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Discussion on Fermi Level of Intrinsic Semiconductor and Pn Junction of Non-Intrinsic Semiconductor

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Abstract: Substances are usually classified according to their electrical conductivity as conductors, insulators, and semiconductors. The specific positions of Fermi energy levels of intrinsic semiconductors and two kinds of extrinsic semiconductors are analyzed. By using carrier concentration, the Boltzmann constant, effective density of states and other physical quantities as well as the related formula, it is concluded that the Fermi energy levels of intrinsic semiconductors lies in the middle of the forbidden band, The Fermi level of n-type semiconductor is higher than the intrinsic Fermi level, while p-type semiconductor is lower than the intrinsic Fermi level. Based on the knowledge of forward bias pn junction and reverse bias pn junction, the basic framework of semiconductor theme is summarized. At the same time, I pay attention to the latest research results of semiconductor, and the future research direction of the semiconductor field has been grasped roughly.

Keywords: Intrinsic Semiconductor; Fermi Level; Carrier; Extrinsic Semiconductor; PN Junction

Introduction

In the middle of the 20th century, the invention of mono-crystalline silicon and semiconductor transistor and the success of the development of silicon integrated circuit led to the electronic industry revolution; At the beginning of 1970s, the invention of quartz optical fiber material and GaAs laser promoted the rapid development of optical fiber communication technology and gradually formed a high-tech industry, making mankind enter the information age. In today's era, information technology is the general trend of the world's economic and social development. Due to the demand of information technology, semiconductor physics, materials and devices have developed faster.

1. Intrinsic semiconductor

1.1 Introduction to intrinsic semiconductor

Semiconductors (also called an undoped semiconductor or i-type semiconductor) can be classified into two categories. One is the internal semiconductor, the other is external semiconductor. Semiconductor with pure crystal structure (Free of impurities) is called intrinsic semiconductor. It is completely contain no impurities and has no lattice defects. Therefore, the properties of the material itself determine the number of holes and electrons. n (number of electrons) = p (number of holes). Typical i-type semiconductors are elements belong to the IVth Group of the periodic table. Intrinsic semiconductors also include GaAs, etc.

1.1.1 Group Ⅳ elements

We have learned that the diamond form of carbon is an insulator. Figures 2.1 show the structure of carbon and silicon (or germanium). The atomic bond of carbon is strong and the atomic radius is small. The atomic bond of silicon is weaker than carbon and the atomic radius is big. These structural characteristics affect the conductivity of materials（doesn't depend on small amounts of additives). Therefore, even though they are all the group Ⅳ elements. Silicon and germanium are semiconductors, The diamond form of carbon is an insulator.

1.1.2 Mixed element semiconductor

Gallium has one less valence electron than germanium, and arsenic has one more valence electron than germanium. If half of a crystal is gallium and the other half is arsenic, the crystal should also be a semiconductor. Gallium arsenide is an important semiconductor.

Extend this reasoning to another semiconductor ZnSe selenide. ZnSe has two valence electrons less than germanium and selenium has 2 more valence electrons than germanium. Each element occupies half of the diamond lattice. Zinc selenide is also one of important semiconductors.

The semiconductors mentioned above are the most commonly used, and there are many other semiconductors with different structures

1.2 Two kinds of carrier in the intrinsic semiconductor

Two adjacent silicon atoms forming a covalent bond. The carriers are free electrons and holes. At room temperature, due to thermal motion, a minority of valence electrons break free of the covalent bonds and become free electrons in silicon. The empty spaces left by covalent bonds are called holes. An atom is positively charged because of losing electrons, or we could say the hole is positively charged. When the intrinsic semiconductor has an applied electric field, the free electrons will move directionally and generate current. Meanwhile, the valence electrons will fill the holes in a certain direction, which means that the holes are also moving in that direction, and they are moving in the opposite direction to the electrons. The sum of these two currents is the current of intrinsic semiconductor .The generation of a free electron will inevitably lead to the generation of a hole, so the free electron and holes appear in pairs. When a valence electron breaks free from covalent bond and forms a free electron, a conductive hole is created.

When the free electrons fall into the hole in motion, they disappear at the same time. This phenomenon is called recombination. At a certain temperature,the concentration of the two carriers is the same.and constantly produce and recombination, reaching a dynamic equilibrium. When the temperature increases, thermal motion increases. The number of electrons breaking away from covalent bond will increase, and the concentration of the electron hole pairs will increase. When the temperature is certain, the equilibrium is established again.

The intrinsic semiconductor has few carriers at room temperature and its conductivity is weak. If increase the light intensity or raise the temperature, more electrons can be excited to make transitions, the number of carriers increases, so the electrical conductivity increases. This characteristic determines that intrinsic semiconductors can be used to make thermal and photosensitive elements, For example, the resistor which resistance varies with temperature or light intensity.

1.3 Fermi Level of intrinsic Semiconductor

According to the definition of Fermi level[1]: the energy where electrons and holes are equally likely to appear. For example, the probability of electrons and holes
appearing in an object at - 1 eV is the same. The Fermi level of this object is - 1 eV.

Therefore, it can be proved that the Fermi level of the intrinsic semiconductor is in the middle of the forbidden band. The above conclusion is only based on our simple judgment, we can also infer the same conclusion using the formula:

The electron - concentration in the conduction band is given as:

$$n = n_c = N_c e^{-(E_c - E_F)/KT} \quad [2.1]$$

The hole concentration in the valance band is given as:

$$p = n_v = N_v e^{-(E_F - E_v)/KT} \quad [2.2]$$

$$N_c e^{-(E_c - E_F)/KT} = N_v e^{-(E_F - E_v)/KT} \quad [2.3]$$

$$\frac{e^{-(E_c - E_F)/KT}}{e^{-(E_F - E_v)/KT}} = \frac{N_v}{N_c} \quad [2.4]$$

$$e^{[2E_F - (E_c + E_v)]/kT} = \frac{N_v}{N_c} \quad [2.5]$$

$$[2E_F - (E_c + E_v)]/kT = \log_e\left(\frac{N_v}{N_c}\right) \quad [2.6]$$

$$\frac{N_v}{N_c} = \frac{2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{3/2}}{2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{3/2}} \quad [2.7]$$

$$\frac{N_v}{N_c} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2} \quad [2.8]$$

$$\frac{[2E_F - (E_c + E_v)]}{kT} = \log_e\left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

[2.9]

$$E_F = \frac{(E_c + E_v)}{2} + \frac{3}{4} KT \log_e\left(\frac{m_h^*}{m_e^*}\right) \quad [2.10]$$

In case of $m_h^* = m_e^*$ or $T = 0k$

[2.11]

$$E_F = \frac{(E_c + E_v)}{2} = \frac{E_g}{2} \quad [2.12]$$

Where K is the Boltzmann constant

T is the absolute temperature of the intrinsic semiconductor

Nc is the effective density of states in the conduction band.

Nv is the effective density of states in the valence band.

The semiconductor materials used to make transistors or integrated circuits require high purity. Many semiconductor devices require material purity to achieve 99.9999999%, the most commonly used semiconductor materials are mono-crystalline silicon. By quantifying "adding" certain other elements to a mono-crystalline silicon substrate, we can obtain electronic devices, such as transistors or integrated circuits and achieve the desired technical state of the product. This amount of addition is very small and the mono-crystalline silicon substrate used cannot contain more than a certain amount of impurities. In fact, not only mono-crystalline silicon needs to be high-purity, all the materials used in the semiconductor manufacturing process are high-purity, and the environment must also be ultra-clean. In the process of semiconductor materials, one of the most important is purification.

1.4 Near-infraredï toï visible high selective thermal radiator[2]

Controlling the thermal emission spectrum of the emitter will improve the efficiency of energy utilization in many fields, such as sensors, energy collection, etc. However, it is very difficult to control in the visible to near-infrared range, the nano structure of the refractory metal emitter can achieve this goal. But as a result of the wide radiation of thermally fluctuating carriers, long wavelength radiation is hard to control,therefore, In recent years, some scientists have proposed a nanostructured heat emitter based on the intrinsic semiconductor. The heat fluctuating electrons are limited to the high-frequency spectrum above the semiconductor band gap, and then the photonic resonance of the structure enhance it. The calculation results show that the intrinsic silicon rod with a diameter of 105 Nm can convert nearly 60% of the input power to the transmit power with a wavelength of less than 1100 Nm at 1400 K.

2. The extrinsic semiconductor

2.1 Basic definition of the extrinsic semiconductor

The extrinsic semiconductor is one that is doped with any trace element or impurity during the manufacturing process. [3]The elements that are added to it are called stimulants, and the process is called stimulants. Therefore, external intrinsic
semiconductors are also known as doped semiconductors. The semiconductor is
better conductive because of the impurities added to it. Thus, in the extrinsic
semiconductor, the number of carriers (electrons and holes) is not equal and depends on the nature of the material and the impurities added.

2.2 Basic introduction of N-type and P-type semiconductor

2.2.1. formation process

For N-type

Semiconductors containing pentavalent impurities such as phosphorus and arsenic are called N-type semiconductors. [4]There are five valence electrons in the doped pentavalent impurity atom, of which only four can combine with the valence electrons in the surrounding four semiconductor atoms to form a covalent bond, while the remaining valence electron easily forms a free electron because it is not bound by a covalent bond. As a result, impurity atoms can provide electrons and are called donors.

2.2.2 Basic knowledge

i. The conductivity of an N-type semiconductor varies with the concentration of atoms in the impurities, the higher the atomic concentration of the impurity, the better the conductivity of the N-type semiconductor.

ii. The pathway of electron production in N-type semiconductors .The electron is supplied by the donor atom in the same concentration as the donor.

The pairing of electrons and holes in an intrinsic semiconductor.

iii. The doping concentration is much greater than the carrier concentration in the intrinsic semiconductor, so in an N-type semiconductor, the concentration of free electrons (majority carriers) is much greater than the concentration of holes (minority carriers), and the semiconductor conducts mainly by free electrons

2.2.3 Formation process

For P-type

Semiconductors with trivalent impurities such as boron and gallium are called aP-type semiconductor. When a trivalent impurity atom forms a covalent bond with a silicon atom, it leaves a hole in the covalent bond because it lacks a valence electron. Because the holes easily capture electrons, the impurity atoms become negative ions. Therefore, trivalent impurities are also called acceptors.

2.2.4 Basic knowledge

i. The conductivity of an N-type semiconductor varies with the concentration
of atoms in the impurities, the higher the atomic concentration of the impurity, the better the conductivity of the N-type semiconductor

ii. The pathway of electron production in P-type semiconductors The holes are produced by doping and the concentration is the same as that of the acceptor atom.

The pairing of electrons and holes in an intrinsic semiconductor.

iii. The doping concentration is much greater than the carrier concentration in the intrinsic semiconductor, so in an P-type semiconductor, the concentration of free holes (majority carriers) is much greater than the concentration of electrons (minority carriers), and the semiconductor conducts mainly by holes.

2.3 Basic introduction of PN junction

i. Definition: p-type semiconductor in contact with n-type

ii. Built-in Voltage

At pn junction, the free electrons on the n-side recombine with the free holes on the p-side, [5]"Depletion region" has no electrons or holes, but a fixed charge from the acceptor and the donor ions, The fixed charges establish an electric field that creates a potential difference between the p and n-side.

iii. Forward-Biased pn Junction

The P region is connected to the positive (+) polarity of the power supply, and the N region is connected to the negative (-) polarity of the power supply. The electric field in the depletion region is below the heat balance value, The width of the depletion region decreases Voltage barrier: decreasing from V_0 to $V_0 - V_d$

iv. Reverse-Biased pn Junction

The P region is connected to the negative (-) polarity of the power supply, and the N region is connected to the positive (+) polarity of the power supply. The electric field in the depletion region increases when it exceeds the thermal equilibrium value. The width of the depletion region increases. Voltage barrier: decreasing from V_0 to $V_0 - V_d$

Conclusion

This investigation starts with the two categories of semiconductor -- intrinsic semiconductor and extrinsic semiconductor. A detailed analysis and a simple extension of these two types of semiconductors are also given. Based on this, we have some basic understanding of semiconductors. In addition, we have learned that the application of semiconductors has played an indelible role in promoting scientific and technological progress in modern times.

The semiconductor industry has a bright future. For example, semiconductor plays a pivotal role in the field of chip, 5G and 6G communication, which are all hot in the world at present. However, there are still some obstacles to the development of semiconductor. For example, when semiconductor is used in spintronic devices, how to generate spin coherent electronic states and how to reduce spin decoherence and other aspects need to be further studied and optimized. This needs not only the research of the older scientists, but also the continuous efforts of our new generation of students who study semiconductors.

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