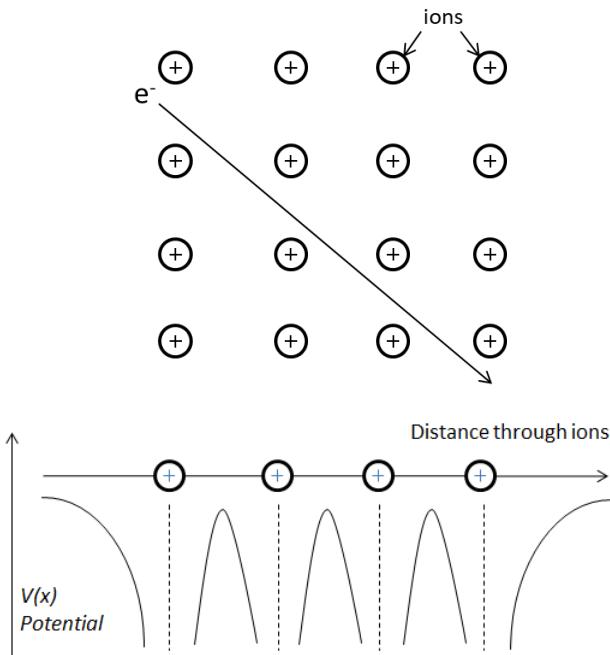


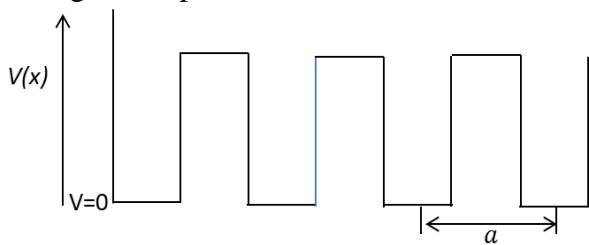
## Solid State Physics

**Que.1. Explain Opening of band gap due to internal electron diffraction and hence explain formation of bands in solids [6]**

When an electron moves through a lattice of positive ions, it experiences varying potentials. The potential of an electron at the positive ion site is zero and is, maximum in between two ions as shown in figure below.

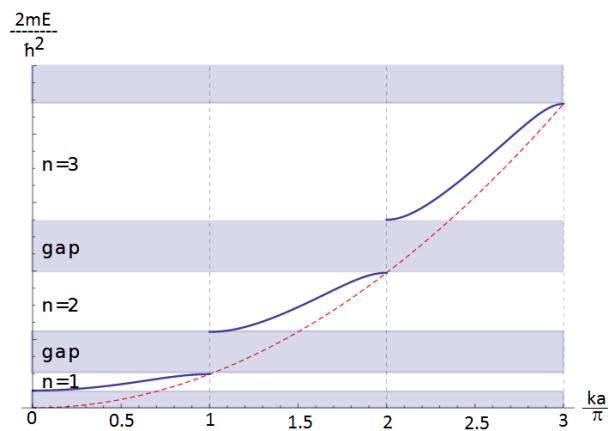


Kronig and Penney approximated these potentials inside the crystal to the shape of rectangular steps.



The energies of electrons can be known by solving Schrödinger's wave equation in such a lattice.

By solving the Schrödinger's wave equation using Bloch theorem, we get **Energy vs K (momentum)** diagram



The dotted line is representing the motion for a free electron. As electron is moving in a periodic potential, it appears that there are gaps which open in energy spectrum at an integer of  $\frac{ka}{\pi}$

These gaps correspond to energy bands inside the solids. Thus, the energy level of electron in the crystal lattice is discrete.

### Formation of Bands:

1. In a single isolated atom, the electrons in each orbit have definite energy associated with it. But in case of solids all the atoms are close to each other, so the energy levels of outermost orbit electrons are affected by the neighboring atoms.
2. Band formation is preferred in solids as atomic spacing is very small. In liquids and gases as atomic spacing is much larger as compared to solids so band formation is not preferred.
3. When two single or isolated atoms are bring close to each other, then the outermost orbit electrons of two atoms are interact or shared with each other i.e. the electrons in the outermost orbit of one atom experience an attractive force from the nearest or neighboring atomic nucleus. Due to this the energies of the electrons will not be in same level, the energy levels of electrons are changed to a value which is higher or lower than that of the original energy level of the electron.
5. However, the energy levels of inner orbit electrons are not much affected by the presence of neighboring atoms.

**Que.2. Explain in brief how free electron theory explains electrical conductivity and thermal conductivity of solids, and relation between electrical and thermal conductivity of solids (Wiedemann–Franz law). What are the limitations of this theory? [4]**

The electrons present in the outermost orbitals of the atom, determine the electrical properties of the solid. The electron theory of solids explains the structures and properties of solids through their electronic structure. The electron theory is applicable to all solids. The theory is developed in three phases:

1. This theory was developed by Drude and Lorentz in 1900 and hence is also known as Drude-Lorentz theory. According to this theory, a metal consists of electrons which are free to move about in the crystal like molecules of a gas in a container.
2. Neglecting the electron-electron interaction and the electron-ion interaction, it appears as if the electrons move in a confined box with periodic collision with ions in the lattice. This idea is utilized to explain many properties of metals satisfactorily such as electrical conductivity, Ohm's law, thermal conductivity etc.
3. Electrical conductivity of metal: It can be shown that Electrical conductivity =  $\sigma = ne\mu$ , where  $n$  is electron density,  $e$  is charge on electron and  $\mu$  is the mobility of electrons.
4. Thermal Conductivity: Thermal conductivity is the property of material's ability to conduct the heat. From free electron theory, it can be shown that thermal conductivity  $K = k_B n v \lambda / 2$ , where  $k_B$  is Boltzmann constant.
5. **Wiedemann-Franz Law:** The Wiedemann–Franz law states that the ratio of the electronic contribution to the thermal conductivity ( $K$ ) and the electrical conductivity ( $\sigma$ ) of a metal is proportional to the temperature ( $T$ ). From free electron

theory it can be shown that  $k/\sigma T = 1.11 \times 10^{-8} \text{ W}\Omega/\text{K}^2$ .

This number is also known as Lorentz's number. This number is based on calculations as per Maxwell-Boltzmann distribution for electrons. If Fermi-Dirac statistics is applied to electrons, this number is modified to  $2.45 \times 10^{-8} \text{ W}\Omega/\text{K}^2$ , which agrees quite well with experimental findings.

6. Advantages (Success) of Free Electron Theory
  - i) It verified Ohm's law
  - ii) It explains electrical and thermal conductivities of metals.
  - iii) It derived Wiedemann-Franz law (i.e. relation between electrical conductivity and thermal conductivity).
  - iv) It explains optical properties of metals.
7. Disadvantages (Limitations) of Free Electron Theory
  - i) The phenomenon such as photoelectric effect, Compton effect, black body radiations, etc could not be explained
  - ii) The theoretical values of specific heat and electronic specific heat as calculated from this theory do not agree with experimental values
  - iii) Electrical conductivity of semiconductors or insulators could not be explained.
  - iv) Wiedemann-Franz law deviates at low temperature.
  - v) Ferromagnetism could not be explained by this theory.
  - vi) The theoretical value of paramagnetic susceptibility is greater than experimental value.

**Que.3. Explain terms (a) valence band (b) conduction band (c) band gap energy. [4]**

There are number of energy bands in solids but three of them are very important. These three energy bands are important to understand the behavior of solids. These energy bands are -

Valence band, Conduction band, Forbidden energy gap.

### Valence band:

The energy band which is formed by grouping the range of energy levels of the valence electrons or outermost orbit electrons is called as valence band.

The topmost filled band at absolute zero temperature is called as Valence band.

### Conduction band:

The energy band which is formed by grouping the range of energy levels of the free electrons is called as conduction band.

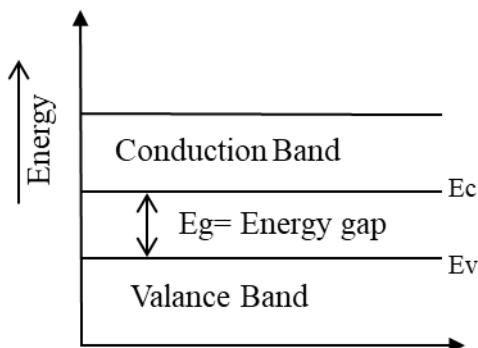
The band of allowed energy levels higher to the valence band will be vacant at absolute zero.

### Forbidden energy gap/bandgap:

The energy gap which is present between the valence band and conduction band by separating these two energy bands is called as forbidden band or forbidden gap.

Ideally it is the energy difference between top of the valence band and bottom of the conduction band.

In solids, electrons cannot stay in forbidden gap because there is no allowed energy state in this region.



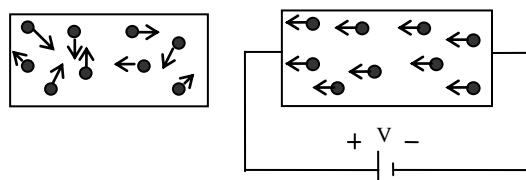
### Que.4. Explain in brief concept of effective mass of electron. [3]

When accelerated by an electric field or magnetic field, an isolated electron freely moving in vacuum has a well-defined mass and it obeys Newtonian mechanics.

- Under the external electric or magnetic field, a moving electron inside a crystal will experience periodic variation of potential of ions.
- The mass of electron in crystal is different from mass of free electron in vacuum and is referred to as effective mass of electron. It is denoted by  $m^*$ .
- The effective mass of electron depends heavily on its location in the energy band.
- In the conduction band, electrons are freely moving inside the crystal. When energy of free moving electron is minimum, it is near the bottom of the conduction band. In this situation its effective mass is nearly identical to the mass of free electron.
- Electrons that are tightly bound to the orbits, near the top of valence band, have negative effective mass.

### Que.6. Derive the expression for conductivity of conductors. [6]

A metal piece consists of large number of closely packed atoms. The valence electrons in these atoms are very loosely bound to the nuclei and are free to move anywhere randomly within the metal. These free electrons are called as 'conduction electrons'. In the absence of external electric field the free electrons in the metal moves randomly in all directions as shown in figure.



When an external field is applied, the random motion of electrons becomes directed as shown in figure. Such directed motion is called as 'drift' and due to external electric field, velocity acquired by the electrons is known as 'drift velocity'.

This drift velocity depends on the applied electric field  $E$ .

$$\therefore v \propto E$$

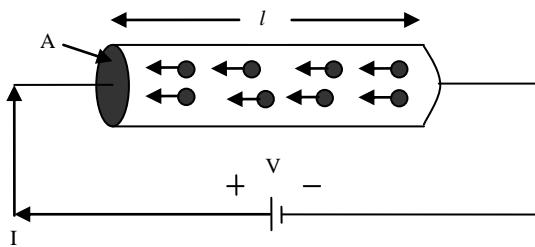
$$\text{or } v = \mu_e \cdot E \quad \text{---(1)}$$

where,  $\mu_e = \text{const.} = \text{electron mobility.}$

$$\therefore \mu_e = \frac{v}{E}$$

Therefore, electron mobility is defined as 'average drift velocity acquired by the electron under unit electric field'.

Consider a conductor of length  $l$  and cross section area  $A$ . Let voltage  $V$  is applied across the semiconductor. The current flowing in the conductor is due to electrons as shown in figure.



Let,

$e$  = charge of an electron

$n$  = number of free electrons/unit volume = electron density.

Current  $I$  is the total charge crossing the volume per unit time

$$\text{i.e. } I = \frac{n_e \times e \times \text{vol}}{t}$$

$$\text{i.e. } I = \frac{n_e \times e \times A \times l}{t} \quad \text{but, } \frac{l}{t} = v = \text{drift velocity}$$

$$\therefore I = n_e \times e \times A \times v_e \quad \text{---(2)}$$

where,  $v_e$  = drift velocity of electrons

$$\text{Now, } v_e = \mu_e \times E$$

$\therefore$  equation(2) becomes,

$$I = n_e \times e \times A \times \mu_e \times E \quad \text{---(3)}$$

$$\text{But, } E = \frac{V}{l}$$

$$\therefore I = n_e \times e \times A \times \mu_e \times \frac{V}{l} \quad \text{---(4)}$$

$$\therefore \frac{V}{I} = R = \frac{l}{n_e \times e \times A \times \mu_e} = \rho \frac{l}{A}$$

by Ohm's law

where,  $\rho$  = resistivity of conductors.

$$\therefore \rho = \frac{1}{n_e \times e \times \mu_e} \quad \text{---(5)}$$

Therefore, conductivity of conductors,

$$\therefore \sigma = \frac{1}{\rho} = n_e \times e \times \mu_e \quad \text{---(6)}$$

**Que.6. Derive the expression for conductivity of intrinsic and extrinsic semiconductors. [6]**

Consider a semiconductor of length  $l$  and cross section area  $A$ . Let voltage  $V$  is applied across the semiconductor. The current flowing in the semiconductor is due to charge carriers both, electrons and holes as shown in figure.

Let,

$n_e$  = electron density in conduction band.

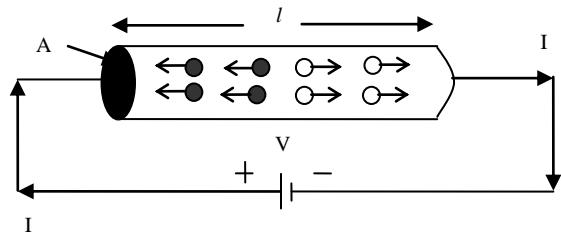
$n_h$  = hole density in valence band.

$\mu_e$  = electron mobility.

$\mu_h$  = hole mobility.

$v_e$  = drift velocity of electrons.

$v_h$  = drift velocity of holes.



We have total current in the semiconductor is total charge crossing the volume per unit time. In semiconductors both electrons and holes are charge carriers.

$$\therefore I = n_e \times e \times A \times v_e + n_h \times e \times A \times v_h$$

where,  $v_e$  &  $v_h$  = drift velocities of electrons & holes respectively.

$$\text{i.e. } I = e \times A (n_e \times v_e + n_h \times v_h) \quad \text{---(2)}$$

$$\text{Now, } v_e = \mu_e \times E = \mu_e \times \frac{V}{l}$$

$$\text{and } v_h = \mu_h \times E = \mu_h \times \frac{V}{l}$$

$\therefore$  equation(2) becomes,

$$I = e \times A (n_e \times \mu_e \times \frac{V}{l} + n_h \times \mu_h \times \frac{V}{l})$$

$$\text{i.e. } I = e \times A \times \frac{V}{l} (n_e \times \mu_e + n_h \times \mu_h)$$

$$\begin{aligned}\therefore \frac{V}{I} &= R = \text{resistance} \\ &= \frac{l}{e \times A \times (n_e \times \mu_e + n_h \times \mu_h)} = \rho \frac{l}{A} \\ \text{where, } \rho &= \text{resistivity of semiconductors.} \\ \therefore \rho &= \frac{1}{e \times (n_e \times \mu_e + n_h \times \mu_h)}\end{aligned}$$

Therefore, conductivity of semiconductors,

$$\therefore \sigma = \frac{1}{\rho} = e \times (n_e \times \mu_e + n_h \times \mu_h) \quad \dots \dots \dots (3)$$

Conductivity of Intrinsic Semiconductors:

In intrinsic semiconductors,  $n_e = n_h = n_i$  say

$$\therefore \sigma_i = e \times n_i \times (\mu_e + \mu_h) \quad \dots \dots \dots (4)$$

Conductivity of Extrinsic Semiconductors:

i) P-type:

For P-type semiconductors,

$$n_e \ll n_h \therefore \text{neglecting } n_e$$

$$\sigma_h = n_h \times e \times \mu_h \quad \dots \dots \dots (5)$$

ii) N-type:

For N-type semiconductors,

$$n_h \ll n_e \therefore \text{neglecting } n_h$$

$$\sigma_e = n_e \times e \times \mu_e \quad \dots \dots \dots (6)$$

**Que.7. What is Fermi level? Explain Fermi-Dirac probability distribution function specifying the meaning of each symbol. [4]**  
**OR**

**Write the formula for the Fermi Dirac probability distribution function. Draw in the same figure the Fermi Dirac probability versus electron energy at  $T=0$  K,  $T_1$  and  $T_2$  (where  $T_2 > T_1 > 0$  K). Explain the significance of the figure. [4]**

The probability that an energy level  $E$  is occupied by an electron, at temperature  $T$  is given by,

$$P(E) = \frac{1}{\exp\left(\frac{E - E_f}{kT}\right) + 1} \quad \dots \dots \dots (1)$$

Where,

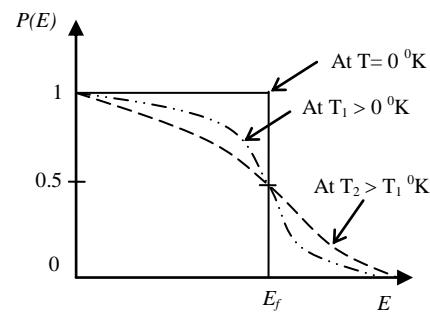
$E_f$  = Fermi Energy (Energy of Fermi level)

$k$  = Boltzmann constant.  $= 1.38 \times 10^{-23} \text{ J/K}$

$P(E)$  is called Fermi Dirac Probability Distribution Function and  $kT$  is the thermal energy of the electron at temperature  $T$  K.

**Fermi Level:** It is the highest possible level of an electron at absolute zero temperature. It need not be the energy level of an electron. It is a statistical concept given for our understanding. (It is a reference energy level between valence band and conduction band to understand whether the energy levels above it or below it are occupied or not.)

The shape of F-D distribution is as shown below in figure.



At  $T=0$  K, probability that all the energy levels below fermi-level are occupied by electrons is 1 and that above fermi-level is 0.

$$\text{if } E < E_f \Rightarrow \exp\left(\frac{E - E_f}{kT}\right) \Rightarrow 0 \quad \therefore P(E) = 1$$

Thus at absolute zero temperature the probability of finding an electron with energy less than Fermi energy is 1. i.e. all the levels below Fermi level are occupied by the electrons.

$$\text{if } E > E_f \Rightarrow \exp\left(\frac{E - E_f}{kT}\right) \Rightarrow \infty \quad \therefore P(E) = 0$$

Thus at absolute zero temperature the probability of finding an electron with energy greater than Fermi energy is 0. i.e. all the levels above Fermi level are empty.

At  $T > 0$  K,

As we increase the temperature above 0 K, the probability of occupancy of levels above fermi-level increases and that of below Fermi-level decreases.

$$\text{if } E = E_f \Rightarrow \exp\left(\frac{E - E_f}{kT}\right) \Rightarrow 1 \quad \therefore P(E) = 0.5$$

Thus for any finite temperature  $T$ ,  $E_f$  is the energy level for which probability of finding an electron is 0.5. It means that there is equal probability that energy levels above and below Fermi level are occupied by electrons.

**Que.8. Using Fermi-Dirac probability distribution function, derive an expression for the position of Fermi energy level in the intrinsic semiconductor. [6]**

**OR**

**Using Fermi-Dirac probability distribution function, prove that the position of Fermi energy level in the intrinsic semiconductor is at the center of forbidden energy gap. [6]**

We assume that,

- The widths of conduction band and valence band are small in comparison with band gap.
- Because of small widths, for all practical purposes, all energy levels in a band have same energy.
- At  $0^0\text{K}$  the valence band is completely filled and the conduction band is completely empty, the solid acts as a insulator.

Let,

$E_c$  = Energy of conduction band.

$E_v$  = Energy of valence band.

$n_c$  = Number of electrons in conduction band at  $T^0\text{K}$ .

$n_v$  = Number of electrons in valence band at  $T^0\text{K}$ .

$N = n_c + n_v$  = Total number of electrons in valence band and conduction band at  $T^0\text{K}$ .

We know that, the probability that an energy level  $E$  is occupied by an electron, at temperature  $T$  is given by Fermi-Dirac probability distribution function,

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

We know,

$$P(E_C) = \frac{n_C}{N}$$

$$\Rightarrow n_C = P(E_C) \cdot N \quad \Rightarrow \quad n_C = \frac{N}{\exp\left(\frac{E_C - E_f}{kT}\right) + 1}$$

$$P(E_V) = \frac{n_V}{N}$$

$$\Rightarrow n_V = P(E_V) \cdot N \quad \Rightarrow \quad n_V = \frac{N}{\exp\left(\frac{E_V - E_f}{kT}\right) + 1}$$

$$\therefore N = n_C + n_V$$

$$= \frac{N}{\exp\left(\frac{E_C - E_f}{kT}\right) + 1} + \frac{N}{\exp\left(\frac{E_V - E_f}{kT}\right) + 1}$$

$$\text{i.e. } \left[ \exp\left(\frac{E_C - E_f}{kT}\right) + 1 \right] \left[ \exp\left(\frac{E_V - E_f}{kT}\right) + 1 \right] = \\ \left[ \exp\left(\frac{E_C - E_f}{kT}\right) + 1 \right] \left[ \exp\left(\frac{E_V - E_f}{kT}\right) + 1 \right]$$

$$\text{i.e. } \exp\left(\frac{E_C - E_f}{kT}\right) \exp\left(\frac{E_V - E_f}{kT}\right) + \exp\left(\frac{E_C - E_f}{kT}\right) + \exp\left(\frac{E_V - E_f}{kT}\right) + 1 = \\ \exp\left(\frac{E_C - E_f}{kT}\right) + \exp\left(\frac{E_V - E_f}{kT}\right) + 2$$

$$\text{i.e. } \exp\left(\frac{E_C - E_f}{kT}\right) \exp\left(\frac{E_V - E_f}{kT}\right) = 1$$

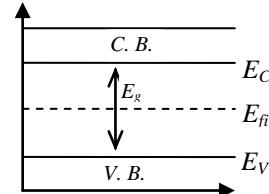
$$\text{i.e. } \exp\left(\frac{E_C + E_V - 2E_f}{kT}\right) = 1$$

$$\text{but } \exp(0) = 1 \quad \Rightarrow \quad \frac{E_C + E_V - 2E_f}{kT} = 0$$

$$\Rightarrow E_C + E_V - 2E_f = 0$$

$$\Rightarrow E_f = \frac{E_C + E_V}{2}$$

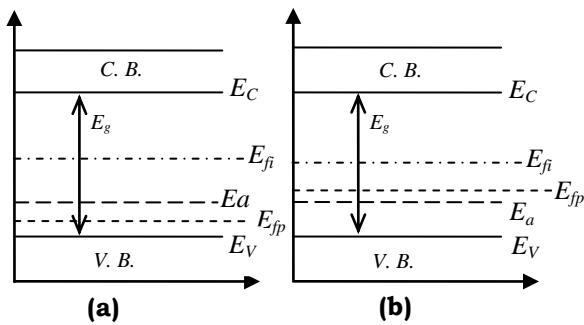
This proves that Fermi energy is exactly midway between  $E_c$  and  $E_v$ . i.e.  $E_f$  is at the center of forbidden energy gap as shown in the figure.



**Que.9. What is Fermi level? Show the position of Fermi level in P-type and N-type semiconductor at T=0K and T>0 K [4]**

**Fermi Level:** It is the highest possible level of an electron at absolute zero temperature. It need not be the energy level of an electron. It is a statistical concept given for our understanding. (It is a reference energy level between valence band and conduction band to understand whether the energy levels above it or below it are occupied or not.)

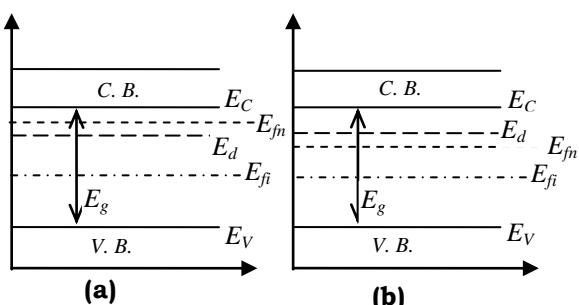
**Position of fermi-level in P-type semiconductor:**



**Figure 1**

When atoms of trivalent impurity are added to a pure semiconductor, there will be vacancies (holes) at absolute zero temperature which stays at accepter level just above the top of valence band. At T = 0<sup>0</sup>K, Fermi level is midway between E<sub>a</sub> and E<sub>V</sub>, as shown in figure 1 (a). As temperature increases (i.e. at T > 0<sup>0</sup>K) E<sub>a</sub> gets saturated by the electrons and more electrons gets excited to the conduction band and E<sub>f</sub> moves above E<sub>a</sub> but remains close to valence band than the conduction band as shown in figure 1 (b).

**Position of Fermi-level in N-type semiconductor:**



**Figure 2**

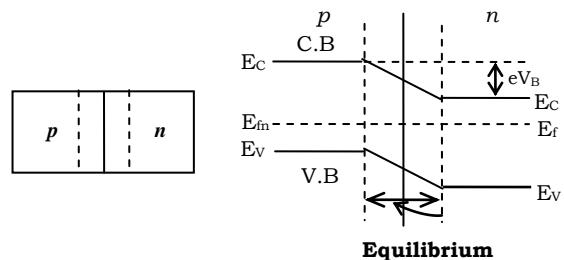
When atoms of penta-valent impurity are added to a pure semiconductor, there will be excess electrons at absolute zero temperature which stays at donor level just below the bottom of conduction band. At T = 0<sup>0</sup>K, Fermi level is midway between E<sub>d</sub> and E<sub>C</sub>, as shown in figure 2 (a). As temperature increases (i.e. at T > 0<sup>0</sup>K) the electrons at E<sub>d</sub> get excited to the conduction band and E<sub>f</sub> moves below E<sub>d</sub> but remains close to valence band than the conduction band as shown in figure 2 (b).

**Que.10. With the help of neat labeled energy level diagram, explain the working of diode in forward bias and reverse bias in comparison with unbiased diagram. [6]**

**OR**

**Que.10. Explain the working of PN junction diode in (a) zero bias (b) forward bias (c) reverse bias on the basis of energy level diagram. [6]**

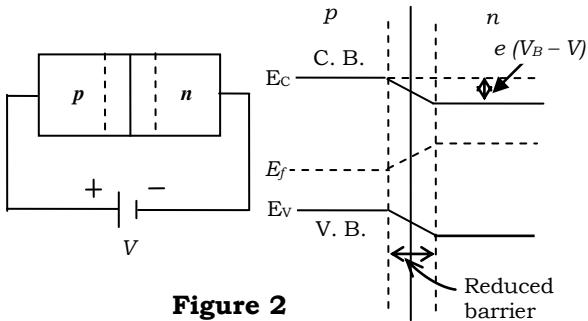
**Unbiased:** The energy band picture of an unbiased diode is as shown in figure 1.



**Figure 1**

In p-type semiconductor the Fermi-level is closer to the valence band and in n-type it is closer to conduction band. When p-n junction is formed the bands on either side shift to equalize the Fermi levels and attain equilibrium. The shift in the conduction and valence band is equal to  $eV_B$ , where  $V_B$  is the barrier potential across the depletion region.

**Forward Bias:** When a d. c. source is connected across the diode such that the positive terminal is connected to p-region and negative terminal is connected to n-region then the diode is said to be in forward bias as shown in figure 2.



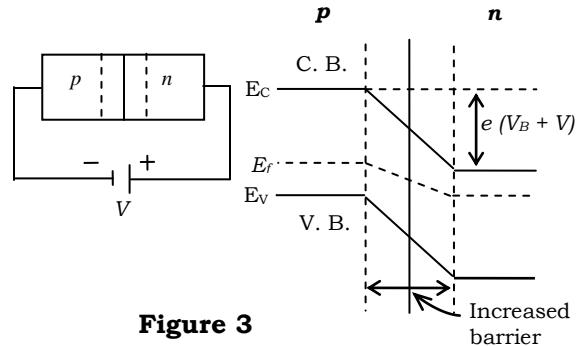
**Figure 2**

The majority carrier electrons in the *n*-region are repelled by the negative terminal of the battery. Therefore the electrons gain some excess energy to cross over the energy barrier. As soon as it reaches the *p*-side, it encounters a large number of holes. Somewhere close to the junction the electron is trapped by a hole so that it becomes a valance electron in the *p*-side. There is large number of holes in *p*-side so that the electron will hop from one hole to other, towards the positive terminal of the battery as it is attracted by it. Finally leaving the crystal from the *p*-side it will enter the positive terminal. Thus the applied d. c. voltage helps the flow of electrons through the junction diode and therefore large forward current flows.

As the forward bias leads to increase the energy of electrons in *n*-region of the crystal the Fermi-level on *n*-side is raised by energy equal to  $eV$ . Where  $V$  is applied d.c. voltage. The bands adjust their positions to suite the elevation of the Fermi-level as shown in figure 2.

### Reverse Bias:

When a d.c. source is connected across the diode such that the positive terminal is connected to *n*-region and negative terminal is connected to *p*-region then the diode is said to be in reverse bias as shown in figure 3.



**Figure 3**

In this case the electrons in the *n*-side move away from the junction towards the positive terminal of the d. c. source and the holes in the *p*-side also move away from the junction towards the negative terminal of the d. c. source. They leave behind ions and the width of the depletion region increases, until the barrier potential equals the applied voltage. Thus reverse bias should not lead to any flow of current. However thermal energy continuously creates electron-hole pairs near the junction on both sides. A small current exists because of flow of minority carriers in both *p* and *n* regions. This reverse current depends more on temperature and less on voltage. This reverse current is very small. In this case Fermi-level moves down and the bands adjust their positions accordingly as shown in figure 3.

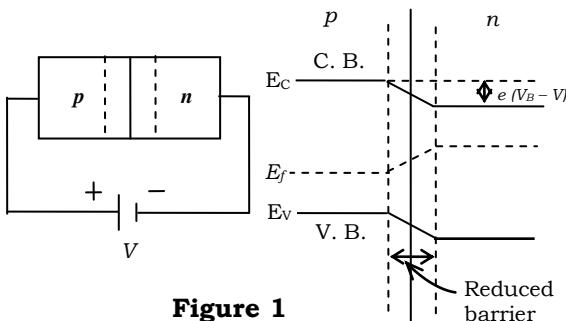
**Que.11. What is Fermi energy in a semiconductor? With the help of a labeled energy level diagram, show the position of Fermi level in case of a diode that is connected in forward bias.** [3]

**OR**

**Que.11. What is Fermi energy in a semiconductor? With the help of a labeled energy level diagram, show the position of Fermi level in case of a diode that is connected in reverse bias.** [3]

**Fermi Energy:** Fermi energy is the energy of fermi-level. Fermi-level is the highest possible level of an electron at absolute zero temperature.

**Forward Bias:** When a d. c. source is connected across the diode such that the positive terminal is connected to *p*-region and negative terminal is connected to *n*-region then the diode is said to be in forward bias as shown in **figure 1**.



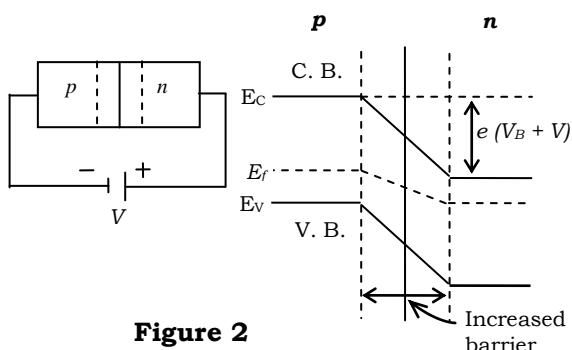
**Figure 1**

As the forward bias leads to increase the energy of electrons in *n*-region of the crystal the Fermi-level on *n*-side is raised by energy equal to  $eV$ . Where  $V$  is applied d.c. voltage. The bands adjust their positions to suite the elevation of the Fermi-level as shown in **figure 1**. The energy difference between conduction band in *p* and *n* region will be  $e(V_B - V)$ .

**OR**

**Reverse Bias:**

When a d.c. source is connected across the diode such that the positive terminal is connected to *n*-region and negative terminal is connected to *p*-region then the diode is said to be in reverse bias as shown in **figure 2**.



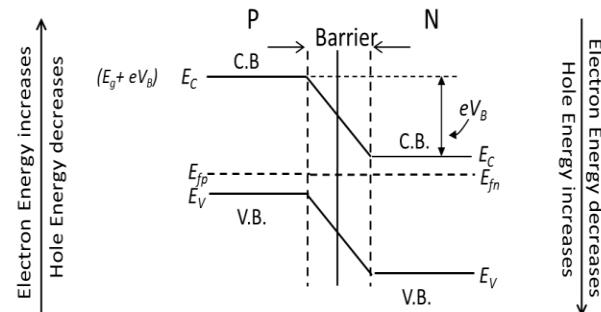
**Figure 2**

As the reverse bias leads to decrease the energy of electrons in *n*-region of the crystal the Fermi-level on *n*-side is drop down by energy equal to  $eV$ . Where  $V$  is applied d.c. voltage. The bands adjust their positions to suite the

elevation of the Fermi-level as shown in **figure 2**. The energy difference between conduction band in *p* and *n* region will be  $e(V_B + V)$ .

**Que.12. Derive the expression for barrier potential for a PN junction. [4]**

The internal potential barrier  $V_B$  can be calculated from the electron concentrations in *p* and *n* regions of the diode.



The electron concentration in the conduction band on the *n*-side can be written as,

$$n_n = N_c e^{-(E_g - E_f)/kT} \quad \dots \dots \dots (1)$$

Due to the barrier potential  $V_B$ , the band gap energy on *p*-region increases by  $(E_g + V_B)$ . The electron concentration on *p*-side can be written as,

$$n_p = N_c e^{-(E_g + eV_B) - E_f/kT} \quad \dots \dots \dots (2)$$

Dividing the two equations, we get

$$\frac{n_n}{n_p} = e^{eV_B/kT} \quad \dots \dots \dots (3)$$

Above equation shows that at thermal equilibrium, concentrations of electrons on both sides of the junction are related through Boltzmann factor.

Taking log of both sides,

$$V_B = \frac{kT}{e} \ln \frac{n_n}{n_p} \quad \dots \dots \dots (4)$$

This equation can be written as

$$V_B = \frac{kT}{e} \ln \frac{n_n p_p}{n_p p_p} \quad \dots \dots \dots (5)$$

At room temperature, all the impurities are ionized, hence:  $n_n = N_D$  &  $p_p = N_A$

Also,  $n_p p_p = n_i^2$

Thus, equation (5) can be written as,

$$V_B = \frac{kT}{e} \ln \frac{N_D N_A}{n_i^2}$$

The factor  $\frac{kT}{e}$  is of the dimensions of voltage and is denoted by  $V_T$ , Thus,

$$V_B = V_T \ln \frac{N_D N_A}{n_i^2} \quad \dots \dots \dots (6)$$

Thus, the barrier potential equation indicates that barrier potential in a junction diode depends on the equilibrium concentration of the impurities in p and n regions and does not depend on the charge density in the depletion region.

**Que.13. Derive the ideal diode equation for a PN junction. [4]**

When the diode is forward biased with potential  $V_F$ , the potential barrier is lowered by an amount of energy  $eV_F$  and the probability of a majority carrier crossing the junction and diffusion current density is increased by a factor of  $e^{eV_F/kT}$

Thus, diffusion current density components  $J_{hp}^*$  and  $J_{en}^*$  in forward bias diode are given by,

$$J_{hp}^* = J_{hp} e^{eV_F/kT} = J_{hn} e^{eV_F/kT} \quad \text{and}$$

$$J_{en}^* = J_{en} e^{eV_F/kT} = J_{ep} e^{eV_F/kT}$$

Where,  $J_{hp}$  and  $J_{en}$  are diffusion current densities in unbiased diode.

The drift current density components have not changed and have the same magnitude as in equilibrium case.

Therefore, the net hole current density across the forward bias junction is,

$$J_h = J_{hp}^* - J_{hn} = J_{hn} (e^{eV_F/kT} - 1)$$

Similarly, the net electron current density across the forward bias junction is

$$J_n = J_{en}^* - J_{ep} = J_{ep} (e^{eV_F/kT} - 1)$$

The total current density across the forward bias junction is the sum of electron and hole current density components. Thus,

$$J = J_e + J_h = J_{hn} - J_{en} (e^{\frac{eV_F}{kT}} - 1) = J_0 (e^{\frac{eV_F}{kT}} - 1)$$

$J = \frac{I}{A}$  is current density. Thus, above equation can be written as,

$$I = I_0 (e^{\frac{eV_F}{kT}} - 1)$$

$$\text{where, } I = \frac{J}{A} \text{ and } I_0 = \frac{J_0}{A}$$

The above equation is known as ideal diode equation where,  $V_F$  is forward voltage. In reverse bias it will be replaced by  $-V_R$  and  $I_0$  denotes reverse saturation current.

**Que.14. What is photovoltaic effect? Explain construction and working of solar cell. Draw IV characteristics of solar cell and define fill factor. [6]**

When light falls on a *p-n* junction produces a potential difference across it. This potential difference is capable of driving a current through an external circuit, producing useful work. This phenomenon is called the '**photovoltaic effect**'.

As thermal energy produces electron-hole pairs in the depletion region to contribute to the reverse current in a diode, current can also be made to flow by illuminating the diode with light of energy greater than the energy gap of the semiconductor used for making a diode. The light energy too creates electron-hole pairs and therefore leads to flow of current.

#### Construction:

The construction of solar cell is as shown in **figure 5.21**. A single crystal Silicon solar cell consists of an *n*-type Silicon wafer with a very thin (in microns) diffused *p*-type region at the surface to form a *p-n* junction. An ohmic contact is made at the bottom of *n*-type wafer. Another contact is made at the top of the *p*-type surface in such a way that the maximum

possible area of the *p*-layer can remain exposed. This surface is used to catch the sunlight. An antireflection coating is applied to reduce the amount of light lost by reflection from the surface. The cell is also covered at the top by glass quartz or sapphire plate, with additional antireflection and uv-rejection filters. The uv photons can degrade the cell performance by damaging it.

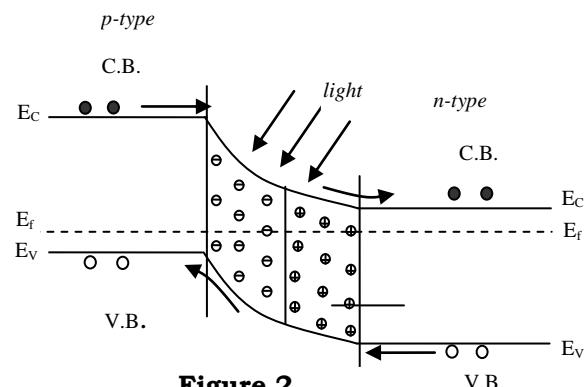


Figure 2

### Working:

When light falls on the *P*-region and reaches at the junction or absorbed by the junction, the electron-hole pairs are generated. They are generated as a minority carriers i.e. electrons in the *P*-region and holes in *N*-region. When they come at the junction they face the built in voltage (barrier potential) which separates them. The electrons moves from *P*-region to *N*-region (and the holes from *N*-region to *P*-region) because there are number of lower energy levels are available in *N*-region. This is shown in **figure 1**. This leads to an increase in the number of holes in *P*-region and electrons in *N*-region. The accumulation of charges on the two sides of the junction produces a voltage or emf known as photo emf. It is known as open circuit voltage and is proportional to the illumination as well as the illuminated area. When an external circuit is connected across the solar cell terminals, current flows through it. Thus solar cell behaves as battery with *N* side as a negative terminal and *P* side as a positive terminal.

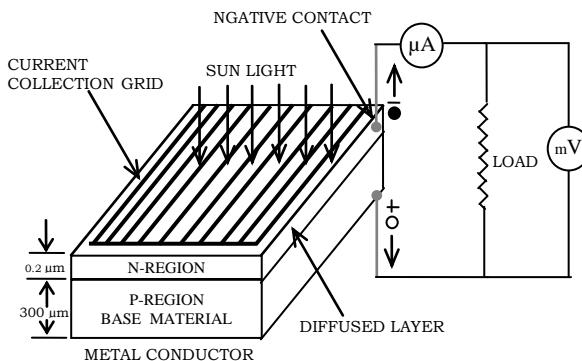


Figure 1

When the voltage is measured between the two ends of the cells, it will be maximum, which is called '**open circuit voltage**' ( $V_{OC}$ ). If the load is connected to cell, then carriers move in the circuit creating current and when value of load is minimum, current will be maximum which is called '**short circuit current**' ( $I_{SC}$ ).

### I-V Characteristics of Solar Cell:

When the solar cell is exposed to the light its IV characteristics is as shown in **figure 3**.

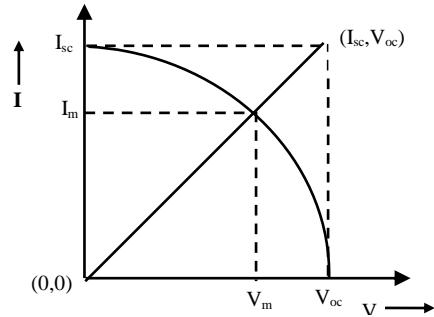


Figure 3

The product  $I_{SC} \times V_{OC}$  gives the theoretical (ideal) maximum power output from the solar cell. However, the actual maximum power is less than this and is given by the product  $I_m \times V_m$ .

The **fill factor** is defined as the ratio of actual maximum power to the ideal power.

$$\text{i.e. } FF = \frac{I_m \times V_m}{I_{SC} \times V_{OC}}$$

**Que.15. State measures to improve efficiency of solar cell. [4]**

There are number of technologies being developed for improving efficiency of solar cells. The efficiency of solar cell could be upto 45% depending on the technology used for its development. Higher the efficiency higher is the production cost or problem of scaling to mass level. The solar cells that are used for commercial purpose are developed using crystalline silicon technology with efficiencies ranging from 15 to 21.5%. Following are the ways of improving efficiency of solar cell:

**Fill factor:** Fill factor refers to the utilization of available surface area and it ranges from about 70 to 90%. The fill factor of solar panels depends on their shape e.g. round or moon shaped (lower fill factor), square cells (more fill factor).

**Solar Cells Glazing:** For long life, solar cells must be protected from the elements (rain, snow, hail, bird dropping etc). Polycarbonate or low-iron glass is generally used due to high optical transmissivity (around 90%). Surface coating treatments reduce reflections for even higher transmissivity.

**Solar Panel Orientation:** For highest output, solar panels must be perpendicular to the sun's rays. However, for roof-top installations solar panels are fitted as per the roof pitch and orientation. For other types of fixed installations, the azimuth is oriented to the south and tilt adjusted for the winter period sun as intensity is low in winter.

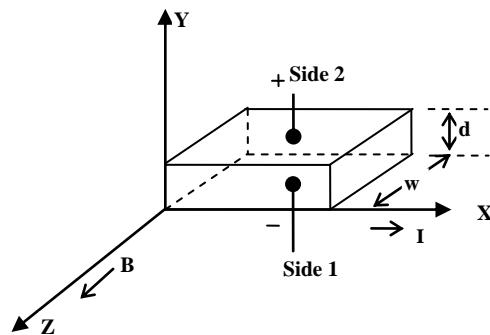
**Solar tracker:** Solar tracker is the rotation of the panel or array of solar cells so that they always directly face the sun. However, the larger the array, the more difficult will be the mechanics. The optimum tilt angle changes slowly as the earth rotates on its axis.

**Light Concentrators:** Solar panel output power may be increased to almost 50% via a light concentrator such as a Fresnel lens or mirror. However, installing concentrators for a large array of solar cells and orientation of the mirror creates an additional tracking problem.

**Solar Charge Controls:** Since the solar panel may not have the correct voltage to charge a battery, it must be controlled via a solar charge controller to prevent battery overcharge. The excess power needs to be dissipated using heat sink.

**Que.16. Explain Hall Effect. Derive the equation of Hall voltage and Hall coefficient. [6]**

Hall observed that, when a strip of semiconductor carrying current is placed in a transverse magnetic field, a potential difference was developed across the strip perpendicular to both direction of current and the magnetic field. The direction of electric field developed because of induced potential depends on whether the current is due to electrons or holes. In order to understand Hall Effect consider a rectangular strip of *n*-type semi-conductor material. Under the application of some potential difference, let current *I* flow through it along positive X-direction. Let the magnetic field *B* act along the positive Z-direction as shown in figure.



As the magnetic field is applied, the magnetic force acts along negative Y-direction. As the semiconductor is *n*-type, the charge carriers are electrons.

The magnitude of force is given by,

$$F_1 = B.e.v \quad \dots \dots \dots (1)$$

Where, *v* = drift velocity.

*e* = charge on electron.

Thus due to this force the electrons are forced to move in negative Y-direction and

soon obstructed by the walls of specimen and get accumulated there. Because of charge accumulation towards side 1, it becomes negatively charged w. r. t. side 2. The electric field is developed between side 1 and side 2 directed along negative Y-direction. This electric field opposes further movement of electrons towards side 1. In equilibrium condition the force due to electric field is balanced to the force due to magnetic field and the current flows in the positive X-direction only. At this stage a steady potential difference is produced between side 1 and side 2 called as 'Hall Voltage',  $V_H$ .

Let  $E$  be the electric field intensity due to Hall Voltage then,

$$F_2 = eE \quad \dots \dots \dots \quad (2)$$

From equations (1) and (2) we get,

$$eE = Bev$$

$$\therefore E = B.v \quad \dots \dots \dots \quad (3)$$

$$\text{But, } E = \frac{V_H}{d} \quad \dots \dots \dots \quad (4)$$

where,  $d$  = distance between side 1 & side 2.

From equations (3) and (4) we get,

$$\frac{V_H}{d} = B.v \quad \text{or}$$

$$V_H = B.v.d \quad \dots \dots \dots \quad (5)$$

We know that,

$$I = n.e.v.A$$

$$\therefore v = \frac{I}{n.e.A} \quad \dots \dots \dots \quad (6)$$

∴ Equation (5) becomes,

$$V_H = \frac{B.I.d}{n.e.A} = \frac{1}{n.e} \frac{B.I.d}{A} \quad \dots \dots \dots \quad (7)$$

where,  $n$  = carrier concentration

$A$  = cross section area of the material

$$= d.w$$

$$\therefore \frac{d}{A} = \frac{1}{w}$$

∴ Equation (7) becomes,

$$V_H = \frac{1}{n.e} \frac{B.I}{w} \quad \dots \dots \dots \quad (8)$$

Here,  $V_H$  is positive at side 2 w. r. t. side 1 as we considered the conduction is due to

electrons. ( $n$ - type semiconductor). If the side 2 is negative w. r. t. side 1 then the charge carriers are holes i.e. the semiconductor is  $p$ -type.

Thus measurement of Hall Voltage helps us to identify whether the given semiconductor is  $p$ -type or  $n$ -type.

In equation (8)  $B$ ,  $I$ ,  $w$ , and  $V_H$  can be measured and then the charge density  $n.e$  can be determined and from that the carrier concentration ( $n$ ) can be determined.

In equation (8) the quantity  $\frac{1}{n.e}$  is the property of the material of the specimen and is called as 'Hall coefficient' ' $R_H$ '

$$\therefore R_H = \frac{1}{n.e} \quad \dots \dots \dots \quad (9)$$

∴ equation (8) becomes,

$$V_H = R_H \frac{B.I}{w}$$

$$\therefore R_H = \frac{V_H \cdot w}{B.I} \quad \dots \dots \dots \quad (10)$$

We know that,

$$\sigma = n.e.\mu \quad \therefore \text{as } R_H = \frac{1}{n.e}$$

$$\sigma = \frac{1}{R_H} \cdot \mu$$

$$\therefore \text{Mobility} = \mu = R_H \cdot \sigma \quad \dots \dots \dots \quad (11)$$

Thus measurement of conductivity and Hall coefficient determines mobility of charge carriers.

Thus Hall Effect can be used for,

- Determination of type of semiconductor
- Determination of carrier concentration.
- Determination of mobility of carriers.

### Problems:

1. The mobilities of carriers in intrinsic germanium sample at room temperature are  $\mu_e = 3600 \text{ cm}^2 / \text{V.sec}$  and  $\mu_h = 1700 \text{ cm}^2 / \text{V.sec}$ . If the density of electrons is same as holes and is equal to  $2.5 \times 10^{13} / \text{cm}^3$ , calculate the conductivity. (Ans: 2.12 mho/m) [4]

2. Calculate the number of acceptors to be added to a germanium sample to obtain the resistivity of  $10 \Omega \text{ cm}$ . [4]

Given,  $\mu = 1700 \text{ cm}^2 / \text{V.sec}$

(Ans:  $3.676 \times 10^{14} / \text{cm}^3$ ) Calculate the conductivity of pure silicon at room temperature when the concentration of charge carriers is  $1.6 \times 10^{10} / \text{cm}^3$ . [4]

Given:  $\mu_e = 1500 \text{ cm}^2 / \text{V.sec}$  and  $\mu_h = 500 \text{ cm}^2 / \text{V.sec}$

(Ans:  $5.12 \times 10^{-6} \text{ mho/cm}$ )

3. Determine the mobility of electrons in copper assuming that each atom contributes one free electron for conduction. [4]

Given: For Cu,  $\rho = 1.7 \times 10^{-6} \Omega \text{ cm}$ ,

density =  $8.96 \text{ gm/cm}^3$  Atomic wt. = 63.5

(Ans:  $n_e = 8.496 \times 10^{22} / \text{cm}^3$ ,  $\mu_e = 43.273 \text{ cm}^2 / \text{V.sec}$ )

4. An N-type semiconductor is to have a Resistivity  $10 \Omega \text{ cm}$ , calculate the number of donor atoms which must be added to achieve this. [4]

Given:  $\mu_d = 500 \text{ cm}^2 / \text{V.sec}$

(Ans:  $n_d = 1.25 \times 10^{15} / \text{cm}^3$ )

5. Calculate the energy gap in silicon, given that it is transparent to radiation of wavelength greater than  $11000 \text{ \AA}^0$ . [2]

(Ans:  $E_g = 1.29 \text{ eV}$ )

6. In an N-type semiconductor the fermi-level lays 0.3 eV below the conduction band at room temperature. If the temperature is increased to 330 K, find the position of Fermi-level. [4]

(Ans: 0.33 eV)

7. A silver wire is in the form of ribbon 0.5 cm wide and 0.1 mm thick. When a current of 2 amp passes through the ribbon perpendicular to 0.8 Tesla magnetic field, calculate the Hall voltage produced. Given: For Silver, [4]

density =  $10.5 \text{ gm/cm}^3$ , Atomic wt. = 108 gm,

AvagadroNo. =  $6.02 \times 10^{23} / \text{gm.mole}$

(Ans:  $n_e = 6 \times 10^{28} / \text{m}^3$ ,  $V_H = 0.333 \times 10^{-7} \text{ V}$ ]

8. A copper specimen having length 1 m, width 1 cm & thickness 1 mm is conducting 1 amp current along its length and is applied with a magnetic field of 1 Tesla along its thickness. Hall voltage of  $0.1 \mu\text{V}$  is developed across its width. Calculate Hall coefficient and mobility

of electrons in copper. Given: conductivity of copper =  $5.8 \times 10^7 \text{ mho/m}$ . [4]

(Ans:  $R_H = 7.4 \times 10^{-11} \text{ m}^3 / \text{C}$ ,  $\mu = 4.3 \times 10^{-3} \text{ m}^2 / \text{V.sec}$ )

9. Calculate the conductivity of Ge specimen if a donor impurity is added to the extent of one part in  $10^8$  Ge atoms at room temperature. [4]

density of Ge =  $10.5 \text{ gm/cm}^3$ , Atomic wt. of Ge = 108 gm,

(Ans:  $\sigma = 0.268 \text{ mho/cm}$ )