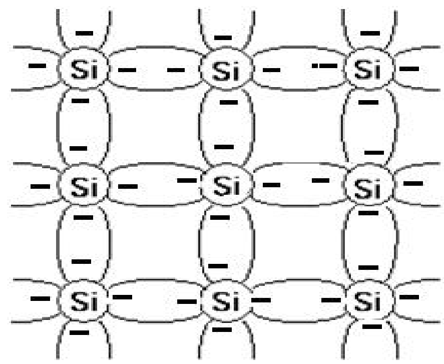
SEMICONDUCTORS

Material which allows partial flow of electricity through it is called semiconductor .Conductivity of semiconductor lies between conductors and insulators.

Silicon and Germanium are the examples for semiconductors. The energy gap for Si is 1.1eV and for Ge is 0.7eV.

INTRINSIC or PURE SEMICONDUCTOR



Let us consider 'Si' with atomic no. 14 and valence is 4. All the silicon atoms form covalent bonds with the neighboring Si atom and no electron is free for conduction at temperature 0 k. Hence pure silicon acts as *insulator* at absolute o k, as the temperature increases above 0 k, these covalent bonds break and some electrons are released. These electrons move in the crystal freely and responsible for conductivity. So they are called free electrons. Each electron leaves behind an empty space called a hole which also acts as current carrier. These electrons and holes move in opposite directions under the effect of external field and constitute current.

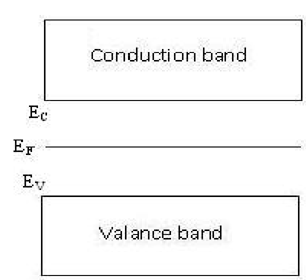
ELECTRON CONCENTRATION IN THE CONDUCTION BAND OF INTRINSIC SEMICONDUCTOR

The no. of electrons per unit volume having energy in a range E and E+dE in the conduction band of an intrinsic semiconductor is,

dn = Z(E)dE F(E) ----------(1)

where F(E) represents the Fermi distribution function gives the probability of occupation of electron with energy E.

$$F(E) = \frac{1}{1+\exp\left(\frac{E-E_F}{K_B T}\right)}$$



Z(E) is the density of states i.e. no. of available states per unit volume of semiconductor.

$$Z(E) = \frac{4\Pi}{h^3}(2m)^{3/2} E^{1/2}$$

$$dn = \frac{4\Pi}{h^3}(2m)^{3/2} E^{1/2} \cdot \frac{1}{1+\exp\left(\frac{E-E_F}{K_B T}\right)} dE$$

For conduction band,

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2}(E-Ec)^{1/2} \cdot \frac{1}{1+\exp\left(\frac{E-E_F}{K_B T}\right)} dE \text{ -------------- } (2)$$

Where m_e^* is effective mass of electron in the conduction band.

in the above equation, for conduction band, $\exp\left(\frac{E-E_F}{K_B T}\right) >> 1$ so 1 can be neglected in the denominator of the equ.(2).

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2}(E-Ec)^{1/2} \exp\left(\frac{-(E-E_F)}{K_B T}\right) \text{ -------------}(3)$$

To get the total no. of electrons per unit vol. in the conduction band is we have to integrate the above equ. Between the bottom of the conduction to top of the conduction band.

$$\therefore n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_F)}{K_B T}\right) dE$$

$$dn = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_F+E_c-E_c)}{K_B T}\right) dE$$

$$n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_{E_c}^{\infty} (E-Ec)^{1/2} \exp\left(\frac{-(E-E_c)}{K_B T}\right) dE$$

put $x = \left(\frac{(E-E_c)}{K_B T}\right)$, so that $dE = K_B T dx$

Lower Limit: when $E = E_c$, $x = 0$ and
Upper Limit: when $E = \infty$, $x = \infty$

$$\therefore n = \frac{4\Pi}{h^3}(2m^*_e)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_{0}^{\infty} e^{-x} (xK_B T)^{1/2} K_B T \, dx$$

$$n = \frac{4\Pi}{h^3}(2m^*_e k_B T)^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \int_{0}^{\infty} e^{-x} (x)^{1/2} \, dx$$

$$n = 4\Pi \left[\frac{2m^*_e k_B T}{h^2}\right]^{3/2} \exp\left(\frac{(E_F-E_c)}{K_B T}\right) \frac{\sqrt{\pi}}{2}$$

$$n = 2\left[\frac{2\,\Pi m_e^* k_B T}{h^2}\right]^{3/2} \exp\left(-\frac{(E_c - E_F)}{K_B T}\right)$$

$$n = N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right)$$

$$\text{Where } N_c = 2\left[\frac{2\,\Pi m_e^* k_B T}{h^2}\right]^{3/2}$$

HOLE CONCENTRATION IN THE VALENCE BAND OF INTRINSIC SEMI CONDUCTOR

The no. of holes per unit volume having energy in a range E and E+dE in the valence band of an intrinsic semiconductor is,

dp = Z(E)dE [1-F(E)] ----------(1)

where [1-F(E)]represents the probability of absence of electron in the particular energy level with energy E.

$$[1-F(E)] = 1- \frac{1}{1 + \exp\left(\frac{E - E_F}{K_B T}\right)} = \frac{\exp\left(\frac{E - E_F}{K_B T}\right)}{1+\exp\left(\frac{E - E_F}{K_B T}\right)}$$

For the valance band 1>> $\exp\left(\frac{E - E_F}{K_B T}\right)$.

So exponential term can be neglected in the denominator of the above equation.

$$\therefore [1-F(E)] = \exp\left(\frac{E - E_F}{K_B T}\right)$$

$$dP = \frac{4\Pi}{h^3}(2m)^{3/2} E^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

For valance band,

$$dp = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} (E_v - E)^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

To get the total no. of holes in the V.B. we have to integrate the above equation between the limits bottom of the V.B. to top of the V.B.

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \int_{-\infty}^{E_v} (E_v - E)^{1/2} \exp\left(\frac{E - E_F}{K_B T}\right) dE$$

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \int_{-\infty}^{E_v} (E_v-E)^{1/2} \exp\left(\frac{E - E_F + E_V - E_V}{K_B T}\right) dE$$

$$p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \exp\left(\frac{E_V - E_F}{K_B T}\right) \int_{-\infty}^{E_v} (E_v-E)^{1/2} \exp-\left(\frac{E_V - E}{K_B T}\right) dE$$

put $\left(\frac{E_V - E}{K_B T}\right) = x$; $dE = -dx\, K_B T$

Lower Limit: when $E = -\infty$, $x = \infty$.
Upper Limit: when $E = E_v$, $x = 0$.

$$\therefore\ p = \frac{4\Pi}{h^3}(2m^*_h)^{3/2} \exp\left(\frac{E_V - E_F}{K_B T}\right) \int_{\infty}^{0} e^{-x} (xK_B T)^{1/2} (-K_B T\, dx)$$

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

$$p = \frac{4\Pi}{h^3}(2\, m_h^* K_B T)^{3/2} \exp\left(\frac{E_V - E_F}{K_B T}\right) \frac{\sqrt{\Pi}}{2}$$

$$p = 2\left(\frac{2m_h^* \pi k_B T}{h^2}\right)^{\frac{3}{2}} \exp\left(\frac{E_V - E_F}{K_B T}\right) \text{ or}$$

$$p = N_v \exp-\left(\frac{E_F - E_V}{K_B T}\right) \text{----------- (2)}$$

Where $N_v = 2\left(\frac{2m_h^* \pi k_B T}{h^2}\right)^{\frac{3}{2}}$

Equ. (2) gives the no. of holes in the V.B of the intrinsic semi conductor.

LOCATION OF FERMI LEVEL IN INTRINSIC SEMICONDUCTOR

In intrinsic semiconductor no. of electrons in the C.B and no. of holes in the V.B are equal.

$\therefore\ n = p$

$$N_c \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) = N_v \exp-\left(\frac{E_F - E_V}{K_B T}\right)$$

$$\exp\left(\frac{-E_c + E_F + E_F - E_v}{K_B T}\right) = \frac{\mathrm{Nv}}{\mathrm{N_C}}$$

$$\frac{2E_F}{K_B T} - \frac{(E_C + E_V)}{K_B T} = \ln \frac{\mathrm{Nv}}{\mathrm{N_C}}$$

$$E_F = \frac{(\mathrm{Ec}+\mathrm{Ev})}{2} + \frac{K_B T}{2} \ln \frac{\mathrm{Nv}}{\mathrm{N_C}} \text{ ----------- (1)}$$

At T = 0 k,

$$E_F = \frac{(\mathrm{Ec}+\mathrm{Ev})}{2} \text{ -------- (2)}$$

Fermi energy level lies exactly in the middle of the forbidden gap at absolute zero K.

INTRINSIC CARRIER CONCENTRATION (n_i) [law of mass action]

In the intrinsic semiconductor, n = p = n_i. Where n_i is known as intrinsic carrier concentration.

$\therefore$ np = n_i^2

$$n_i^2 = 2\left[\frac{2\,\mathrm{m}_e^* \pi \mathrm{k_B T}}{\mathrm{h}^2}\right]^{3/2} \exp\left(-\frac{(E_c - E_F)}{K_B T}\right) 2\left(\frac{2m_h^* \pi k_B T}{h^2}\right) \exp-\left(\frac{E_F - E_V}{K_B T}\right)$$

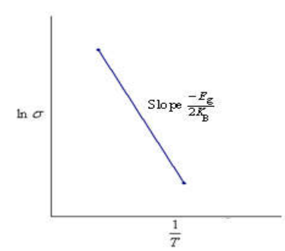
$$n_i^2 = 4\left[\frac{2\,\Pi \mathrm{k_B T}}{\mathrm{h}^2}\right]^3 \left(m_e^* m_h^*\right)^{3/2} \exp\left(\frac{-E_c + E_F - E_F + E_V)}{K_B T}\right)$$

$$n_i^2 = 4\left[\frac{2\,\Pi \mathrm{k_B T}}{\mathrm{h}^2}\right]^3 \left(m_e^* m_h^*\right)^{3/2} \exp\left(\frac{-(E_c - E_V)}{K_B T}\right)$$

$$n_i = 2\left[\frac{2\,\Pi \mathrm{k_B T}}{\mathrm{h}^2}\right]^{3/2} \left(m_e^* m_h^*\right)^{3/4} \exp\left(\frac{-E_g)}{2K_B T}\right) \quad (\text{since } E_c - E_v = E_g)$$

This equ Shows that for a given semiconductor the product of holes and electron concentration at a given temp. is equal to square of the intrinsic semiconductor carrier concentration. This is called law of mass action and holds both for intrinsic and extrinsic semiconductors.

CONDUCTIVITY OF INTRINSIC SEMICONDUCTORS



When the electric field is applied to the semiconductor, charge carriers acquire velocity.

$v_d \propto E$

$v_d = \mu E$ --------- (1)

where μ is called mobility of charge carriers.