

33

BASICS OF SEMICONDUCTORS

33.1 INTRODUCTION

Electronics is one of the most important branch of physics which has its impact very obvious in our daily life. All of us are aware of electronic entertainment systems like television, video, tape recorder etc.; communication systems like telephone, pager, satellite communication etc.; medical diagnostic systems like electrocardiogram, various scanners etc. and other systems.

All these systems use devices like transistors, diodes, light emitting diodes, integrated circuits, chips etc. These are all made up of a material called semiconductor. As is obvious from its name itself, its conductivity will lie in between that of a conductor and an insulator. In order to understand the various aspects of semiconductors, let us study about these semiconductors, their types and behavior in this lesson.

33.2 OBJECTIVES

After studying this lesson, you should be able to:

- explain energy levels, energy bands and band gaps;
- differentiate between a conduction band and a valence band;
- explain the difference between conductors, insulators and semiconductors with their energy level diagrams;
- distinguish between intrinsic and extrinsic semiconductors;
- explain the concept of a 'hole', its location in the crystal lattice and difference from an electron; understand the 'hole current' and 'electron current' in semiconductors;
- differentiate between n-type and p-type semiconductors;
- define the terms 'mobility' and 'conductivity'; and
- explain the effect of temperature on mobility and conductivity; explain the effect of dopin in semiconductors.

33.3 ATOMIC STRUCTURE

As you have already learnt, all materials are made up of atoms. An atom consists of a small nucleus in the centre. It contains protons and neutrons. Protons are positively charged particles. Neutrons have no charge at all. Outside the nucleus, there are electrons. These are negatively charged particles. You have read about Bohr's postulates; so you can recall that the electrons revolve around the nucleus in well defined *orbits*, as shown in Fig.33.1

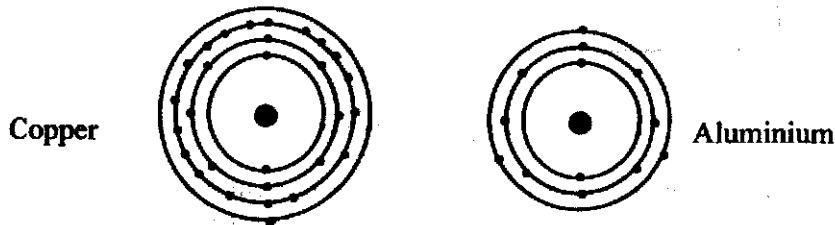


Fig. 33.1 : Distribution of electrons in different atoms

Atoms of different elements have different number of electrons. The negative charge of an electron is exactly equal and opposite to the positive charge of the protons. In a neutral atom, the number of electrons is equal to the number of protons.

The electrons in the orbits close to the nucleus are *tightly bound*. As compared to these, the electrons in the outermost orbit are *loosely bound*. These electrons, located in the outermost orbit are called the *valence electrons*. The electrical and chemical properties of an element are largely determined by these electrons.

33.4 ENERGY LEVELS

The different orbits of electrons have different but fixed energies. These energies depend upon their distance from the central nucleus and are governed by specific quantum numbers. These can be represented as first energy level ($n = 1$), second energy level ($n = 2$) and so on (Fig.33.2 and Fig.33.3).

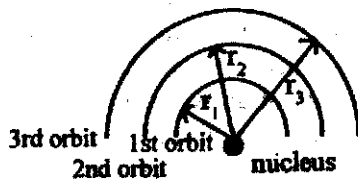


Fig. 33.2 : permitted orbits of electron

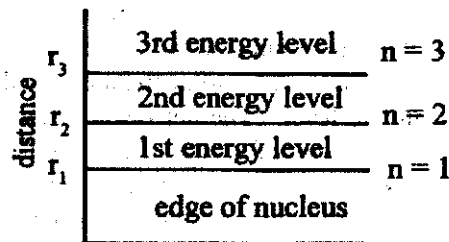


Fig. 33.3 : Energy level diagram of an atom

Electrons can have energies corresponding to these levels only. No other energy value is permitted. The energy levels of hydrogen atom are shown in Fig.33.4.

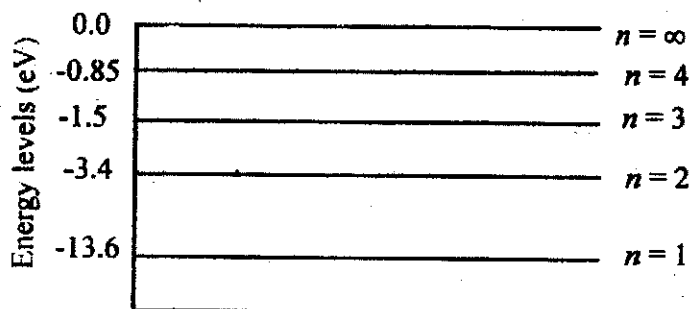


Fig. 33.4 : Energy levels of hydrogen atom

Hydrogen atom has only one electron. It has the tendency to occupy a lowest or minimum energy state. So, the electron tends to remain in the $n = 1$ principal quantum state. This state of electron is called the ground state and the atom is most stable in this state. The electron can however jump to the next higher state i.e. $n = 2$ state, if it receives energy equal to the difference of energies of the $n = 2$ and $n = 1$ state. It is then said to be in an excited state. The excited state is not stable and the electron can fall back to the ground state ($n = 1$ state). In this process it will give out or emit the energy again equal to the difference of energy of the two states.

The energy possessed by electrons in atoms is a very small amount. It is measured in the units of electron volt (eV) which is a small unit of energy.

1 eV is the Energy acquired by an electron when it is accelerated through a potential difference of 1 volt and its value in joules is

$$= 1.602 \times 10^{-19} \text{ Joule}$$

33.4.1 Energy Bands

We talk of energy levels in the case of isolated atoms. You know that in a crystal of some element, there are a very large number of atoms (of the order of 10^{23}). Also, these atoms are very close together. As the atoms are brought closer, they interact with each other. As a result of this interatomic interaction, there is a splitting of each individual energy level into multiple levels, in order to accommodate all the electrons which were originally in the similar atomic level. The net result is that each energy level of an isolated atom now spreads into a *band* of energy. These bands contain large number of discrete but closely spaced energy levels and can be considered as essentially continuous. An electron in the crystal can possess only that energy which falls within one of these bands. *A group of a large number of very closely spaced energy levels in a definite small energy range is called an energy band.*

The energy levels of the inner-shell electrons are less affected as they are tightly bound to the nuclei. The splitting is, therefore, less for the inner energy levels. The outermost electrons are the most affected. The width of the band is the largest for the outermost electrons.

These energy bands are separated by regions of energy in which no energy level exist. Therefore, no electron can be found in these energy regions. These regions are, therefore, forbidden energy regions called band gap or energy gap. *A range of forbidden energies between two allowed bands of energy is known as Band gap or Energy gap.*

Let us consider this process of the formation of energy bands with the help of an example. In the case of Na atom, there are 11 electrons. Their distribution is represented as $1s^2, 2s^2, 2p^6, 3s^1$ (Fig.33.5). According to Pauli's exclusion principle, 10 of these are accommodated in the first two completely filled levels. The third level has only one electron.

As N atoms of sodium are brought together, the individual energy level are transformed into respective energy bands (as seen from Fig.33.6).

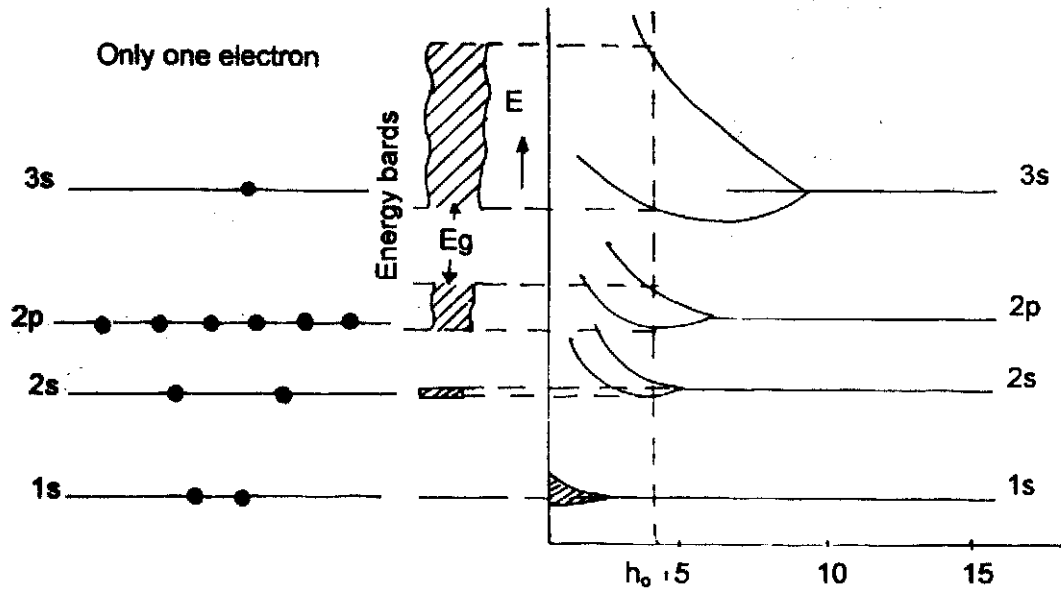


Fig. 33.5: Electron distribution in isolated Na atom

Fig. 33.6: Formation of energy bands when N atoms are brought together

The equilibrium separation, r_0 , for the sodium atoms in the crystal is 33.6 \AA . It can be seen from the Fig.33.6 that at this separation, the width of the various bands keeps increasing with the increasing order of the energy level. According to the Pauli's exclusion principle, the inner-bands upto 2 p level are completely filled. These inner completely filled bands are not of much importance. Since, the 3s level has only one electron whereas it can accommodate two electrons; the 3s energy band will remain half filled. It is this band which is important in controlling the properties of the element.

Now, the outermost filled band occupied by valence electrons is called the valence band. This represents the range of energies that can be possessed by valence electrons. This is the band formed by the valence levels of individual atoms. This is the highest occupied band. It may be either completely filled or partially filled with electrons, but can never be empty. *An energy band occupied by valence electrons is called Valence band.*

The next higher band to the valence band is called the *conduction band*. It is generally empty or partially filled. It may also be defined as the lowest unfilled energy band. On acquiring sufficient energy, valence electrons may leave the valence band and come to the

conduction band. They are then almost free or are only weakly held to the nucleus and are called the conduction electrons. These electrons can move freely in the conduction band and conduct electric current. That is why they are called conduction electrons. *An energy band occupied by conduction electrons which can move freely in a solid is called Conduction band.*

As shown in Fig.33.7, the valence band and conduction band are separated by the forbidden energy gap, E_g . This much energy is required to lift an electron from the valence band to the conduction band.

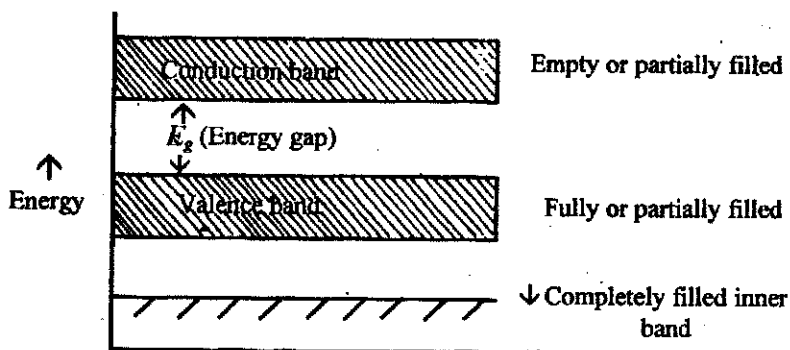


Fig. 33.7 : Energy band diagram of a crystal

INTEXT QUESTIONS 33.1

- 1 Differentiate between a conduction electron and a valence electron.
- 2 Define 1 eV.
3. Fill in the blanks with appropriate word(s)
 - i) The electrons in the atom of an element which determine its electrical and chemical properties are called----- electrons.
 - ii) Whereas single isolated atoms have energy levels, solids have energy-----.
 - iii) Each energy band of a small piece of a solid containing 10^{23} atoms will consist of ----- closely spaced energy levels.
 - iv) Electrons in the conduction band have----- energy than those in the valence band.

33.5 CONDUCTORS, INSULATORS AND SEMI-CONDUCTORS

In this section, we will discuss about three types of materials in terms of the occupancy of valence and conduction bands. The electrical conduction properties of these different materials can also be explained in terms of the electrons having energies in the valence and conduction bands. The electrons lying in the lower energy bands, which are normally completely filled, play no part in the conduction process.

(a) Conductors

Conductors are those materials in which plenty of free electrons are available for conduction. In terms of energy bands, it means that conductors have

- overlapping valence and conduction bands, and
- absence of forbidden energy gap.

This is shown in Fig.33.8 (a)

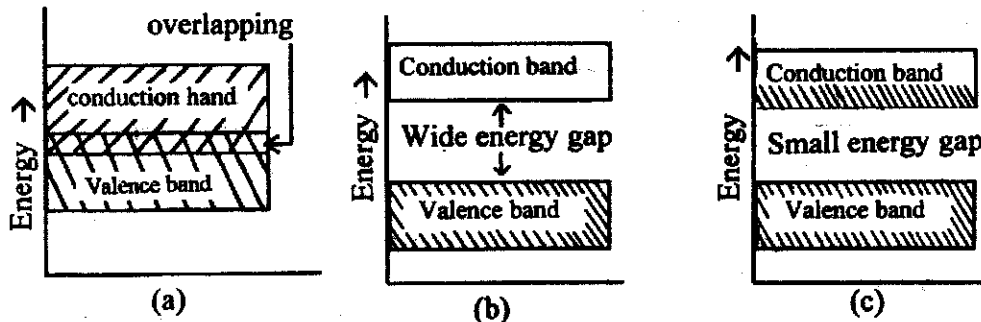


Fig. 33.8 : Energy band diagrams of (a) Conductors, (b) Insulators, and (c) semi-conductors

In fact, there is no physical distinction between the valence and conduction band. Hence, there is an availability of a large number of conduction electrons. The application of a small amount of voltage results in a large amount of current. These are, therefore, good conductors of electricity. It can also be said that these materials offer very small resistance to the flow of current and their resistivity is very small.

All metals, like silver, copper, gold, aluminium etc. are good conductors of electricity. Out of these, silver is the best and copper is the second best. The resistivity of copper is 1.7×10^{-8} ohm-metre and that of aluminium is 2.6×10^{-8} ohm-metre.

(b) Insulators

Insulators are those materials in which the valence electrons are very tightly bound to their parent atoms. In terms of energy bands, it means that insulators have

- Completely valence band ;
- an empty conduction band, and
- a large energy gap (of several eV) between them.

This is shown in Fig.33.8 (b). For conduction to take place, electrons must be given sufficient energy to jump from the valence band to the conduction band. This energy is not available at the room temperature. Increase in temperature enables some electrons to go to the conduction band. These materials are, therefore, bad conductors of electricity and have very high electrical resistivity.

Wood, porcelain, hard rubber, glass etc. are examples of insulators. The resistivity of porcelain is 3.0×10^9 ohm-metre and that of hard rubber is 1.0×10^{16} ohm-metre.

(c) Semi-conductors

A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. In terms of energy bands, semiconductors can be defined as those materials which at room temperature have

- partially-filled conduction band;
- partially – empty valence band, and
- a small energy gap (of the order of 1 eV) between them.

This is shown in Fig.33.8(c). At 0 K, there are no electrons in the conduction band of semiconductors and their valence band is completely filled. It means that at absolute zero temperature, a semiconductor acts like an insulator. However, with increase in temperature, some electrons are liberated into the conduction band. Thus, a small current flows with the application of a voltage and these materials have a resistivity mid-way between those of conductors and insulators.

Silicon and Germanium are the commonly used semiconductors. Their resistivity and energy gap are given in the following table.

Material	Resistivity	Energy gap
Silicon	2.0×10^3 ohm-metre	1.14 eV
Germanium	6.5×10^{-1} ohm-metre	0.67 eV

INTEXT QUESTIONS 33.2

1. Give the order of the values of energies of energy band gaps in the case of conductors, insulators and semiconductors.
2. Give some examples of conductors, insulators and semiconductors.
3. Fill in the blanks with appropriate word(s)
 - i) The forbidden energy gap of silicon crystal at 0 K is _____
 - ii) Resistivity of wood is _____ than that of copper.
 - iii) There are plenty of free electrons available in _____
 - iv) _____ have a full valence band and an empty conduction band.
 - v) Pure semiconductor at absolute zero acts as an _____

33.6 CHARGE CARRIERS IN SEMICONDUCTORS – ELECTRONS AND HOLES

In this section, we will study about the details of the crystal structure of semiconductors. The semiconductors – Silicon and Germanium, are group IV elements. It means that the atoms of these elements have four electrons in their outermost orbit. According to the octet-rule of stable – configuration, every atom requires 8 electrons in its outermost orbit. Hence, every atom makes covalent – bonds with four neighbouring atoms (as shown in Fig.33.9). These bonds are formed by sharing of a pair of electrons between two Si atoms. Thus, a regular repetitive structure of a pure Si (or Ge) crystal is formed. The bonds so formed, are very strong and directional in nature. The outermost electrons involved in these bonds are bound-electrons (which are bound to the nuclei of two sharing atoms). These electrons lie in the valence band and do not contribute to the conduction of current. This case corresponds to the completely filled valence band at the absolute zero temperature. The substance behaves as a perfect insulator at absolute zero.

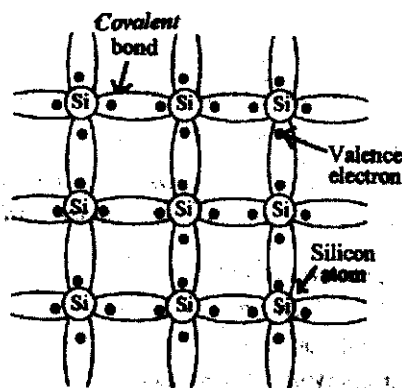


Fig. 33.9 : Covalent bond formation in a silicon crystal

At a higher temperature (room temperature), some of the electrons acquire sufficient energy to break the covalent bond. In other words, they are able to overcome the band gap and come to the conduction band. Now, these are *free electrons* and can move easily in the conduction band. (These free electrons are shown by dots outside the covalent bonds in (Fig. 33.10). This is important to note that as an electron leaves a covalent bond and becomes free, it leaves behind a 'vacancy' of electron in the corresponding energy state. This vacant electron energy state in the valence band behaves as though it were a positively charged particle. This vacancy is known as a *hole*. It also acts as a charge carrier, like the free electron. *A vacancy in the valence band which acts as a positively charged carrier is known as hole.*

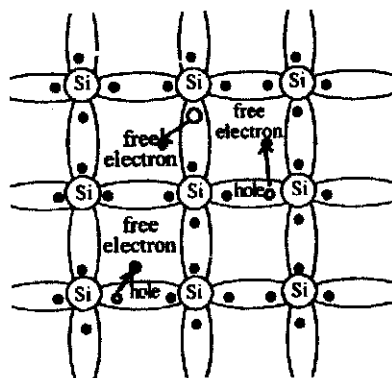


Fig. 33.10: Electron-hole pair creation in pure Si crystal

Now, it can be seen that every liberated electron becomes 'conduction electron' and leaves a 'hole' in the valence band. A combination of such a free electron and a hole is known as *electron-hole pair*. This process is known as *Thermal generation of electron-hole pairs*. If an electron falls back from the conduction band and combines with (or fills) the 'hole', then the process is called *recombination of electron-hole pair*. In this process, both the free electron and hole disappear.

Occurrence of holes is a particular feature of semiconductors. Since holes are present only in the valence band; they are not found in conductors, as conductors have overlapping valence and conduction bands. Both the electrons (in the conduction band) and the holes (in the valence band) act as charge carriers in semiconductors.

33.6.1 Mechanism of Current Flow in Semiconductors

Under the influence of an applied electric field, both types of charge carriers (the free electrons as well as holes), move and constitute electric current. Let us consider these two contributions separately.

a) Electron Current

Let us consider a semiconductor bar AB made of pure germanium. The dots in it represent the free electrons (Fig.33.11). An electric field is applied to the bar by connecting it to a battery of voltage V . Conduction electrons are attracted towards end A and travel through the connecting wires into the positive terminal of the battery. At the same time, additional electrons leave the negative terminal of the battery and enter the semiconductor at B. This flow of electrons in the counter-clockwise direction, both within the semiconductors as well through the outer connecting wires, constitutes the *electron current*. This process is similar to the process of current flow in conductors.

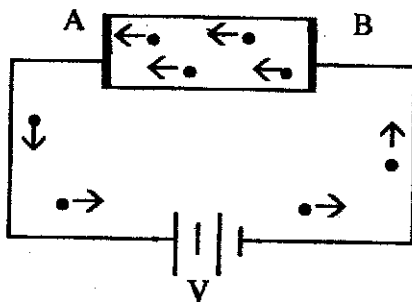


Fig. 33.11: Electron current in a semiconductor

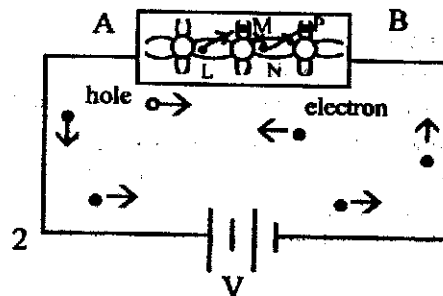


Fig. 33.12: Hole current in a semiconductor

b) Hole Current

Again we consider a germanium bar AB connected to a battery V as shown in Fig.33.12. Let us consider the crystal structure within the bar with a hole at the location L of a covalent bond. The hole is a strong centre of attraction for the electron. Under the action of the applied electric field, a valence electron (say at M) from a nearby covalent bond comes to fill in the hole at L (by recombination process taking place there) and the creation of a new hole at M. Another valence electron (say at N) in turn may leave its bond to fill the hole at M, thus creating a hole at N. Thus, the hole, having a positive charge has moved from L to M to N, i.e. towards the negative battery terminal. This constitutes *hole current*. This process of hole movement continues till the hole reaches the end B. There it meets an electron supplied by the negative battery terminal and disappears. This recombination at end B is associated with a generation process at end A where a new covalent bond breaks, producing an electron to move in the outer circuit and a hole to again move inside towards the end B. This process continues.

It is important to note that the *hole current within the semiconductor from left to right is due to the movement of valence electrons from one bond to another bond from the right to left*. But we still call it a hole current because the conduction by valence electrons is basically due to the presence of holes in the covalent bonds. Thus, *we see that the electrons and hole move in the opposite directions within the semiconductor*. Both of these movements add-up to give the total conventional current in the direction of movement of holes. However, the current in the outer circuit is only the electron current.

INTEXT QUESTIONS 33.3

- Fill in the blanks with appropriate word(s)
 - Covalent bonds are formed by _____ of electrons between two atoms.
 - When a covalent bond breaks, usually one electron and one _____ are produced.
 - Free electrons move in _____ band whereas holes move in _____ band.
 - A single silicon atom is bound to _____ other atoms in its crystal structure.
- State whether 'True' or 'False'.
 - Ionic bonds provide binding force in semiconductors.
 - If given sufficient energy, holes can be lifted from valence band to the conduction band.
 - No new hole is created when an existing hole is filled by a free or excess electron.
 - The missing valence electron is called a hole.

3. Select one of the items lettered a, b, c or d that correctly completes the statement.
- Silicon has $Z = 14$; its outermost orbit is
 - partially filled
 - half-filled
 - completely filled
 - empty
 - Electrons involved in covalent bonds of semiconductors
 - act as free electrons
 - have higher energy than the conduction electrons.
 - are bound to the nuclei of sharing atoms
 - have higher energy than the conduction electrons.
4. Fill in the blanks with appropriate word(s)
- In semiconductors, current flow is due to ----- charge carriers.
 - The direction of movement of a hole in a semiconductor is ----- to the direction of movement of an electron.
 - The hole current is due to the shifting of ----- from one bond to another.

33.7 TYPES OF SEMICONDUCTORS

Semiconductors can be divided into two categories:

33.7.1 Intrinsic Semiconductors

An *intrinsic semiconductor* is one which is made of the semiconductor material in its extremely pure form. The common examples are pure silicon and germanium.

As discussed in a previous section., pure silicon and germanium have electron-hole pairs as charge carriers (Fig.33.10) at room temperature. The rate of thermal generation of pair carriers depends upon two factors:

- The temperature of semiconductor (higher temperature means larger number of pair carriers).
- The band gap of semiconductor (smaller band-gap means larger number of pair carriers).

Since, the band gap in Si is larger than that in Ge; the number of electron-hole pairs in Si at a particular temperature will be less than that in Ge. But, it should be noted that in intrinsic semiconductors the charge carriers are produced or generated only in pairs of opposite type. Hence, *in an intrinsic semiconductor, the number of conduction electrons is exactly equal to the number of holes in the valence band.*

This is represented in the energy-band diagram of an intrinsic semiconductor at room temperature (Fig.33.13).

In other words, we can also say that the concentration ' n ' of the free electrons (i.e. number of electrons/cm³) is equal to the concentration ' p ' of the holes (i.e. number of holes/cm³). Each of these intrinsic carrier

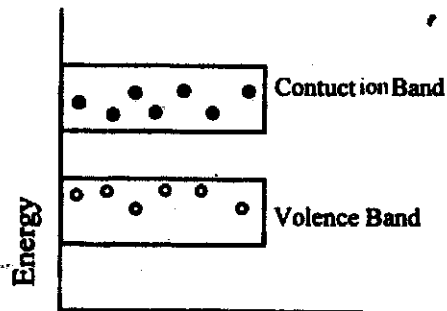


Fig. 33.13 : Energy band diagram of an intrinsic semiconductor at room temperature

concentration is commonly denoted by n_i .

Thus, for an intrinsic semiconductor, concentration of free electrons, n
 = concentration of holes, p
 = intrinsic carrier concentration, n_i

It should be noted at this stage that this carrier concentration (either n or p) in intrinsic semiconductor is quite small at room temperature. However, it increases with temperature, but still, the conductivity of intrinsic semiconductor is negligible. Therefore, it is not of any practical significance.

33.7.2 Extrinsic Semiconductors

In order to make the intrinsic semiconductors useful, small amounts of some suitable impurity atoms are added to them. The resulting semiconductors are called impure or extrinsic semiconductors. *This process of adding impurity atoms to the intrinsic semiconductors is known as doping.*

The impurity that is added is called the *dopant*. The amount of impurity added is extremely small (generally about 1 part in 10^8 of the intrinsic semiconductor atoms). The purpose of adding impurity is to increase either the number of free electrons or holes in a semiconductor. Usually, the impurity atoms are taken either from group V elements (having 5 valence electrons) or from group III elements (having 3 valence electrons). Since the percentage of impurity atoms is very small, it does not change either the crystal structure or the chemical properties of the semiconductor.

Depending on the type of dopant used, extrinsic semiconductors can be further subdivided into two classes: n-type semiconductor and p-type semiconductor.

a) n-type Semiconductor

This type of semiconductor is obtained when pentavalent impurity atoms (i.e. atoms containing 5 valence electrons) are added to pure germanium or silicon crystal. The examples of such impurities are elements from group V like antimony (Sb), arsenic (As), phosphorus (P) and bismuth (Bi).

When a pentavalent impurity is added to a pure semiconductor, it displaces some of its atoms. Fig.33.14 shows the structure of a silicon crystal containing an antimony atom at the central position. It may be noted that out of 5 valence electrons, 4 electrons will form covalent bonds by sharing one electron each with the electrons of four neighbouring Si atoms. The fifth electron is an extra electron, and is loosely bound with the antimony atom. Hence, it can be easily excited to the conduction band (becomes free) by supplying an amount of energy which is much smaller than that required for breaking a covalent bond. Thus each impurity atom contributes one free electron

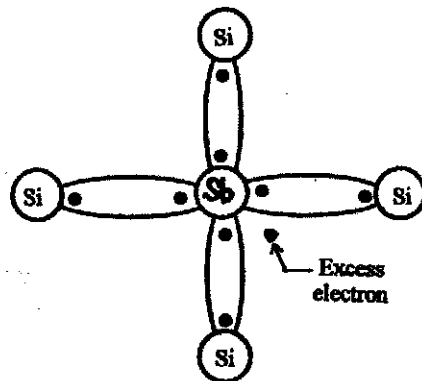


Fig. 33.14: A silicon atom replaced by an antimony (Sb) atom in a crystal lattice

to the semiconductor without creating a positive hole. As the impurity that is added contributes free electrons, it is called a *donor* impurity or donor dopant. *The group V impurity elements which supply free electrons to an intrinsic semiconductor are known as donor.*

After the donation, the impurity atom becomes a positively charged ion and is known as a *donor ion*. This ion is bounded by four covalent bonds in the crystal lattice and therefore cannot take part in conduction. The energy state of the fifth valence electron is in the forbidden gap and is just below the conduction band. This energy level is indicated by a dashed line in Fig.33.15, and is called the *donor level*. Usually, the donor level is 0.01 eV below conduction band for Ge and 0.05 eV for Si.

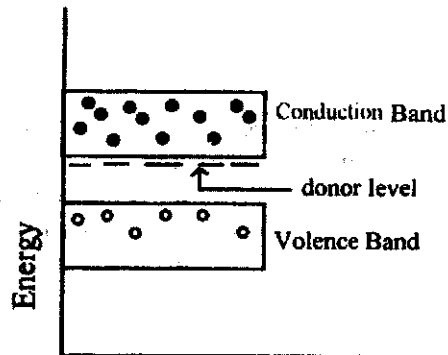


Fig. 33.15: Energy band diagram of n-type semiconductor'

The electrons in this donor level will have no difficulty in absorbing sufficient thermal energy at room temperature to move into the conduction band and contribute to electric current. The semiconductor containing donor type of impurity is called n-type semiconductor.

At a given temperature, the number of electrons and holes generated thermally will be equal whether the material is intrinsic or extrinsic. But in extrinsic material there will be additional carriers of charge due to doping. In the n-type material, therefore, the number of free electrons will be much more than the number of holes. Hence, a major part of the current flows due to the movement of electrons. The electrons are thus called *majority carriers*. The holes being much less in number, are called *minority carriers*.

As an aid to memory, you can associate the letter 'n' in 'n-type semiconductor' with the 'n' in 'negative charge carrier' (i.e. electron) or in 'donor'.

b) p-type Semiconductors

This type of semiconductor is obtained when trivalent impurity atoms (i.e. atoms having 3 valence electrons) are added to pure germanium or silicon. The examples of such impurities are elements from group III like gallium (Ga), indium (In), aluminium (Al) and boron (B).

In this case, the three valence electrons of the trivalent impurity atom (say indium) form covalent bonds with four surrounding germanium atoms (say germanium). However, the fourth covalent bond is incomplete and has a vacancy of electron or a hole (as shown in Fig.33.16). Thus, every group III impurity atom produces a hole in the valence band of the semiconductor. The indium atom being short of one electron to complete the covalent bonds, has a strong tendency

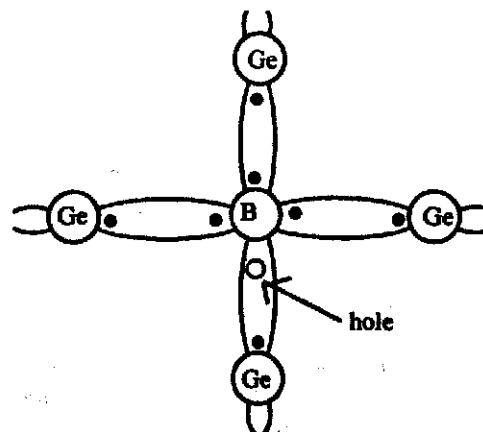


Fig. 13.16 : A silicon atom replaced by a boron (B) atom in a crystal lattice

to capture or accept an electron. Hence, the *group III impurity atom are called acceptor impurity or acceptor dopant which supply holes (or accept electrons) to an intrinsic semiconductor.*

After accepting an electron, the indium atom becomes a negatively charged ion called *acceptor ion*. This ion is immobile and do not contribute to conduction.

The result of the acceptor doping is that a discrete energy level appears in the forbidden energy gap just above the valence band. This level is called an *acceptor level* (as shown in Fig.33.17). This acceptor level is usually 0.01 eV above the valence band for Ge and 0.05 eV above the valence band for Si.

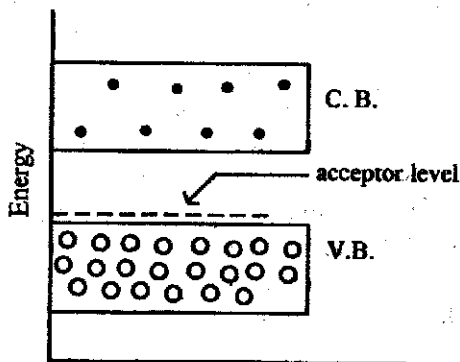


Fig. 33.17: Energy band diagram of p-type semiconductor

Electrons from the valence band can therefore be readily agitated thermally to move into the vacant acceptor level. In doing so, they produce holes in the valence band and make the trivalent atom negatively charged ion. These holes are mobile and contribute to electric current. The semiconductor containing acceptor type impurity is called a p-type semiconductor.

Now, it is clear that the number of impurity generated holes in p-type semiconductor will be far more than the number of thermally generated electrons. Thus, in this case, holes are the majority carriers and electrons the minority carriers.

As an aid to memory, you can associate the letter 'p' in 'p-type semiconductor' with the letter 'p' in 'positive charge carrier' (i.e. hole) or in 'acceptor'.

It should be understood at this stage, that the *majority carriers (electrons) in the n-type semiconductor are available in the conduction band of the crystalline lattice of the solid; whereas, the majority carriers (holes) in the p-type semiconductor are available in the valence band.* Also, that the p-type or n-type semiconductors are *not* positively or negatively charged. These are electrically neutral as a whole. In the p-type semiconductor, there are equal number of negative acceptor ions as there are holes. Similarly, in the n-type semiconductor, there are equal number of the donor ions as there are free electrons.

INTEXT QUESTIONS 33.4

1. Fill in the blanks with appropriate word(s)
 - i) A pure semiconductor is called _____.
 - ii) Elements added to semiconductors to increase the conductivity are called _____.
 - iii) The process of adding impurity to a semiconductor is called _____.
 - iv) Intrinsic semiconductors have _____ number of holes and electrons.

2. Explain the term 'impurity atoms' in reference to semiconductors.

3. Name the elements used to prepare p-type and n-type semiconductors.

4. What causes current in (a) p-type semiconductor, (b) n-type semiconductor?

5. State whether the following statements are 'True' or 'False'
 - i) n-type germanium can be batterned by doping intrinsic germanium with Aluminium.
 - ii) p-type germanium crystal is positively charged.
 - iii) The donor type impurities must have five valence electrons.
 - iv) Trivalent impurities produce holes in the conduction band.

33.8 ELECTRICAL CONDUCTIVITY OF SEMICONDUCTORS

As explained earlier, two types of charge carriers i.e. electrons and holes are available in intrinsic as well as extrinsic semiconductors. These are oppositely charged carriers. Both of these contribute to the flow of current in a semiconductor. In this section, we intend to obtain mathematical expressions for drift velocity, current density and electrical conductivity for semiconductors. We start with the simpler case of conduction in metals. We will use the relations in the case of metals to develop similar relations for semiconductors.

33.8.1 Conduction in Metals

We know that the conduction electrons in a metal move continuously at random. During their movement, they collide with other electrons and stationary ions. After each collision, the direction of their movement is changed. The average distance between collisions is known as mean free path. Since, the motion of electrons is at random, there will be as many electrons passing through a unit area in the metal in any direction as in the opposite direction in a given time. Thus, the average value of the current is zero.

Now, if an electric field is applied to a metal, the electrons will accelerate and suffer multiple collisions. At each collision they will loose some energy and will accelerate again. The electric field does not stop collision and random motion, but it does *not* cause the electrons to drift in a resultant direction opposite to that of the applied electric field. A steady state condition is reached, where the electrons gain an average directed value of drift velocity which is proportional to the applied electric field. This transport of electrons constitutes *drift current*.

Let, E = Strength of the applied electric field, F = Force experienced by an electron due to the applied electric field, a = acceleration, which the electron obtains due to the force experienced by it, t = average time between two consecutive collisions, v = drift velocity, q = charge of an electron, and m = mass of an electron

We know that the force experienced by an electron due to applied field is given by

$$F = qE$$

and acceleration, $a = \text{Force/Mass} = F/m = qE/m$

Therefore drift velocity, $v = a.t = qEt/m = \mu E$ (33.1)

where μ is equal to qt/m and is known as *mobility* of an electron. *The average drift velocity of a charge carrier per unit electric field is known as Mobility.*

The mobility is expressed in $\text{m}^2/(\text{volt}\cdot\text{sec})$. Such a directed flow of electrons constitutes the drift current. As you have read in lesson 16 the value of drift current through a conductor of length L and of uniform cross-sectional area is given as,

$$\text{the drift current, } I = qnvA \quad (33.2)$$

Where, n is the concentration of electrons per unit volume, and the current per unit area called current density,

$$J = qnv \quad (33.3)$$

Substituting the value of v from equation (33.1)

$$J = qn(\mu E) = \sigma E \quad (33.4)$$

where $\sigma = qn\mu$ is known as *conductivity* of the metal. The above relation indicates that the current density (J) within a metal is directly proportional to the applied electric field (E). *Conductivity of a metal is defined as the electric current density of a material per unit electric field.*

The conductivity is expressed in Amp/(Volt-m) or Siemens/m. Now, we know that the resistivity of a metal is reciprocal to its conductivity, i.e.

$$\delta = 1/\sigma = 1/qn\mu \quad (33.5)$$

33.8.2 Conduction in Intrinsic Semiconductor

Based on the above treatment; we can now find the expression for electrical conductivity in intrinsic semiconductor. We take the following parameters for the semiconductor

Let q be the charge of an electron, as well as charge of a hole; n , concentration of electrons in an intrinsic semi conductor ; p , concentration of holes in an intrinsic semi conductor ; μ_n , mobility of electrons ; μ_p , = mobility of holes ; and E is the applied electric field strength .

Using the relation (33.4), the current density due to the movement of electrons only, is given by

$$J_n = qn\mu_n E$$

A similar expression can be written for current density due to holes and is given by

$$J_p = qp\mu_p E$$

The total current density within intrinsic semiconductor,

$$\begin{aligned} J &= J_n + J_p \\ &= qn\mu_n E + qp\mu_p E \\ &= q(n\mu_n + p\mu_p) E \\ &= \sigma E \end{aligned} \quad (33.6)$$

where σ equal to $q(n\mu_n + p\mu_p)$ is called the *electrical conductivity* of a semiconductor. It is evident from equation (33.6) that the current density within a semiconductor is directly proportional to the applied electric field.

We know that for an intrinsic semiconductor, $n = p = n_i$ where n_i is called the intrinsic carrier concentration. Substituting this in equation (33.6)

$$J = q.n_i (\mu_n + \mu_p) E$$

and conductivity of an intrinsic semiconductor,

$$\sigma_i = q.n_i (\mu_n + \mu_p) \quad (33.7)$$

It is evident from the above relation that the electrical conductivity of an intrinsic semiconductor depends upon the following factors:

- *intrinsic concentration (n_i)*
- *mobility of electrons (μ_n), and*
- *mobility of holes (μ_p)*

The electrical conductivity is directly proportional to these three factors. Hence, the increase in any one of the above factors will increase the electrical conductivity of the semiconductor and vice-versa.

It should be noted that in a pure semiconductor, under the influence of an electric field, electrons move in a nearly empty conduction band, whereas holes move in a nearly filled valence band. Therefore, an electron in conduction band is subjected to different conditions compared to a hole (or a valence electron) in the valence band. A hole in the valence band will suffer more collision and will have smaller mean free time than a conduction electron. Thus, mobility of a hole is smaller than that of a conduction electron (eqn.33.1).

33.8.3 Effect of Temperature on Semiconductor Parameters

Most of the semiconductors operate on a wide range of temperature. Therefore, study of variations of semiconductor parameters with temperature are very important. In this section, we discuss the effect of temperature on some of the parameters of semiconductors.

a) Intrinsic Concentration

In an intrinsic semiconductor, the concentration (n_i) increases with the increase in temperature. The dependence of intrinsic concentration on the temperature is given by the relation,

$$n_i^2 = A_0.T^3.e^{-E_{g0}/kT}$$

where, A_0 is a constant independent of the temperature; T , temperature (in K); E_{g0} = Energy gap at 0 K (in eV), and k is the Boltzmann's constant (in eV/K).

b) Mobility

The mobility of an intrinsic semiconductor decreases with the increase in temperature, because at higher temperatures, the number of carriers is more and they are more energetic

also. This causes an increased number of collisions with the atoms and thus the mobility decreases.

The mobility μ of an intrinsic semiconductor varies as T^{-m} over a temperature range of 100 to 400 K. For silicon, $m = 2.5$ for electrons and 2.7 for holes. Similarly, for germanium, $m = 1.66$ for electrons and 2.33 for holes.

c) Conductivity

We have seen that the conductivity of an intrinsic semiconductor depends upon the number of electron-hole pairs and mobility. The number of electron-hole pairs increases with the increase in temperature, whereas the mobility of electrons and holes decreases. However, the increase in electron-hole pairs is greater than the decrease in their mobility. Therefore, **the conductivity of an intrinsic semiconductor increases with the increase in temperature.** The conductivity at any temperature (T) in Kelvin is given by the relation.

$$\sigma = \sigma_0 (1 + \alpha \cdot \Delta T)$$

where, σ_0 is conductivity at 0 K; α is the temperature coefficient, i.e. the rate at which conductivity increases per degree kelvin, and ΔT is the rise in temperature ($= T - T_0$)

The conductivity of extrinsic semiconductors decreases with the increase in temperature. This is because of the fact that with the increase in temperature, the number of majority carriers is nearly constant, but mobility decreases. This causes the conductivity to decrease.

INTEXT QUESTIONS 33.5

1. Select one of the items lettered a, b, c or d that correctly completes the statement.
 - i) Conduction electrons have more mobility than holes because they
 - a) are lighter
 - b) have negative charge
 - c) experience collisions more frequently
 - d) need less energy to move
 - ii) Mobility of a charged particle does not depend upon
 - a) the applied electric field
 - b) the charge of the particle
 - c) the mass of the particle
 - d) the time between the collisions

Example 33.1 : At room temperature, copper has free electron density of 8.4×10^{28} per m^3 . Find electron drift velocity in a copper conductor having a cross-section of $10^{-6} m^2$ and carrying a current of 5.4 Amp.

Solution: we know,

$$I = qnVA$$

Given, $I = 5.4 \text{ Amp.}, q = 1.16 \times 10^{-19} \text{ C},$
 $n = 8.4 \times 10^{28}/m^3, A = 10^{-6} m^2$

Therefore $5.4 = v \times 1.6 \times 10^{-19} \times 8.4 \times 10^{28} \times 10^{-6}$

Hence, $v = 4 \times 10^{-4} \text{ m/s} = 0.4 \text{ mm/s}$

Example 33.2 : *Mobilities of electrons and holes in a sample of intrinsic germanium at room temperature are $0.36 \text{ m}^2/\text{V}\cdot\text{s}$ and $0.17 \text{ m}^2/\text{V}\cdot\text{s}$ respectively. If the electron and hole densities are each equal to $2.5 \times 10^{19}/\text{m}^3$, calculate the conductivity of germanium.*

Solution : We know,

$$\sigma_i = qn_i (\mu_n + \mu_p)$$

$$\text{Given, } q = 1.6 \times 10^{-19} \text{ C, } n_i = 2.5 \times 10^{19}/\text{m}^3$$

$$\mu_n = 0.36 \text{ m}^2/\text{Vs, } \mu_p = 0.17 \text{ m}^2/\text{Vs}$$

Therefore, $\sigma_i = 2.12 \text{ Siemens/m}$

33.9 WHAT YOU HAVE LEARNT

- Electrons in isolated atoms revolve in definite orbits or energy levels.
- The electrons in the outermost orbit are called valence electrons.
- In crystal structure, large number of energy levels confined within a certain small energy range are known as allowed band of energy or energy band.
- There are forbidden regions of energy between two allowed energy bands. These are called band gaps or energy gaps.
- The outermost filled band occupied by valence electrons is called the valence band.
- The next higher band to the valence band is called the conduction band. It accommodates free electrons or conduction electrons.
- Solids may be classified into conductors, insulators and semiconductors.
- Semiconductors have small energy gap and show small conductivity at room temperature.
- Semiconductors have two types of charge carriers i.e. electrons and holes; both of which contribute to the conduction of current.
- There are two types of semiconductors – intrinsic semiconductors, which are pure forms of semiconductors and extrinsic semiconductors, which are formed by selected impurities added to intrinsic semiconductor.
- Extrinsic semiconductors are further of two types, n-type or p-type depending on the type of impurity added.
- n-type semiconductor has ‘donor’ impurity added, which provides a large number of free electrons as charge carriers.
- p-type semiconductor has ‘acceptor’ impurity added, which provides a large number of holes as charge carriers.
- Electrons and holes have different mobilities, which is a measure of the average drift velocity acquired by them in a unit electric field.
- Conductivity of a semiconductor measures its electric current density in a unit electric field.
- The intrinsic charge concentration, mobility and conductivity, all are affected by the change in temperature.

33.10 TERMINAL QUESTIONS

1. What is difference between the hole current and electron flow ?
2. Distinguish between intrinsic and extrinsic semiconductors.
3. What are donors and acceptors in regard to extrinsic semiconductors ?
4. Name the charge carriers in case of electric conduction in
 - (i) an intrinsic semiconductor.
 - (ii) p-type semiconductors.
 - (iii) n-type semiconductors.
5. What is the order of magnitude of energy gap in case of semiconductors?
6. Differentiate between energy level and energy band.
7. Distinguish between conductors, insulators and semiconductors on the basis of energy bands.
8. State two points of similarities and dissimilarities between a free electron and a hole.
9. Explain the movement of holes in the crystalline structure of a semiconductor.
10. What are intrinsic and extrinsic semiconductors? Give examples of each.
11. Distinguish between n-type and p-type semiconductors with examples.
12. Define mobility, Give its units. What are the factors on which the mobility of a hole depends?
13. State the factors which can affect the conductivity of a semiconductor.
14. Explain the effect of temperature on the charge carrier concentrations in a semiconductor.
15. Why is there no hole current in a good conductor ?

CHECK YOUR ANSWERS

Intext Question 33.1

3. (i) valence (ii) bands (iii) 100 (iv) more

Intext Questions 33.2

3. (i) 1.14 eV (ii) more (iii) Conductors
(iv) insulators (v) insulator

Intext Questions 33.3

1. (i) sharing (ii) hole (iii) conduction, valence
(iv) four
2. (i) False (ii) False (iii) True (iv) True
3. (i) b (ii) c
4. (i) two types of (ii) opposite (iii) valence electron

Intext Questions 33.4

1. (i) intrinsic semiconductor (ii) dopants
(iii) doping (iv) equal
2. (a) holes (b) electrons
3. (i) False (ii) False (iii) True (iv) False

Intext Questions 33.5

1. (i) c (ii) a