For hydrogen $Z = 1$

$$E_n = -\frac{13.6}{n^2} \text{ eV}$$

(i) For K-shell, $n = 1$

$$\therefore \quad E_1 = -\frac{13.6}{1^2} = -13.6 \text{ eV}$$

(ii) For L-shell, $n = 2$

$$\therefore \quad E_2 = -\frac{13.6}{2^2} = -3.4 \text{ eV}$$

(iii) For M-shell, $n = 3$

$$\therefore \quad E_3 = -\frac{13.6}{3^2} = -1.51 \text{ eV etc.}$$

The different permitted orbits with their associated electronic energies are shown in Fig. 12.9. It is seen that the electrons can have certain specific amounts of energy only. In the $n = 1$ orbit, it can have an energy of -13.6 eV and in the $n = 2$ orbit, it can have -3.4 eV. It cannot have any energy lying in between these two values. For example, we will have to give it an extra amount of energy $= (13.6) - (3.4) = 10.2$ eV to raise it from the lower $n = 1$ orbit to the higher $n = 2$ orbit. If we try to give it, say, 8 eV, it will simply not accept it because it is forbidden (by Quantum Theory) to lie anywhere in between the permitted orbits.

Fig. 12.9

Example 12.4. *Determine the frequency of radiation emitted by an electron in an excited hydrogen atom when it jumps from $n = 3$ orbit to $n = 2$ orbit. Take $h = 6.625 \times 10^{-34}$ J-s.*

Solution. As seen from Art. 12.5, $E_3 = -1.51$ eV and $E_2 = -3.4$ eV

$$\therefore \quad E_3 - E_2 = -1.51 - (-3.4) = 1.89 \text{ eV}$$

$$= 1.89 \times 1.6 \times 10^{-19} \text{ J}$$

Now, $\quad E_3 - E_2 = hf$

or $\quad 1.89 \times 1.6 \times 10^{-19} = 6.625 \times 10^{-34} \times f$

$$\therefore \quad f = 4.57 \times 10^{14} \text{ Hz}$$

If required, wavelength of the radiations emitted can also be found.

Now, $\quad c = f\lambda$

where c is the velocity of light in vacuum.

$$\therefore \quad 3 \times 10^8 = 4.57 \times 10^{14} \times \lambda$$

$$\therefore \quad \lambda = 6563 \times 10^{-10} \text{ m}$$

12.16. Energy Levels in an Isolated Atom

We will consider a *single isolated* atom of hydrogen i.e., an atom which is so far removed from other atoms as not to be affected at all by their electric fields. In that case, energies possessed by various electrons in different orbits would remain totally unaffected by any external influence. The orbital energies have already been given in Art. 13.15 above. However, instead of drawing various orbits to the scale of their radii as in Fig. 12.9, it is customary (and also more convenient) to draw horizontal lines to an energy scale as shown in Fig. 12.10. Such a diagram is called an *energy-level diagram* (ELD) of the atom.

Each energy level is represented by a horizontal line of the same length although the length and thickness of the lines have no significance. It is seen that in this diagram

1. less negative energies are at the *top* whereas more negative ones are at the *bottom*. It means that it is easier to remove electrons from higher orbits than from lower ones.
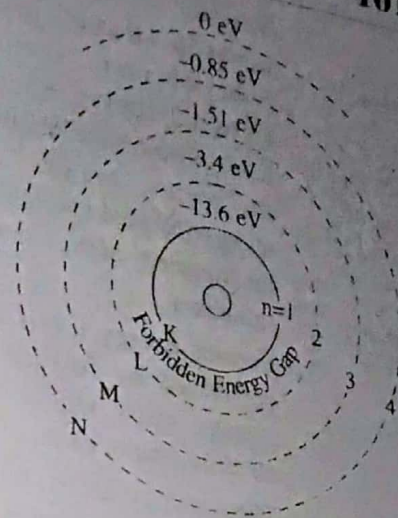
2. Various electron jumps between allowed orbits now become vertical arrows between energy levels. Greater the length of the arrow, greater the energy released and higher the frequency of the emitted radiations.

3. Various energy levels are separated by forbidden energy gaps where an electron cannot exist.

4. These energy levels, however, carry *no indication of their occupancy by electrons* which level an electron will occupy at a given time depends on the total energy possessed by it. However, the maximum number of electrons which an ene level can have is given by $2 n^2$ and has been shown in the ELD of Fig. 12.10.
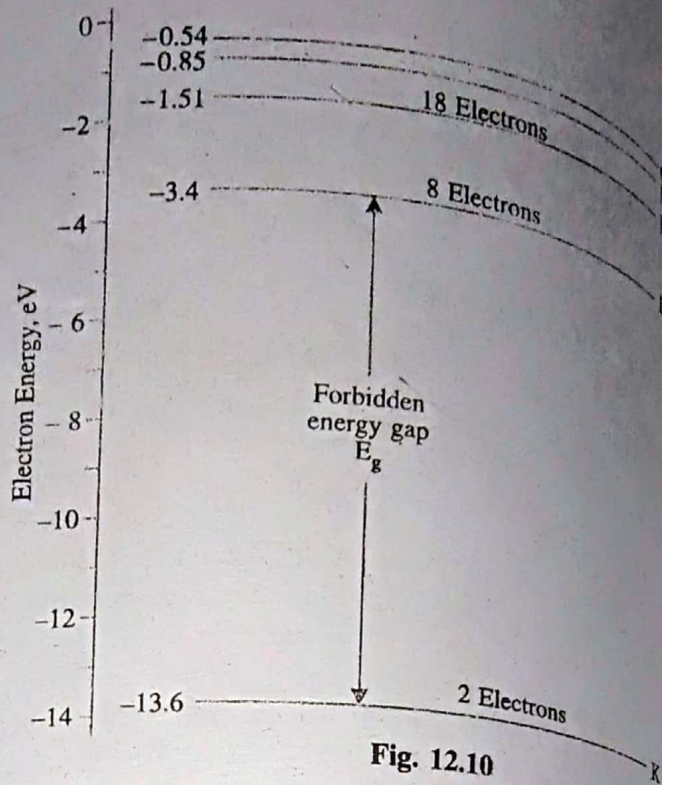
Fig. 12.10

12.17. Energy Bands in Solids

So far we have considered electron energy *levels* in a *single isolated* atom. Atoms of gases can be considered isolated because of their greater spacing under normal pressure and temperature. Hence, energy levels of such atoms are not affected by other distant atoms. But there are significant changes in the energy levels when atoms exist close together as in solids. If there are 100 atoms in a piece of solid material, then there will 100 levels of slightly different energies for each *n*-value. *i.e.,* 100 *energy-level-diagrams* would superimposed on each other. Consequently, a single energy level of an isolated atom will become band of energy in a solid as shown in Fig. 12.11.
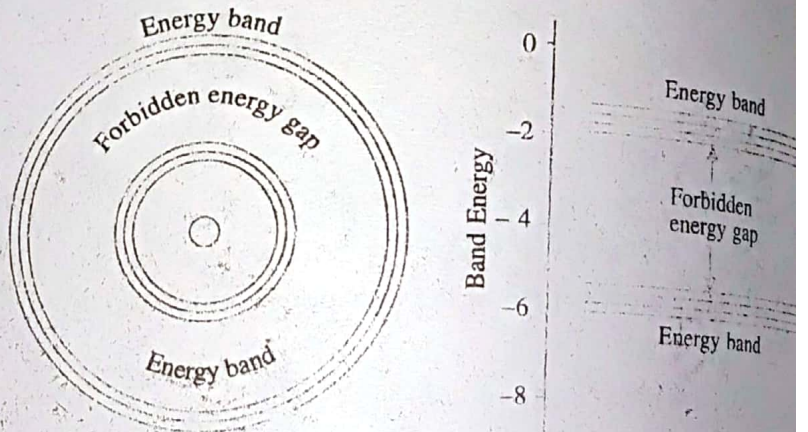
Fig. 12.11

Only four levels have been shown in each band though their number should be equal to number of atoms which are close enough to influence each other (in the present case, 100).

Let us, for example, consider the lithium element which exists as a solid metal at ordinar room temperature. Each lithium atom has three electrons two of which occupy the K-shell (o K-level), whereas the third one occupies the first sub-shell s_1 of the L-shell. As explained earlier Art. 12.11, this subshell is half-filled because it can accommodate a total of two electrons. Of cours suborbit s_2 is unoccupied. The ELD of single lithium atom along with its state of electron occupanc is shown in Fig. 12.12 (a).
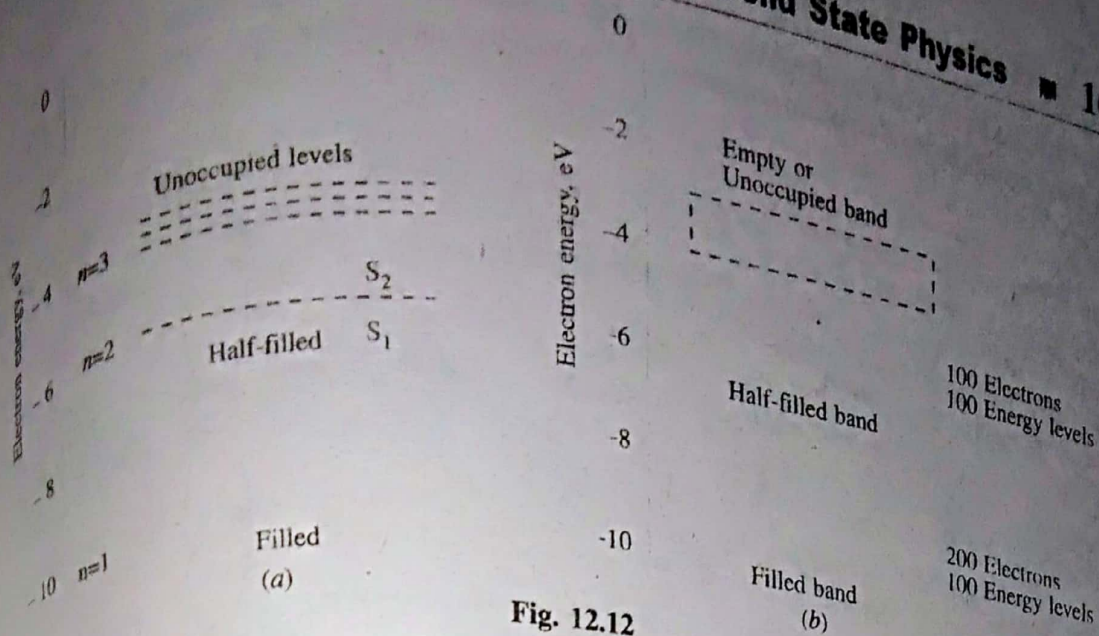
Fig. 12.12

(a) — Filled, Half-filled S_1, S_2, Unoccupied levels, $n=1$, $n=2$, $n=3$

(b) — Filled band (200 Electrons, 100 Energy levels), Half-filled band (100 Electrons, 100 Energy levels), Empty or Unoccupied band

Now, consider a small piece of lithium metal containing 100 atoms. It is obvious that there would be 100 K-levels differing in energy by extremely small amounts. They are, in fact, so close as to merge into one energy band as shown in Fig. 12.12 (b). Similarly, the 100 L-levels also blend into one energy band.

Now, let us consider the electron occupancy of these bands. Since each K-level has two electrons, there would be $2 \times 100 = 200$ electrons occupying the first or K-energy band. Since, the first sublevel s_1 of the main L-level of each atom has one electron, it is half-filled. Hence, the energy band corresponding to this sublevel s_1 of Fig. 12.12 (a) is half-filled i.e., it contains only 100 electrons though it could accommodate 200 electrons. Of course, all the higher energy bands are unoccupied because Li atom has no electrons to fill them.

12.18. Bonds in Solids

There are three major types of atomic bonds created by the valence electrons. These are known as

1. ionic bonds, 2. covalent bonds, and 3. metallic bonds.

These bonds determine the electrical conductivity of the solid.

(i) Ionic Bonds

These occur between two *different* atoms and are due to *permanent transfer* of valence electrons from one atom to another. It is a very strong bond. Such bonds are formed between sodium and chlorine atoms during the formation of sodium chloride (NaCl) crystals.

(ii) Covalent Bonds

These can occur between two similar or dissimilar atoms. In this case, there is only *sharing* of one or more valence electrons between the two atoms each of which tries to fill up its outermost orbit.

Fig. 12.13 depicts two ways of showing this covalent bonding which occurs mostly in semi-conductor materials like Si and Ge. Only valence electrons have been shown in the figure. As seen, each tetravalent Si atom shares one electron each with four surrounding atom thereby completing its quota of 8 electrons in its outermost orbit (Rule 1 of Art. 12.9). Such bonds can be broken by supplying sufficient energy to the
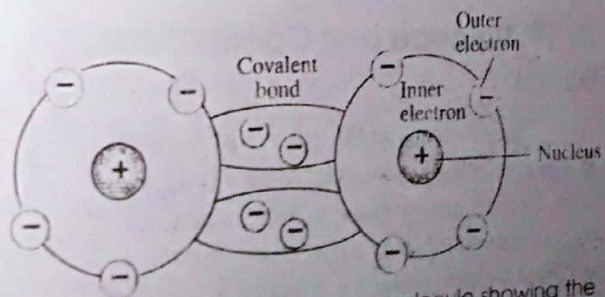
Covalent bonds of the oxygen molecule showing the sharing of the outer electrons.

solid. The electron set free by breaking the bond leaves behind a vacancy called positive hole. Hence, each bond breakage results in the production of two charge carriers i.e., one electron and hole.
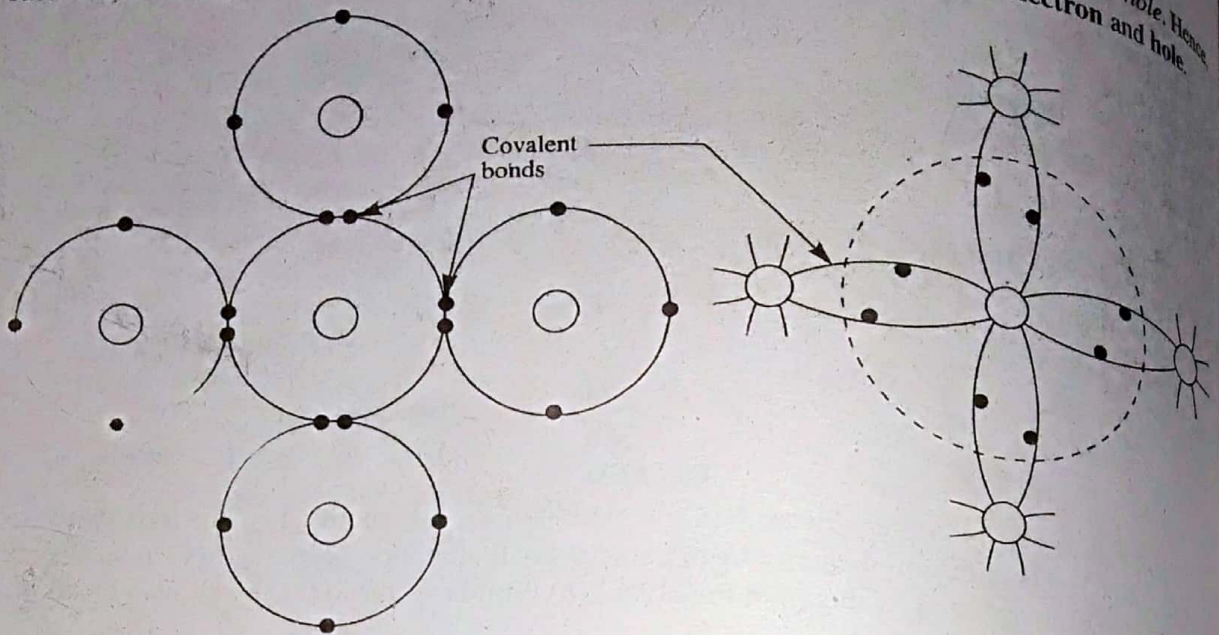
Covalent bonds

Fig. 12.13

(iii) Metallic Bonds

As the name indicates, such bonds, exist in metals and their alloys. They arise due to *sharing of variable number of electrons by a variable number of atoms*. It has been found that in metals (like Cu), each atom loses its valence electron at room temperature and becomes positively-charged ion. These free and mobile electrons form a kind of electron *cloud* or *gas* which permeates all atoms. In fact, one may look upon a metal as consisting of an array of closely-packed positive ions immersed in a sea of electrons. These valence electrons are not bound to any particular atom but freely move about from one atom to another. In fact, high electrical conductivity of metals is primarily due to the easy availability of such free electrons in extremely large numbers.

Positive metal ions in fixed positions

'Sea' of electrons which are free to move
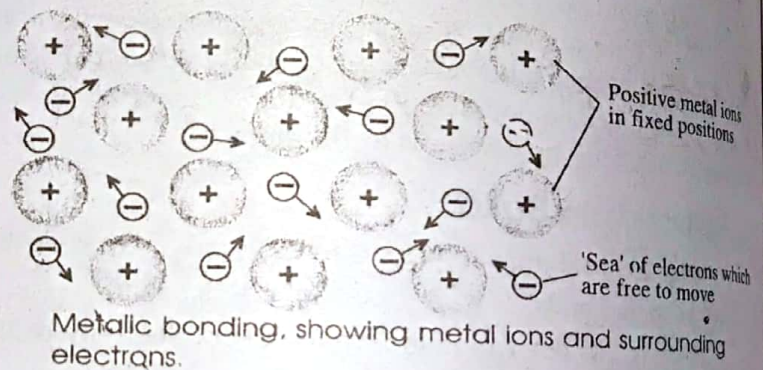
Metallic bonding, showing metal ions and surrounding electrons.

12.19. Valence and Conduction Bands

The electrons in the outermost shell of an atom are called *valence* electrons. They have least *binding* energy though their orbital energy is maximum. It is these electrons which are most affected when a number of atoms are brought *very close* together as during the formation of a solid. The states of lower-energy
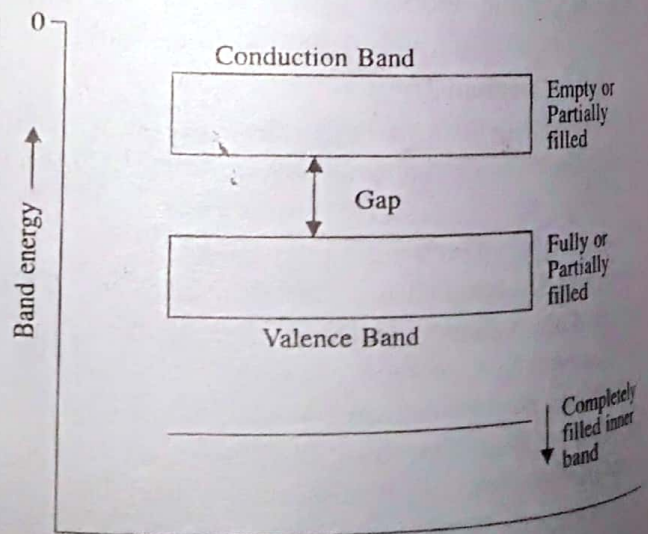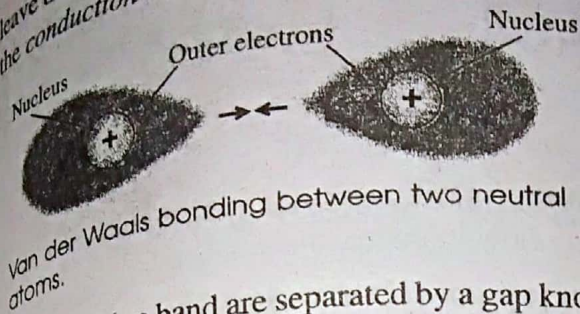
Conduction Band

Empty or Partially filled

Gap

Fully or Partially filled

Valence Band

Completely filled inner band

Band energy

Fig. 12.14

electrons orbiting in shells nearer to the nucleus are little, if at all, affected by this atomic proximity.

The energy band occupied by the valence electrons is called the valence band and is, obviously, the highest occupied band. As regards occupancy, it may be either completely-filled or partially-filled with electrons but can never be empty.

The electrons which have left the valence band are called conduction electrons. They practically leave the atom or are only weakly held to the nucleus. The band occupied by these electrons is called the conduction band. This band lies next to the valence band. It may either be empty (when no free electrons are available) or partially filled with electrons. In fact, it may be defined as the lowest unfilled energy band in an atom.

In conduction band, electrons move freely and conduct electric current through the solid. That is why they are called conduction electrons.

As shown in Fig. 12.14, the valence band and conduction band are separated by a gap known as forbidden energy gap. Energy is required to lift an electron from the valence band, take it across the gap and put it in the conduction band.

Outer electrons Nucleus Nucleus

Van der Waals bonding between two neutral atoms.

12.20. Conduction in Solids

Current flow occurs in a given material when a voltage of suitable magnitude is applied to it which causes the charge carriers within the material to move in a desired direction. This may be due to one or both of the processes i.e., electron motion and hole transfer. In electron motion, free electrons in the conduction band are moved under the influence of the electric field set up by the applied voltage. They travel from the negative terminal of the applied voltage to its positive terminal.

Hole transfer involves electrons in the valence band which (unlike conduction electrons) are still attached to the atom.

In good conductors, current flow is due to free or conduction electrons only [Fig. 12.15 (a)]. There is no hole current in them (Art. 12.28). However, current flow in semiconductors consists partly of electron current and partly of hole current [Fig. 12.15 (b)].
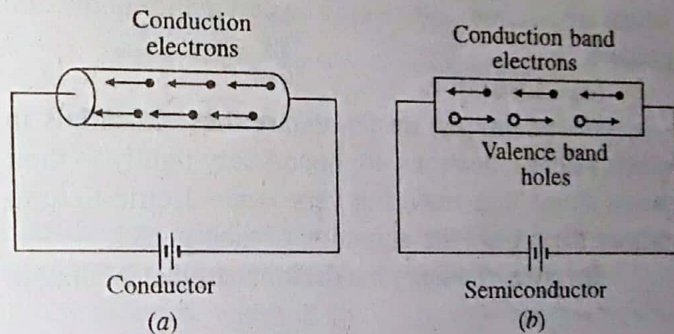
Conduction electrons

Conduction band electrons

Valence band holes

Conductor
(a)

Semiconductor
(b)

Fig. 12.15

Another point worth noting is that free electrons require much less energy than holes to move them because they are already disconnected from their atoms. It is for this reason that conduction electrons have greater mobility than holes.

12.21. Hole Formation and its Movement

As explained earlier, the covalent forces of the crystal lattice have their source in the valence band. If an electron in the valence band gets sufficient energy, it can jump across the forbidden energy gap and enter the conduction band. As shown in Fig. 12.16 (a), suppose covalent bond at A breaks due to the departure of an electron. A vacancy is left behind in the valence band which is called a positive hole. The chain of events that follows is depicted in Fig. 12.16 (a). An electron at B from an adjacent atom jumps into the hole at A. This fills the original hole but creates a new hole at B. Next, an electron at C jumps into the hole at B and so on. In this way, by a succession of electron movement, a hole appear at G and a negative charge would have moved from G to A. But it is more convenient to consider as if a positive hole has moved from A to G.

It should be carefully noted that holes are filled by electrons which move from adjacent atoms *without* passing through the forbidden energy gap. It means that *hole movement takes place in valence band only.* No new hole is created if an existing hole is filled by a free electron and not by one from the adjacent atom.
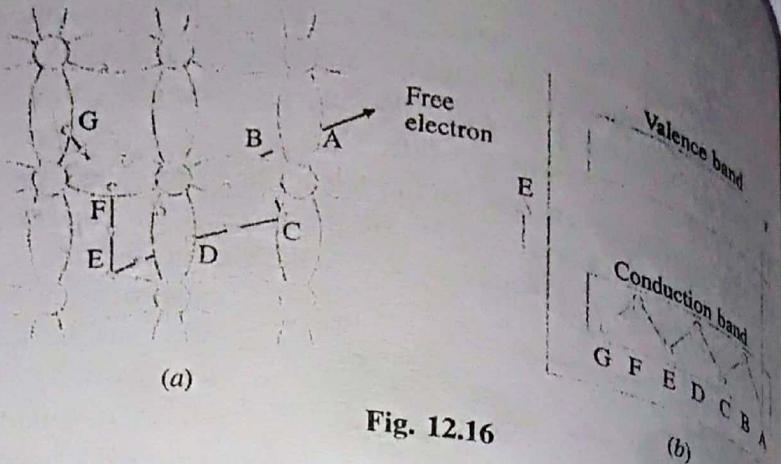

Fig. 12.16

To summarise the above, it may be repeated that

1. conduction electrons are found in and freely flow in the conduction band,
2. holes exist in and flow in the valence band,
3. electronic current is in conduction band but hole current is in valence band,
4. conduction electrons move almost twice as fast as the holes.

12.22. Conductors, Semiconductors and Insulators

The electrical conduction properties of different elements and compounds can 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 filled, play no part in the conduction process.

(a) Insulators

Stated simply, insulators are those materials in which valence electrons are bound very tightly to their parent atoms thus requiring very large electric field to remove them from the attraction of their nuclei.

In terms of energy bands, it means that insulators have

1. full valence band,
2. an empty conduction band, and
3. a large energy gap (of several eV) between them.

This is shown in Fig. 12.17 (a). For conduction to take place, electrons must be given sufficient energy to jump from the valence band to the conduction band. Increase in temperature enables some electrons to go to the conduction band which fact accounts for the negative temperature coefficient of resistance of insulators.

(b) Conductors

Conducting materials are those in which plenty of free electrons are available for electric conduction.

In terms of energy bands, it means that electrical conductors are those which have *overlapping valence and conduction bands* as shown in Fig. 12.17 (b).

In fact, there is no physical distinction between the two bands. Hence the availability of a large number of conduction electrons.

Single-core wire

Insulated multi-strand wire

Pairs of wires with insulation
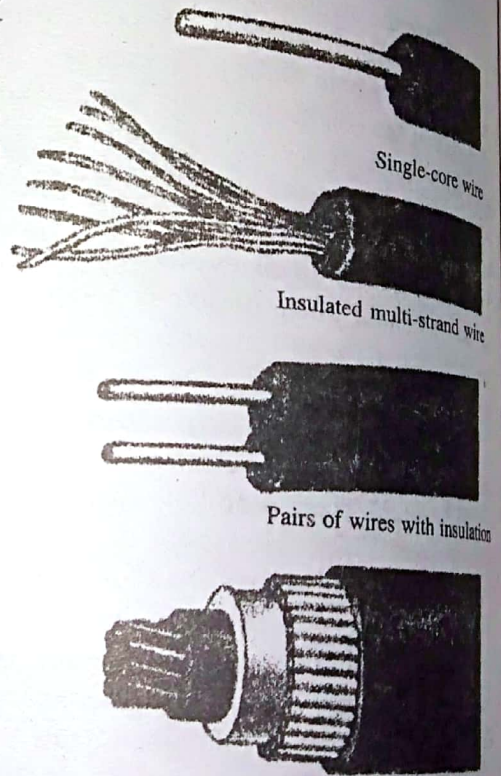
Electrical cable with three layers of insulation

By placing a rubber or plastic insulator as a sheath around a good conductor, such as a copper wire, electricity can flow along the wire without causing harm.
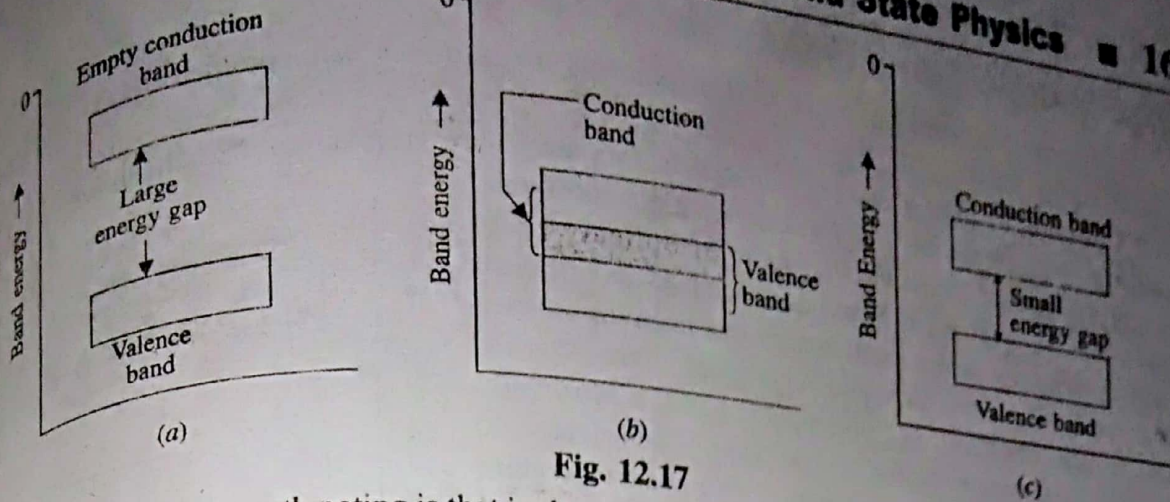
Fig. 12.17

Another point worth noting is that in the absence of forbidden energy gap in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons. It is exactly for this reason that the existence of holes was not discovered until semi-conductors were studied thoroughly.

(c) Semiconductors

A semiconductor material is one whose electrical properties lie in between those of insulators and good conductors. Examples are : germanium and silicon.

In terms of energy bands, semicon-ductors can be defined as those materials which *at room temperature* have

1. partially-filled conduction band,
2. partially-filled valence band, and
3. a very narrow energy gap (of the order of 1 eV) between them.

No current flowing

Copper atom

Electron

Edge of wire

Current flowing

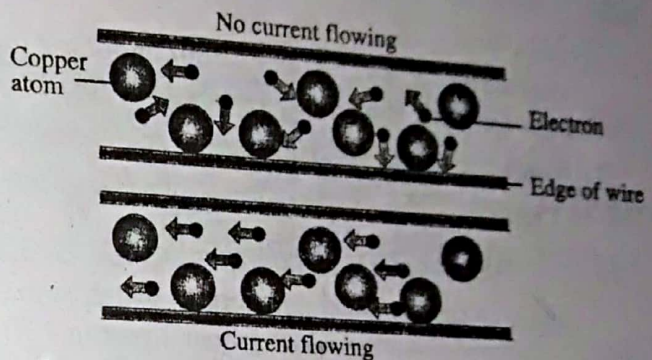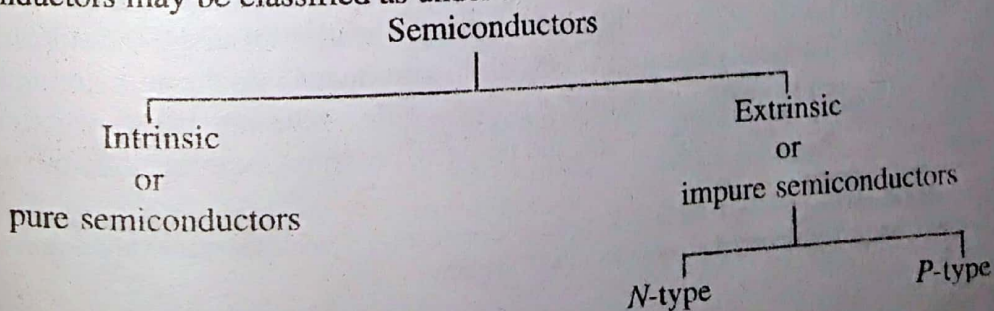Current moves through materials that conduct electricity.

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 piece of Ge or Si acts like a perfect insulator. However, with increase in temperature, width of the forbidden energy band is decreased so that some of the electrons are liberated into the conduction band. In other words, con-ductivity of semiconductors increases with temperature. It means that they have *negative* temperature coefficient of resistance.

Typical resistivities are of the following order :

Conductors	10^{-8} Ω-m
Semiconductors	10^{-3} Ω-m
Insulators	10^{-12} Ω-m

12.23. Types of Semiconductors

Semiconductors may be classified as under :

Semiconductors

Intrinsic or pure semiconductors

Extrinsic or impure semiconductors

N-type   P-type

12.24. Intrinsic Semiconductors

An intrinsic semiconductor is one which is made of the semiconductor material in its extremely pure form.

Common examples of such semiconductors are : pure germanium and silicon which have forbidden energy gaps of 0.72 eV and 1.1 eV respectively. The energy gap is so small that even at ordinary room temperature, there are many electrons which possess sufficient energy to jump across the small energy gap from the valence to the conduction band. However, it is worth noting that for each electron liberated into conduction band, *a positively-charged hole is created in the valence band*. When an electric field is applied to an intrinsic semiconductor at a temperature greater than 0°K, conduction electrons move to the anode and the holes in the valence band move to the cathode. Hence, semiconductor current consists of movement of electrons and holes in *opposite* directions in the *conduction* and *valence* bands respectively.
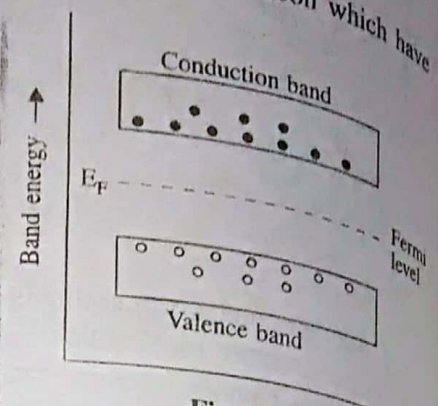

Fig. 12.18

Alternatively, an intrinsic semiconductor may be defined as one in which the number of *conduction electrons is equal to the number of holes.*

Schematic energy band diagram of an intrinsic semiconductor at room temperature is shown in Fig. 12.18. Here, Fermi level* lies in the middle of the forbidden energy gap.

12.25. Extrinsic Semiconductors

Those intrinsic semiconductors to which some suitable impurity or doping agent has been added in extremely small amount (about 1 part in 10^8) are called *extrinsic or impurity* semiconductors.

Usually, the doping agents are pentavalent atoms having five valence electrons (bismuth, antimony, arsenic, phosphorus) or trivalent atoms having three valence electrons (gallium, indium, aluminium, boron). Pentavalent doping atom is known as *donor atom* because it *donates* or contributes one electron to the conduction band of pure germanium. The trivalent atom, on the other hand, is called *acceptor atom* because it *accepts* one electron from the germanium atom. The reason why doping materials are called *impurities* is that they *alter the structure of pure semiconductor crystals.*

Depending on the type of doping material used, extrinsic semiconductors can be further subdivided into two classes :

(i) *N*-type semiconductors and　　(ii) *P*-type semiconductors.

(i) N-type Extrinsic Semiconductor

This type of semiconductor is obtained when a pentavalent material like antimony (Sb) is added to pure germanium crystal. As shown in Fig. 12.19 (a), each antimony atom forms covalent bonds with the surrounding four germanium atoms with the help of four of its five electrons. The fifth electron is superfluous and is loosely bound to the antimony atom. Hence, it can be easily excited from the valence band to the conduction band by the application of electric field or increase in its thermal energy. Thus, practically every antimony atom introduced into the germanium lattice contributes one conduction electron *without creating a positive hole*. Antimony is called donor impurity and makes the pure germanium an *N*-type (*N* for the negative) extrinsic semiconductor.

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* For the present discussion, Fermi level may be defined as the energy which corresponds to the centre of gravity of conduction electrons and holes weighted according to their energies.
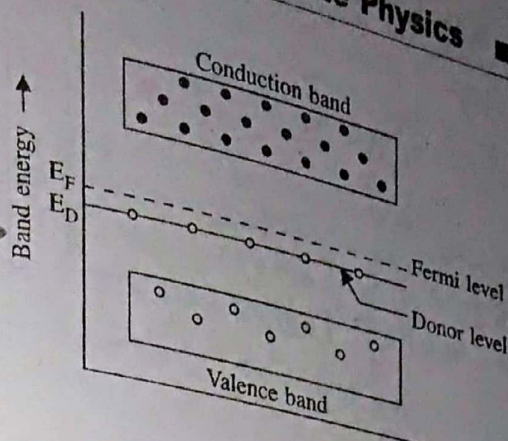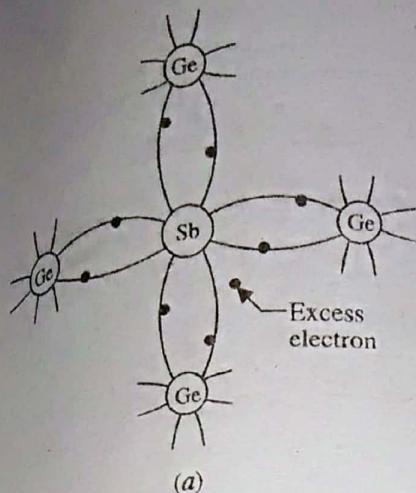
(a)

Fig. 12.19 (b)

As an aid to memory, the student should associate the letter N in 'doNor' with the N in 'N-type extrinsic semiconductor' and with the N in 'Negative charge carrier'.

It may be noted that by giving away its one valence electron, the donor atom becomes a positively-charged ion. But it cannot take part in conduction because it is firmly fixed or tied into the crystal lattice.

As seen, in addition to the electrons and holes intrinsically available in germanium, the addition of antimony greatly increases the number of conduction electrons. Hence, concentration of electrons in the conduction band is increased and exceeds the concentration of holes in the valence band. Because of this, Fermi level shifts *upwards* towards the bottom of the conduction band as shown in Fig. 12.19 (b).

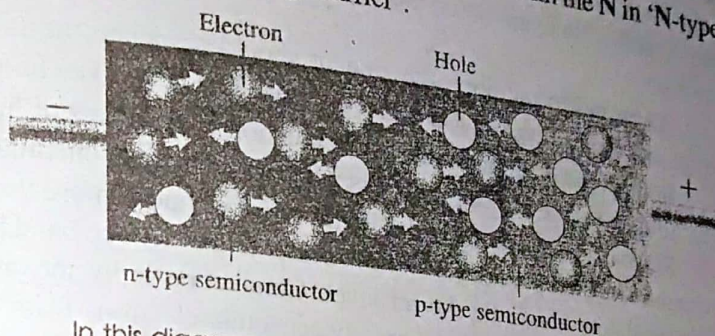In this diagram, current flows in the preferred direction.

In terms of energy levels, the fifth antimony electron has an energy level (called donor level) just below the conduction band. Usually, donor level is 0.01 eV below conduction band for germanium and 0.054 eV for silicon.

It is seen from the above description that in an N-type semiconductor, electrons are the majority carriers while holes constitute the minority carriers.
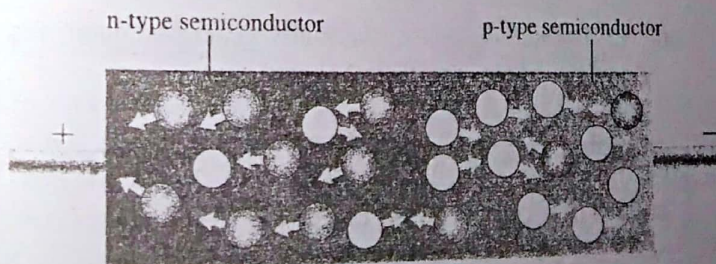
(ii) P-type Extrinsic Semiconductor

This type of semiconductor is obtained when traces of a trivalent impurity like boron (B) are added to a pure germanium crystal.

In this case, the three valence electrons of boron atom form covalent bonds with four surrounding germanium atoms, but one bond is left incomplete and gives rise to a hole as shown in Fig. 12.20 (a).

In this diagram, voltage is reversed and very little. current flows.
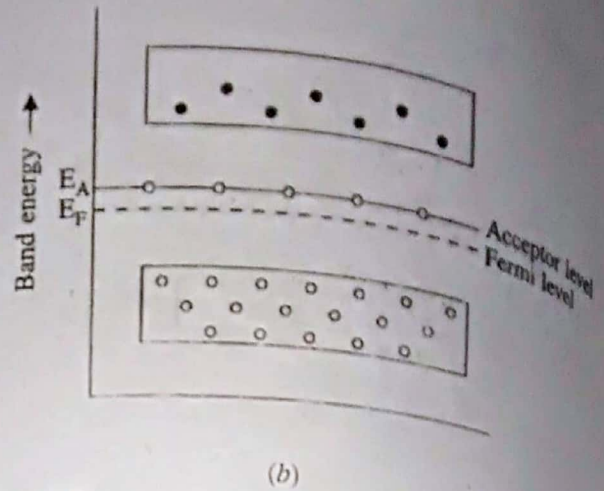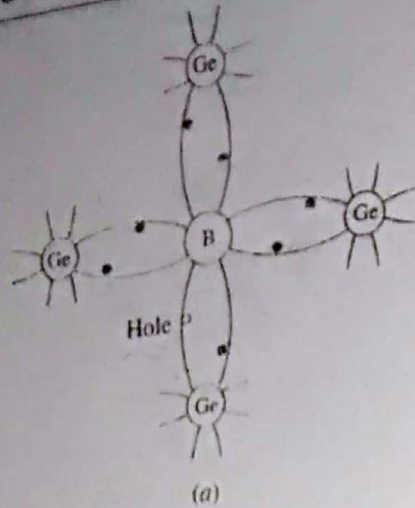
(a)

(b)

Fig. 12.20

Thus, boron which is called an acceptor impurity, causes as many positive holes in a germa-nium crystal as there are boron atoms thereby producing a P-type (P for the Positive) extrinsic semi-conductor.

As an aid to memory, the student should associate the letter P in 'accePtor' with the P in P-type extrinsic semiconductor' and with the P in 'Positive charge carrier'.

In this type of semiconductor, conduction is by means of holes in the valence band.* Accord-ngly, holes form the majority carriers whereas electrons constitute minority carriers.

Since concentration of holes in the valence band is more than the concentration of electrons in he conduction band, Fermi level shifts nearer to the valence band [Fig. 12.20 (b)]. The acceptor level ies immediately above the Fermi level. Conduction is by means of hole movement at the top of valence band, the acceptor level readily accepting electrons from the valence band.

12.26. Majority and Minority Charge Carriers

In a piece of pure germanium or silicon, no free charge carriers are available at $0°K$ Art. 12.23). However, as its temperature is raised to room temperature, some of the covalent bonds re broken by heat energy and, as a result, electron-hole pairs are produced. These are called ther-nally-generated charge carriers. They are also known as intrinsically-available charge carriers. Or-linarily, their number is quite small.

An intrinsic (or pure) germanium can be converted into a P-type semiconductor by the addi-ion of an acceptor impurity which adds a large number of holes to it. Hence, a P-type material ontains following charge carriers :

  (a) large number of positive holes—most of them being the added impurity holes with only a very small number of thermally generated ones;

  (b) a very small number of thermally-generated electrons (the companions of the thermally-generated holes mentioned above).
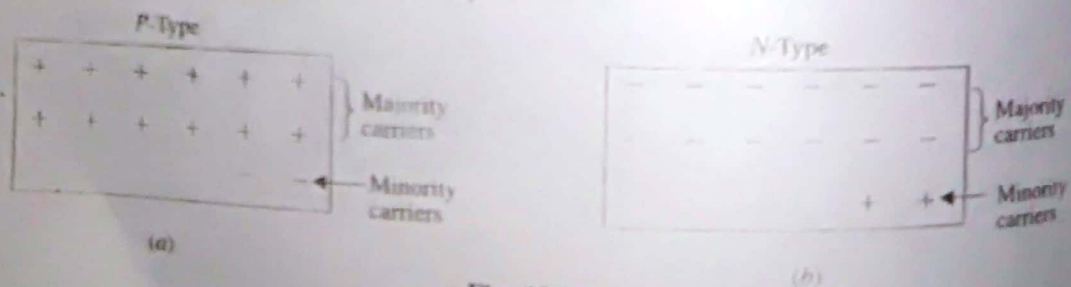

Fig. 12.21

Hole current flows more slowly than electron current in N-type semiconductors.

Obviously, in a P-type material, the number of holes (both added and thermally-generated) is much more than that of electrons. Hence, in such a material, holes constitute majority carriers and electrons form minority carriers as shown in Fig. 12.21 (a) where plus (+) sign represents hole and negative (−) sign represents electron.

Similarly, in an N-type material, the number of electrons (both added and thermally-generated) is much larger than the number of thermally-generated holes. Hence, in such a material, electrons are majority carriers whereas holes are minority carriers as shown in the Fig. 12.21 (b).

12.27. Mobile Charge Carriers and Immobile Ions

As discussed in Art. 12.25, P-type material is formed by the addition of acceptor impurity atoms like boron to the pure Ge or Si crystals. The number of holes added is equal to the number of added boron atoms because each added boron atom contributes one hole. Now, when a hole moves away from its parent atom, the remaining atom becomes a negative ion. Unlike the mobile and free-moving hole, this ion cannot take part in conduction because it is fixed in the crystal lattice. In Fig. 12.22 (a), these immobile ions are shown by circled minus signs whereas free and mobile holes are shown by uncircled plus signs. Thermally-generated electrons (which form minority carriers) are shown by uncircled minus signs.
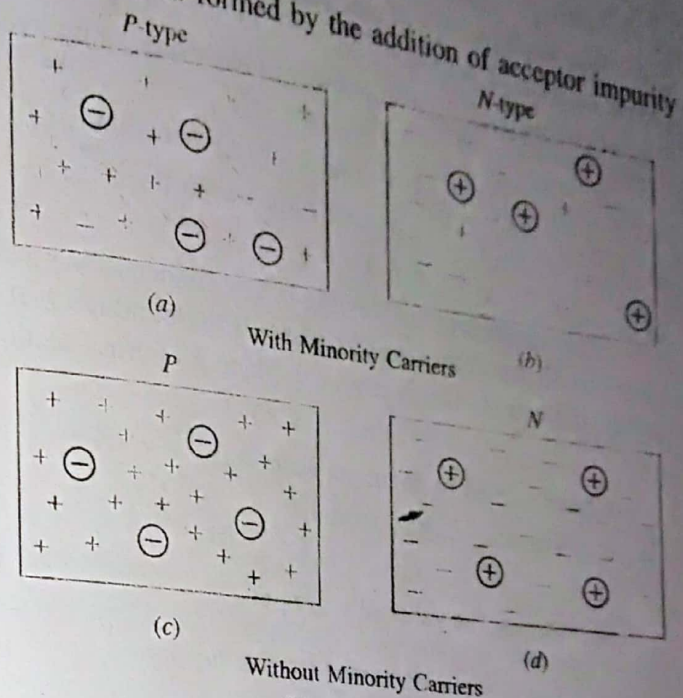

With Minority Carriers (b)

Without Minority Carriers

Fig. 12.22

Similarly, addition of pentavalent atoms like antimony to pure Ge or Si crystal produces N-type material. The number of free and mobile electrons which are added equals the number of donor Sb atoms. Again, when an electron moves away from its parent atom, it leaves behind a positive ion. This ion being fixed in crystal structure, cannot take part in conduction. As shown in Fig. 12.22 (b), these immobile ions are represented by circled plus signs whereas free and mobile electrons are represented by uncircled minus signs. The thermally-generated holes (which form minority carriers in this case) are shown by uncircled plus signs. In Fig. 12.22 (c) and (d), minority carriers of both types have been neglected. Hence, the figure does not show the small number of free electrons in the P-type material or the small number of holes in the N-type material.

12.28. Drift Current in Good Conductors

If an electric field is applied to an electron existing in a free space, it will accelerate the electron in a *straight line* from the negative terminal to the positive terminal of the applied voltage. But same thing does not happen in the case of electrons available in good conductors. As explained earlier, good conductors have plenty of free electrons moving randomly in between the fixed positive ion cores. If no voltage is applied, the net flow of charge in any direction is zero.
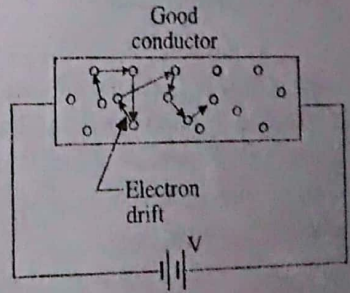

Fig. 12.23

However, as shown in Fig. 12.23, when an electric field is applied to a conductor at room temperature, electrons move towards the positive terminal of the applied voltage but they continuously

collide with atoms along the way. Each time the electron collides with an atom, it rebounds in random fashion. At each collision, the electron loses some kinetic energy, then accelerates in gains certain component of velocity in the direction of $-E$ and loses its energy at the next collision. Obviously, the presence of the electric field *does not stop collisions and random motion but it does* cause the electrons to *drift* towards the positive terminal of the applied voltage V. Consequently, the electrons gain an average directed drift velocity v which is directly proportional to E.

$$\therefore \qquad v = \mu_e E$$

where μ_e is called electron mobility*.

The resulting flow of electrons carrying negative charge at drift velocity V constitutes electric current called drift current.

Let

n = number of electrons per unit volume of the conductor i.e., electron density (per m³)

A = conductor cross-section (m²)

l = conductor length (m)

$E = V/l$ — applied electric field (V/m)

Now, electric current flowing in any conductor is given by the amount of charge which flows in one second across any normal plane of the conductor. It is seen from Fig. 12.24 that the total number of electrons which cross any plane P of cross-section A in one second

$$= n \times (v \times A)$$

Charge carried by them per second is $= e\, n\, v\, A$

It represents the drift current.

$$\therefore \qquad I = v\, e\, n\, A$$

Substituting the value of v, we get

$$I = ne\, A\, \mu_e E = ne\, A\, \mu_e \frac{V}{l}$$

Now, $$R = \frac{V}{I} = \frac{l}{A} \cdot \left(\frac{1}{ne\mu_e} \right)$$

Now, $$\rho = \frac{l}{A}$$

$\therefore$ Resistivity, $$\rho = \frac{1}{ne\mu_e} \, \Omega\text{-m}$$

and conductivity, $\sigma = ne\mu_e$ siemens/m

Fig. 12.24

12.29. Drift Current in Intrinsic Semiconductors

In the case of intrinsic semiconductors, current flow is due to the movement of electrons and holes in opposite direction (Fig. 12.25). Even though number of electrons and holes is equal, hole mobility is practically half of electron mobility.

$$I = I_c + I_h = env_e A + epv_h A$$

Fig. 12.25

$$*\mu_e = \frac{V \text{ metre/second}}{E \text{ volt/metre}} = \frac{v}{E} \text{ m}^2/\text{V-s} \text{ . This also gives the unit of mobility.}$$
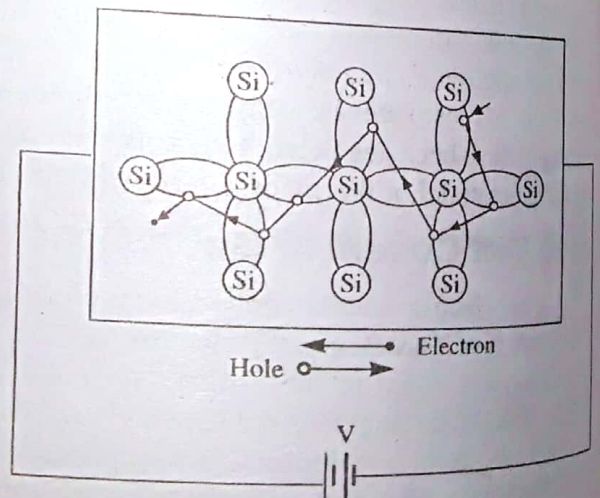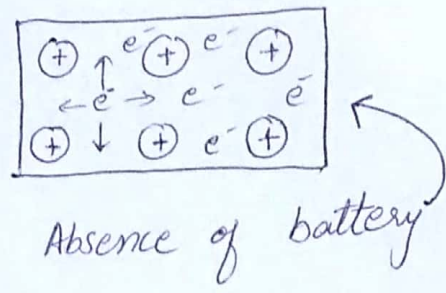
12.28 Drift Current in Good Conductors
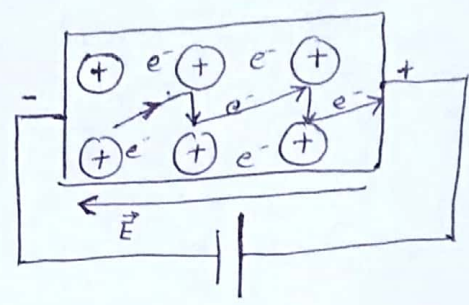
Key Points

→ **Metals**
- Positive ions
- Free electrons due to thermal energy

→ **Lattice points**

Fixed points where ions are present

→ **Zero current**

Random motion of electrons

Space b/w +ve ions

e^- direction is not uniform

→ **External battery**

Provide energy to e^-

Force is exerted, e^- accelerates

displacement, velocity

→ **Drift velocity**

The velocity gained by the electron when being pushed continuously by external energy offered by the battery is called Drift velocity.

- Fixed direction of e^-

→ **Relaxation time**

Average time of two collisions by an electron with +ve ions

Absence of battery

Derivation of Drift Velocity

Electric field $= \vec{E} = \dfrac{\vec{F}}{q}$

$$\vec{F} = q\vec{E} = e\vec{E}$$

$$ma = eE$$

$$\boxed{a = \dfrac{eE}{m}}$$

$$a = \dfrac{V_d}{t}$$

$$V_d = a \times t$$

$$\boxed{V_d = \dfrac{eE}{m} \times t}$$

Drift velocity (V_d) and Current density (J)
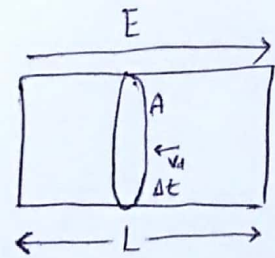
$J =$ current density

 Flow of electrons per unit area

$A = $ crossection Area

$\Delta t = $ time interval by electron to cross this area

$E = $ External Field , $L = $ Length of Conductor

$V_d = $ Drift Velocity

$$V_d = \dfrac{distance}{time} = \dfrac{L}{\Delta t}$$

$$L = V_d \times \Delta t$$

$$Volume = A \times L = A V_d \Delta t$$

No. of electrons in a given volume called number density n

$$n = \frac{N}{V}$$

N = Total number of electrons

$$N = nV = nAV_d \Delta t$$

Drift Current $= I = \dfrac{\Delta Q}{\Delta t} = \dfrac{Ne}{\Delta t}$

$$= \frac{nAV_d \Delta t e}{\Delta t}$$

$$\boxed{I = V_d e nA} \quad OR \quad venA$$

Current density $= J = \dfrac{I}{A} = \dfrac{V_d enA}{A}$

$$\boxed{J = V_d e n}$$

$e = 1.6 \times 10^{-19} C$