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Overview of Semiconductor in Physics

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Abstract – There is no question that semiconductors have altered the universe beyond everything conceivable before them. Although people can still need data to be transmitted and processed, it is thanks to semiconductors that these two essential tasks have become simple and take infinitely less time than, for example, vacuum tubes. The building blocks of the entire electronics and computer industry are semiconductor materials. Without integrated circuits (chips), which involves semiconductor materials, compact, lightweight, high-speed and low power consumption devices would not be possible. This paper gives a general discussion of the form of semiconductor materials.

Key Ward – Semiconductor, P-Type, N-Type

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1. INTRODUCTION

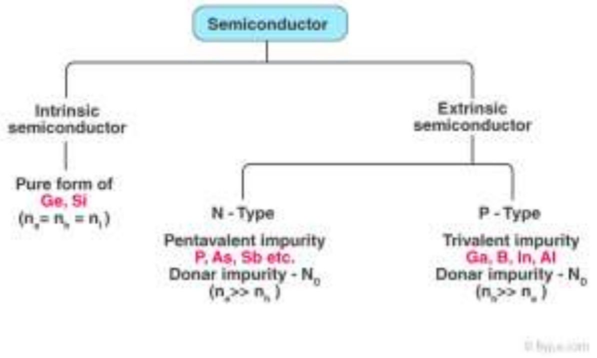
A semiconductor is a solid material with electrical conductivity between a conductor and an insulator; across that wide range, it can vary permanently or dynamically. The materials that have conductivity between conductors (usually metals) and non-conductors or insulators are semiconductors (such as ceramics). Semiconductors can be compounds such as gallium arsenide or pure elements such as germanium or silicon.. The theories, properties and the mathematical approach governing semiconductors are explained in physics.

Semiconductor Examples: Gallium arsenide, germanium, and silicon are among the most commonly used semiconductors.. In electronic circuit production, silicon is used and laser diode, gallium arsenide is used in solar cells etc.

1.1 TYPES OF SEMICONDUCTOR

Semiconductors can be classified as:

- Intrinsic Semiconductor
- Extrinsic Semiconductor



1.1.1 Intrinsic Semiconductor

An intrinsic type of semiconductor material is chemically rendered to be very pure. Only a single form of element is made up of it.

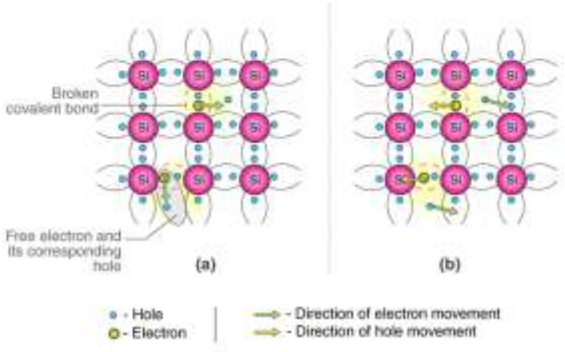


Figure 1.1 : Conduction Mechanism of Intrinsic Semiconductors (a) In absence of electric field (b) In presence of electric Field

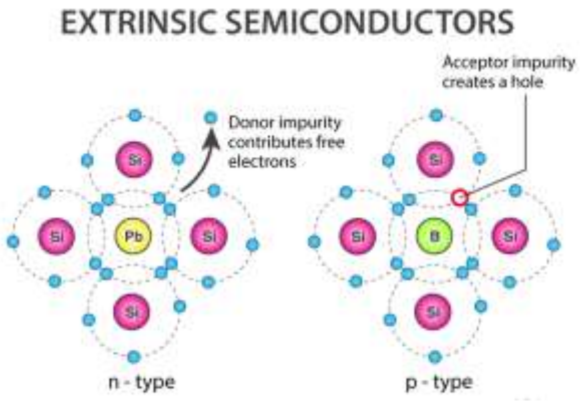
The most popular types of intrinsic semiconductor elements are germanium (Ge) and silicon (Si). Four valence electrons are in them (tetravalent). They are bound to the atom by covalent bonding at absolute zero(0) temperature.

As the temperature increases, due to collisions, few electrons are unbounded and free to pass through the lattice, causing an absence in its original position (hole). In the semiconductor, the conduction of electricity contributes to these free electrons and holes. The number of carriers of negative and positive charges is equal in sum.

1.1.2 Extrinsic Semiconductor

By adding a small number of suitable substitute atoms called IMPURITIES, the conductivity of semiconductors can be greatly improved. The method of adding impurity atoms is called DOPING to the pure semiconductor. Usually, in the doped semiconductor, only 1 atom in 107 is substituted by a dopant atom. It is possible to classify an extrinsic semiconductor further into:

- N-type Semiconductor
- P-type Semiconductor



► N-type semiconductor

The N-type semiconductor (N for Negative) is obtained by doping, i.e. by adding valence-five element impurity to the valence-four semiconductor, in order to increase the number of free-charge carriers (in this case negative).

As the doping material is added, it gives off (donates) weaklv-bound outside electrons to the semiconductor atoms. This form of doping agent is also known as the donor material because it gives away some of its electrons [1] and [2]

The aim of N-type doping is to generate in the material an excess of mobile or 'carrier' electrons. Consider the case of silicon to better explain how N-type doping is done (Si). There are four valence electrons in Si atoms, each of which is bonded covalently with each of the four neighboring Si atoms. If an atom is introduced into the crystal lattice instead of a Si atom with five valence electrons, such as those from the periodic table (e.g. phosphorus (P), arsenic (As), or antimony (Sb)) group 15 (old group V(a), a.k.a. nitrogen group), the atom will have four covalent bonds and one unbonded electron. This additional electron is only weakly bound to the atom and can be passed easily into the conduction band..

At normal temperatures, nearly all such electrons are thrust into the conduction band. Since the excitation of these electrons does not give rise to the formation of a vacuum, the number of electrons in such a material is much greater than the number of holes. In this case, the primary carriers are the electrons and the holes are the minority carriers. Since the five-electron atoms have an extra electron to 'donate', they are called donor atoms. Note that each movable electron is never far away from an immobile positive dopant ion within the semiconductor, and the N-doped material usually has a zero net electrical charge. In an N-type semiconductor, the fermi level is nearer to the edge of the conduction band [4]

► P-type Semiconductor

A P-type semiconductor (P for Positive) is obtained through a doping process that involves adding a certain sort of atom to the semiconductor to increase the number of free-of-charge carriers (in this case positive).

As the doping material is added, it takes away (accepts) weakly-bound outer electrons from the semiconductor atoms. Also known as acceptor material, this type of doping agent is also known, and holes are known as semiconductor atoms that have lost an electron.

The aim of P-type doping is to create an excess of holes. The crystal lattice is replaced by a trivalent atom in the case of silicon (typically from group IIIA of the periodic table, such as boron or aluminium).The outcome is that one electron is absent from one of the four usual silicon lattice covalent bonds. The dopant atom will then accept an electron from the covalent bond of the neighbouring atoms to complete the fourth bond. Dopants of this kind are called acceptors. [6] An electron is accepted by the dopant atom, which induces the loss of half of one bond from the neighbouring atom and results in the creation of a 'hole.' A nearby negative-charged dopant ion is associated with each hole and the semiconductor as a whole remains electrically neutral. Once each hole has drifted away into the lattice, however, an electron at the position of the hole can 'expose' one proton in the atom and no longer cancel it. A hole serves as a positive charging number for this purpose. When a sufficiently large number of acceptor atoms are added, the holes greatly outnumber the thermal-excited electrons. Holes are thus the main carriers, while the minority carriers are electrons in P-type materials. Blue diamonds (Type Lib), containing boron (B) impurities, are an instance of a naturally occurring P-type semiconductor. [6]

1. MAJORITY AND MINORITY CARRIERS IN SEMICONDUCTORS

Electrons and holes serve as charge carriers in semiconductors. Many carriers are called the more plentiful carriers of charge. They are electrons in N-type semiconductors, while in P-type semiconductors they are holes. The less abundant charge carriers are called minority carriers; they are holes in N-type semiconductors, whereas they are electrons in P-type semiconductors .[3]

They recombine when an electron meets a hole and these free carriers essentially vanish. The energy emitted may be either thermal, semiconductor heating (thermal recombination, one of the semiconductor waste heat sources), or photon-released (optical recombination, used in LEDs and semiconductor lasers).

2. CARRIER GENERATION AND RECOMBINATION

Carrier generation and recombination are processes by which mobile electrons and electron holes are generated and removed in the solid state physics of semiconductors. For the operation of many optoelectronic semiconductor devices, such as photodiodes, LEDs, and laser diodes, carrier generation and recombination processes are important. A complete study of P-N junction components, such as bipolar junction transistors and P-N junction diodes, is also important. [7]

The electron-hole pair is the basic generation and recombination unit that corresponds to the transfer of an electron between the valence band and the conduction band.

3. BAND STRUCTURE

Semiconductor materials have, like other solids, an electronic band structure defined by the material's crystal properties. The Fermi energy and the temperature of the electrons explain the real energy distribution between the electrons. Both electrons have energy below Fermi energy at absolute zero temperature, but the energy levels are randomised at non-zero temperatures, and some electrons have energy above Fermi.

The Fermi energy is in the centre of a prohibited band or band gap between two permissible bands, called the valence band and the conduction band, in semiconductors. The valence band is typically quite nearly entirely filled, directly below the forbidden band. Normally, the conduction band, above the Fermi stage, is almost completely empty. The electrons are not mobile, and do not flow as electrical current, since the valence band is too nearly complete.

However, if an electron acquires sufficient energy in the valence band to enter the conduction band, it will pass freely between the energy states of the almost empty conduction band.[8] In addition, it can also leave behind an electron hole that can flow exactly like a physical charged particle as current. Carrier generation describes processes by which electrons gain energy and transfer from the valence band in fig 1.1

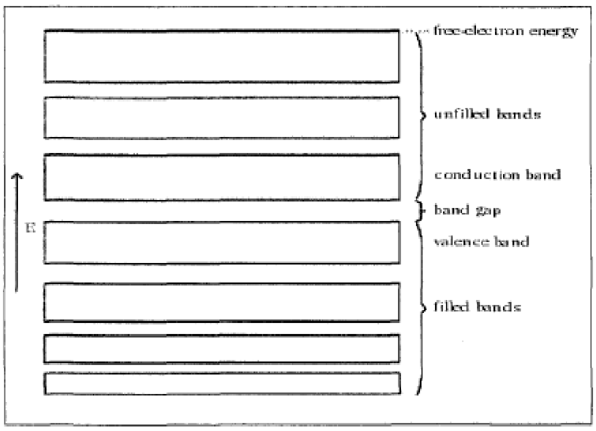


Fig.1.1 structure of Electronic band of a semiconductor material.

In a thermal equilibrium content, generation and recombination are balanced, so that the density of the net charge carrier remains constant. Thermodynamics calculates the equilibrium carrier density that emerges from the balance of these interactions. Fermi-Dirac statistics give the resulting probability of occupancy of energy states in each energy band .[9]

4. GENERATION AND RECOMBINATION PROCESSES

The generation and recombination of carriers results from the interaction of electrons with other carriers, either with the material lattice or with optical photons. As the electron travels from one band of energy to another, the energy obtained or lost must take some other form.

5. Shockley-Read-Hall (SRH) process

In the centre of the band gap, the electron in transition between bands passes through a state created by an impurity in the lattice. The impurity state will absorb differences in momentum among the carriers, so this process is the dominant generation and recombination process in silicon and other indirect bandgap materials. The energy is transferred in the form of lattice vibration or a phonon, which shares thermal energy with the material.[4,5, 10]

6. Auger recombination

The energy is given to a third carrier that, without transferring to another energy band, is excited at a higher energy level. The third carrier usually loses its excess energy to thermal vibrations after the contact. Since this process is a three-particle interaction, when the carrier density is very high, it is usually only important in non-equilibrium conditions. The method of generating Auger is not easy to create, because in the unstable high-energy state, the third particle will have to begin the process. [11]

7. Depletion region

The depletion area, also referred to as the depletion layer, depletion zone, junction region or space charge region in semiconductor physics, is an insulating region inside a conductive, doped semiconductor material where an electric field has diffused or pushed the charge carriers away.

The depletion region is so called because, by eliminating all free-charge carriers, it is created from a conducting region, leaving none to bear a current.

1.2 SEMICONDUCTOR MATERIALS

In the electronics industry, semiconductor materials have been playing a crucial role since the second half of the last century. The quest for new semiconductor materials and the development of existing materials has been continuous due to their use in devices such as transistors (and, subsequently, computers), gas sensors and lasers. As shown in Fig. 1.1, the semiconductor resistivity, p, is usually 10'2 to 108 Q-cm.

A semiconductor material's main property is that it can be doped with impurities that controllably change its electronic properties. Crystalline inorganic solids are the most widely used semiconductor materials.

It is possible to classify these materials according to the periodic table classes from which their constituent atoms come. Table 1.1 provides a list of popular semiconductors. (This list includes only a small fraction of known semiconductors.) It is important to remember that oxide semiconductors, such as ZnO or SnO_2, are commonly researched and will be addressed as gas sensing materials.

1.2.1 Basic principles of semi conductivity

It can have a strong electrical conductivity temperature. A semiconductor can be distinguished from a conductor by the fact that the uppermost filled electron energy band is completely filled into a semiconductor at absolute zero, but only partly filled into a conductor. A semiconductor has a band gap that is small enough to thermally populate its conduction band with electrons at room temperature, whereas an insulator has a band gap that is too large for electrons that are thermally enabled to populate its conduction band at room temperature.

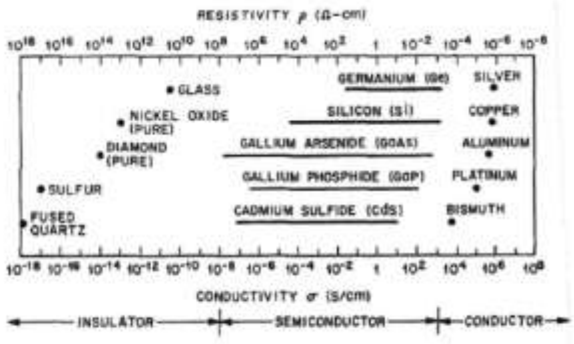


Figure 1.1: Typical range of conductivities for insulators, semiconductors, and conductors.

Table 1.1: List of some common semiconductors

Group IV Semiconductors	III-V Semiconductors	II -VI Semiconductors	Oxide Semiconductors
Diamond (C)	Boron nitride (BN)	Cadmium selenide (CdSe)	ZnO
Silicon (Si)	Gallium arsenide (GaAs)	Cadmium telluride (CdTe)	TiO_2
Germanium (Ge)	Indium nitride (InN)	Zinc selenide	SnO_2

An insulator is an entirely pure silicon crystal, but it donates free electrons and promotes conduction when an impurity, e.g. arsenic, is introduced in amounts small enough not to completely break the regularity of the crystal lattice. Since a mobile charge carrier has been added, conduction is possible. Alternatively, to make silicon conductive, silicon can also be doped with boron. In this case, as boron has a valence of 3+, the mobile charge carrier is a void.

The doping level itself is extremely low, and this is the secret to the activity of semiconductors. The carrier population is exceptionally high in metals: one carrier charge per atom. In metals, the charge carriers must be swept out by applying a voltage to turn a large amount of the material into an insulator. This voltage is, consequently, extremely high. However, there is only one mobile charge carrier per million atoms or more in lightly-doped semiconductors. It is easy to achieve the amount of voltage needed to sweep a few charge-carriers out of a large volume of the material. It is possible to rapidly change doped semiconductors into insulators, while metals cannot.

1.2.1.1 Band structure of semiconductors

Semiconductors are classified as solids in which the valence band, the uppermost band of occupied electron energy states, is fully full at absolute zero (0 K). Fermi energy is the energy level at which accessible electron states are occupied under absolute zero conditions. There is a distribution of the electrons' energy at room temperatures, such that a small number have enough energy to cross the distance in the energy band into the conduction band. Thus, this electron redistribution in the semiconductor allows the transport of charges. There are now missing electrons, or holes, in the covalent bonds from which these excited electrons have come, that are also free to travel around. In the semiconductor, the size of the band gap represents the energy needed to excite the electrons and allow them to hop to the conduction band from the valence band. In addition, a line between semiconductors and insulators is drawn by the scale of this energy band difference. Semiconductors are usually considered to be materials with a band gap energy of less than about 3 electron volts (eV), whereas those with higher band gap energy are considered to be insulators. Fig. 1.2.provides a graphical representation of the band distance in different materials.

1.2.1.2 Doping of semiconductors

For electronic applications, semiconductors are very helpful because their electronic properties can be altered by introducing small amounts of impurities in a controllable way. Such impurities are known as dopants. A heavily doped semiconductor will increase a wide margin of its conductivity. By means of doping, two types of semiconductors can be distinguished: intrinsic and extrinsic semiconductors.

An intrinsic semiconductor is a semiconductor that is pure enough that its electrical behaviour is not greatly influenced by the impurities in it. All carriers are formed from the complete valence band into the empty conduction band by thermally or optically exciting electrons. In an intrinsic semiconductor, an equal number of electrons and holes are present. In an intrinsic semiconductor, the concentration of carriers depends heavily on temperature. The valence band is fully full at low temperatures, thereby making the material an insulator. Increasing the temperature results in an increase in the number and conductivity of carriers.

In order to adjust the number and form of free-charge carriers present, an extrinsic semiconductor is a semiconductor doped with impurities. A semiconductor called degenerate is a semiconductor doped to such high levels that the dopant atoms are an appreciable part of the semiconductor. A semiconductor that is degenerated behaves more like a conductor than a semiconductor.

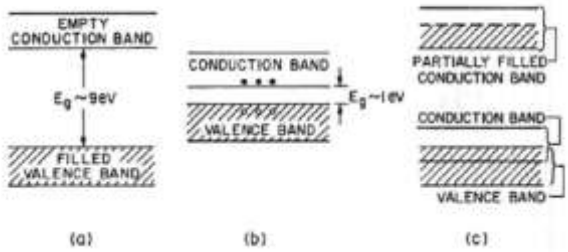


Fig. 1.2: Schematic energy band representation of (a) an insulator, (b) a semiconductor, and (c) conductor

Two types of doping exist, depending on the specifications of the form of charge carrier in a doped semiconductor: n-type and p-type doping. The goal of n-type doping is the creation of mobile electrons in the material. If, for example, silicon (Si) is doped with ions of greater valence than Si, these mobile electrons are incorporated into the semiconductor. Antimony (Sb) or phosphorus may be such ions (P). Then there would be four covalent bonds and one essentially un-bonded electron in the impurity atom. This extra electron is only weakly bound to the atom and can easily be pulled into the band of conduction. At room temperature, almost all such electrons are thrust into the conduction band. In this case, the primary carriers are the electrons and the holes are the minority carriers. They are called donors because their additional electrons are donated by the five-electron atoms. In p-type doping, on the other hand, the major carriers are 'holes'. A dopant is a trivalent molecule in the case of silicone, such as boron. The consequence is that one electron is missing from one of the four normal covalent bonds of the silicon lattice. The dopant atom accepts an electron, causing the loss of one bond from the surrounding atom and resulting in the formation of a hole. When a sufficiently large number of acceptor atoms are added, the holes greatly outweigh the thermally excited electrons. Holes are thus the primary carriers, while the minority carriers are electrons in p-type materials.

1.2.1.3 Charge transport in semiconductors

A break in the action of doped germanium conductivity at low temperatures was observed following the discovery of the transistor effect in the second half of the 1940s by Bardeen, Brattain and Shockley. Conwell and Mott proposed a model for a "new" conduction mechanism in 1956 in which charge carriers conduct the electrical current from an occupied site to an empty site by thermally enabled tunnelling. This approach was known as phononon-assisted hopping and was the starting point for a variety of theories of transport, such as the Miller and Abrahams model. This model has become the most generally accepted theory of action between localised states and is the basis of Mott's theory of Variable Range Hopping

(VRH). According to this model, electrons are "intelligent" because they hop as low as possible from an initial state I to another "j" with energy in the conduction process. The site "j" is statistically located far from I for such an energy, involving a range rjj = R, which is normally far larger than the wave function's decay period. Conductivity depends on two factors, according to Mott, a Boltzmann factor: ***exp (~^r).***

Factor depending on the overlap of the wave functions: ***exp (-2aR),*** where k is the Boltzmann constant, T is temperature, W is the hopping energy, a'^{1} is the wave function decay length, and R is the distance separating sites "i" and "j"

Mott considers that the conductivity o behaves linearly with the factor

$exp\left(-2\alpha R - \frac{W}{kT}\right)$ and may be written in the form:

$$\sigma = \sigma_0 . exp\left(-2\alpha R - \frac{W}{kT}\right) \qquad (1.1)$$

where ao is a factor that is weakly temperature dependent. The idea of Mott was to maximize the hopping probability. To do so one must express the hopping energy W in the form:

$$W = \frac{3}{4\pi R^3 N(E_F)} \qquad (1.2)$$

This yields the optimum value of R:

$$R = \frac{3^{1/2}}{[8\pi\alpha N(E_F)k]^{1/4} . T^{1/4}} \qquad (1.3)$$

where ***N(Ep)*** is the density of states at the Fermi level. It then appears that the distance of a hop increases as T decreases. Substituting Eq. (1.2) and Eq. (1.3) into Eq. (1.1), we obtain the [T$^{1/4}$] Mott conductivity for non-crystalline semiconductors:

$$\sigma_{3D} = \sigma_0^{3D} . exp\left[-\left(\frac{T_0^{3D}}{T}\right)^{1/4}\right] \qquad (1.4)$$

A powerful method to describe and classify electrical transport in semiconductors is this proposed mechanism. Unfortunately, under this model, not all semiconductors can be mounted. The mechanisms of Nearest Neighbor Hopping (NNH) or Granular Metal (GM) are only a few examples of different mechanisms that have been applied as an alternative to the theory of VRH. In certain cases, the measured transport characteristics indicate a combination of different transport mechanisms. Thus, it is possible to apply various models at different temperatures, which shows that transport in a semiconductor is a very complex matter..

2. CONCLUSION

Semiconductor device models are very important for circuit design applications. Some relevant aspects to model devices are: to improve the existent device models, propose new device models for new components and optimize the implementation of device models in different circuit simulation platforms. The typical problems found in the proposed methods of modeling are a compromise between convenience, accuracy, numerical efficiency and implementation precision considering the most important physics behaviors. Then, the most precise model in simulation is the mathematical model, which is based on semiconductor physics.

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