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Physical Basics of Semiconductors

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Abstract. The article outlines the fundamentals of materials science and semiconductor technology, which allow one to gain a general understanding of the basic laws of formation of semiconductor phases, the mechanisms of their growth, production conditions, as well as to gain an understanding of the most widely used industrial methods for the production of bulk semiconductors and epitaxial semiconductor films with specified properties. This knowledge is necessary for students specializing in semiconductor physics to understand the specialized literature. Indeed, almost every article devoted to the study of the properties of semiconductors or the creation of devices based on them begins with a description of the method for producing the material, since its properties, as will be shown in this course, are closely related to the method of its production.

Key words: Metal, semiconductor, dielectric, electron, hole, energy, atom, crystal, charge, motion, voltage, silicon, valence band, conduction band.

Introduction

One of the physical properties of materials is electrical conductivity. Electrical conductivity – characterizes the properties of materials to conduct electric current. Depending on the ability of materials to conduct electric current, they are divided into dielectrics, semiconductors and conductors.

Electric current arises as a result of the movement of electric charge carriers, and the more per unit volume of a material there are under moving electric charge carriers, the greater its electrical conductivity. In metals, the carriers of electric current are, as a rule, valence electrons, which determines their high electrical conductivity. The electrical resistivity of conductors is on average $\rho=10^{-4}$ om cm, semiconductors $\rho=10^{-4}\div10^{10}$ om cm, dielectrics $\rho= 10^{10}$ om cm and higher. In dielectrics, there are significantly fewer free carriers, so their resistivity is high and they do not conduct electric current.

Semiconductors are a cross between conductors and dielectrics.

To create semiconductor devices, materials such as 4-valent germanium, silicon and gallium arsenide, 3-valent aluminum, boron, indium and 5-valent phosphorus, arsenic, and antimony are used.

All semiconductors can be divided into two groups: pure, (pure) or i-type semiconductors, materials consisting of atoms of one element, and impurity semiconductors.

In practice, silicon and germanium are most widely used.

A flat model of a germanium crystal is shown in Fig. 1. The atoms of semiconductors are arranged in space in the form of a crystal lattice, which arises by combining the electrons of neighboring atoms (covalent bond). Thus, each atom in a given lattice is surrounded by four neighboring atoms, with which it has a close paired electronic bond and there are no free electrons that could participate in charge transfer, which makes the semiconductor an insulator [1-8]. Pure semiconductors at zero absolute Kelvin temperature are ideal dielectrics. As the temperature increases, electrons gain additional energy, and some of them break their covalent bonds, becoming free. As a result of this, two carriers are formed: an electron with a negative charge, and the place that it left becomes a vacancy - a “hole”. It is conventionally assumed that a hole has a positive charge, numerically equal to the charge of an electron.

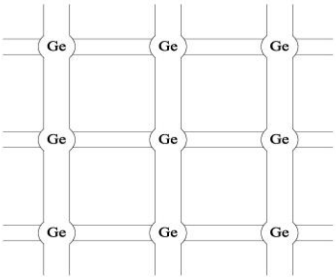

Fig.1. Flat graphical model of a 4-valence semiconductor..

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Thus, with increasing temperature, free charge carriers appear in the semiconductor, and a balance is observed, the concentration of electrons in a pure semiconductor is equal to the concentration of holes, i.e., $n_i=p_i$. The process of formation of a free electron and hole is called generation of an electron-hole pair. When electrons move through the volume of a crystal lattice, some of them can take the place of a hole, which is called recombination of an electron-hole pair.

Pure semiconductors are almost never used, since their conductivity strongly depends on temperature, which makes it possible to use this property in the creation of temperature sensors. Impurity semiconductors are used to control the flow of electrons and holes in semiconductor devices. The process of introducing impurities into a semiconductor is called doping, and impurity semiconductors are doped. Depending on the nature of the introduced impurity, two types of impurity semiconductors can be obtained: electronic *n* -type and hole *p* -type.

n-type semiconductor is obtained by introducing atoms of a 5-valence impurity into a 4-valence semiconductor. Each atom of such an impurity creates one free electron. Such an impurity is called a donor impurity.

p-type semiconductors are obtained by introducing a 3-valence impurity into their own 4-valence semiconductor. Each atom of such an impurity takes an electron from its neighboring atom, creating holes. Such an impurity is called an acceptor impurity.

To create semiconductor devices, impurity semiconductors are mainly used, since their conductivity is determined by the impurity concentration, and not by temperature, illumination and other external factors [9-15].

Method

The operating principle of most semiconductor devices is based on physical phenomena occurring in the area of contacts of solids such as: semiconductor-semiconductor; semiconductor metal; metal-dielectric-semiconductor. A thin layer in the contact area, for example, a semiconductor-semiconductor, is called an electron-hole *p-n* junction. An electron-hole junction is created in a single semiconductor crystal using complex technological operations.

Due to diffusion, electrons and holes, passing through the contact towards each other in the near-contact region of the hole semiconductor, form an uncompensated charge of negative *n*-ions of acceptor impurities, and in an electronic semiconductor an uncompensated charge of positive donor ions. Thus, in the contact *n*-an excess of holes appears in the region (charged positively), and *V* hole excess electrons (charged negatively). The appearance of these charges will lead to the appearance of its own electric field E at the boundary of the semiconductor regions, created by two near-contact layers of space charges and voltage *U* (Fig. 2) [16-24]. This field will push *p*-region holes to the left of the semiconductor interface, and *n*-region electrons to the right of this boundary. Outside the boundary region of the space charge, the *n*- and *p*-type semiconductor regions remain electrically neutral.

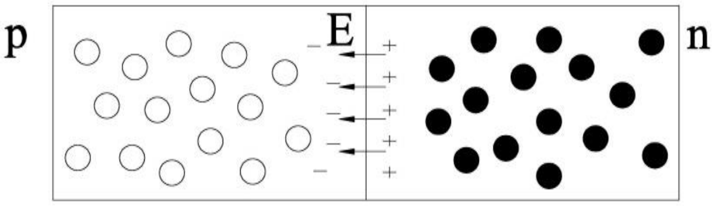

Fig. 2. Charge distribution in the pn junction region

If an external voltage source is applied to the *p* - *n* region, the semiconductor will behave differently depending on the polarity of the applied voltage (Fig. 3). Applied by the “plus” of the power source to the *n* -region of the *p* - *n* junction, and by the “minus” to the *p*-region is called reverse. Under the influence of the reverse voltage U_{rev}, a very small reverse current I_{rer} flows through the junction , since the field created by the reverse voltage E_{arr}, is added to the field of the contact potential difference E_{to}. As a result, the thickness of the barrier layer itself increases ($d_{arr} > d$), and the potential barrier increases. This layer is even more depleted of carriers, and its resistance increases significantly, i.e. e. $R_{arr} >> R_{av}$. For *n=3* and 4, additional *d-(l = 2)* and f-orbitals *(l = 3)* appear, respectively. In this case, each electronic layer must have five *d-*

orbitals (Fig. 4) and seven *f*-orbitals. All orbitals with the same n have similar radial electron density distributions and significantly different angular distributions.

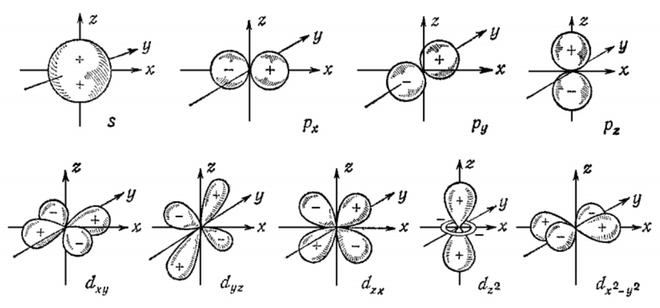

Fig. 4. S-, p- and d-type orbitals.

Discussion and results

The external field pulls the majority charge carriers away from the *p* - *n* junction. The movement of free charge carriers through the *p* - *n* junction decreases, and at a reverse voltage approximately equal to $U_{arr} = 0,2\ V$, the diffusion current through the junction stops, i.e. $I_{diff} = 0$, since the carriers own velocities are not sufficient to overcome the potential barrier. However, non-majority carriers will move through the *p* - *n* junction, creating a current flowing from the *n*-region to the *p*-region (reverse current I_{rev}). It is the drift current (conduction current) of minority carriers through the *p* - *n* junction [25-28].

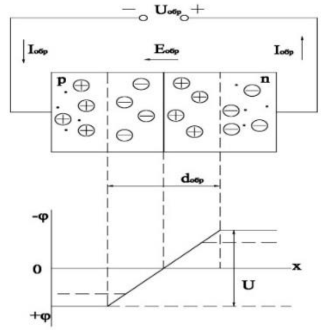

Fig.5. Reverse bias p-n junction.

If the positive pole of the power source is connected to the *p*-region, and the negative pole to the *n*-region, then the inclusion of the *p* - *n* junction is called direct. Direct connection of a *p* - *n* junction is shown in Fig. 5.

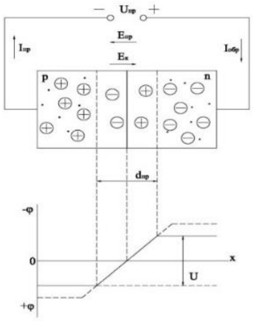

Fig.6.Forward bias p - n junction

Since the resistance of the *p* - *n* junction significantly exceeds the resistance of the neutral *p*- and *n*-regions, the external voltage U_{pr} almost completely drops at this transition. Direct voltage creates an external electric field in the junction, directed towards its own, which reduces the potential barrier of the junction. As a result of a decrease in the potential barrier, a larger number of main charge carriers are able to move into the neighboring region due to the diffusion phenomenon, and such a current is called the diffusion current. At the boundaries of the p-n junction, another current appears, called the drift current, which is generated by minority carriers. This current depends only on the concentration of impurities in the semiconductor and temperature.

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Conclusion

Thus, a *p* - *n* junction allows current to pass in one direction forward, and does not allow current to pass in the other direction - reverse, which ensures conductivity properties in one direction of the *p* - *n* - junction. A structurally designed device with a similar property is called a semiconductor diode.

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