MODULE II

SEMICONDUCTORS & TRANSPORT PHYSICS

3.2 INTRINSIC SEMI-CONDUCTORS &CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTOR

A semiconductor in pure form is called intrinsic semiconductor. At 0K the conduction band is empty and valence band is completely filled. Hence it behaves as an insulator at 0K.

When the temperature is increased ,the electrons are moving from valence band to conduction band as shown in figure.Hence there are free electrons in the conduction band to produce current. Hence it behaves as conductor.

No of electrons in condction band = No of hole in valence band

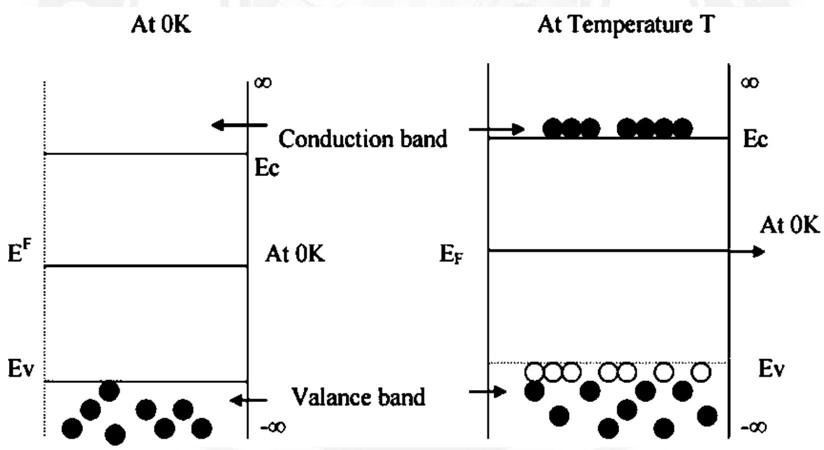

Fig 3.2 Energy band diagram of Intrinsic Semi Conductor

3.2.1.DENSITY OF ELECTRONS IN CONDUCTION BAND

$$n = \int_{Ec}^{\infty} Z(E)dE\,(F(E)) \quad \text{----------------(1)}$$

$$Z(E)dE = \frac{4\pi}{h^3}\,(2m_e^*)^{\frac{3}{2}} E^{\frac{1}{2}}\,dE$$

Me^* --effective mass of electron

Here E= E- E_c --------------------------(3)

Since to move an electron from valavce band to conduction band the energyrequired is greater then 4 K_BT (i.e) $E - E_F >> K_BT$ (or) $(E - E_F) / K_BT >> 1$

$$(or)\ e^{(E-E_F)/K_BT} >> 1$$

$$1 + e^{(E-E_F)/K_BT} = e^{(E-E_F)/K_BT} \quad ---------------------- (4)$$

$$n=\int_{Ec}^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} (E-Ec)^{1/2}\, e^{\frac{Ef-E}{KT}} dX \quad ----(5)$$

Put	Lower limit	Upper Limit
$E-E_c = X$	$E = E_c$	$E = \infty$
$E = E_c + X$	$X = E-E_c$	$X = \infty$
$dE = dX$	$X=0$	

(5) becomes

$$n=\int_0^{\infty} \frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \quad X^{1/2}\, e^{\frac{Ef-X-Ec}{KT}} dX$$

$$n=\frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} \int_0^{\infty} X^{1/2} \quad e^{\frac{Ef-X-Ec}{KT}} dX$$

$$n=\frac{4\pi}{h^3} (2m_e^*)^{\frac{3}{2}} e^{\frac{Ef-Ec}{kT}} \int_0^{\infty} X^{1/2} \quad e^{\frac{-X}{KT}} Dx$$

$$n=\frac{4\pi}{h^3} (2m_e{}^{*})^{\frac{3}{2}} e^{\frac{Ef-Ec}{kT}} \frac{\pi^{1/2}(KT)^{3/2}}{2}$$

$$n = 2\,\frac{(2\pi m_e^* kT)^{\frac{3}{2}}}{(h^2)^{3/2}}\, e^{\frac{Ef-Ec}{kT}} \quad ----------------(6)$$

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

3.2.2 DENSITY OF HOLES IN VALENCE BAND.

$$P = \int_{-\infty}^{Ev} Z(E)dE\,\left(1-F(E)\right) \quad ------------------(7)$$

$$Z(E)dE = \frac{4\pi}{h^3} (\, 2m_h^*)^{\frac{3}{2}} E^{\frac{1}{2}}\, dE$$

M_h^* --effective mass of hole

Let the maximum energy in valance band be Ev and the minimum energy be -∞.Therefore, density of hole in valance band is given by

$$P = \int_{-\infty}^{Ev} \frac{4\pi}{h^3}\,(2m_h^*)^{\frac{3}{2}}(Ev-E)^{1/2}\,dE(1-F(E)) \qquad \text{------------(8)}$$

Here

$$1 - F(E) = 1 - \frac{1}{(E\text{-}E_F)/K_BT}$$

$$1 - F(E) = \frac{e^{(E\text{-}E_F)/kT}}{1 + e^{(E\text{-}E_F)/K_BT}}$$

Here $E - E_F << K_BT$, $(E - E_F)/K_BT << 1$

$$e^{(E-E_F)/K_BT} << 1$$

$$1 + e^{(E-E_F)/K_BT} = 1$$

$$1 - F(E) = e^{(E\text{-}E_F)/K_BT}$$

Substituting this in (8)We get

$$P = \int_{-\infty}^{Ev} \frac{4\pi}{h^3}\,(2m_h^*)^{\frac{3}{2}}(Ev-E)^{1/2}\,dE\,e^{\frac{E-Ef}{kT}} \qquad \text{-----------------(9)}$$

Put	Lower limit	Upper Limit
E_v-E = X	E = -∞	E = E_v
E=E_v - X	X = E_v-E	X =0
dE =-dX	X= ∞	

(9) becomes

$$P=\int_{\infty}^{0} \frac{4\pi}{h^3}\,(2m_h^*)^{\frac{3}{2}}\,X^{1/2}\,e^{\frac{Ev-X-Ef}{KT}}(-dX)$$

$$P=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}\int_0^{\infty} X^{1/2}\quad e^{\frac{Ev-X-Ef}{KT}}dX$$

$$P=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}e^{\frac{Ev-Ef}{kT}}\int_0^{\infty} X^{1/2}\quad e^{\frac{-X}{KT}}\,dX$$

$$P=\frac{4\pi}{h^3}(2m_h^*)^{\frac{3}{2}}e^{\frac{Ev-Ef}{kT}}\,\frac{\pi^{1/2}KT^{3/2}}{2}$$

$$P= 2\frac{(2\pi m_h^* kT)^{\frac{3}{2}}}{(h^2)^{3/2}} e^{\frac{Ev-Ef}{kT}} \quad \text{----------------(6)}$$

This is the expression for density of holes in valence band.

3.2.3CARRIER CONCENTRATION IN AN INTRINSIC SEMICONDUCTORS.

We know that

The number of electrons in conduction band =The number of holes in valence band = CARRIER CONCENTRATION

$$\text{ie } n= P =n_i$$

$$n_i^2 = n_i \times n_i = nxp$$

$$n_i^2 = 2\frac{(2\pi m_e^* kT^{\frac{3}{2}}}{(h^2)^{3/2}} e^{\frac{Ef-Ec}{kT}} \times 2\frac{(2\pi m_h^* kT)^{\frac{3}{2}}}{(h^2)^{3/2}} e^{\frac{Ev-Ef}{kT}}$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^{\frac{3+3}{2}} m_e^{*\,3/2} m_h^{*\,3/2} e^{\frac{Ef-Ec+Ev-Ef}{KT}}$$

$$= 4\left(\frac{2\pi kT}{h^2}\right)^{\frac{6}{2}} (m_e^* m_h^*)^{3/2} e^{\frac{-Ec+Ev}{KT}}$$

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{3/2} e^{\frac{-Eg}{KT}}$$

$$\boxed{n_i = 2\left(\frac{2\pi kT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4}} e^{\frac{-Eg}{2KT}}$$

This is the expression for carrier concentration in Intrinsic semi conductor.

3.2.4.Variation of Fermi function with respect to temperature

We know that

Density of elecctrons in conduction band = Density of holes in valence band

$$2\frac{(2\pi m_e^* kT)^{\frac{3}{2}}}{(h^2)^{3/2}} e^{\frac{Ef-Ec}{kT}} = 2\frac{(2\pi m_h^* kT)^{\frac{3}{2}}}{(h^2)^{3/2}} e^{\frac{Ev-Ef}{kT}}$$

$$\frac{e^{\frac{Ef-Ec}{kT}}}{e^{\frac{Ev-Ef}{kT}}} = \frac{m_h^{*\,3/2}}{m_e^{*\,3/2}}$$

$$e^{\frac{Ef-Ec-Ev+EF}{kT}} = \frac{m_h^{*\,3/2}}{m_e^{*\,3/2}}$$

Taking log on both side

$$\frac{2Ef - Ec - Ev}{kT} = \log(\frac{m_h^{*\frac{3}{2}}}{m_e^{*\frac{3}{2}}})$$

$$2Ef - Ec - Ev = kT\log(\frac{m_h^{*\frac{3}{2}}}{m_e^{*\frac{3}{2}}})$$

$$2Ef = E_c + E_v + kT\log(\frac{m_h{}^*}{m_e{}^*})^{3/2}$$

$$Ef = \frac{E_c + E_v}{2} + \frac{kT}{2}\log(\frac{m_h{}^*}{m_e{}^*})^{3/2}$$

$$Ef = \frac{E_c + E_v}{2} + \frac{3kT}{4}\log(\frac{m_h{}^*}{m_e{}^*})$$

This is the expression for Fermi level for an intrinsic semi conductor.

Variation with temperature

Case 1:At T =0K

If $m_h^* = m_e^*$

Then $E_F = \frac{E_c+E_v}{2}$

Fermi level lies half way between the valence band and conduction band.

Case 2: As the temperature is increased Fermi level shifts upwards as in fig.

Case 3: In real $m_h^* > m_e^*$ Fermi level rises with temperature.