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The Electronic Properties of Semiconductors and Their Related Applications

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Abstract. The 21st century is characterized by its reliance on science and technology. The booming development of high-tech industries such as artificial intelligence, computers, smartphones, and new energy vehicles is inseparable from the development of microelectronics. Human beings are constantly researching ways to reduce the size of microchips, which according to Moore's Law, has profoundly impacted the progress of computing science and driven societal advancements. All of this scientific progress depends on semiconductor materials. Due to their unique electronic properties, semiconductor materials play a crucial role in contemporary technology. As society progresses rapidly, the electronic properties of semiconductors are becoming increasingly understood, and researchers worldwide are devoting more energy to their study. This paper mainly studies and analyzes the electronic properties of semiconductor materials and their main applications. This paper can provide relevant knowledge for those in the semiconductor industry. This paper finds that traditional semiconductor materials, relying on their unique electronic properties, can be applied to a variety of uses. Electronic properties mainly depend on the mobility of charge carriers, and the special p-n junction provides semiconductor materials with unique electronic properties.

Keywords: energy level, electronic property, junction region, semiconductor

1. Introduction

Semiconductors are special materials with electrical conductivity between that of insulators and conductors. Their ability to transfer electrons under specific conditions is determined by their unique band gap structure. This structure lies between the energy difference of the valence band (VB) and conduction band (CB), allowing for precise control of semiconductors between insulator and conductor states under varying conditions such as temperature, illumination, and doping. Due to their unique and controllable properties, semiconductor materials such as silicon (Si) and gallium arsenide (GaAs) are widely used in diodes, transistors, and integrated circuits. For example, GaAs acts as an insulator at low temperatures but becomes a conductor under illumination, heating, or applied voltage. The reception and emission of light also play a crucial role in enhancing the electronic properties of semiconductors. Electrons can cross the band gap from lower energy states, causing charge carriers in the material to separate, forming electrons and voids, moving from the

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valence band to the conduction band. This process is called a transition. Since modern societal progress is inseparable from microelectronics, and semiconductors are key materials for chip manufacturing, and emerging industries such as artificial intelligence (AI) rely on the development of electronic chips, studying the electronic properties of semiconductors is of paramount importance. This paper primarily studies the distribution of semiconductor types, the reasons for their related electronic properties, and the main applications of semiconductor materials in modern society. This research can provide a theoretical foundation for the development of the semiconductor industry and offers valuable insights for future semiconductor development and research on electronic properties.

2. Classification and electronic properties of semiconductors

2.1. Principles of semiconductor materials

Based on their electrical conductivity, materials can be classified into three categories:

a) Conductors: Exhibiting very high conductivity and low resistivity, common conductors include metals, primarily because free electrons can easily pass through them.

b) Insulators: Insulators have very high resistivity, making the corresponding material a poor conductor. This property is inherent to the material and cannot be arbitrarily changed. Common examples include various plastics.

c) Semiconductors: Their conductivity is enhanced primarily by doping with specific impurities, or by altering environmental characteristics such as light and temperature. Common examples include silicon and germanium. Their unique electronic capabilities are the cornerstone of modern electronics.

Semiconductor materials have unique band structures, and their electron-carrying capacity is also an important factor in evaluating electronic properties. This section mainly introduces the electronic properties of semiconductors.

2.1.1. Semiconductor energy level

The fundamental difference between semiconductors and other materials lies in their distinct band structures. The core of electronic properties is band theory. The key to band theory is energy level splitting. Due to the Pauli exclusion principle [1], in crystal structures, no two electrons can simultaneously occupy the same quantum state. Energy level splitting in crystal structures occurs at their corresponding characteristic atomic spacing. Because of the physical constraint of repulsive forces between different types of atoms, atomic boundaries are established. These atomic constraints set clear limits on the degree of energy level splitting, resulting in different energy bands. Each energy level comprises multiple closely spaced states. Electrons move freely within these energy bands, and the electronic behavior of these bands fundamentally determines whether a material's electronic properties are those of an insulator, conductor, or semiconductor.

2.1.2. Semiconductor junction region

Pure intrinsic semiconductor materials have an extremely limited range in device manufacturing. By selecting specific impurity atoms and introducing them into pure semiconductors, we can adjust the conductivity of the corresponding materials. The main reason for the change in the conductivity of semiconductor materials after doping comes from the change in the density of free electrons and holes in the material, namely n-type semiconductors and p-type semiconductors, also known as

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doped semiconductors. Their conductivity is higher than that of the intrinsic materials that form the basis. In n-type semiconductors, electrons are the main charge carriers and holes are the minority charge carriers. In contrast, in p-type semiconductors [2], holes are the majority charge carriers and electrons are the minority charge carriers. For semiconductors formed by group IV atoms, the doped atoms in n-type semiconductors belong to group V. Since they have one more electron than group IV atoms, free electrons will be provided to the conduction band of the main semiconductor for conduction. On the other hand, group V atoms are also called donor atoms. In another case, in p-type semiconductors, the doped atoms belong to group III atoms, which are called acceptor atoms. Since they have one less electron than group IV atoms, holes are formed, which can accept electrons in the valence state of the semiconductor. Taking Si from group IV as an example, intrinsic semiconductor silicon is in a stable quasi-ancient state. When a p atom replaces the silicon in the lattice, it gains an extra electron, causing it to separate from the parent atom. The energy required to break this chemical bond is less than that required to break a covalent bond, so the electron generated by the breakage can improve conductivity. When we use boron (B) to replace silicon, the B atom has only three valence electrons, which is one less electron. Compared to silicon, it forms ionization and thus holes, which helps to improve conductivity [2], as shown in Figure 1.

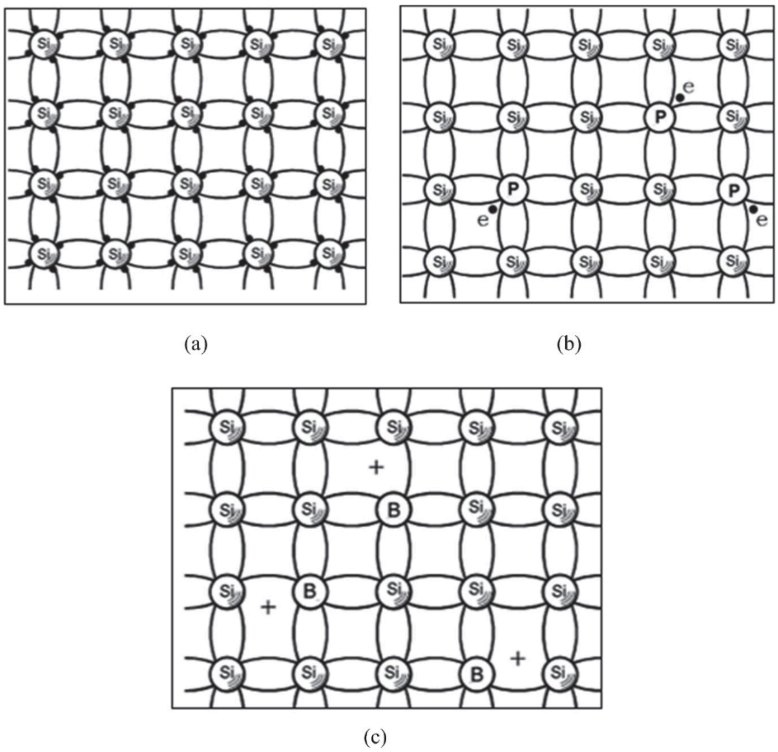

Figure 1. Doping principle diagram. (a)Intrinsic semiconductor si; (b) n-type doped semiconductor; (c)p-type doped semiconductor

2.1.3. Semiconductor charge carriers

Semiconductors are solid materials intermediate between metals and insulators, generated by electronic particles (electrons, holes, or polarons). Charge carriers are generated through intrinsic excitation (thermal excitation), doping introduction, and the generation of charge carriers. Current is primarily due to various scattering mechanisms of conduction electrons, such as lattice vibrations, impurities, lattice defects, grain boundaries, and vacancies. For example, excessively high doping

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concentrations can increase ion hybridization scattering and reduce migration rates. Simultaneously, external conditions such as temperature, electric field strength, and strain stress also affect charge carrier transport.

2.2. Classification of semiconductor materials

Semiconductors are classified into elemental semiconductors (silicon, germanium) and compound semiconductors (oxides and sulfides of main group metals and subgroup metals), as well as crystalline and amorphous semiconductors. We primarily distinguish them based on their structure, classifying them into direct and indirect semiconductors. The distinction between direct and indirect semiconductors mainly depends on the lower edge of the conduction band and the upper edge of the valence band, as shown in Figure 2.

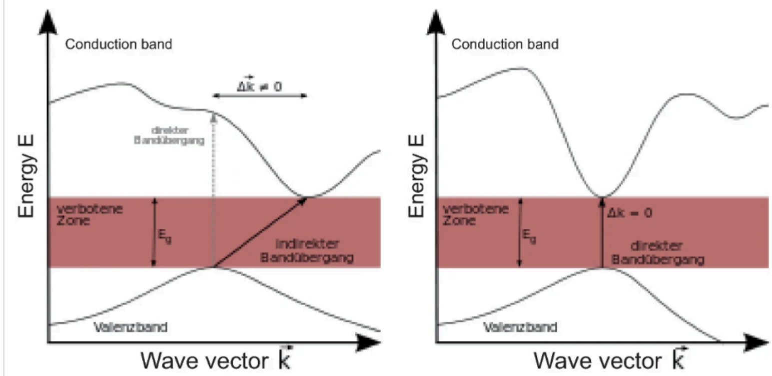

Figure 2. Energy E and vector relationship diagram

The minimum energy at the lower conduction band edge and the maximum energy at the upper valence band edge represent the minimum band gap size that an electron must overcome to transition from the valence band to the conduction band [3].

2.2.1. Direct semiconductor

In direct semiconductors, excited electrons can fall back into the valence band directly after a very short time, without covering the measured conduction band distance. Direct semiconductors only change their energy, not their momentum. If the wave vectors k in two directions are different, leading to a transition, both momentum and energy would change. However, this does not happen in direct semiconductors; therefore, only direct semiconductors can produce effective radiation.

2.2.2. Indirect semiconductor

In indirect semiconductors, electrons cannot immediately return from the conduction band to the valence band. Because the wave vector k varies in indirect semiconductors, recombination can only occur simultaneously due to lattice vibrations or through non-radiative generation by trace impurities in the products. Therefore, in indirect semiconductors, electrons travel a long distance before falling back to the valence band, which is equivalent to the transmission of electric current. Indirect semiconductors are commonly used in solar power generation.

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3. Application of semiconductor electronic properties

3.1. Solar cells

Solar cells mainly utilize the photoelectric effect of semiconductor P-N junctions. When light shines on the corresponding two sides of the p-n junction, a voltage is generated. This is because the absorption of energy by light quanta causes electron-hole pairs to be generated in the p-n junction, thus creating a potential gradient. Electrons move towards the n-junction, and holes move towards the p-junction, thereby generating current [4], as shown in Figure 3.

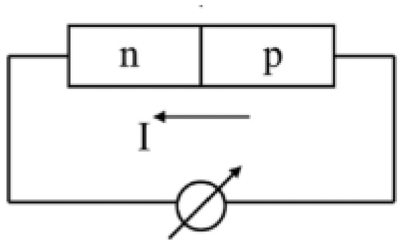

Figure 3. Solar cell schematic diagram

3.2. LED

The principle of an LED (diode) is the opposite of that of a solar cell [5]. Similarly, through a p-n junction, an applied current causes electrons to enter the p-n junction region and holes to enter the n-doped region. Electrons recombine with holes in the p-doped region, and holes recombine with electrons in the n-doped region. The external current releases excess energy as photons (lighting). In this way, a diode can be formed Figure 4 [4].

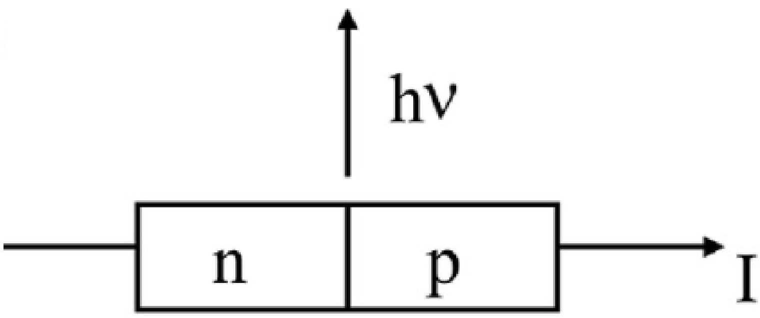

Figure 4. LED Schematic diagram

3.3. Semiconductor integrated manufacturing

Silicon is the semiconductor material we are most familiar with. Transforming a doped crystal into an integrated circuit requires high-precision utilization of its highly stable silicon oxide thin film at every step. All processing involves only the silicon surface, and electronic integration is limited to the vicinity of the silicon surface. Simultaneously, a stable insulating layer is used for selective etching, allowing for the selective connection of different circuits. Placing the three active elements

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of a transistor (emitter, base, and collector) on a single plane is also known as planar semiconductor technology [6].

4. Conclusion

The foundation and progress of modern society are inseparable from semiconductor materials. Their unique inherent electronic properties make them indispensable. However, with the continuous miniaturization of electronic products, various electronic devices offer advantages such as high speed, low cost, and low energy consumption, meeting the diverse demands of modern society. From silicon, the first-generation semiconductor material, to GaAs, the second-generation semiconductor material, and then to GaN, these materials are not only the core of the emerging semiconductor optoelectronic industry but have also brought about a revolution in digital storage in the IT industry, fundamentally changing human history. As the requirements for the size of various devices become increasingly stringent, the limitations of traditional semiconductor materials in internal interconnection technology are becoming increasingly apparent. This paper does not provide a detailed introduction to how the novel material graphene can improve internal interconnection technology. Due to its unique arrangement structure and electron distribution characteristics, future research can focus primarily on graphene materials.

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