Module 6: Basics of semiconductor Physics

Q.1 Define drift current, diffusion current and mobility of charge. (3m)

Ans:

Drift current is the electric current that results from the motion of charge carriers (such as electrons or holes) under the influence of an **applied electric field**.

When an electric field is applied across a conducting material (like a semiconductor or conductor), it exerts a force on the free charge carriers, causing them to move in a particular direction. This directed motion of carriers constitutes **drift current**.

The drift current density (J_d) can be expressed as:

$$J_d = n.q.\ \mu.E$$

Where,

n = number of charge carriers per unit volume,

q = charge of a single carrier (e.g., electron charge $=1.6\times10^{-19}$ C),

μ = mobility of the charge carriers,

E = applied electric field.

Diffusion current is the electric current that arises due to the **concentration gradient** of charge carriers.

If charge carriers (electrons or holes) have a higher concentration in one region than another, they will naturally move from the region of higher concentration to the region of lower concentration. This movement of carriers leads to **diffusion current**.

The diffusion current density (J_{diff}) can be expressed as:

$$J_{diff} = -q \cdot D \cdot \nabla n$$

Where,

q = charge of the carrier,

D= diffusion coefficient,

∇n = gradient of the carrier concentration (n).

The negative sign indicates that the current flows from regions of higher carrier concentration to lower concentrations.

The **mobility** of a charge carrier refers to the ability of a charge carrier to move in response to an applied electric field.

Mobility (μ) is a measure of how quickly a charged particle (electron or hole) moves through a material when exposed to an electric field.

Mobility (μ) is defined as:

$$\mu = V_d / E$$

where,

V_d = drift velocity of the carriers,

E = applied electric field.

The unit of mobility is typically expressed in **$m^2/V \cdot s$** (square meters per volt-second).

The **conductivity** of a semiconductor refers to its ability to conduct electric current. It is a measure of how easily charge carriers (electrons and holes) can move through the material under the influence of an electric field.

In semiconductors, conductivity depends on the presence of **free charge carriers** (electrons in the conduction band and holes in the valence band), which are influenced by factors such as temperature, doping, and electric fields.

The **electrical conductivity (σ)** of a semiconductor is given by:

$$\sigma = q\,(n\,\mu_n + p\,\mu_p)$$

where,

q = charge of a single electron or hole (1.6×10^{-19} coulombs),

n = number of electrons in the **conduction band** per unit volume,

p = number of holes in the **valence band** per unit volume,

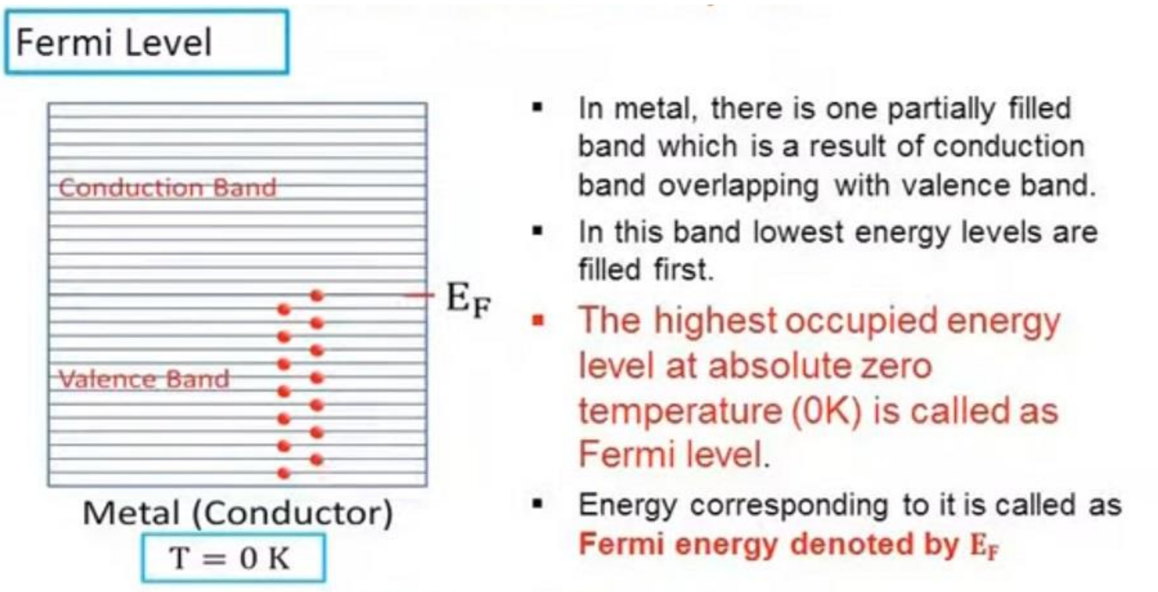
μ_n = mobility of electrons,

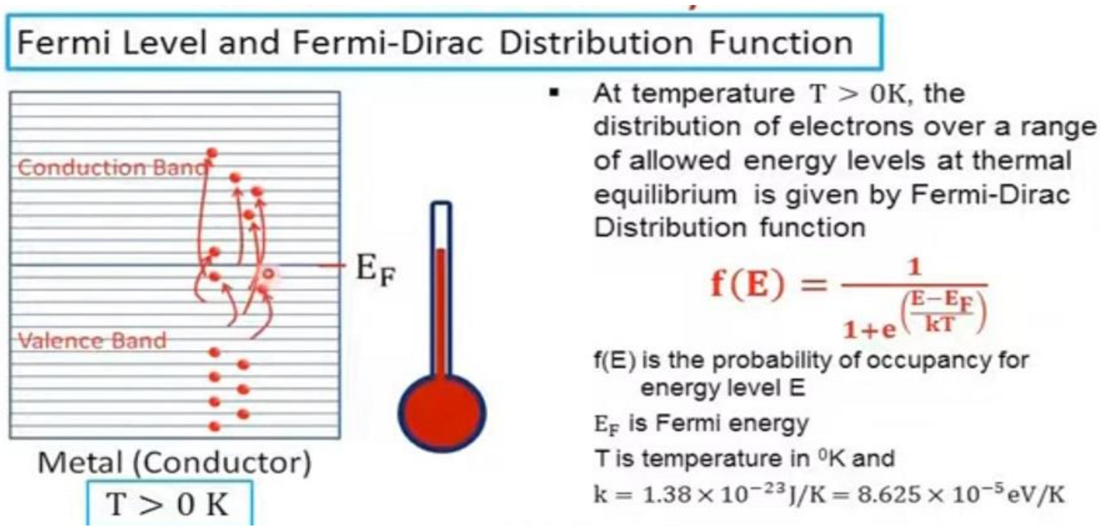
μ_p = mobility of holes.

For **intrinsic semiconductors**, $n=p$ (equal number of electrons and holes).

For **extrinsic semiconductors**, the number of electrons or holes can vary depending on the type of doping (n-type or p-type).

Q.2 What is Fermi level? Write Fermi Dirac distribution function.(3m)





When $E<E_F$:

- The exponent $(E-E_F)/(k_BT)$ is negative because E is less than E_F,
- f(E) is close to 1, meaning that states below the Fermi level are highly likely to be occupied.

When $E>E_F$:

- The exponent $(E-E_F)/(k_BT)$ is positive because E is greater than E_F ,
- f(E) is close to 0, meaning that states above the Fermi level are unlikely to be occupied.

At T = 0 K:

- $f(E)=1$ for $E<E_f$,
- $f(E)=0$ for $E>E_F$,
- The distribution becomes a step function at T=0 K.

Q. 3 For intrinsic semiconductor show that the Fermi level lies in the centre of the forbidden energy gap.(3m)

- It can be shown for intrinsic semiconductors, Fermi energy level E_F lies midway between conduction and valence band. The proof is given below.
- At any temperature T > 0° K,

$$n_e = \text{Number of electrons in conduction band}$$

$$n_v = \text{Number of holes in valence band}$$

We have $n_e = N_C e^{-(E_C - E_F)/KT}$ ...(6.7.4)

Where N_C = Effective density of states in conduction band

And $n_v = N_V e^{-(E_F - E_V)/KT}$ ...(6.7.5)

Where N_V = effective density of states in valance band

For best approximation $N_C = N_V$ ...(6.7.6)

For intrinsic semiconductor $n_C = n_v$

$$\therefore N_C \cdot e^{-(E_C - E_F)/KT} = N_V \cdot e^{-(E_F - E_V)/KT}$$

$$\therefore \frac{e^{-(E_C - E_F)/KT}}{e^{-(E_F - E_V)/KT}} = \frac{N_V}{N_C}$$

$$\therefore e^{-(E_C - E_F - E_F + E_V)/KT} = \frac{N_V}{N_C}$$

$$\therefore e^{-(E_C + E_V - 2E_F)/KT} = \frac{N_V}{N_C}$$

as $N_V = N_C = 1$

$$e^{-(E_C + E_V - 2E_F)/KT} = 1$$

$\therefore$ Taking *ln* on both sides

$$\frac{-(E_C + E_V - 2E_F)}{KT} = 0$$

$$\therefore (E_C + E_V) = 2E_F$$

$$\therefore E_F = \frac{E_C + E_V}{2} \quad ...(6.7.7)$$

Thus, the Fermi level in an intrinsic semiconductor lies at the center of forbidden energy gap.

Q.4 Discuss the effect of variation in temperature on the Fermi energy level of n-type Semiconductor with the help of labelled diagram.(3m)

(i) **At low temperature :** When the temperature in the semiconductor is low, only few donor atoms get ionized and electrons move from the donor level to the conduction band.

Hence, Fermi level for n-type semiconductor at low temperature lies midway between the bottom of the conduction band and donor level.

(ii) **At moderate temperature :** At moderate temperature all donor atoms are ionized. So, the concentration of electrons in conduction band is equal to the concentration of donor atoms.

When the temperature increases upto moderate value, Fermi level slowly shifts away from the conduction band and moves towards the center of the forbidden gap.

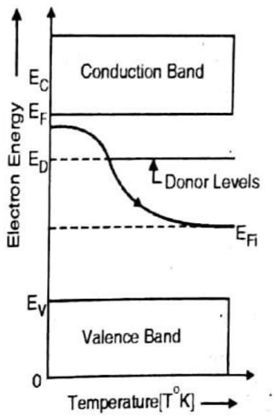


Fig. 6.8.1: Variation of E_F with temperature in n-type material

(iii) **At higher temperature :** At high temperature, the concentration of transfer of electrons from valence band to conduction band is more compared to concentration of electrons from donor atoms and Fermi level is shifted to middle of the forbidden gap.

The variation of Fermi level with temperature for n-type of material is shown in Fig. 6.8.1.

Q.5 Discuss the effect of variation in temperature on the Fermi energy level of p-type Semiconductor with the help of labelled diagram.(3m)

(i) At low temperature : At low temperature only few acceptor levels are occupied, and simultaneously holes are produced in valence band.

So, Fermi level lies in the middle of the top of the valence band and the acceptor level.

(ii) At moderate temperature : At moderate temperature, all acceptor levels are filled.

So, at moderate temperature, Fermi level gradually moves up i.e. moves towards the middle of the forbidden gap.

(iii) At higher temperature : At very high temperature, the contribution of conduction band for the formation of holes in the valence band is more compared to acceptor impurity.

Hence, at very higher temperature, Fermilevel approaches the middle of the energy gap i.e. the position of E_{Fi} for intrinsic semiconductor. The variation of E_F with temperature in p- type material is shown in Fig. 6.8.2.

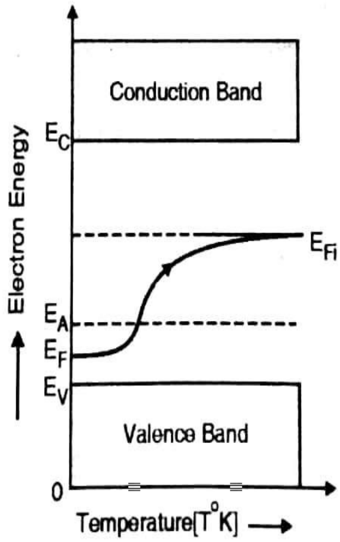


Fig. 6.8.2 : Variation of E_F with temperature in p-type material

Q.6 Draw and explain Fermi level diagram of p-n junction diode? (5m)

Ans: Refer solution of Q.4 and Q.5 for this question.

Q.7 Draw Fermi level and explain it in detail for conductors.(5m)

(a) At T = 0° K

- At 0° K electrons occupy the lower energy levels in the conduction band leaving upper energy levels vacant.
- The band is filled up to a certain energy level E_F, therefore Fermi level may be regarded as the uppermost filled energy level in conductor at 0°K. Let us see some important conclusions from Equation (6.6.1).

At T = 0° K, levels below E_F have $E < E_F$

$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/KT}} = \frac{1}{1+e^{-\infty}} = \frac{1}{1+0} = 1$$

f(E) = 1 means all the levels below E_F are occupied by electrons.

At T = 0° K, levels above E_F have $E > E_F$

$$\therefore f(E) = \frac{1}{1+e^{(E-E_F)/KT}} = \frac{1}{1+e^{\infty}} = \frac{1}{1+\infty} = 0$$

$\therefore$ f(E) = 0 means all the levels above E_F are vacant.

At T = 0° K, for $E = E_F$

$$f(E) = \frac{1}{1+e^{(E-E_F)/KT}} = \frac{1}{1+e^{0/0}}$$

$\therefore$ f(E) is indeterminable.

This is summarized in Fig. 6.6.2.

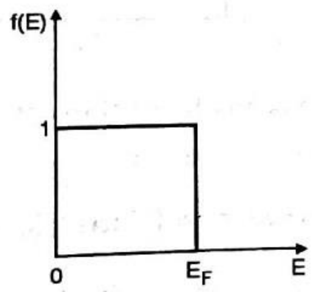


Fig. 6.6.2 : Fermi-Dirac distribution at T = 0°K

(b) At T > 0° K

- At temperature above 0° K, few electrons are excited to vacant levels above E_F. This happens to those electrons which are close to E_F hence probability to find an electron at $E > E_F$ will become greater than unity which was zero at T = 0° K.
- Similarly, due to excitation of electrons, few levels just below E_F will be become vacant and f(E) will be slightly reduced which was unity at T = 0° K.
- In a simple way one can understand that, what increase in f(E) at T > 0° K above $E = E_F$ we get is equal to reduction in f(E) below $E = E_F$. This is shown as below in Fig. 6.6.3.

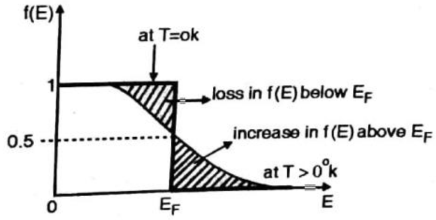


Fig. 6.6.3 : Electron occupancy at T > 0°K

$$\text{At } E = E_F \text{ for } T > 0° K$$

$$f(E) = \frac{1}{1+e^{0}} = \frac{1}{1+1} = \frac{1}{2} = 0.5$$