CHAPTER

4

SEMI-CONDUCTOR PHYSICS

4.1. INTRODUCTION

The branch of physics which deals with the semiconductors is known as Semiconductor Physics.

All the engineering materials that are used in electrical and electronics engineering can be classified as per their functions as :

1. Conductors
2. Insulators
3. Semiconductors.

The materials which allow the passage of electric current through them easily are called, ***conductors.*** These have low electrical resistance. Some of the examples of conductors are metals such as Iron, Copper, Silver etc.

The materials which donot allow the electric current to pass through them are called **insulators.** These have very high electrical resistance. Most of the non-metals and organic materials are insulators. Examples are Rubber, Mica, Wood, Ceramics etc.

Semiconductor materials *are those which possess the conductivity higher than insulators but, lesser than conductors and are used* for manufacturing most of the active components. Their conductivity is largely dependent upon the electric field and impurities etc. Some examples of semiconductor materials are Silicon, Germanium, Selenium etc.

Table 4.1 shows primary classification of engineering materials.

TABLE 4.1.

Engineering materials		
Conductors	Semiconductors	Insulators
Copper, Silver, Gold Platinum and other metals.	Silicon, Germanium, elements of Group IV, Silicon carbide, Gallium, Arsenide etc.	Rubber, Wood, Paper, Ceramics, transformer oil and various other organic materials
Resistance		
Low	Medium	High

To understand the conductivity in materials it is important to know the atomic structure of materials.

The Atomic Structure : The much accepted structure of atom was idealized by Bohr in 1905. The main points of **Bohr's model of atom** are :

1. The atom consists of two parts *i.e.* nucleus and extra-nuclear part. The electrons revolve around the nucleus in the extra-nuclear part.

2. All the electrons revolve around the nucleus in the extra-nuclear part in definite orbits having fixed amount of energy.

3. The distribution of electrons in orbits in the extra-nuclear part is determined by the formula $N = 2n^2$, where n is the number of the orbit. Thus, there will be 2 electrons in 1st orbit, 8 in 2nd and 18 in 3rd orbit. The energy possessed by these electrons is also fixed. The electrons in the 1st shell have least energy and that in the extreme most have the highest energy.

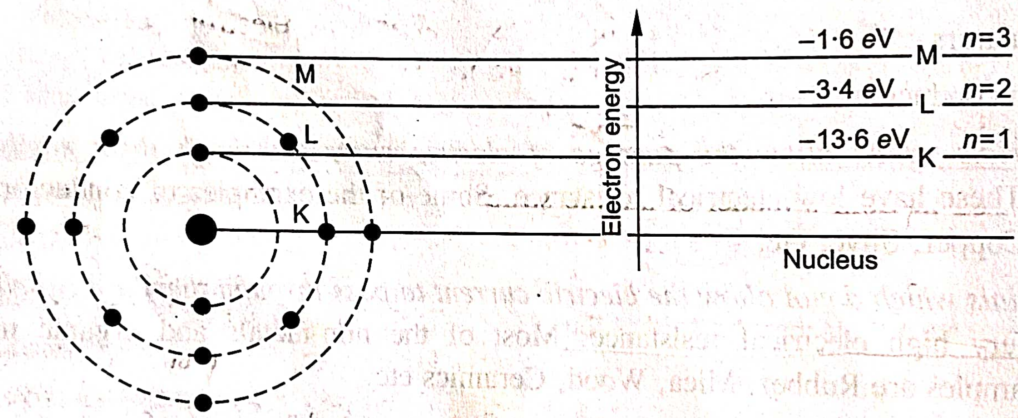


Fig. 4.1. Structure of silicon atom with energy levels.

4. An electron is lifted to higher orbit when energy is supplied to it. The atom is then said to be excited. The excited state does not last long. The electron jumps back to the initial stage and releases that energy.

A simple electronic structure of silicon atom is shown in Fig. 4.1. The atom has 14 electrons which resolve around the nucleus in fixed shells. There are four electrons in the 3rd shell (outermost) and hence it is called **Tetravalent atom.**

The electrons in the outermost shell are called **Valence electrons** and are responsible for the amount of conductivity of materials.

4.2. IDEA OF ENERGY LEVELS

It is clear from Bohr's model of atomic structure that electrons can revolve only in permitted orbits (*i.e.* orbit of radii r_1, r_2 and r_3) and not in any intermediate orbit.

realme Shot by Ranjeet

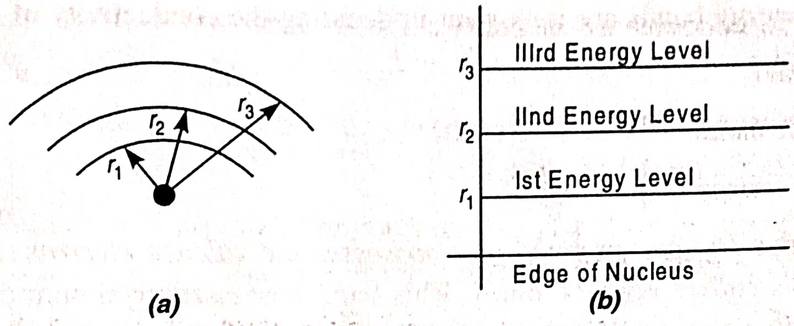


Fig. 4.2. Energy levels

Thus, the radii between these permitted orbit radii *i.e.* r_1 and r_2 or r_2 and r_3 are forbidden. Each orbit exhibits a fixed amount of energy and the electrons revolving in that particular orbit exhibits the energy of that orbit. The energy depends upon the orbits, the larger is orbit greater is the energy possessed by the electrons. Thus, the electrons in the outermost orbit possesses more energy than the electrons of inner orbits.

The level of energy obtained by different orbits can be well understood by the energy level diagram shown in Fig. 4.2. From this fig., it is clear that an electron has greater energy in the higher orbits. Thus, energy level is another way of representing the orbital radius.

4.3. ENERGY BANDS IN SOLIDS

As discussed in Bohr's model of atomic structure, electrons revolving around the nucleus in a particular orbit have definite energy. However, a soild contains a number of atoms and each atom is greatly affected by the neighbouring atom. Hence, electrons in the same orbit don't possess exactly the same energy and they may be said to be present in the same energy band rather than the same energy level. An energy band has the electrons which lie in the same shell of the atom and have energies almost equal to each other. *Thus, the range of energies possessed by electrons of the same orbit is known as* **Energy band.**

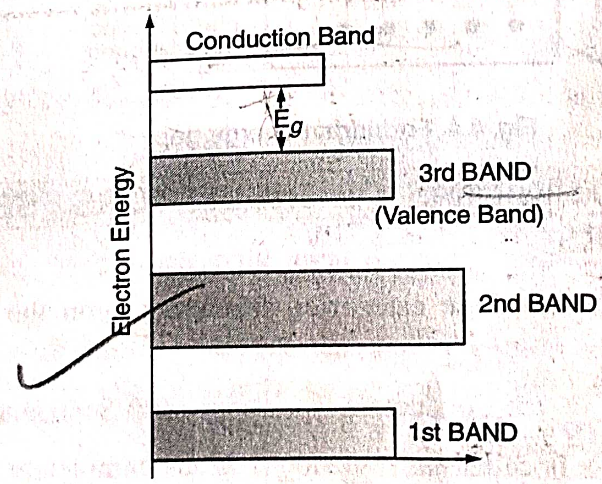


Fig. 4.3.

Fig. 4.3 shows the energy band diagram of solids.

realme Shot by Ranjeet

Only following energy bands are important in deciding the conductivity of materials :

1. Valence band
2. Conduction band
3. Forbidden energy Gap.

1. Valence Band : *The energy band that possesses the valence electrons (i.e. the electrons in the outermost shell) is called* **Valence band.** This band possesses maximum energy electrons. The valence band may be partially filled or completely filled. However completely filled valence band does not accommodate more electrons and hence it cannot contribute to electric current.

2. Conduction Band : This band represents next large group of permissible energy level. An electron in this band has negligible interference from nucleus and is free to move under the influence of electrical energy. Basically, the electrons in the conduction band do not belong to a particular atom. If a material has empty conduction band, it cannot be a conductor.

3. Forbidded Energy GAP : *The minimum energy required to lift one electron from valence band to the conduction band is called* **forbidden energy.** In the energy level diagram, the difference between the energies of conduction band and valence band is called 'forbidden energy gap'. Greater the forbidden energy gap, lesser is possibility of electron to jump from valence band to conduction band and hence conduct.

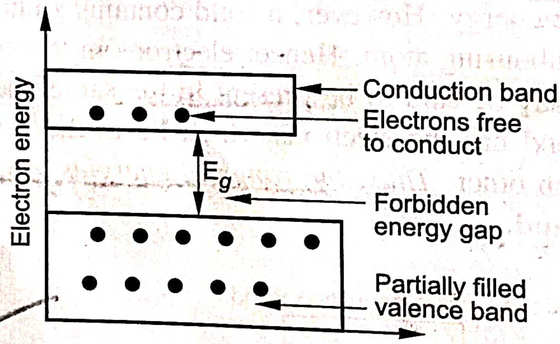


Fig. 4.4. Forbidden energy gap

4.4. ENERGY BAND DIAGRAMS OF INSULATORS, SEMICONDUCTORS AND CONDUCTORS

Materials can be classified into three categories depending upon the energy band structure. They are,

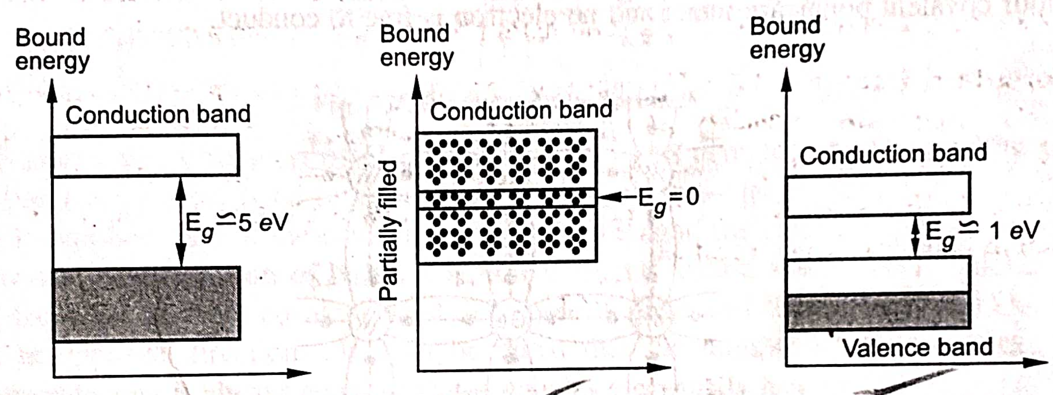
(*i*) Insulators (*ii*) Conductors (*iii*) Semiconductors.

(*i*) **Insulators.** A materials is called an insulator if it has completely filled valence band and empty conduction band. The energy gap between the two bands is of the order of 5 eV or more. This gap is very large and cannot be covered up by increase in temperature.

(*ii*) **Conductors.** Conductors are the material which have plenty of free electrons. A material is said to be a conductor if it has partially filled valence band and partially filled conduction band. The forbidden energy gap is very small *i.e.* the two bands may overlap each other as shown in Fig. 4.5 (*b*). In case of conductors the electrons in the valence band also take part in conduction.

(*iii*) **Semiconductors.** The semiconductors are materials which have normally empty conduction band at 0 °C and partially filled valence band. The Forbidden energy gap between the two is of the order of 1 eV.

Since the energy gap is very small. It can be overcome by increasing the temperature or supplying energy by any other external manner to the electron in the valence band. The electrons after receiving the energy jump to the conduction band and are free to take part in conduction.



(*a*) **For insulators** (*b*) **For Conductors** (*c*) **For Semiconductors**

Fig. 4.5. Energy Band Diagrams for Materials.

Semiconductors are of two types :

(*a*) Intrinsic semiconductors

(*b*) Extrinsic semiconductors.

(*a*) **Intrinsic semiconductors.** These semiconductors are in the purest form. A semiconductor is not truely intrinsic unless its impurity content is less than 1 part in 100 million parts of semiconductor. The intrinsic semiconductor have little conductivity. Their conductivity is uncontrolled *i.e.*, it depends only upon the temperature. Thus, they are of least practical significance.

(*b*) **Extrinsic semiconductors.** When we add a certain amount of impurity in intrinsic semiconductor it becomes extrinsic semiconductor. By adding impurity, (some atoms) the conductivity of semiconductor increases as well as it becomes controllable, *i.e.* the conductivity will depend upon the amount of doping (*i.e.* addition of impurity atoms).

The impurity atoms are added from Group III or Group V of periodic table. The impurities from Group III such as boron, are called **acceptor impurities** and the impurities from Group V such as antimony and bismuth are called **donor impurities.**

The extrinsic semiconductors are of two types *i.e.,* P-type semiconductors and N-type semiconductors. When we add impurity from Group III such as boron, the resulting semiconductor is P-type semiconductor and when we add impurity from Group V, such as antimony, the resulting semiconductor is N-type semiconductor.

4.4.1. Crystal Line Structure of Semiconductors

To understand the phenomenon of conduction in semiconductors, one should understand the crystalline structure of it. In a crystal, the atoms are bonded together in a cohesive manner. The semiconductor atoms have 4 electrons in the outermost shell. To fill the outermost shell each atom acquires four more electrons by sharing one electron each from the four adjacent atoms and hence from a crystal. Fig 4.6 shows simplified two dimensional crystalline structure of intrinsic semiconductor (Ge). In the fig. the core represents the nucleus and all other electrons except valence electrons. The valence electrons take part in forming covalent bonds with four neighbouring atoms. At absolute zero, all four covalent bonds are intact and no electron is free to conduct.

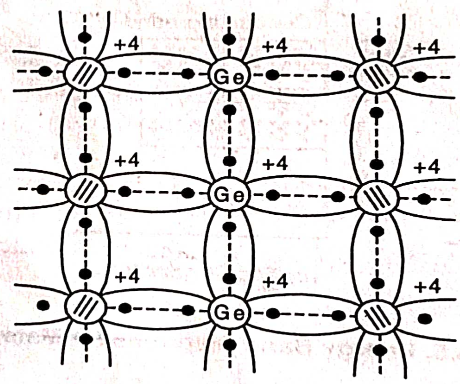


Fig. 4.6. Crystalline structure of intrinsic semi-conductor at 0 K.

4.4.2. Generation and Recombination of Electron Hole Pairs

At absolute zero, the valence band in the intrinsic semiconductors is totally filled and the conduction band is empty. Since there are four covalent bonds, each bond is not so strong. When the temperature is increased, the electrons get sufficient energy to break the covalent bond *e.g.*, room temperature may be sufficient to make a valence electron to move away from the influence of its nucleus. When this happens, the electron becomes free to conduct and hence appears in the conduction band.

When an electron moves away to the conduction band, a vacancy is created in the valence band. This vacancy is called ***hole.*** Whenever a free electron is generated, a hole is created simultaneously. This type of generation is called **thermal generation.**

In order to understand semiconductor physics, we must consider hole as a current carrier. However, practically the hole is nothing but +vely charged nuclear part of the semiconductor atom

realme Shot by Ranjeet

(Ge or Si) that is tightly held in the crystal lattice and is unable to move. The +ve charge on the hole results due to loss of one electron that moves away to the conduction band. However, the semiconductor material remains electrically neutral.

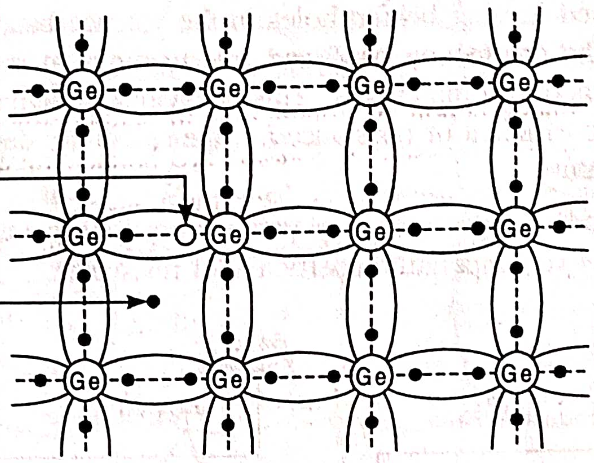
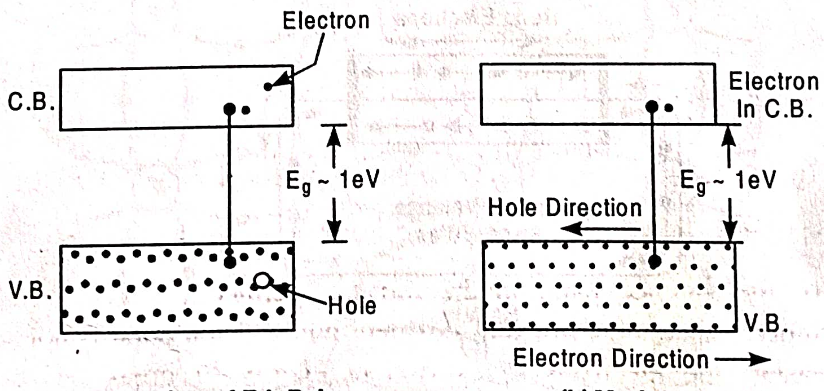


Fig. 4.7. Electron-hole concept

Fig. 4.8 shows the generation of electron hole pair in semiconductor. The amount of energy required to break a covalent bond in germanium is 0·72 eV and that in silicon is 1·12 eV. When such energy is supplied, one of the covalent bonds is broken and the electron appears in conduction band. This results in **generation of holes.** The hole does not remain stable and is quickly filled by the electron from the adjacent covalent bond. The hole is generated there. This way electrons and holes move in opposite directions. It must be noted that the number of electrons and holes in intrinsic semiconductors is always equal so that it remains electrically neutral.



(a) **Generation of E,h Pair** *(b)* **Motion**

Fig. 4.8. Generation of electron-hole pair

When some external energy is supplied to the semi-conductor, the electrons of the valence band are lifted to the conduction band and becomes free leaving holes in the valence band. The orbits of conduction band in which free electrons are moving are larger than the orbits of valence band in which holes are created. The conduction band orbit of one atom can intersect the hole orbit of another. Due to this, conduction band electron generally falls into a hole. Merging of a free electron and a hole is called **recombination.** When recombination occurs, hole disappears.

realme Shot by Ranjeet

4.5. EFFECT OF TEMPERATURE ON CONDUCTIVITY OF SEMI-CONDUCTORS

A semiconductor behaves as insulator at 0°K. When temperature is increased or some heat energy is supplied to them, the covalent bonds are broken and some of the valence electrons are lifted to conduction band leaving behind holes in the valence band as shown in Fig. 4.9 (*b*). The electrons reaching at the conduction band and *free* to move at random. The holes created in the crystal also move at random in the crystal. This behaviour of semiconductors shows that they have negative temperature co-efficient of resistance *i.e.* the resistivity decreases or conductivity increases with the rise in temperature.

Hence, the semiconductor possesses –ve temperature coefficient of resistance. It is in contrast to the metals which have +ve temperature coefficient of resistance.

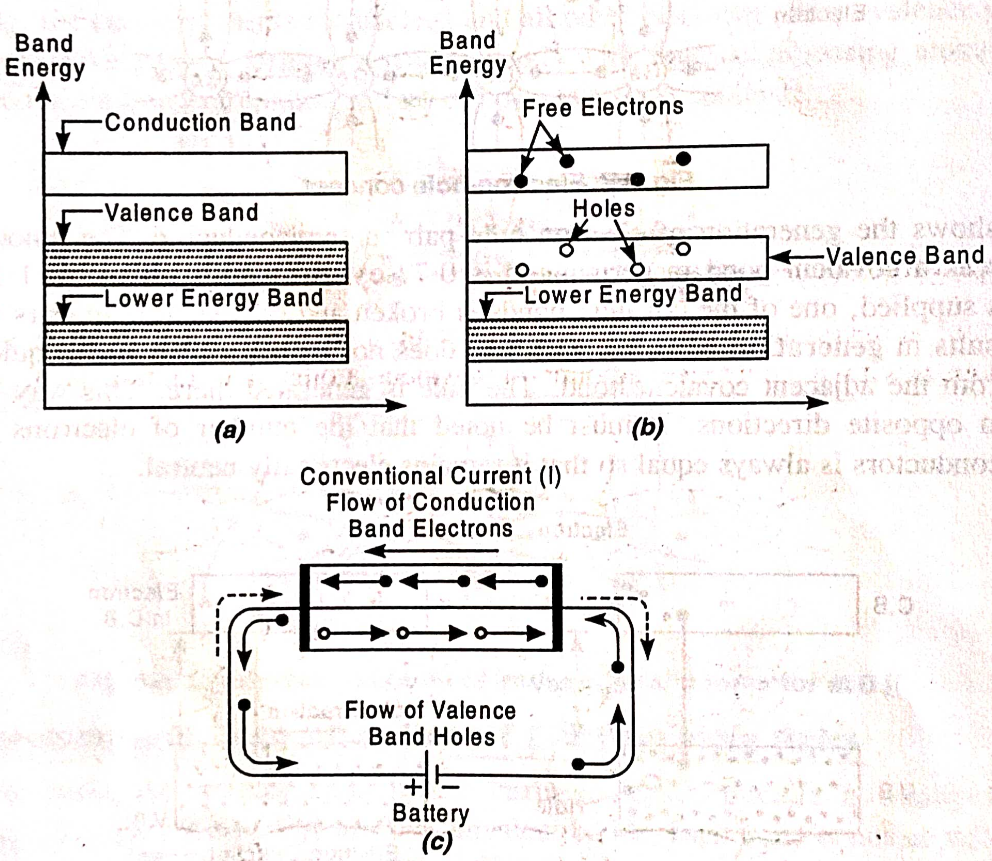


Fig. 4.9.

4.6. N-TYPE AND P-TYPE SEMI-CONDUCTORS

4.6.1. N-type semiconductor or Donor type semi-conductor

When a pure semiconductor of silicon (Si) or germanium (Ge) in which each atom has four valence electrons is doped with a suitable amount of pentavalent atoms, like arsenic, phosphorus, antimony or bismuth which have five valence electrons, the impurity atoms will replace the Si or Ge atoms and one extra electron is added into the crystal which is responsible for conduction. This type

realme Shot by Ranjeet

of semiconductor in which the number density of electrons is more is called a n-type or donor type semiconductor.

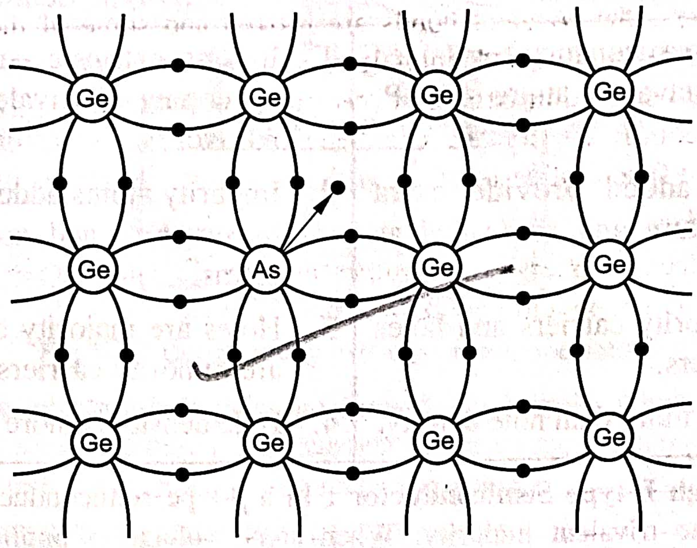


Fig. 4.10.

4.6.2. P-type semiconductor or Acceptor type semi-conductor

When a pure semiconductor of silicon or germanium in which each atom has four valence electrons is doped with a controlled amount of trivalent atoms like Indium (In), Boron (B) or

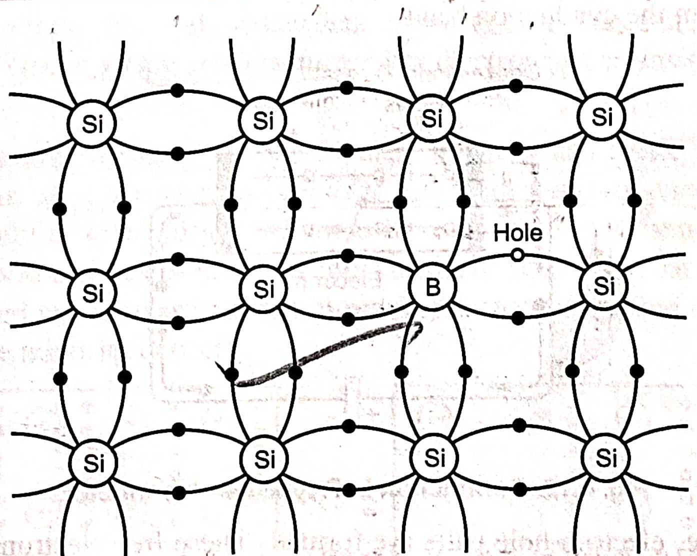


Fig. 4.11.

Aluminium (Al) which have three valence electrons, the impurity atoms will replace the Si atoms, forming three covalent bonds and one hole free. In this way the number of holes in the semiconductor increases which are responsible for electrical conduction. This type of semiconductor in which the number density of holes is more than electrons is called a p-type or acceptor type semiconductor.

realme Shot by Ranjeet

Distinction between N-type and P-type Semiconductors

N-type Semiconductor	P-type Semiconductor
1. It is an extrinsic semiconductor obtained by doping of pentavalent atoms like P, Bi, As, etc.	1. It is an extrinsic semiconductor obtained by doping of trivalent atoms like B, In, Al, etc.
2. Impurity atoms added provide extra electrons in structure and are called as donor atoms.	2. Impurity atoms added provide extra holes in structure and are called as acceptor atoms.
3. Electrons are majority carriers and holes are minority carriers.	3. Holes are majority carriers and electrons are minority carriers.
4. Electron density is more than hole density.	4. Hole density is more than electron density.

Conduction Through P-type Semiconductor : In a *p*-type semiconductor, a large number of holes are created by the trivalent impurity. When some voltage is applied across this type of semiconductor, as shown in Fig. 4.12, the holes available in the valence band are directed towards the negative terminal, constituting electric current. As the current flow through the crystal is by holes, which are carriers of positive charge, this type of conductivity is called *positive* or *p-type conductivity*. In fact, in *p*-type conductivity, the valence electrons move from one covalent bond to another (this gives a look as if holes are moving) unlike the *n*-type where current conduction is by free electrons available in the conduction band.

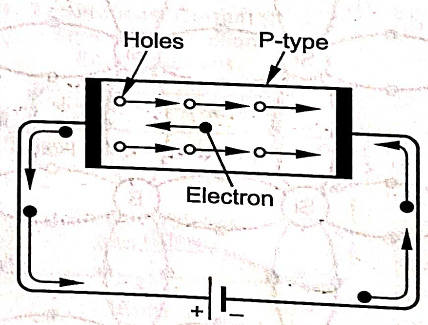


Fig. 4.12. Conduction in P-type semiconductor.

At room temperature, electron-hole pairs are formed. These free electrons which are available in minute quantity also constitute a little current in the *p*-type semiconductor as shown in Fig. 4.12.

Conduction Through N-type Semiconductor : In a *n*-type semiconductor, a large number of free electrons (donated by the impurity atoms) are available in the conduction band. When some voltage is applied across this type of semiconductor as shown in Fig. 4.13, the free electrons are directed towards the positive terminal, constituting electric current. As the flow of current through the crystal is constituted by free electrons which are carriers of negative charge, therefore, this type of conductivity is called *negative* or *n-type conductivity*.

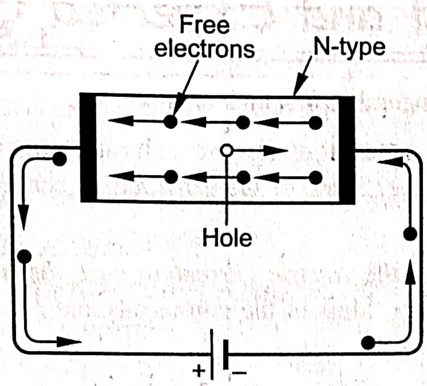


Fig. 4.13. Conductivity in N-type semiconductor.

At room temperature, electron-hole pairs are formed. These holes which are available in minute quantity in valence band also constitute a little current in the *n*-type semiconductor as shown in Fig. 4.13. This negligible current is neglected in all practical purposes.

4.7. MAJORITY AND MINORITY CARRIERS

The extrinsic semiconductors are formed by adding some impurity atoms to pure semiconductor material. This results in generation of exclusive electrons or holes in excess. Moreover there are intrinsic carriers as well, which are generated through breakdown of covalent bonds at room temperature. So, the number of electrons and holes will not be equal in extrinsic semiconductors.

In *n*-type semiconductors, we add pentavalent impurity and hence a large number of free electrons are available. *Thus, a n-type semiconductor has electrons as majority carriers and holes as minority carriers.*

In *p*-type semiconductors, similarly we add trivalent impurity and hence a large number of free holes are generated. *Thus, in a p-type semiconductor holes are majority carriers and electrons are minority carriers.* In addition to majority and minority carriers, *n*-type semiconductors consist of fixed +ve charge carriers and *p*-type semiconductors consist of fixed –ve charge carriers as shown in Fig. 4.14. It must be noted that forward current in semiconductors flows due to majority carriers and leakage current due to the minority carriers.

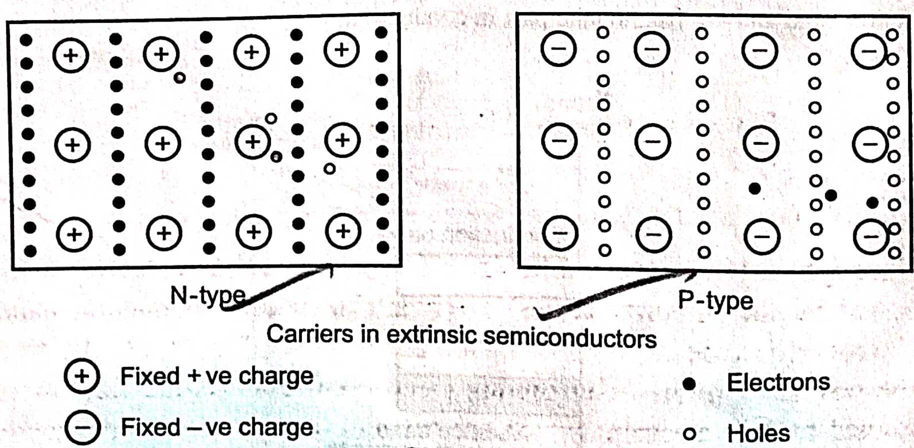


Fig. 4.14.

realme Shot by Ranjeet

Important and Expected Questions

Q.1. Explain about conductors, semiconductors and insulators.

Ans. *The materials which allow the passage of electric current through them easily are called* **Conductors.** These have low electrical resistance. Some of the examples of conductors are metals such as Iron, Copper, Silver etc.

The materials which donot allow the electric current to pass through them are called **Insulators.** These have very high electrical resistance. Most of the non-metals and organic materials are insulators. Examples are Rubber, Mica, Wood, Ceramics etc.

Semiconductor materials *are those which possess the conductivity higher than insulators but lesser than conductors and are used* for manufacturing most of the active components. Their conductivity is largely dependent upon the electric field and impurities etc. Some examples of semiconductor materials are Silicon, Germanium, Selenium etc.

Q.2. Explain the following :

(a) Valence band

(b) Conduction band.

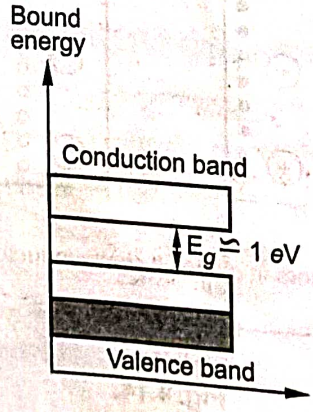
Ans. **(a) Valence Band :** *The energy band that possesses the valence electrons (i.e. the electrons in the outermost shell) is called* **Valence band.** This band possesses maximum energy electrons. The valence band may be partially filled or completely filled. However completely filled valence band does not accommodate more electrons and hence it cannot contribute to electric current.

(b) Conduction Band : This band represents next large group of permissible energy level. An electron in this band has negligible interference from nucleus and is free to move under the influence of electrical energy. Basically, the electrons in the conduction band do not belong to a particular atom. If a material has empty conduction band, it cannot be a conductor.

Q.3. Define semiconductor. What are different types of semiconductors ?

Ans. The semiconductors are materials which have normally empty conduction band at 0 °C and partially filled valence band. The Forbidden energy gap between the two is of the order of 1 eV.

Since the energy gap is very small. It can be overcome by increasing the temperature or supplying energy by any other external manner to the electron in the valence band. The electrons after receiving the energy jump to the conduction band and are free to take part in conduction.



realme Shot by Ranjeet

Q. 5. Give points of distinction between N-type and P-type semiconductors.

Ans.

N-type Semiconductor	P-type Semiconductor
1. It is an extrinsic semiconductor obtained by doping of pentavalent atoms like P, Bi, As, etc.	1. It is an extrinsic semiconductor obtained by doping of trivalent atoms like B, In, Al, etc.
2. Impurity atoms added provide extra electrons in structure and are called as donor atoms.	2. Impurity atoms added provide extra holes in structure and are called as acceptor atoms.
3. Electrons are majority carriers and holes are minority carriers.	3. Holes are majority carriers and electrons are minority carriers.
4. Electron density is more than hole density.	4. Hole density is more than electron density.

Objective Type Questions

1. The branch of physics which deals with the semiconductors is known as ....
2. Semiconductors are those materials which have resistivity .... than the conductors and than insulators.
3. The valence electrons are present in .... orbit of an atom.
4. The conduction band of a semiconductor is .... at absolute zero temperature.
5. The minimum energy required to lift one electron from valence band to the conduction band is called ....
6. In intrinsic semi conductors, at absolute zero temperature the valence band is .... and conduction band is ....
7. To lift the electrons of valence band to conduction band the temperature is ....
8. The process of adding impurity to an intrinsic semiconductor is called ....
9. In N-type semiconductor, electron density is .... than the hole density.
10. In P-type semiconductor, ... are majority carriers and .... are minority carriers.

Answers

1. semi-conductor physics		2. lesser, higher	3. outermost
4. empty	5. forbidden energy	6. completely filled, completely empty	
7. increased.	8. doping	9. more	10. holes, electrons.

****

Review Questions

1. Why are semiconductors important in electronics ?
2. Write a short note on energy levels.
3. Discuss the energy bands which are important in deciding the conductivity of materials.
4. Explain the difference in conductors, insulators and semiconductors using the energy band diagrams.
5. What is the main difference between intrinsic and extrinsic semiconductors ?
6. Explain the effect of temperature on the conductivity of semiconductors.
7. Give points of distinction between *n*-type and *p*-type semiconductors.
8. Write a short note on minority and majority carriers.

****

realme Shot by Ranjeet🥰