec{r}$ and $\vec{v}$ (or $\vec{P}$) vectors. According to the classical theory $r_0 \approx 10^{-15}\,m$, the specific volumes of electrons cannot be taken into account, since $V_0 \approx 10^{-45}\,m^3$ the radius of electrons is in the arrangement and the volume corresponds to it. If we assume that the concentration of electrons $n \approx 10^{28} m^{-3}$ is in the arrangement, then the total volume of free electrons in the volume considered under normal conditions is equal to the total volume of electrons under normal conditions. $b = nV_0 = 10^{28} \cdot 10^{-45} = 10^{-17}$ He took his part. This is a very small number, as it turns out. However, it is important to consider the interaction between electrons. Thus, since the charge of the electrons $e = 1{,}6 \cdot 10^{-19}$ *is Kl*, the Coulomb interaction force between them $r = 10^{-10}$ at a distance m in the crystal lattice is $2 \cdot 10^{-8}$ *N,* in this case, each electron can acquire an acceleration m/sec2 under the influence of such a force, and the potential energy of the interaction between them is within $2 \cdot 10^{22}$ $r = 10^{-10}$ the crystal lattice.It is assumed that it is in the form of ~14 eV at a distance m. In such a convergence, the total energy of the coulomb interaction (repulsion) of the electrons must have a very large value. However, as the experiment shows, the energy of electrons in metals is negative compared to the energy of infinitely spaced electrons. This is due to the fact that, in addition to the coulomb repulsion forces of electrons from each other, they also have gravitational forces reciprocal with their nuclei. The interaction energies of electrons with nuclei are the interaction energies between them. **The electron moving in the crystal lattice in the field created by all the electrons and nuclei is affected by both repulsion and gravitational forces. Under the simultaneous influence of these two types of forces, the movement of an electron gives rise to the idea of free movement.**

Electrons move chaotically in the crystal lattice. During this movement, the electrons collide with the ions of the crystal cage, and as a result, their velocities **change at any moment in**

terms of value and **direction**. A change in the velocity of the electrons causes the kinetic energy of the electron to change. In the case of thermodynamic equilibrium, the temperature of the electron gas must be equal to the tempe-rature of the ions in the cage. This means that as a result of collisions, neither the electron gas to the cage ions nor the cage ions are energized on average.

If we change the temperature of the electron gas, the temperature of the cage must also change due to the exchange of energy between electrons and the ions of the crystal lattice.

SECTION 3. ELECTRON THEORY OF ELECTRICAL CONDUCTIVITY OF SOLID OBJECTS.

In 1900, Drude laid the groundwork for scientific ideas about the electrical conductivity of metals and semiconductors. Lawrence later developed this theory. Zommerfeld brought this theory to a modern level by incorporating elements of quantum statistics. In modern times, the theory of the electrical conductivity of a solid is based on the concepts of quantum mechanics. This theory is now known as the Drude–Lawrence theory. Let's take a general look at the basics of classical electron theory.

Many concepts of semiconductor physics are based on the electron theory of metals. On the basis of this theory, quantities such as electron conductivity, load carrier conductivity, free escape distance, etc., are also applied to semiconductors, respectively.

In classical electron theory of metals, free electrons in the thermal equilibrium with the ions of the crystal cage in the metal are regarded as the ideal gas in molecular physics. In this case, the specific volume of the ideal gas and the interaction of electrons with each other are not taken into account. The state of each particle is divided into six numbers: three x, y, z coordinates, and three $\upsilon_x, \upsilon_y, \upsilon_z$ Velocity (or Px, Py, Pz momentum) is characterized by the sum of momentum. Often the radius of a particle in a crystal $\vec{r}$ and the velocity vector. $\vec{v}$ (or $\vec{P}$ It is made up of clarifications. Radius of electrons according to classical theory $r_0 \approx 10^{-15}\,m$ In the case of the Spurs, the Spurs are in the same league as the Spurs. $V_0 \approx 10^{-45}\,m^3$ In this case, it is practically impossible to calculate the specific volumes of electrons. If the concentration of electrons $n \approx 10^{28} m^{-3}$ If we assume that the electrons in the free electron gas are the total volume of the object. $V^{\backslash} = nV_0 = 10^{28} \cdot 10^{-45} = 10^{-17}$ He might have taken his part. This is a very small amount compared to the total volume. However, the interaction between electrons cannot be overlooked. The charge of electrons $e = 1{,}6 \cdot 10^{-19}$ Kl, in the Crystal Lattice $r = 10^{-10}$ *m* A Close Encounter Between the Forces of Darkness $2 \cdot 10^{-8}$ *N* This is because each electron is under the influence of this force. $2 \cdot 10^{22}$ *m/san2* It is possible that the energy of the interaction between them is within the crystal cage. $r = 10^{-10}$ *m* Əlaqə *~14 eV* If we look at it this way, we can see the importance of interoperability. In this case, the total energy of the Coulomb interaction (repulsion) of the electrons must have a very large value in such an approximation. However, as the experiment shows, the energy of electrons in metals is negative compared to the energy of infinitely spaced electrons. This is explained by the fact that in addition to the coulomb repulsion forces of electrons from each other, they also have gravitational forces reciprocal with their nuclei. The interaction energies of electrons with nuclei are the interaction energies between electrons.

The electron moving in the crystal lattice in the field created by all the electrons and nuclei is affected by both repulsion and gravitational forces. Under the simultaneous influence of these two types of forces, the movement of an electron gives rise to the idea of free movement.

Electrons move chaotically in the crystal lattice. During this motion, the electrons collide with the ions of the crystal cage, and as a result, their velocities change at any moment in **terms of value** and **direction**. A change in the velocity of an electron causes a change in its kinetic energy. In the case of thermodynamic equilibrium, the temperature of the electron gas must be equal to the temperature of the ions in the cage. This means that as a result of collisions, neither the electron gas to the cage ions nor the cage ions are energized on average.

The temperature of the electron gas changes, and the temperature of the cage must also change due to the exchange of energy between electrons and the cage ions. Since the scattering of electrons during collisions with the cage is random, the average velocity of an electron over a long period of time and its average displacement must be zero. Since all electrons are in the same condition, this condition is true for any electron. Thus, since the mean displacement vector of electrons in chaotic thermal motion is zero, the thermal motion cannot create an electric current, i.e., a directed flow of electric charges from any cut-off. Therefore, in order to create an electric current, it is necessary to create a directional movement of the loaders.

Such directional motion of freight carriers can be created due to the influence of electric field, temperature gradient, uneven illumination of the crystal, radiation of the crystal and other factors.

If we create an electric field with an intensity of E *in a metal*, then the force is acting like every electron $\vec{F} = eE$. Under the influence of this force, the electron

$$\vec{a} = \frac{\vec{F}}{m} = \frac{e}{m}\vec{E} \tag{1}$$

It takes the urgency. *The* velocity of an electron over time t is the speed at which an electron is absorbed

$$\vec{\upsilon} = \vec{a}t = \frac{et}{m}\vec{E} \tag{2}$$

If the electron has an initial velocity $\vec{\upsilon}_T$, *then the* velocity of t is also the velocity of the electron.

$$\vec{a}t + \vec{\upsilon}_T = \frac{et}{m}\vec{E} + \vec{\upsilon}_T \tag{3}$$

They can. (3) It is evident from the statement that the accumulations of the velocities of the electrons in the direction of the field decrease, while the accumulations in the opposite direction of the field, on the contrary, increase, and as a result, the whole electron gas takes a directional motion. Thus, in addition to the chaotic motion of electrons, there is also an additional motion of electrons directed against the field.

In an electric field, the entire directional motion of electrons is called drift, and the velocity of this movement υ_d is called the drift velocity. During the period of t-time $\vec{E}$, an electron is formed under the influence of an intense electric field.

$$\vec{\ell}(t) = \frac{et^2}{2m}\vec{E} \tag{4}$$

It changes its location.

In classical electron theory, a change in the velocity of an electron is seen as the result of an electron's interaction with a crystal lattice (atom or ions). In other words, the interaction of an electron with a lattice atom or ion is similar to the collision of particles in mechanics. To characterize the motion of the electron ℓ, the concepts of the average length of the free escape path and the time interval expended on τ it is used. τ The average time interval between two consecutive collisions ℓ is called the average running distance.

The average running distance is related to the average running time as follows.

$$\ell = \upsilon_T \tau \tag{5}$$

This is the υ_T average velocity of the electron's thermal conduction.

From the above judgments, it is possible to determine the average drift velocity.
Since the velocity of motion of the electron at the moment t = 0 is equal to zero, then t = τ instantaneously correspondingly

$$\vec{a}\tau = \frac{e\tau}{m}\vec{E} \tag{6}$$

We can write it. The drift velocity must be equal to the numerical average value of the starting and ending velocities:

$$\vec{\upsilon}_d = \frac{0 + \vec{a}\tau}{2} = \frac{e\tau}{2m}\vec{E} \tag{7}$$

From the above expression, it can be seen that the average velocity of directed motion $\vec{\mathrm{E}}$ is directly proportional to the intensity of the electric field.

The quantitative factor that correlates the drief velocity to the intensity of the electric field is called the validity of electrons and is usually μ denoted by the letter:

$$\vec{\upsilon}_d = \mu\vec{E} \tag{8}$$

Let's take a look at the comparison of the above statements:

$$\mu = \frac{e\tau}{2m} \;;$$

In other words, the **conductivity of electrons is equal to the drift velocity of a single field of electric intensity in numerical terms.**

If there is a **concentration** of electrons n , then the density of the electric current passing through the unit width at a single time:

$$\vec{j} = ne\vec{\upsilon}_d = en\mu\vec{E} = \sigma\vec{E} \tag{9}$$

They can. This expression is differently an expression of Ohm's law. (9) For special electrical conductivity, we take from the expression:

$$\sigma = en\mu \tag{10}$$

Or let's take it:

$$\sigma = \frac{e^2 n\tau}{2m} \tag{11}$$

The expression (11) **was taken by** Drude. If we τ find it from the expression (5) and write it in place of (11)

$$\sigma = \frac{e^2 n\ell}{2m\upsilon_T} \tag{12}$$

We get it.

Ohm's law applies only when the concentration and efficiency of the freight carriers do μ not depend on the intensity of the electric field. These areas **are called weak electrical** fields. However, as the field intensity increases, the moment comes when the concentration and density of the electrons does not remain constant, but changes. These electric fields **are called strong electric** fields. In strong electric fields, deviations from Ohm's law are observed, resulting in the emergence of entirely new effects. Let's take a look at an example of a change of pace. In the deduction of Ohm's law, we assume that at the end of the free escape path, the electron gives its energy completely to the cage when it collides with the ion of the cage. In weak electric fields, the drift velocity is very, very small than the velocity of heat movement, so its duration does not depend on τ the intensity of the electric field $\vec{E}$. However, with the increase in the electric field, the speed of the drift also increases, and the moment comes when it is in the same order as the speed of heat movement. In this case, it is a free escape.

$$\tau = \frac{\ell}{\upsilon_T + \upsilon_d} \qquad (13)$$

The smaller the velocity of thermal movement υ_T, the smaller the temperature of the object, the greater the load-bearing capacities in weak areas, the $\vec{E}$ smaller the values of the crisis areas corresponding to the deviations from Ohm's law.

If we destroy the electric field at any given moment, then the directed motion of the flood of electrons will continue until they completely transfer the additional energy they gain in the field to the crystal cage and complete their movements. This directed motion is interrupted after the average τ time, and the chaotic thermal motion of the electrons is restored. Thus, as can be seen from the judgments, while collisions bring a set of electrons into equilibrium, the electric field disturbs this equilibrium.

The transition of any system from imbalance to equilibrium is called the relaxation process or relaxation, and the time it takes to do so is called the relaxation period. In other words, **when it comes to relaxation, it is understood that the time it takes to restore the disturbed balance for any reason.** Based on the above-mentioned judgments, it can be noted that the period of **free escape is** the period of **relaxation**.

In the International System of Units (ISS), electrical conductivity is measured in simens (Sm) and specific electrical conductivity is measured in simens/meter (Sm/m). In this case, the formula (8) for the unit of power in BS

$$[\mu] = \left(A \cdot san^2\right) kq^{-1}$$

We get it. Units of velocity and electric field intensity are used to calculate the unit of velocity.

$$[\mu] = \frac{m^2}{V \cdot san}$$

Some can be expressed.

SECTION 4. CHARACTERISTIC PARAMETERS OF SEMICONDUCTORS; SPEED OF ELECTRONS, FREE RUNNING DISTANCE, CONDUCTIVITY OF ELECTRONS

As a result of the collision of electrons with the cage, a scattering process occurs. Typically, the scattering of electrons from the cage is random. Therefore, the average velocity of an electron over a long period of time and its average displacement must be zero. Since all electrons in a crystal are in the same condition, this condition is true for any electron. Thus, since the mean displacement vector for electrons in chaotic thermal motion is zero, the thermal motion cannot create an electric current, i.e., a flow of electric charges from any cut-off. In order to create an electric current, a directional movement of the loaders must occur. Such a directed movement of freight carriers can be made possible due to the influence of factors such as the electric field, temperature gradient, uneven illumination of the crystal, and so on.

If we create an electric field of E-intensity *in a metal wire*, then each electron is affected by the force of the electric field $\vec{F} = e\vec{E}$. Under the influence of this force, the electron

$$\vec{a} = \frac{\vec{F}}{m} = \frac{e}{m}\vec{E} \tag{1}$$

He takes the urgency. *The velocity of the electron* gained during the period of time

$$\vec{\upsilon} = \vec{a}t = \frac{et}{m}\vec{E} \tag{2}$$

If there is an initial velocity of an electron $\vec{\upsilon}_T$, then the velocity of the electron at t moment of time is the velocity of the electron.

$$\vec{a}\,t + \vec{\upsilon}_T = \frac{et}{m}\vec{E} + \vec{\upsilon}_T \qquad (3)$$

They can. From this it can be seen that the accumulation of the velocities of the electrons in the opposite direction of the field decreases, while the accumulation in the opposite direction of the field increases, and as a result, as a whole, the entire electron gas receives a certain directional motion. Thus, in addition to the chaotic motion of electrons, there is also an additional motion of electrons directed against the field as a whole.

In an electric field, the direction of the electrons as a whole is called the drift motion, and the velocity of this motion υ_d is called the drift velocity. *During the period of* t-time $\vec{E}$, an electron is formed under the influence of an intense electric field.

$$\vec{\ell}(t) = \frac{et^2}{2m}\vec{E} \qquad (4)$$

It changes its location.

In classical electron theory, a change in the speed of an electron is seen as the result of its interaction with the crystal lattice (atoms or ions). In other words, the interaction of an electron with a lattice atom or ion is likened in mechanics to the collision of particles. In this case, it is assumed that the electron travels the distance between two successive collisions like a free particle, without being affected by the cage and the rest of the electrons. To characterize the motion of an electron ℓ, the concepts of the average length of the free escape path and the time interval expended on τ it are introduced. **Here τ is the average time interval between two consecutive collisions, ℓ**

and the average running distance is the average running distance.

Of course, the average running distance is the average running time.

$$\ell = \upsilon_T \tau \tag{5}$$

Someone has to be in a relationship. Here υ_T is the average velocity of heat movement. From the above judgments, it is possible to determine the average drift velocity. *Since the velocity of motion of the electron at the beginning t=0* is equal to zero*, t=* τ instantaneously corresponds to zero.

$$\vec{a}\tau = \frac{e\tau}{m}\vec{E} \tag{6}$$

We can write it. The drift velocity must be equal to the numerical mean of the beginning and end velocities: i.e.

$$\vec{\upsilon}_d = \frac{0+\vec{a}\tau}{2} = \frac{e\tau}{2m}\vec{E} \tag{7}$$

From this expression, it can be seen that the average velocity of the directed motion $\vec{\mathrm{E}}$ is directly proportional to the field intensity of the electric field.

The quantitative factor that correlates the drief velocity to the intensity of the electric field is called the validity of electrons and is usually μ denoted by the letter:

$$\vec{\upsilon}_d = \mu\vec{E} \tag{8}$$

To compare (8) and (7)

$$\mu = \frac{e\tau}{2m}\ ; \tag{8a}$$

We get your expression. From this it can be seen that **the efficiency of the electrons is equal to the rate of drift gained by the electron in a field of uniform intensity in numerical**

value. If there is a concentration of electrons n , then the electron flow passing through the single node of the sample at a given time is the density of the electric current:

$$\vec{j} = ne\vec{\upsilon}_d = en\mu\vec{E} = \sigma\vec{E} \tag{9}$$

They can. This equation is the expression of Ohm's law in a differential way. A special electrical conductivity of the last expressions

$$\sigma = en\mu \tag{10}$$

and

$$\sigma = \frac{e^2 n\tau}{2m} \tag{11}$$

We get it. The last expression was first **taken by Drude**. If we τ find the expression (5) and replace it with (11), we get it for conductivity;

$$\sigma = \frac{e^2 n\ell}{2m\upsilon_T} \tag{12}$$

SECTION 5. A WEAK AND STRONG ELECTRIC FIELD. RELAXATION DURATION

It is derived from classical electron theory that Ohm's law is paid only if the concentration *and validity* of the loaders do μ not depend on the intensity of the electric field. This field is **called** a **weak electric field**. However, as the intensity of the electric field increases, there is a moment when the concentration and charge of the electrons does not remain stable and begins to change depending on the field. These electric fields **are** called **strong electric** fields. In the case of strong electric fields, there are exceptions to Ohm's law, which results in the emergence of entirely new phenomena. Let's take a look at this as an example of a change of scenery. In the deduction of the expression of the Ohm law, it is assumed that at the end of the free escape path the electron gives its energy completely to the cage in a collision with the ion of the cage. In weak electric fields, the drift velocity is very, very small than the velocity of heat movement, so τ its duration does not depend on the intensity of the electric field $\vec{E}$. However, with the increase in the electric field, the speed of the drift also increases, and the moment comes when the drift speed is the same as the speed of the thermal movement. In this case, it is a free escape.

$$\tau = \frac{\ell}{\upsilon_T + \upsilon_d} \tag{1}$$

It decreases accordingly, which leads to a decrease in conductivity, as well as a decrease in electrical conductivity.

If the electric field disappears at any given moment, then the directed movement of the flood of electrons will continue until they completely transfer the additional energy they gain in the field to the crystal cage and complete their movements. This directed motion is interrupted after an average τ time, and the mixed (chaotic) thermal motion of the electrons is restored. Thus, while collisions bring a set of electrons into equilibrium, the electric field disturbs this equilibrium**.**

The transition of any system from a state of imbalance to equilibrium is called the relaxation process or relaxation, and the time it takes to do so is called the relaxation period. In other words, **when it comes to relaxation, it is understood that the time it takes to restore the disturbed balance for any reason. In other** words, **the time to relax is the time to relax.**

In the International System of Units (BS), electrical conductivity is measured by simensis (Cm), and special electrical conductivity is measured by simens/meter (*Cm/m).* It is measured. In this case, we will get the following for the unit of execution in BS:

$$[\mu] = \left(A \cdot san^2\right) kq^{-1}$$

Units of velocity and electric field intensity are used to calculate the unit of velocity.

$$[\mu] = \frac{m^2}{V \cdot san}$$

Someone can express it.

SECTION 6. CRYSTAL CRYSTALS. TRANSYLATION PERIOD

All solids in nature are divided into two groups: crystalline and amorphous substances. Most solid semiconductors and solid metals have a crystalline structure. The set of atoms that make up these substances is arranged in a certain order in space. When we talk about the orderly arrangement of atoms in space**, we understand the properties of spatial periodicity** or **translation symmetry**. The concept of a crystal lattice is used to describe these regularities. A crystal cage can be thought of as a three-dimensional grid. Atoms (ions or molecules) are located at the node points of this network. It is possible to imagine three $\vec{a}_1$ $\vec{a}_2$ vectors that are not on the same plane $\vec{a}_3$, and when you move these vectors along the length of the crystal by the same number of their exact times, they overlap (repeat) with themselves. In this case, since the effect of thermal motion and each real crystal are limited, it is not necessary to take into account the presence of outer surfaces. $\vec{a}_i(i=1,2,3)$ The directions of the vectors can be selected in different ways in the cage. On the other hand, $\vec{a}_i$– when you move a crystal as many vectors equal to the exact times of the crystal, it $\vec{a}_i$– overlaps on its own.Vectors are the smallest vectors that pay the periodicity in the selected direction $\vec{a}$. In such a selection, $\vec{a}_i$ the vectors are called **translation, scale,** or fundamental vectors, as well as the **translation period** of the crystal lattice. $\vec{a}_i$ A parallel piped element **or** crystalline core **built on three vectors** is called a crystal core. $\vec{a}_i, \vec{a}_2$ And $\vec{a}_3$ let us orient the vectors in the positive directions of the x, y, and z axes in the right coordinate system. He is right on the right side of the

In the coordinate system, the vector product is the volume of the elementary nucleus.

$$\Omega_0 = \left(\vec{a}_1 \left[\vec{a}_2 \vec{a}_3\right]\right) = \left(\vec{a}_3 \left[\vec{a}_1 \vec{a}_2\right]\right) = \left(\vec{a}_2 \left[\vec{a}_3 \vec{a}_1\right]\right) \qquad (1)$$

Someone can express it.

The arrangement of atoms in the elementary nucleus is different for different matters. Atoms are located at the vertices, faces, and intersections of the diagonal of the parallelpipe. If we were to put a large number of such elementary nuclei together in an orderly manner, we would get an ideal monocrystal.

The simplest linear cage is used to determine the geometric properties of a crystal cage. A linear cage is also known as **a one-dimensional** cage. In such a cage, the particles are arranged periodically along an infinite line. Such a cage can be achieved by moving an atom or group of atoms along a straight line a as sequentially as many as the same pieces. In the case of a linear lattice, we have only one $|\vec{a}_1| = a$ translation vector, and the volume of such a lattice Ω_0 is equal to the length of this segment.

$\Omega_0 = a$

Figure 1 shows three different linear cages. The black and white circles represent different types of atoms.

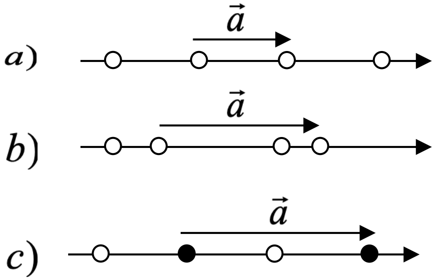
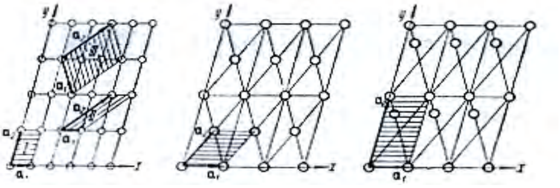


Figure 1. A linear one-dimensional cage

As can be seen from the condition of payment of periodicity , a in the case of) the linear lattice consists of one, b and in c the case of) and) in the case of two atoms. Accordingly, a the cages are simple or **primitive**b) and c the cages are called **complex** cages. Figure 2 shows the plane cages.

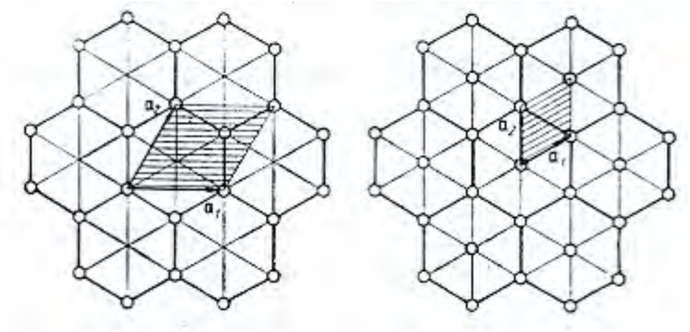
If the principal $\vec{a}_i$ vectors are selected in such a way that any translation of the lattice n_{i-} can be described by integer values $\sum_i n_i \vec{a}_i$, then the $\vec{a}_i$ elementary core on which it is built is called a primitive core. A lattice in the form of 2, a is a simple lattice. Another simple lattice in the form of 2,b is described.



a) b) c)

Figure 2. Planar lattices

If we place the same type of atoms at the intersections of the diagonals of the parallelograms in the lattice of this lattice in the form of 2,a, we get the lattice in 2.b. In such a lattice, the primitive nucleus can be selected as a striped part, and if we shift the atoms at the intersections of the diagonals in the same way, then we get a primitive nucleus with two atoms, as described in Figure 2,c. If we place atoms of different types at the intersections of parallelograms in the form of 2,b, a complex cage is obtained, since in this case the nodes of the cage are not equivalent.



a) b)

Figure 3. Symmetrical Plane Cages

A symmetrical plane lattice is depicted in Figure 3.a. $\vec{a}_1$ A $\vec{a}_2$ primitive nucleus, which is built on vectors, consists of two atoms. However, if we place the same type of atoms at the intersections of the diagonals of hexagons, we get a simple lattice (Figure 3,b).

SECTION 7. CRYSTALLINE SYSTEMS. BRAVE CAGES

The atoms that make up solid bodies arrange in space with a certain regularity, forming a crystal lattice. The basis of the crystallographic cages is a geometric figure in the form of a parallelepiped. In the science of crystallography, it has been accepted that the lengths of three sides intersecting on one a, b, c side of a parallel pipe, and the angles between these sides $\overset{\wedge}{ac} = \alpha,\ \overset{\wedge}{bc} = \beta$, are indicated by and with and $\overset{\wedge}{ab} = \gamma$ (Fig. 1).

In the case of a three-dimensional metallic cage, the tongues and angles of the crystal core a, b, c are denoted by the tongues and angles α, β, γ . Depending on the value of the crystal core, tongues, and angles, the crystals are divided into 14 possible types of crystal structures and 7 syngonia. The 14 crystal cages that are part of these seven crystal cages are called **Brave cages.**

1. **A Regular or Cubic Syngon** (Fig. 1). In this case, the angles and sides are equal $\alpha = \beta = 90^0$ to each other and are in harmony $a = b = c$ with each other. Three types of cages are possible in this system: a simple cage (Figure 2.a), a volume-centered cage (Figure 2.b), and a surface-centered cage (Figure 2.c).
2. **Tetragonal or quadratic syngony.** In this case, the seat of the elementary core is a rectangular parallelepiped with a square seat (Fig. 3) $\alpha = \beta = \gamma = 90^0$ and $a = b \neq c$. In this system, there is a simple (3 a) and volume-centered (Fig. 3 b) cage.

3. **Rhombic or orthogonal system**. In such a lattice $\alpha = \beta = \gamma = 90^0$, $a \neq b \neq c$ i.e., the elementary core is a rectangular parallelpiped with different languages. There are four types of cages here (Figure 4): simple (a), base-centered (b), volume-centered (d), and surface-centered (c).
4. **Monoclonal system**: $\alpha = \beta = 90^\circ$, $\gamma \neq 90^\circ$ and $a \neq b \neq c$. In this system, the elementary core mail is parallelogramed, with two pairs of faces rectangular and one pair of faces parallelogram. In this syngon, two types of cage are possible: simple (a) and base-centered (b) cage (Fig. 5).
5. **Rhombohedric or trigonal syngony.** $a = b = c, \alpha = \beta = \gamma \neq 90^0$ It is *less than 1200.* In this case, the primary core is the rhombohedrk. There is only one type of primitive cage in this syngon (Fig. 6).
6. **Hexagonal syngony** (Fig. 7). In this system $\alpha = 120^0$, $\beta = \gamma = 90^0$. $a = b \neq c$ . . Here, three simple nuclei together form a hexagonal prism, which is the elementary core of syngony.
7. Triglycerides Synagogues. In this system, all languages and angles are different, i.e., $\alpha \neq \beta \neq \gamma$. $a \neq b \neq c$ There is only one type of cage **here (**Fig. 8).

Often there are structures in real crystals that cannot be described with a Brave cage. Such structures are depicted by several Brave cages dressed (slid relative to each other) clad inside each other.

Brave Cages

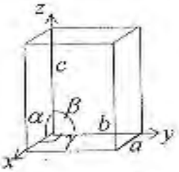
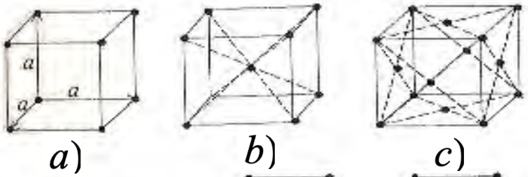
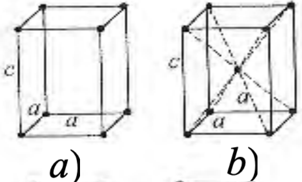


Figure 1



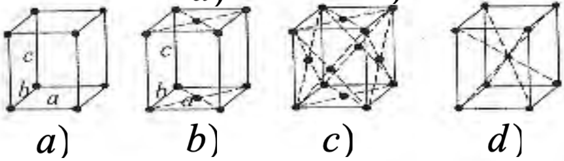
a) b) c)

Figure 2



a) b)

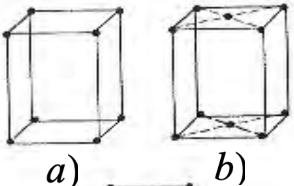
Figure 3



a) b) c) d)

Figure4

Figure 5



a) b)

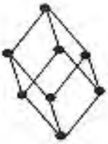


Figure 6

Figure 7

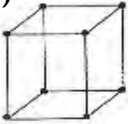


Figure 8

SECTION 8. A MODEL FOR THE CONDUCTIVITY OF SEMICONDUCTORS IMAGINE. AN UNDERSTANDING OF THE HOLES

The formation of a crystal is formed on the basis of the interaction of the l-cage atoms, and the nature of this interaction is determined by the structure of the electron layers of the atoms that make up the crystal. In this case, the main role is played by the exchange effect, as a result of which the atoms interacting during the formation of a crystal lattice can exchange electrons with each other and give or receive electrons. This process leads to the formation of gravitational forces between them. If a crystal lattice is made up of atoms of the same element, it is called homopolar bonds because these bonds are formed between the same atoms . Homopolar bonds are primarily involved in valence electrons, so it is also called covalent bonding. The strongest covalent bond occurs when atoms communicate with pairs of electrons with spins directed opposite each other. It seems to me that the covalent bond must have the property of saturation. The presence of the third electron cannot strengthen the bond, because then the Pauli principle is violated.

This property of a covalent or electron pair bond is derived from the Pauli principle, and for the given case, it can be expressed as follows: two electrons with the same spin projections cannot be located in the same region of the space between atoms. Examples of covalent-related substances include diamond, silicon, germanium, etc.

If the crystal lattice is formed as a result of the interaction of atoms of different elements, it shifts towards the atom that has more electrons in the oblast valent zone of the electron cloud with the maximum density, as a result of which this atom is converted into a negatively charged ion, and the other atom is converted into a positively charged ion, and the Coulomb interaction force plays a key role between them, such a bond is called ion bonding, respectively. Ion bond is found in alkaline-hologenic salts (NaCl, KCl, LiF, etc.) It makes itself more self-explanatory. Ion bonding can also be viewed as a limit state of covalent bonding. In general, it is never possible to talk about a single communication, it can only be said that any communication prevails. Therefore, when we are talking about sulfides or oxides of the elements of the second group, for example, we can say what percentage of the bond is ion, and what percentage belongs to another type. The other limit of the exchange interaction occurs in metallic communications. In the crystal cages of metals, some of the valence electrons, which are very weakly bonded with their atoms, do not belong to a specific atom, but belong to the crystal cage as a whole, and are collected. Even the electron gas in the crystal lattice, which behaves as a kind of ideal gas, creates metallic bonds and, as the definition suggests, is mainly characteristic of metals. In any case, there can be no sharp boundary between these three connections. Organic crystals exhibit weaker bonds as a result of the Van der Waals interaction, also known as molecular bonding. In such crystals, the density of the electron cloud within the cage can change at any time as a result of fluctuations in different parts, even if it is small, which leads to the formation of a dipole moment in that part. The interaction of such instantaneous dipole moments ensures the stability of the crystal as a whole.

Thus, all of the types of communication that we see in real crystals can manifest themselves to varying degrees at the same time, but since always one of them plays a superior role, the properties of the crystal are largely determined by it. Covalent communication plays a decisive role in the formation of semiconductor properties, which are our main research objects.

Let us analyze the silicon crystal example of semiconductor electrical conductivity. Germanium and silicon, which have a wide range of applications, are mainly simple semiconductors with covalent bonds, with a diamond-type crystal coefficient (Figure 1.23,a). Each crystal structure is characterized by the number of closest neighboring atoms located at equal distances (d) from the atom taken. This number is called the coordinate number and is denoted by z. For example, a simple cube for a $z = 6,\ d = a,$ crystal is a volume-centric cube for a crystal.

$$z = 8,\ d = \frac{\sqrt{3}}{2}a.$$

The elementary lattice of a diamond crystal groove can be described by a Brave cube lattice centered on two surfaces that are slid diagonal for about a quarter of it relative to each other (Figure 1). In such a lattice, each atom has four closest neighbors (z = 4). As can be seen from the picture, in a cubic crystal lattice, an atom falls on each elementary nucleus $8 \cdot \frac{1}{8} + 6 \cdot \frac{1}{2} + 4 = 8$, it should be noted that the elementary core in the lattice can also be represented as a cube (Fig. 1,c), which is an atom in the center of the cube and four atoms at the vertices. Each of these atoms has two atoms.

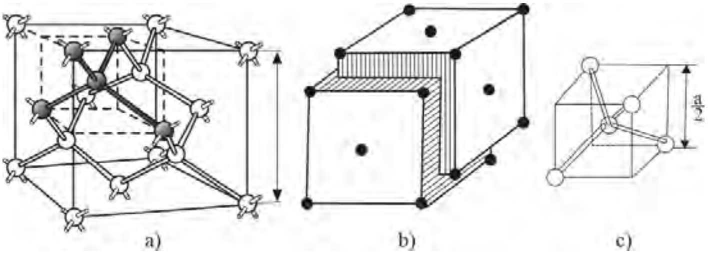
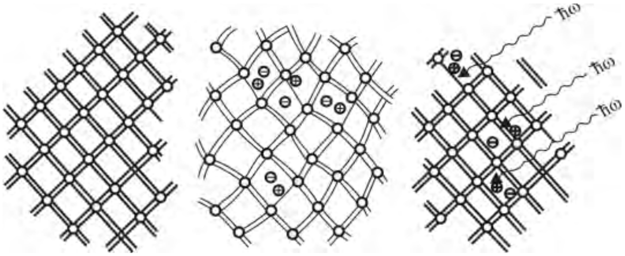


Figure 1. Diamond Crystal Crystal Lattice

A diamond-like silicon atom has 14 electrons and is divided into electron layers as $(1s^2)(2s^2)(2p^6)(3s^2)3p^2$. The third layer, which is not fully filled, has 4 valence electrons. As we have noted, silicon has a diamond-type crystal structure, and each atom located in the center of the tetrahedrin in such a cage is connected to its electron pairs with the other four atoms that are closest to it. Thus, the four valence electrons of each silicon atom are involved in the formation of the tetrahedric covalent bond. Since such a crystal does not have free carriers, it does not conduct an electric current. In order for a crystal to have electrical conductivity, it is necessary to tear off some of the electrons involved in the covalent bond by any means (quantum, thermal energy, irradiation, etc.) and release it inside the crystal lattice. In the energy diagram, let's refer to the energy of the electron involved in the communication *as EV, and* the energy of the electron disconnected from the communication *with ES*. As you can see from this diagram, the energy used to break the connection is *ES-EV*. This energy is equal to 1.08 eV for silicon. When an electron is disconnected from the bond, an incomplete bond is formed.

Figure 2 shows the ideal crystal diagram (a), the formation of a free electron as a result of the thermal dances of the crystal cage (b), and the absorption of the corresponding energetic photon (c). A covalent bond moves chaotically on an electron crystal that has been torn from the bond.

If the electron approaches the place where it is disconnected, it can send its energy into the cage or radiate it in the form of a photon and reunite with the atom. This process **is** called **recombination**. This process is the opposite of the process of separation of the bonded electron from the bond. In the process of generation, a free electron is directly generated, while in the process of recombination both carriers are destroyed.



a) b) c)

Figure 2. *Formation of conductivity due to lattice vibrations and the excitation of semiconductors*

In a pure semiconductor, the number of free electrons and incomplete bonds is the same, and therefore the electroneutrality of the crystal as a whole is not disturbed. If we $\vec{E}$ apply an external electric field to such a crystal, each free electron is affected by the force of this field $e_n\vec{E}$, so they gain a drift velocity in the opposite direction of the field, resulting in a density of

$$\vec{j}_n = e_n \mu_n n \vec{E} = \sigma_n \vec{E} \qquad (1)$$

Some of them create a set of electrical currents. Here the concentration of the n-electron is the strength of the μn-electrons. While the concentration of electrons in metals does not depend on external factors such as illumination, thermal energy, radiation, etc., since these factors play a key role in semiconductors, their electrical conductivity can vary over a wide range. However, there are other mechanisms of conductivity in semiconductors. Indeed, as a result of the motion of the electron, the broken bond can change its position from one atom to another, and this movement occurs in a manner similar to the chaotic motion of an electron. $\vec{E}$ When applying an external electric field, the movement of electrons opposite the field (drift motion) prevails, and they are able to occupy empty contact points in the direction of their motions. If all the connections are complete in ideal crystals, the movement of the connected electrons would be impossible according to Pauli's principle. The presence of broken communication points allows electrons to move opposite the field, thereby allowing a set of valence electrons to participate in conduction. In this case, the validity of the bonded electrons should depend on the number of vacancy sites (the greater the number of broken bonds in the crystal, the more likely they are to be captured by neighboring bonded electrons). If we denote the number of bonded electrons *by N, and* their conductivity μ_N, then the corresponding current density generated by them:

$$\vec{j}_N = e_n \mu_N N \vec{E} \qquad (2)$$

They can. There are two types of charge carriers in semiconductors - free electrons and bonded electrons. This is why the final sentence of the sentence is:

$$\vec{j} = \vec{j}_n + \vec{j}_N = (e_n \mu_n n + e_N \mu_N N)\vec{E} \qquad (3)$$

This is expressed by the sum of the currents. The movement of the connected electrons in the opposite direction of the field gives rise to the movement of the broken communication points in the direction of the field, which is equal to the charge of the electrons and is as strong as the motion of the e+-positive charge in the field (Figure 3). In this case, it should be borne in mind that the **positive charge** $e^+\vec{E}$ **is not due to the effect of the force acting** on it (the force cannot act in vain!), but because of **the movement of the electron opposite to the field, it changes its position in the direction of the field.** If we denote the number of broken connections (vacancies) p and their validity **by μP**, we get the corresponding current density for them:

$$\vec{j}_N = e_N \mu_N N \vec{E} = e_p \mu_p p \vec{E} = \vec{j} \quad (4)$$

In the method of Brillouin zones, the mobility μP should not depend on p. Therefore, the motion of bound electrons in the direction opposite to the field can be replaced by the motion of an elementary positively charged quasi-particle moving in the direction of the field. This quasi-particle is conventionally called a **hole**. The conductivity arising due to holes is called **hole conductivity**. The parameter P denotes the concentration of holes, μP is the mobility of holes, and $e = e^+$ is the charge of the hole. Free electrons and holes generated in the crystal lattice due to any external factor during the generation process are called intrinsic charge carriers, and the conductivity they produce is called **intrinsic conductivity.**

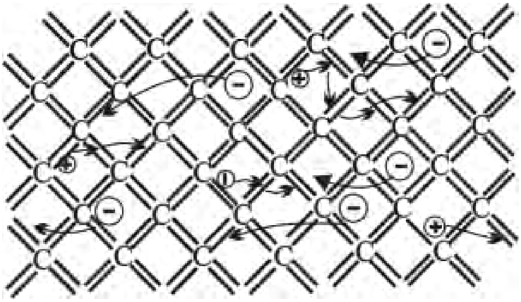


Figure 3. In the field of electricity and electricity
The Movement of the Vacancy

Semiconductors whose conductivity is generated by proprietary carriers are called semiconductors.In specific semiconductors, the concentrations of holes and electrons are the same: n = p, then the final current density

$$\vec{j} = \sigma \vec{E} = (e_n \mu_n n + e_p \mu_p p)\vec{E} = (\sigma_n + \sigma_p)\vec{E} \quad (5)$$

Some can be expressed. If we take the validity as a scalar quantity and mark it by their ratio for electrons and holes, $b = \left|\mu_n\right| / \left|\mu_p\right|$ we get for the electrical conductivity of specific semiconductors:

$$\sigma = e_n \mu_n n + e_p \mu_p p = e_p p \mu_p \left(1 + \frac{\mu_n}{\mu_p} \right) = e_p p \mu_p (1 + b) \tag{6}$$

SECTION 9. INTRINSIC CONDUCTIVITY IN SEMICONDUCTORS

If we apply an intense external electric field to a semiconductor crystal $\vec{E}$, then since the force of the field affects each free electron $e_n\vec{E}$, they gain a drift velocity in the opposite direction of the field, resulting in a current density.

$$\vec{j}_n = e_n \mu_n n \vec{E} = \sigma_n \vec{E} \qquad (1)$$

Some of them create a set of electrical currents. Here the concentration of the *n*-electron is the strength of μn-them. While the concentration of electrons in metals does not depend on external factors such as illumination, thermal energy, radiation, etc., since these factors play a key role in semiconductors, their electrical conductivity can vary over a wide range. In addition to this, there are other types of semiconductors that are also used in semiconductors. Indeed, as a result of the movement of the electron, the broken bond can change its position from one atom to another, and this movement occurs in a manner similar to the chaotic motion of an electron. $\vec{E}$ When applying an external electric field, the movement of electrons opposite the field (drift motion) prevails, and they are able to occupy empty communication positions in the direction of their movements. If all the connections are complete in ideal crystals, the movement of the connected electrons is impossible according to the Pauli principle. The presence of broken communication points allows electrons to move opposite the field, thereby allowing a set of valence electrons to participate in conduction. In this case, the validity of the connected electrons should depend on the number of vacant positions. If we denote the number of bonded electrons with N, and their conductivity μ_N , then the corresponding current density is given to them:

$$\vec{j}_N = e_n \mu_N N\vec{E} \tag{2}$$

They can. Thus, semiconductors involve two types of charge carriers - free electrons and bonded electrons. This is the reason why the final density of the

$$\vec{j} = \vec{j}_n + \vec{j}_N = (e_n \mu_n n + e_N \mu_N N)\vec{E} \tag{3}$$

The movement of the related electrons in the opposite direction of the field gives rise to the movement of the broken communication points in the direction of the field, which is equal to the charge of the electrons and the movement of the e+-positive charge in the field (Figure 2). In this case, it should be taken into account that **the positive charge changes its position in the direction $e^{+}\vec{E}$ of the field as a result of the opposite movement of the electron as a result of the force exerting it. If we denote** the number of broken bonds (vacancies) p, and their validity by μP, we can write them for the corresponding current density:

$$\vec{j}_N = e_N \mu_N N\vec{E} = e_p \mu_p p\vec{E} = \vec{j} \tag{4}$$

Thus, the motion of the bound electrons in the opposite direction of the field can be replaced by the motion of an elementary positively charged quasi-particle moving in the direction of the field.

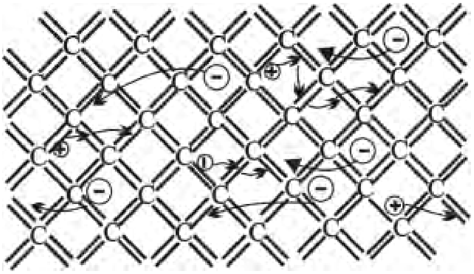


Figure 2. The Movement of Electricity and Vacancy in the Field of Electricity

This quasi-particle **is called a hole**. The amount of time that is generated by **the calculations is called the calculus**. *P-quantity* is called the concentration of holes, μP is the density of holes, and *e=e+* is the charge of the hole. Free electrons and holes formed in the crystal lattice due to any external factor are proprietary **carriers, and the** conductivity created by them is called proprietary conductivity.

Semiconductors whose conductivity is generated by proprietary carriers are called proprietary semiconductors.

In specific semiconductors, the concentrations of holes and electrons are the same: *n* = *p*, then the final current density

$$\vec{j} = \sigma\vec{E} = (e_n\mu_n n + e_p\mu_p p)\vec{E} = (\sigma_n + \sigma_p)\vec{E} \tag{5}$$

Some can be expressed. If we take the validity as a scalar quantity and denote their ratio for electrons and holes

$b = |\mu_n| / |\mu_p|$, we get for the electrical conductivity of special semiconductors:

$$\sigma = e_n\mu_n n + e_p\mu_p p = e_p p\mu_p\left(1 + \frac{\mu_n}{\mu_p}\right) = e_p p\mu_p(1 + b) \tag{6}$$

SECTION 10. EXTRINSIC CONDUCTIVITY IN SEMICONDUCTORS

It is clear from the study of the conductivity of special semiconductors that the concentration of electrons and holes in special semiconductors is the same. However, in some cases, this condition is not met. This difference between the concentrations of electrons and holes is created by the introduction of extraneous element atoms into the semiconductors. In this case, the atoms of the outer element are called supernovae. The process of getting into the habit of getting into the habit is called a slippery slope. To understand the essence of this conductivity, let's look at the cases in which group IV element germanium is adjacent to the atoms of group V and group III elements.

Suppose we have replaced one of the atoms in the germanium crystal lattice with a phosphorus atom of group V (Figure 1). As can be seen from the arrangement of phosphorus' electron layers ($P^{15}(1s^2)(2s^2)(2p^6)(3s^2)(3p^3)$), two of its five valent electrons are at the level of 3s and three are at the level of 3p. Four of them are involved in covalent communications, and the fifth, since there is no empty space in the communications, belongs only to the phosphorus atom itself and remains in the orbit around it. This means that it takes energy to release this fifth valent electron of phosphorus.

For this reason, the admixture atoms can be easily ionized, and as a result of the easy ionization of the five-valent phosphorus atoms included in the four-valent germanium cage, a very large number of free electrons are formed.

These types of electrons that can be donated by themselves are called **donor-type supplements**. Phosphorus atoms that lose their electrons are converted into positively charged ions. However, these ions are not involved in conduction, and their role is mainly limited to supplying the crystal with free electrons.

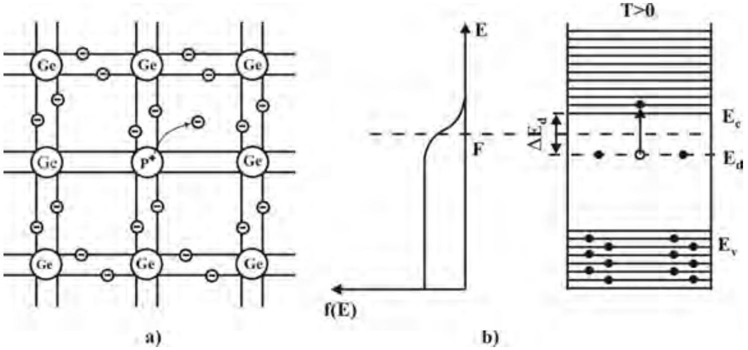


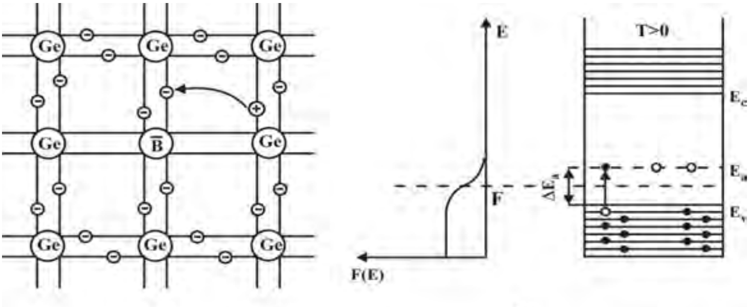
Figure 1. Model of free electron formation in phosphorus-doped germanium crystal. a – in the planar representation; b – in the energy band diagram

Along with the ionization of the adsorptive atoms, the partial ionization of the basic material atoms also occurs, but since their concentration and therefore their share of conductivity are much smaller than that of the adsorptive atoms, the total number of free electrons is very, very large than the number of holes. Since the main charge is carried by electrons as the current passes through such a crystal, they are called the main charge carriers, and the holes are called non-primary charge carriers (Figure 2). Such a semiconductor **is called an electron** or **n-type semiconductor**. Since the electrical conductivity of an electron-type semiconductor is p<<n and σp<<σn,

$$\sigma = \sigma_n + \sigma_p \approx \sigma_n = e_n \mu_n n \qquad (1)$$

Some can be expressed.

Suppose that a germanium crystal contains three valents, such as a boron atom. Since boron has three valent electrons, it will remain unfilled with a germanium atom in a tetrahedric envelope (Figure 2). In order to complete this bond, a valence electron from a neighboring germanium atom must pass through that empty bond point, and as a result, thatgerm-nium atom is converted into a positively charged ion.



a) b)

Figure 2. Model of free hole formation in boron-doped germanium crystal. a – in the planar representation; b – in the energy band diagram

What we are trying to say is that we are still in the process of developing an electron **receptor that accepts electrons**. The number of holes in such crystals, as we have noted, is much greater than the number of free electrons, and they play a key role in conductivity. As a result, these semiconductors **have a perforated permeability.** In P-type semiconductors, the main loads are holes, so n<<p and σn<<σp are conditioned and their conductivity is met.

$$\sigma = \sigma_n + \sigma_p \approx \sigma_p = e_p \mu_p p \qquad (2)$$

Someone can express it.

Thus, it is common for an electron (n-type) conductivity to be observed when the valence of the adsorptive atom is greater than the valence of the element atom, and when it is small, the permeability of the hole (p-type) is observed.

Since the concentration of freight carriers in a suspended semiconductor is higher than that of a proprietary semiconductor, the special resistance of any type of superconducting substance is less than that of pure one. In other words, **when a semiconductor is exposed to a substance, its electrical resistance decreases.**If both types of additives are present in the substance at the same time, mutual compensation occurs (Fig. 3). If the concentrations of the absorber and donor-type additives are equal, then complete compensation occurs and the substance behaves as a special semiconductor. Such substances are called compensated semiconductors and have a high resistance. Semiconductors that depend on the type of pollution are called **amphoteric semiconductors**.

When the concentration of the adgent atoms is large enough, the zone of admixture levels can expand and partially cover the cold basin or valence zone (Fig. 4).

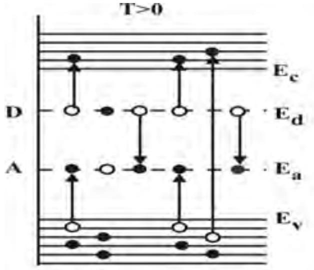


Figure 3

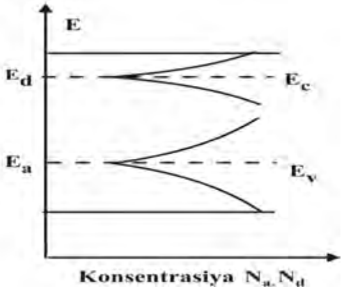


Figure 4

In addition, as the amount of additives in the semiconductors increases, the ionization energies of the superconducting centers decrease, and this ionization energy can reach zero when the corresponding levels overlap each other at sufficiently large values of the superconductor concentration.

SECTION 11. CONCENTRATION OF ELECTRONS AND HOLES. FERMI LEVEL

In order to determine the concentration of free carriers in a certain zone, it is necessary to know the distribution function of energy, in addition to the number of quantum levels falling into a single energy interval in a single volume crystal ($N(E)=\frac{dZ}{dE}$this is the expression state function). $f_0(E)$ The E probability that the energy level will be captured by the electron $f_0(E)$ is determined by the function. $\frac{1}{2}$ The distribution of particles in thermodynamic equilibrium of a system of particles consisting of the same type of particles, which is equal to single times of spini and follows the Pauli principle, is subject to the Fermi-Dirac statistics. In this case, the electron is in the crystal cage.

$$f_0(E,T)=\frac{1}{e^{\frac{E-F}{k_0T}}+1} \qquad (1)$$

The ratio is compensated.

If the case density and distribution function are known, we can calculate the concentration of loaders in any zone. If spin is also taken into account, then the concentration of electrons can be calculated by the following function

$$n=2\int_{E_1}^{E} f_0(E,T)N(E)dE \qquad (2)$$

It is the energy that corresponds to the E_1 E_2 lower and upper boundaries of the given zone. If we want to calculate the concentration of an electron in the conductivity zone, then we need to take the lower boundary of the integral from the bottom of the conductivity zone: $E_1 = E_c = E_{\min}$, and the upper boundary $E_2 = E_{\max}$. To make it easier to calculate, $E_1 = E_c = 0$ we can choose the starting lineup. If we f take into account the sharp dependence of the distribution function on energy, then we can take the upper limit $E_2 = \infty$ (for large energy prices $f_0 \to 0$). Then we can use the expressions (1) and (2) to write (.2) as follows:

$$n = \int_0^\infty \frac{4\pi \left(\frac{2m_{dn}^*}{h^2} \right)^{\frac{3}{2}} E^{\frac{1}{2}} dE}{e^{\frac{E-F}{k_0 T}} + 1} \tag{3}$$

Let's make the following substitution:

$$\frac{E}{k_0 T} = x; \quad \frac{F}{k_0 T} = \eta \tag{4}$$

And here x they are, and η they are nameless. x The energy brought to is η called the Fermi level or the chemical potential brought in. And if we are to make a change in the name of the Prophet (peace and blessings of Allaah be upon him), then we will be able to do it.

$$n = \frac{2N_c}{\sqrt{\pi}} F_{1/2}(\eta) \tag{4}$$

From this it can be seen that **the concentration of electrons is a function of temperature and Fermi level:** $n = n(T, F)$

We can also use the function of distribution for holes. If any energy level is captured by an electron, then the probability that the electron will be at that level is 1. In this case, the probability that the electron is not at this level, i.e., the probability that there will be a hole at this level, will be defined as follows:

$$f_{0p}(E,T) = 1 - f_0(E,T) = 1 - \frac{1}{e^{\frac{E-F}{k_0T}} + 1} = \frac{1}{e^{\frac{F-E}{k_0T}} + 1}. \quad (5)$$

Considering the above expressions, by analogy we obtain for the concentration of holes in the valence band

$$p = \int_{-\infty}^{E_V} f_{op}(E)N(E)dE = \int_{-\infty}^{E_V} 4\pi\left(\frac{2m_{dp}^*}{h^2}\right)^{\frac{3}{2}} \cdot \frac{(E_V - E)^{\frac{1}{2}}dE}{e^{\frac{F-E}{k_0T}} + 1}$$

(6)

it is given as

SECTION 12. THE DENSITY OF THE STATE. NUMBER OF QUANTUM STATES

.

The physical phenomena that occur in semiconductors are acutely dependent on the concentration of free carriers in the corresponding zones.

In order to find the concentration of free electrons (or holes) in a crystal, E it is $E+dE$ necessary to know the number of quantum levels falling into the energy interval and the probability of an electron (or hole) being at these levels (i.e., the distribution function). In an electron approximation, the interaction of electrons with each other in the crystal is included in the self-binding potential. Electrons move independently of each other in such a potential field. In an electron approximation, the electrons in the crystal can be viewed as ideal gas molecules. Since this type of gas is $\frac{1}{2}$ made up of particles with spins, it will be subject to the Fermi-Dirac statistic in the state of thermodynamic equilibrium. The distribution of electrons or holes at quantum levels can be determined, the distribution function of the load carriers according to the conditions, the average cost of physical quantities, and the density of quantum levels.

Suppose that a single-volume crystal E has a quantum level $E+dE$, taking into account the energy and dz the spin in the interval.

The number of quantum levels in a single energy interval in a single volume of a crystal ***is called*** **state density**. It includes:

$$N(E)=\frac{dz}{dE}\cdot \qquad (1)$$

If the probability of any quantum level being captured by an electron in the temperature T interval observed at any temperature interval is $f_0(E,T)$ known, then dE the number of electrons in the interval is:

$$dn = f_0(E,T)dz = f_0(E,T)\,N(E)dE. \qquad (2)$$

They can. To find the exact number of electrons in the region under consideration, it is necessary to integrate the expression (2) with the possible values of the energy:

$$n = \int_{E_1}^{E_2} f_0(E,T)N(E)dE, \qquad (3)$$

This E_1 is the minimum cost of energy and the E_2 highest (maximum) of energy in the zone. Since the expression () is taken for a single-volume crystal, this expression gives the concentration of the electron.

For the simplest case, let's determine the state density in the conductivity zone Suppose there is only one minimum of energy in the conductivity zone, and the energy around this minimum is defined as follows:

$$E = E_c + \frac{h^2k^2}{8\pi^2 m_n^*} = E_c + \frac{p^2}{2m_n^*}\,. \qquad (4)$$

In this expression, the effective mass is a scalar quantity, while isoenergetic surfaces are spherical in shape.

$E(\vec{p}) = const$ and

$E(\vec{p} + d\vec{p}) = E(\vec{p}) + dE = const$

Let's take a look at the spherical layer that remains between the two isoenergetic surfaces that satisfy the condition (Figure 1). The size of this layer:

$$dV = 4\pi p^2 dp. \qquad (5)$$

To determine the dV number of quantum levels in a volume here, it is necessary to divide it by the volume corresponding to a level in the Brillyuen zone (momentum space). You can see that this volume is equal to h^3 the volume. Let's show this for a simple cubic crystal cage. In this case, the Brillyuen zone is in the form of a cube, and its volume in the space of the wave vector $\left(k_i = \pm\frac{\pi}{a}, i = 1,2,3\right)$ is:

$$V_B = \left(\frac{2\pi}{a}\right)^3$$

who is. $p_i = \frac{1}{2\pi}hk$ In this case, the volume of the Brillyuen zone in the momentum space is as follows:

$$V_B = \left(\frac{2\pi h}{a2\pi}\right)^3 = \frac{h^3}{a^3} = \frac{h^3 N}{a^3 N} = \frac{h^3 N}{V} \qquad (.6)$$

They can. Here, the a^3 volume of the elementary nucleus in a flat crystal cage is N the volume of the crystal $V = a^3 N$ (since in a simple cubic crystal there is one atom per elemental nucleus, the volume of the crystal is equal to the volume of an elementary nucleus multiplied by the number of atoms in the crystal).

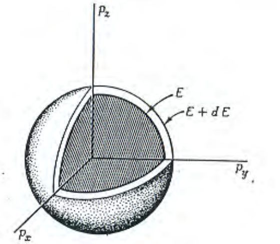


Figure 1.

$E(\vec{p}) = const$ And $E(\vec{p} + d\vec{p}) = E + dE = const$ the number of quantum states between energy intervals is dE equal to the number of states in a spherical layer with thickness

Since there is a level in each zone, as can be seen from the expression (6), $(V = 1sm^3)$ it is for a crystal of uniform volume $\frac{V_B}{N} = h^3$, i.e., each energy level in the Brillyuen zone corresponds to a volume equal to (excluding spin friction). h^3

When the crystal is formed, all other forms of friction disappear and only the spin friction remains. And if we take into account the spin, then we will see the number of levels in the volume of the sphere layer (5):

$$dz = 2 \cdot \frac{dV}{h^3} = \frac{8\pi}{h^3} p^2 dp. \tag{7}$$

They can. p And dp E if we use the relation (4) to express through, we get:

$$p = (2m_n^*)^{\frac{1}{2}} (E - E_c)^{\frac{1}{2}} \tag{8}$$

and

$$dp = \frac{1}{2} (2m_n^*)^{\frac{1}{2}} (E - E_c)^{-\frac{1}{2}} dE. \tag{9}$$

After a certain mathematical operation, the following expression is obtained for the density of the state:

$$N(E) = \frac{dz}{dE} = 4\pi \left(\frac{2m_n^*}{h^2} \right)^{\frac{3}{2}} (E - E_c)^{\frac{1}{2}}. \tag{10}$$

This expression refers to only one energy minimum in the Brillyuen zone and the case density in the conductivity zone for the case where isoenergetic surfaces are spherical.

In the same way, we can calculate the case density for the valence zone. The expression of energy near the maximum.

$$E = E_V - \frac{p^2}{2m_p^*} \tag{11}$$

If this is the case, then we are going to take a look at the density:

$$N(E) = 4\pi \left(\frac{2m_p^*}{h^2} \right)^{\frac{3}{2}} (E_V - E)^{\frac{1}{2}}. \tag{12}$$

To get an expression similar to the formula (12) for the case density for holes, it is necessary to take the effective mass of the holes as follows:

$$m_{dp}^* = \left(m_{1p}^{*\frac{3}{2}} + m_{2p}^{*\frac{3}{2}} \right)^{\frac{2}{3}}. \tag{14}$$

For example, for silicon $m_{dp}^* = 0{,}59\,m_0$, and for germanium $m_{dp}^* = 0{,}37\,m_0$.

SECTION 13. SCHRÖDINGER'S EQUATION FOR CRYSTAL

In classical mechanics, the motion of objects is the mathematical expression of Newton's second law.

$$\dot{F} = m\frac{d\vartheta}{dt}$$

It is described by the equation. By means of this equation, when the force acting on an object is known, the coordinate, velocity, and trajectory of the object are determined. This equation is called the basic equation of classical mechanics.

In quantum mechanics, the motion of a microparticle cannot be described by Newton's equation. Because. Microparticles have a dual nature. They behave like particles and waves. In quantum mechanics, an equation must be found that describes the motion of microparticles. This equation must take into account the wave nature of the particle.

In quantum mechanics, the moment a particle is given its state in space is Ψdetermined by a function (x,y,z). ΨThe function (x,y,z) has no physical meaning. However, the square of this function is the probability that there is a *particle at* the coordinate point x, y, and z of space at the given moment t.

A solid body is made up of a huge number of atoms and electrons. To determine the energy spectrum and stationary states of a system of such particles, it is necessary to solve Schrödinger's equation:

$$\hat{H}\Psi = E\Psi \qquad (1)$$

where the $\hat{H}$ Hamiltonian value of the crystal Ψ is its specific function, E is its specific value, or the energy of the crystal. The wave function of a crystal depends on the coordinates of all the particles that make up it:

$$\Psi = \Psi\left(\vec{r}_1, \vec{r}_2, \ldots, ; \vec{R}_1, \vec{R}_2, \ldots\right) = \Psi\left(\vec{r}_i, \vec{R}_\alpha\right) \qquad (2)$$

Here $\vec{r}_1, \vec{r}_2, \ldots,$ are the coordinates of the electrons $\vec{r}_i$, $\vec{R}_1, \vec{R}_2, \ldots$ or $\vec{R}_\alpha$ the nuclei of the atoms.

The Hamilton operator combines the following types of energy:

1) Kinetic Energy of Electrons $\hat{T}_e$:

$$\hat{T}_e = \sum_i \hat{T}_i = \sum_i \left(-\frac{\hbar^2}{2m} \Delta_i \right) \qquad (3)$$

Here $\Delta_i = \nabla_i^2 - i -$is the Laplace operator for the C electron:

$$\Delta_i = \nabla_i^2 = \frac{\partial^2}{\partial x_i^2} + \frac{\partial^2}{\partial y_i^2} + \frac{\partial^2}{\partial z_i^2} \qquad (4)$$

2) Kinetic Energy of Nuclei $\hat{T}_z$:

3) The Dual Interaction Energy of Electrons

$$\hat{T}_z = \sum_\alpha \hat{T}_\alpha = \sum_\alpha \left(-\frac{\hbar^2}{2M_\alpha} \Delta_\alpha \right) \qquad (5)$$

Here M_α are the masses of the nuclei.

$$\Delta_\alpha = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \qquad (6)$$

Dual interaction energies of electrons $\hat{U}_e$:

$$\hat{U}_e = \frac{1}{2}\sum_{i,j\neq i}\frac{e^2}{4\pi\varepsilon_0\left|\vec{r}_i - \vec{r}_j\right|} = \frac{1}{2}\sum_{i\neq j}\hat{U}_{ij} \qquad (7)$$

4) The Dual Interaction Energy of the Nuclei $\hat{U}_z$:

$$\hat{U}_z = \frac{1}{2}\sum_{\alpha\neq\beta}\frac{Z_\alpha Z_\beta e^2}{4\pi\varepsilon_0\left|\vec{R}_\alpha - \vec{R}_\beta\right|} = \frac{1}{2}\sum_{\alpha\neq\beta}\hat{U}_{\alpha\beta} \qquad (8)$$

Here $Z_\alpha e$ and $Z_\beta e - \alpha$ are the charges of the nuclei.

5) The Interaction Energy of Electrons with Nuclei

$$\hat{U}_{ez} = -\sum_{i,\alpha}\frac{Z_\alpha e^2}{4\pi\varepsilon_0\left|\vec{r}_i - \vec{R}_\alpha\right|} = \sum_{i,\alpha}\hat{U}_{i\alpha} \qquad (9)$$

6) The energies of all particles in the outer field $\hat{V}$:

$$\hat{V} = \hat{V}\left(\vec{r}_1, \vec{r}_2, \ldots; \vec{R}_1, \vec{R}_2, \ldots\right) \qquad (10)$$

In this case, the Hamiltons of the crystal can be written on the outside field as follows:

$$\begin{gathered}\hat{H} = \hat{T}_e + \hat{T}_z + \vec{U}_e + \vec{U}_z + \vec{U}_{ez} + \hat{V} \\ \hat{H}\Psi = E\Psi\end{gathered} \qquad (11)$$

Schrödinger's equation (11) includes a number of variables 3(Z+1)N, where N is the number of atoms in the crystal. (11) By solving the equation (11), it is possible to determine all the information about the crystal: the possible values of energy, the configuration of the nucleus, and the spatial distribution of electrons. Since a crystal $^{\text{has}}$ about 1023 atoms in a volume of 1 cm3, its equation (11) has a very large number of variables, and therefore its exact solution is practically impossible. Therefore, the main problem of solid state theory is to solve the Schrödinger equation for the crystal by applying approximate solution methods and obtain the necessary information. One of these methods is the possible approximation for an electron moving in the periodic field of the crystal lattice. This approach leads to the energetic diagram of the crystal zone.

To solve Schrödinger's equation, it is necessary to bring a system of interacting particles into a system of non-interacting particles. In this case, the Schrödinger equation for the system of particles is divided into a system of equations, each describing a particle separately. Indeed, the total Hamiltonian of the system can be expressed as the sum of the Hamiltonians:

$$\hat{\mathrm{H}} = \sum_{\mathrm{k}} \hat{\mathrm{H}}_{\mathrm{k}} \ , \tag{12}$$

It $\hat{\mathrm{H}}_{\mathrm{k}}$ depends only on the coordinates of the k-particle.

$$\hat{H}_k = -\frac{\hbar^2}{2m_k}\Delta_k + \hat{U}_k\left(\vec{r}_k\right) \tag{13}$$

The wave function of a system can be expressed as the product of the wave functions of individual particles, and the energy can be expressed as the sum of their energy:

$$\Psi = \Psi\left(\vec{\mathrm{r}}_1, \vec{\mathrm{r}}_2, \ldots\right) = \Psi_1\left(\vec{\mathrm{r}}_{\mathrm{i}}\right)\Psi_2\left(\vec{\mathrm{r}}_2\right)\ldots \tag{14}$$

and

$$\mathrm{E} = \sum_{\mathrm{k}} \mathrm{E}_{\mathrm{k}} \ , \tag{15}$$

In this case, K and Ψ_K are intertwined.

$$\hat{\mathrm{H}}_{\mathrm{k}}\Psi_{\mathrm{k}}\left(\vec{\mathrm{r}}_{\mathrm{k}}\right) = \mathrm{E}_{\mathrm{k}}\Psi_{\mathrm{k}}\left(\vec{\mathrm{r}}_{\mathrm{k}}\right) \tag{16}$$

And they are the ones who

The transition from equation of the system of interacting particles (11) to a system of equations describing non-interacting particles is possible within the framework of certain approximate approximations.

Let's assume that there are no external fields:

$$V\left(\vec{r}_1, \vec{r}_2, \ldots, ; \vec{R}_1, \vec{R}_2, \ldots\right) = 0 \qquad (17)$$

Before moving on to the simplification of the Sredinger equation, the expression of the energy of a crystal

$$E = \int \Psi^*\left(\vec{r}_1, \vec{r}_2, \ldots, ; \vec{R}_1, \vec{R}_2, \ldots\right) \hat{H} \Psi\left(\vec{r}_1, \vec{r}_2, \ldots, ; \vec{R}_1, \vec{R}_2, \ldots\right) d\tau \qquad (18)$$

Let's write it down. In this case, the integration is carried out at the coordinates of all the particles.

$$d\tau = dx_1 dy_1 dz_1 \ldots dX_1 dY_1 dZ_1 \ldots = d\tau_e d\tau_z \qquad (19)$$

$\Psi\left(\vec{r}_1, \ldots; \vec{R}1, \ldots\right)$ The wave function allows us to determine the motion of any particle in a crystal. With its help, it is possible to theoretically determine the crystalline structure of matter and its possible modifications from the minimum energy condition of the state of the system.

SECTION 14. ADIABATIC APPROXIMATION. BORN-OPPENHEIMER APPROXIMATION

One of the methods for simplifying the Schrödinger equation is the ***adiabatic approximation*** or the ***Born-Oppenheimer approximation***. The essence of this lies in the significant difference between the motions of electrons and nuclei, such that since electrons move at much greater speeds relative to the nuclei, it can be assumed that at any given moment the nucleus is at rest relative to the electron. The physical meaning of this method is that the motions of electrons and nuclei can be characterized independently of each other. Then the crystal can be considered as a structure composed of two subsystems: fast-moving electrons and practically stationary nuclei. Thus, the problem concerning the system of nuclei and electrons can be reduced to a simpler problem characterizing the state of electrons moving in a lattice formed by these nuclei.

$\vec{R}_\alpha = \vec{R}_\alpha^0$ Since the kinetic energies of the nuclei are equal to zero, and the potential energy of the interaction of the nuclei is constant Face, it is possible to equate the coordinate beginning to zero by selecting the coordinate beginning in the appropriate order. In the meantime, $\hat{T}_z = 0$, and $\vec{U}_z = 0$ in the meantime, Tony Blair

$$\hat{H}_e = \hat{T}_e + \vec{U}_e + \vec{U}_{ez} \tag{1}$$

Someone can write. Let's take a look at the wave function of electrons Ψ_e . In this case, $\Psi_e(\vec{r}_i; R_\alpha^0)$ the condition of uniform normalization in the integration of electrons at any value of the coordinates of nuclei must be paid:

$$\int \Psi^*\left(\vec{r}_1,...,;\vec{R}_1^0,...\right)\Psi_e\left(\vec{r}_1...;\vec{R}_1^0...\right)d\tau_e \tag{2}$$

Under these conditions, Schrödinger's equation can be written as follows:

$$\hat{H}_e \Psi_e = E_e \Psi_e \tag{3}$$

$$\left[\sum_i \left(-\frac{h^2}{2m}\Delta_i\right) + \frac{1}{8\pi\varepsilon_0}\sum_{i\neq j}\frac{e^2}{\left|\vec{r}_i - \vec{r}_j\right|} - \frac{1}{4\pi\varepsilon_0}\sum_{i,\alpha}\frac{Ze^2}{\left|\vec{r}_i - \vec{R}_\alpha^0\right|}\right]\Psi_e = E_e\Psi_e$$

In this expression $\vec{R}_\alpha^0$, this equation is entered not as a variable, but as a parameter that affects the wave function and the value of the crystal's energy:

$$E_e = \int \Psi_e^* \hat{H}_e \Psi_e d\tau_e = E_e\left(R_1^0, R_2^0, \ldots\right) \tag{4}$$

E is the energy of electrons moving in the field of nuclei that are at rest.

The idea of a nuclear reactor is extremely superficial. In fact, it is important to note that the cores are moving. In this case, the Hamiltonian of the crystal can be described as follows:

$$\hat{H}_z = \sum_\alpha \left(-\frac{h^2}{2M_\alpha}\Delta_\alpha\right) + \hat{U}_\alpha + \hat{E}_e\left(\ldots, \vec{R}_\alpha, \ldots\right) \tag{5}$$

(5) Let us call the operator included in the expression (5) the nuclear part of the Hamiltonian crystal. Then we can write:

$$\hat{H} = \hat{H}_e + \hat{H}_z - \hat{E}_e \tag{6}$$

Let's describe the wave function of a crystal Ψ as a derivative:

$$\Psi\left(\ldots, \vec{r}_i, \ldots, ; \ldots, \vec{R}_\alpha, \ldots\right) = \Psi\left(\ldots, \vec{r}_i, \ldots ; \ldots \vec{R}_\alpha, , \ldots\right)\Phi_z\left(\ldots, \vec{R}_\alpha, \ldots\right) \tag{7}$$

This expression can be substituted for the Schrödinger equation for crystals, and $\Phi_z\left(\vec{R}_1, \ldots\right)$ the equation can be defined as:

$$\hat{H}\Psi = (\hat{H}_e + \hat{H}_z - \hat{E}_e)\Psi_e\Phi_z = \Phi_z\hat{H}_e\Psi_z + H_z\Psi_e\Phi_z - \hat{E}_e\Psi_z\Phi_z = E\Psi_e\Phi_z \tag{8}$$

Or (3)

$$\hat{H}\Psi = \hat{H}_z\Psi_e\Phi_z = E\Psi_e\Phi_z = E\Psi \qquad (9)$$

You can write.
Someone can write it. After a certain mathematical equation

$$\int \Psi_e^*\Psi_e d\tau_e = 1 \qquad (10)$$

In the light of the fact that it is

From the above statements, it is evident that the wave function of the crystal in the adiabatic approximation

$$\Psi\left(\vec{r}_i,...,;...,\vec{R}_1,...\right) = \Phi_z\left(\vec{R}_1,...\right)\Psi_e\left(\vec{r}_1,...;R_1,...\right) \qquad (11)$$

Some can be written.

$$\hat{H}_e\Psi_e = E_e\Psi_e,$$

$$\hat{H}_z\Phi_z = E_z\Psi_z = E\Phi_z$$

It can be found in the equations.

In adiabatic approximation, the wave function of electrons is determined by the instantaneous state of the nuclei ($\hat{H}_e$the Weez limit in Weez), while the wave function of the nuclei is determined by the mediated area of the electrons.

SECTION 15. A SINGLE-IMPURITY SEMICONDUCTOR

Now let's take a look at a semiconductor that is a kind of addictive center, let's say donor-type addicts: $N_d \neq 0,\ N_a = 0$ In this case, the neutrality equation is:

$$n - (p + N_d^+) = 0. \quad (1)$$

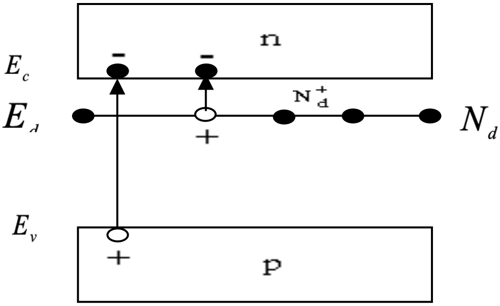


Figure 1. Thermal generation of charge carriers in a semiconductor with donor-type impurity

In general, this F is the third order according to the equation. Now the free holes in the valence zone are only due to the ionization of specific atoms, and the free electrons in the conductivity zone are due to the ionization of electrons from both the valence zone and the donor zone.

It is located in the middle of the area (Figure 1). Therefore, $p << N_d^+$ in the conditionally paid temperature interval ("low" temperatures), the main role will be played by the overflow centers, and $p >> N_d^+ = N_d$ in the conditionally paid interval ("high" temperatures), the main role will be played by the transitions from the valent zone to the conductivity zone. Let's take a look at both of them separately.

a) Low temperatures. As we have already mentioned, this $p << N_d^+$ includes the temperature interval that satisfies the condition. In this case, we can see that (3.6.1) $p \quad N_d^+$ is not the same as (3.6.1). (3.3.19) and (3.4.5) (3.6.1):

$$N_c e^{\frac{F}{k_0T}} - \left(N_d - \frac{N_d}{\frac{1}{2} e^{\frac{E_d - F}{k_0T}} + 1} \right) = 0$$

Or

$$\frac{1}{2} N_c e^{\frac{E_d}{k_0T}} + N_c e^{\frac{F}{k_0T}} - \frac{1}{2} N_d e^{\frac{E_d - F}{k_0T}} = 0. \tag{2}$$

If we make a change like this:

$$e^{\frac{F}{k_0T}} = x, \tag{3}$$

$$\frac{1}{2} N_c e^{\frac{E_d}{k_0T}} + N_c x - \frac{1}{2} N_d e^{\frac{E_d}{k_0T}} \cdot x^{-1} = 0,$$

To put it simply:

$$x^2 + \frac{1}{2} e^{\frac{E_d}{k_0T}} x - \frac{N_d}{2N_c} e^{\frac{E_d}{k_0T}} = 0. \tag{4}$$

From here:

$$x = \frac{1}{4} e^{\frac{E_d}{k_0T}} \left[-1 \pm \sqrt{1 + \frac{8N_d}{N_c} e^{-\frac{E_d}{k_0T}}} \right] \tag{5}$$

If we take into account that this is the $x > 0$ case , we can omit the negative sign in front of the root expression. Then we get from (3.6.3) and (3.6.5) for the Fermi level:

$$F = k_0 T \ln\left\{ \frac{1}{4} e^{\frac{E_d}{k_0 T}} \left[\sqrt{1 + \frac{8N_d}{N_c} e^{-\frac{E_d}{k_0 T}}} - 1 \right] \right\} \tag{6}$$

The following inequality can be calculated N_c due to the change in temperature at sufficiently low temperatures:

$$\frac{8N_d}{N_c} e^{-\frac{E_d}{k_0 T}} >> 1. \tag{7}$$

In (3.6.6) we can subtract the units:

$$F = k_0 T \ln\left\{ \frac{1}{4} e^{\frac{E_d}{k_0 T}} \sqrt{\frac{8N_d}{N_c}} e^{-\frac{E_d}{2k_0 T}} \right\} = k_0 T \ln\left\{ \sqrt{\frac{N_d}{2N_c}} \, e^{\frac{E_d}{2k_0 T}} \right\} = \frac{E_d}{2} + \frac{k_0 T}{2} \ln\frac{N_d}{2N_c}. \tag{8}$$

Since it is calculated from the bottom of the energy conduction zone $(E_c = 0)$, the energy corresponding to the level of the adversity (the "depth of the adversity") is negative:

$$E_d < 0.$$

E_d $(\Delta\varepsilon_d)$ F And if we are to be honest with ourselves, then we are to be honest with ourselves.

$$F = -\frac{\Delta\varepsilon_d}{2} + \frac{k_0 T}{2} \ln\left(\frac{N_d}{2N_c} \right) \tag{9}$$

From this it can be seen that $T = 0$ $F = -\dfrac{\Delta\varepsilon_d}{2}$ it happens when, i.e., at absolute zero, the Fermi level passes through the middle of the distance between the conductivity zone and the adjacent level. Increasing with the increase in temperature F , it approaches the bottom of the permeability zone, takes the maximum price, and then begins to decrease, $2N_c = N_d$ recurring in its price $F = -\frac{\Delta\varepsilon_d}{2}$ (but here (3.6.7) conditional must be paid, otherwise the expression (3.6.9) is not correct).

Let's find the concentration of electrons:

$$n = N_c e^{-\frac{\Delta\varepsilon_d}{2k_0T}+\frac{1}{2}\ln\left(\frac{N_d}{2N_c}\right)} = \left(\frac{N_d N_c}{2}\right)^{\frac{1}{2}} e^{-\frac{\Delta\varepsilon_d}{2k_0T}},$$

$$n = \left(\frac{N_d N_c}{2}\right)^{\frac{1}{2}} e^{-\frac{\Delta\varepsilon_d}{2k_0T}} \tag{9a}$$

From here, it seems that again, $\ln\left(nT^{-\frac{3}{4}}\right)$ $\frac{1}{T}$ A straight line is given in the form of a straight line (Figure 2). Ashgar Level

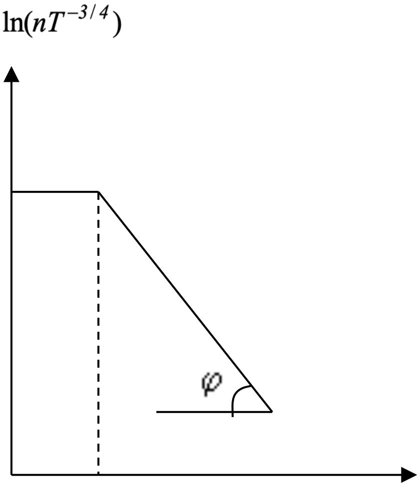


Figure 2. In a semiconductor with one type of impurity at low temperatures $\ln(nT^{-3/4}) = f(1/T)$

The Activation
of Energy

This line can be found by (φ) the angle of inclination:

$$\Delta\varepsilon_d = 2 \cdot k_0 tg\varphi . \tag{10}$$

3.6.7 And we shall see that the LORD hath made a covenant with the LORD of hosts, and he hath made a covenant with the LORD of hosts.

$$\frac{8N_d}{N_c} e^{\frac{\Delta\varepsilon_d}{k_0 T}} << 1. \tag{11}$$

In order for the same concentration of additives (N_d 11) to be correct, relatively higher temperatures are required, and conditional temperatures must also be met at these temperatures $N_c >> 8N_d$. In this case, if we divide the expression (3.6.6) $y = \frac{8N_d}{N_c} \cdot e^{\frac{\Delta\varepsilon_d}{k_0 T}}$ into the order above, then we will suffice the first two terms:

$$F = k_0 T \ln\left\{ \frac{1}{4} e^{-\frac{\Delta\varepsilon_d}{k_0 T}} \left(1 + \frac{4N_d}{N_c} e^{\frac{\Delta\varepsilon_d}{k_0 T}} + \ldots - 1 \right) \right. = k_0 T \ln\frac{N_d}{N_c} \tag{12}$$

$N_d << N_c$ This means that $\ln\frac{N_d}{N_c} < 0$ as the temperature increases F , it drops below the bottom of the conductivity zone.

To do this, let's find the concentration of electrons:

$$n = N_c e^{\frac{F}{k_0 T}} = N_c e^{\ln\frac{N_d}{N_c}} = N_d \tag{13}$$

That is, the concentration does not change depending on the temperature (all donor centers are ionized). This is called an oblast where the electrons of the donor centers are completely depleted. Here it is $N_d^+ = N_d$ ...

(b) High temperatures. If we continue to increase the temperature, N_d^+ the concentration of the carriers will increase due to the specific conductivity, being constant $(N_d^+ = N_d)$. We can write the equation of neutrality like this:

$$n = p + N_d. \tag{14}$$

$p = \frac{n_i^2}{n}$ Considering that it is:

$$n - \frac{n_i^2}{n} - N_d = 0,$$

$$n^2 - N_d n - n_i^2 = 0. \tag{15}$$

From here:

$$n = \frac{N_d}{2}\left(1 + \sqrt{1 + \frac{4n_i^2}{N_d^2}}\right). \tag{16}$$

We have removed the negative solution here because it does not have a physical meaning. Concentration of holes:

$$p = \frac{n_i^2}{n} = \frac{2n_i^2}{N_d\left(1 + \sqrt{1 + \frac{4n_i^2}{N_d^2}}\right)}. \tag{17}$$

And then there's the Farm Level.

$$F = k_0 T \ln \frac{n}{N_c} = k_0 T \ln \left\{ \frac{N_d}{2N_c} \left(1 + \sqrt{1 + \frac{4n_i^2}{N_d^2}} \right) \right\} = \\ = k_0 T \ln \left\{ \frac{N_d}{2N_c} \left(1 + \sqrt{1 + \frac{4N_c N_V}{N_d^2} e^{-\frac{\Delta E_g}{k_0 T}}} \right) \right\}. \tag{18}$$

$$\frac{4n_i^2}{N_d^2} << 1 \tag{19}$$

And when we do that, we're going to have to look at it from the perspective of the donor centers.

$$\frac{4n_i^2}{N_d^2} << 1 \tag{19, a}$$

And when that happens, we get a non-translucent semiconductor that has a special conductivity.

Thus, when there is only one type of surcharge center in the semiconductor, the value of the Fermi level is determined by the expression (3.6.6) or (3.6.18). Figure 3 shows the temperature dependence of the three values of the concentration of donor F centers:

$$1 - N_{d_1},\ 2 - N_{d_2},\ 3 - N_{d_3},\ \ N_{d_1} > N_{d_2} > N_{d_3}.$$

We can easily get the appropriate expressions in the same manner for the acne type of acne. In this case, for the lower temperatures:

$$F = k_0 T \ln \left\{ \frac{e^{\frac{\Delta\varepsilon_a}{k_0 T}}}{4} \left(\sqrt{1 + \frac{8N_a}{N_V} e^{-\frac{\Delta\varepsilon_a}{k_0 T}}} - 1 \right) \right\} \tag{20}$$

For higher temperatures:

$$F = -\Delta E_g - k_0 T \ln\left\{ \frac{N_a}{2N_V}\left(1+\sqrt{1+\frac{4n_i^2}{N_a^2}}\right)\right\} \qquad (.21)$$

Figure 4 shows the temperature dependence of the Fermi level in the semiconductor for three different concentrations of absorbor-type admixture centers: $1 - N_{a_1}$, $2 - N_{a_2}$, $3 - N_{a_3}$, $N_{a_1} > N_{a_2} > N_{a_3}$.

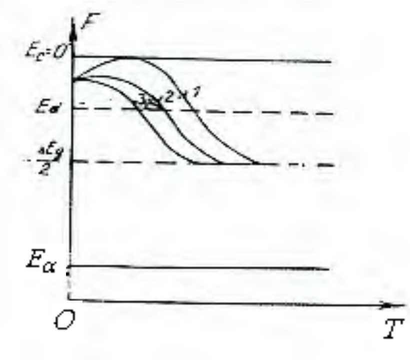


Figure 3.

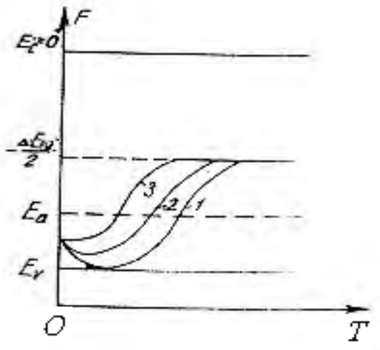


Figure 4.

SECTION 16. THE EFFECTIVE MASS OF THE ELECTRON

Suppose that (or $\vec{P}_0$) is an extreme $\vec{k}_0$ point in dependence

$$E(\vec{k}_0) = E_0 = E_{extr} \tag{1}$$

$\vec{k}_0$ In addition to the point, there must also be other extreme points in the dependence, e.g., symmetrical - $\vec{k}_0$ point. And not only $\vec{k}$ that, but also because of the power of the Internet, it is also the source of all things.

$$E(k_x, k_y, k_z) = E(-k_x, k_y, k_z) = \ldots \tag{2}$$

Therefore, it can be affirmed that the number of extreme points must be determined by the elements of symmetry of the crystal field. For example, a cubic lattice with 24 elements of symmetry should have a total of 24 equivalent extremes.

$E(\vec{k})$ Let's take a look at some of the most important aspects of Taylor's case:

$$E(\vec{k}) = \sum_{\ell=0}^{\infty} \frac{d'E(\vec{k})}{d\vec{k}^{\ell}}\bigg|_{\vec{k}_0} \frac{(\vec{k} - \vec{k}_0)^{\ell}}{\ell!} = E(\vec{k}_0) + \frac{dE(\vec{k})}{d\vec{k}}(\vec{k} - \vec{k}_0) + \ldots \tag{3}$$

$d/d\vec{k}$ Since the vector argument consists of the sum of three quantities (with corresponding differentiation to the sum of three quantities (kz, ky, kz), this expression ℓ is called a tensor.

ℓ If = 0, we get a scalar, and ℓ if = 1, we get a tensor–vectorfrom the first rank; ℓ =2.3,... If this is the case, then the second, third, and so on will be used. Let's just write the first two paragraphs: ℓ =1, ℓ =2:

$$\frac{dE}{d\vec{k}} = \left(\frac{\partial E}{\partial k_x}, \frac{\partial E}{\partial k_y}, \frac{\partial E}{\partial k_z} \right);$$

(4)

$$\frac{d^2E}{d\vec{k}^2} = \left(\frac{d}{\partial \vec{k}} \frac{\partial E}{\partial k_x}, \frac{d}{\partial \vec{k}} \frac{\partial E}{\partial k_y}, \frac{d}{\partial \vec{k}} \frac{\partial E}{\partial k_z} \right) =$$

$$= \begin{vmatrix} \frac{\partial^2 E}{\partial k_x^2} & \frac{\partial^2 E}{\partial k_y \partial k_x} & \frac{\partial^2 E}{\partial k_z \partial k_x} \\ \frac{\partial^2 E}{\partial_x k \partial k_y} & \frac{\partial^2 E}{\partial k_y^2} & \frac{\partial^2 E}{\partial k_z \partial k_x} \\ \frac{\partial^2 E}{\partial k_x \partial k_z} & \frac{\partial^2 E}{\partial k_y \partial k_z} & \frac{\partial^2 E}{\partial k_z^2} \end{vmatrix}$$

(5)

Mixed derivatives do not depend on the sequence of differentials:

$$\frac{\partial^2 E}{\partial k_i \partial k_j} = \frac{\partial^2 E}{\partial k_j \partial k_i} \qquad (6)$$

Such tensors *are called* ***symmetric*** tensors, and $\partial^2 E / \left(\partial k_i^2 \right)$ some boundaries are called ***diagonal*** elements. A derivative ℓ of the component ℓ consists of three elements ℓ - a ranked tensor.

$\vec{k}_0$ Let's take a look around the little one. In this case, the first steps may suffice. As a result of the extremity of the series, the $\left.\frac{dE}{d\vec{k}}\right|_{\vec{k}} = 0$ series begins with the quadratic limits.

$$E(\vec{k}) = E_0 + \frac{1}{2}\frac{d^2E}{d\vec{k}^2}(\vec{k}-\vec{k}_0)^2 + \ldots = E_0 + \frac{1}{2}\sum_{i,j}\frac{\partial^2 E}{\partial k_i \partial k_j}(k_i - k_{0i})(k_j - k_{0j}) + \ldots \tag{7}$$

From this it can be seen that the isoenergetic surface in the vicinity of the extremum is described with sufficient accuracy by a second-order surface. When the price of energy is close to the extreme value of E0, this condition is more accurately calculated. This is due to the fact that the first few steps are very small compared to the first one:

$$\frac{1}{6}\frac{d^3E}{d\vec{k}^3}(\vec{k}-\vec{k}_0)^3 << \frac{1}{2}\frac{d^2E}{d\vec{k}^2}(\vec{k}-\vec{k}_0)^2 \tag{8}$$

By selecting the coordinate axes, it is possible to bring the second-order tensor into a diagonal shape, so that the non-diagonal elements are converted to zeros on these axes. In the context of these circumstances

$$\frac{\partial^2 E}{\partial k_i \partial k_j} = 0, \ (i \neq j) \tag{9}$$

In this case, the equations of isoenergetic surfaces

$$E(\vec{k}) = E(\vec{k}_0) + \frac{1}{2}\sum_{i=1}^{3}\frac{\partial^2 E}{\partial k_i^2}(k_i - k_{0i})^2 = \text{const} = E \tag{10}$$

Or

$$E(k) - E_0 = \frac{1}{2}\frac{\partial^2 E}{\partial k_x^2}(k_x - k_{0x})^2 + \frac{1}{2}\frac{\partial^2 E}{\partial k_y^2}(k_y - k_{0y})^2 + \\ + \frac{1}{2}\frac{\partial^2 E}{\partial k_z^2}(k_z - k_{0z})^2 = \mathrm{const}, \tag{11}$$

Drop it into your image.

Since the sequencing is carried out with respect to the extreme point, the signs in all derivatives are the same–: plus at minimum and minus at maximum, so isoenergetic surfaces are ***ellipsoid-shaped***.

Let's look at isoenergetic surfaces in quasi-impulse space.

It’s obvious that

$$E(\vec{p}) = E(\vec{p}_0) + \frac{1}{2}\frac{d^2E}{d\vec{p}^2}(\vec{p} - \vec{p}_0)^2 + \frac{1}{6}\frac{d^3E}{dp^3}(\vec{p} - \vec{p}_0)^3 + \ldots \tag{12}$$

$\vec{P}_0 = \hbar\vec{k}_0$And since it's an extreme $\vec{P}_0$ point, it's just a matter of getting close to it.

$$E(\vec{p}) = E_0 + \frac{1}{2}\frac{d^2E}{d\vec{p}^2}(\vec{p} - \vec{p}_0)^2 + \ldots \tag{13}$$

"We can write it down.

$$\frac{d^2E}{d\vec{p}^2} = m^{*-1} \tag{14}$$

Let's accept it. It is clear that K is m^{*-1} the sum of its parts.

$$m_{ij}^{*-1} = \frac{\partial^2 E}{\partial p_i \partial p_j} \tag{15}$$

who is. m_{ij}^{*-1} – The unit of measurement coincides with the unit of measurement of the inverse value of the mass:

$$\left[m_{ij}^{*}\right]=\left[\frac{\partial^{2}E}{\partial p_{i}\partial p_{j}}\right]^{-1}=[M]$$

$m^{*-1}=\dfrac{d^{2}E}{d\vec{p}^{2}}$ The quantity is called the ***inversely effective mass*** tensor.

SECTİON 17. THE ELECTRON NEUTRALITY EQUATION.

If the Fermi level (F) is known, then it is easy to drill a hole and calculate the concentration of the electron. However, the Fermi level is highly dependent on the degree of clearance and temperature of the semiconductor. When there is an external coating in the semiconductor, local levels of sulfur are generated in the prohibited area. These levels can be held by both electrons and holes. The redistribution of loaders by energy levels is regulated by the change in the level of the Fermi.

Typically, to determine the state of the Fermi level, they use the condition that the crystal is neutral in terms of its electric charge, and the equation that expresses this condition. To get this equation, we need to take the sum of the negative charges in the crystal equal to the sum of the positive charges. Suppose there are both donor and acceptor-type additives in the semiconductor, and their concentrations N_d are respectively and N_a . In the state of equilibrium, as a result of thermal ionization, a certain amount of electrons pass through both the suspension centers and the principal atoms (the valence zone) to the conductivity zone. Let's write the condition for the neutrality of the electric charge for a single-volume crystal. To do this, we need to calculate the number of negative and positive charges separately (Figure 1).

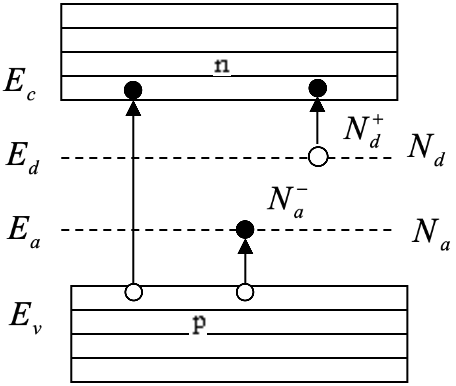


Figure 1. Heat generation of freight carriers in semiconductors with donor and acceptor-type alloys

Negative charges are electrons in the conduction zone and the receptor centers that have captured the electron (let's indicate the concentration of such N_a^- centers). The sum of them is:

$$(n + N_a^-)e^- .$$

Positive charges are free holes in the valence zone and donor centers that have lost their electrons (N_d^+ let's indicate the concentration of such centers). The sum of the positive loads:

$$(p + N_d^+)e^+,$$

here e^- and e^+ accordingly shows the charge of the electron and the hole $(e^- = -e^+)$. Now let's write the neutrality condition of the electric charge:

$$(n + N_a^-)e^- + (p + N_d^+)e^+ = 0 \qquad (1)$$

or

$$(n + N_a^-) + (p + N_d^+) = 0. \qquad (2)$$

This is called the equation of neutrality of the electric charge of a crystal or the equation of electroneurity.

SECTION 18. TEMPERATURE DEPENDENCE OF FERMI LEVEL IN SPECIAL SEMICONDUCTORS

If there are no external superconducting atoms in the semiconductor, it is called a special semiconductor. In this case $N_d = N_a = 0$, it is. The equation (3.60) takes a very simple picture:

$$n = p, \tag{1}$$

In other words, the number of free electrons in the conductivity zone is equal to the number of free holes in the valence zone (Figure 1).

For a non-semiconductor, we take the expression (1):

$$2\left(\frac{2\pi m_{dn}^* k_0 T}{h^2}\right)^{\frac{3}{2}} e^{\frac{F}{k_0 T}} = 2\left(\frac{2\pi m_{dp}^* k_0 T}{h^2}\right)^{\frac{3}{2}} e^{-\frac{F+\Delta E_g}{k_0 T}}. \tag{2}$$

From here:

$$e^{\frac{2F+\Delta E_g}{k_0 T}} = \left(\frac{m_{dp}^*}{m_{dn}^*}\right)^{\frac{3}{2}}.$$

From this formula F we can find:

$$F = -\frac{\Delta E_g}{2} + \frac{k_0 T}{2}\ln\left(\frac{m_{dp}^*}{m_{dn}^*}\right)^{\frac{3}{2}}. \tag{3}$$

If $m_{dp}^* = m_{dn}^*$ it does, then the Fermi level passes through the middle of the forbidden zone and does not depend on temperature (Figure 2). $m_{dp}^* \neq m_{dn}^*$ At absolute zero temperatures, the Fermi level falls into the middle of the forbidden zone, and as the temperature increases, it approaches either the conductivity $(m_{dp}^* > m_{dn}^*)$ zone or the valence zone $(m_{dp}^* < m_{dn}^*)$ linearly.

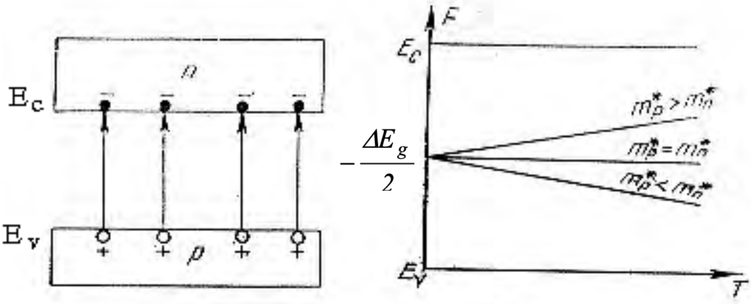


Figure 1.Temperature dependence of the Fermi heat generation level of loaders in a proprietary semiconductor

If we refer to the concentration of loaders for a particular semiconductor n_i , we get the expression (3.3.34):

$$n_i = n = p = \sqrt{np} = \sqrt{N_c N_V} e^{-\frac{\Delta E_g}{2k_0T}} =$$

$$= 4{,}82 \cdot 10^{15} \left(\frac{m_{dn}^* m_{dp}^*}{m_0^2} \right)^{\frac{3}{4}} T^{\frac{3}{4}} e^{-\frac{\Delta E_g}{2k_0T}} = CT^{\frac{3}{4}} e^{-\frac{\Delta E_g}{2k_0T}}, \tag{4}$$

Here $C = 4{,}82 \cdot 10^{15} \left(\frac{m_{dn}^* m_{dp}^*}{m_0^2} \right)^{\frac{3}{4}} sm^{-3}$ is a constant quantity for the given semiconductor. From (3.5.4)

$$n_i T^{-\frac{3}{2}} = Ce^{-\frac{\Delta E_g}{2k_0T}},$$

And then there's the fact that this phrase is a logic:

$$\ln\left(n_i T^{-\frac{3}{2}}\right) = \ln C - \frac{\Delta E_g}{2k_0} \cdot \frac{1}{T}. \qquad (5)$$

As you can $\ln\left(n_i T^{-\frac{3}{2}}\right)$ $\frac{1}{T}$ see, it depends on the line (Figure 2). (3.5.5) and Figure 2 shows that

$$\Delta E_g = 2k_0 tg\alpha$$

.

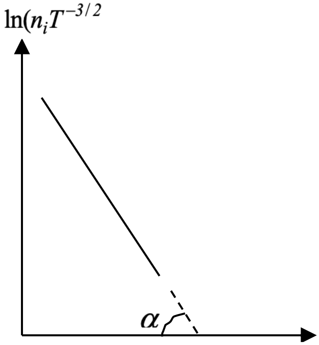


Figure 2. Dependence of $\ln(n_i T^{-3/2}) = f(1/T)$ *in an intrinsic semiconductor*

Thus, the dependence of the concentration of loaders on temperatures in a special semiconductor makes it possible to determine the width of the prohibited zone.

SECTION 19. UNDERSTANDING OF QUASI-PARTICLES

When we looked at the motion of the electron in the crystal, we took the permissible values of energy in the form of zones as a result of the periodicity of the crystal potential, i.e., the result of the regular arrangement of atoms over long distances. This is commonly referred to as long-distance regularity. However, in semiconductors, the zoned character of energy is also observed in cases where the order is disturbed over long distances, for example, when the semiconductor melts and turns into a liquid (in the case of a liquid there is regularity only over small distances), the zoned character of the energy is often preserved. This shows that "remote order" is not a necessary condition for the receipt of energy in the form of zones, but in fact it is only one of the sufficient conditions that allows us to solve an electronic problem. It seems that a sufficient conditional constitutes the structure of the potential (close order) at close distances, but such an approximation requires solving a multi-object problem. We have already talked about the complexity of the problem.

It is clear from simple physical judgments that when free atoms combine to form crystals, the same (flaked) states of the electrons of different atoms must form zones as a result of the disintegration (elimination of friction).

It is possible to talk about the role of the proximity zone in terms of the proximity of the order. This is because the atoms are statistically distributed in the crystal, and there can be no talk of their orderly arrangement (periodicity) over long distances.

Describing the physical properties of a solid object is made sharply easier by incorporating the concept of some quasi-particles. Such particles cannot exist freely outside of the environment (in a vacuum). In fact, the electron and the hole that create electrical conductivity in the crystal and have a certain effective mass and quasi-momentum are such quasi-particles.

Apart from charged quasi-particles (i.e., particles involved in the transport of electric charge), there may also be other types of quasi-particles in a solid body – non-charged. To explain the possibility of the formation of such particles, let's take a look at the mechanism of formation of an electron-hole pair in a special semiconductor. The electron absorbs energy equal to the width of the forbidden zone and passes into the conduction zone, thus creating a free electron in the conduction zone and a free hole in the valence zone, which are also involved in the electrical conduction of the crystal. If the energy absorbed is smaller than the width of the forbidden zone, then a special state called excitation may occur in the crystal (excitation in English). The existence of an exciton state was first proposed by Frankel (1931). An exciton is such a bonded state of an electron and a hole in which the coulomb interacts with each other that it has a certain quasi-momentum and forward motion energy, and can move along the entire crystal. It is possible to imagine the formation of an exiton in a different way. When a free electron and a free hole are formed in a particular semiconductor, a coulomb interaction (gravitation) force occurs between them. As a result, an "atom" will be formed - an exciton, similar to a hydrogen atom, but here it is not a positively charged particle proton, but a positively charged hole with a mass equal to the mass of an electron.

The movement of the electron-hole pair in the exciton state does not cause the formation of an electric current and does not affect the electrical conductivity of the crystal. Therefore, the absorption of light, which results in the formation of an exciton, does not cause photoconductivity. The resulting exciton undergoes a chaotic diffusion motion within the crystal, and this state continues until one of two conditions occurs:

1) one of the particles that form the exciton is captured by one of the crystal disorders. At this time, the other particle is still free in the corresponding area; (2) It recombines with the electron. In this case, the energy absorbed during the formation of an exciton is either released in the form of a quantum of light or converted into the thermal energy of the crystal cage. Of course, in both cases, the exciton is broken.

In general, the solution to the problem of electron formation goes beyond the approach of an electron. However, given the interaction between an electron in the conductivity zone and a hole in the valence zone, it is possible to include excitation excitation in the band theory (note that such an exciton is called a Mott or Vanier exciton). If the size of such an exciton is large enough than the crystal constant, then we can view the interaction of the electron-hole pair with great accuracy as a coulomb interaction of two charged particles in the dielectric medium (where the main crystal cage plays the role of the dielectric medium). In this case, it is necessary to take the optical (high-frequency) dielectric constant as the dielectric constant of the medium. Because the electron and the hole move so "inertly" that the operator that characterizes their coulomb interaction does not need to include the polarization associated with the displacement of the crystal ions.

If we refer to the radius-vectors $\vec{r}_n$ that $\vec{r}_p$ characterize the state of the electron and the hole in the exciton, and their effective masses m_n^*, and with them m_p, we can write the Schrödinger equation, which describes the state of the exciton, as follows:

$$\left[-\frac{\hbar^2}{2m_n^*}\Delta n-\frac{\hbar^2}{2m_p^*}\Delta p-\frac{e^2}{\varepsilon_{0n}\left|\vec{r}_n-\vec{r}_p\right|}\right]\psi(\vec{r}_n,\vec{r}_p)=E\psi(\vec{r}_n,\vec{r}_p)\cdot \quad (2.19.1)$$

Here, the first and second limits on the left side of the equation describe the kinetic energy of the electron and the hole (Δ_n and Δ_p the Laplace operator taken according to the coordinates of the electron and the hole, respectively), and the third limit describes the interaction energy of the electron-hole pair.

This system is the radius vector of the center of inertia of the electron-hole pair:

$$\vec{R} = \frac{m_n^* \vec{r}_n + m_p^* \vec{r}_p}{m_n^* + m_p^*} \qquad (2.19.2)$$

And it can be described by the radius-vector, $\vec{\rho}$ which determines the position of the electron in relation to the hole:

$$\vec{\rho}_n = \vec{r}_n - \vec{r}_p \cdot \qquad (2.19.3)$$

We can show that when we express the newly entered variables (2.19.1), the equation looks like this:

$$\left[-\frac{\hbar^2}{2M} \Delta\vec{R} - \frac{\hbar^2}{2m_n^*} \Delta\vec{\rho} - \frac{e^2}{\varepsilon_{0n}\rho} \right] \psi(\vec{R},\vec{\rho}) = E\psi(\vec{R},\vec{\rho}), \qquad (2.19.4)$$

Here $M = m_n^* + m_p^*$, m_{np}^* is the mass of the electron-hole pair:

$$m_{np}^* = \frac{m_n^* \cdot m_p^*}{m_n^* + m_p^*} \qquad (2.19.5)$$

(2.19.4) The equation is solved by separating the variables:

$$\psi(\vec{R},\vec{\rho}) = \psi_1(\vec{R}) \cdot \psi_2(\vec{\rho}) \cdot \qquad (2.19.6)$$

2.19.6 (2.19.4) and divide it into two parts $\psi(\vec{R},\vec{\rho})$:

$$-\frac{\hbar^2}{2M} \cdot \frac{1}{\psi_1(\vec{R})} \cdot \Delta_{\vec{R}} \psi_1(\vec{R}) - \frac{1}{\psi_2(\vec{\rho})} \left[\frac{\hbar^2}{2m_{np}^*} \Delta_{\vec{\rho}} \psi_2(\vec{\rho}) + \frac{e^2}{\varepsilon_{0n}\rho} \psi_2(\vec{\rho}) \right] = E$$

. (2.19.7)

The first limit of the left side depends on only R, and the second limit depends only $\vec{\rho}$ on , but the sum of them is E equal to a fixed quantity. In this case, each limit must be equal to a constant quantity separately ($\vec{R}$ and $\vec{\rho}$ not dependent on each other):

$$-\frac{\hbar^2}{2M}\Delta_{\vec{R}}\psi_1(\vec{R}) = T^{ek}\psi_1(R), \tag{2.19.8}$$

$$\left[-\frac{\hbar^2}{2m_{np}^*}\Delta_{\vec{\rho}} - \frac{e^2}{\varepsilon_{0n}\rho}\right]\psi_2(\vec{\rho}) = E^{ek}\psi_2(\vec{\rho})\cdot \tag{2.19.9}$$

It’s obvious that:

$$E = T^{ek} + E^{ek}. \tag{2.19.10}$$

The equation (2.19.8) is reminiscent of Schrödinger's equation for a free electron and $M = m_n^* + m_p^*$ describes the free movement (translation) of a mass particle (exciton) across the entire crystal. The solution to this equation is in the form of a plane wave, energy:

$$T^{ek} = \frac{\hbar^2\left|\vec{k}^{ek}\right|^2}{2(m_n^* + m_p^*)} \tag{2.19.11}$$

It is expressed by the formula. Here, the wave vector of the exciton is defined as follows:

$$k^{ek} = \frac{\sqrt{2(m_n^* + m_p^*)}}{\hbar}\cdot\sqrt{T^{ek}}. \tag{2.19.12}$$

Thus, the equation (2.19.8) describes the motion of the center of inertia of the exciton. The kinetic energy that performs this motion is T^{ek}. Another equation – (2.19.9) describes the internal (hydrogen-like) motion of the exciton relative to the center of inertia. In this case, the specific values of energy are determined as in the case of a hydrogen atom. In the case of a hydrogen atom, however, the energy of an electron that has moved away from its atom to an infinite distance is first taken as a starting point. In an exciton, it is necessary to choose the beginning $n=\infty$ in such a way that and $\rho=\infty$ when it is $E^{ek}=E_v+E_c$ obtained (n - the prime quantum number, E_v and E_c the values of the energy corresponding to the maximum of the valence zone and the minimum of the conductivity zone). In this case, let's take a look at the Exciton:

$$E_n^{ek}=E_v+E_c-\frac{1}{n^2}\cdot\frac{m_{np}^*e^4}{2\hbar^2\varepsilon_{0n}^2}=E_v+E_c-\frac{13,5}{\varepsilon_{0n}^2}\left(\frac{m_{np}^*}{m_0}\right)\cdot\frac{1}{n^2}(eV)\cdot \qquad (2.19.13)$$

If we calculate the maximum of the valence zone of energy $(E_v=0)$, then we get the main state of the exciton $(n=1)$:

$$E_1^{ek}=\Delta E_g-\frac{13,5}{\varepsilon_{0n}^2}\cdot\left(\frac{m_{np}^*}{m_0}\right)(eV)\cdot \qquad (2.19.14)$$

From the expressions (2.19.13) and (2.19.14), it is evident that the energy levels of the exciton are located in the vicinity of the conduction zone in the forbidden zone.

The value of the radii of the boron orbits of the exciton is determined by the following formula:

$$a_n^{ek}=\frac{n^2\hbar^2}{e^2m_{np}^*}\varepsilon_{0n}=0,53n^2\left(\frac{m_0}{m_{np}^*}\right)\varepsilon_{0n}(\overset{\circ}{A})\cdot \qquad (2.19.15)$$

The lower the effective mass of the loaders and the higher the value of the dielectric constant (ε_{0n}) , the less energy of the exciton and the greater the radius of the boron orbit. In practice, it is more difficult to observe excites with large radiations. This is because the energy levels of such excites are very close to the conductivity zone (almost fused with it). An exciton with a large radius (relative to the parameter of the crystal cage) is called a Mott exciton.

The total energy of the exciton:

$$E_{yM} = T^{ek} + E^{ek} \qquad (2.19.16)$$

Each energy level must be converted into a zone with a sufficiently wide width. However, in experiments, when light is absorbed by an exciton, its energy levels are observed in the form of lines with very narrow energy levels. This, in turn, is related to the selection of the wave vector of the exciton.

Another type of exciton is an exciton with a small radius or a strong bond. These are commonly referred to as Frankel's excitement. Such excites can be described by the convergence of a strongly bonded electron. In this case, the expression for the specific values of the energy of the exciton is the same as the expression for a strongly bonded electron. Thus, the energy spectrum of the exciton is made up of separate zones.

A further excited state in crystals dominating the ion bond can be described by means of a quasi-particle. In such crystals, the conductive electron (and the ionized adsorption atom) polarizes its immediate surroundings through its electric field, and the greater the dielectric constant of this polarizing medium, the stronger it is. As a result of polarization, the energy of the electron decreases, i.e., a potential hole is formed around the electron. Thus, a state arises that is self-connected and can move along the entire crystal. Self-bonding consists in the fact that the localized electron polarizes the crystal, while the polarization of the crystal, in turn, helps to maintain the localized state of the electron. When the electron moves, it also "follows" the polarization of the crystal. Thus, the electron polarizes the regions that have just come across on its path, and the previously polarized regions return to their previous state as the electron moves away from it. Such free charges, which move in the environment in which they are polarized, were first studied by S.I. Pekar (in 1946). He called it the polyaron, which is formed in the crystal. Therefore, when we say polyaron, it is necessary to understand the electron and the region that it polarizes in the crystal around its vicinity.

It should be noted that the formation of polarion is not caused by the complete polarization of the crystal, but only by the inertia part of the crystal, which is associated with the displacement of heavy ions $10^{-13} san$. The other part of the electron that is associated with the polarization of the electron layers (orbit) ($10^{-15} san$ which has a relaxation period) moves inertially along with the free electron, and thus enters the self-bound periodic potential, which is directly affected by the crystal on the electron.

The polaron state forms an entire zone in the crystal, and the polaron moves in this zone. The movement of the polar in this zone is the same as the laws that the electron follows during its movement in the conductive zone. However, there is only one condition that must be met, so that the polarization of the medium does not lag behind the displacement of the electron (not too inert).

If the energy of interaction with the hole that the electron itself has "drilled" is greater than the thermal energy, then the communication on the polaron is strong enough, and it is more energetically favorable to be in the state of polaron, which is located in the forbidden zone below it, than to be in the zone of conduction to the electron. If we refer to the number of electrons in the conductivity zone n_e and the number of electrons in the polaron state n_n , then the polaron is ε_n the energy of the polaron.

$$\frac{n_e}{n_n} \sim e^{\frac{\varepsilon_n}{kT}}. \tag{2.19.17}$$

It should be noted that the polaron zone is located below the conductivity zone and its width is smaller than the width of the conduction zone; as well as the effective mass of the electron (polarion) carrying the "fur" with it in the corresponding zone may be quite large compared to the electron of the conduction zone. Accordingly, the temperature dependence of the polaron on is completely different from that of an electron in nature. And the Prophet (peace and blessings of Allaah be upon him) said: "O Messenger of Allah, I am the Messenger of Allah, To illustrate this, let's imagine a polaron (polyaron packet) localized near any node point in the crystal cage. This type of situation that does not have translational symmetry cannot be sustainable. It will either travel through a tunnel through the entire crystal like an electron in the conduction zone (but with a greater effective mass) (the wave packet will "propagate" across the entire crystal), or it will fall into the hole created by the heat dances of the crystal cage in its neighborhood without expending any energy. With a certain effective "sedentary" duration τ_1, the probability of the transition of the described first state W_1 does not depend on the temperature at the first approach. The τ_2 probability of the second case, which is characterized by duration, W_2 will depend exponentially on the temperature, since the probability of the formation of an "empty" hole increases W_2 exponentially depending on the temperature:

$$W_2 \sim e^{-\frac{\varepsilon_n'}{kT}} \qquad (2.19.18)$$

Here ε_n' is the energy of the formation of the empty pit. The outcome of the poll will depend on which of these two cases prevails. It is less likely that an "empty" hole will form due to heat energy at sufficiently low temperatures. That's why $W_1 >> W_2$. $\tau_1 << \tau_2$ . . Thus, after a randomly localized polar period, it τ_1 will again become a zone electron, and the heat dances inhibit the movement of the zone electron. In this case, with an increase in temperature, the validity of the polar vortex decreases. At high temperatures, on the contrary, empty holes are more likely to form. Therefore, $W_2 >> W_1$ and $\tau_2 << \tau_1$. As the intensity of the heat dances increases, empty holes will form very often, and the polaron will "jump" from one of them to the other. Since it is already available $W_1 << W_2$, the displacement of polar (either as a result of diffusion or by the influence of the field) will be mainly due to the second mechanism. This is called the jump (or jumping) mechanism. In this case, the validity of polyarone will increase exponentially with the increase in temperature:

$$\mu \sim e^{-\frac{\varepsilon_n'}{kT}} . \qquad (2.19.19)$$

In its own way, this expression is similar to the dependence of the flow of ionism on temperature. This is why the mechanism that we have described above is called the leap mechanism. It should also be noted that the exponential dependence of polarity on temperature is related to the probability of the formation of a sufficiently deep hole in the neighborhood, which itself ε_n' is not the depth of the hole, but the energy of its formation.

Localized polyarone can remain "stuck" near any defect (defect) of the crystal cage. This is exactly the same as an electron caught by a defect.

Another type of quasi-particle is uncharged particles, which describe waves that correspond to the propagation of the heat dances of the crystal cage. As a result of the propagation of the heat dances of atoms, there are a large number of stationary waves in the crystal, which differ from each other in wavelengths. Just as in the corpuscular theory of light it is possible to replace every wavelength of light with a particle of a certain energy with a particle of a certain energy, so in the theory of solids, it is possible to replace each static wave of heat dances with a certain wavelength with a particle of corresponding energy. This particle is called a phonograph. Thus, the static waves created by the heat dances in the crystal cage are replaced by phonon gas. This makes it easier to describe a number of properties of a crystal cage.

SECTION 20. THE FUNCTION OF DISTRIBUTING THE DISTANCE AND DURATION OF THE FREE ESCAPE

The average length of the jt freeway and the duration of the free run varies from zero to infinity over a wide range for different loaders. Therefore, it is necessary to determine the probability of finding a free escape. For this purpose, let's assume that,

1) The probability of an electron *being subjected to a collision at a given DT* time interval is directly proportional to the *DT* interval;

2) The probability of a collision in a single time is a constant quantity with respect to time;

In order to determine the distribution function of this purpose\free escape path*, let's express the probability of a particle moving without being subjected to collision in the time interval* t, t + dt as follows:

$$d\varpi = d\varpi(dt) \qquad (1.3.1)$$

where ϖthe quantity (t) is (t, t+1), ϖand (t+dt) t+dt, t+dt+1 is the probability of free motion of the dread in the time interval t+dt+1. ϖ The value (t+dt) can be expressed as follows: On the one hand,

$$\varpi(t+dt) = \varpi(t) + \frac{d\varpi}{dt}dt \qquad (1.3.2)$$

On the other hand, the free tact of motion during *the period t+dt* can be expressed as the product of two motions according to probability theory. For example, event C can be expressed as the product of two events; And *the* Prophet (peace and blessings of Allaah be upon him) said: "O Messenger of Allah, I am the

Messenger of Allah (peace and blessings of Allah be upon him) and I am the Messenger of Allah (peace and blessings of Allah be upon him).

$$C=AB \tag{1.3.3}$$

The probability of the product of two events is equal to the probability of the conditional probability of the other event:

$$\varpi(C)=\omega(A)\varpi\left(\frac{B}{A}\right)=\varpi(B)\varpi\left(\frac{A}{B}\right) \tag{1.3.4}$$

Since event A does not depend on event B, ϖ (A/B) = ϖ (We can write A. Event B does not depend on event A, so it can be written:

$$\varpi(t+dt)=\varpi(t)d\varpi(dt) \tag{1.3.5}$$

We can also express the probability of free movement during the period under consideration by the probability of scattering during that period. Since the probability of scattering (collision) in a unit time adt is 1, and the probability of free movement is 1, adt we can write:

$$d\varpi(dt)=1-adt \tag{1.3.6}$$

Let's take a look at the comparison of the above statements:

$$\varpi(t+dt)=\varpi(t)+\frac{d\varpi}{dt}dt=\varpi(t)[1-adt]=\varpi(t)-\varpi(t)adt \tag{1.3.7}$$

This is ϖ for the function (t).

$$\frac{d\varpi}{dt}=-\varpi a \tag{1.3.8}$$

This leads to the differential equation.

Let's take a look at the average price of a free spin <t> as follows:

$$< t >= \int_0^\infty t\varpi(t)dt = \int_0^\infty tae^{-at}dt = \frac{1}{a}$$

(1.3.13)

If we substitute the average running time τ with <t>=τ, then we get according to (1.2.13) that the **probability of a collision in a unit time is equal to the inverse value of the average free running time:**

$$a = \frac{1}{\tau} = \tau^{-1} \qquad (1.3.14)$$

In this case, the distribution function normalized to unity is

$$\varpi(t) = \frac{1}{\tau}e^{-\frac{t}{\tau}} \qquad (1.3.15)$$

In a similar way ℓ, we can find the distribution function $\varpi(x)$ of the free escape route:

$$\varpi(x) = \frac{1}{\ell}e^{-\frac{x}{\ell}} \qquad (1.3.16)$$

The assigned distribution functions are calculated for the most common cases. Apply them to the motion of an electron in an electric field. Moving rapidly in the electron field $\frac{eE}{m}$, during the T-free run.

$$\vec{\upsilon}(t) = \frac{et}{m}E \qquad (1.3.17)$$

It gains velocity, and it travels the distance x in time.

$$x = \frac{eE}{2m}t^2 \;\; ; \;\; \vec{x} = \frac{et^2}{2m}\vec{E} \qquad (1.3.18)$$

In this case, the average velocity of the drift is

$$\vec{\upsilon}_d = \int_0^\infty \vec{\upsilon}(t)\varpi(t)dt = \frac{e\vec{E}}{m}\int_0^\infty te^{-\frac{t}{\tau}}\frac{dt}{\tau} = \frac{e\tau}{m}\vec{E}\,, \qquad (1.3.19)$$

In contrast to the middle field, the

$$\vec{\ell} = \int_0^\infty \vec{x}(t)\varpi(t)dt = \frac{e\vec{E}}{2m}\int_0^\infty t^2 e^{-\frac{t}{\tau}}\frac{dt}{\tau} = \frac{e\tau^2}{m}\vec{E} \qquad (1.3.20)$$

They can. Here's a breakdown of the speed and speed of the drive:

$$\vec{\upsilon}_d = \frac{e\tau}{m}\vec{E} = \mu\vec{E}, \qquad (1.3.21)$$

$$\mu = \frac{e\tau}{m} \qquad (1.3.22)$$

From all of this, it can be concluded that the τ average running time is or the time between two collisions. It is determined not by the speed of the drift motion, but by the length of the free-running path and the full velocity of the particle. The full velocity depends on the energy of the particle, and for this **reason, the free running time is a function of the energy of the particle.** If the free escape route itself is also dependent on energy, this dependence becomes even more complicated.

SECTION 21. INVERTED CRYSTAL CAGE

The arrangement of atoms within the crystal lattice has a certain periodicity. In other words, a crystal is a vector in its entirety $\vec{a}_n$.

$$\vec{a}_n = n_1\vec{a}_1 + n_2\vec{a}_2 + n_3\vec{a}_3 \tag{1}$$

And if we continue to do so, it will continue to fall on its own. Here, $\vec{a}_1, \vec{a}_2, \vec{a}_3$, the numerical value is equal to the corresponding languages of the elementary crystal core, and the vectors oriented in their positive direction n_1, n_2, n_3 are integers (positive and negative). $a_i(i=1,2,3)$ Vectors are called translational or base vectors.

Within the crystal, such as electrostatic potential, electron cloud density, etc., have three-dimensional periodicity. Since the points within the crystal $\vec{r}$ and $\vec{r}+\vec{a}_n$ characterized by its vectors are equivalent, the following condition is met for the electrostatic potential:

$$V(\vec{r}) = V(\vec{r} + \vec{a}_n), n = 1,2,3... \tag{2}$$

To simplify the calculation, let's $\vec{a}_i(i=1,2,3)$ use the vectors and select three new vectors like this:

$$\vec{b}_1 = \frac{[\vec{a}_2\vec{a}_3]}{(\vec{a}_1[\vec{a}_2\vec{a}_3])};\ \vec{b}_2 = \frac{[\vec{a}_3\vec{a}_1]}{(\vec{a}_1[\vec{a}_2\vec{a}_3])};\ \vec{b}_3 = \frac{[\vec{a}_1\vec{a}_2]}{(\vec{a}_1[\vec{a}_2\vec{a}_3])}, \tag{3}$$

Here the expression in the denominator of all three vectors is the mixed product of the base vectors. It is known that this product $a_i(i=1,2,3)$ is equal to the volume of the parallelpiped (i.e., the elementary core) built on these vectors. Ω_0 Let's take a look at it:

$$\Omega_0 = \left(\vec{a}_1\left[\vec{a}_2\vec{a}_3\right]\right) \tag{4}$$

(3) It can be seen from the expression (3) that $b_i\left(i=1,2,3\right)$ the degree of dimension of the vectors is equal to the inverse of the dimension of length. For example, if we are going to use the Cubic Synagogue $a_1 = a_2 = a_3 = a$ $b_1 = b_2 = b_3 = b$, we $b = \frac{1}{a}$ will take it. $a = 1$ If we could get the SMS $b = 1\frac{1}{sm}$, it would be fine.

If we $\vec{b}_i\left(i=1,2,3\right)$ build parallelpipes on their vectors and arrange these parallelpipes side by side in all three directions, we will still get a three-dimensional lattice, just like in a crystal lattice. This type of three-dimensional grid **is called an inverted crystal lattice**. They $\vec{b}_1, \vec{b}_2, \vec{b}_3$ are base (or translation) vectors in an inverse crystal lattice. In a $\vec{b}_i\left(i=1,2,3\right)-$parallelpipe built on vectors, we will call it the elementary core of an inverted crystal lattice. A vector that connects any two node points of an inverted crystal lattice is called an inverse crystal lattice vector. In general, we can express this vector as follows:

$$\vec{b}_g = g_1\vec{b}_1 + g_2\vec{b}_2 + g_3\vec{b}_3 \tag{5}$$

Here g_1, g_2 are the g_3 exact numbers.

Here are $\vec{a}_n$ the vectors of the straight crystal $\vec{b}_g$ cage.

The volume of the elemental core of an inverted crystal lattice is equal to the inverse value of the volume of the elemental core of a flat crystal lattice:

$$\left(b_1\left[b_2 b_3\right]\right)=\frac{1}{\Omega_0} \tag{6}$$

In crystallography, the idea of an inverse crystal lattice arose from the problem of dividing any function with the periodicity of a flat crystal lattice into the Fourier order. Such an approach facilitates the study of the motion of an electron in a solid body (in a periodic field) on the basis of quantum mechanics.

The inverse crystal lattice vector has the following two important properties.

Theorem 1. If g1 : g2 : g3 = h : k : l, then the $\vec{b}_g = g_1\vec{b}_1 + g_2\vec{b}_2 + g_3\vec{b}_3$ **inverse lattice vector is perpendicular to the plane of the flat lattice (HKL)** (Figure 1).

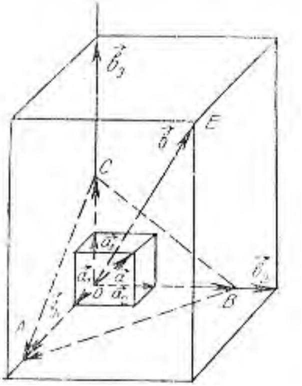


Figure1.

Theorem 2. The $\vec{b}_{hkl}$ **– length of the inverse lattice vector is equal to the inverse value of the distance between two adjacent planes in a family of parallel planes corresponding (HKL) in a straight lattice.**

SECTION 22. PERIODIC FIELD OF THE CRYSTAL LATTICE. BLOX WAVE

The Schrödinger equation for a single electron is expressed as follows:

$$[(-\hbar^2/2m)\Delta + U(\vec{r})]\Psi(\vec{r}) = E\Psi(\vec{r}),$$

(1)

Here, $U(\vec{r}) = U_i(\vec{r}_i) = \Omega(\vec{r}_i) + V_i(\vec{r}_i)$ the area of the electron in the crystal lattice and the rest of the energy interacting with the electrons depend on the properties of the lattice. One of the most important features of the crystal cage is its periodicity. In this $\vec{n}$ way, as far as the translation vector goes, a point that is identical to the initial point is obtained: $\vec{n} = n_1\vec{a}_1 + n_2\vec{a}_2 + n_3\vec{a}_3$, $\vec{a}_1, \vec{a}_2, \vec{a}_3$ it is the base of the cage. Of course, there is a need for a periodic table of energy.

$$U(\vec{r} + \vec{n}) = U(\vec{r}) \qquad (2)$$

It has to be in shape.

In the case of an operator, this condition is

$$\hat{T}(\vec{n})U(\vec{r}) = U(\vec{n} + \vec{r}) \qquad (3)$$

It can be written here, but here $\hat{T}(\vec{n})$ it is called the translation operator. 2) It is evident from the equation that $\vec{r}$ and $\vec{n} + \vec{r}$ its points are physical equivalent. So, if we write in Schrödinger's equation $\vec{r}$ instead $\vec{r} + \vec{n}$, the wave $\vec{r} + \vec{n}$ function corresponding to his argument $\Psi(\vec{r})$ differs from the wave function Cn by the constant multiplication:

$$\Psi(\vec{r} + \vec{n}) = C_n\Psi(\vec{r})$$

In other words, the $U(\vec{r})$ modulus of the wave function remains unchanged due to the periodicity of the potential field

$\left|\Psi(\vec{r})\right|$ in the shift as much as the translation vector , but only its phase changes.

$\Psi(\vec{r}+\vec{n})$ The normalization condition for the wave function is as follows:

$$\int_{-\infty}^{\infty}\Psi(\vec{r}+\vec{n})\Psi^{*}(\vec{r}+\vec{n})dr=\left|C_{n}\right|^{2}\int_{-\infty}^{\infty}\Psi(\vec{r})\Psi^{*}(\vec{r})dr \qquad (4)$$

In accordance with the terms of normalization:

$$\int_{-\infty}^{\infty}\Psi(\vec{r})\Psi^{*}(\vec{r})dr=1, \qquad (5)$$

It will be taken from him $\left|C_{n}\right|^{2}=1$. This means that Cn is equal to either a unit or an imaginary exponent. CNN is considered to be an –imaginary exponent. Taking into account that the top of the exponent is an unnamed number and $\vec{n}$ – in is a unit of length, it is assumed that one-third is an additional multiplication with a unit of measurement $^{m-1}$. This quantity is called a **wave vector** and $\vec{K}$ is denoted by it. The modulus of this quantity *is called the wave number*, and its ***physical meaning*** is π the waves that are located in 2 parts:

$$\left|\vec{k}\right|=\frac{2\pi}{\lambda} \qquad (6)$$

So,

$$C_{n}=e^{i\vec{k}\vec{n}} \qquad (7)$$

The effect of the periodic field of the crystal lattice on the wave function of the free electron mathematically appears as an additional multiplication in front of this function:

$$\Psi(\vec{r}+\vec{n})=e^{i\vec{k}\vec{n}}\Psi(\vec{r}) \qquad (8)$$

This condition is called the translation property of the wave function of the electron in the crystal . This is in the form of an operator.

$$\hat{T}(\vec{n})\Psi(\vec{r}) = e^{i\vec{k}\vec{n}}\Psi(\vec{r}) \tag{9}$$

who is written. In this case $\Psi(\vec{r})$, the function of the broadcast operator is $e^{i\vec{k}\vec{r}}$ its own value. As we know from quantum mechanics, the Hamiltonian $\hat{H}$ and the translation operator command $\hat{T}(\vec{r})$ each other, which means that they have a common system of wave functions. It follows from this that during the movement of the electron in the crystal, the wave function of Hamiltonian satisfies the translation condition, and the wave function $\vec{K}$ depends on the wave vector: $\Psi = \Psi(\vec{k})$. Hamiltonian's specific values $\vec{K}$ will depend on $E = E(\vec{k})$ the energy and wave vector of the system. This statement ***is called the law of dispersion*** of the energy of the electron in the crystal. $E(\vec{r})$ And the $\Psi_{\vec{k}}(\vec{r})$ ***search for their dependencies is the main problem of the zone theory of solid-state physics.***

Let's take a look at the solution of Schrödinger's equation for the motion of an electron in the periodic field of the crystal. For this purpose, let's multiply both sides of equation (8): $e^{-i\vec{k}(\vec{r}+\vec{n})}$

$$e^{-i\vec{k}(\vec{r}+\vec{n})}\Psi(\vec{r}+\vec{n}) = e^{-i\vec{k}\vec{r}-i\vec{k}\vec{n}+i\vec{k}\vec{n}}\Psi(\vec{r}) = e^{-i\vec{k}\vec{r}}\Psi(\vec{r})$$

$e^{-i\vec{k}\vec{r}}\Psi(\vec{r}) = \varphi_{\vec{k}}(\vec{r})$ If we accept this expression, it would look like the following:

$$e^{-i\vec{k}(\vec{r}+\vec{n})}\Psi(\vec{k}+\vec{n}) = e^{-i\vec{k}\vec{r}}\Psi(\vec{r}) = \varphi_{\vec{k}}(\vec{r})$$

And so it $\varphi_{\vec{k}}(\vec{r}) - u(\vec{r})$ has the same periodicity as the potential field:

$$\varphi_{\vec{k}}(\vec{r} + \vec{n}) = \varphi_{\vec{k}}(\vec{r}) \tag{10}$$

Then the wave function $\Psi_{\vec{k}}(\vec{r})$, which is the solution of Schradinger's equation for the motion of an electron in a crystal

$$\Psi_{\vec{k}}(\vec{r}) = \varphi_{\vec{k}}(\vec{r}) e^{i\vec{k}\vec{r}} \tag{11}$$

It can be in shape.

Thus, using the condition of the periodicity of the potential field of the crystal, we determined the shape of the wave function of the electron, without solving the Schrödinger equation. (11) It is derived from the statement that the solution of Schrödinger's equation for an ideal crystal is a plane wave modulated by amplitude $(e^{i\vec{n}\vec{k}}$ with the periodicity of the crystal lattice (11). This solution ***is called the Blox wave*** or ***the Blox function***. From the expression of the blox wave, it appears that it does not depend on n. $e^{i\vec{n}\vec{k}}$ We think of a plane wave as a function of a variable amplitude wave modulated in a crystal lattice tact $\varphi_k(\vec{r})$. Since it is different for different wave vectors $\varphi_{\vec{k}}(\vec{r})$, $\varphi_{\vec{k}}(\vec{r})$ the markup is accepted.

When we compare the Bloch wave with the de Broyle wave $\Psi_{\vec{k}}(\vec{r}) = Ae^{i\vec{k}\vec{r}}$, it has a more visual physical meaning. If the electron changes its position from free space to crystal, then, of course, the wave function of the electron will be modulated by the constant period of the crystal lattice according to the expression (10) under the influence of the periodic field of the crystal.

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SECTION 23. THE RELATIONSHIP BETWEEN VELOCITY AND QUASI-IMPULSE

The acceleration operator $\hat{\vec{v}}$ is determined by Poisson's quantum brackets:

$$\hat{\vec{v}} = \frac{d\hat{\vec{r}}}{dt} = \left[\hat{H}, \hat{\vec{r}}\right] = \frac{1}{i\hbar}\left(\hat{\vec{r}}\hat{H} - \hat{H}\hat{\vec{r}}\right), \tag{1}$$

This is $\hat{\vec{r}}$ the coordinate operator, $\hat{H}$ and the Hamilton operator is the Hamilton operator. $\hat{\vec{r}}$ and $\hat{H}$ to calculate their operators, it $\vec{k}$ is more convenient to move to E or -descriptions, so that all operators $\vec{k}$ are expressed in the form of certain operations on functions that depend on the operators. $\hat{H}$ The Hamilton operator, $\vec{k}$ or in the descriptions of E, is either **the multiplication operator,** or simply the energy E($\vec{k}$).

$$\hat{H}\left(\vec{k}\right) \equiv E\left(\vec{k}\right) \tag{2}$$

In order to define the $\hat{\vec{r}}$ operator ($\vec{k}$) here, we can use the condition $\psi_k\left(\vec{r}\right)$ that the function $\hat{\vec{r}}$($\vec{k}$) is closely related to $\psi_k\left(\vec{r}\right)$ the function of the operator, which is a special function:

$$\hat{\vec{r}}\left(\vec{k}\right)\psi_r\left(\vec{k}\right) = \vec{r}\psi_r\left(\vec{k}\right) \tag{3}$$

Here $\vec{r}$ is the value of the coordinate operator, $\psi_r\left(\vec{k}\right)$ and its $\vec{k}$ specific function is given in the description.

It is known from quantum mechanics that the special functions of two operators in a mutual description are in a simple relationship: $\hat{\vec{L}}$ The function of the operator in the M Diagram

$\psi_L(M)$:

$$\hat{\vec{L}}(M)\psi_L(M)=L\psi_L(M) \tag{4}$$

$\hat{\vec{M}}$ This $\psi_M(L)$ is the function of the operator in the description of L.

$$\hat{\vec{M}}(L)\psi_M(L)=M\psi_M(L) \tag{5}$$

And if they do, then they will have

$$\psi_L(M)=\psi_M^*(L) \tag{6}$$

They can. In this $\vec{k}$ case, $\hat{\vec{r}}(\vec{k})$ the function of the operator is the function of the operator.

$$\psi_r(\vec{k})=\psi_k^*(\vec{r})=e^{-i(\vec{k}\,\vec{r})}\varphi_k^*(\vec{r}) \tag{7}$$

It can be written that from now on, we can easily find the picture of the operator $\hat{\vec{r}}(\vec{k})$ based on the equations corresponding to special functions and special values:

$$\hat{\vec{r}}(k)\psi_r(\vec{k})=\vec{r}\psi_r(\vec{k}) \tag{8}$$

Or

$$\hat{\vec{r}}(k)\psi_k^*(\vec{r})=r\psi_k^*(\vec{r}) \tag{9}$$

The implication of these relationships is that $\hat{\vec{r}}(\vec{k})$ it is necessary to choose the form of the operator in such $\psi_k^*(\vec{r})$ a way that the product of that function $\vec{r}$ is obtained as a result of its influence on its function. This $\psi_k^*(\vec{r})$ $\vec{k}$ has to be done in terms of the function of time.

$\frac{d}{d\vec{k}}=\nabla_{\vec{k}}$ Let's take a look at the function of the operator

$\psi_{\mathrm{k}}^{*}(\vec{\mathrm{r}})$:

$$\nabla_{\vec{k}}\psi_{\vec{k}}^{*}(\vec{r})=\nabla_{\vec{k}}\left[e^{-i(\vec{k}\vec{r})}\varphi_{k}^{*}(r)\right]=-i\vec{r}\,\psi_{k}^{*}(\vec{r})+e^{-i(\vec{k}\vec{r})}\nabla_{\vec{k}}\varphi_{\vec{k}}^{*}(\vec{r})= \quad (10)$$

$$=-i\vec{r}\,\psi_{k}^{*}(\vec{r})+\psi_{\vec{k}}^{*}(\vec{r})\left[\nabla_{\vec{k}}\,ln\,\varphi_{л}^{*}(r)\right],$$

Or

$$\vec{r}\,\psi_{\vec{k}}^{*}(\vec{r})\equiv\left[i\nabla_{\vec{k}}-\left(i\nabla_{\vec{k}}\,ln\,\varphi_{\vec{k}}^{*}\right)\right]\psi_{\vec{k}}^{*}(\vec{r})\equiv\hat{\vec{r}}(\vec{k})\psi_{\vec{k}}(\vec{r}), \quad (11)$$

So,

$$\hat{\vec{\mathrm{r}}}(\vec{\mathrm{k}})=\mathrm{i}\nabla_{\vec{\mathrm{k}}}-\mathrm{i}\left(\vec{\nabla}_{\vec{\mathrm{k}}}\ln\varphi_{\vec{\mathrm{k}}}^{*}\right) \quad (12)$$

The operator is given in the form of a sum consisting of the product of any function that $\vec{\mathrm{k}}$ is differentiated by the number of waves (or quasi-impulse) and $\vec{\mathrm{k}}$ (or $\vec{\mathrm{r}}$ depends on). -$\mathrm{i}\left(\vec{\nabla}_{\vec{\mathrm{k}}}\ln\varphi_{\vec{\mathrm{k}}}^{*}\right)$ Instead of a limit $\nabla_{\vec{\mathrm{k}}}\varphi_{\mathrm{k}}^{*}$, the function φ_{k} can be divided by its functions and $\vec{\Omega}$ any operator can be included. $\mathrm{U}(\vec{\mathrm{r}})$When =sonst, the second limit is converted to zero, and $\hat{\vec{\mathrm{r}}}(\vec{\mathrm{k}})$ the operator $\vec{\mathrm{p}}$ becomes the usual coordinate operator in the -description, so that in this case the quasi-impulse and the momentum are identical. Now the expression of the velocity operator $\vec{\mathrm{k}}$ in the -description

$$\hat{\upsilon}(\vec{\mathrm{k}})=\frac{1}{\mathrm{i}\hbar}\left\{\hat{\vec{\mathrm{r}}}(\vec{\mathrm{k}})\mathrm{E}(\vec{\mathrm{k}})-\mathrm{E}(\vec{\mathrm{k}})\hat{\vec{\mathrm{r}}}(\vec{\mathrm{k}})\right\}=\frac{1}{\hbar}\frac{\mathrm{dE}(\vec{\mathrm{k}})}{\mathrm{d}\vec{\mathrm{k}}} \quad (13)$$

It can be written in the form of a **multiplication operator for the derivative of energy by quasi-impulse:**

$$\hat{\vec{\upsilon}}(\vec{\mathrm{k}})=\frac{1}{\hbar}\frac{\mathrm{dE}(\vec{\mathrm{k}})}{\mathrm{d}\vec{\mathrm{k}}}=\frac{\mathrm{dE}}{\mathrm{d}\vec{\mathrm{P}}}=\hat{\vec{\upsilon}}(\vec{\mathrm{P}})=\vec{\upsilon}\,. \quad (14)$$

This relationship is similar to the expression of the wavepacket for the group velocity:

$$\vec{\upsilon}_{qr} = \frac{dE}{d\vec{P}} \tag{15}$$

$E(\vec{k})$The average velocity of an electron in an energetic state (but $\psi_k^*(\vec{r})$ not $\psi_k(\vec{r})$ with a wave function) has a completely definite value, and it depends on this case.

$$< \vec{v} > = \vec{v} = \frac{1}{\hbar}\frac{dE}{d\vec{k}} = \frac{dE}{\vec{P}} \tag{16}$$

Some of them are (< > here).

Thus, in a very small energy interval, the average value of the velocity of an electron **in certain energetic states** is determined as the derivative of the energy relative to the quasi-impulse. In the case of the extreme, the average velocity in the quantum mechanical sense is equal to zero (after that, we will discard the words "average velocity in the quantum mechanical sense").

If we look at the proximity of the extreme points, the energy in this interval is a quadratic function of the quasi-impulse:

$$E - E_0 = \frac{1}{2m^*}\left(\vec{P} - \vec{P}_0\right)^2 = \frac{1}{2}\sum_{i=1}^{3}\frac{\left(P_i - P_{oi}\right)\left(P_j - P_{oj}\right)}{m_{ij}} \tag{17}$$

Speed

$$\upsilon_i = \frac{\partial E}{\partial P_i} = \sum_{i=1}^{3}\frac{P_j - P_{oj}}{m_{ij}}, \tag{18}$$

Or in the form of a vector.

$$\vec{\upsilon} = \frac{1}{m^*}\left(\vec{P} - \vec{P}_0\right) \tag{2.7.19}$$

In other words, in general, **the velocity is equal to the scalar product of the quasi-impulse to the inversely effective mass**

tensor. If the tensor m^{*-1} is diagonal in shape,

$$\left\{m^{*-1}\right\}_{ij} = m_i^{-1}\delta_{ij} \tag{20}$$

In this case, the expression (18) is simple:

$$\upsilon_i = \frac{P_i - P_{oi}}{m_i} \tag{21}$$

Since velocity is an energy gradient in quasi-impulse space, it is $\vec{P} - \vec{P}_0$ directed according to the normal of the surface at all points with a radius-vector on isoenergetic surfaces.

Since the radius-vector and the normal surface are not collinear on ellipsoidal isoenergetic surfaces, the directions of velocity and quasiimpulse do not coincide. The collinearity condition for such surfaces will be paid only along the axes of the ellipsoids (Fig. 1), in this case

$$P_i = P_{oi} = \sqrt{2m_i\left(E - E_0\right)} \tag{22}$$

São

$$\upsilon_i = \frac{\sqrt{2\left(E - E_0\right)}}{\sqrt{m_i}} \tag{23}$$

We get it.

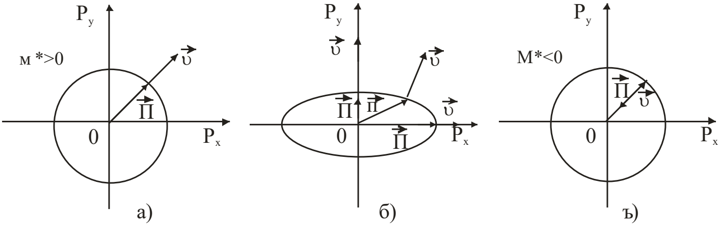
Thus, **at the same value of energy, the velocity along the axes of the ellipsoid is inversely proportional to the square root of the corresponding component of the effective mass.** Ellipsoids

$$a_i = \sqrt{2m_i\left(E - E_0\right)} \tag{24}$$

To get the speed of the arrows

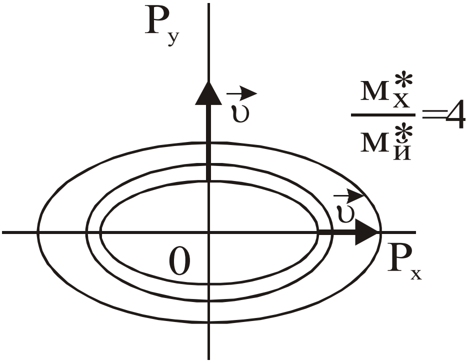
$$\upsilon_i = \frac{a_i}{m_i} = \frac{\sqrt{2\left(E - E_0\right)}}{\sqrt{m_i}} \tag{25}$$

We get their expressions. It is evident that the more the ellipsoids are stretched, the smaller the velocity in that direction. If we build a family of isoenergetic energy levels, this becomes more noticeable (*Fig. 2*). The smaller the effective mass, the more dense the isoenergetic surfaces are located in this direction, and accordingly, the velocity along that axis is greater.



Fügure 1 Directions of the normal radius-vector and isoenergetic surface:
a- spherical isoenergetic surface; b- ellipsoidal isoenergetic surface;
c- Spherical isoenergetic surface, m<0.*

It is important to note an important moment in connection with the sign of effective mass. For simplicity's sake, let's assume that the effective mass is a scalar quantity. In this case $\vec{\upsilon}$, and $\left(\vec{P} - \vec{P}_0\right)$ the vectors are colliniary, but their direction depends on the shape of the extreme. For the minimum, m*>0 and $\vec{\upsilon}$ its velocity $\left(\vec{P} - \vec{P}_0\right)$ coincide with the direction. For the maximum energy, m*<0 is in this case, in which case $\vec{\upsilon}$ the copy vector is $\left(\vec{P} - \vec{P}_0\right)$ directed opposite to the quasi-impulse vector (Fig. 1c).



Sugar. 2. The relationship between fast effective mass and the density of isoenergetic surfaces

SECTION 24. ZONAL STRUCTURE OF SOME SEMICONDUCTORS

Calculating the quantitative structure of any substance is associated with certain difficulties. The problem with this approach is that there is no definitive analysis of the potential of the crystal cage. Therefore, all such calculations usually involve physical parameters that can only be computed empirically in the basic formulas. Such parameters include, for example, the width of the prohibited zone, the value of the effective mass, etc.

For a crystal, an electron problem can be solved by quasi-free and quasi-closed electron convergences with two types of approximation. Another method is the orthogonalized plane wave method, which consists of a convenient combination of these. Here, during the movement of the electron in the crystal, the wave function is distinguished as a combination of plane waves, from which the wave functions of the inner electrons for the atom are derived. The wave functions of the internal electrons themselves are selected as a combination of the Blox function, which is in the approximation of a strongly bonded electron. Thus, the wave function of the electron in the crystal behaves as a plane wave in the interatomic space, and at the node points (around the atoms) as an atomic wave function. In this case, however, there are some challenges to solve. For example, when this method is applied to silicon and germanium crystals, it is necessary to solve an equation with a formula of 146 to obtain the expression of energy at the arbitrary point of the Brillyuen zone. In this case, the problem is solved by the application of group theory, and although it is simplified enough for points with load-symmetry, the equation of 16 machullui is still obtained, which can only be solved by numerical calculations.

Let's take a look at some of the more common types of semiconductor substances.

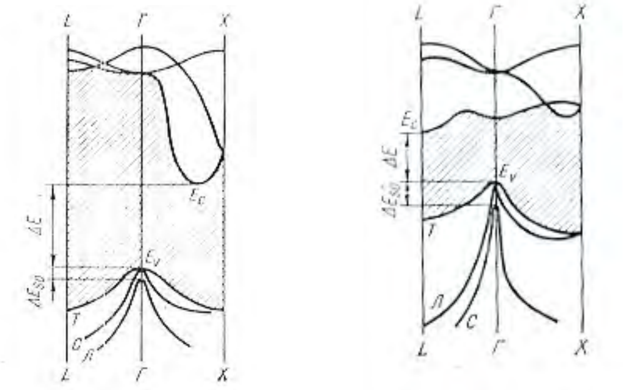
(a) Silicon and germanium crystals. As can be seen from the structure of the electron layers (2), the last, partially charged layer in these substances p is the layer, where two electrons are located with spins parallel to each other, i.e., the main state is a triplet. The zone structure of silicon and germanium has been calculated by German and others for a number of points in the Brillyuen zone that have high symmetry by the orthogonalized plane wave method. For other points, the prices of energy $[E(\vec{k})]$ are obtained by interpolation.

The theoretical calculations were compared with the results obtained in practice, checked, and a number of adjustments were made to them. Both substances p are involved in the formation of conductivity and valence zones. Therefore, p it is necessary to use wave functions that correspond to the Blox function of the spin convergence (which has triple friction if spin is not taken into account) when compiling the Blox function.

As a result of the interaction, friction disappears, and each of the two zones (valence and conductivity zones) consists of three bands. In the meantime, the two sides are partly divided into two zones.

Figures 1a and 1b show the dependence of energy on the wave vector in the directions [111] and [100] for silicon and germanium. This attitude varies in different directions. In the conductivity zone (for both substances), one of the branches of energy is located much lower than the other two. The state of the lowest minimum (absolute minimum) of this branch determines the bottom of the permeability zone.

In silicon, it is in the absolute minimum direction [100] (within the Brillyuen zone). There are 6 such minimum (since there are 6 equivalent directions).



a) *b*)

Figure 1. (a) *Structure of the energy zones* (b) *of silicon and germanium*

In germanium it is in the direction of the absolute minimum [111] (at the end of the Brillyuen zone), so the number of equivalent minimums is 8. The isoenergetic surfaces near the absolute minimums are in the form of a rotational ellipsoid. The axis of rotation itself was the great axis of rotation, coinciding with the direction for silicon[100] and for germanium [111]. $\vec{k}$ This is how the energy dependence around these minimums is as follows:

$$E(\vec{k}) = E(\vec{k}_0) + \frac{\hbar^2[(k_x - k_{0x})^2 + (k_y - k_{oy})^2]}{2m_1} + \frac{\hbar^2(k_z - k_{0z})^2}{2m_3} \qquad (1)$$

It $m_1 = m_2 \neq m_3$ is called "$m_1 = m_2 = m_t$ transverse" and $m_3 = m_l$ "longitudinal" effective mass, and their numerical values are determined in experiment by means of cyclotron resonance. For silicon $m_t = 0{,}19m_0$, $m_l = 0{,}98m_0$ (m_0 which is the mass of a free electron): $m_0 = 9{,}1 \cdot 10^{-28}q$

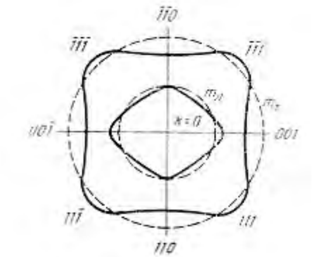
$\frac{m_l}{m_t = 5{,}16}$ The ratio determines the anisotropic properties of isoenergetic surfaces. The Ratio of Arrows:

$$\sqrt{\frac{m_3}{m_2}} = 2{,}27.$$

Its minimum points are located within the Brillyuen zone, near its border. The shape of the isoenergetic surfaces near the minimum points for the conductivity zone of silicon is shown in Figure 2.

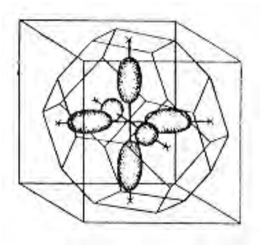
For Germanium: $m_1 = m_2 = m_t = 0{,}822m_0, m_3 = m_l = 1{,}58m_0$

$$\frac{m_3}{m_1} = \frac{m_l}{m_t} = 19{,}3; \qquad \sqrt{\frac{m_3}{m_1}} = 4{,}4.$$



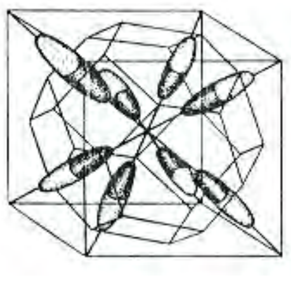
a)

Figure 2



b)

Figure 3



Cross-section of silicon and germanium with (a) the plane of isoenergetic surfaces (001) in the isoenergetic conductive zone in the valence zone (b) of silicon and germanium

The shape of isoenergetic surfaces near the minimums in the conductivity zone for Germanium is shown in Figure 3. Half of each ellipsoid remains in the first Brillyuen zone, as its minimum points fall within the boundary of the Brillyuen zone. In other words, there are 4 complete ellipsoids, i.e., there are 4 complete ellipsoids in the conductivity zone, not 8.

The maximum of the valence zone of silicon and germanium is located at the central point of the Brillyuen zone for all three branches of energy $\vec{k}=0$. Here the two zones overlap with each other, i.e., there is a double rotation, if the spin rotation is not taken into account, and the third band is separated from the other two band as a result of the interaction of the spin of the electron and the magnetic field corresponding to its orbital motion (spin-orbital interaction). The cost of fission as a result of the spin-orbital interaction is 0.035 eV for silicon and 0.28 eV for germanium.

The dependence of energy on the wave vector is more complex than the expression of the $\vec{k}=0$ approximate circumference (1) of its maximum point for the first two branches, and is determined by the following formula:

$$E_{1,2}(\vec{k})=E(0)-\frac{\hbar^2}{2m_0}\left[Ak^2\pm\sqrt{B^2k^4+C^2(k_x^2k_y^2+k_y^2k_z^2+k_z^2k_x^2)}\right] \tag{2}$$

Here m_0 - the mass of the free electron A,B,C - is an immeasurable constant. For silicon $A=4{,}1\pm0{,}2;\ B=1{,}6\pm0{,}2;\ C=3{,}3\pm0{,}5$, for germanium:

$$A=13{,}0\pm0{,}2;\ B=8{,}9\pm0{,}1;$$

$C = 10{,}3 \pm 0{,}2$ In this case, isoenergetic surfaces are not ellipsoids, but deformed ("shrunk") spheres (see Figure 3). Therefore, although it is k_x, k_y, k_z unisex dependent on energy (2), the nature of this dependence is such that it does not allow the use of the effective mass tensor. If $\vec{k}$ we use a spherical coordinate system that coincides with the polar axis in space, then we can write the expression (2.18.2) as follows: $\vec{k}_z$

$$E_{1,2}(\vec{k}) = E(0) - \frac{\hbar^2 k^2}{2m_0}\left[A \pm \sqrt{B^2 + C^2 \sin^2\theta(\sin^2\varphi\cdot\cos^2\varphi\cdot\sin^2\theta + \cos^2\theta)}\right]. \tag{3}$$

Let's take a look at the average price of all the variables in the variables:

$$\begin{aligned}&\frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi}\sin^2\theta(\sin^2\varphi\cdot\cos^2\varphi\cdot\sin^2\theta + \cos^2\theta)\sin\theta\, d\theta\, d\varphi = \\ &= \frac{1}{4\pi}\left[\int_0^{2\pi}\left(\int_0^{\pi}\sin^5\theta\, d\theta\right)\sin^2\varphi\cos^2\varphi\, d\varphi + \int_0^{\pi}\sin^3\theta\cos^2\theta\, d\theta\int_0^{2\pi}d\varphi\right] = \\ &= \frac{1}{4\pi}\left[\frac{4\pi}{15} + \frac{8\pi}{15}\right] = \frac{1}{5}.\end{aligned} \tag{4}$$

It includes:

$$E_{1,2}(\vec{k}) = E(0) - \frac{\hbar^2 k^2}{2m_0}\left[A \pm \sqrt{B^2 + \frac{C^2}{2}}\right] \tag{5}$$

And We have brought them to the surface of the earth. In this case, we will take the following scalar quantity for the effective mass of the holes:

$$m_p^* = \frac{m_0}{A \pm \sqrt{B^2 + \frac{C^2}{5}}} \tag{6}$$

In other words, each energy branch has its own characteristic scalar effective mass:

$$m_{1p}^* = \frac{m_0}{A - \sqrt{B^2 + \frac{C^2}{5}}}; \qquad m_{2p}^* = \frac{m_0}{A + \sqrt{B^2 + \frac{C^2}{5}}} \quad (7)$$

As shown in the (7) formula $m_{1p}^* > m_{2p}^*$. Therefore, holes in the zone that correspond to a large effective mass are called heavy holes, and holes in a zone that corresponds to a small effective mass are called light holes. For example, if we substitute the values of the corresponding parameters for silicon into (7):

$$m_{1p}^* = 0{,}52 m_0,$$
$$m_{2p}^* = 0{,}16 m_0,$$
$$m_{1p}^* / m_{2p}^* = 3{,}3.$$

Values derived from the experience:

$$\frac{m_{1p}^*}{m_{2p}^*} = 3{,}1, \ \ m_{1p}^* = 0{,}49 m_0, \ \ m_{2p}^* = 0{,}16 m_0.$$

Here are the results of the experiment for Germanium:

$$m_{1p}^* = 0{,}34 m_0, \ \ m_{2p}^* = 0{,}04 m_0, \ \ \frac{m_{1p}^*}{m_{2p}^*} = \sim 8.$$

For the third branch of the valence zone, the dependence of energy k on is quadratic:

$$E_3(\vec{k}) = -E_{s0} - \frac{\hbar^2}{2m_0} A k^2, \quad (8)$$

where E_{s0} the value of -spin-orbital fission is 0.035 eV for silicon and 0.28 eV for germanium. (8) It can be seen that the effective mass for the third arm is the scalar quantity:

$m^*_{3p} = \dfrac{m_0}{A}$, for silicon $m^*_{3p} = 0{,}24m_0$, for germanium $m^*_{3p} = 0{,}077m_0$. Obviously, the isoenergetic surfaces for this branch are spherical in shape.

(b) Intermetallic compounds. Substances formed from the combination of group III and V elements ($A^{III}B^{V}$ type compounds) (called intermetallic compounds) have semiconductor properties. These are the types of units that belong to this class: *GaAs*, *InSb*, *GaP*, *GaSb* and so on.

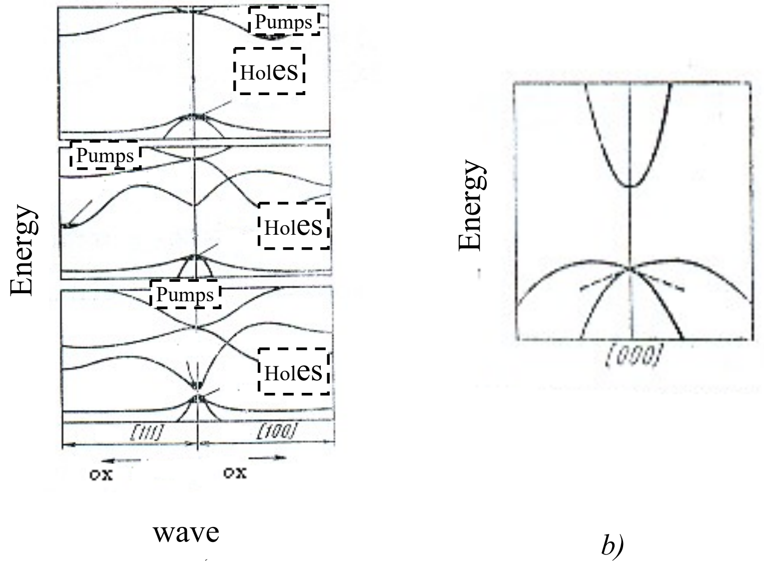
The theoretical calculation of the zonal structure of intermetallic compounds is carried out in a comparative manner with the zonal structure of the elements of the fourth group. This is due to the fact that $A^{III}B^{V}$ the type of compounds crystallizes (ZnS) in the crystal structure of the zinc sulfide ZnS.The crystal structure differs from that of diamonds in that only A atoms and B types alternate with each other . The result is that the periodic area of the crystal cage of intermetallic compounds does not have an inversion center, i.e. $U(\vec{r}) \neq U(-\vec{r})$. To solve the problem, the potential of the corresponding group IV element, whose zone structure is known, is used when compiling the periodic potential of the crystal lattice of the intermetallic compound. $A^{III}B^{V}$ The potential of the combination is taken as the sum of any excitatory antisymmetric potential with the potential of the corresponding group IV element. It is determined how the known structure of the element of group IV will change under the influence of this excitatory field (potential). This $A^{III}B^{V}$ is the potential for a combination of the following:

$$U^{III-V}(\vec{r}) = U_S^{IV-IV}(\vec{r}) + U_a^{IV-IV}(\vec{r}) + \left[\Delta U_S(\vec{r}) + \Delta U_a(\vec{r})\right],$$

Here $U_S^{IV-IV}(\vec{r})=U_S^{IV-IV}(-\vec{r}),\ U_a^{IV-IV}(\vec{r})=-U_a^{IV-IV}(-\vec{r})$, i.e., U_S the $U_a - A^{IV}B^{IV}$ symmetric and antisymmetric portion of the potential, respectively, for the "combination", ΔU_S and ΔU_a the symmetric and antisymmetric part of excitement, respectively. In order to solve the problem, the BN zonal structure of the diamond (the diamond modification "C" of carbon), $GaAS$ the structure of Ge-un, AIP - Si for, and $InSb$ $\alpha - Sn$ for -is taken as a basis. A few $A^{III}B^{V}$ of the types of combinations are shown in Figure 4. Here, the structure of the conductivity zone does not differ qualitatively from the zone structure of silicon and germanium. The valence zone also consists of three branches (zones), and the third zone itself (V_3) is separated from the other two zones as a result of spin orbital interaction. The difference between the valence zone of intermetallic compounds is that the first two zones, which correspond to light and heavy holes $(V_1$, and $V_2)$ the antisymmetrical part of the potential area, are located in the center of the Brillyuen zone $(\vec{k}=0)$. It is broken down. Therefore, the maximum energy of the light and heavy holes slips relative to each other and falls slightly beyond the center of the Brillyuen zone. It could be that one of them is at the maximum, or one of them $\vec{k}=0$. However, as a rule, the slippage is so small that $\vec{k}=0$ the $InSb$ prices of energy at its point and maximum point differ from each other by as much as one hundredth or a thousandth of 1eV. The structure $InAs$ of the valence zone of the combination *is given in* some detail in the form of 4 b $InSb$. As it turns out, the maximum of the valence zone and the absolute minimum of the conductive zone fall at the same time as the center of the Brillyuen zone $(k=0)$

.

It is parabolically dependent on energy near the minimum $\vec{k}$, and the effective mass of the electron located at the bottom of the zone itself is very small $m_n^* = 0{,}013\, m_0$ (the value taken from the cyclotron resonance measurements).



b)

Figure 4. Zone structure and valence band structure of $A^{III}B^{V}$ (a) and Structure of the Valentine Zone (b)

For relatively large energy prices, the conductivity zone is no longer in the form of a parabola, and its curvature is reduced. Therefore, the effective mass of an electron depends on the degree of filling of this zone. This, in turn, depends on the temperature and concentration of additives.

$InSb$ Taking into account the interaction of the conductivity and valence zones in the combination (since the width of the forbidden zone is small), Kane showed that the expression of energy for different zones should be calculated from the following cubic equation:

$$\left(E-\frac{\hbar^2k^2}{2m_0}\right)\left(E-\frac{\hbar^2k^2}{2m_0}+\Delta E_g\right)\left(E-\frac{\hbar^2k^2}{2m_0}+\Delta E_g+E_{s0}\right)- \\ -k^2P^2\left(E-\frac{\hbar^2k^2}{2m_0}+\Delta E_g+\frac{2}{3}E_{s0}\right)=0, \tag{9}$$

Here E - the energy of the carrier - E_{s0} spin-orbital disintegration P - is constant, taking into account the interaction of the conductivity and valence zone.

If the effective mass is too small $(m_n^* << m_0)\frac{\hbar^2k^2}{2m_0}$, the excess may not be taken into account. From (9):

$$k^2=\frac{E(E+\Delta E_g)(E+\Delta E_g+E_{s0})}{P^2\left(E+E_g+\frac{2}{3}E_{s0}\right)} \tag{10}$$

This dependence is called a expression derived from the three-zone Kane model.

$InSb$ Taking into account E_{s0} that the combination is large, and after making a series of simplifications, we can express the dependence of energy on the wave vector for the conduction zone from (2.18.9) as follows:

$$E(\vec{k})=\frac{\hbar^2k^2}{2m_n^*}(1-\alpha k^2) \tag{11}$$

Here $\alpha = \dfrac{\hbar^2}{2m_n^* \Delta E_g}$ is the parameter that describes the conductivity zone moving out of the parabolic zone.

The above examples illustrate the main characteristics of the zone structure of semiconductors. Therefore, we are not going to show the structure of other items here.

LABORATORY STUDY No 2

INVESTIGATION OF TEMPERATURE DEPENDENCE OF SEMICONDUCTOR SAMPLE CONDUCTIVITY

Materials: *rectangular semiconductor sample, heater, milliammeter, millibolt meter, constant current source, ruler, micrometer, connecting wires.*

Purpose: *The purpose of the work is to calculate the conductivity of the sample, study its temperature dependence, and establish a temperature dependence graph of the conductivity* $\sigma = f(t)$.

A Brief Introduction to Theory

Among the substances that exist in nature, in addition to metals, there are substances which, like metals, have electron conductivity, and in them, unlike metals, the concentration of freight carriers increases sharply with the increase in temperature. *Such substances have a very large resistance at low temperatures and are practically insulators, but with an increase in temperature, their special resistance decreases sharply and at sufficiently high temperatures it acquires a small value*. These types of substances are called ***semiconductors***. Semiconductors belong to a class of substances whose conductivity is strongly dependent on external conditions, especially temperature. At the small value of the forbidden zone, the semiconductor state corresponds and at absolute zero tempe-rature it is converted into dielectricity. In the conductive zone, electrons and in the valence zone, the holes move under the influence of an electric field and create a current. As the temperature increases, the number of electrons and holes passing through increases rapidly, and the resistance of the semiconductor decreases with speed.

The main feature of semiconductors is that they do not have free loads, electric carriers are formed as a result of external influence. Examples of such external influences include temperature, radiation, strong electric field, and so on. Since there are two types of negative and positive loads in semiconductors, semiconductors have *electron* and *perforated conductivity* .A semiconductor whose hole is equal to the number of electrons belongs to a class of semiconductors. In N-type semiconductors, the main loads are electrons, and *in P-type semiconductors, the main loads are holes.*

The conductivity of semiconductors is explained based on the theory of quantum mechanics. This theory is called zone theory. It is known from the zonal theory that in any isolated atom, electrons can only receive discrete energy values, called energy levels. According to Pauli's principle, no two electrons characterized by the same quantum numbers can be located at each energy level. In other words, there can be only one electron at each energy level with 4 quantum numbers identical. If there is a second electron, then its spin quantum number must be directed in the opposite direction. An electron that is located at a higher energy level in an atom is called an electron valence electron. When atoms in solid bodies come close to the interatomic distance, the interaction between their electron clouds causes the energy levels of the individual atoms to break down to form the energy zones of the solid body. Each energy zone creates discrete levels whose number is equal to the number of atoms in a crystal, but located very close to each other. Figure 1 shows the electronic structure of the germanium-specific semiconductor and the formation of an electron-hole transition as a result of external influence. Germanium is 4 valents. When one of the bonds is broken as a result of an external influence, a free electron is formed in the crystal and a hole is formed in its place. Under the influence of the external field, the electrons are the opposite of the field. The holes move in the direction of the field, creating an electric current.

$$\dot{I}=\dot{I}_e+\dot{I}_d$$

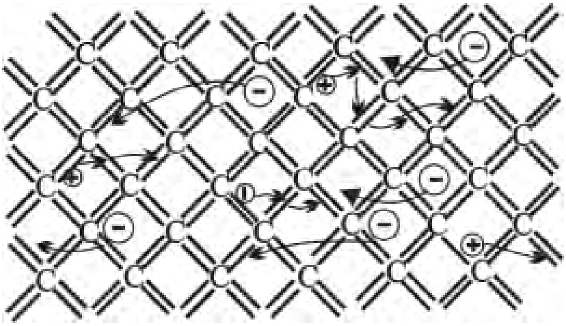


Figure 1. Electron Conductivity and Conductivity of Germanium Crystal

The conductivity of chemically pure semiconductors **is called specific conductivity**, and the semiconductors themselves **are called** special semiconductors.Examples of such semiconductors are Ge*, Si, S, Ga, As, and* PbS, InSe, GaS *from chemical compounds* . The conductivity of semiconductors is acutely dependent on the external atoms that are fired at them, i.e. *the superconductors*. For example, when only 0.001% *boron* is added to silicon, its conductivity at room temperature increases by about 1,000 times.

The energy zone generated by the energy levels of the valent electrons is called the valence zone, and at a certain temperature, this level is completely filled. The zone above the valence zone is called the ***conductive zone***, and all its energy levels are empty. The difference in energy between the bottom of the conductive zone and the ceiling of the valence zone ***is called the width of the restricted zone***. The bottom of the conductive zone is the minimum, and the ceiling of the valence zone is the maximum energy levels. In the main case, the valence zone in the semiconductor is completely filled, and there are no freight carriers that can participate in the electrical conductivity in the crystal. In this case, all the electrons are in a covalent bond. Under such conditions, the semiconductor material is no different from dielectric. As the temperature increases, the electron gains energy that can break that connection. In this case, a free electron is formed in the crystal cage that does not come into contact with any atom, and where the connection is broken**,** ***an empty hole*** is formed. According to the zone theory, as a result of the movement of the electron, the electron passes through the forbidden zone and passes into the conductive zone, and in the valence zone a hole is formed in its place. (Figure 2). Above the full valence zone is a completely empty zone. Under certain external influence, electrons pass from the I valent zone to the second zone. On the other hand, the zone I that has lost some of the electrons will also be the zone that is no longer filled. As a result of the formation of such zones, matter acts as a conductor

Figure 2. The mechanism of formation of conductivity in the semiconductor is the I-valent zone, the II conductive zone, ΔE_0 the width of the forbidden zone

The permeability of the semiconductors is acutely dependent *on the additives* that are shot at them. For example, when only 0.001% *boron* is added to silicon, its permeability at room temperature increases by 1,000 times. *In semiconductors,* *the permeability created by the solvent* is called ***superconductivity**, and such semiconductors* are called ***superconductivity***. To determine the effect of additives on the conductivity of the semiconductor*, let's investigate the effect* of 5 valent As *and 3 valent* In on the *Ge* crystal.*It*'s kind of like a slap in the face to the S-Curve. In such a lattice, each atom has a valent bond with four neighboring atoms. Suppose *that a portion of the Ge* atoms is replaced by 5-valent *As atoms, and the* As *atom expends 4 electrons* to form a valent bond with 4 adjacent neighboring atoms *(Figure 3a). The* 5th electron of the ace atom is not involved in the valence bond and remains empty. This is how this process is explained according to zone theory.

According to zone theory, between the valence zone of Ge and the conductive zone*, the donor energy level of the valence electrons* of As is generated *D*. This level is located at a distance *of Ed* = 0.015 *eV* from the lower level of the conductive zone and ***is called the donor level***. When the electrons at the donor level are energized *by Ed* = 0.015 *eV*, they pass into the conductive zone. Since the *excitation energy* of the Ed electrons at the donor-level is approximately two components less than the excitation energy of the electrons specific to *Ge* Δε, approximately two components, when this semiconductor is heated, the acid atoms will be excited first, and as a result, their concentration will be greater than the concentration of the specific electrons. Therefore, *the* conductivity of Ge will be mainly due to the superconductivity of electrons.The enzymes *that create electron conductivity* ***are called*** *donors.*

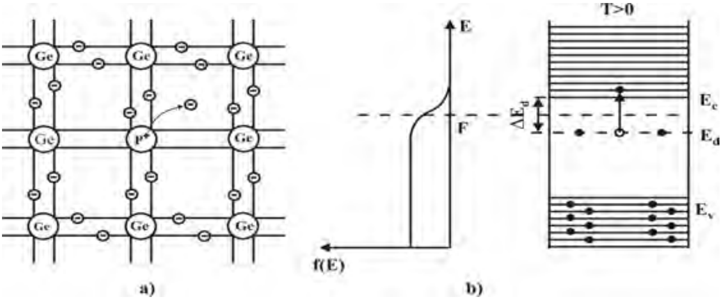


Figure 3.

Now suppose that some *of the Ge* atoms in the space cage *of Ge* are replaced by 3-valent *In-atoms* (Figure 3). The In atom lacks 1 electron to form a valent bond with the four neighboring atoms in the same cage . An electron can be obtained from an atom *of Ge*. Calculations show that Ed $\Delta = 0.015\ eV$ of energy is required for this. This is not the first time that the S-Class has been in the same position as the S-Class, but it is moving freely in the S-Class.

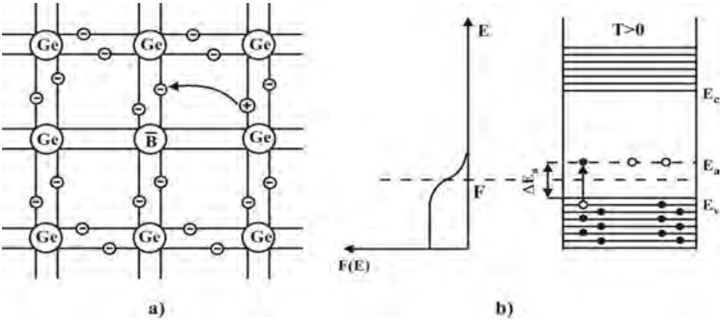


Figure 4.

The electrical resistance of semiconductors decreases sharply with the increase in temperature. The resistance of semiconductors at certain temperature intervals decreases by an exponential law with the increase in temperature.

$$R = R_0 e^{\frac{\Delta E_0}{kT}} \qquad (1)$$

The resistance is at R_0 a temperature of 0^0 C, ΔE_0 the width of the prohibited zone. This is a special case for the Conservative Party

$$\sigma = \sigma_0 e^{-\frac{E_a}{kT}} \qquad (2)$$

It is in the picture. The quantitative characteristic of a given semiconductor ΔE_0 is called the activation energy and also the width of the prohibited zone.

Using the relationship between conductivity and resistance, we get:

$$R = \rho \frac{d}{S}\ ,\ \rho = \frac{RS}{d}\ ,\ \sigma = \frac{1}{\rho} = \frac{d}{RS} \text{ and } R = \frac{U}{I} \qquad (3)$$

If we look at it this way, we are going to take a look at the following:

$$\sigma = \frac{I}{U} \cdot \frac{d}{S} \qquad ()$$

Here $I -$ is the current strength flowing through the semiconductor sample, $U -$ the voltage drops in the sample, *d*-sample of the length *and* $S -$ the area of the cross-section.

COURSE OF STUDY

1. Determine the linear dimensions of the sample with a caliper (or millimeter ruler).
2. And then he goes on to say, "Wow, this is a great way to get the most out of it, and to get the most out of it."

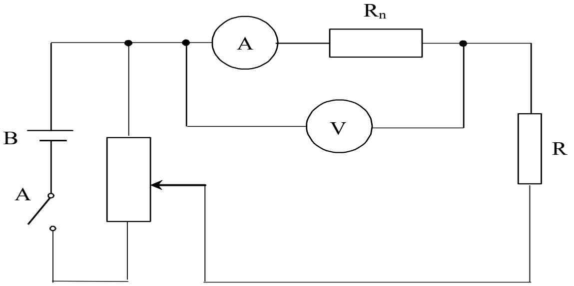


Figure 5. Principle circuit diagram for studying semiconductor conductivity

3. It is necessary to turn on the heater and measure the temperature. The temperature of the heater should be changed by 10^0 degrees Celsius each time
4. The temperature should vary from room temperature to 100^0- degrees Celsius
5. At each temperature, it is necessary to measure the current passing through the sample and the voltage drop in the sample.
6. At each temperature, $\sigma = \frac{I}{U} \cdot \frac{d}{S}$ the value of the permeability must be calculated. To achieve this, the temperature of the conductor $\sigma = f(t)$ must be determined on a millimeter sheet of paper

LABORATORY STUDY No. 3

The Study of the Hall Effect

Purpose: The purpose of study investigates the Hall effect in semiconductor crystals, to measure the Hall stress, to determine the Hall constant, to determine the marking and concentration of the loaders in the sample.
Materials: rectangular semiconductor sample with electrical contacts, constant current source, ammeter, microvoltmeter, magnet with gqc.

A Brief Introduction to Theory

The electrical conductivity of metals depends on the concentration of electrons and their conductivity. Both of these quantities are the most basic quantities of metals, and it is of great importance to determine them correctly. A phenomenon called the Hall effect is used to determine the concentration of metals in an experiment. The Hall effect can be explained with the help of the following experiment. Suppose that in the form of a rectangular parallelopiped***, a current with a current with a current intensity J*** passes through the sample (Figure 1).

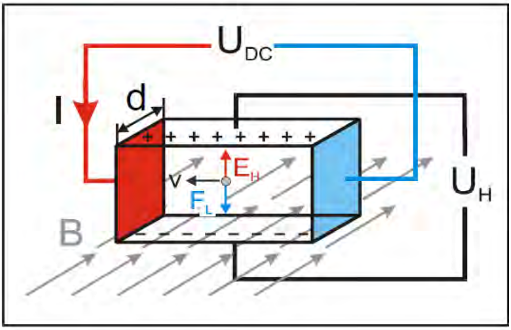


Figure 1. An example of a semiconductor to determine the Hall effect

Obviously, within the example, equipotential surfaces are surfaces that are perpendicular to the direction of current. On the faces of the specimen, probes are placed symmetrically on equipotential surfaces. In the absence of a magnetic field, the potential difference between the probes is zero. Let's create a magnetic field of a genus with an induction ***B in the direction perpendicular to the flow direction of the current*** . As a result of the magnetic field, there is a potential difference between the probes on the surfaces of the sample. This difference in potential is called the Hall's potential. The phenomenon of a potential difference in the faces of a current sample as a result of the influence of a magnetic field is called the Hall effect. To visualize the Hall effect, the sample is placed in a strong mantle field.

It has been established from experiment that the difference in latitude potentials $\varphi_1 - \varphi_2$ is proportional to the current intensity ***J***, the magnetic induction ***B,*** and the width of the sample ***A***.

$$\varphi_1 - \varphi_2 = R\frac{JB}{a} \tag{1}$$

This is called ***the*** R-Holl constant. The Hall constant depends on the type of sample.

The Hall phenomenon can be explained by the fact that the Lawrence force exists. Each electron is affected by the Lawrence force in a direction perpendicular to the magnetic field. This is the force

$$f_L = e\upsilon B \tag{2}$$

Electrons are exposed to the opposite of the magnetic field.

$$F_e = eE$$

And then there is the power of the force, and then there is a balance between these forces. Then you can write:

$$eE = e\upsilon B\,,\ \upsilon = \frac{E}{B}\ \text{and}\ ;\ E = \frac{\varphi_1 - \varphi_2}{d}\ ;\ \upsilon = \frac{\varphi_1 - \varphi_2}{B \cdot d}$$

And if we look at it from the other side, $J = ne\upsilon S$ we get:

$$J = \frac{\varphi_1 - \varphi_2}{B \cdot d} \cdot neS \tag{3}$$

where $S = a\,S = a \cdot d$ is the area of the finest part of the example. And then we get it:

$$\varphi_1 - \varphi_2 = \frac{J\,B\,d}{n\,e\,S} = \frac{JBd}{n\,e \cdot ad} = \frac{JB}{n\,e\,a};\ \varphi_1 - \varphi_2 = \frac{1}{ne} \cdot \frac{JB}{a} \tag{4}$$

From here;

$$R = \frac{1}{n\,e} \tag{5}$$

is taken. In other words, the Hall coefficient depends on the concentration of the loaders and the price of the electric load:

$$\varphi_1 - \varphi_2 = R \cdot \frac{j\,B}{a} \tag{6}$$

In the words of Hall of Fame,

$$R = \frac{1}{n\,e} \tag{7}$$

It is possible to calculate the concentration of loads from the expression.

Figure 2 shows a ready-made Hall device, and Figure 3 shows an experimental device for the Hall effect

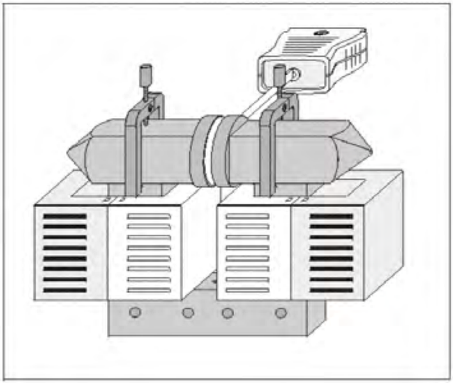


Figure 2: Magnetic field calibration scheme

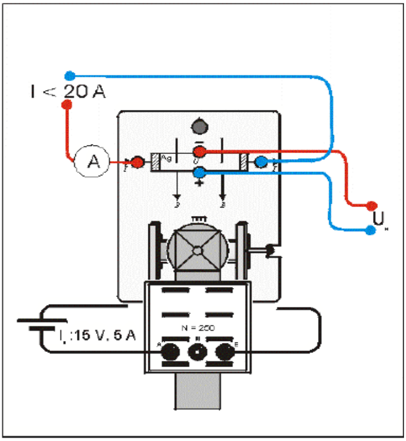


Figure 3. *Measuring the dependence of the Hall voltage on the magnetic field*

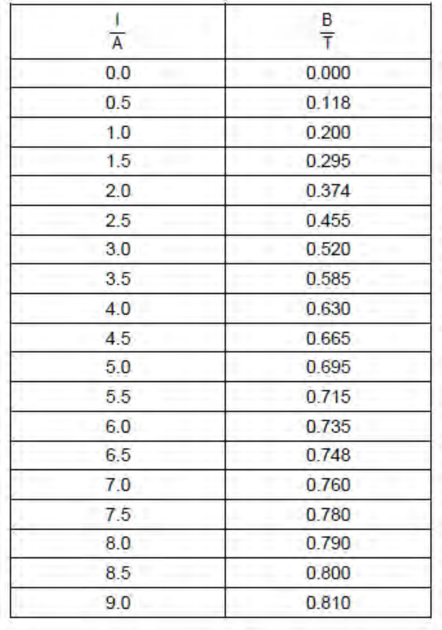
COURSE OF STUDY

1. The size of the semiconductor sample should be measured with a caliper.
2. In the example, the current passing through the sample should be measured in ammeters.
3. The voltage generated by the hall between the probes must be measured in millivolts.
4. The value of the magnetic induction must be taken from the table.
5. It has to be calculated based on the results obtained.

Measurement example

a) Calibration of the magnetic field

Table 1: Magnetic field B as a function of the *current I* flowing through the reels.



$\frac{I}{A}$	$\frac{B}{T}$
0.0	0.000
0.5	0.118
1.0	0.200
1.5	0.295
2.0	0.374
2.5	0.455
3.0	0.520
3.5	0.585
4.0	0.630
4.5	0.665
5.0	0.695
5.5	0.715
6.0	0.735
6.5	0.748
7.0	0.760
7.5	0.780
8.0	0.790
8.5	0.800
9.0	0.810

The data from Table 1 are shown in Figure 4.

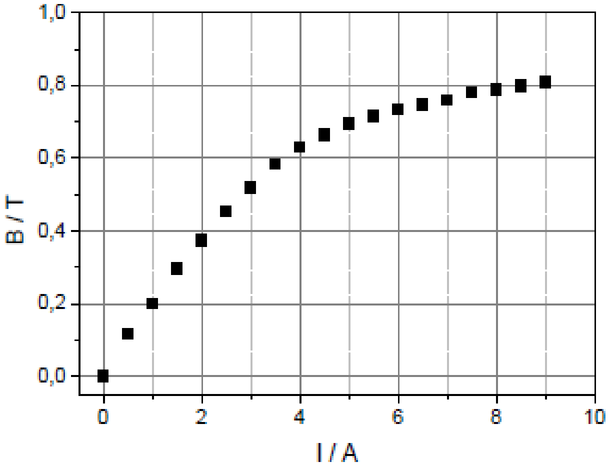
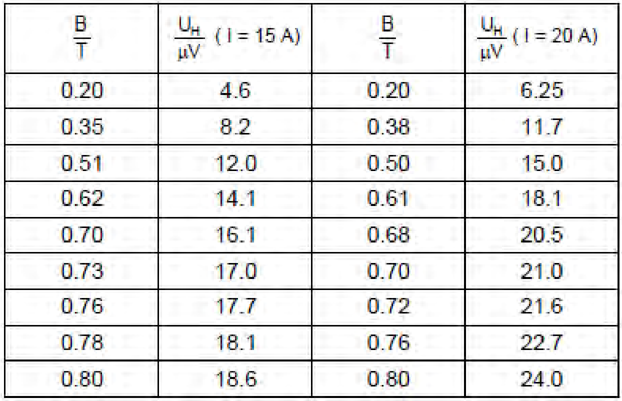


Figure 4: *Calibration curve as a function of* the current *I* of the magnetic field.

(b) To measure the dependence of the Hall voltage on the magnetic field

Table 2: As a function of the magnetic field *B of the* U_H Hall voltage (absolute value) *for constant latitude* I *currents*.



$\frac{B}{T}$	$\frac{U_H}{\mu V}$ (I = 15 A)	$\frac{B}{T}$	$\frac{U_H}{\mu V}$ (I = 20 A)
0.20	4.6	0.20	6.25
0.35	8.2	0.38	11.7
0.51	12.0	0.50	15.0
0.62	14.1	0.61	18.1
0.70	16.1	0.68	20.5
0.73	17.0	0.70	21.0
0.76	17.7	0.72	21.6
0.78	18.1	0.76	22.7
0.80	18.6	0.80	24.0

The U_H Hall voltage signal has been determined to be negative.

Əlaqə

(b) To measure the dependence of the Hall voltage on the magnetic field

For the latitude *currents* I = 15 A and I = 20 A, the data shown in Table 2 are graphically given in Figure 5.

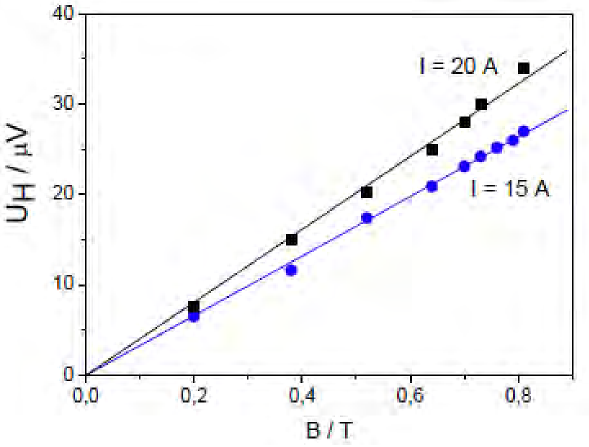


Figure 5: *Dependence of* U_H Hall voltage on magnetic field B: I = 15 A (circles) and I = 20 A (squares). Whole lines correspond to equation (1).