

(ii) The electrons can revolve around the nucleus only in certain permitted orbits *i.e.* orbits of certain radii are allowed.

(iii) The electrons in each permitted orbit have a certain fixed amount of energy. The larger the orbit (*i.e.* larger radius), the greater is the energy of electrons.

(iv) If an electron is given additional energy (*e.g.* heat, light etc.), it is lifted to the higher orbit. The atom is said to be in a state of *excitation*. This state does not last long, because the electron soon falls back to the original lower orbit. As it falls, it gives back the acquired energy in the form of heat, light or other radiations.

Fig. 4.1 shows the structure of silicon atom. It has 14 electrons. Two electrons revolve in the first orbit, 8 in the second orbit and 4 in the third orbit. The first, second, third orbits etc. are also known as *K, L, M* orbits respectively.

These electrons can revolve only in permitted orbits (*i.e.* orbits of \*radii  $r_1, r_2$  and  $r_3$ ) and not in any arbitrary orbit. Thus, all radii between  $r_1$  and  $r_2$  or between  $r_2$  and  $r_3$  are forbidden. Each orbit has fixed amount of energy associated with it. If an electron in the first orbit is to be lifted to the second orbit, just the \*\*right amount of energy should be supplied to it. When this electron jumps from the second orbit to first, it will give back the acquired energy in the form of electromagnetic radiations.



Niels Bohr (1885-1962)

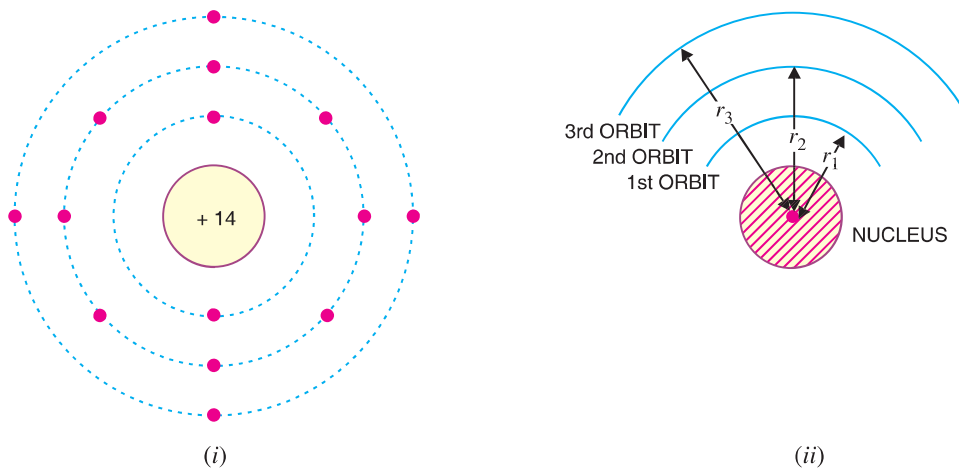


Fig. 4.1

## 4.2 Energy Levels

It has already been discussed that each orbit has fixed amount of energy associated with it. The electrons moving in a particular orbit possess the energy of that orbit. The larger the orbit, the greater is its energy. It becomes clear that outer orbit electrons possess more energy than the inner orbit electrons.

A convenient way of representing the energy of different orbits is shown in Fig. 4.2 (ii). This is known as energy level diagram. The first orbit represents the *first energy level*, the second orbit

\* The values of radii are determined from quantum considerations.

\*\* So that its total energy is equal to that of second orbit.

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indicates the *second energy level* and so on. The larger the orbit of an electron, the greater is its energy and higher is the energy level.

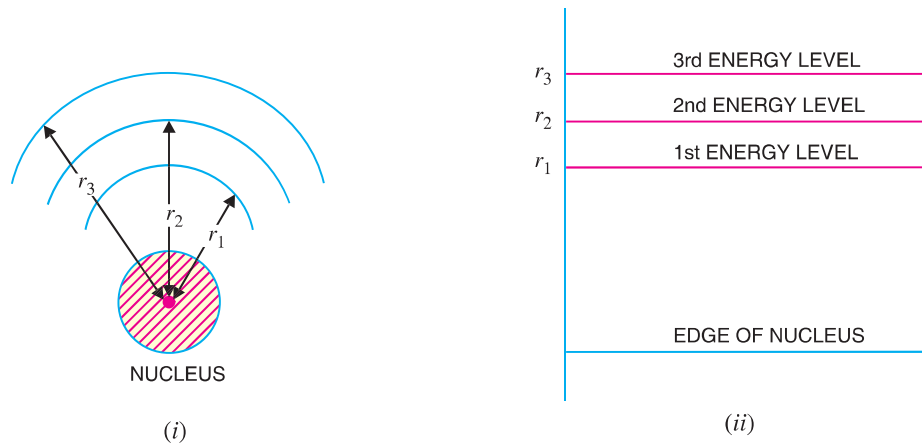


Fig. 4.2

### 4.3 Energy Bands

In case of a single isolated atom, the electrons in any orbit possess definite energy. However, an atom in a solid is greatly influenced by the closely-packed neighbouring atoms. The result is that the electron in any orbit of such an atom can have a range of energies rather than a single energy. This is known as *energy band*.

*The range of energies possessed by an electron in a solid is known as **energy band**.*

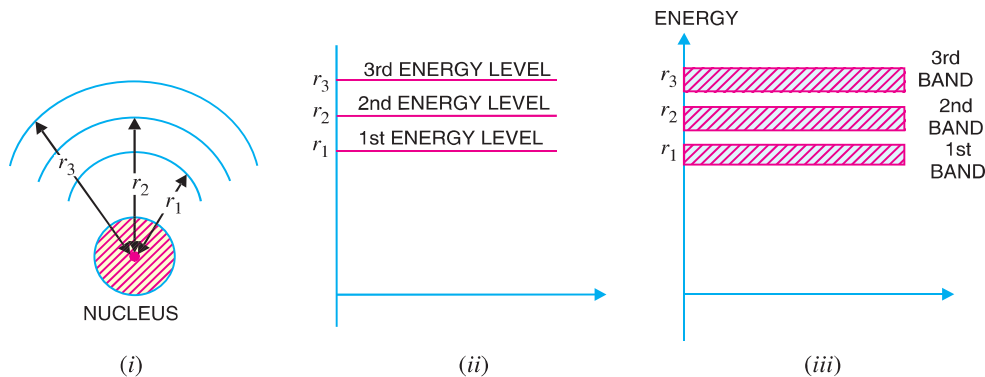


Fig. 4.3

The concept of energy band can be easily understood by referring to Fig. 4.3. Fig. 4.3 (ii) shows the energy levels of a single isolated atom of silicon. Each orbit of an atom has a single energy. Therefore, an electron can have only single energy corresponding to the orbit in which it exists. However, when the atom is in a solid, the electron in any orbit can have a range of energies. For instance, electrons in the first orbit have slightly different energies because no two electrons in this orbit see exactly the same charge environment. Since there are millions of first orbit electrons, the slightly different energy levels form a band, called 1st energy band [See Fig. 4.3 (iii)]. The electrons in the first orbit can have any energy range in this band. Similarly, second orbit electrons form second energy band and so on.

## 4.4 Important Energy Bands in Solids

As discussed before, individual  $K, L, M$  etc. energy levels of an isolated atom are converted into corresponding bands when the atom is in a solid. Though there are a number of energy bands in solids, the following are of particular importance [See Fig. 4.4] :

(i) **Valence band.** *The range of energies (i.e. band) possessed by valence electrons is known as valence band.*

The electrons in the outermost orbit of an atom are known as valence electrons. In a normal atom, valence band has the electrons of highest energy. This band may be completely or partially filled. For instance, in case of inert gases, the valence band is full whereas for other materials, it is only partially filled. The partially filled band can accommodate more electrons.

(ii) **Conduction band.** In certain materials (e.g. metals), the valence electrons are loosely attached to the nucleus. Even at ordinary temperature, some of the valence electrons may get detached to become free electrons. In fact, it is these free electrons which are responsible for the conduction of current in a conductor. For this reason, they are called *conduction electrons*.

*The range of energies (i.e. band) possessed by conduction band electrons is known as conduction band.*

All electrons in the conduction band are free electrons. If a substance has empty conduction band, it means current conduction is not possible in that substance. Generally, insulators have empty conduction band. On the other hand, it is partially filled for conductors.

(iii) **Forbidden energy gap.** *The separation between conduction band and valence band on the energy level diagram is known as forbidden energy gap.*

No electron of a solid can stay in a forbidden energy gap as there is no allowed energy state in this region. The width of the forbidden energy gap is a measure of the bondage of valence electrons to the atom. The greater the energy gap, more tightly the valence electrons are bound to the nucleus. In order to push an electron from valence band to the conduction band (i.e. to make the valence electron free), external energy equal to the forbidden energy gap must be supplied.

## 4.5 Classification of Solids and Energy Bands

We know that some solids are good conductors of electricity while others are insulators. There is also an intermediate class of semiconductors. The difference in the behaviour of solids as regards their electrical conductivity can be beautifully explained in terms of energy bands. The electrons in the lower energy band are tightly bound to the nucleus and play no part in the conduction process. However, the valence and conduction bands are of particular importance in ascertaining the electrical behaviour of various solids.

(i) **Insulators.** Insulators (e.g. wood, glass etc.) are those substances which do not allow the passage of electric current through them. In terms of energy band, the valence band is full while the conduction band is empty. Further, the energy gap between valence and conduction bands is very large ( $\approx 15$  eV) as shown in Fig. 4.5. Therefore, a very high electric field is required to push the valence electrons to the conduction band.

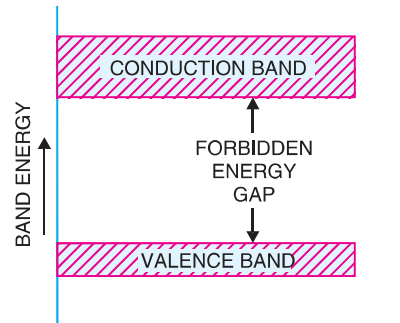


Fig. 4.4



Insulators

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For this reason, the electrical conductivity of such materials is extremely small and may be regarded as nil under ordinary conditions.

At room temperature, the valence electrons of the insulators do not have enough energy to cross over to the conduction band. However, when the temperature is raised, some of the valence electrons may acquire enough energy to cross over to the conduction band. Hence, the resistance of an insulator decreases with the increase in temperature *i.e.* an insulator has negative temperature coefficient of resistance.

**(ii) Conductors.** Conductors (*e.g.* copper, aluminium) are those substances which easily allow the passage of electric current through them. It is because there are a large number of free electrons available in a conductor. In terms of energy band, the valence and conduction bands overlap each other as shown in Fig. 4.6. Due to this overlapping, a slight potential difference across a conductor causes the free electrons to constitute electric current. Thus, the electrical behaviour of conductors can be satisfactorily explained by the band energy theory of materials.

**(iii) Semiconductors.** Semiconductors (*e.g.* germanium, silicon etc.) are those substances whose electrical conductivity lies in between conductors and insulators. In terms of energy band, the valence band is almost filled and conduction band is almost empty. Further, the energy gap between valence and conduction bands is very small as shown in Fig. 4.7. Therefore, comparatively smaller electric field (smaller than insulators but much greater than conductors) is required to push the electrons from the valence band to the conduction band. In short, a semiconductor has :

- (a) almost full valence band
- (b) almost empty conduction band
- (c) small energy gap ( $\approx 1$  eV) between valence and conduction bands.

At low temperature, the valence band is completely full and conduction band is completely empty. Therefore, a semiconductor virtually behaves as an insulator at low temperatures. However, even at room temperature, some electrons (about one electron for  $10^{10}$  atoms) cross over to the conduction band, imparting little conductivity to the semiconductor. As the temperature is increased, more valence electrons cross over to the conduction band and the conductivity increases. This shows that electrical conductivity of a semiconductor increases with the rise in temperature *i.e.* a semiconductor has negative temperature co-efficient of resistance.

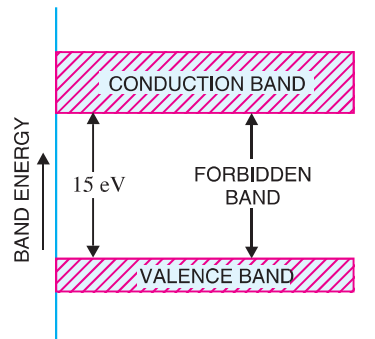


Fig. 4.5

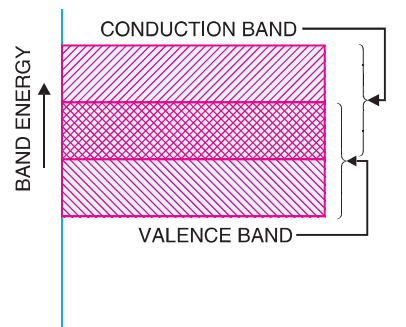


Fig. 4.6

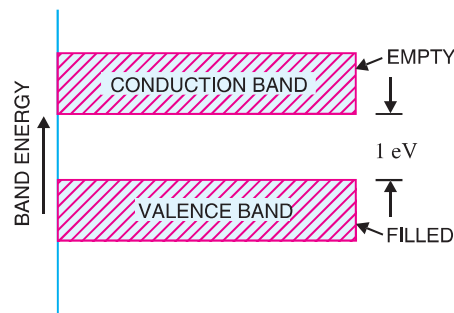


Fig. 4.7

## 4.6 Silicon

During the infancy of electronic industry, both germanium and silicon were used in the manufacture of semiconductor devices. As the electronic field advanced, it was realised that silicon was superior to germanium in many respects. Since silicon is the most widely used material in the manufacture of semiconductor devices, we shall continue to discuss the properties of this material (as compared to germanium) as and when we get the chance.

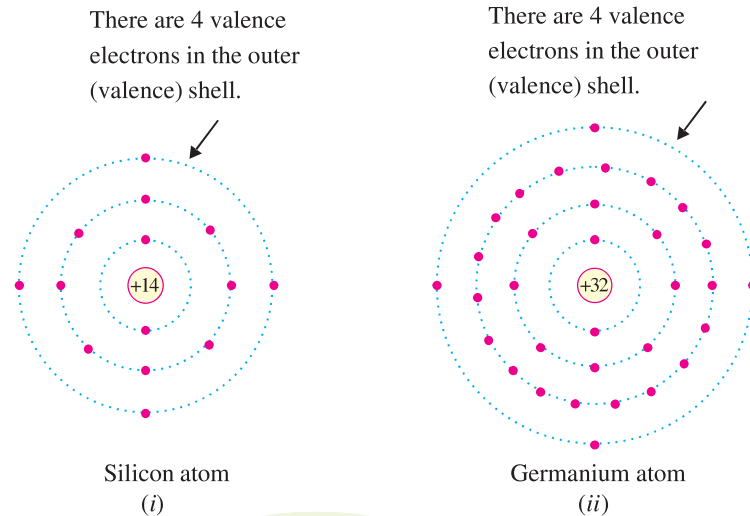


Fig. 4.8

(i) Note the atomic structure of germanium and silicon in Fig. 4.8 carefully. The valence electrons in germanium are in the fourth orbit while the valence electrons in silicon are in the third orbit; closer to the nucleus. Therefore, the germanium valence electrons are at higher energy level than those in silicon. This means that germanium valence electrons require smaller amount of additional energy to escape from the atom and become free electron. What is the effect of this property? This property makes germanium more unstable at high temperatures. This is the basic reason why silicon is widely used as semiconductor material.

(ii) Fig. 4.9 shows the energy level/band of silicon atom. The atomic number of silicon is 14 so that its 14 electrons are distributed in 3 orbits. Each energy level/band is associated with certain amount of energy and is separated from the adjacent bands by energy gap. **No electron can exist in the energy gap.** For an electron to jump from one orbit to the next higher orbit, external energy

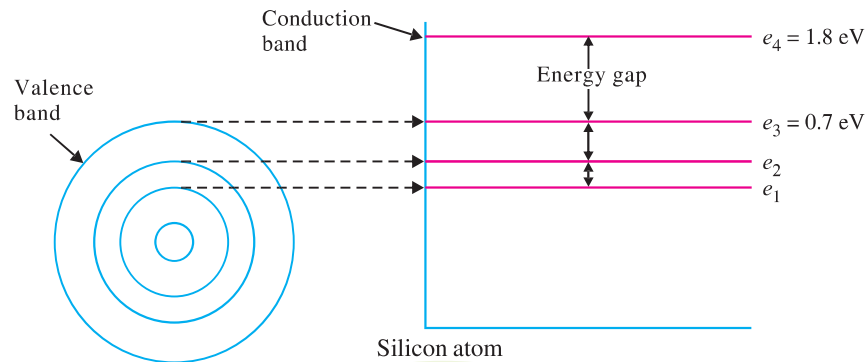


Fig. 4.9

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(e.g. heat) equal to the energy difference of the orbits must be supplied. For example, the valence band is shown to have an energy level of 0.7 eV. The conduction band is shown to have an energy level of 1.8 eV. Thus for an electron to jump from the valence band to the conduction band, an energy =  $1.8 - 0.7 = 1.1$  eV must be supplied. As you will see, the energy band description of substances is very important in understanding many fields of science and engineering including electronics.

### MULTIPLE-CHOICE QUESTIONS

- The electrons in the third orbit of an atom have ..... energy than the electrons in the second orbit.  
(i) more (ii) less  
(iii) the same (iv) none of the above
- When an electron jumps from higher orbit to a lower orbit, it ..... energy.  
(i) absorbs (ii) emits  
(iii) sometimes emits, sometimes absorbs  
(iv) none of the above
- Which of the following is quantized according to Bohr's theory of atom ?  
(i) linear momentum of electron  
(ii) linear velocity of electron  
(iii) angular momentum of electron  
(iv) angular velocity of electron
- A semiconductor has ..... band.  
(i) almost empty valence  
(ii) almost empty conduction  
(iii) almost full conduction  
(iv) none of the above
- The electrons in the conduction band are known as .....  
(i) bound electrons (ii) valence electrons  
(iii) free electrons (iv) none of the above
- In insulators, the energy gap between valence and conduction bands is .....  
(i) very large (ii) zero  
(iii) very small (iv) none of the above
- In a conductor, the energy gap between valence and conduction bands is .....  
(i) large (ii) very large  
(iii) very small (iv) none of the above
- According to Bohr's theory of atom, an electron can move in an orbit of .....  
(i) any radius  
(ii) certain radius  
(iii) some range of radii  
(iv) none of the above
- In a semiconductor, the energy gap between valence and conduction bands is about .....  
(i) 15 eV (ii) 100 eV  
(iii) 50 eV (iv) 1 eV
- The energy gap between valence and conduction bands in insulators is about .....  
(i) 15 eV (ii) 1.5 eV  
(iii) zero (iv) 0.5 eV

### Answers to Multiple-Choice Questions

- |        |          |          |         |          |
|--------|----------|----------|---------|----------|
| 1. (i) | 2. (ii)  | 3. (iii) | 4. (ii) | 5. (iii) |
| 6. (i) | 7. (iii) | 8. (ii)  | 9. (iv) | 10. (i)  |

### Chapter Review Topics

- Explain the salient features of Bohr's atomic model.
- Explain the concept of energy bands in solids.
- Describe the valence band, conduction band and forbidden energy gap with the help of energy level diagram.
- Give the energy band description of conductors, semiconductors and insulators.

### Discussion Questions

- Why is the energy of an electron more in higher orbits ?
- What is the concept of energy band ?
- Why do conduction band electrons possess very high energy ?
- Why are valence electrons of a material so important ?
- What is the difference between energy level and energy band ?