ELECTRICAL CONDUCTIVITY IN METALS, SEMICONDUCTORS, AND DIELECTRICS

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Annotation. This article provides an in-depth theoretical analysis of the electrical conductivity of solids. From a scientific perspective, it examines the electronic structure of metals, semiconductors, and dielectrics, the theory of energy bands, charge carrier mechanisms, as well as the effects of temperature, external electric fields, and impurities on electrical conductivity. The formulas presented serve as an important theoretical foundation for solid-state physics and modern electronics.

Keywords: electrical conductivity, solid state, metal, semiconductor, dielectric, energy bands, electron.

ЭЛЕКТРИЧЕСКАЯ ПРОВОДИМОСТЬ В МЕТАЛЛАХ, ПОЛУПРОВОДНИКАХ И ДИЭЛЕКТРИКАХ

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Аннотация. В данной статье на глубокой теоретической основе анализируется электрическая проводимость твёрдых тел. С научной точки зрения рассматриваются электронная структура металлов, полупроводников и диэлектриков, теория энергетических зон, механизмы носителей заряда, а также влияние температуры, внешнего электрического поля и примесей на электрическую проводимость.

Приведённые формулы служат важной теоретической основой для физики твёрдого тела и современной электроники.

Ключевые слова: электрическая проводимость, твёрдое тело, металл, полупроводник, диэлектрик, энергетические зоны, электрон.

METALL, YARIMO‘TKAZGICH VA DIELEKTRIKLARDA ELEKTR O‘TKAZUVCHANLIK

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Annotatsiya. Mazkur maqolada qattiq jismlarning elektr o‘tkazuvchanligi chuqur nazariy asosda tahlil qilinadi. Metall, yarimo‘tkazgich va dielektriklarning elektron tuzilishi, energetik zonalar nazariyasi, zaryad tashuvchilar mexanizmi hamda harorat, tashqi elektr maydon va aralashmalarning elektr o‘tkazuvchanlikka ta’siri ilmiy nuqtayi nazardan yoritilgan. Keltirilgan formulalar qattiq jism fizikasi va zamonaviy elektronika fanlari uchun muhim nazariy asos bo‘lib xizmat qiladi.

Kalit so‘zlar: elektr o‘tkazuvchanlik, qattiq jism, metall, yarimo‘tkazgich, dielektrik, energetik zonalar, elektron.

Introduction

The electrical properties of solids represent one of the most important and practically significant areas of physics. The ability of materials to conduct or resist electric current is directly related to their internal structure, electronic configuration, and the structure of energy bands, a topic that is thoroughly studied within solid-state physics. Understanding the phenomenon of electrical conductivity is not only essential for theoretical physics but also crucial for the development of practical technologies [1].

The rapid advancement of modern technology, microelectronics, information technology, and the energy sector is closely connected with the in-depth study of the

electrical conductivity properties of materials. The functioning of integrated circuits, transistors, semiconductor lasers, solar cells, and various sensors relies fundamentally on the electrical characteristics of materials. Therefore, investigating the mechanisms of electrical conductivity in metals, semiconductors, and dielectrics plays a decisive role in the creation of next-generation electronic devices.

Furthermore, the ability to control and regulate electrical conductivity is of great importance in developing energy-saving technologies, high-speed electronic systems, and nanoscale devices. Thus, a detailed analysis of the electrical properties of solids represents a key direction in the advancement of modern science and technology.

Electrical conductivity reflects a material's ability to conduct electric current under the influence of an external electric field. Experiments show that different materials conduct electricity differently. Based on this, solids are classified into metals, semiconductors, and dielectrics [2].

The purpose of this article is to theoretically analyze the mechanisms of electrical conductivity in these three types of materials, to reveal their physical nature, and to explain them using fundamental mathematical expressions. The relationship between the current density **j** and the electric field strength **E** is expressed by the following relation:

$$\vec{j}=\sigma\vec{E}$$

Here, σ is the electrical conductivity. The electrical conductivity depends on the concentration of charge carriers and their mobility:

$$\sigma=nq\mu$$

Here, nnn is the concentration of charge carriers, qqq is the charge magnitude, and μ is the mobility of charge carriers [3]. This formula is general for all types of solids, with the only difference being the nature of the charge carriers.

In metals, valence electrons are weakly bound to atoms and can move freely throughout the crystal lattice. These electrons are considered as a gas of free electrons. In the energy diagram of a metal, the valence and conduction bands partially or completely overlap [4]. The average drift velocity of electrons under the influence of an electric field is given by:

$$v_d=\mu E$$

The current density, in turn, is given by:

$j=nqv_d=nq\mu E$

This is the microscopic form of Ohm's law.

In metals, as the temperature increases, vibrations of the crystal lattice (phonons) become stronger. As a result, electron scattering increases, and their mobility decreases:

$\rho(T)=\rho_0(1+\alpha T)$

Here, ρ is the electrical resistivity, and α is the temperature coefficient [5]. Therefore, in metals, electrical conductivity decreases with increasing temperature.

Electrical Conductivity in Semiconductors – Energy Band Theory In semiconductors, the valence band is completely filled, while the conduction band is empty. The energy of the forbidden (band) gap between them is:

$E_g \approx 0.1 \div 3$ eV

As the temperature increases, electrons move from the valence band to the conduction band, creating holes [6].

In intrinsic semiconductors, the number of electrons and holes is equal, that is:

$n=p=n_i$

The electrical conductivity is expressed by the following formula:

$\sigma=e(n\mu_n+p\mu_p)$

Its temperature dependence is of an exponential form:

$\sigma \propto e^{-Eg2kT}$

The introduction of donor or acceptor-type impurities into semiconductors significantly alters their electrical properties, resulting in the formation of n-type and p-type semiconductors, respectively.

Donor impurities (for example, phosphorus, arsenic) have extra valence electrons compared to the host atoms. When incorporated into the crystal lattice, they provide additional free electrons, enhancing electronic conductivity. Such semiconductors are called n-type semiconductors.

In contrast, acceptor impurities (for example, boron, aluminum) consist of atoms with fewer valence electrons. When introduced into the crystal lattice, they create electron

deficiencies—known as holes. These holes act as the main charge carriers, and materials with such impurities are considered p-type semiconductors.

The process of doping semiconductors with impurities allows for very precise and delicate control over their electrical conductivity. This property forms the basis for the creation of transistors, diodes, integrated circuits, and other semiconductor electronic devices. Therefore, semiconductors controlled by donor and acceptor impurities are fundamental materials in modern electronics.

In dielectrics, the forbidden band (band gap) is wide and is equal to:

$E_g > 3$ eV

Under normal conditions, there are no free charge carriers. Electrical conductivity is very low and occurs mainly due to the slow movement of ions or via the tunneling effect under a strong electric field [7]. In dielectrics, electrical conductivity is given by:

$\sigma \approx 10^{-10} \div 10^{-18}$ S/m

Electrical conductivity is influenced by the following factors:

- Temperature
- Crystal defects
- Concentration of impurities
- External electric and magnetic fields

These factors play a decisive role in the technological applications of materials.

Conclusion

In this article, the phenomenon of electrical conductivity in metals, semiconductors, and dielectric materials was analyzed in depth from a theoretical perspective, and their physical nature was explained based on the energy band theory. The study demonstrated that the electronic structure, the arrangement of valence and conduction bands, the width of the forbidden gap, and the nature of charge carriers are the main factors determining the electrical properties of these three classes of materials.

It was established that metals possess high electrical conductivity due to the almost free movement of valence electrons throughout the crystal lattice. The temperature-dependent variation of electrical resistivity in metals was explained by lattice vibrations and electron scattering mechanisms. This understanding is crucial for interpreting the

behavior of metallic materials in electrical circuits and for their proper application in technology.

In semiconductors, electrical conductivity is associated with the small energy gap between the valence and conduction bands and arises from the generation and movement of electrons and holes. It was shown that the electrical properties of semiconductors can be precisely controlled through doping, highlighting their important role in the development of microelectronics, integrated circuits, transistors, and sensors.

In dielectrics, the wide band gap results in an almost complete absence of free charge carriers under normal conditions, making them poor conductors of electricity. However, under strong electric fields or elevated temperatures, dielectrics can exhibit very small electrical conductivity, a factor that must be considered when selecting insulating materials.

Overall, a detailed study of the electrical conductivity properties of metals, semiconductors, and dielectrics provides a solid scientific foundation for modern electronics, nanoelectronics, energy systems, and the development of new functional materials. The results of this research are of significant importance for the future design of high-efficiency electronic devices, energy-saving technologies, and next-generation materials.

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