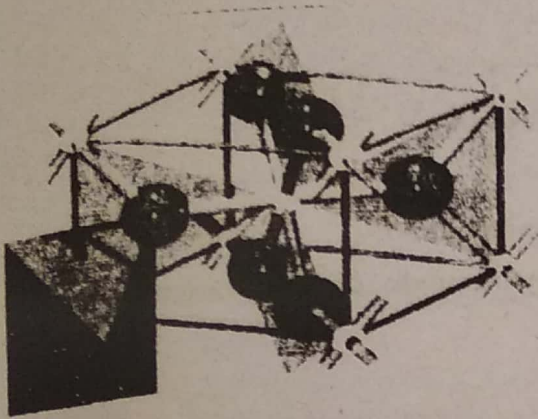
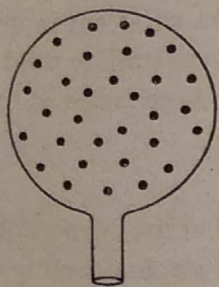


## Solid State Physics

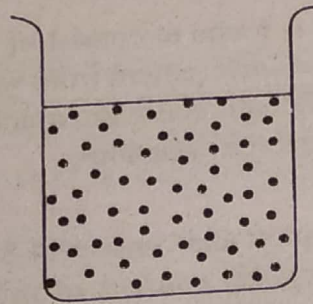


### 12.1. Definition of Matter

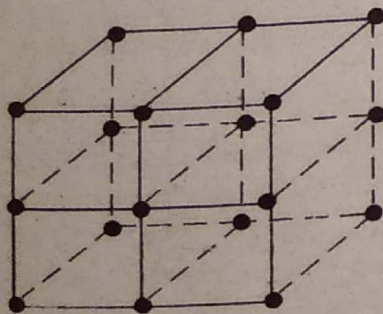
**M**atter is anything which has mass and occupies space. It can exist in any of the following three states :



Gas  
(a)



Liquid  
(b)



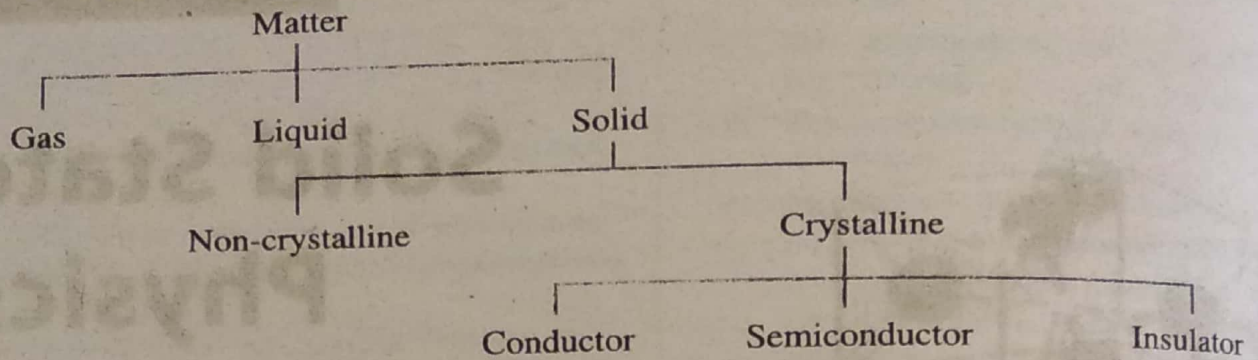
Solid  
(c)

Fig. 12.1

1. Crystalline Solids
2. Unit Cell
3. Forms of Matter
4. Atom and Molecule
5. Atomic Structure
6. Electron Orbits or Shells
7. Electron Distribution of Different Atoms
8. Electrons Suborbits or Subshells
9. Energy Bands in Solids
10. Bonds in Solids
11. Valence and Conduction Bands
12. Conduction in Solids
13. Conductors, Semiconductors and Insulators
14. Majority and Minority Charge Carriers
15. Drift Current in Good Conductors
16. Drift Current in Intrinsic Semiconductors
17. Intrinsic Conduction

1. solid      2. liquid      3. gas

In the gaseous state, the atoms or molecules are separated from each other by comparatively large distances and are *haphazardly arranged* as shown in Fig. 12.1 (a). In the liquid state, they are somewhat closer but are still arranged haphazardly as shown in Fig. 12.1 (b). In the solid state, atoms are the *closest* and take on an orderly three-dimensional geometric pattern called *crystal lattice* as shown in Fig. 12.1 (c).



In fact, considered in the materials context, matter may be subdivided into various categories, shown above.

## 12.2. Crystalline Solids

These are the solids in which atoms or molecules are arranged in a very regular and orderly fashion in a three-dimensional pattern. Each atom or molecule is fixed at a definite point in space at a definite distance and in a definite direction from all others surrounding it. In fact, there is an internal spatial symmetry of atomic orientation within a crystalline solid. This spatial pattern of atoms is called *space lattice* or *lattice array*.

## 12.3. Unit Cell

The entire lattice structure of a crystal is found to consist of identical blocks of atoms or unit cells. This unit cell is the smallest block or geometric pattern from which the entire crystalline solid is built up by repetition in three dimensions. The unit cell with which we are more concerned in this chapter has cubic structure with the following three variations :

### (a) Simple Cube

This unit cell or space lattice is the simplest and consists of 8 atoms located at the corners of a cube as shown in Fig. 12.2 (a). The entire crystal consists of millions of such cubical unit cells stacked one upon the other. The different atoms are held together by atomic binding forces.

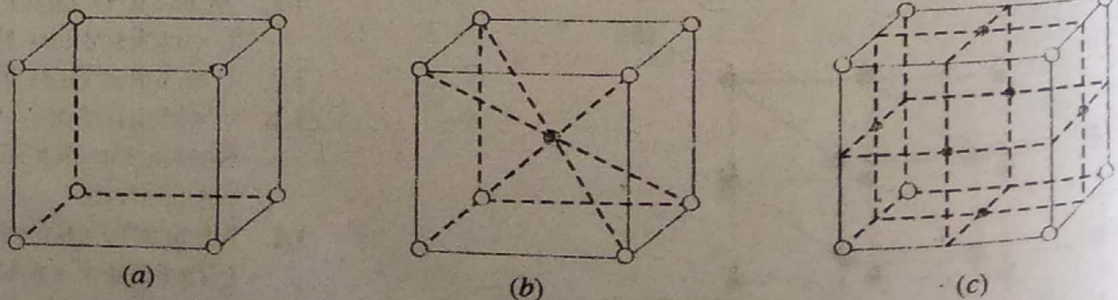
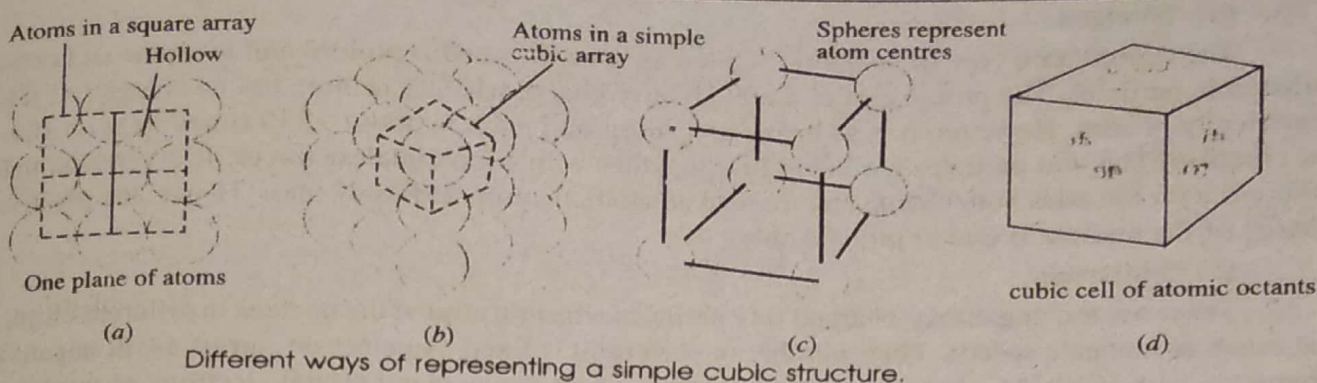


Fig. 12.2

### (b) Body Centred Cube

In this unit cell, apart from 8 corner atoms, there is one additional atom at the centre of the cube as shown in Fig. 12.2 (b). Obviously, in this case, 9 atoms are involved as compared to 8 atoms in a simple cubic lattice. The two most important semiconductor materials silicon and germanium form this type of cubic crystal lattice.



**(c) Face Centred Cube**

In this arrangement, apart from the 8 corner atoms, there is one atom each at the centre of the six faces of the cube as shown in Fig. 12.2 (c). In all, there are  $(8 + 6) = 14$  atoms which are bonded together by atomic forces. Copper forms this type of lattice.

**12.4. Forms of Matter**

In nature, matter is found in the form of either elements or compounds.

**(a) Element**

It is a substance which cannot be broken down any further by chemical methods into a simpler substance.

For example, copper can neither be decomposed into simpler substances nor can it be built up from any simpler substances. Elements are identified by such properties as colour, density and melting temperature etc. Common examples of elements are : oxygen, bromine, aluminium, copper, silicon, germanium and uranium etc. They all are made up of identical atoms which themselves consist of electrons, protons and neutrons etc. Till today, 106 elements have been discovered.

**(b) Compound**

It is a substance which consists of more than one element in chemical combination. For example, water is formed from the chemical union of two elements *i.e.*, hydrogen and oxygen. Sodium carbonate is an example of a compound formed from the union of three elements *i.e.*, sodium, carbon and oxygen. The smallest part of a compound which retains its chemical characteristics is called a *molecule*.

**12.5. Atom and Molecule**

The atoms of most elements cannot exist by themselves, hence they generally combine to form molecules. A molecule is the smallest particle of a substance that retains all the characteristic properties of the original substance. Molecules are composed of one or more atoms and are called monoatomic, diatomic and triatomic molecules etc.

**12.6. Atomic Structure**

Our present planetary atomic model was proposed by Niels Bohr in 1913. According to this model, an atom is composed of negatively-charged electrons moving in fixed circular or elliptical orbits around a heavy positively-charged nucleus made up of protons and neutrons as shown by the three-dimensional diagram of Fig. 12.3.

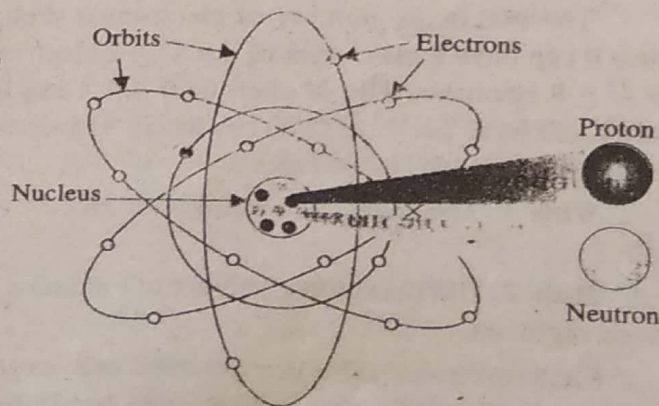


Fig. 12.3

**(a) Nucleus**

The central hard core of an atom is called nucleus. It contains protons and neutrons and other subatomic particles. The proton carries a unit positive charge whereas neutron has no charge *i.e.*, it is electrically neutral. However, it is as heavy as proton and each is about 1840 times heavier than an electron. The two particles are held close together with strong nuclear forces. It is obvious that whereas a proton adds both charge and mass to an atom, neutron adds only mass. Hence, the positive charge of the nucleus is due to protons only.

**(b) Electrons**

These are the negatively-charged tiny particles whirling around the nucleus in different elliptical orbits at fantastic speeds. Their number in each orbit is fixed. An electron carries a unit negative charge ( $= -1.6 \times 10^{-19}$  C) but has negligible mass. There are as many orbital electrons as there are protons in a given atom which, therefore, makes the entire atom electrically neutral.

The centripetal force ( $= mv^2/r$ ) necessary to keep electrons rotating round the nucleus is supplied by the force of attraction between their opposite charges as given by Coulomb's Law. It is obvious that nearer an electron is to the nucleus, greater is the force with which it is bound to it.

**12.7. Atomic Number (Z)**

It is equal to the number of protons (or electrons) contained in an atom.

For example, hydrogen (*H*) atom has one proton in the nucleus (and of course, one orbital electron). Hence, for hydrogen,  $Z = 1$ . For carbon (*C*),  $Z = 6$ , for copper (*Cu*),  $Z = 29$ , for silicon (*Si*)  $Z = 14$  and for germanium (*Ge*),  $Z = 32$ .

**12.8. Atomic Mass Number (A)**

It gives the total number of protons and neutrons contained in the nucleus of an atom. For example, *Si* has 14 protons and 14 neutrons in its nucleus. Hence, its  $A = 28$ . Similarly, *Ge* has 32 protons and 41 neutrons thereby having  $A = 73$ .

The atomic weight is the *actual* weight of an atom and numerically differs slightly from the atomic mass number.

**12.9. Electron Orbits or Shells**

According to Planck's Quantum Theory, an electron cannot revolve round the nucleus in any arbitrary orbit but in only certain definite discrete and fixed orbits. These orbits are designated by alphabetical letters *K, L, M, N, O, P* etc., starting from the nucleus outwards. The orbit (or shell) closest to nucleus is called *K*-shell, the next farther one is called *L*-shell and so on. These shells are also known by their principal quantum number  $n$  which can have values of  $n = 1$  for *K*-shell,  $n = 2$  for *L*-shell and so on.

The maximum number of electrons a shell can have  $= 2n^2$ . For example, for *K*-shell,  $n = 1$ , hence it can have a maximum of  $2 \times 1^2 = 2$  electrons. Similarly, *L*-shell with  $n = 2$ , can accommodate  $2 \times 2^2 = 8$  electrons. The *M*-shell with  $n = 3$  can have a maximum of  $2 \times 3^2 = 18$  electrons whereas *N*-shell can have  $2 \times 4^2 = 32$  electrons etc. However, this electronic distribution in all atoms is subject to the following two basic rules :

**Rule 1.** The maximum number of electrons in the outermost shell of an atom cannot exceed eight.

**Rule 2.** The maximum number of electrons in the shell just prior to the outermost shell cannot exceed eighteen.

Each electronic orbit is associated with a certain definite amount of energy. While revolving in these permitted orbits, an electron does not radiate out any energy. But it does radiate out some

definite energy when jumping from one orbit to another. If  $E_2$  and  $E_1$  are the energies corresponding to the two orbits before and after the jump, the frequency of the emitted radiation is given by the relation

$$E_2 - E_1 = hf \quad \text{or} \quad \Delta E = hf$$

where  $h = \text{Planck's constant}$   
 $= 6.625 \times 10^{-34} \text{ J-s.}$

### 12.10. Electron Distribution of Different Atoms

In Fig. 12.4 is shown the two-dimensional schematic distribution of electrons in different orbits for hydrogen, boron, silicon and germanium atoms. Following facts are clear from the diagram.

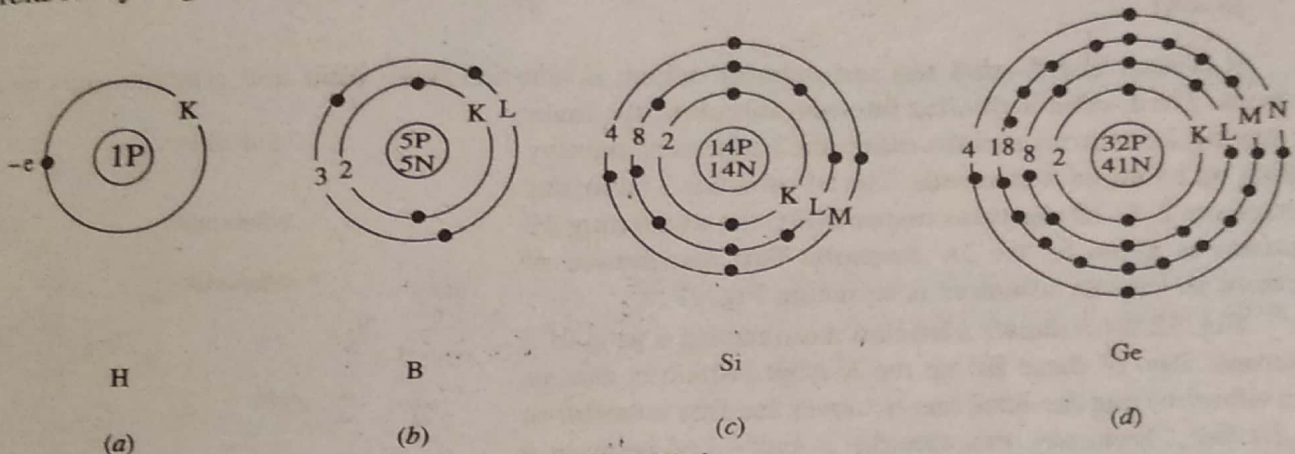


Fig. 12.4

The hydrogen atom [Fig. 12.4 (a)] has one positive proton in its nucleus symbolised as "1P". To balance this charge, it has one electron revolving in the extra-nuclear K-shell.

As shown in Fig. 12.4 (b), a boron atom has 5 protons and 5 neutrons inside its nucleus and 5 electrons outside it. Two electrons occupy K-shell which is then said to be completely- or fully-occupied because it cannot hold more electrons as per the  $2n^2$  formula. The other three electrons occupy the next L-shell which, obviously, is not full or completely-occupied because it can hold a total of 8 electrons.

The Si atom of 12.4 (c) has K- and L-shells completely filled whereas M-shell is partially-occupied because it has only four electrons\*.

Similarly, Ge atom of Fig. 12.4 (d) has first three orbits fully occupied whereas the fourth (and the outermost) orbit is partially filled. It could also have at least four additional electrons (Rule 1 of Art. 12.9).

### 12.11. Electrons Suborbits or Subshells

It has been found that each electron orbit actually contains a number of *suborbits* with the exception of the  $n = 1$  or K-orbit which is its own suborbit. The number of suborbits in an orbit equals its principal quantum number,  $n$ . For example, K-orbit ( $n = 1$ ) has one suborbit, L-orbit ( $n = 2$ ) has two suborbits and M-orbit ( $n = 3$ ) consists of three suborbits etc. These orbits and suborbits are also respectively known as shells and subshell. The total number of electrons (which equals  $2n^2$ ) gets distributed amongst these subshells as shown on next page in Table 12.1.

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 energy level can have is given by  $2n^2$  and has been shown in the ELD of Fig. 12.10.

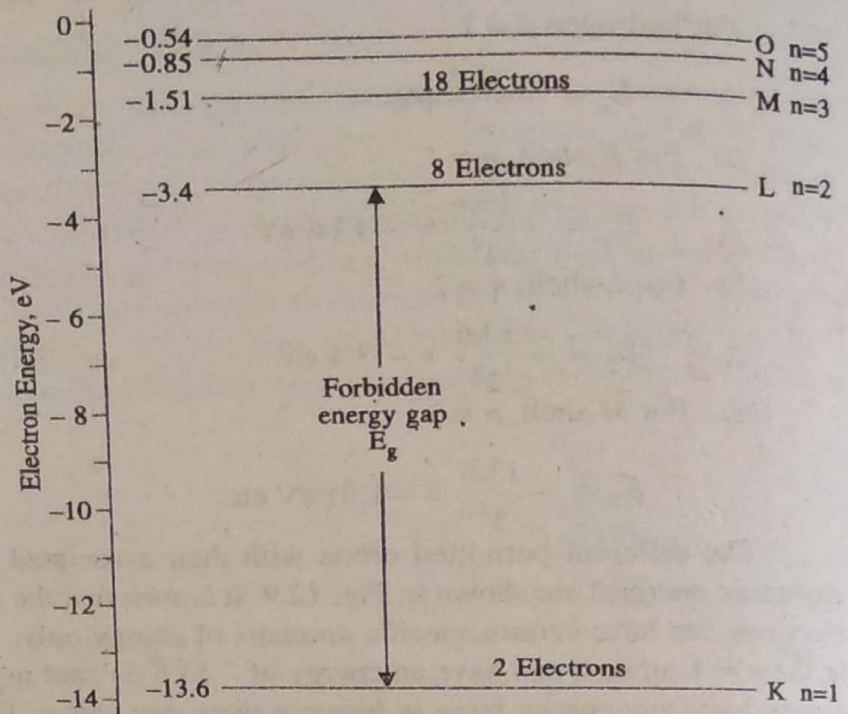


Fig. 12.10

### 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

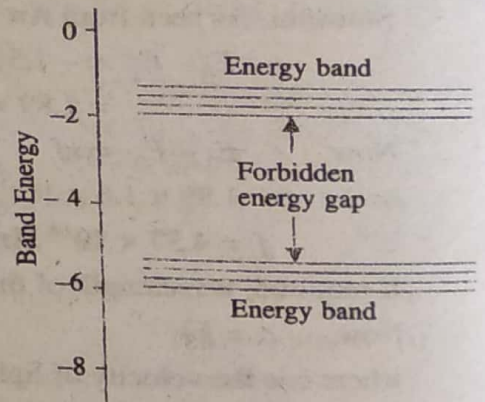
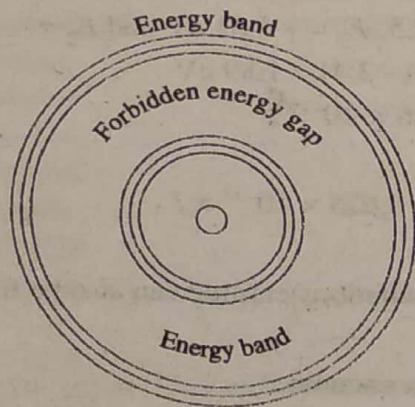


Fig. 12.11

exist close together as in solids. If there are 100 atoms in a piece of solid material, then there will be 100 levels of slightly different energies for each  $n$ -value i.e., 100 energy-level-diagrams would be superimposed on each other. Consequently, a single energy level of an isolated atom will become a band of energy in a solid as shown in Fig. 12.11.

Only four levels have been shown in each band though their number should be equal to the 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 ordinary room temperature. Each lithium atom has three electrons two of which occupy the  $K$ -shell (or Art. 12.11, this subshell is half-filled because it can accommodate a total of two electrons. Of course, suborbit  $s_2$  is unoccupied. The ELD of single lithium atom along with its state of electron occupancy is shown in Fig. 12.12 (a).

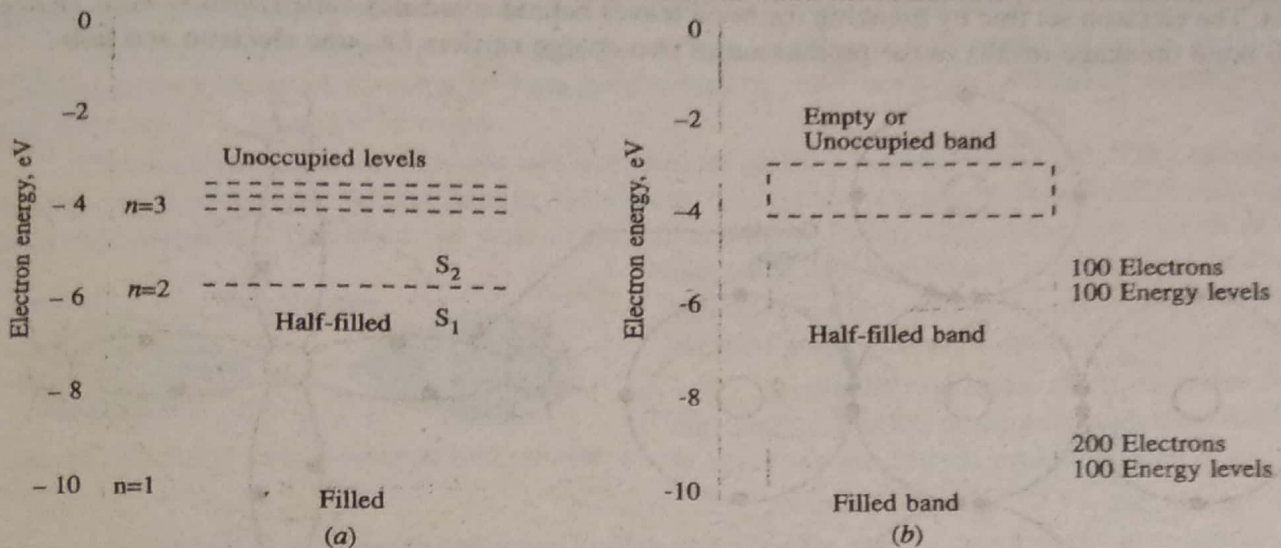


Fig. 12.12

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.

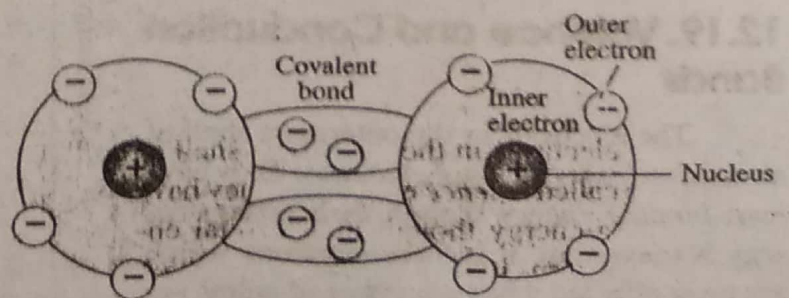
#### (i) Ionic Bonds

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 atoms 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.

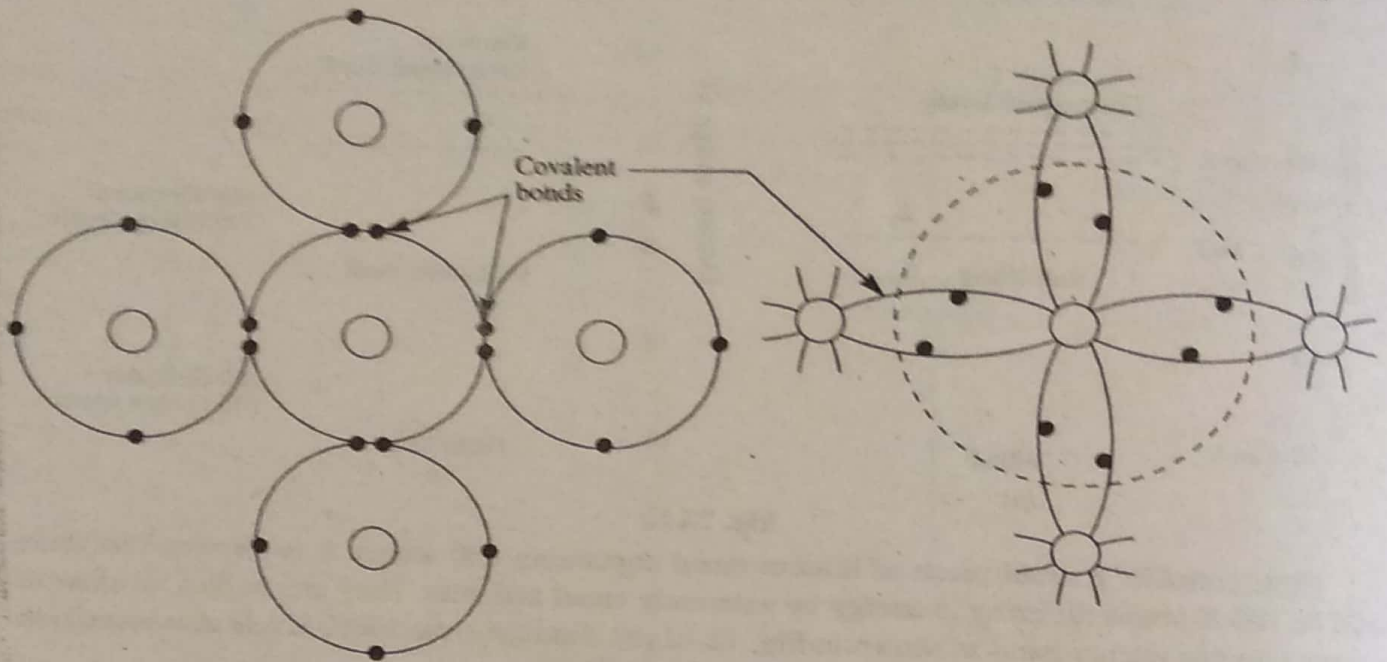
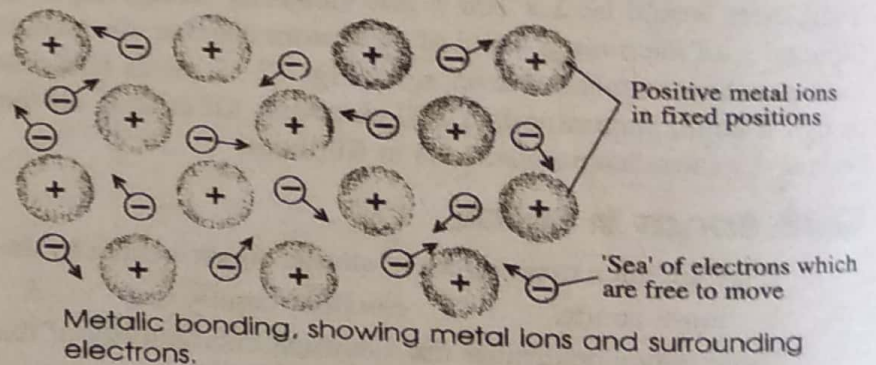


Fig. 12.13

**(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.

**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

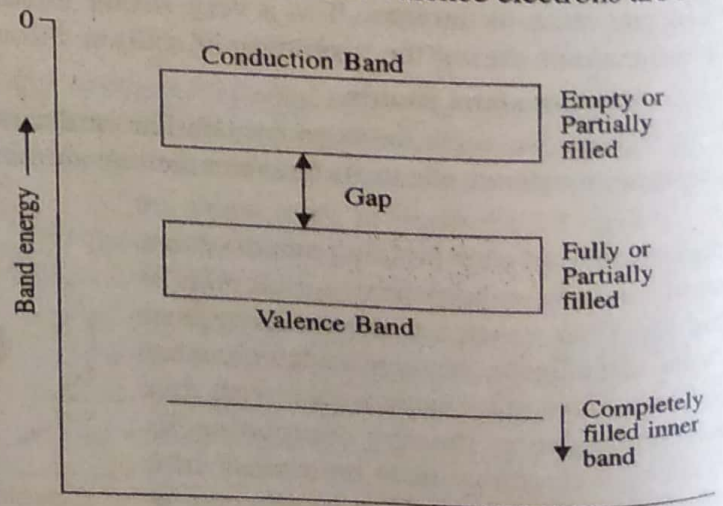


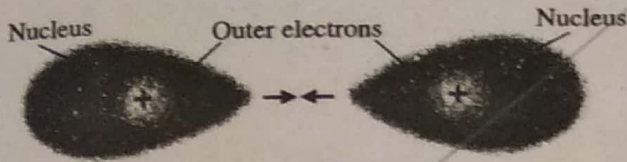
Fig. 12.14



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*.



Van der Waals bonding between two neutral atoms.

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.

## 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)].

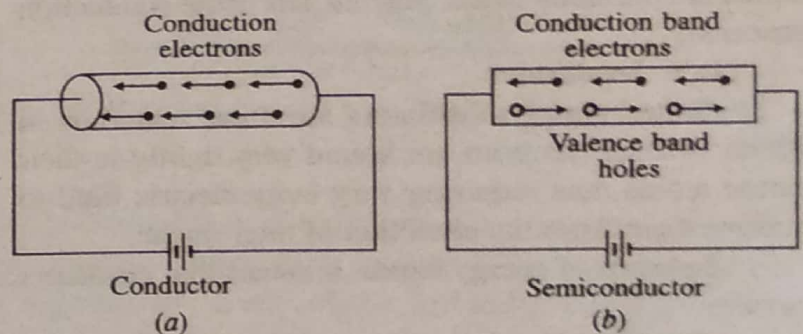


Fig. 12.15

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.

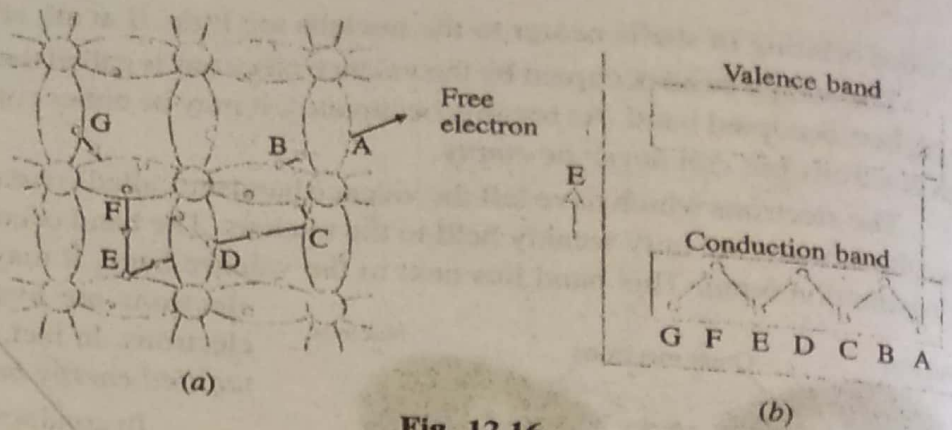


Fig. 12.16

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.

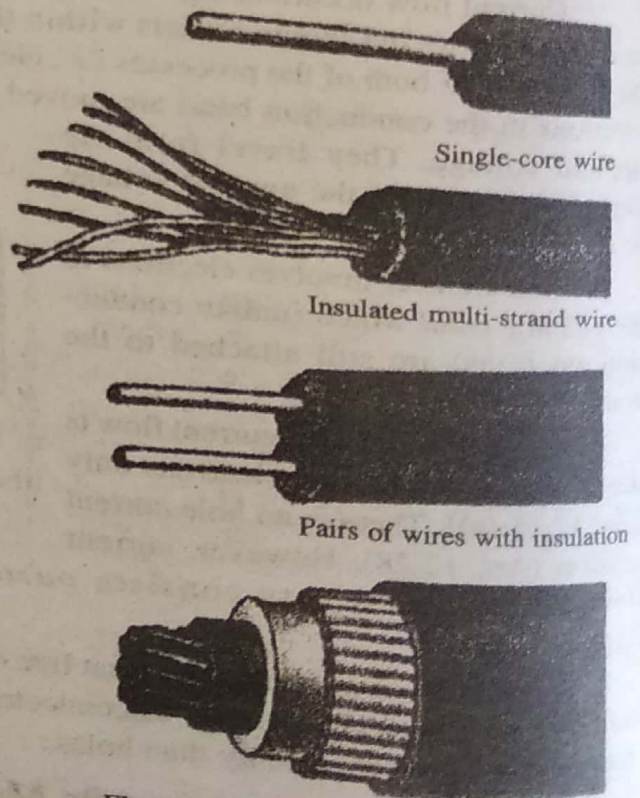
This is shown in Fig. 12.17 (a). For conduction to take place, electrons must be given sufficient energy to jump from the valence band to the conduction band. Increase in temperature enables some electrons to go to the conduction band which fact accounts for the negative temperature coefficient of resistance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



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.

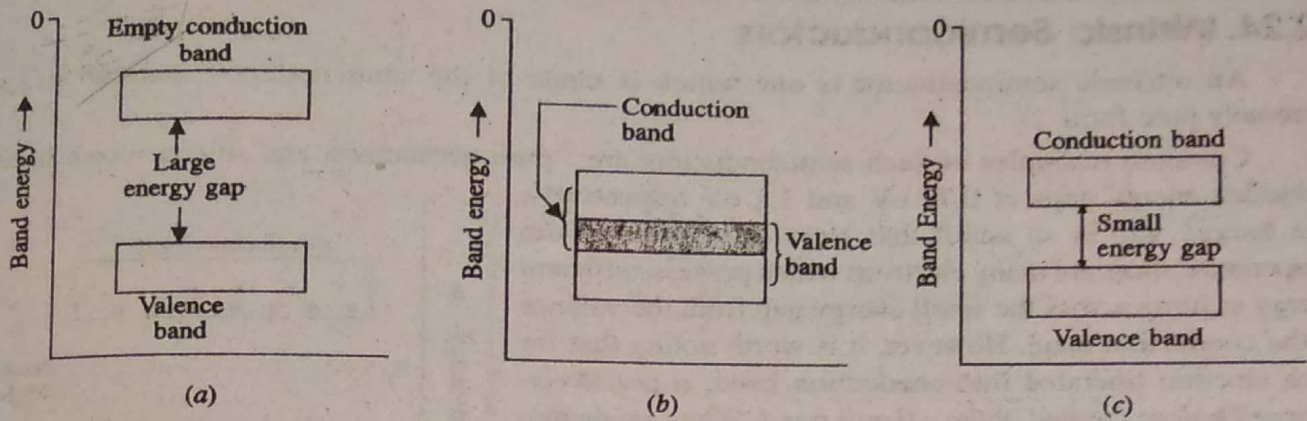


Fig. 12.17

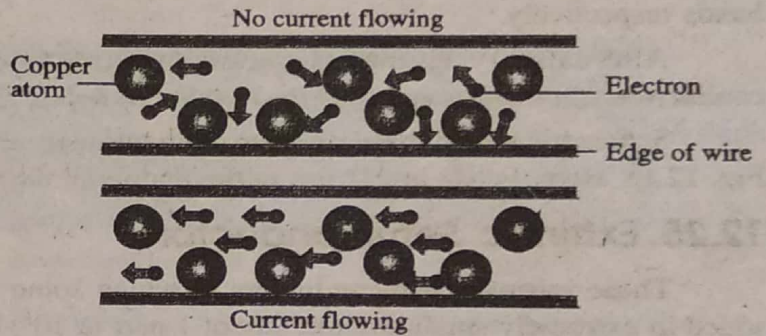
Another point worth noting is that in the absence of forbidden energy gap in good conductors, there is no structure to establish holes. The total current in such conductors is simply a flow of electrons. It is exactly for this reason that the existence of holes was not discovered until semiconductors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



Current moves through materials that conduct electricity.

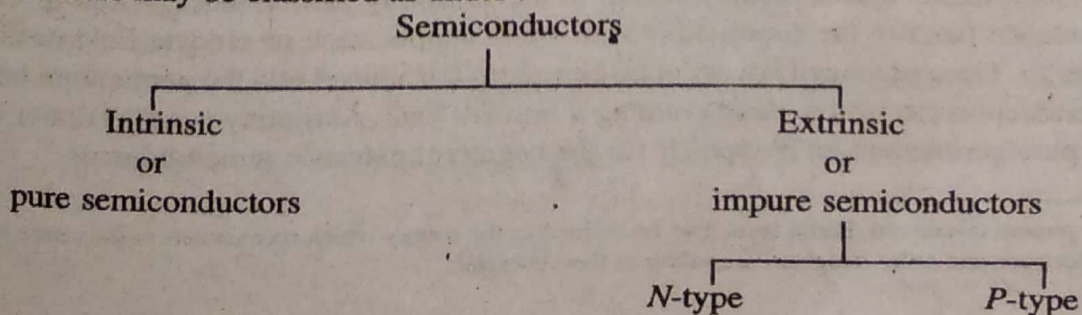
At 0°K, there are no electrons in the conduction band of semiconductors and their valence band is completely filled. It means that at absolute zero temperature, a piece of Ge or Si acts like a perfect insulator. However, with increase in temperature, width of the forbidden energy band is decreased so that some of the electrons are liberated into the conduction band. In other words, conductivity of semiconductors increases with temperature. It means that they have *negative* temperature coefficient of resistance.

Typical resistivities are of the following order :

Conductors	$10^{-8} \Omega\text{-m}$
Semiconductors	$10^{-3} \Omega\text{-m}$
Insulators	$10^{12} \Omega\text{-m}$

**12.23. Types of Semiconductors**

Semiconductors may be classified as under :



## 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.

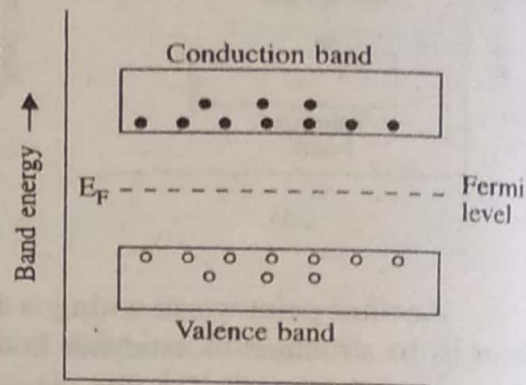


Fig. 12.18

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.

\* 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.

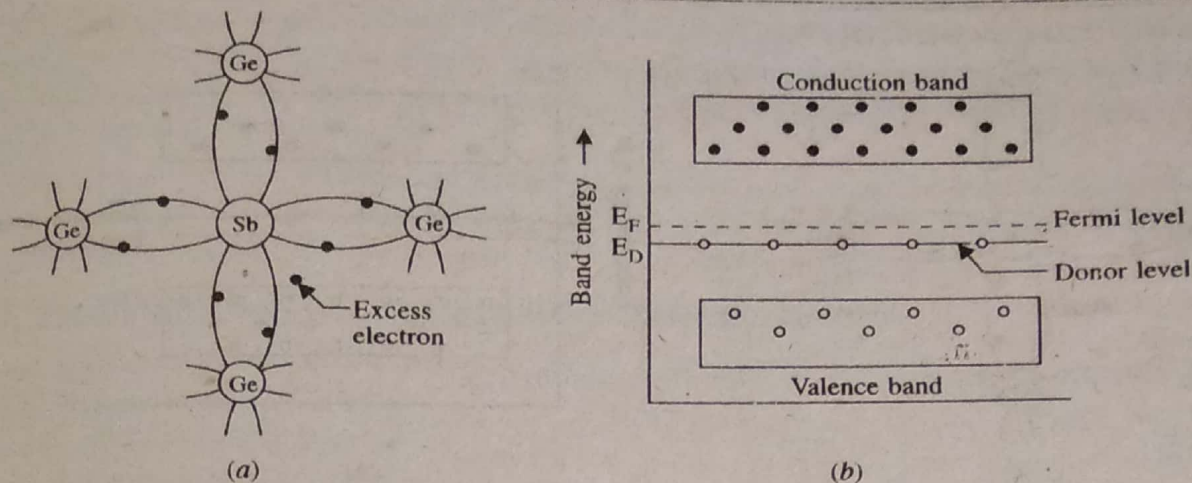


Fig. 12.19

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).

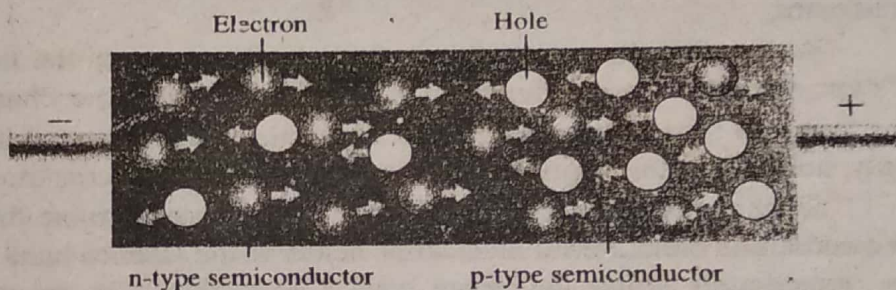
In terms of energy levels, the fifth antimony electron has an energy level (called donor level) just below the conduction band. Usually, donor level is 0.01 eV below conduction band for germanium and 0.054 eV for silicon.

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

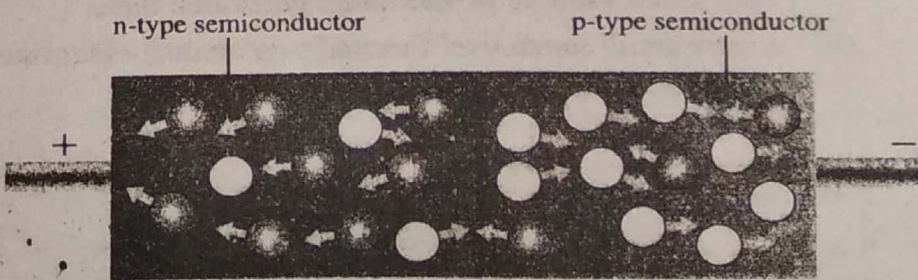
**(ii) P-type Extrinsic Semiconductor**

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, current flows in the preferred direction.



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

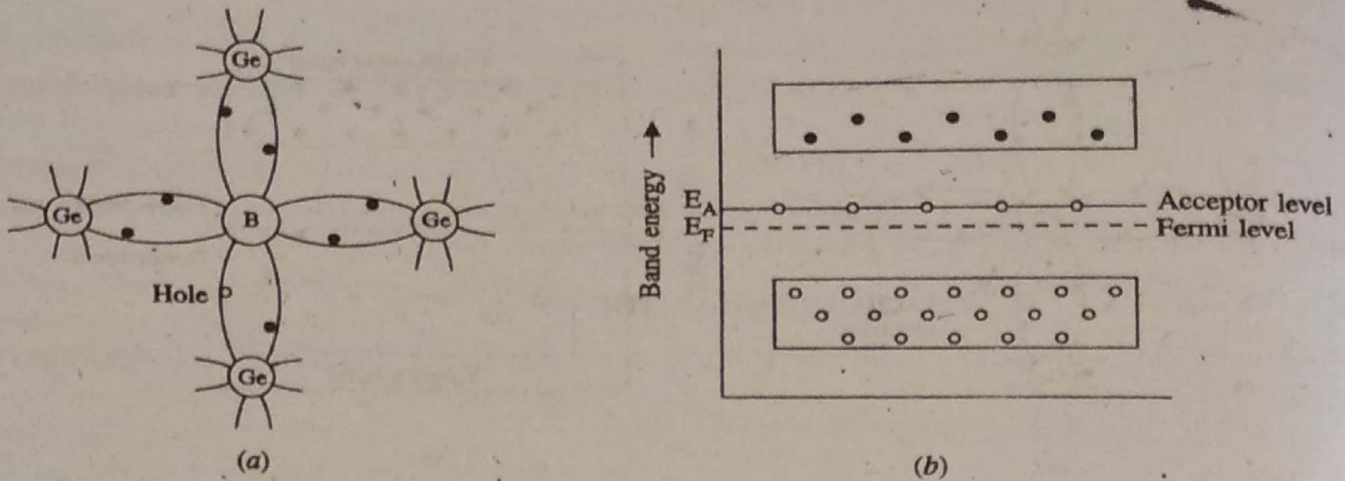


Fig. 12.20

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

As an aid to memory, the student should associate the letter **P** in 'acce**P**tor' 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.\* Accordingly, 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 the conduction band, Fermi level shifts nearer to the valence band [Fig. 12.20 (b)]. The acceptor level lies 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 are broken by heat energy and, as a result, electron-hole pairs are produced. These are called *thermally-generated charge carriers*. They are also known as *intrinsically-available charge carriers*. Ordinarily, their number is quite small.

An intrinsic (or pure) germanium can be converted into a *P*-type semiconductor by the addition of an acceptor impurity which adds a large number of holes to it. Hence, a *P*-type material contains 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).

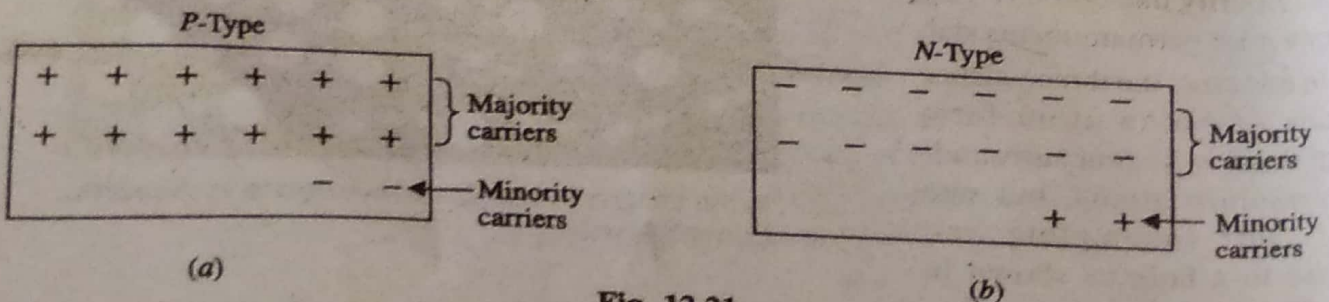


Fig. 12.21

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 such 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.

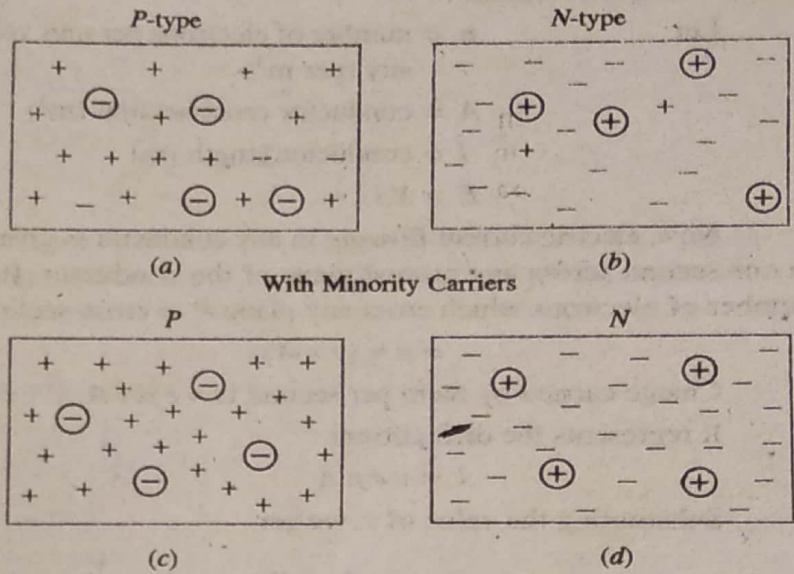


Fig. 12.22

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.

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

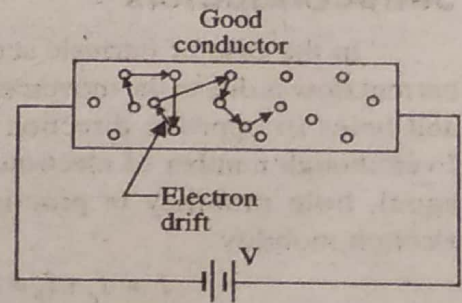


Fig. 12.23

collide with atoms along the way. Each time the electron collides with an atom, it rebounds in a random fashion. At each collision, the electron loses some kinetic energy, then accelerates again, 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  $E$ .

$$\therefore v = \mu_e E$$

where  $\mu_e$  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  $m^3$ )
- $A$  = conductor cross-section ( $m^2$ )
- $l$  = 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.

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

Substituting the value of  $v$ , we get

$$I = n e A \mu_e E = n e A \mu_e \frac{V}{l}$$

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

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

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

and conductivity, 
$$\sigma = n e \mu_e \text{ siemens/m}$$

### 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.

$$I = I_c + I_h = e n v_e A + e p v_h A$$

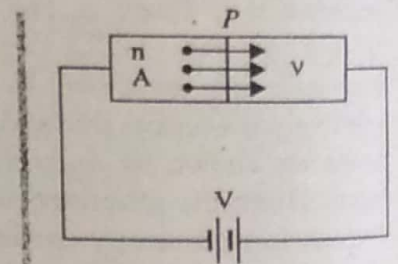


Fig. 12.24

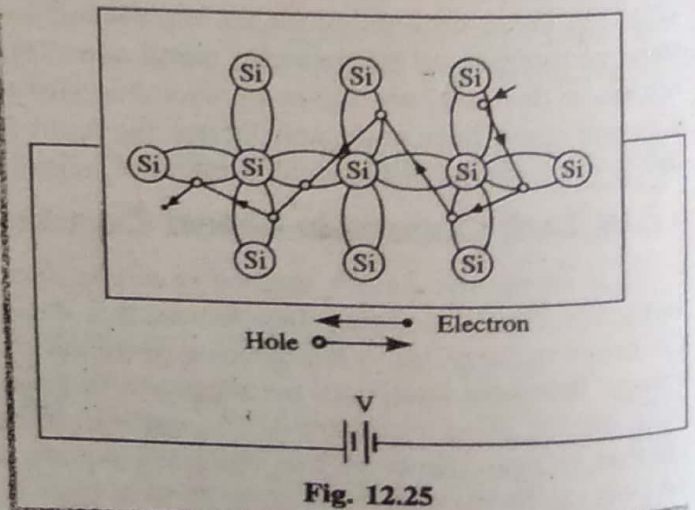


Fig. 12.25

\*  $\mu_e = \frac{V \text{ metre/second}}{E \text{ volt/metre}} = \frac{v}{E} m^2/V\text{-s}$ . This also gives the unit of mobility.