

## FORMATION OF *P*-, *N*-CONDUCTIVITY IN SEMICONDUCTORS

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### *Abstract:*

*The paper considers the energy position of negative ions of impurity atoms in the band gap of a semiconductor. Owing to the Boltzmann law, the energy levels of negative ions in the vicinity of the conduction band supply electrons to the conduction band, while resonance exchange of electrons occurs from the energy levels of negative ions in the vicinity of the allowed terms of the atoms of the main crystal. It is shown how energy band diagrams of *n*-conductivity and *p*-conductivity are formed. The applied external electric field acts oppositely on the impurities located in the vicinity of the conduction band and on those located in the vicinity of the allowed energy levels of the atoms of the main crystal. Impurity conductivity is determined by dielectric permittivity formed by the induced electric dipole moments of negative ions.*

*Key words: n-conductivity, p-conductivity, negative ions, electron affinity, thermionic emission, polarization.*

### Introduction

Nano-electronics is developing at a particularly rapid pace. This progress became possible after *p*- and *n*-conductivity<sup>1</sup> had been discovered in semiconductors featuring a wide enough band gap with the allowed energy levels. Semiconductor plates not exceeding 100  $\mu\text{m}$  in width are cut from a crystal in plane (111). The conductivity of *n*-type is obtained using various techniques, by introducing atoms of boron, tellurium, gallium or indium into the body of a plate. The conductivity of *p*-type is created when atoms of arsenic, phosphorus or selenium are

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<sup>1</sup> For clarity sake, commonly used terminology will be followed here. The terminology will be specified in due course.

introduced into the body of a semiconductor material. The action of the external electric field on n- and p-conductivity has been considered, for the most part, qualitatively. The quantitative substantiation of the phenomenon in terms of electronic theory was sufficiently performed in the 70s of the last century (Gretchikhin & Lenets, 1972).

The results could be put to practical use and, therefore, microelectronic engineering has been developed so far, for the major part, experimentally.

Advances in nanotechnologies resulted in a dramatic development of new techniques related to micro- and nano-electronics. In connection to this, there appeared an urgent need to understand what happens in the process of micro- and nanostructures formation. Former concepts based on the electronic theory of Drude-Lorentz-Sommerfeld do not reflect the true state of things. New approaches are necessary. In this regard, former physical concepts have already being rethought now. In his time, Nikola Tesla, as an alternative to the electronic theory, suggested electric and magnetic phenomena to be considered in terms of electromagnetic fields interaction. Nikola Tesla's ideas in electrodynamics were systematically developed in the following works: (Gretchikhin, 2008a), (Gretchikhin, 2016), (Gretchikhin, 2004) and (Gretchikhin, 2008b). However, so far, there has been no clear physical basis for the occurrence of p- and n-conductivity at atomic-molecular and cluster levels since the following fundamental directions remain unclear:

It is not clear why introducing various impurities into a semiconductor makes it possible to obtain p- or n-conductivity.

1. *It is unclear what qualities, along with valence, introduced atoms should possess to ensure p- or n-conductivity.*
2. *What does chemical potential represent and why it should be located in the middle of the band gap.*

All the above directions are clear in a quantitative sense under the assumption that the chemical potential in semiconductors is located in the middle of the band gap. Therefore, it is very difficult to hope for a clear understanding of nano-technologies or their wide and effective applications in daily practice until a rigorous theory of p- and n-conductivity which offers profound explanation of the phenomena at atomic-molecular level with further transfer onto nano-level has been developed. In this regard, it is vital to set the following *goal*: to develop a profound explanation of p- and n-conductivity taking into account the latest achievements of experimental and theoretical physics at the nano-level and with a firm rejection of the electronic theory. To reach the goal, it is essential to solve the following problems:

- to provide a rigorous explanation of the crystal structure of semiconductors;
- to provide an explanation of how  $p$ - and  $n$ -conductivity are formed;
- to provide an explanation of the temperature dependence of  $p$ - and  $n$ -conductivity;
- to ascertain how  $p$ - and  $n$ -conductivity behave under the action of external electric fields;
- to find out the essence of semiconductor conductivity based on new physical concepts;

Let us consider, one after another, these problems.

### Structure of the Semiconductor Surface

In the case of silicon and germanium, the papers (Gretchikhin et al, 2015a) and (Gretchikhin, 2004) provide a theoretical explanation of their crystal structure and present the valence electron distribution in the first Brillouin zone. The paper (Gretchikhin et al, 2015a) presents the crystalline structure appearing on the surface taking into account the cluster structure of the condensed state; the following binding energies have been determined in the paper:

1. Binding energy when forming diatomic and triatomic molecules of silicon.
2. Binding energy among triatomic molecules of silicon within cluster structures.
3. Binding energy among silicon clusters in the intercluster lattice structure with a due explanation of the melting temperature.

In order to verify theoretical calculations, the silicon surface was carefully investigated by means of a tunneling microscope.

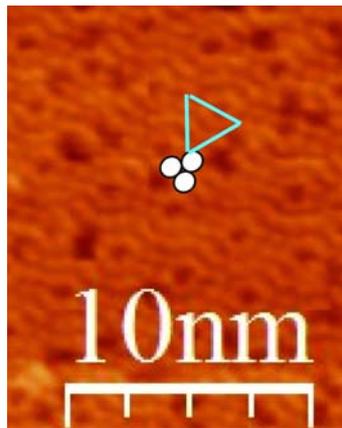


Figure 1 – Silicon Si (111) surface  
 Рис. 1 – Поверхность кремния Si (111)  
 Слика 1 – Поверхина силицијума Si (111)

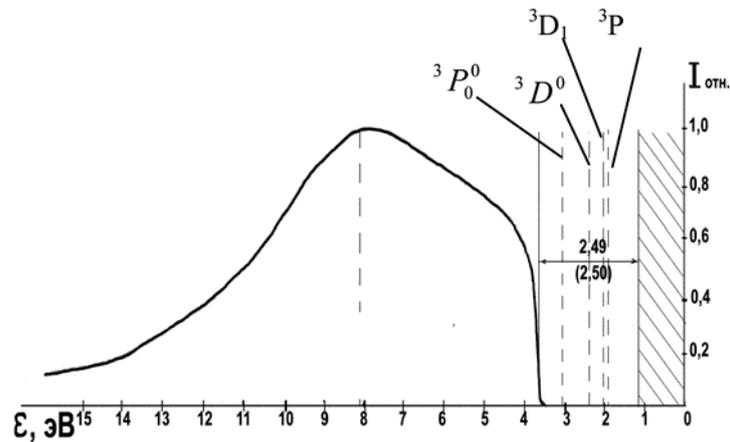


Figure 2 – General form of the first Brillouin zone for a silicon crystal  
 Рис. 2 – Общий вид первой зоны Бриллюэна для кристалла кремния  
 Слика 2 – Општи облик прве Брилуинове зоне код кристала силицијума

Figure 1 show a scanned silicon surface with an adhesion cell, filled with atoms and molecules of other elements, marked with a triangle. The theoretically calculated silicon surface shows agreement with the experimental data for all parameters of the design: in shape and in size of triatomic molecules on the silicon surface (Gretchikhin et al, 2015a).

Therefore, the Si(111) silicon surface is formed by triatomic molecules  $\text{Si}_3$  with the radius of 2.122 Å (Gretchikhin et al, 2015a), accompanied by the formation of column-like gaps of 8.1 Å. Valence electrons in the crystalline state form a cloud which obeys the Fermi-Dirac distribution law. Figure 2 presents the results of the distribution calculated for silicon (Gretchikhin, 2004). The Fermi level of the silicon crystal possesses the energy of 2.49 eV. There are four allowed energy levels in the band gap; the levels feature the following values relative to the bottom of the conduction gap: 0.84; 1.03; 1.38 and 2.04 eV.

When neutral atoms are introduced as impurities onto the Si(111) surface of a silicon crystal they are located in places with the maximum binding energy. For instance, it has been proved experimentally that indium applied onto the silicon surface results in adhesion occurring on the surface between column-like gaps. The adhesion occurring between column-like gaps is formed by three triatomic molecules of silicon with close packing, marked with a triangle in Figure 1.

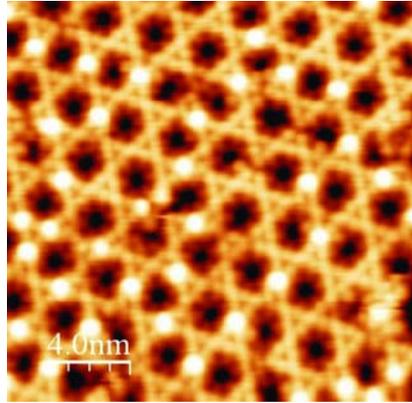


Figure 3 – Complete filling of the silicon surface when indium is sprayed onto the surface  
 Рус. 3 – Полное заполнение поверхности кремния при напылении индием  
 Слика 3 – Потпуно испуњавање површине силицијума при nanoшењу индијума прскањем на површину

Flat indium clusters consisting of three diatomic molecules are precipitated (Gretchikhin et al, 2015b). When such a cluster interacts with the silicon surface, the cluster and, at the same time, the molecules are deformed substantially. As this takes place, each atom independently interacts with the electron cloud of the valence electrons of the silicon crystal and with the ions of the crystal lattice. This situation with a complete filling of the silicon surface with indium atoms has been proved experimentally and is presented here in Figure 3. The emission properties are determined by individual atoms. A similar structure of atom arrangement on the silicon surface must be realized for other substances introduced into the silicon crystal.

Let us consider in detail the process of interaction of neutral atoms of different elements with the electron cloud of the first Brillouin zone of a silicon crystal, and find out what phenomena may occur in the process.

### Formation of $p$ - and $n$ -Conductivity

The atoms embedded in the crystal structure must carry an excessive positive or negative electric charge to create an induced electric moment and, therefore, to participate in the conductivity of electric current. In this case, there may be positive ions created due to the ionization of neutral atoms, or negative ions in case of neutral atoms possessing a noticeable electron affinity. Table 1 presents the main parameters of the elements introduced into the silicon crystal to organize  $p$ - or  $n$ -conductivity.

Table 1 – Main parameters of the elements introduced into the silicon crystal  
 Таблица 1 – Основные параметры вводимых элементов в кристалл кремния  
 Табела 1 – Основни параметри елементата уведених у кристал силицијума

Parameters	Introduced elements						
	Boron	Gallium	Tellurium	Indium	Arsenic	Phosphorus	Selenium
Atomic radius (Å)	1.166	1.811	1.429	1.999	1.355	1.253	1.221
Ionization energy (eV)	8.30	6.00	9.01	6.79	9.82	10.49	9.75
Affinity energy (eV)	0.277	0.300	0.200	0.300	0.810	0.747	2.021
Share of emission centers	0.288	0.693	0.432	0.846	0.387	0.333	0.315

It follows from Table 1 that the process of ionization in the silicon crystal is practically impossible under normal conditions because of a high ionization energy. Therefore, the atoms of various elements cannot remain in the form of positive ions on the surface of the silicon crystal. A different situation arises when atoms possessing electron affinity other than zero are introduced into silicon. Such atoms are able to stay on the crystal surface in the form of negative ions which possess affinity energies within the band gap of the silicon crystal.

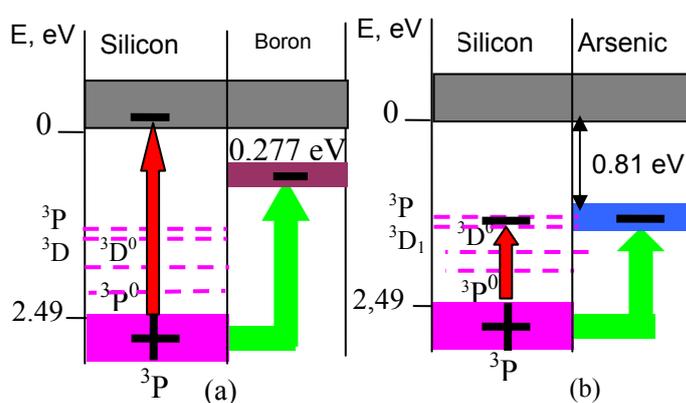


Figure 4 – Energy band diagrams of the formation of: (a) n- conductivity and (b) p- conductivity  
 Рис. 4 – Энергетическая схема формирования: а) n-проводимости и б) p-проводимости  
 Слика 4 – Энергетска шема формирања (а) n-проводљивости и (б) p-проводљивости

Figure 4 demonstrates, as an example, the principal energy band diagram in the case of boron and arsenic introduced into the silicon crystal. Boron and arsenic possess the ionization energies of 8.3 eV and 9.82 eV and, accordingly, are located in the vicinity of the electron density distribution maximum of the first Brillouin zone of the silicon crystal (Figure 2). Since these atoms possess electron affinity energy, they freely capture electrons from the first Brillouin zone of the silicon crystal and are turned into negative ions with further transition to the band gap where they permanently stay in the form of negative ions, regardless of various external influences. This process presents an obvious and fundamental fact.

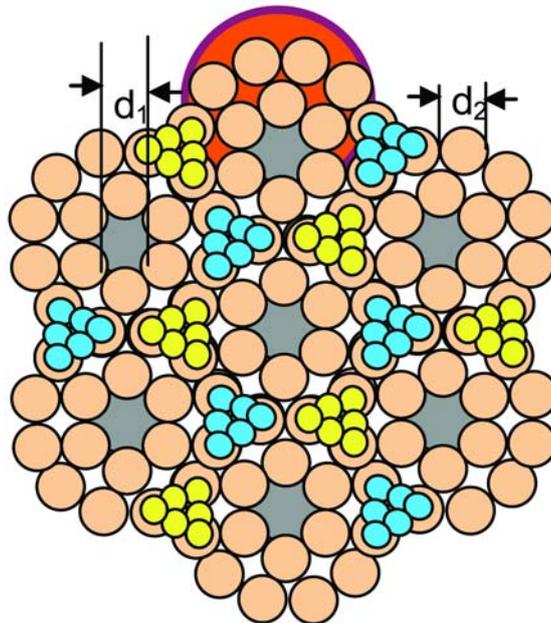


Figure 5 – Distribution of impurities on the silicon surface  
 Рис. 5 – Расположение примесей на поверхности кремния  
 Слика 5 – Дистрибуција примеса на површини силицијума

Figure 5 shows the arrangement of impurities on the silicon surface. Each adhesion cell is surrounded by three intermolecular gaps with the size of  $d_p = (\sqrt{2} - 1)r_m$ . The effective radius of triatomic molecules of silicon amounts to  $r_m = 2.122 \text{ \AA}$  (Gretchikhin et al, 2015a). In this case  $d_p = 3 \text{ \AA}$ . As the sizes of boron and arsenic atoms are known to be less

than 3 Å, then a part of the atoms will be captured by the gaps, and a certain share of the part may not participate in the thermal emission of electrons. The sizes of gallium and indium atoms exceed 3 Å. Therefore, these atoms will be located on the silicon surface and will fully participate in the thermionic process. Then, it follows from Figure 5 that the maximum concentration of introduced impurities (boron as well as arsenic) in the form of monolayer will amount to:

$$n_p \cong \frac{6 \cdot 4}{\pi(d_1 + 3d_2)^2 \cdot (d_2 + d_3)} m^{-3}, \quad (1)$$

where  $d_1$  is the diameter of the column-like gap,  $d_2$  is the diameter of a triatomic silicon molecule, and  $d_3$  is the diameter of impurity atoms. Based on formula (1), the maximum concentration of the atoms in the surface layer of boron impurity amounts to  $2.68 \cdot 10^{27} m^{-3}$  while that one of the arsenic atoms is equal to  $2.53 \cdot 10^{27} m^{-3}$ .

In accordance with the Maxwell-Boltzmann distribution law, the negative ions of boron and, correspondingly, those of arsenic, will supply electrons to the conduction band due owing to thermionic emission. This process should last continuously until the electric field strength created by the electric dipole of silicon compensates the thermal emission of electrons from the negative ions of impurities. Thermionic emission is determined as follows (Gretchikhin, 2008a):

$$J_T = \frac{\gamma e}{4r_a^3} \sqrt{\frac{8k_b T}{\pi m_e} \left( \frac{EA}{k_b T} + 1 \right)} \exp\left( -\frac{EA}{k_b T} \right) (A \cdot m^{-2}), \quad (2)$$

where  $\gamma$  is the number of emission centers per unit of the surface area<sup>2</sup>;  $e$  is the electron charge;  $m_e$  is the electron mass;  $r_a$  is the radius of the emitted particle;  $k_b$  is the Boltzmann constant; and  $EA$  is the electron affinity energy.

In case of boron, the electron flow resulting from the thermionic emission is compensated by the reverse flow of electrons created by the electric field arising between the valence band and the conduction band, forming this way an electric dipole, while in case of arsenic an electric dipole moment occurs between the valence band and the level of its negative ion. Then, on the basis of the dimensional analysis, it follows that:

<sup>2</sup> It follows from Figure 4 that:  $\gamma = 24\pi r_a^2 / \pi(d_1 + 3d_2)^2$

$$J_{op} = en_p \sqrt{\frac{2e\Delta\phi}{m_e}} \quad (3)$$

Here:  $\Delta\phi$  is the potential difference between the conduction band and the negative ion for  $n$ -conductivity, while for  $p$ -conductivity  $\Delta\phi$  means the potential difference between the valence band and the negative electron position in the band gap under the dynamic equilibrium  $J_T = J_{op}$ . The potential difference  $\Delta\phi$  is derived from this equation. Table 2 presents the results of the calculations for the elements featuring small affinity energies only.

*Table 2 – Potential difference between the conduction band and the valence band  
Таблица 2 – Разность потенциалов между валентной зоной и зоной проводимости  
Табела 2 – Разлика потенцијала проводне зоне и валентне зоне*

Impurity	Temperature (° K)									
	298	300	350	400	450	500	550	600	650	700
Boron	$2.7 \cdot 10^{-6}$	$5.5 \cdot 10^{-6}$	$1.2 \cdot 10^{-4}$	$1.2 \cdot 10^{-3}$	$7.6 \cdot 10^{-3}$	0.032	0.107	597 K - 0.277 eV		
Gallium	$3.8 \cdot 10^{-7}$	$4.4 \cdot 10^{-7}$	$1.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-4}$	$1.1 \cdot 10^{-3}$	$5.3 \cdot 10^{-3}$	0.019	0.057	0.141	698 K - 0.3 eV
Tellurium	$7.1 \cdot 10^{-4}$	$7.8 \cdot 10^{-4}$	$7.4 \cdot 10^{-3}$	$2.7 \cdot 10^{-6}$	0.040	462 K - 0.2 eV				
Indium	$3.1 \cdot 10^{-7}$	$3.6 \cdot 10^{-7}$	$1.0 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$9.0 \cdot 10^{-4}$	$4.4 \cdot 10^{-3}$	0.016	0.046	0.116	0.257
	711 K - 0.3 eV									

Each line of Table 2 shows the limit values of the temperature polarization which ensures complete compensation of the affinity energy of the introduced impurity. At the temperature polarization limit value, the conductivity of a semiconductor transforms into the conductivity peculiar to metals.

In case of arsenic, phosphorus or selenium, the heating of the silicon substrate to the melting point can be ignored since these elements possess quite high affinity energy that is quite large (Table 1); these elements feature the temperature polarization limit values much higher than the melting point of silicon (1688 K).

Now let us consider the effects of external electric fields on  $n$ - и  $p$ -conductivity.

## Action of Electric Fields on *n*- and *p*-Conductivity

An external electric field applied to a semiconductor with its surface containing impurities results in appropriate polarization of negative ions. Polarization energy will strengthen or weaken the impurity atom affinity energy depending on the direction of the applied field. If the electron affinity energy is known, then the energy under question can be represented as a model of a hydrogen atom with the effective charge and the radius of the negative ion, namely:

$$EA = \frac{Z^* e^2}{4\pi \varepsilon_0 r_i}. \quad (4)$$

The radius of the negative ion practically does not differ from the radius of the neutral atom (Gretchikhin & Kamarouskaya, 2016). Therefore, given the affinity energy, (4) determines the effective charge of the negative ion. For the negative ion of boron, the value equals to 0.0224 while for arsenic it equals to 0.0762. Let us apply this model to analyze the action of an external electric field on the negative ion. Under the action of an external electric field, the negative ion is polarized and then the interaction force between the external field and the valence electron of each particle of the substance must be compensated by a change in the internal binding forces of the valence electron with the effective charge of the particle. Therefore (Gretchikhin, 2008a),

$$eE_y = \frac{Z^* e^2}{4\pi \varepsilon_0 r_i^2} - \frac{Z^* e^2}{4\pi \varepsilon_0 (r_i \pm \Delta r_i)^2}. \quad (5)$$

where  $\Delta r_i$  is the displacement of the charge cloud of the negative ion relatively to its center.

Based on equations (4) and (5), the following expression for the displacement of the charge cloud is derived:

$$\Delta r_i = \pm \frac{4\pi \varepsilon_0 E_y r_i^3}{2Z^* e}. \quad (6)$$

The work done for the polarization:

$$A = eE_y \Delta r_i. \quad (7)$$

Based on (4) – (7), the following value of the effective electron affinity for the negative ion is derived:

$$EA_{eff} = EA \left( 1 \pm \frac{e^2 E_3^2 r_i^2}{2EA^2} \right). \quad (8)$$

Finally, the thermionic current density (2), while taking into account (8), equals to:

$$J_T = \frac{\gamma e}{4r_a^3} \sqrt{\frac{8k_b T}{\pi m_e}} \left[ \frac{EA}{k_b T} \left( 1 \pm \frac{e^2 E_3^2 r_i^2}{2EA^2} \right) + 1 \right] \exp \left[ -\frac{EA}{k_b T} \left( 1 \pm \frac{e^2 E_3^2 r_i^2}{2EA^2} \right) \right] (A \cdot m^{-2}). \quad (9)$$

It follows from Figure 4 that the applied external electric field affects the negative ion affinity levels in different ways. When an external electric field is applied in the direction from the valence band to the conduction band, the energy affinity levels in the vicinity of the conduction band increase and the thermionic current decreases while the energy affinity levels in the vicinity of the valence band decrease and the thermionic current, in contrast, increases. The change in the direction of the applied external field results in a reverse direction of the thermionic current.

Impurities in semiconductors induce dipole electric moments while their concentration determines the change in the dielectric permittivity of semiconductors with impurities. This phenomenon, in turn, affects the conductivity of semiconductors.

### Impurity Conductivity of Semiconductors

As an alternative to considering electric current as a movement of electric charges, Nikola Tesla proposed to consider it as a propagation of electromagnetic waves. In these terms, the energy transferred by electromagnetic waves is determined by the Poynting vector:

$$\vec{P} = [\vec{E} \cdot \vec{H}]. \quad (10)$$

where  $\vec{E}$  is the electric field strength and  $\vec{H}$  is the magnetic field strength.

In the absence of charges, according to the Lorentz equation, the electric field strength and the magnetic field strength in an electromagnetic wave are related by the following equation:

$$\vec{E} = [\vec{v} \cdot \vec{B}] = \mu_0 \mu_r [\vec{v} \cdot \vec{H}]. \quad (11)$$

Here  $v = 1/\sqrt{\varepsilon\mu} = c/\sqrt{\varepsilon_r\mu_r}$  is the velocity of propagation of electromagnetic waves in a medium with given dielectric permittivity  $\varepsilon = \varepsilon_r \varepsilon_0$  and magnetic permittivity  $\mu = \mu_r \mu_0$ . In their turn,  $\varepsilon_r$  и  $\mu_r$  are

relative dielectric permittivity and relative magnetic permittivity, respectively, while  $\varepsilon_0 = 8.854 \cdot 10^{-12} \text{ F/m}$  and  $\mu_0 = 4\pi \cdot 10^{-7} \text{ Gn/m}$ , according to Sommerfeld, present the absolute dielectric permittivity of classical vacuum, and  $c = 1/\sqrt{\varepsilon_0\mu_0}$  is light speed in vacuum.

When an electromagnetic wave propagates along a semiconductor, the electric field on the surface has tangential and normal components. Then Poynting vector becomes as follows:

$$\vec{P} = [\vec{E}_\tau \vec{H}] + [\vec{E}_n \vec{H}], \quad (12)$$

where  $E_\tau$  and  $E_n$  are the components of the electric field strength along the conductor and normal to its surface.

The first term is due to the current conductivity determined by the Joule-Lenz law and Ohm's law while the second term is formed by the bias current which appears on the semiconductor surface and determines the transfer of electromagnetic field energy along the semiconductor (Gretchikhin, 2008b). Since the energy densities of the electric and magnetic fields are equal, it follows from (12) that  $E_\tau = E_n$  on the semiconductor surface. Therefore, the resulting electric field strength of the electromagnetic wave is directed at an angle of  $45^\circ$  relative to the semiconductor surface (Gretchikhin, 2008b).

Let us consider an electric current  $I$  flowing through a semiconductor with a circular cross section of radius  $r$  and length  $l$ . When the electric current flows through the conductor, the intensity of the magnetic field is determined as  $H = I/2\pi r$  and the tangential component of the electric field strength is determined as  $E_\tau = (\varphi_1 - \varphi_2)/l$ . Then equation (11) transforms as follows:

$$\varphi_1 - \varphi_2 = \sqrt{\frac{\mu_0\mu_r}{\varepsilon_0\varepsilon_r}} \frac{rl}{2\pi r^2} I. \quad (13)$$

For conductors, the linear relationship between current and voltage was established by Gustav Ohm and represents Ohm's law. Ohm's law is also valid for semiconductors. The difference lies in the different definition of relative permittivity and different manner of the interaction between the external electric field and the internal electric fields determined by the presence of induced and internal electric dipoles. Based on (13), the tangential component of the resistivity in case of propagation of electromagnetic waves through a semiconductor is derived as follows:

$$\rho = \sqrt{\frac{\mu_0 \mu_r}{\varepsilon_0 \varepsilon_r}} \frac{r}{2}. \quad (14)$$

For most materials including semiconductors  $\mu_r \approx 1$  and so the resistivity is inversely proportional to the square root of the relative dielectric permittivity of the medium ( $\sqrt{\varepsilon_r}$ ) and proportional to  $\sqrt{\mu_0 / \varepsilon_0} = 120\pi$ , i.e. so-called "characteristic impedance of vacuum", as well as to the radius of the semiconductor with a circular cross section.

It follows from the general definition of the electric displacement vector that:

$$\varepsilon_r = 1 + \frac{1}{\varepsilon_0 E_\tau} \frac{\sum_i p_{e,i}}{\Delta V} = 1 + \frac{\sum_i n_i p_{e,i}}{\varepsilon_0 E_\tau}, \quad (15)$$

where summation is performed over all electric dipole moments built-in and induced within the volume of  $\Delta V$  while  $n_i$  is the concentration of the built-in and induced electric dipole moments, and  $p_{e,i}$  is, correspondingly, their electric dipole moment. In most cases, the relative permittivity exceeds unit substantially. Then

$$\varepsilon_r = \frac{\sum_i n_{a,i} p_{e,i}}{\varepsilon_0 E_\tau}. \quad (16)$$

It is known that impurity conductivity far exceeds the intrinsic conductivity of semiconductors (Gretchikhin & Lenets, 1972). Therefore, impurity conductivity of semiconductors is determined only by the concentration of the introduced impurities while the value of resulting induced electric dipole moment is as follows:

$$\sum_i n_{a,i} p_{e,i} = e r_a n_{a,0} \exp \left[ -\frac{EA}{k_b T} \left( 1 \pm \frac{e^2 \Delta \varphi^2}{EA^2} \right) \right], \quad (17)$$

where  $\Delta \varphi$  is the potential difference applied to the monolayer of impurity atoms,  $n_{a,0}$  is the concentration of impurity atoms in the surface layer.

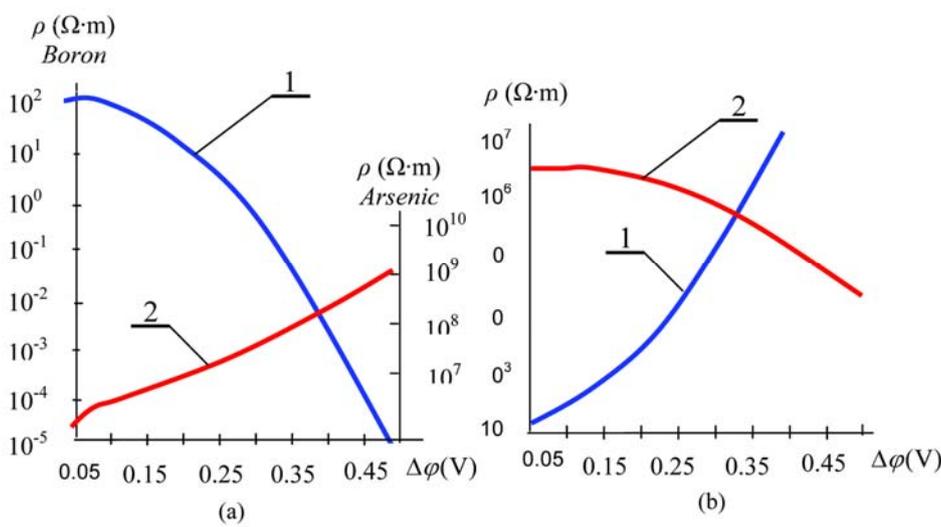


Figure 6 – Dependence of the resistivity of silicon: (1) with boron impurity, and (2) with arsenic impurity: (a) external electric field strength is directed from the valence band to the conduction band, and (b) external electric field strength is directed from the conduction band to the valence band.

Рис. 6 – Зависимость удельного сопротивления кремния 1 - с примесью бора и 2 – с примесью мышьяка: а) напряженность внешнего электрического поля направлена от валентной зоны к зоне проводимости и б) напряженность внешнего электрического поля направлена от зоны проводимости к валентной зоне.

Слика 6 – Зависност отпорности силицијума са (1) примесама бора и (2) примесама арсеника: (а) снага спољашњег електричног поља усмерена је од валентне зоне до проводне зоне, и (б) снага спољашњег електричног поља усмерена је од проводне зоне ка валентној зони

Based on (14) - (17), it is possible to completely determine the resistivity of a semiconductor with impurities. When determining the resistivity, normally the pills with a diameter of 1 cm and thickness of 3 mm are used. Figure 6 presents the results of the calculations, using such pills, for silicon with maximum concentrations of boron and arsenic impurities at the surface.

For metals, the resistivity amounts to  $10^{-7}$ - $10^{-8} \Omega \cdot m$ . Under an external electric field directed from the valence band to the conduction band, silicon with introduced boron acquires the conductivity inherent in metals when the potential difference at the contact boron-silicon reaches  $\sim 0.5$  V. Silicon with introduced arsenic acquires the “metal” conductivity when the potential difference at the contact arsenic-silicon amounts to  $\sim 1.1$ - $1.2$  V.

It follows from Figure 6 that the lower the affinity energy of the introduced impurity is, the more the specific resistance varies depending on the value of the applied external electric field. As the applied electric field increases, the impurity conductivity tends to decrease linearly, or the resistivity tends to increase logarithmically along the ordinate axis, that is, the exponential dependence of the resistivity versus the applied external electric field becomes clearly recognized.

## Conclusion

Summarizing the proposed alternative model for impurity conductivity occurring in semiconductors, we here formulate its main features:

1. In the band gap of a semiconductor, the energy position of the negative ions of impurity atoms is considered instead of considering the chemical potential relative to which the impurities are distributed.

2. The ionization of impurities distributed mainly on the crystal surface occurs not due to weakening the ionization energies because of high dielectric permittivity inside the crystal, but as a result of resonance electron capture from the Fermi-Dirac density distribution by neutral atoms possessing electron affinity.

3. Owing to the Boltzmann law, the energy levels of negative ions in the vicinity of the conduction band supply electrons to the conduction band. In this case, electric dipole moments are formed between the valence band and the conduction band, while the concentration of negative ions remains constant.

4. Resonance exchange of electrons occurs from the energy levels of negative ions in the vicinity of the allowed terms of the atoms of the main crystal accompanied with a formation of an electric dipole moment between the valence band and the allowed energy levels within the band gap of the main crystal. At the same time, the transition of electrons to the valence band from these energy levels is parity-forbidden.

5. Silicon crystal is formed by triatomic molecules. The structure of the silicon surface is considered and it is shown that the adsorption of impurities occurs in the region where the maximum surface density of silicon molecules is realized.

6. It is shown how the energy band diagram of *n*-conductivity and *p*-conductivity is formed and the potential differences due to the temperature polarization of impurity atoms are determined.

7. An applied external electric field acts oppositely on the impurities located in the vicinity of the conduction band and on those located in the vicinity of the allowed energy levels of the atoms of the main crystal.

8. Impurity conductivity is determined by dielectric permittivity formed by the induced electric dipole moments of negative ions but not by the electric dipole moments of the particles of the main crystal.

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## ФОРМИРОВАНИЕ P-, N-ПРОВОДИМОСТИ В ПОЛУПРОВОДНИКАХ

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### Резюме:

*В запрещенной зоне полупроводника рассматривается энергетическое положение отрицательных ионов примесных атомов. Уровни энергий отрицательных ионов вблизи зоны проводимости вследствие закона Больцмана поставляют электроны в зону проводимости, а с уровнями энергий отрицательных ионов вблизи разрешенных термов атомов основного кристалла происходит резонансный обмен электронами. В работе представлено, как формируются энергетические схемы n-проводимости и p-проводимости. Приложенное внешнее электрическое поле действует взаимоположенно на примеси вблизи зоны проводимости и вблизи разрешенных уровней энергий атомов основного кристалла. Примесная электропроводность определяется диэлектрической проницаемостью, которая формируется наведенными дипольными электрическими моментами отрицательных ионов.*

*Ключевые слова: n-проводимость, p-проводимость, отрицательные ионы, сродство к электрону, термоэлектронная эмиссия, поляризация.*

## ФОРМИРАЊЕ ПРОВОДЉИВОСТИ КОД ПОЛУПРОВОДНИКА П-ТИПА И Н-ТИПА

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### Сажетак:

*Рад се бави енергетском позицијом негативних јона атома примеса у енергетским процепима полупроводника. Захваљујући Болцмановом закону, енергетски нивои негативних јона у близини*

проводне зоне снабдевају проводну зону електронима, док до резонантне размене електрона долази из правца енергетских нивоа негативних јона у близини дозвољених термина атома главног кристала. Показано је како долази до стварања дијаграма енергетских зона проводљивости *N*-типа и *P*-типа. Примењено спољашње електрично поље делује супротно на примесе које се налазе у близини дозвољених енергетских нивоа атома главног кристала. Проводљивост примеса одређује се помоћу диелектричне пермитивности која се формира услед индукованог електричног диполног момента негативних јона.

*Кључне речи:* проводљивост *N*-типа, проводљивост *P*-типа, афинитет према електрону, термојонска емисија, поларизација.

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