

SEMICONDUCTORS

INTRODUCTION

Semiconductors are materials which have electrical conductivities lying between those of good conductors and insulators. There are elemental semiconductors such as germanium and silicon which belong to group IV of the periodic table. Besides these, there are certain compound semiconductors such as gallium arsenide, indium phosphide, cadmium sulphide etc., which are formed from the combinations of the elements of group III and V, or groups II and VI. Important characteristic of the semiconductors is that they have small band gap. This property determines the wavelength of radiation which can be emitted or absorbed by the semiconductor and helps to construct devices such as light emitting diodes and lasers.

All the semiconductors have negative temperature coefficient of resistance. The importance of semiconductors is further increased due to the fact that the conductivity and the effective band gaps of these materials can be modified by the introduction of impurities which strongly affect their electronic and optical properties. The interesting feature about semiconductors is that they are bipolar and current is transported by two charge carriers of opposite sign. The number of carriers can be drastically enhanced by doping the semiconductor with suitable impurities. The doped semiconductor, which exhibits high conductivity, is called an extrinsic semiconductor. The remarkable feature of extrinsic semiconductors is that current is transported in them through two different processes, namely drift and diffusion. In this chapter we shall see the physics of semiconductors and the phenomenon that takes place in these solids.

INTRINSIC SEMICONDUCTORS

Chemically pure semiconductors in which the electrons and holes are produced by the thermal activation are called intrinsic semiconductors. Silicon and germanium serve as good examples for intrinsic semiconductors. To understand the mechanism of conduction, consider the case of silicon with atomic number 14. Each silicon atom has four valence electrons which are distributed among the outer most 's' and 'p' orbital's and can form four covalent bonds with

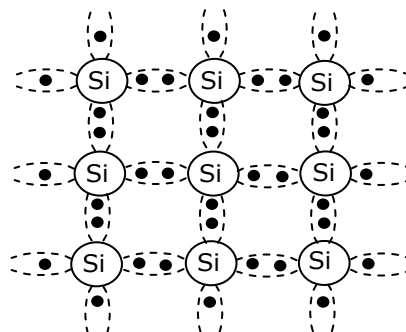


Fig. 7.1

four neighbouring silicon atoms which are directed along the corners of a regular tetrahedron. The silicon crystal exhibits a three-dimensional regular network type structure which, for simplicity, is represented by a two dimensional network as shown in the figure 7.1. All the valence electrons in a silicon crystal participate in the formation of covalent bonds and no electron is free to cause conduction particularly at 0 K. Hence pure silicon behaves as an insulator at 0 K. The energy band diagram of the intrinsic semiconductor at 0 K is shown in the figure 7.2.

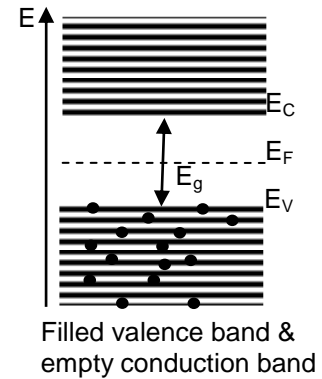


Fig. 7.2

As the temperature increases, some of the valence electrons may acquire sufficient thermal energy to break their covalent bonds and become free from the influence of cores of the atoms. The energy required to break such a covalent bond is about 0.72 eV for Germanium and 1.1 eV for Silicon. At room temperature the thermal energy is sufficient to break the covalent bonds. These electrons move randomly in the crystal and are referred to as the conduction electrons. Each escaped electron leaves behind an empty space called a hole which also acts as a current carrier. Thus when a valence electron breaks away from a covalent bond, an electron-hole pair is generated and two carriers of electricity are produced as shown in the figure 7.3.

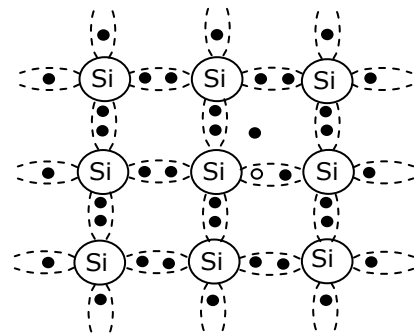


Fig. 7.3

When a valence electron located adjacent to a hole acquires sufficient energy, it may jump into the hole position to reconstruct the broken covalent bond and a hole is created at the initial position of the electron. Thus the motion of valence electron may also be regarded as the motion of a hole in the opposite direction. These electrons and holes move in opposite directions under the effect of an external electric field and constitute the current. The energy band diagram of the intrinsic semiconductor above 0 K is shown in the figure 7.4.

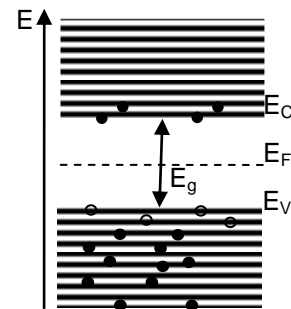


Fig. 7.4

As temperature increases, some of the valence band electrons acquire sufficient thermal energy to jump to the conduction band leaving behind an equal number of holes in the valence band.

From an energy band point of view, it means that some electrons which receive the energy equal to or more than band gap energy, are excited from the valence band to the conduction band. This band gap energy is a characteristic of the material. Thus, the band gap energy is the minimum amount of energy required to excite an electron from valence band to the conduction band. The conditions for the movement of electrons are, however, different from the conditions for movement of holes. The electrons move mainly under the influence of the applied electric field while the holes move under the combined effect of the applied field and the ionic field of the lattice. Thus the properties such as effective mass, mobility of a hole are quite different from the corresponding properties of electrons. It is now clear that, in an intrinsic semiconductor, the number of electrons n_i in the conduction band is always equal to the number of holes p_i in the valence band.

Besides the generation of free electron-hole pairs, there is another process called recombination of carriers in semiconductors. A free electron moving rapidly in a semiconductor may encounter a hole and combine with it so as to reconstruct the broken covalent bond. Thus the electron-hole pair is destroyed and the free electron is converted into the bound electron. This recombination process is equivalent to an electron jumping from the conduction band to the valence band and occurs with release of energy equal to the band gap energy in the form of electromagnetic radiations. In intrinsic semiconductor, the rate of generation of carriers depends on the temperature and nature of the material. The recombination rate depends on the concentration of electrons and holes in a material at that temperature. The two phenomena balance each other bringing about thermal equilibrium which is essentially dynamic in nature as far as carriers are concerned.

Significance of band gap E_g :

The band gap energy E_g is the minimum amount of energy required for breaking a covalent bond. It is the minimum amount of energy required to excite an electron from the valence band to the conduction band. Also, it is the minimum amount of energy required to convert a bound electron in to a free electron. The energy required to break a covalent bond in Germanium is 0.72eV at 300 K and that in Silicon it is 1.1eV.

CARRIER CONCENTRATION IN INTRINSIC SEMICONDUCTORS

At equilibrium, the number of electrons present per unit volume in the conduction band is equal to the number of holes per unit volume in the valence band. In order to calculate the

intrinsic carrier concentration, we first calculate the number of electrons excited into the conduction band at any temperature T and also the number of holes created in the valence band. The concentration of electrons and holes can be obtained from the knowledge of the densities of available states in the valence band, the conduction band as well as the Fermi-Dirac distribution function.

1) DERIVE AN EXPRESSION FOR DENSITY OF ELECTRONS IN CONDUCTION BAND IN AN INTRINSIC SEMICONDUCTOR?

The number of free electrons per unit volume in an energy range E and $E + dE$ can be written as

$$dn = D(E) f(E) dE \text{----- (1)}$$

where $D(E)$ is the density of states defined as the total number of allowed electronic states per unit volume in a semiconductor and $f(E)$ is the Fermi distribution function representing the probability of occupation of a state with energy E . The expression for $f(E)$ is given by

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{kT}\right) + 1} \text{----- (2)}$$

Where k is Boltzmann constant and T is the absolute temperature, E_F is the energy of the Fermi level. The energy corresponding to the highest occupied level at zero degree absolute is called the Fermi energy, and the energy level is referred to as the Fermi level.

Under thermal equilibrium the free electrons acquire energy obeying a statistical rule known as Fermi-Dirac statistics. Fermi-Dirac statistics is applicable to the assembly of particles which obey Pauli's exclusion principle. They must also be identical particles of spin $1/2$ and are indistinguishable. Since electrons satisfy these conditions, they obey Fermi-Dirac statistics. Fermi-Dirac statistics permits the evaluation of probability of finding electrons occupying energy levels in a certain energy range.

The expression for $D(E)$ is given by

$$D(E) = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \text{----- (3)}$$

Using (2) & (3) in (1), one obtains

$$dn = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} f(E) dE \text{ ----- (4)}$$

An electron occupying an energy state E in the conduction band possesses the kinetic energy $(E - E_C)$. E_C is the energy corresponding to the bottom edge of the conduction band. Hence E must be replaced by $(E - E_C)$ in the expression for dn .

$$dn = \frac{4\pi}{h^3} (2m_n^*)^{3/2} (E - E_C)^{1/2} \frac{1}{\exp\left(\frac{E - E_F}{kT}\right) + 1} \text{ ----- (5)}$$

Where m_n^* is the effective mass of the electron in the conduction band. The concentration of electrons n in the conduction band is obtained by integrating equ. (5) from $E = E_C$ to $E = \infty$. As the probability of electrons occupying upper levels of conduction band approaches zero for higher energies, the upper limit, namely the top of conduction band is taken as ∞ .

When a metal is subjected to the influence of an electric field, a free electron in the metal moves under the combined influence of the applied electric field and that of a periodic potential due to lattice ions. Because of such a superposed effect, the electron responds as if it possesses a mass called effective mass which is different from its true mass with which it is accounted if it were to be under the influence of external field alone.

$$n = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \int_{E_C}^{\infty} \frac{(E - E_C)^{1/2} dE}{\exp\left(\frac{E - E_F}{kT}\right) + 1}$$

Near room temperature, $kT \cong 0.026 \text{ eV}$. For energies greater than E_C ,

$$1 + \exp\left(\frac{E - E_F}{kT}\right) \cong \exp\left(\frac{E - E_F}{kT}\right)$$

$$n = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \int_{E_C}^{\infty} (E - E_C)^{1/2} \exp\left[-\left(\frac{E - E_F}{kT}\right)\right] dE$$

$$n = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \exp\left(\frac{E_F - E_C}{kT}\right) \int_{E_C}^{\infty} (E - E_C)^{1/2} \exp\left[-\left(\frac{E - E_C}{kT}\right)\right] dE$$

$$\text{Let } \frac{E - E_C}{kT} = x$$

$$dE = kT dx$$

For $E = E_C$, $x = 0$

$$n = \frac{4\pi}{h^3} (2m_n^*)^{3/2} \exp\left(\frac{E_F - E_C}{kT}\right) \int_0^\infty x^{1/2} (kT)^{1/2} e^{-x} kT dx$$

$$n = \frac{4\pi}{h^3} (2m_n^* kT)^{3/2} \exp\left(\frac{E_F - E_C}{kT}\right) \int_0^\infty x^{1/2} e^{-x} dx$$

$$\int_0^\infty x^{1/2} e^{-x} dx = \left(\frac{\pi}{4}\right)^{1/2}$$

$$n = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} \exp\left[-\left(\frac{E_C - E_F}{kT}\right)\right]$$

From equ. (2), the probability of occupancy of level E_C is given by

$$f(E_C) = \frac{1}{\exp\left(\frac{E_C - E_F}{kT}\right) + 1} \cong \exp\left[-\left(\frac{E_C - E_F}{kT}\right)\right]$$

Therefore, equation for n becomes

$$n = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2} f(E_C)$$

The first term on the right hand side must represent the effective density of states of electrons at the conduction band edge. Denoting it by N_C , we have

$$n = N_C \exp\left[-\left(\frac{E_C - E_F}{kT}\right)\right]$$

Where

$$N_C = 2 \left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

This is the expression for the density of electrons in conduction band.

2) DERIVE AN EXPRESSION FOR DENSITY OF HOLES IN VALENCE BAND IN AN INTRINSIC SEMICONDUCTOR?

The number of holes per unit volume in the energy range E and $E + dE$ can be written as

$$dp = D(E)[1 - f(E)] dE \text{----- (1)}$$

where $D(E)$ is the density of states.

$f(E)$ is the Fermi distribution function representing the probability of occupation of a state with energy E . The expression for $f(E)$ is given by

$$f(E) = \frac{1}{\exp\left(\frac{E - E_F}{kT}\right) + 1} \text{----- (2)}$$

Where k is Boltzmann constant and T is the absolute temperature, E_F is the energy of the Fermi level. The energy corresponding to the highest occupied level at zero degree absolute is called the Fermi energy, and the energy level is referred to as the Fermi level.

If $f(E)$ is the probability for the occupancy of an energy state at E by an electron, then the probability that the energy state is not occupied by an electron i.e., vacant is given by $\{1 - f(E)\}$. Since a hole represents a vacant state in the valence band, the probability for the occupancy of a state E by a hole is equal to the probability of absence of an electron at that state which is $\{1 - f(E)\}$.

$$1 - f(E) = 1 - \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)} = 1 - \left[1 + \exp\left(\frac{E - E_F}{kT}\right)\right]^{-1}$$

Since $(E - E_F) \gg kT$

$$\left[1 + \exp\left(\frac{E - E_F}{kT}\right)\right]^{-1} = 1 - \exp\left(\frac{E - E_F}{kT}\right) + \dots$$

$$1 - f(E) = \exp\left(\frac{E - E_F}{kT}\right)$$

It follows that the probability of finding holes decreases exponentially with increase in depth into the valence band. The kinetic energy of a hole in the energy state E in the valence band is $(E_V - E)$. The density of states per unit volume in the valence band can be written as

$$D(E) = \frac{4\pi}{h^3} (2m_p^*)^{3/2} (E_V - E)^{1/2}$$

Where m_p^* is the effective mass of a hole in the valence band. Equ (1) can be written as

$$dp = \frac{4\pi}{h^3} (2m_p^*)^{3/2} (E_V - E)^{1/2} \exp\left(\frac{E - E_F}{kT}\right) dE$$

Taking the top of the valence band energy as reference, the holes can have any lower energy value i.e., up to $-\infty$. If E_V is the energy corresponding to the top of the Valence band, the number of holes in the valence band can be calculated by integrating the above equation from $-\infty$ to the energy corresponding to top of the Valence band E_V . Then

$$p = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \int_{-\infty}^{E_V} (E_V - E)^{1/2} \exp\left(\frac{E - E_F}{kT}\right) dE$$

$$p = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \int_{-\infty}^{E_V} (E_V - E)^{1/2} \exp\left(\frac{E - E_V}{kT}\right) dE$$

$$\text{Let } \frac{E_V - E}{kT} = x$$

$$dE = -kT dx$$

$$\text{For } E = E_V, x = 0$$

$$p = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \int_{\infty}^0 (x)^{1/2} (kT)^{1/2} e^{-x} (-kT) dx$$

$$p = \frac{4\pi}{h^3} (2m_p^*)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) (kT)^{3/2} \int_{\infty}^0 (x)^{1/2} e^{-x} dx$$

$$p = \frac{4\pi}{h^3} (2m_p^* kT)^{3/2} \exp\left(\frac{E_V - E_F}{kT}\right) \left(\frac{\pi}{4}\right)^{1/2}$$

$$p = 2 \left(\frac{2\pi m_p^* kT}{h^2} \right)^{3/2} \exp\left[-\left(\frac{E_F - E_V}{kT}\right)\right]$$

$$p = N_V \exp \left[- \left(\frac{E_F - E_V}{k T} \right) \right]$$

where

$$N_V = 2 \left(\frac{2 \pi m_p^* k T}{h^2} \right)^{3/2}$$

The above equation represents the effective density of holes at the valence band edge.

INTRINSIC CARRIER CONCENTRATION

A single event of bond breaking in a pure semiconductor leads to generation of an electron-hole pair. At any temperature T , the number of electrons generated will be equal to the number of holes generated. Since in an intrinsic semiconductor the number of electrons and holes are equal $n = p = n_i$ where n_i is called the intrinsic carrier concentration.

$$n_i^2 = n p = 2 \left(\frac{2 \pi m_n^* k T}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_F - E_C}{k T} \right) \right] \times 2 \left(\frac{2 \pi m_p^* k T}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_V - E_F}{k T} \right) \right]$$

$$n_i^2 = 4 \left(\frac{2 \pi k T}{h^2} \right)^3 (m_n^* m_p^*)^{3/2} \exp \left[\left(\frac{E_V - E_C}{k T} \right) \right]$$

$$n_i^2 = 4 \left(\frac{2 \pi k T}{h^2} \right)^3 (m_n^* m_p^*)^{3/2} \exp \left[\left(\frac{-E_g}{k T} \right) \right]$$

where $E_g = E_C - E_V$ is the band gap energy.

Therefore, the intrinsic carrier concentration is given by

$$n_i = 2 \left(\frac{2 \pi k T}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} \exp \left[\left(\frac{-E_g}{2 k T} \right) \right]$$

VARIATION OF INTRINSIC CARRIER CONCENTRATION WITH TEMPERATURE

The intrinsic carrier concentration is given by

$$n_i = 2 \left(\frac{2 \pi k T}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} \exp \left[\left(\frac{-E_g}{2 k T} \right) \right]$$

$$n_i = 2 \left(\frac{2 \pi k}{h^2} \right)^{3/2} (m_n^* m_p^*)^{3/4} T^{3/2} \exp \left[\left(\frac{-E_g}{2 k T} \right) \right]$$

The following important points may be inferred from the above relation.

- 1) The intrinsic carrier concentration is independent of Fermi level.
- 2) The intrinsic carrier concentration has an exponential dependence on the band gap value E_g .
- 3) It strongly depends on the temperature.
- 4) The factor 2 in the exponent indicates that two charge carriers are produced for one covalent bond broken.

FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

We know that in intrinsic semiconductor the density of electrons in the conduction band is equal to the density of holes in the valence band. i.e., $n = p$.

$$2 \left(\frac{2 \pi m_n^* k T}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_F - E_C}{k T} \right) \right] = 2 \left(\frac{2 \pi m_p^* k T}{h^2} \right)^{3/2} \exp \left[\left(\frac{E_V - E_F}{k T} \right) \right]$$

Cancelling the like terms on either side we get

$$(m_n^*)^{3/2} \exp \left[\left(\frac{E_F - E_C}{k T} \right) \right] = (m_p^*)^{3/2} \exp \left[\left(\frac{E_V - E_F}{k T} \right) \right]$$

Rearranging the terms in both sides

$$\exp \left(\frac{2 E_F - E_C - E_V}{k T} \right) = \frac{(m_p^*)^{3/2}}{(m_n^*)^{3/2}}$$

Taking logarithms on both sides, we get

$$\frac{2 E_F}{k T} = \frac{3}{2} \ln \frac{m_p^*}{m_n^*} + \frac{(E_V + E_C)}{k T}$$

$$E_F = \frac{3KT}{4} \ln \frac{m_p^*}{m_n^*} + \frac{(E_v + E_c)}{2}$$

If the effective mass of a free electron is assumed to be equal to the effective mass of a hole

$$m_p^* = m_n^* \Rightarrow \ln \frac{m_p^*}{m_n^*} = 0 \Rightarrow E_F = \frac{E_c + E_v}{2}$$

$$E_F = \frac{E_c - E_v}{2} + E_v \Rightarrow E_F = \frac{E_g}{2} + E_v$$

If we denote the top of the valence band as zero level, $E_v = 0$.

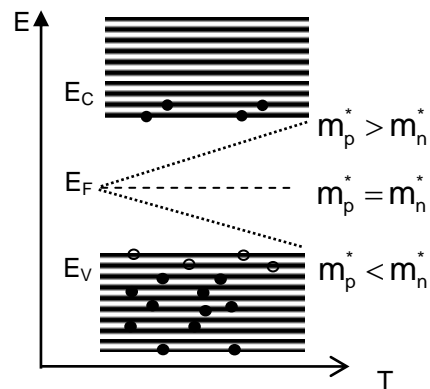
$$E_F = \frac{E_g}{2}$$

The above result shows that in an intrinsic semiconductor, the Fermi level lies in the middle of the forbidden gap.

An important point to be noted here is that the Fermi level is not an allowed energy level in semiconductors. It only serves as a reference energy with reference to which we specify the energies of electrons and holes in a semiconductor.

Variation of Fermi level with temperature in an intrinsic semiconductor :

With an increase in temperature, the Fermi level gets displaced upward to the bottom edge of the conduction band if $m_p^* > m_n^*$ or downward to the top edge of the valence band if $m_p^* < m_n^*$ as shown. In most of the materials, the shift of Fermi level on account of $m_p^* \neq m_n^*$ is insignificant. The Fermi level in an intrinsic semiconductor may be considered as independent of temperature and as staying in the middle of the band gap.



LIMITATIONS OF INTRINSIC SEMICONDUCTOR

1) Conductivity is low. For example, Germanium has a conductivity which is nearly 10^7 times smaller than that of copper.

- 2) Conductivity is a function of temperature and increases exponentially as the temperature increases.
- 3) Conductivity cannot be controlled from outside.

EXTRINSIC SEMICONDUCTORS

Due to the poor conductivity of intrinsic semiconductors at room temperature, these are not useful as such in the electronic devices. This necessitates the increase in conductivity of the semiconductor.

Without approaching larger temperatures, we can increase the conducting capability by adding some impurities to the intrinsic semiconductor. It makes the current more voltage dependent than temperature dependent. This process of **controlled addition of impurities to the intrinsic semiconductor is called doping and the impurities added are referred to as dopants. This semiconductor with impurities in it is called an extrinsic semiconductor.**

The amount of impurity added is extremely small. This doping is done during crystallization process. The impurity atoms are nearly of the same size as semiconductor atoms and easily substitute themselves in place of the host atoms in the semiconductor crystal. Thus, they are substitutional impurities and do not cause any distortion in the original structure.

Advantages of extrinsic semiconductors: (1) Conduction is high (2) Conductivity can be varied to the desired value through the control of doping concentration (3) Conductivity is not a function of temperature.

Based on the type of impurities added, the extrinsic semiconductors are classified into two types; p-type and n-type.

n-TYPE SEMICONDUCTORS

When some pentavalent (group – V) impurity atoms such as As, Sb, P, Bi, are added to an intrinsic semiconductor (Si or Ge), then we get an n-type semiconductor. These pentavalent impurities donate electrons to the host crystal and hence referred to as donor impurities.

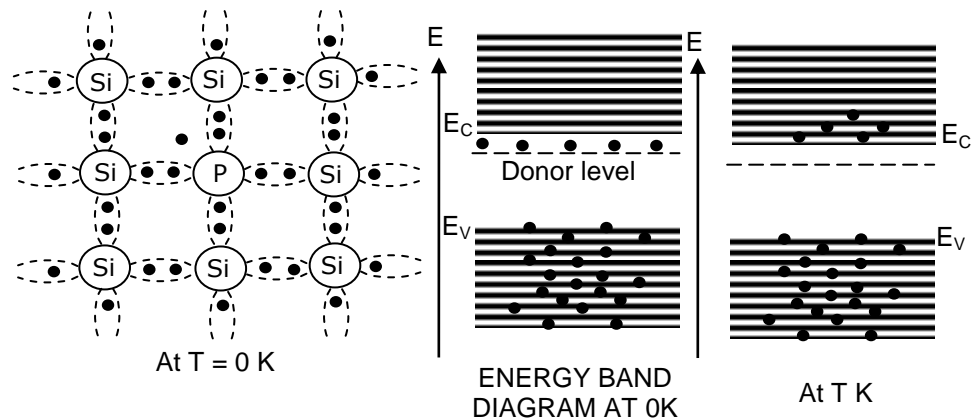
Let us explain the changes in the band structure of an intrinsic semiconductor when doped with a pentavalent impurity with an example.

Silicon has four valence electrons and phosphorous has five valence electrons. When silicon is doped with phosphorous atoms, each phosphorous atom gets locked into the crystal by forming covalent bonds with the surrounding silicon atoms.

The fifth electron of the phosphorous is left alone which is loosely bound to the phosphorous atom at 0K. The ground state energy of this fifth electron lies just below the conduction band of silicon and is called the donor level.

The number of states in this level is equal to the number of phosphorous atoms per unit volume of the materials.

At 0K, the fifth electron of phosphorous occupies these states.



The ionization energy of the fifth electron is very small. It is found to be 0.045 eV. The ionization energy is so small that the thermal energy can easily liberate the fifth electron from the nucleus. If we raise the temperature of the material slightly, then this fifth electron gets excited easily to the conduction band. Now these electrons will participate in conduction. Thus, every phosphorus atom contributes one conduction electron without any generation of holes in the valence band. As a result of this doping process, the number of electrons in the conduction band far exceeds the number of holes in the valence band of an n-type semiconductor. Thus, in an n-type semiconductor, the majority carriers are electrons and the minority carriers are holes.

p-TYPE SEMICONDUCTORS

A p-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent impurities such as, B, Al, Ga, In, etc. These trivalent impurities accept electrons from the host crystal and thus are referred to as acceptor impurities.

Let us now discuss the phenomenon that happens when a trivalent impurity is added to an intrinsic semiconductor with a suitable example.

When a trivalent impurity atom substitutes a host silicon atom, its three valence electrons enter the covalent bonds with the neighboring three silicon atoms while the fourth bond is not completed due to the deficiency of one electron. Thus the trivalent impurity atom has a tendency to accept one electron from a neighbouring silicon atom to complete the fourth bond. This process requires a small amount of energy which is easily provided by the thermal agitation in the crystal. The transferred electron leaves behind a broken covalent bond, i.e., a hole, which acts as a current carrier.

The boron atoms introduce an energy level just above the valence band in the energy gap of the silicon crystal. This energy level is called acceptor level since it readily accepts the electrons from the valence band.

Any stray electron in the vicinity can be trapped by this hole and the boron atom thereafter becomes negatively charged. The region from which the electron has come becomes positively charged.

This process will introduce number of holes in the valence band without simultaneous generation of

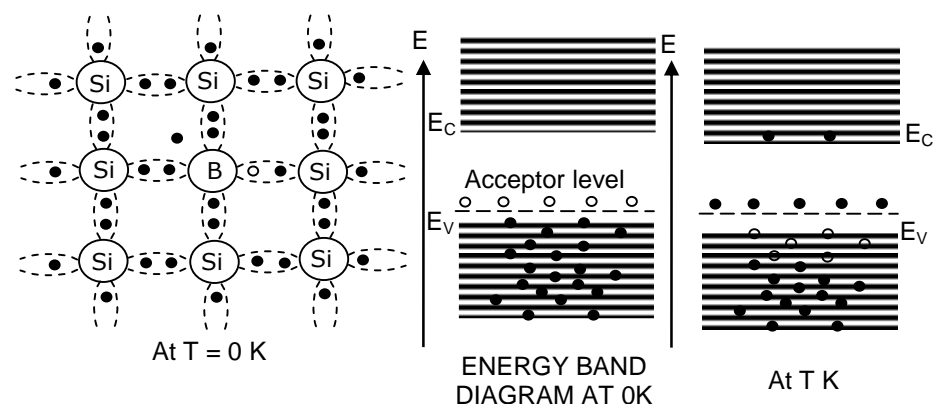
electrons in the conduction band.

Thus, in p-type semiconductor,

holes are majority carriers and the electrons are

minority carriers. It may also be noted

that in either type of semiconductors, the overall charge neutrality is maintained as no charge is added to or removed from the material.



3) DISTINGUISH BETWEEN INTRINSIC AND EXTRINSIC SEMICONDUCTORS ?

Intrinsic semiconductor	Extrinsic semiconductor
1) It is a pure material	It is an impure material, obtained by adding a group III or group V element as dopant into an intrinsic semiconductor
2) It behaves as an insulator at 0K	It behaves as an insulator at 0K
3) At normal temperatures, the conductivity is low	At normal temperatures, the conductivity is high
4) Carrier generation is due to breaking of covalent bonds	Carrier generation is due to ionization of impurity atoms forming majority carriers and breaking of covalent bonds forming minority carriers
5) Current carriers i.e., electrons and holes are equal in number	Current carriers are essentially majority carriers at normal temperatures
6) Fermi level lies at the centre of the forbidden energy gap at all temperatures	At 0K, the Fermi level lies close to the conduction band in n-type semiconductors and close to the valence band in p-type semiconductors. The Fermi level moves towards the centre of the band gap as the temperature increases
7) Hall coefficient is negative due to higher mobility of electrons	Hall coefficient is negative for an n-type semiconductor and positive for a p-type semiconductor

4) Derive an expression for the density of electrons in the conduction band for an n-type semiconductor ?

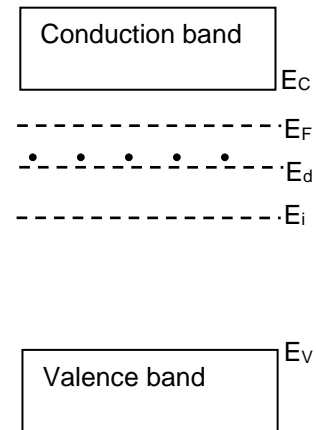


Fig. 7.10

The energy level diagram for an n-type semiconductor is shown in the figure 7.10. At 0 K all the donors are in the unionized state i.e., all the donor levels are occupied with electrons. As the temperature increases slightly, some of the donors get ionized and contribute to the conduction band. Also some of the valence band electrons may jump to the conduction band leaving behind holes in the valence band. The number of holes produced in this process is quite small. Therefore, the Fermi level must lie somewhere near the middle of the donor level and the bottom of the conduction band. We determine the equilibrium carrier concentration at a temperature T . Let there be N_D donors per unit volume occupying the donor levels with energy E_D . Assuming that E_F lies more than few kT below the conduction band, the electron concentration in the conduction band is given by

$$n = N_C \exp \left[- \left(\frac{E_C - E_F}{kT} \right) \right]$$

The electron concentration must be equal to the sum of the concentration of ionized donors, N_D^+ in the donor levels and the concentration of thermally generated holes in the valence band.

$$n = N_D^+ + p \text{ ----- (7.9)}$$

If a sufficient number of donors are present to produce electrons in the conduction band, the concentration of thermally generated holes may be neglected. Equation (7.9) becomes

$$n = N_D^+ \text{ ----- (7.10)}$$

The concentration of ionized donors = Concentration of donors – concentration of unionized donors

$$\text{i.e., } N_D^+ = N_D - N_D^0 \text{ ----- (7.11)}$$

where N_D^0 is the number of atoms left unionized at the energy level E_D .

The concentration of unionized donors can be expressed in the following way

The concentration of unionized donors = Concentration of donors \times Probability of Donor possessing the energy E_D

$$\text{i.e., } N_D^0 = N_D f(E_D) \text{ -----(7.12)}$$

Where $f(E_D)$ is the probability that a donor atom possess the energy E_D , being given by Fermi-Dirac distribution function as

$$f(E_D) = \frac{1}{1 + \exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}} \text{ -----(7.13)}$$

$$\therefore N_D^+ = N_D - N_D f(E_D)$$

The concentration of ionized donors is calculated as

$$N_D^+ = N_D [1 - f(E_D)] = N_D \left[1 - \frac{1}{1 + \exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}} \right]$$

$$N_D^+ = N_D \left[\frac{\exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}}{1 + \exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}} \right] = N_D \exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}$$

We have neglected the exponent term in the denominator assuming that E_F lies more than a few $k T$ above E_D . Substituting the expressions for n and N_D^+ in (7.10), we obtain

$$n = N_C \exp\left[-\left(\frac{E_C - E_F}{k T}\right)\right] = N_D \exp\left\{-\left(\frac{E_F - E_D}{k T}\right)\right\}$$

$$\ln N_C - \left(\frac{E_C - E_F}{k T}\right) = \ln N_D - \left(\frac{E_F - E_D}{k T}\right)$$

$$-\left(\frac{E_C - E_F}{k T}\right) + \left(\frac{E_F - E_D}{k T}\right) = \ln N_D - \ln N_C$$

$$E_F = \frac{E_D + E_C}{2} + \frac{k T}{2} \ln\left(\frac{N_D}{N_C}\right)$$

This expression gives the position of the Fermi level at moderate temperatures. This equation is not valid for $T = 0 K$ (Since N_C varies as $T^{3/2}$) and for $T \rightarrow \infty$ (at high T assumption of suppressing holes does not hold good). The only valid information obtainable from this equation

is that Fermi level lies somewhere near the middle of the donor level and the conduction band edge at moderate temperatures. As T increases, the Fermi level moves downwards and crosses the donor level. For sufficiently large temperatures, it drops to $\frac{E_g}{2}$. This means Fermi level coincides with the intrinsic level E_i . The extrinsic semiconductor behaves like an intrinsic semiconductor.

The free electron concentration in the conduction band is obtained by substituting the value of E_F in the expression for electron concentration in the conduction band

$$n = N_C \exp \left[\left(\frac{E_D - E_C}{2 k T} \right) \right] + \frac{1}{2} \ln \left(\frac{N_D}{N_C} \right)$$

$$n = N_C \left(\frac{N_D}{N_C} \right)^{1/2} \exp \left(\frac{E_D - E_C}{2 k T} \right)$$

$$n = (N_D N_C)^{1/2} \exp \left(\frac{E_D - E_C}{2 k T} \right)$$

$$n = (N_D N_C)^{1/2} \exp \left(\frac{-\Delta E}{2 k T} \right)$$

where $\Delta E = E_C - E_D$ represents the ionization energy of donors. This shows that the carrier concentration at moderate temperatures varies as $\sqrt{N_D}$.

5) Derive an expression for the density of holes in the valence band for a p-type semiconductor ?

The energy level diagram for a p-type semiconductor is shown in the figure 7.11. The acceptor impurity atoms occupy the acceptor levels E_a which lie above the valence band.

For $T > 0 K$, a part of these acceptors is ionized by acquiring electrons from the valence band, thus creating holes in the valence band which cause p-type conduction. Apart from these holes, some thermally generated holes are also present in the valence band. If n, p, N_a and N_a^- represent electron concentration in the conduction band, hole concentration in the valence band, total acceptor concentration and concentration of ionized acceptors respectively,

then

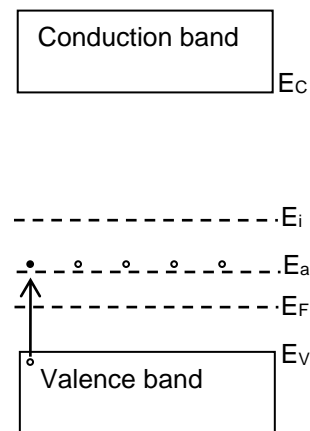


Fig. 7.11

$p = n + N_a^-$. Neglecting n in comparison with N_a^- for a p-type semiconductor, we get $p \cong N_a^-$.

The concentration of ionized acceptors

= Concentration of acceptors \times Probability of an acceptor being ionized

= Concentration of acceptors \times Probability of an electron excited to acceptor levels E_a

$$= N_a f(E_a)$$

The concentration of ionized acceptors is given by

$$N_a^- = N_a f(E_a) = \frac{N_a}{1 + \exp\left(\frac{E_a - E_F}{k T}\right)}$$

Assuming $(E_a - E_F)$ to be large as compared to $k T$, the above equation can be written as,

$$N_a^- \cong N_a \exp\left(\frac{E_F - E_a}{k T}\right)$$

The hole concentration in the valence band is given by,

$$p = N_V \exp\left[-\left(\frac{E_F - E_V}{k T}\right)\right]$$

Using expressions for n and N_a^- and in $p \cong N_a^-$, we obtain

$$N_V \exp\left[-\left(\frac{E_F - E_V}{k T}\right)\right] = N_a \exp\left(\frac{E_F - E_a}{k T}\right)$$

The above equation on simplification gives

$$E_F = \frac{E_a + E_V}{2} - \frac{k T}{2} \ln\left(\frac{N_a}{N_V}\right)$$

This expression gives the position of the Fermi level at moderate temperatures. The Fermi level lies near the middle of the acceptor level and the top of the valence band. It moves upwards with increase in temperature and finally coincides with the intrinsic level. The expression is not valid at very high temperatures where n can not be neglected.

The hole concentration in the valence band is obtained by substituting the value of E_F into the expression for p .

$$p = N_V \exp \left[\frac{E_V - E_a}{2 k T} + \frac{1}{2} \ln \left(\frac{N_a}{N_V} \right) \right]$$

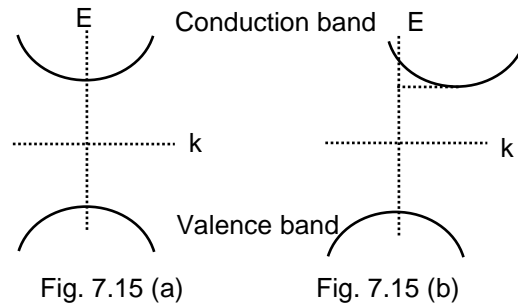
$$p = N_V \left(\frac{N_a}{N_V} \right)^{1/2} \exp \left[\frac{E_V - E_a}{2 k T} \right]$$

$$p = (N_a N_V)^{1/2} \exp \left[\frac{E_V - E_a}{2 k T} \right]$$

The above equation represents the concentration of carriers in a p-type semiconductors.

DIRECT & INDIRECT BAND GAP SEMICONDUCTORS

The energy band diagrams which we have used to describe semiconductors are too simplified and are not sufficient to explain the behaviour of semiconductors. For example, the recombination process is dependent not only on the presence of electron-hole pairs but also requires the conservation of momentum. The energy and momentum distribution of carriers may be explained using band diagrams in k-space. These



are called E-k diagrams. Figure 7.15 shows typical E-k diagrams. The forbidden energy gap for this semiconductor will be the energy difference between the valence band maximum and the conduction band minimum. If these two extreme points lie at the same k-value, the semiconductor is said to be a direct band gap semiconductor. If the valence and conduction band edges do not lie at the same value of k, the semiconductor is called indirect band gap semiconductor.

Silicon and germanium are indirect band gap semiconductors, whereas gallium arsenide is an example of direct band gap semiconductor. In the case of a direct band gap semiconductor, when an energy equal to the band gap energy is supplied, a direct transition of an electron from the valence band maximum to the conduction band minimum can occur. In case of an indirect band gap semiconductor, in addition to the energy requirement, a transition can occur only with the assistance of a phonon (lattice vibration).

6) Distinguish between direct and indirect bandgap semiconductors ?

	Direct band gap semiconductors	Indirect band semiconductors
1	Valence band maximum and conduction band minimum are located at the same momentum (k) value.	Valence band maximum and conduction band minimum are not located at the same momentum (k) value.
2	The electron can make transition from valence band to conduction band without any change in momentum.	The transition involves a change in momentum
3	A photon of energy $h\nu = E_g$ can excite an electron from the valence band to conduction band.	Photons have very small momentum while the electron has to undergo a large change in momentum for the transition, which is achieved by the involvement of lattice phonon which can support the required momentum
4	It is a direct transition	It is an indirect transition
5	Photons are emitted	The energy is released in the form of heat
6	Used in the fabrication of photo sensitive devices like light emitting diodes, laser diodes etc.,	Used in the fabrication of diodes, bipolar junction transistors, field effect transistors (FETs), ICs etc.,
7	Ex: Compound semiconductors like In P, Ga As	EX: Elemental semiconductors like Si, Ge

7) Derive an expression for drift and diffusion currents in semiconductors ?

DRIFT CURRENT

We know that a semiconductor consists of holes and electrons. When it is subjected to an electric field, holes move towards negative terminal and electrons move towards the positive terminal. This movement of charge is called drift motion and results in the current flow through the semiconductor. The current which flows under the action of an electric field is called drift current.

We know that electric current density is given by,

$$J = n e V_d \text{ where } V_d \text{ is the drift velocity}$$

Again we have $V_d \propto E \Rightarrow V_d = \mu E$, where μ is called mobility of the charge carrier within the crystal. Mobility is defined as the average velocity acquired by a carrier in unit field.

$$J = n e V_d = n e \mu E$$

In a semiconductor, the current flow would be due to both the electron motion and the hole motion. Correspondingly, the current densities of the electrons and holes are given as,

$$J_n (\text{drift}) = n e \mu_n E \text{ and } J_p (\text{drift}) = p e \mu_p E$$

Though these charge movements are in opposite directions, the total current density is the sum of the two components.

$$J (\text{drift}) = J_n (\text{drift}) + J_p (\text{drift}) = n e \mu_n E + p e \mu_p E$$

$$J (\text{drift}) = (n e \mu_n + p e \mu_p) E$$

$$\therefore \sigma = n e \mu_n + p e \mu_p$$

For an intrinsic semiconductor, $n = p = n_i$, hence $\sigma_i = n_i e (\mu_n + \mu_p)$.

The conductivity is a function of temperature in case of intrinsic semiconductor. When temperature increases, conductivity also increases. For extrinsic semiconductors with typical dopant levels, the minority carrier component is negligible at normal operating temperatures. It is to be noted that the drift current depends upon the carriers concentration and the electric field.

DIFFUSION CURRENT

In addition to the drift motion, the carriers in the semiconductors may move due to diffusion. Diffusion occurs whenever there is a non-uniform concentration of charge carriers at some place of the crystal.

The carrier density in a semiconductor is uniform at equilibrium. Suppose an external agent such as light, or temperature acts momentarily at one end of the semiconductor. This external agent generates additional electron-hole pairs leading to a sudden increase in the concentration of charge carriers at that end. The concentration of the carriers at the other parts of the crystal remains same.

This difference in the concentration causes migration of carriers from the region of higher concentration to the region of lower concentration in order to restore equilibrium. Such a migration of carriers is called diffusion and the current constituted in the process is called the diffusion current.

Let us suppose that the concentration Δn of electrons varies with the distance x in the semiconductor, the concentration gradient being $\frac{\partial \Delta n}{\partial x}$.

According to the Fick's law, the rate at which the carriers diffuse is proportional to the density gradient and the movement is in the direction of the negative gradient. The rate of flow of electrons is proportional to $-\frac{\partial \Delta n}{\partial x}$.

Hence, the rate of flow across unit area = $-D_n \frac{\partial \Delta n}{\partial x}$, where D_n is called the diffusion coefficient of electrons in that semiconductor. This flow constitutes an electron diffusion current density which is given by,

$$J_n (\text{diffusion}) = -e \times \text{rate of flow of charge} = e D_n \frac{\partial \Delta n}{\partial x}$$

Similarly,

$$J_p (\text{diffusion}) = e \times \text{rate of flow of charge} = -e D_p \frac{\partial \Delta p}{\partial x}$$

where D_p is the hole diffusion coefficient.

If there is an electric field E and concentration gradient in x direction, then the total electron current is the sum of the drift and diffusion components.

$$J_n = J_n(\text{drift}) + J_n(\text{diffusion}) = n e \mu_n E + e D_n \frac{\partial \Delta n}{\partial x}$$

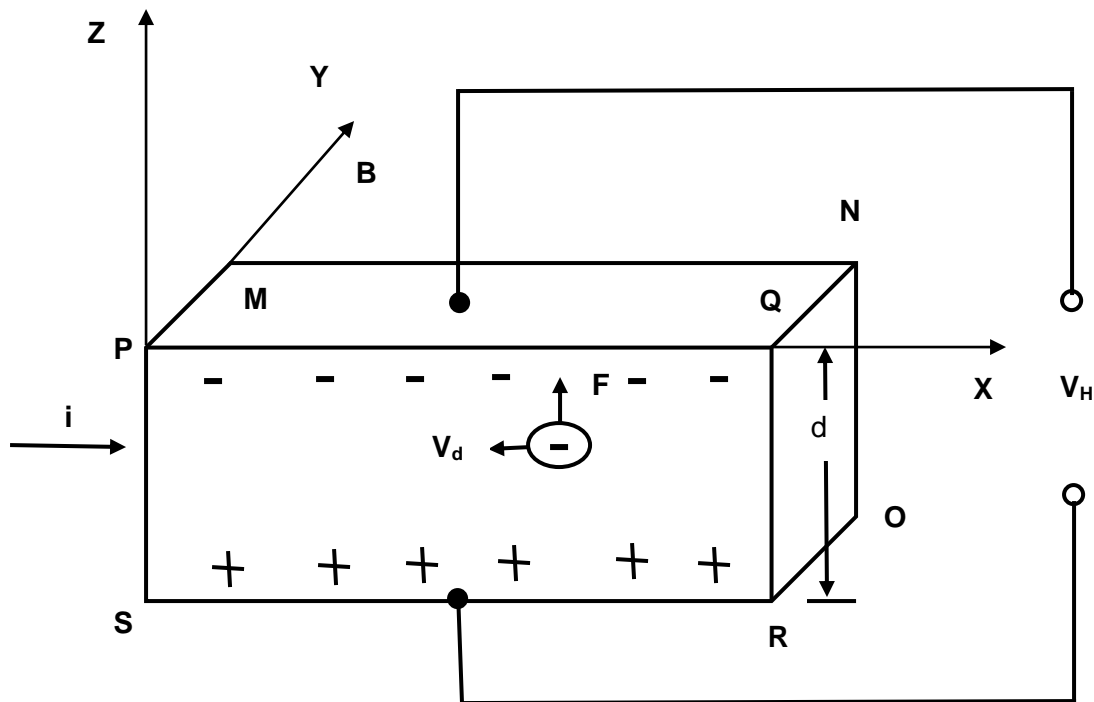
Similarly for the holes,

$$J_p = J_p(\text{drift}) + J_p(\text{diffusion}) = p e \mu_p E - e D_p \frac{\partial \Delta p}{\partial x}$$

It may be observed that diffusion transport of carriers depends only on one variable, namely concentration gradient.

8) State and explain Hall effect ? Obtain expression for Hall coefficient.

If a conductor carrying current is placed in a transverse magnetic field, an electric field is produced in the conductor in a direction perpendicular to both the current and the magnetic field. This phenomenon is called Hall effect. The electric field generated is called Hall field and the corresponding voltage, Hall voltage.



As shown in figure, consider a uniform, thick metal strip placed with its length parallel to X -axis. Let a current i is passed in the conductor along X -axis and a magnetic field B is established along Y -axis. Due to the magnetic field, the charge carriers experience a force F perpendicular to X - Y plane i.e., along Z -axis. The direction of this force is given by Fleming's left hand rule. If the charge carriers are electrons, then they will experience a force in the positive direction of Z . Hence they will be accumulated on the upper surface of the strip i.e., on face $PQNM$ as shown in the figure. Due to this fact the upper side will be charged negatively while the lower side will be charged positively. Thus a transverse potential difference is created.

As discussed above, there is a displacement of charge carriers. This gives rise to a transverse field known as Hall electric field E_H . This field acts inside the conductor to oppose the sideways

drift of the charge carrier. When the equilibrium is reached, the magnetic deflecting forces on the charge carriers are balanced by the electric forces due to Hall electric field.

$$\text{Magnetic deflecting force} = e (\overline{V_d} \times \overline{B})$$

$$\text{Hall electric deflecting force} = e \overline{E_H}$$

As the net force on the charge carriers become zero

$$e (\overline{V_d} \times \overline{B}) = e \overline{E_H} \Rightarrow \overline{E_H} = -(\overline{V_d} \times \overline{B})$$

Writing in terms of magnitude only

$$E_H = -V_d B$$

We know that, $V_d = \frac{J}{n e}$, where n is the number of charge carriers per unit volume and J is the current density.

$$\therefore E_H = \left(\frac{1}{n e} \right) J B$$

If V_H be the Hall voltage in equilibrium, then

$$E_H = V_H / d$$

Where d is the width of the bar. Thus by measuring the potential difference V_H between the two faces, E_H can be calculated.

By measuring current i in the slab, the current density J can be calculated by using $J = \frac{i}{A}$, where A is the area of cross section of the slab. The magnetic field B can be measured by a Gauss-meter. So by substituting the values of E_H , J and B in equation $E_H = \left(\frac{1}{n e} \right) J B$, we can calculate the value of $\left(\frac{1}{n e} \right)$.

The ratio of Hall electric field E_H to the product of J and magnetic induction B is known as Hall coefficient R_H .

$$R_H = \frac{E_H}{J B} = \frac{1}{n e}$$

The Hall coefficient is negative when the charge carriers are electrons and positive when charge carriers are holes.

APPLICATIONS

- 1) Hall effect gives information about the sign of charge carriers.
- 2) Hall effect is quite helpful in understanding the electrical conduction in metals and semiconductors.
- 3) Hall effect can be used to measure the drift velocity of the charge carriers. We know that

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

- 4) Measurement of Hall coefficient gives the number of current carriers per unit volume. If n be the number of charge carriers per unit volume and A be the face area of plate, then

$$i = n e A V_d$$

Also

$$V_d = \frac{E_H}{B}$$

$$\therefore i = n e A \left(\frac{E_H}{B} \right)$$

Let b be the breadth and d be the width of face area of conductor, then $A = b d$. So

$$i = n e b d \left(\frac{E_H}{B} \right)$$

$$n = \frac{i B}{e b d E_H}$$

9) Discuss some important applications of semiconductors.

Semiconductors are the materials whose conductivity lies in between those of conductors and insulators, which can be controlled from external sources. As such, the semiconductors become the building blocks in various electronic devices in the form of diodes, transistors and ICs which replaced the vacuum tubes. Such devices are also known as solid state electronic devices.

Apart from these device applications, the semiconductors particularly extrinsic semiconductors because of their characteristic behavior under suitable external conditions, are used in the fabrication of accurate and high performance devices like magnetic flux meters, laser sources, LEDs, photodiodes, photo detectors, microwave elements, sensors etc.,

(1) Magnetic Flux meters: By using the Hall effect in semiconductors, using a material with known Hall Coefficient, magnetic flux densities present in a region can be determined very accurately. Such devices are quite compact and can be operated very easily.

(2) LED/ Laser sources : By using the phenomena of recombination of opposite charge carriers in the junction region of a diode under proper bias, semiconducting materials can be used to fabricate Light Emitting Diodes (ordinary light) or Lasers (amplified light) with high efficiency. such elements are very useful in various applications like digital watches, display devices and in communication devices.

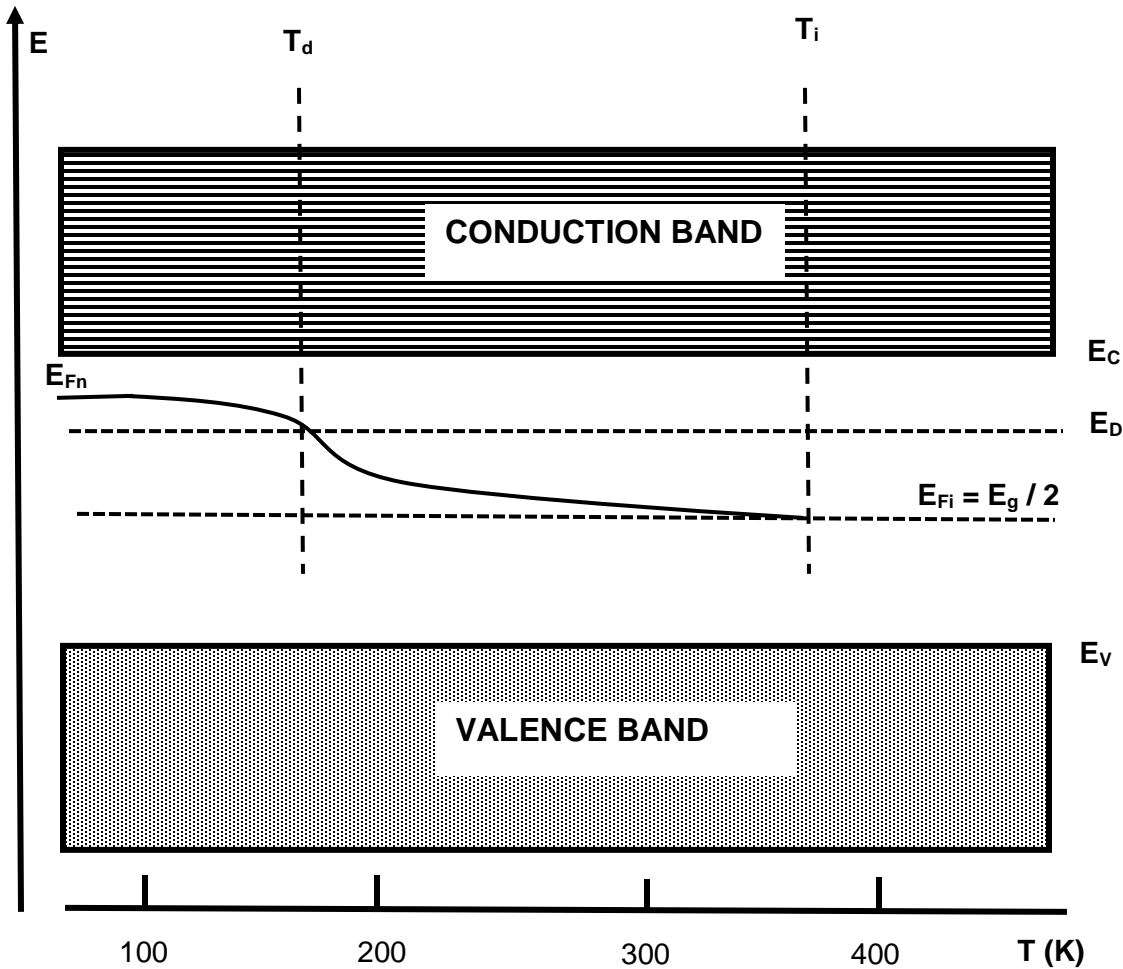
(3) Photo diode/solar cell : Semiconducting junction diodes can be used to convert solar energy into electric energy and Junction diodes used in various devices can be operated using ordinary light also.

(4) Because of their temperature dependence on resistance, some semiconductors can be used to fabricate electronic sensor devices for smoke, pollution, temperature etc.,

10) Explain the variation of Fermi level in n-type and p-type semiconductors with temperature and doping concentrations ?

Variation of Fermi level with temperature in an n-type semiconductor :

The variation of Fermi level E_{Fn} in an n-type semiconductor with temperature is shown in the following figure.



When $T = 0 \text{ K}$, E_{Fn} lies midway between the donor levels and the bottom of the conduction band.

$$E_{Fn} = \frac{E_C + E_D}{2} \text{ at } T = 0 \text{ K}$$

As the temperature increases the donor levels gradually get depleted and the Fermi level moves downward. At the temperature of complete depletion of donor levels, T_D , the Fermi level coincides with the donor level E_D .

$$E_{Fn} = E_D \text{ at } T = T_D$$

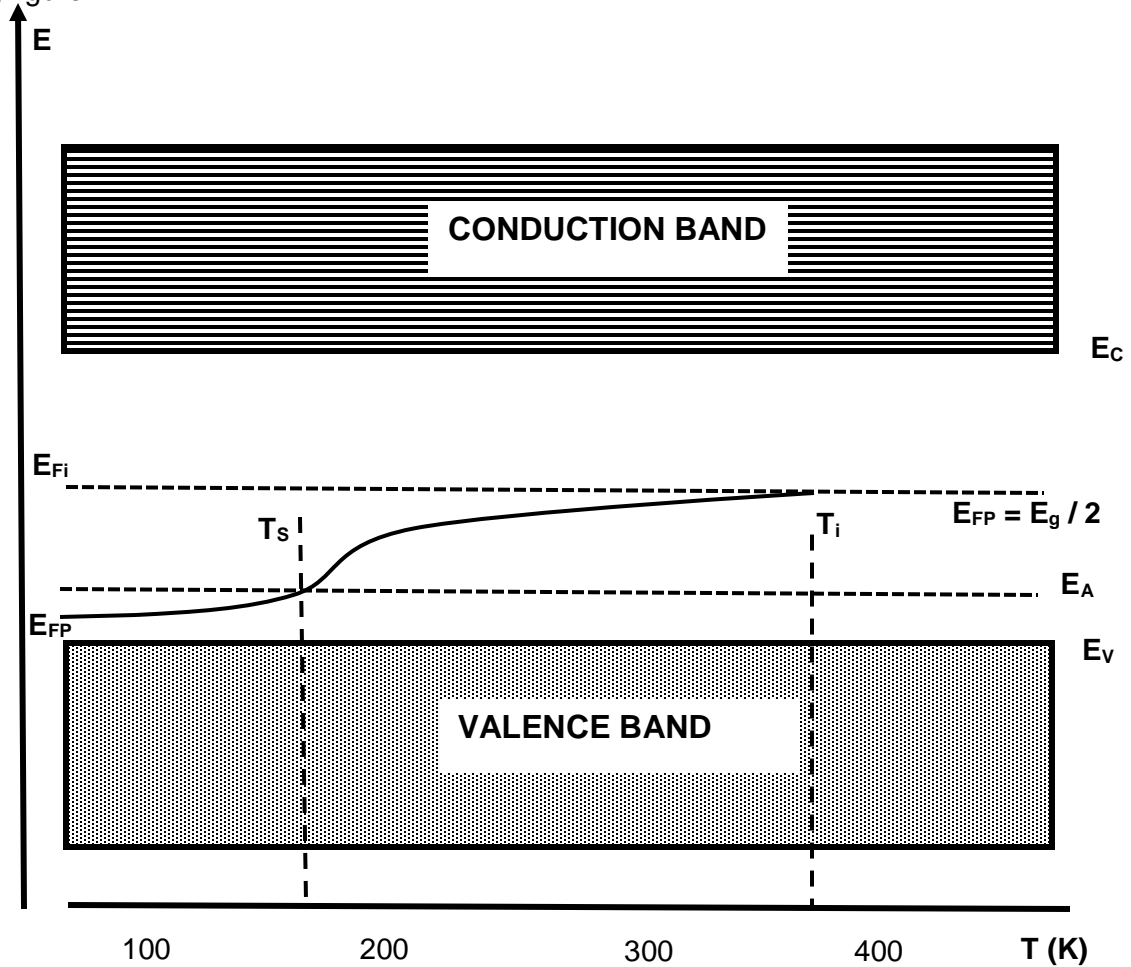
As the temperature grows further above T_D , the Fermi level shifts downward in an approximately linear fashion. At a temperature T_i , the intrinsic process contributes to electron concentration significantly. At high temperatures, the n-type semiconductor loses its extrinsic character and

behaves as an intrinsic semiconductor. In the intrinsic region, the electron concentration in conduction band increases exponentially and the Fermi level approaches the intrinsic value.

$$E_{Fn} = E_{Fi} = \frac{E_g}{2} \text{ at } T \geq T_i$$

Variation of Fermi level with temperature in an p-type semiconductor :

The variation of Fermi level E_{Fn} in an p-type semiconductor with temperature is shown in the following figure.



When $T = 0$ K, E_{Fn} lies midway between the acceptor levels and the top of the valence band.

$$E_{Fp} = \frac{E_V + E_A}{2} \text{ at } T = 0 \text{ K}$$

As the temperature increases the acceptor levels gradually get filled and the Fermi level moves upward. At the temperature of saturation, T_S , the Fermi level coincides with the acceptor level E_A .

$$E_{Fp} = E_A \text{ at } T = T_S$$

As the temperature grows further above T_S , the Fermi level shifts upward in an approximately linear fashion. At a temperature T_i , the intrinsic behavior sets in. At high temperatures, the p-type

semiconductor loses its extrinsic character and behaves as an intrinsic semiconductor. In the intrinsic region, the hole concentration in valence band increases exponentially and the Fermi level approaches the intrinsic value.

$$E_{Fp} = E_{Fi} = \frac{E_g}{2} \text{ at } T = T_i$$

Variation of Fermi level with impurity concentration :

n-type semiconductor :

The addition of donor impurity to an intrinsic semiconductor leads to the formation of discrete donor levels below the bottom edge of the conduction band. At low impurity concentrations, the impurity atoms are distantly spaced from one another, approximately, by 100 atom spacings. Therefore, they do not interact with each other. With an increase in the impurity concentration, the separation between impurity atoms decreases and they tend to interact. As a result, the donor levels undergo splitting and form an energy band below the conduction band, as shown in the following figure.

The larger the doping concentration, the broader is the impurity band and at one stage the impurity band overlaps on the conduction band. Then the upper vacant levels in the conduction band are accessible to the donor electrons. The broadening of donor levels into a band is accompanied by a decrease in the width of the forbidden gap and also by the upward displacement of Fermi level. The Fermi level shifts closer and closer to the conduction band with increasing impurity concentration and finally moves into the conduction band when the donor band overlaps on the conduction band.

p-type semiconductor :

In p-type semiconductor, the acceptor levels broaden and form into a band with increasing impurity concentration. The acceptor band ultimately overlaps on the valence band. The Fermi level moves down closer to the valence band and finally at very high impurity concentration it will shift into the valence band.

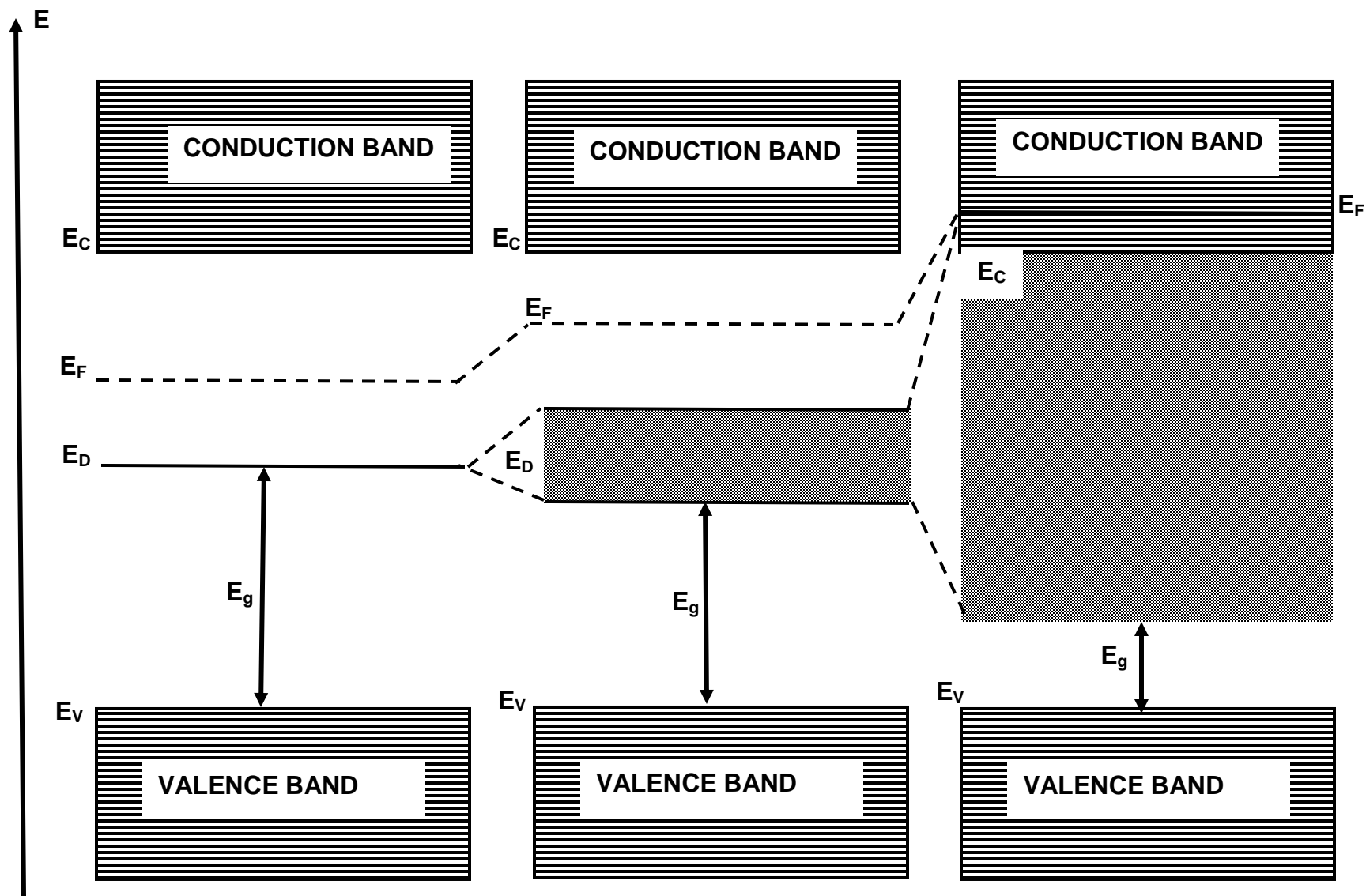


FIGURE (A)
Low level doping

FIGURE (B)
medium doping

FIGURE (C)
heavy doping

11) Deduce Einstein's relation relating to drift and diffusion currents.

The mobility μ expresses the ability of carriers to drift while the diffusion constant D expresses the ability of carriers to diffuse. There exists a close relationship between them, since both these parameters are determined by the thermal motion and scattering of the free carriers. In thermal equilibrium, the net current through the semiconductor is zero and hence the drift current must balance the diffusion current.

$$(dn) e E \mu_n = e D_n \frac{dn}{dx}$$

The force F on excess carriers restoring equilibrium is given by the product of excess charge and electric field.

$$F = (dn) e E = \left(e D_n / \mu_n \right) \frac{dn}{dx}$$

This force also depends on the thermal energy of excess carriers. According to the kinetic theory of gases, if the molecular concentration of a gas increases by (dn) , the gas pressure increases by $(dn) k T$. The force corresponding to the pressure gradient is given by Fick's law,

$$F = k T \frac{dn}{dx}$$

By making an analogy between the excess carriers in semiconductors and gas molecules in a container, we have

$$k T \frac{dn}{dx} = \left(e D_n / \mu_n \right) \frac{dn}{dx}$$

$$k T = \left(e D_n / \mu_n \right)$$

$$D_n = \frac{\mu_n k T}{e} \text{ or } \frac{D_n}{\mu_n} = \frac{k T}{e}$$

This is the relation between diffusion coefficient and mobility of charge carriers and is termed as Einstein relation. This relation for holes is given by

$$D_p = \frac{\mu_p k T}{p} \text{ or } \frac{D_p}{\mu_p} = \frac{k T}{p}$$

$$\frac{D_n}{D_p} = \frac{\mu_n}{\mu_p}$$

According to Einstein equation, the ratio between the diffusion constant and the mobility of charge carriers is directly proportional to the absolute temperature of the semiconductor.

SHORT ANSWER QUESTIONS

1) What are the peculiar properties exhibited by semiconductors?

All the semiconductors have negative temperature coefficient of resistance. Important characteristic of the semiconductors is that they have small band gap. The importance of semiconductors is further increased due to the fact that the conductivity and the effective band gaps of these materials can be modified by the introduction of impurities which strongly affect their electronic and optical properties. The interesting feature about semiconductors is that they are bipolar and current is transported by two charge carriers of opposite sign. The number of carriers can be drastically enhanced by doping the semiconductor with suitable impurities. The doped semiconductor, which exhibits high conductivity, is called an extrinsic semiconductor. The remarkable feature of extrinsic semiconductors is that current is transported in them through two different processes, namely drift and diffusion.

2) What are intrinsic semiconductors?

Chemically pure semiconductors in which the electron-hole pairs are produced by the thermal activation are called intrinsic semiconductors. Silicon and germanium serve as good examples for intrinsic semiconductors. Intrinsic semiconductor behaves as an insulator at 0 K.

3) What is the band gap energy?

The band gap energy is the minimum amount of energy required for breaking a covalent bond. It is the minimum amount of energy required to excite an electron from the valence band to the conduction band. Also, it is the minimum amount of energy required to convert a bound electron into a free electron. The energy required to break a covalent bond in Germanium is 0.72eV at 300 K and that in Silicon it is 1.1eV.

4) Write a short note on Fermi-Dirac statistics.

Under thermal equilibrium, the free electrons acquire energy obeying a statistical rule known as Fermi-Dirac statistics. Fermi-Dirac statistics is applicable to the assembly of particles which obey Pauli's exclusion principle. They must also be identical particles of spin $1/2$ and are indistinguishable. Since electrons satisfy these conditions, they obey Fermi-Dirac statistics. Fermi-Dirac statistics permits the evaluation of probability of finding electrons occupying energy levels in a certain energy range.

$f(E)$ is the Fermi distribution function representing the probability of occupation of a state with energy E . The expression for $f(E)$ is given by

$$f(E) = \frac{1}{\exp\left(\frac{E-E_F}{kT}\right) + 1}$$

Where k is Boltzmann constant and T is the absolute temperature, E_F is the energy of the Fermi level.

5) What is Fermi energy?

The energy corresponding to the highest occupied level at zero-degree absolute is called the Fermi energy, and the energy level is referred to as the Fermi level. It is used to know the status of the electrons. Electrons are completely filled below the Fermi energy level and completely empty above the Fermi level at 0 K.

6) What are the factors on which intrinsic carrier concentration depends?

- 1) The intrinsic carrier concentration is independent of Fermi level.
- 2) The intrinsic carrier concentration has an exponential dependence on the band gap value E_g .
- 3) It strongly depends on the temperature.
- 4) The factor 2 in the exponent indicates that two charge carriers are produced for one covalent bond broken.

7) What are the limitations of intrinsic semiconductors?

- 1) Conductivity is low. For example, Germanium has a conductivity which is nearly 10^7 times smaller than that of copper.
- 2) Conductivity is a function of temperature and increases exponentially as the temperature increases.
- 3) Conductivity cannot be controlled from outside.

8) What are extrinsic semiconductors?

Without approaching larger temperatures, we can increase the conducting capability by adding some impurities to the intrinsic semiconductor. It makes the current more voltage dependent than temperature dependent. This process of controlled addition of impurities to the intrinsic semiconductor is called doping and the impurities added are referred to as dopants. This semiconductor with impurities in it is called an extrinsic semiconductor.

The amount of impurity added is extremely small. This doping is done during crystallization process. The impurity atoms are nearly of the same size as semiconductor atoms and easily

substitute themselves in place of the host atoms in the semiconductor crystal. Thus, they are substitutional impurities and do not cause any distortion in the original structure.

Based on the type of impurities added, the extrinsic semiconductors are classified into two types; p-type and n-type.

9) What are the advantages of extrinsic semiconductors?

Advantages of extrinsic semiconductors: (1) Conduction is high (2) Conductivity can be varied to the desired value through the control of doping concentration (3) Conductivity is not a function of temperature.

10) What are n-type semiconductors?

When some pentavalent (group – V) impurity atoms such as As, Sb, P, Bi, are added to an intrinsic semiconductor (Si or Ge), then we get an n-type semiconductor. These pentavalent impurities donate electrons to the host crystal and hence referred to as donor impurities. In an n-type semiconductor, the majority carriers are electrons and the minority carriers are holes.

11) What are p-type semiconductors?

A p-type semiconductor is obtained by doping an intrinsic semiconductor with trivalent impurities such as B, Al, Ga, In, etc. these trivalent impurities accept electrons from the host crystal and thus referred to as acceptor impurities. In p-type semiconductor, holes are majority carriers and the electrons are minority carriers.

12) Explain drift current in semiconductors.

We know that a semiconductor consists of holes and electrons. When it is subjected to an electric field, holes move towards negative terminal and electrons move towards the positive terminal. This movement of charge is called drift motion and results in the current flow through the semiconductor. The current which flows under the action of an electric field is called drift current. The drift current depends upon the carrier concentration and the electric field.

13) Explain diffusion current in semiconductors.

Diffusion occurs whenever there is a non-uniform concentration of charge carriers at some place of the crystal. The carrier density in a semiconductor is uniform at equilibrium. Suppose an external agent such as light, or temperature acts momentarily at one end of the semiconductor. This external agent generates additional electron-hole pairs leading to a sudden increase in the concentration of charge carriers at that end. The concentration of the

carriers at the other parts of the crystal remains same. This difference in the concentration causes migration of carriers from the region of higher concentration to the region of lower concentration in order to restore equilibrium. Such a migration of carriers is called diffusion and the current constituted in the process is called the diffusion current. Diffusion transport of carriers depends only on one variable, namely concentration gradient.

14) State and explain Hall effect.

If a conductor carrying current is placed in a transverse magnetic field, an electric field is produced in the conductor in a direction perpendicular to both the current and the magnetic field. This phenomenon is called Hall effect. The electric field generated is called Hall field and the corresponding voltage, Hall voltage.

15) State the applications of Hall effect.

- 1) Hall effect gives information about the sign of charge carriers.
- 2) Hall effect is quite helpful in understanding the electrical conduction in metals and semiconductors.
- 3) Hall effect can be used to measure the drift velocity of the charge carriers.
- 4) Measurement of Hall coefficient gives the number of current carriers per unit volume.