

SEMICONDUCTOR DEVICES

* Why n-type & p-type are electrically neutral?

→ Electronics is nothing but applied semiconductor devices.

Classical e⁻ theory :-

$$F = ma \quad \text{and} \quad F_e = -eE$$

$$\therefore F_R = F_E \Rightarrow -\frac{mv}{\tau}$$

So,

$$m \frac{dv}{dt} = -eE = -\frac{mv}{\tau}$$

$$\text{as } \frac{dv}{dt} = 0$$

$$eE = -\frac{mv}{\tau}$$

$$v = -\frac{eEt}{m}$$

→ This velocity is drift velocity.

So,

$$v_d = -\frac{eEt}{m}$$

* The velocity possessed by a charged particle in presence of a field is called drift velocity.

* Time interval between successive collision of an e⁻ and inside lattice while it is moving under the influence of an E is defined as relaxation time τ .

Current density $J = \rho v_d$ ^{charge density}

$$\Rightarrow J = (ne) v_d - \textcircled{1}$$

also,

$$J = \sigma E - \textcircled{2}$$

by $\textcircled{1} + \textcircled{2}$

$$\sigma E = nev_d$$

$$E = ne \left(\frac{eEI}{m} \right)$$

$$\sigma = \frac{ne^2 I}{m} - \textcircled{A}$$

Now, mobility $(\mu = \frac{v_d}{E})$

→ mobility is defined as drift velocity per unit E .

$$\mu = \frac{1}{E} \times \left(\frac{eEI}{m} \right) \Rightarrow \frac{eI}{m}$$

$$\mu = \frac{eI}{m} - \textcircled{B}$$

Using eqn \textcircled{A} and \textcircled{B}

$$\sigma = ne\mu$$

also,

$$\rho = \frac{1}{\sigma}$$

$$\rho = \frac{1}{ne\mu}$$

Success of classical theory :-

- (1) It explains Ohm Laws.
- (2) It explains conductivity possessed by metal successfully.
- (3) It can't explain conductivity possessed by semiconductors & insulators.
- (4) It can't explain photoelectric effect, compton effect & black body radiation spectrum.
- (5) It fails to explain ferrromagnetism possess by material

Ques. $\rho_{silver} = 10.5 \times 10^3 \text{ kg/m}^3$
 $\text{atomic wt} = 107.9$

Assume each silver atom can provide one conduction e⁻.
Calculate e⁻ density and mobility. (conductivity of silver is $6.8 \times 10^7 \text{ ohm/m}$)

Soln

No. of e⁻ existing per unit volume.
 $\Rightarrow \frac{\rho \times \text{avagadro no.}}{\text{mol weight}}$

$$n = \frac{10.5 \times 10^3 \times 6.023 \times 10^{23}}{107.9}$$

$$\left[n = 5.86 \times 10^{28} \text{ / m}^3 \right]$$

Also, $\sigma = n e \mu$

$$\Rightarrow \mu = \frac{\sigma}{n e}$$

$$\mu = \frac{6.8 \times 10^7}{5.86 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$\left[\mu = 0.72 \times 10^{-4} \frac{\text{m}^2}{\text{Volts.s}} \right]$$

Ques. find mobility, relaxation time of an e⁻ of ~~the~~ Copper atom obeying classical laws.

$$\rho_{Cu} = 8.92 \times 10^3 \text{ kg/m}^3$$

resistivity of Cu = 1.73×10^{-8} .

$$m = 63.5$$

$$\sigma = \mu \times n_e$$

$$\frac{1}{\rho} = n_e \mu$$

$$\mu = \frac{1}{n_e f}$$

$$\mu = \frac{1}{0.45 \times 10^{28} \times 1.6 \times 10^{-19} \times 1.73 \times 10^{-8}}$$

$$n = \frac{\rho \times N_A}{m}$$

$$n = \frac{8.92 \times 10^3 \times 6.02 \times 10^{26}}{63.5}$$

$$n = 0.45 \times 10^{28}$$

$$\left\{ \mu = 4.0 \times 10^{-1} \frac{\text{m}^2}{\text{V} \cdot \text{s}} \right\}$$

$$0.0487 \frac{\text{m}^2}{\text{V} \cdot \text{s}}$$

Ques. Calculate free e⁻ concn, mobility, σ in an Al wire of length 5 m and resistance is 0.06 Ω. carrying a current of 15 A. Assume that each Al atom constitutes free e⁻ for conduction.

$$\rho = 2.78 \times 10^{-8} \text{ ohm m}$$

$$m = 26.98$$

$$\text{density} = 2.7 \times 10^3 \text{ kg/m}^3$$

$$n = \frac{\rho \times N_A}{m}$$

$$\Rightarrow \frac{2.7 \times 10^{-8} \times 6.023 \times 10^{26}}{26.98}$$

$$n \Rightarrow \underline{\underline{6.02 \times 10^{28} / \text{m}^3}}$$

$$U_M = \frac{qE}{m}$$

NOW,

$$\rho = \frac{1}{ne\mu}$$

$$\mu = \frac{1}{ne\rho}$$

$$\mu = \frac{1}{6.02 \times 10^{28} \times 1.6 \times 10^{-19} \times 2.78 \times 10^{-8}}$$

$$\left[\mu = 0.0037 \frac{m^2}{V \cdot s} \right]$$

also,

$$\sigma E = nev_d$$

$$\frac{1}{\rho} \times \frac{v}{d} = nev_d$$

$$\frac{v}{ne\rho d} = v_d$$

$$v_d = \frac{iR}{ne\rho d}$$

$$v_d = \frac{15 \times 0.06}{6.02 \times 10^{28} \times 1.6 \times 10^{-19} \times 2.78 \times 10^{-8} \times 5}$$

$$(ne\rho) E = nev_d$$

$$[\mu E = v_d]$$

$$0.0037 \times \frac{v}{d} = v_d \Rightarrow \frac{0.0037 \times 15 \times 0.06}{5} = v_d$$

$$\left[v_d = 6.66 \times 10^{-4} \text{ m/s} \right]$$

* Density of state function gives number of energy states available for the e⁻ to occupy in an energy band or somewhere.

→ density of states is defined as no. of energy states available per unit volume.

$$E \xrightarrow{dE} E + dE$$

Now,

$$\pi(E) dE = \frac{\pi n^2}{2} dn \quad \text{--- (1)}$$

also,

$$E = n^2 h^2$$

$$8mL^2$$

$$\begin{aligned} \Rightarrow n^2 &= \frac{8mL^2 E}{h^2} \\ \Rightarrow n &= \sqrt{\frac{8mL^2 E}{h^2}} \end{aligned}$$

$$dn = \left(\frac{1}{2n}\right) \left(\frac{8mL^2}{h^2}\right) dE$$

$$dn = \frac{1}{2} \left(\frac{h^2}{8mL^2 E}\right)^{1/2} \left(\frac{8mL^2}{h^2}\right) dE$$

$$dn = \frac{1}{2} \left(\frac{8mL^2}{h^2}\right)^{1/2} \frac{dE}{E^{1/2}}$$

$$\pi(E) dE = \frac{\pi}{2} n^2 dn$$

$$\text{So, } \pi(E) dE = \frac{\pi}{2} \times \frac{8mL^2 E}{h^2} \times \frac{1}{2} \left(\frac{8mL^2}{h^2}\right)^{1/2} \frac{dE}{E^{1/2}}$$

$$\Rightarrow \frac{\pi}{4} \left(\frac{8mL^2}{h^2} \right)^{3/2} E^{1/2} dE$$

$$\Rightarrow \frac{\pi}{4} (2^2 2m)^{3/2} \left(\frac{L}{h} \right)^3 E^{1/2} dE$$

$$\Rightarrow \frac{8\pi}{4h^3} (2m)^{3/2} L^3 E^{1/2} dE$$

$$\boxed{\pi(E) dE = \frac{2\pi}{4h^3} (2m)^{3/2} L^3 E^{1/2} dE}$$

Ques. Calculate density of states variables for a free e^- with its energy values ranging b/w 0 and 1 eV

Accn to pauli's exclusion principle, each state is occupied by 2 e^- with opposite sign of spin.

So,

$$\pi(E) dE = 2 \times \frac{2\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

$$\Rightarrow \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

$$\text{Ans} \rightarrow 4.5 \times 10^{21} \text{ states/cm}^3$$

Ques. Calculate total no. of states in Si b/w conduction band E_C and $E_C + kT$ at 300K ($k = 1.38 \times 10^{-23} \text{ J/K}$)
 $\Rightarrow 8.62 \times 10^{25} \text{ ev/K}$

$$\Rightarrow 2.012 \times 10^{19} / \text{cm}^3$$

Ques. Determine total no. of energy states in Si b/w 0 eV & $E_U - kT$.

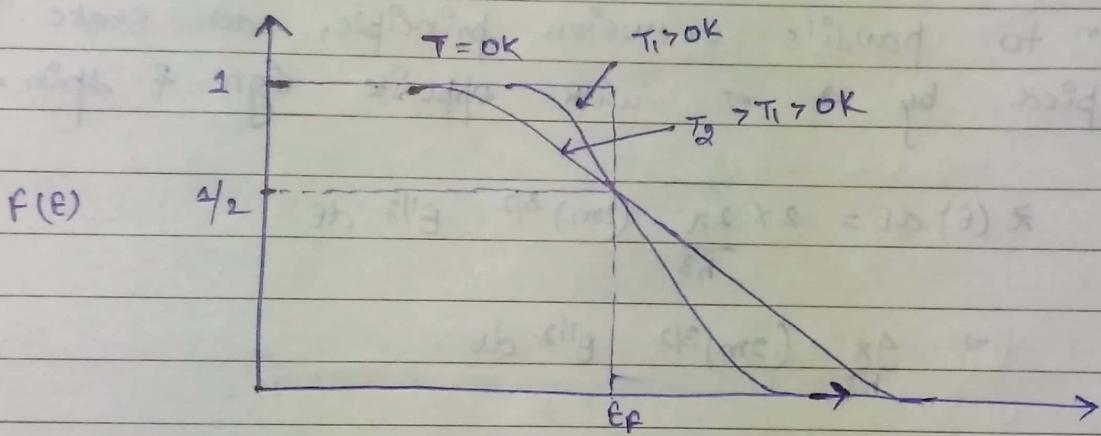
$$7.92 \times 10^{18} / \text{cm}^3$$

* Fermi-Dirac distribution function :-

→ Is a probability function used to define probability of occupying an energy state by the e^-

Accn to fermi Dirac distribution fn., the probability of energy state by the e^- is given by

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



at $T=0K$

$$\begin{aligned} E < E_F &\Rightarrow f(E) = 1 \\ E > E_F &\Rightarrow f(E) = 0 \end{aligned}$$

Fermi-level :- Is that energy level at which probability of occupying an e^- in an energy state is $1/2$ or 0.5 at all the temperatures above $0K$.
OR

It is the max energy of filled states at temp equal to $0K$.

Ques. Evaluate fermi energy for an energy state which is kT above the fermi energy.

$$f(E) = \frac{1}{1 + \exp(E/kT)}$$

$$\frac{1}{1+e} \approx 0.269$$

Ques. At what temperature we can expect a 10% probability than an e^- in silver have an energy which is 1% above the fermi-energy. The fermi-energy is 5.5 eV.

$$f(E) = \frac{1}{1 + \exp(E - E_F/kT)} \quad E = E_F + \frac{\epsilon_F \times 1}{100}$$

$$\frac{10}{100} = \frac{1}{1 + \exp\left(\frac{(E_F + \frac{\epsilon_F \times 1}{100}) - E_F}{kT}\right)}$$

$$T = 290.2 \text{ K}$$

Ques. find the temp at which there is 1% probability of state with an energy value 0.5 eV above the fermi energy level is occupied by an e^- .

$$\frac{1}{100} = \frac{1}{1 + \exp\left(\frac{0.5}{kT}\right)}$$

$$0.99 = \exp\left(\frac{0.5}{8.62 \times 10^{-5} T}\right)$$

$$T = 1096 \text{ K}$$

Ques. Assuming that Fermi-energy level is 0.3 eV below the conduction band. Determine the probability of states been occupied by an e^- at conduction band at $T = 300K$.

Soln. :-

$$f(E) = \frac{1}{1 + \exp\left(\frac{0.3}{300 \times 8.62 \times 10^{-5}}\right)}$$

$$\boxed{f(E) = 9.3 \times 10^{-6}}$$

* Calculate an expression for e^- concn in conduction band of intrinsic semi-conductor.

$$\bar{n}(E)dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} dE$$

$$\bar{n}(E)dE = \frac{4\pi}{h^3} (2m_e^*)^{3/2} (E - E_c)^{1/2} dE$$

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

$$\text{if } E - E_F \gg kT$$

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

Substituting in ①

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

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

$$\text{Let } E - E_c = \alpha$$

$$\text{So, } E = E_c + \alpha$$

$$dE = d\alpha$$

$$n = \frac{4\pi}{h^3} (2m_e^*)^{3/2} \exp\left(\frac{E_F}{kT}\right) \int_{E_c}^{\infty} (\alpha)^{1/2} \exp\left(\frac{-E_c + \alpha}{kT}\right) d\alpha$$

Simplifying integral 0 to ∞ using gamma fn.

$$n = (kT)^{3/2} \frac{(n)^{1/2}}{q}$$

$$\text{So, } n = \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(\frac{E_F - E_c}{kT}\right)$$

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

$N_C \rightarrow$ effective density of state fn. in conduction band
Its value is constant at given temp and changes
slightly with temp.

$$N_C \propto T^{3/2}$$

$$\frac{N_{C1}}{N_{C2}} = \left(\frac{T_1}{T_2}\right)^{3/2}$$

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

$$P = N_V \exp\left(\frac{E_V - E_F}{kT}\right)$$

N_V is called effective density of state fn. in
valence band

$$6.43 \times 10^{15} / \text{cm}^3$$

No.

Date

Ques Calculate thermal equilibrium hole concentration in Si at 400K [$E_F = 0.27 \text{ eV}$] above the valence band and effective density of state $f(v)$ in valence band is $1.04 \times 10^{19} / \text{cm}^3$ at 300K. and forbidden energy gap of silicon is 1.2 eV.

$$N_V = 1.04 \times 10^{19} / \text{cm}^3$$

$$T = 400 \text{ K}$$

$$E_F = 0.27 \text{ eV}$$

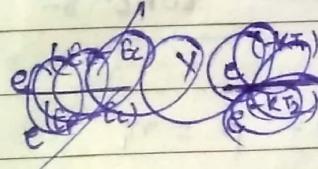
$$P_1 = \frac{1.04 \times 10^{19}}{106} \exp\left(\frac{1.2 - 0.27}{8.62 \times 10^{-5} \times 400}\right)$$

$$\Rightarrow 4.3199 \times 10^{34} / \text{cm}^3$$

$$P_1 = N_V e^{\left(\frac{E_F - E_C}{kT_1}\right)}$$

$$P_2 = N_V e^{\left(\frac{E_F - E_C}{kT_2}\right)}$$

$$\frac{P_1}{P_2} =$$



$$e^{(kT_1 + kT_2)}$$

$$P_2 = P_1 \times \frac{e^{\left(\frac{E_F - E_C}{kT_1}\right)}}{e^{\left(\frac{E_F - E_C}{kT_2}\right)}}$$

$$P_2 = 4.3199 \times 10^{34} \times \frac{e^{\left(\frac{-0.62 \times 10^{-5} \times 400}{k(400 - 300)}\right)}}{e^{\left(\frac{-0.62}{k(400 - 300)}\right)}}$$

$$P_2 = 6.43 \times 10^{15} / \text{cm}^3$$

$$e^{100K}$$

Ques. Calculate thermal equilibrium of e^- & hole concn in silicon at 300K when $E_F = 0.22$ eV below the conduction band [$E_g = 1.12$ eV, $N_{Si} = 2.0 \times 10^{19}/cm^3$, $N_{Si} = 1.62 \times 10^{13}/cm^3$]

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

$$\Rightarrow 2.0 \times 10^{19} \exp\left(\frac{-0.22}{8.62 \times 10^{-5} \times 300}\right)$$

$$n_{e^-} = 5.73 \times 10^{15} / cm^3$$

Similarly,

$$n_p = 8.43 \times 10^{13} / cm^3$$

Ques. Calculate thermal equilibrium hole & e^- concn in (GaAs) semi-conductor at 400K with E_F level 0.30 eV above the valence band E_g for GaAs is ~~1.43~~ 1.43 eV.

* Intrinsic carrier concn :-

$$n = p = n_i$$

$$n \times p = n_i^2$$

$$\Rightarrow N_c N_v \exp\left(\frac{E_F - E_c}{kT}\right) \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$\Rightarrow N_c N_v \exp\left(\frac{E_v - E_c}{kT}\right)$$

$$n_i^2 = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

Ques. Calculate intrinsic carrier concn in (GeAs) at T = 300K and 400K. $N_c = 4 \times 10^{17} / \text{cm}^3$, $N_b = 7 \times 10^{18} / \text{cm}^3$, $E_g = 1.042 \text{ eV}$

$$n_i^0 = N_c N_b \exp\left(-\frac{E_g}{kT}\right)$$

$$n_i^0 = 4 \times 10^{17} \times 7 \times 10^{18} \exp\left(-\frac{1.042}{8.62 \times 10^{-5} \times 300}\right)$$

$$\boxed{n_{i,300}^0 = 2.26 \times 10^6 / \text{cm}^3}$$

$$\boxed{n_{i,400}^0 = 3.05 \times 10^{10} / \text{cm}^3}$$

Ques. find the intrinsic carrier concn of Si at 200K & 400K.

$$E_g \uparrow$$

$$200K = 7.68 \times 10^4 / \text{cm}^3$$

$$400K = 2.38 \times 10^{12} / \text{cm}^3$$

Ques. for Ge

$$200K = 2.10 \times 10^6 / \text{cm}^3$$

$$400K = 8.6 \times 10^{14} / \text{cm}^3$$

* Intrinsic Fermi energy level position in Si :-

$$n = p$$

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

$$\exp\left(\frac{E_V - E_F}{kT}\right)$$

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

$$\exp\left(\frac{2E_F}{kT}\right) = \left(\frac{m_p^*}{m_e^*}\right)^{3/2} \exp\left(\frac{E_C + E_V}{kT}\right)$$

Taking log on both sides

$$\frac{2E_F}{kT} = \frac{3}{2} \log\left(\frac{m_p^*}{m_e^*}\right) + \left(\frac{E_C + E_V}{kT}\right)$$

$$E_F = \frac{3}{4} kT \log\left(\frac{m_p^*}{m_e^*}\right) + \frac{E_C + E_V}{2}$$

* Conductivity of an intrinsic semiconductor

$$\sigma = p\mu$$

↳ charge density

$$\sigma = (ne)\mu$$

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

↳ mobility of e

$$\text{also, } n = p = n_i$$

$$\sigma = n_i e (\mu_n + \mu_p)$$

$$n_i^2 = N_c N_a \exp\left(\frac{E_V - E_C}{kT}\right)$$

$$\Rightarrow N_c N_a \exp(-E_g/kT)$$

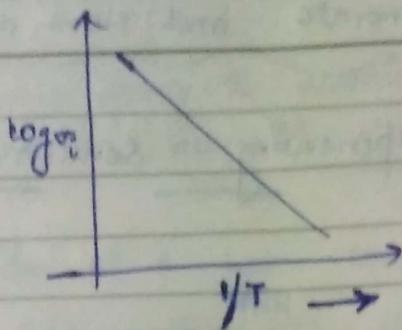
$$n_i = \sqrt{N_c N_a} \exp\left(-\frac{E_g}{2kT}\right)$$

$$\sigma = \sqrt{N_c N_a e (\mu_n + \mu_p)} \left(\exp\left(-\frac{E_g}{2kT}\right) \right)$$

↓
A

$$\sigma_i^o = A \exp(-E_g/2kT)$$

$$\log \sigma_i = \log A - \frac{E_g}{2kT}$$



* forbidden energy gap of an intrinsic SD :-

$$\sigma_i^o = A \exp\left(-\frac{E_g}{2kT}\right)$$

$$\frac{1}{\sigma} = \frac{1}{A} \exp\left(\frac{E_g}{2kT}\right)$$

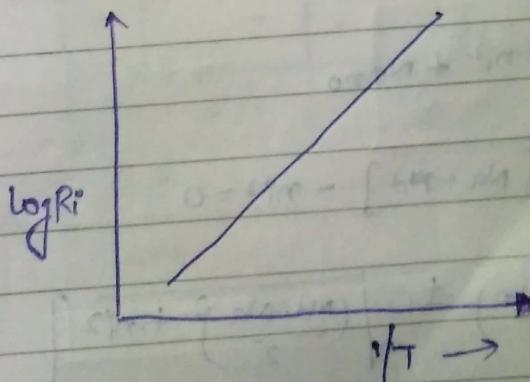
$$\frac{R_a}{L} = \frac{1}{A} \exp\left(\frac{E_g}{2kT}\right)$$

$$R = \frac{L}{\alpha A} \exp\left(\frac{E_g}{2kT}\right)$$

$$R = C \exp\left(\frac{E_g}{2kT}\right)$$

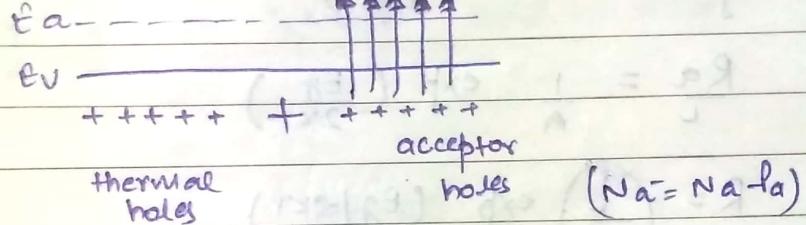
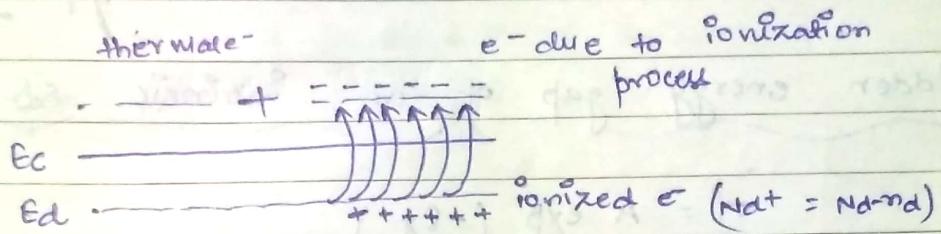
$$\log R = \log C + \frac{E_g}{2kT}$$

$$\boxed{\log R_i^o = \log C + \frac{E_g}{2kT}}$$



* Degenerate and Non-degenerate Semiconductors

→ Compensating Semiconductors



$$n_0 + Na^- = P_0 + Na^+$$

$$n_0 + (Na^- - la) = P_0 + (Nd - nd)$$

$$P_a = Nd = 0 \Rightarrow n_0 + Na = P_0 + Nd \quad (1)$$

$$\text{and } n_0 P_0 = n_i^2 \Rightarrow P_0 = \frac{n_i^2}{n_0} \quad (2)$$

$$n_0 + Na = \frac{n_i^2}{n_0} + Nd$$

$$n_0^2 + Nn_0 = n_i^2 + Nd n_0$$

$$n_0^2 + n_0 [Na - Nd] - n_i^2 = 0$$

$$n_0 = \left(\frac{Na - Nd}{2} \right) \pm \sqrt{\left(\frac{Nd - Na}{2} \right)^2 + n_i^2}$$

where

N_{d^+} = total no. of donor atoms in material

N_{a^-} = total no. of acceptor atoms in semi-conductor

Ques. Calculate thermal equilibrium e⁻ & hole conc^o in a compensating SB of p-type using following data.

$$T = 800\text{K}$$

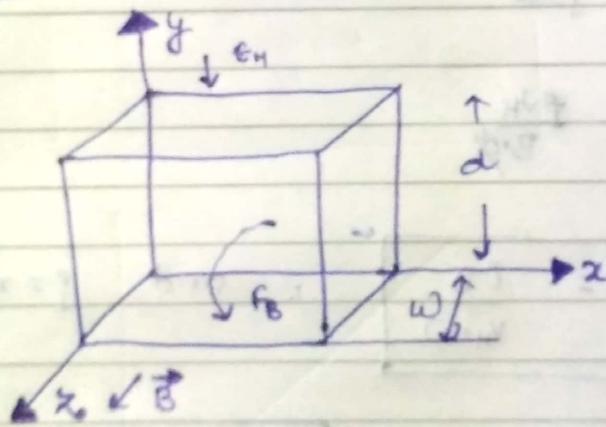
$$N_{d^+} = 10^{16} / \text{cm}^3$$

$$N_{a^-} = 3 \times 10^{15} / \text{cm}^3$$

$$N_i = 1.5 \times 10^{10} / \text{cm}^3$$

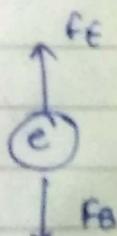
* Hall effect - Whenever a SB specimen carrying current is placed in a transverse magnetic field then L direction to both current & magnetic field, an electric field will produce. This phenomenon is called Hall effect.

- useful in finding the nature of semi-conductor.
- to determine carrier conc.



$$\vec{f}_B = qvB\hat{i}$$

$$\vec{f}_E = E_H q\hat{j}$$



$$F_B = F_E$$

$$qVB = E_H qB$$

$$E_H = Vd \cdot B$$

$$V_H = E_H \cdot d$$

$$V_H = Vd \cdot B \cdot d$$

$$\left[Vd = \frac{V_H}{Bd} \right]$$

also, $J = i/A$

and $J = p Vd$

↳ charge density

$$\frac{i}{wd} = p Vd$$

$$\frac{i}{wd} = \frac{e V_H}{B \cdot d}$$

$$\boxed{p = \frac{i B}{V_H \cdot d}}$$

and $p = ne$

$$ne = \frac{i B}{V_H \cdot d} \Rightarrow$$

$$\boxed{n = \frac{i B}{e V_H \cdot d}}$$