Unit I :- Chapter One :- Semiconductor Materials

The operation of electronic devices depends upon the motion of charged particles within them.

Structure of Solids

Most of the solids are crystalline in structure. It means that a solid consists of atoms or molecules arranged in a periodic manner. That is, there is always some basic arrangement of atoms which are repeated throughout the entire solid material. Such an arrangement of atoms within a solid is called <u>crystal lattice</u>.

Crystalline Structure

Amorphous structure

But there are some other solid materials which do not have crystalline structure. Such solid materials are called <u>Amorphous Solids.</u>

<u>Example of Crystalline materials</u>:- All metals and semiconductors like Silicon(Si) and Germanium(Ge).

Examples of Amorphous solid materials:- Wood, paper, glass, plastic etc.

Classification of Solid Materials

Solid materials are classified into three groups:-

(I) Conductors:-

Conductors are those materials which are good conductors of electricity. This is due to the fact that in conductors, there are large number of free electrons [or mobile charge carriers] which carry electric current. When the temperature of a conductor is increased, its resistivity increases. It means that conductors have positive temperature coefficient of resistance.

Examples:- Copper, Silver, aluminium etc.

(II) Insulators:-

Insulators are those materials which are bad conductors of electricity. In other words, they have very high resistivity. This is due to the fact that they have no charge carriers or free electrons to carry electric current.

Examples:- Rubber, Wood, plastic, glass, bakelite etc.

(III) Semiconductors:-

Semiconductors are those materials whose conductivity lies between conductors and insulators. They have poor conductivity than conductors and have higher conductivity than insulators.

When the temperature of a semiconductor is increased, its resistivity decreases or conductivity increases. It means that at higher temperature, a semiconductor conducts better. Therefore, semiconductors have negative temperature coefficient of resistance.

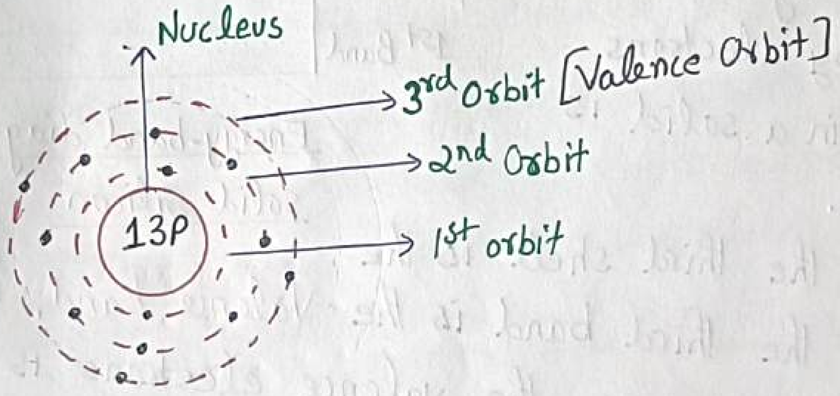
Examples:- Silicon (Si) ⇒ Atomic Number = 14

Germanium (Ge) ⇒ Atomic Number = 32

Atomic Structure of few elements:-

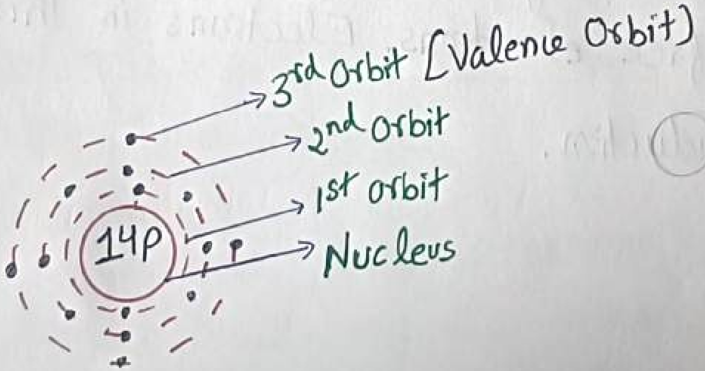
(a) **Aluminium atom**

Atomic Number → 13 = $1s^2\,2s^2\,2p^6\,3s^2\,3p^1$



(b) **Silicon atom**

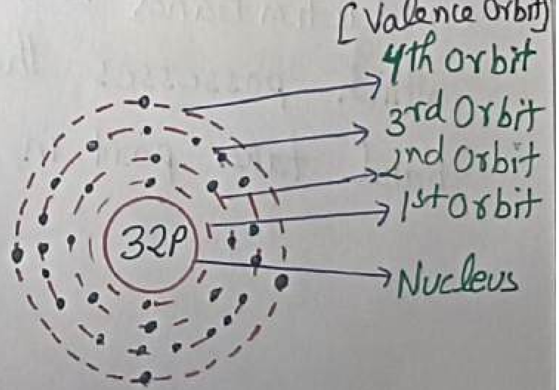
Atomic Number → 14 = $1s^2 2s^2 2p^6 3s^2 3p^2$



(c) **Germanium atom**

Atomic Number ⇒ 32

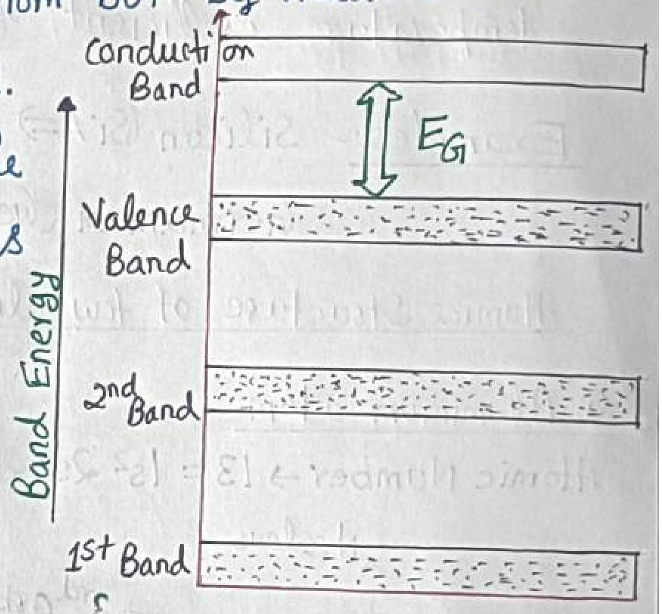
$1s^2\,2s^2\,2p^6\,3s^2\,3p^6\,4s^2\,3d^{10}\,4p^2$



Energy Bands in Solid Silicon

In a single isolated atom, the electrons revolving in any shell possess a certain amount of energy. But when atoms form a solid, the orbit of an electron is affected not only by the charges of its own atom but by nucleus and electrons of each atom in a solid.

Because of this, the electrons in the same orbits have a range of energies rather than a single energy. This is called as energy band.



Energy-band diagram of solid Silicon

In other words, the range of energies possessed by electrons of the same orbit in a solid is called energy band.

In the given figure, the third shell is the Valence shell and the third band is the Valence band. The energy band which possesses the valence electrons is called Valence band.

Conduction band is the next higher energy band level which possesses the free electrons. Electrons in this band take part in conduction.

Forbidden Energy Gap or Energy Gap [E_G]

The energy gap between the valence band and the conduction band is called forbidden energy gap or energy gap E_G.

An electron can be sent from the valence band to the conduction band if we provide some energy to the Silicon. This energy should be kept larger than or equal to energy gap, E_G. If we provide less energy than E_G, the electron will not be lifted because there is no other energy level between valence band and conduction band. Due to this reason, this energy gap E_G is called forbidden energy gap.

Note:- (a) To make the valence electrons free, some external energy through heat or light equal to the forbidden energy gap should be supplied.

(b) The forbidden energy gap E_G for Si and Ge is given as

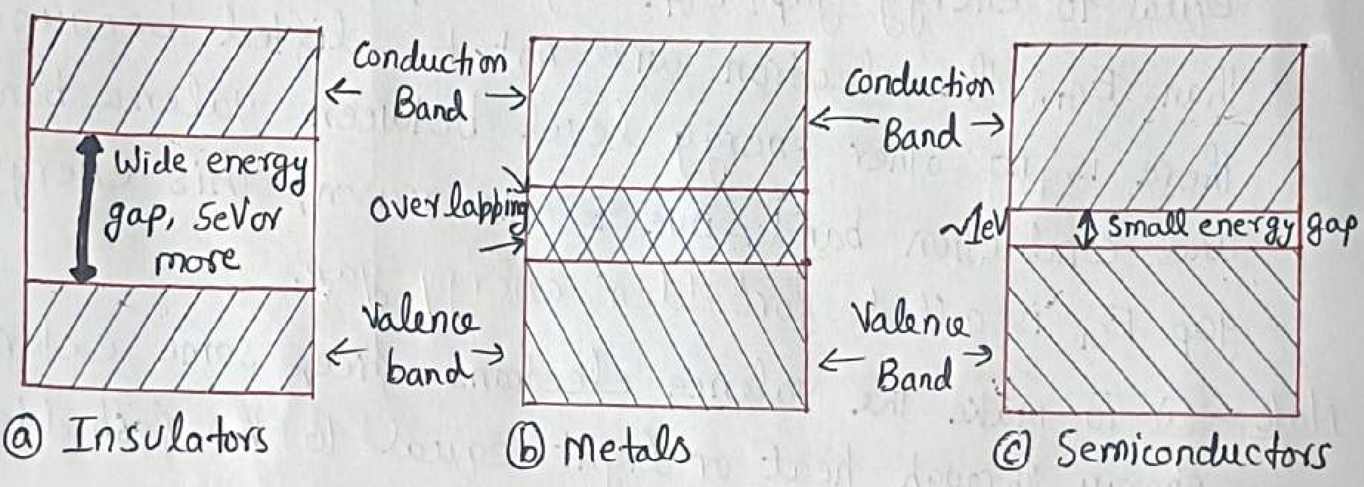
	E_G
Si →	1.12eV
Ge →	0.725eV

Insulators, Conductors and Semiconductors on the basis of Energy Band Diagram:-

(a) Insulators:-

In Insulators, there is generally no electron in the conduction band and the valence band is completely filled. It can be observed from the energy-band diagram that there is a wide energy gap between valence and conduction band. The forbidden energy gap is generally 5eV or more. Due to this wide gap, it is almost impossible for an electron to cross the gap and jump from valence band to conduction band.

Examples:- Wood, Rubber, Glass, Paper etc.



Energy band diagram

(b) Metals or Conductors :-

It can be observed that forbidden energy gap or energy gap between valence band and conduction band is zero. In fact, the valence and conduction bands overlap each other.

Examples:- Silver, Copper, Aluminium etc.

(c) Semiconductors :-

It can be observed that energy gap E_G is not very wide for semiconductors. It is 0.725eV for Ge and 1.12eV for Si.

Comparison between Conductors, Insulators and Semiconductors

S.No	Parameter of comparison	Conductors	Insulators	Semiconductors
1	Conductivity	Very high	Very Low	Moderate
2	Resistivity	Very low	Very high	Moderate
3	Forbidden Energy Gap, E_G	No (zero) energy gap	Large gap [$E_G \approx 5eV$]	Medium $E_G \approx 1eV$
4	Temperature coefficient of resistance	Positive	Negative	Negative
5	Number of electrons available for conduction	Very Large	Very Small	Moderate
6	Conductivity at room temperature	Very good	Poor	Moderate
7	Effect of temperature on resistance	R increases as T increases	R decreases as T increases	R decreases as T increases.
8	Examples	Aluminium, silver, copper	Paper, Glass, wood, rubber	Ge & Si
9	Applications	As conductors wires etc	Capacitors, insulation for wires	Semiconductor devices.

Semiconductor Materials :- Intrinsic and Extrinsic

Basically semiconductors are of two types:-

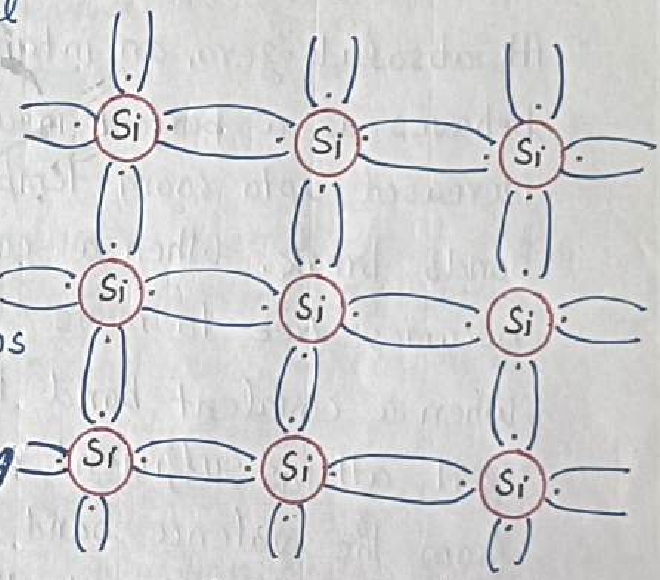
① Intrinsic Semiconductor

② Extrinsic Semiconductor

① Intrinsic Semiconductor or Pure Semiconductor :-

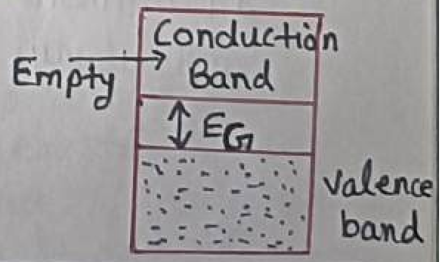
A semiconductor in an extremely pure form is known as intrinsic semiconductor. The silicon and germanium are the two most widely used intrinsic semiconductors.

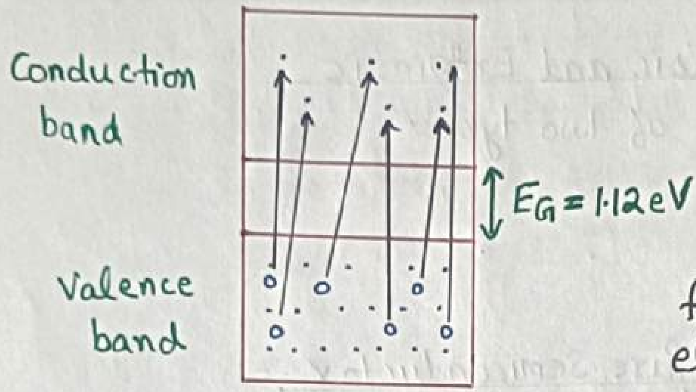
Figure shows the two dimensional crystal structure of silicon.
There are four electrons in the outermost orbit or valence shell.
Each of the four valence electrons takes part in forming covalent bonds with the four neighbouring atoms.



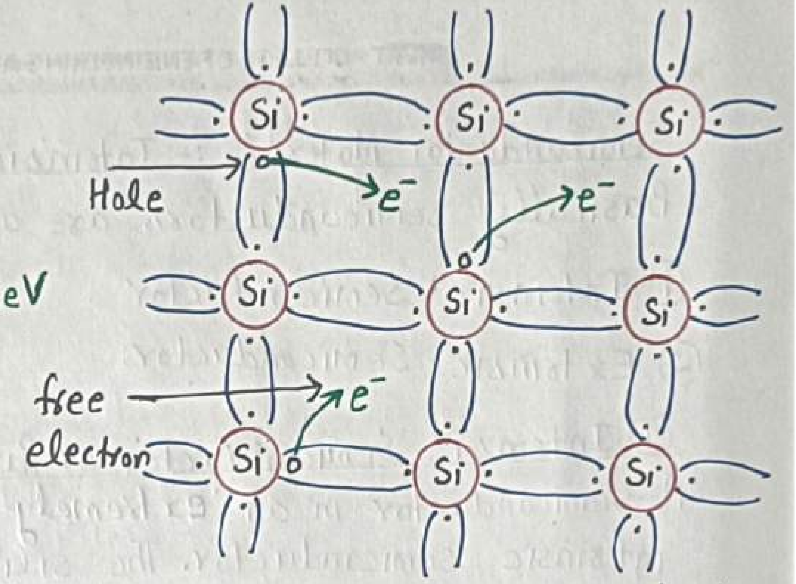
Intrinsic Semiconductor at T=0K

At a low temperature such as absolute zero (0K), all the valence electrons are tightly held by parent atoms and by covalent bonds with other atoms. So, no free electrons are available to conduct electricity. Hence, intrinsic semiconductors, at absolute zero (0K) behave as an insulator.





Energy-band diagram



Intrinsic Semiconductor at room temperature (300K).

At absolute zero, an intrinsic semiconductor behaves as a perfect insulator. But if the temperature is increased upto room temperature (300K), some covalent bonds break. When a covalent bond breaks, the electron becomes free to move through the crystal.

When a covalent bond breaks, electron becomes free and if it attains sufficient energy [more than E_G] then it jumps from the valence band to the covalent band and becomes free electron. Due to this, a deficiency is created in the valence band and this deficiency of electron is known as a hole. This means that electrons and holes are produced in pairs.

In intrinsic semiconductors, the concentration of free electrons will always be equal to the concentration of holes. i.e.

$$n_e = n_h$$

where n_e = concentration of e^-
n_h = concentration of holes.

This type of simultaneous generation of electrons and holes due to temperature is also called thermal generation.

Hence, at room temperature intrinsic semiconductor has some conductivity. These electrons and holes are also called free charge carriers because they are free to move throughout the crystal.

Whenever an electron-hole pair generates, the hole remains in the valence band and electron moves to the conduction band to take part in conduction of current.

Note:- An electron is a negatively charged particle [$q = 1.6 \times 10^{-19}$ C], the vacancy [or hole] created by this electron will be assumed as positively charged.

Recombination:-

In case of an intrinsic semiconductor, electron-hole pairs are generated due to temperature or thermal agitation. These thermally generated electrons and holes move freely throughout the crystal. Due to this, there is a possibility of collision between electrons and holes.

Whenever, there is a collision, an electron takes the position of holes and both of them disappear. This process is called recombination.

Thus, in the process of recombination, both the free electron and hole disappear and energy is released in the form of heat or light.

Carrier Life Time/ mean life time:- Before recombination, an electron or hole covers some distance or exists for a very small time. This average time of existence of an electron or hole is called mean lifetime or carrier life time. This lifetime falls in the range of $1\mu s$ to $10^3 \mu s$.

Effect of Temperature on the Conductivity of Intrinsic Semiconductor

As we know, any semiconductor [Si or Ge] acts as a perfect insulator at absolute zero [i.e. T=0K]. However, at room temperature [300K] some electron-hole pairs are produced due to thermal energy.

For example, the intrinsic carrier concentration of silicon and Germanium at 300K is $1.5 \times 10^{16}/m^3$ and 2.5×10^{19} per m^3 respectively.

This means that intrinsic semiconductor has small conductivity i.e.

$$\sigma = nq\mu,$$

$$\text{or, } \sigma = n_e q \mu_e + n_h q \mu_h$$

$$\text{or, } \sigma = n_i q \mu_e + n_i q \mu_h \qquad \{\because n_i = n_e = n_h\}$$

$$\text{or, } \boxed{\sigma_i = n_i q [\mu_e + \mu_h]}$$

where n_i = intrinsic concentration of charge carriers $= n_e = n_h$ since always equal number of $\bar{e}s$ and holes (h) are produced.

μ_e & μ_h are the mobility of $\bar{e}s$ and holes.

$$\sigma_i = 1.5 \times 10^{16} \times 1.6 \times 10^{-19} \times [1300 + 500] = 4.32 \text{ S/m}.$$

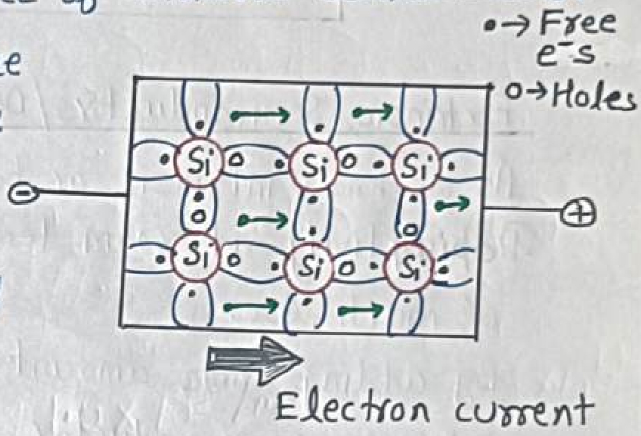
It is very low.

But if the temperature is raised further, more electron-hole pairs are produced. Hence, the higher the temperature, the higher is the concentration of charge carriers.

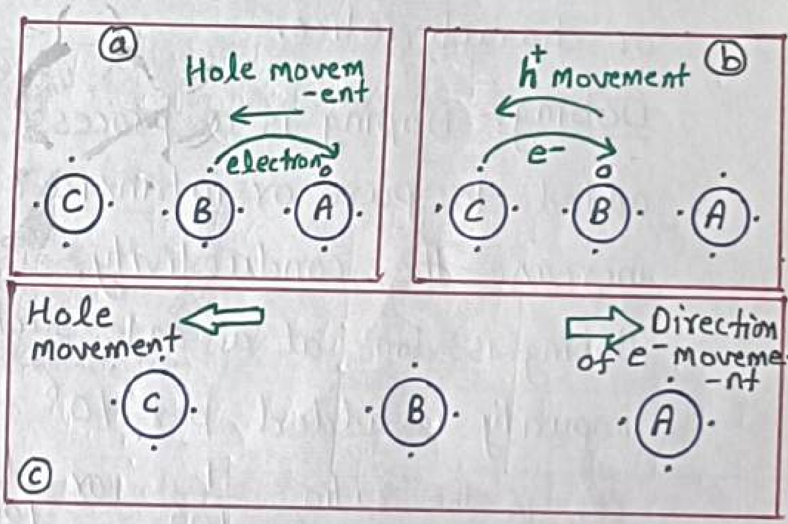
Therefore, the conductivity of the intrinsic semiconductor will increase with the increase in temperature.

Electron and Hole current in Intrinsic Semiconductor

When we apply voltage across a piece of intrinsic semiconductor material, the thermally generated free electrons in the conduction band are attracted towards the positive end. The current produced due to the movement of free electrons is called as electron current.



In figure three neighbouring silicon atoms A, B and C is shown. The covalent bonds do exist but for convenience they have not been shown. A hole exist in a broken covalent bond with atom A. A valence electron may jump from another atom B to fill up this hole as shown. When it jumps, the electron leaves a hole behind it and thus the hole has moved in the direction opposite to that of the electron. Similarly, the hole passes from atom B to atom C. The current produced due to this hole movement is called as hole current.



<u>Total current</u> ⇒ The flow of an electric current is due to the movement of electrons in the conduction band and movement of holes in the valence band. i.e.,