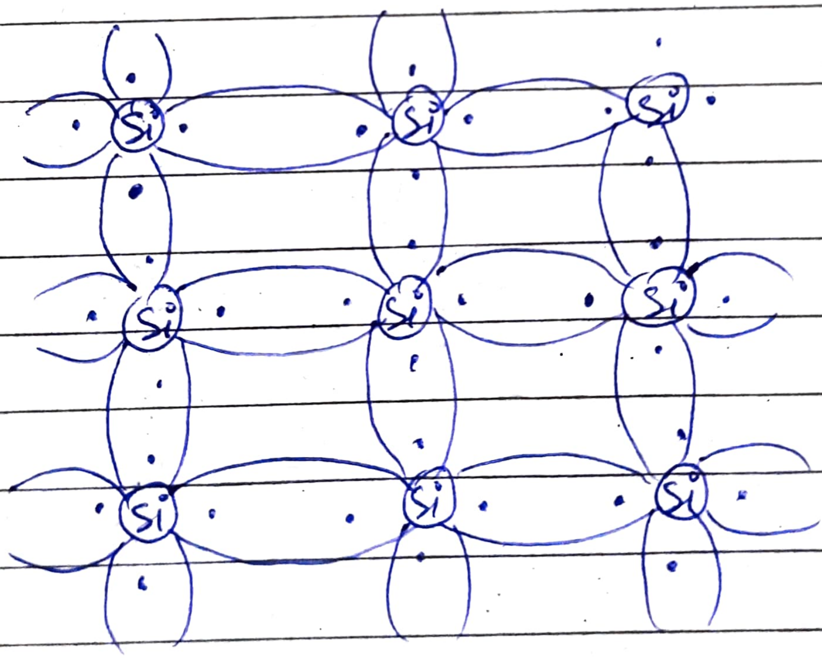
→ Intrinsic Semiconductors -

- Pure semiconductors
- Free e^- are only due to natural causes (light energy or thermal energy)

→ Extrinsic Semiconductors -

- Impurity atoms are added.
- Two types of impurities are there.
- Added 1 part in 10 million.
- Process of adding certain impurity atoms to pure semiconductor is called doping.



→ Intrinsic Semiconductor
  ↳ Natural / Pure / without any impurity

Eg → Pure silicon (14)
  → $1s^2 2s^2 2p^6 \underbrace{3s^2 3p^2}$

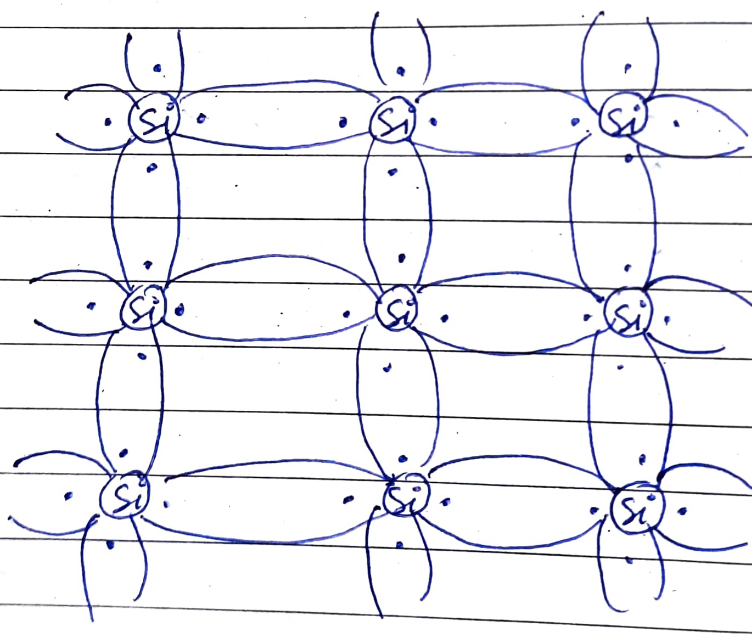
4 Valence e⁻

• Pure Germanium (32)
→ $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} \underbrace{4s^2 4p^2}$

4 Valence e⁻

→ All 4 valence e⁻ are involved in covalent bond formation in Si or Ge crystal.

0K

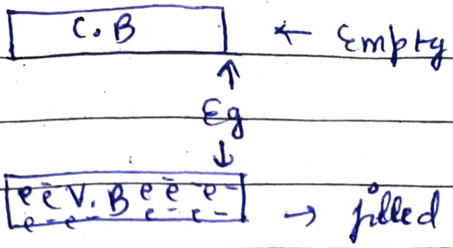


→ At absolute 0K temp. there are no free e⁻ as all the valence e⁻ are involved in covalent bond.

→ A semiconductor will behave like an insulator at 0K.

→ Eg → 1.1eV pure Si
  0.7 eV pure Ge

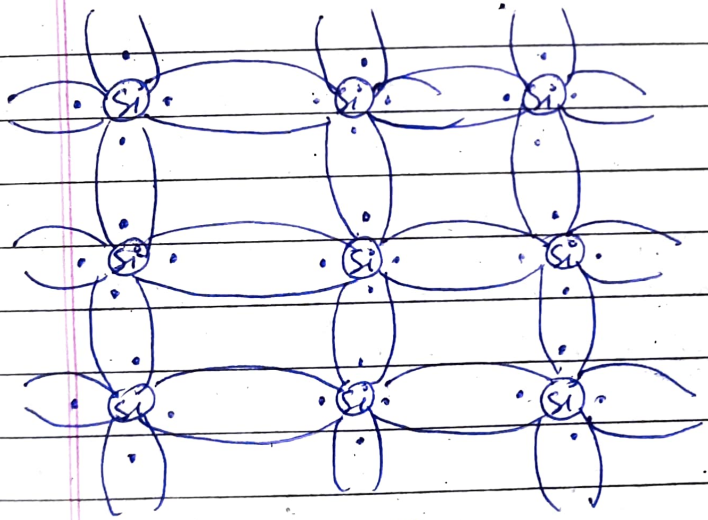
At 0K

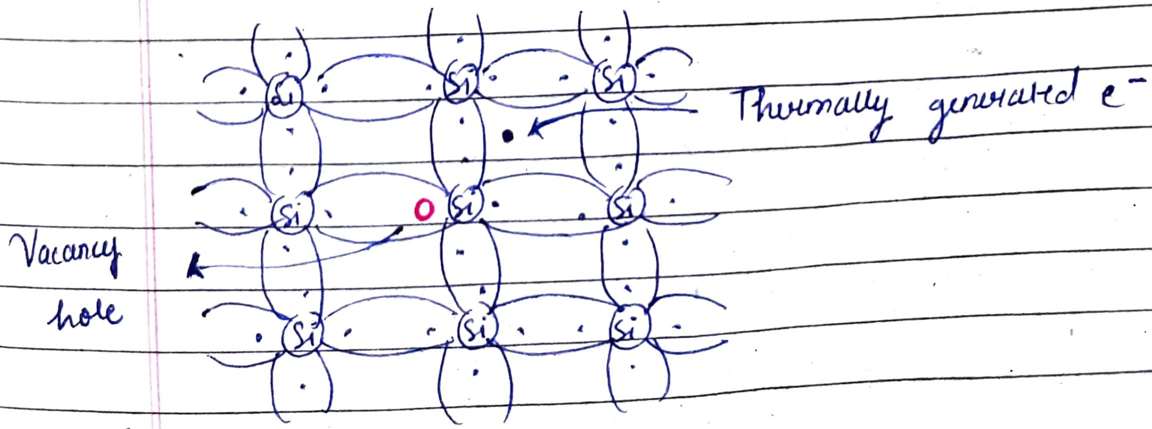


→ On increasing temp. more and more thermal energy is available so, some covalent bond may break and some free e^- are generated.

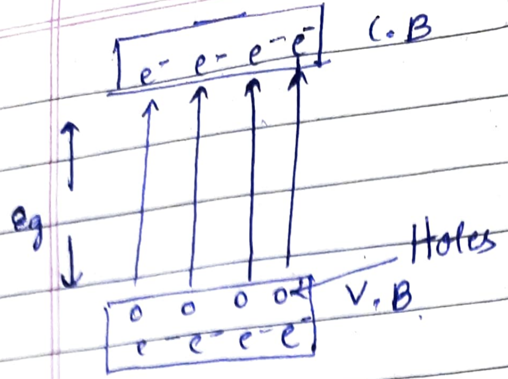
→ At 300K / 27°C / room temperature one covalent bond breaks in 10^{29} atoms.

At 300K





holes → vacancy due to thermally generated free e^-.



→ Recombination of thermally generated e^- and holes takes place at all temp.

→ Number of thermally generated free e^- (n_e) is equal to no. of holes (n_h)

$$n_e = n_h = n_i$$

n_i = intrinsic concentration / Intrinsic charge carrier density

→ At room temp (300K)

$n_i = 2.4 \times 10^{19} / m^3$ for Ge

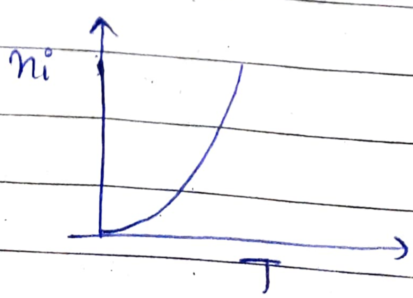
$n_i = 1.5 \times 10^{16} / m^3$ for Si

$$\boxed{n_i \propto e^{-E_g/KT}}$$

E_g → Forbidden Energy Gap

K → Boltzmann Constant

T → Temp. in Kelvin



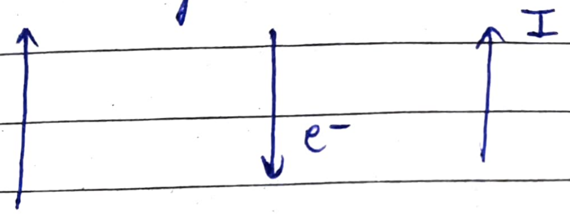
→ Current in S.C is due to –

i) Thermally generated free e^-

ii) Holes.

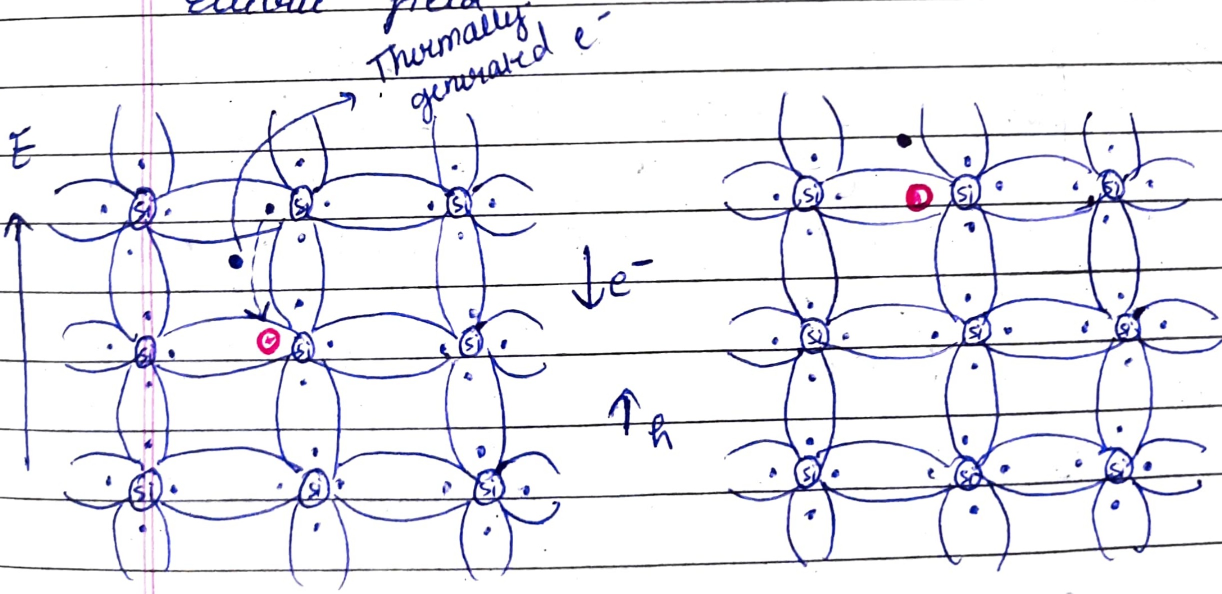
→ Thermally generated free e^- – Current due to it I_e

Electric field



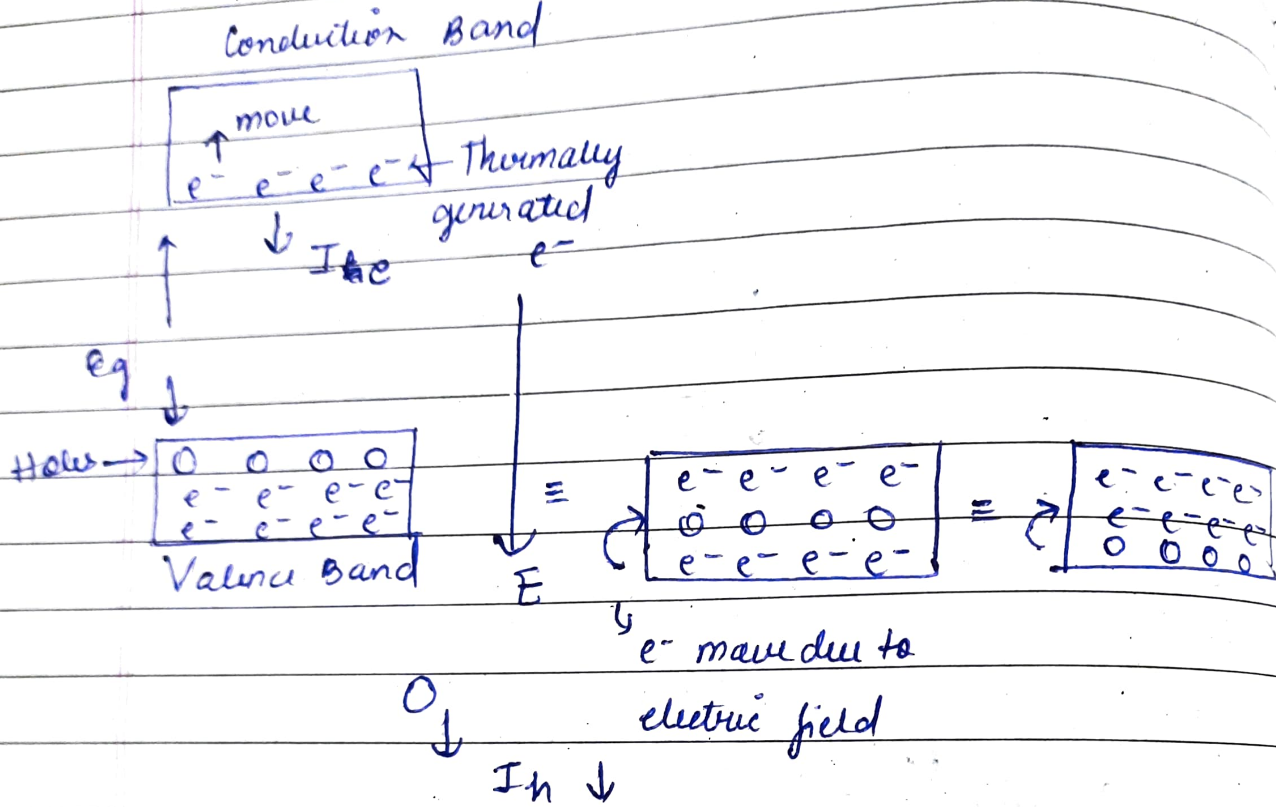
→ Holes → current due to it I_h

→ Holes apparently move in direction of applied Electric field.



→ Bonded e^- will move.

→ Energy Band



$$\boxed{I_{net} = I_e + I_h}$$

I_e → due to thermal generated free e⁻

I_h → apparant due to motion of holes or due to actual motion of valence band e⁻

$I_e > I_h$ in Intrinsic semiconductors

I_e is due to e⁻ in C.B which are free to move. I_h is due to e⁻ in V.B which are not free to move.

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→ Extrinsic Semiconductors (n-type and p-type).

→ The electrical conductivity of Intrinsic S.C increases with temperature.
Even on reaching Room temperature (27°C) its conductivity is very poor.
→ The addition of certain impurities can increase the conductivity of intrinsic S.C.
→ Very small amount (in ppm) of impurity atoms can increase conductivity of intrinsic S.C. many times.
→ The S.C. ~~to~~ thus obtained is called extrinsic semiconductor.
→ The process of addition of impurities (intentionally) is called 'doping.'
The impurity atom is called 'Dopant'.
The impure S.C. thus called is doped 'S.C'.

→ Doping can be done in many ways -
- Heating pure S.C. in atomosphere of impurity atoms so that impurity atoms diffuse in pure crystal.
- Bombarding pure crystal with ions of impurity atoms.

→ Extrinsic S.C. can be of two types based on the type of impurity atom -

a) n-type S.C → pentavalent impurity atom
eg → (Phosphorus, Antimony (Sb), Arsenic (As)).

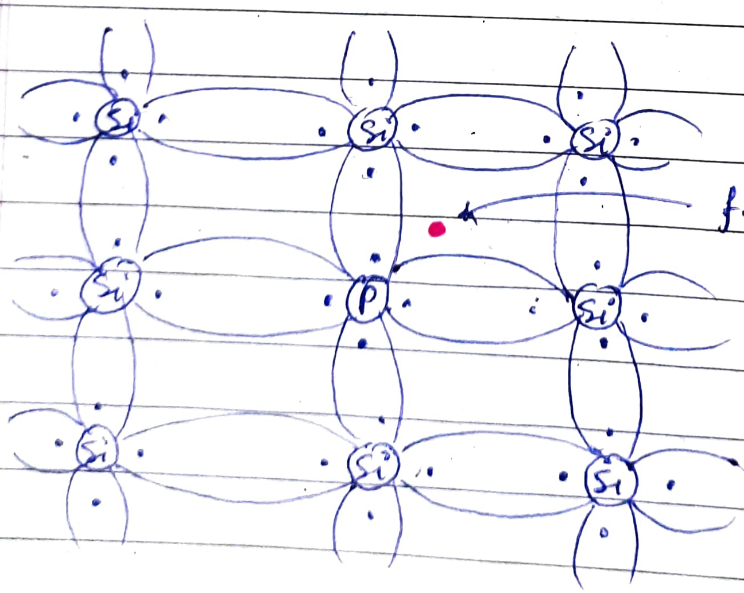
(b) p-type S.C → trivalent impurity atom.
eg → Aluminium (Al), Boron (B), Indium (In).

→ n-type S.C →

① Pentavalent impurity atoms (P, Sb, As) replaces pure Si (or Ge) atoms in crystals.

P (15)

→ $1s^2 2s^2 2p^6 3s^2 3p^3$



→ 4 out of 5 Valence e- of phosphorus forms Covalent band with neighbouring Si atom but 5th e- is nearly free.

remove an e^- from last shell.

→ The ionisation energy required to free 5th Valence e^- is very low.
(0.01eV in Ge, 0.05eV in Si)

→ In pure S.C energy is required to break covalent bond to free e^-

→ The energy required to free 5th Valence e^- can be obtained at room temp. So this e^- is set free and it goes to C.B and is available for electrical conduction.

→ Pentavalent impurity donates one e^- per atom and hence they are called 'Donor impurity'.

→ The conductivity increases with doping.
more doping = more donor impurity = more free e^-.

→ Conductivity of n type do not depend on temp.

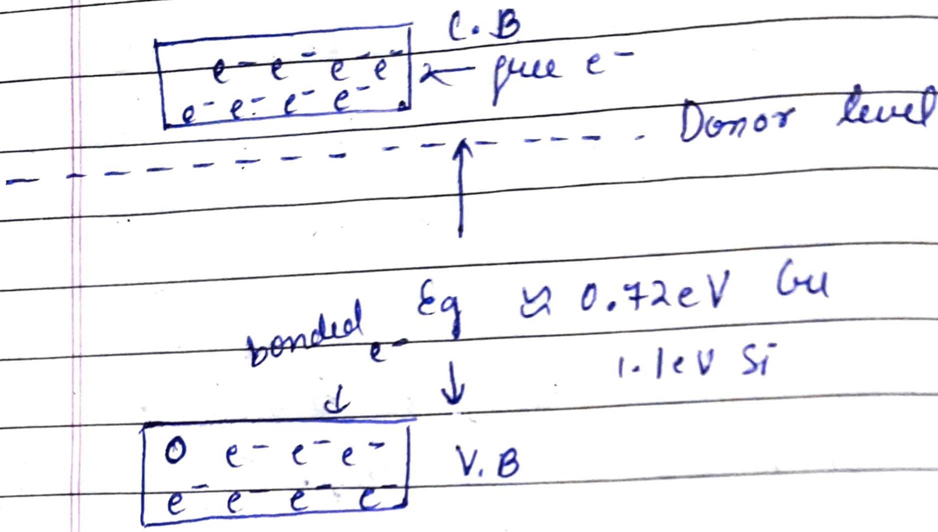
→ Some free e^- are also generated thermally due to breaking of few covalent bonds and equal no. of holes are also generated

→ (n_e) → due to Pentavalency impurity
→ due to breaking of covalent bond

(n_h) → due to breaking of covalent bonds

$\boxed{n_e >> n_h.}$

Energy band for n-type–



9 e⁻ in C.B are from donor one e⁻-hole pair is generated due to breaking of covalent bond

→ e⁻ are majority charge carriers and holes are minority charge carriers

→ n- type
└→ negative type → as negative charge carriers (e⁻) are majority.

→ n-type S.C. are electrically neutral
pentavalent impurity brings one extra e⁻ but it also bring one extra proton.

→ p-type semiconductors–

→ Trivalent impurity atoms
Eg → (B, Al, In) replaces atoms of pure (Si or Ge) in crystal.

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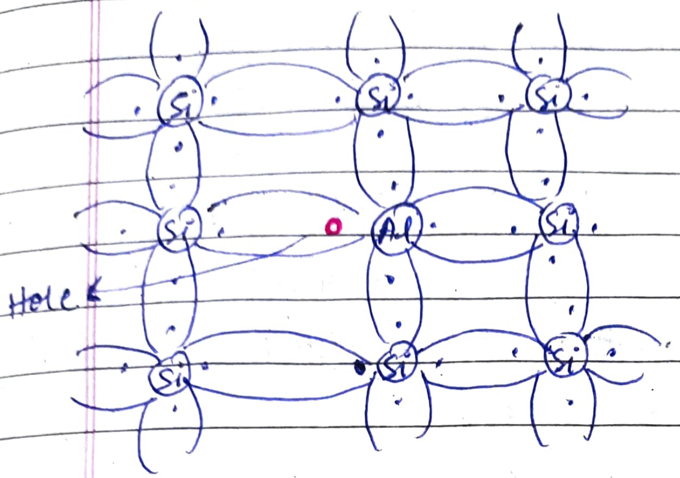
Al (13)
→ $1s^2 2s^2 2p^6 3s^2 3p^1$



→ 3 valence e^- of Al forms 3 covalent bonds with neighbouring Si atoms.

→ A vacancy hole is left at one side of trivalent impurity atom

→ On application of electric field an e^- from one covalent bond may jumps to hole and a new hole appears at the side of e^-

→ This requires very small amount of energy (0.01eV - Ge, 0.05eV Si)

→ This energy is available at room temp. hence large no. of holes are available for electrical conduction.

→ Trivalent impurity 'Accepts' an e^- from neighbouring atom and hence called 'Acceptor impurity'.

→ The electrical conductivity depends of level of doping

→ More doping = more Acceptor impurity = more holes.

and is ~~impurity~~ independent of temp.

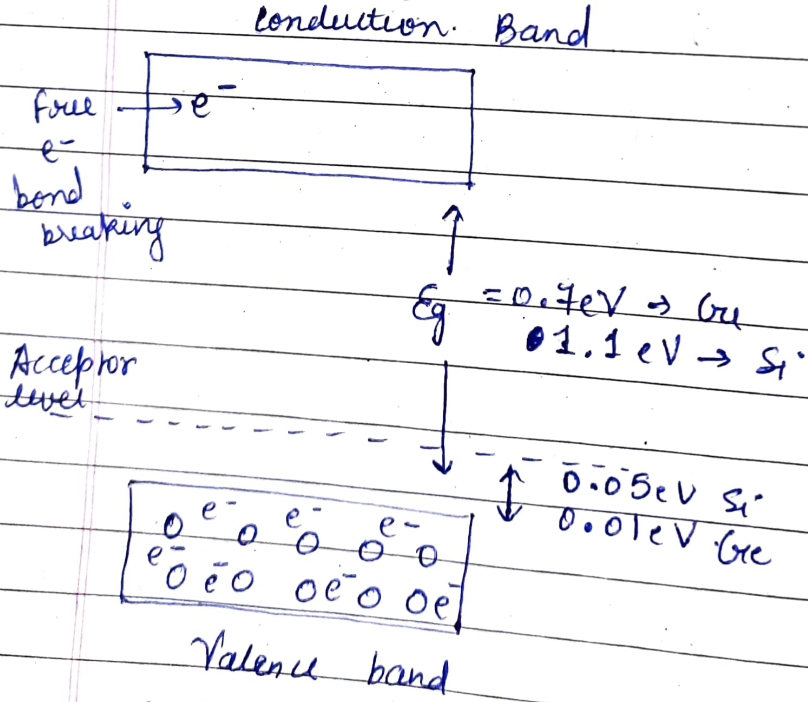
→ few covalent bonds may break which generates free e^- and equal no. of holes.

→ n_h → due to acceptor impurity (trivalent impurity)
→ due to breaking of covalent bonds

n_e → due to breaking of covalent bonds

$$\boxed{n_h >> n_e}$$

→ Energy band for p-type -



→ 9 holes are generated due to Acceptor impurity
1 e^- - hole pair generated by breaking of bond.

→ Holes are majority charge carriers and e^- are minority charge carriers.

→ p-type
  → positive-type
    → majority charge carriers (holes) which are positive.

p-type s.c. are also neutral

→

n-type	p-type
① Pentavalent impurity	① Trivalent impurity
② One extra e^- in Valence shell	② Short of one e^- in valence shell
③ Majority carriers → e^-	③ Majority carriers → holes
④ Donor level	④ Acceptor level.

$$\boxed{n_e n_h = n_i^2}$$ Approximate and hypothetical

- 1 Donor Atom → 1 free e^-
- 1 Acceptor atom → 1 hole

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→ Carrier concentration :-

$$n = \int_{E_C}^{\infty} n(E)\, dE$$

→ $n(E)$ → variation of e^- w.r.t Energy.

$$n(E) = f(E) \cdot f(E)$$

$f(E)$ → variation of states w.r.t Energy.

$f(E)$ → probability of occupation.

$$\boxed{n = \int_{E_C}^{\infty} f(E) \cdot f(E)\, dE}$$

→ Fermi Dirac Distribution (Fermi function) -

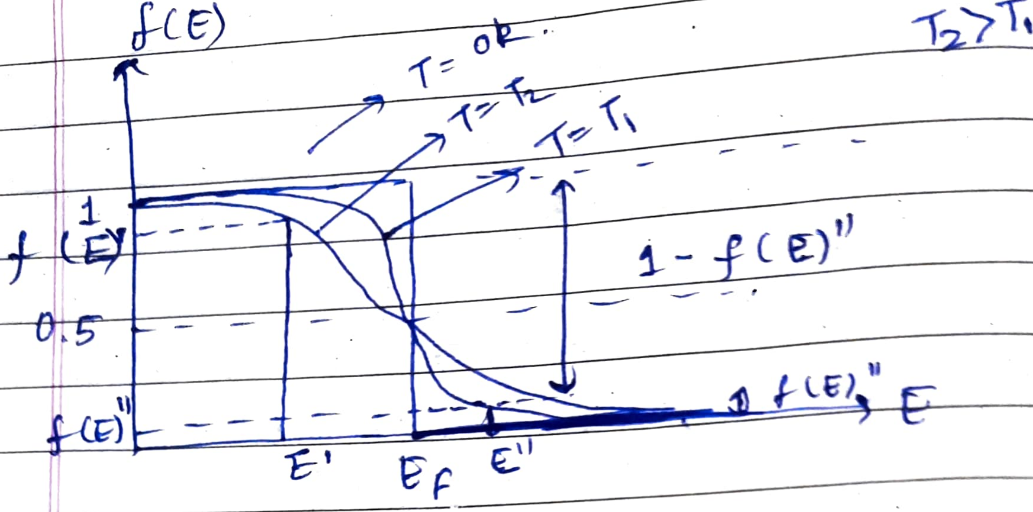
$$f(E) = \frac{1}{1 + e^{(E - E_F)/KT}}$$

E_F = Fermi level.

K = Boltzmann's constant.

at $E = E_F$ ⟶ Fermi level.

$$f(E_F) = \frac{1}{2} = (0.5).$$



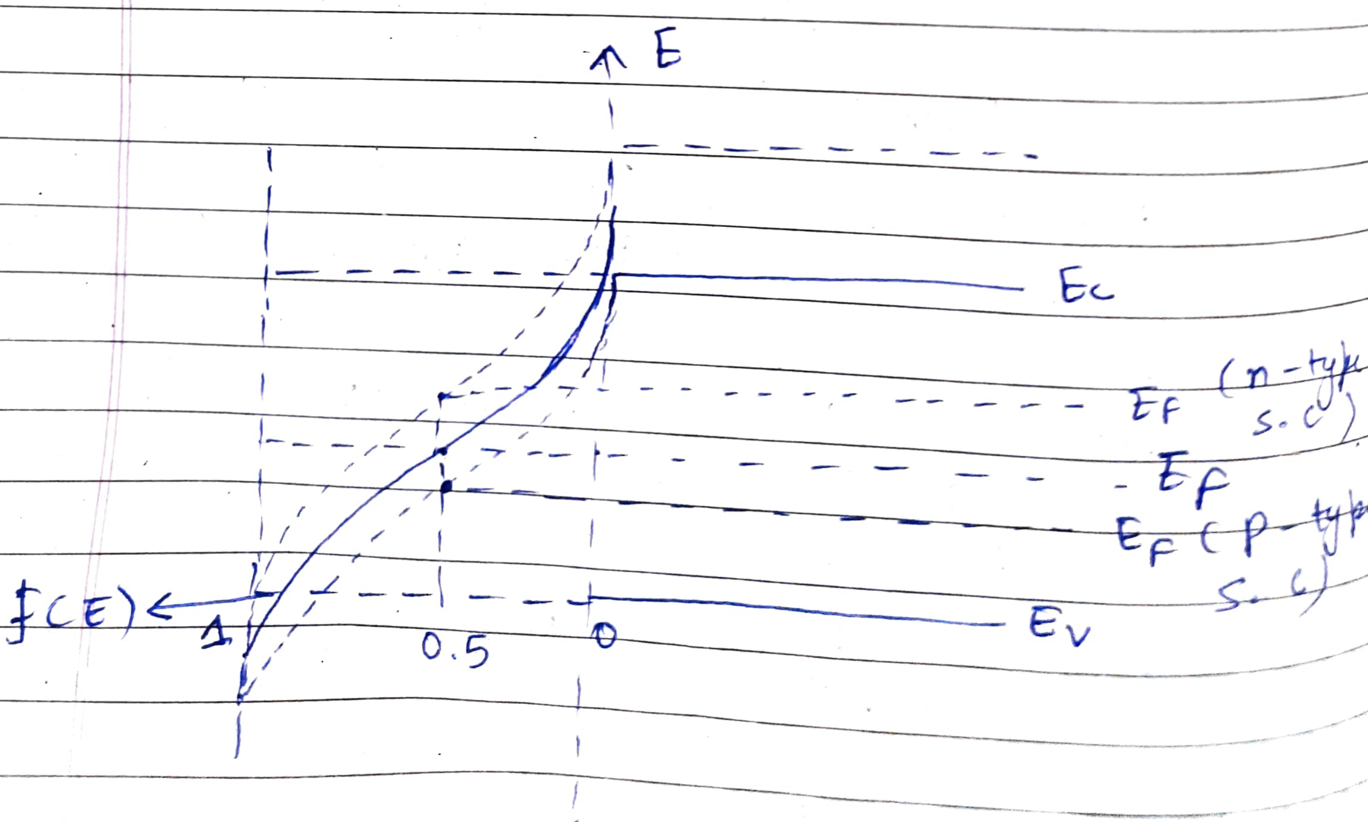
at room Temperature $T = 300K$

$KT = .026\ eV$

$f(E)$ = probability of occupation by an e^-

$1 - f(E) \rightarrow$ probability of occupation by hole.

$f(E_f + \Delta E) = 1 - f(E_f - \Delta E)$



for n-type semiconductor the fermi level shifts towards conduction band and for p-type semiconductor the fermi level shifts towards Valence band.

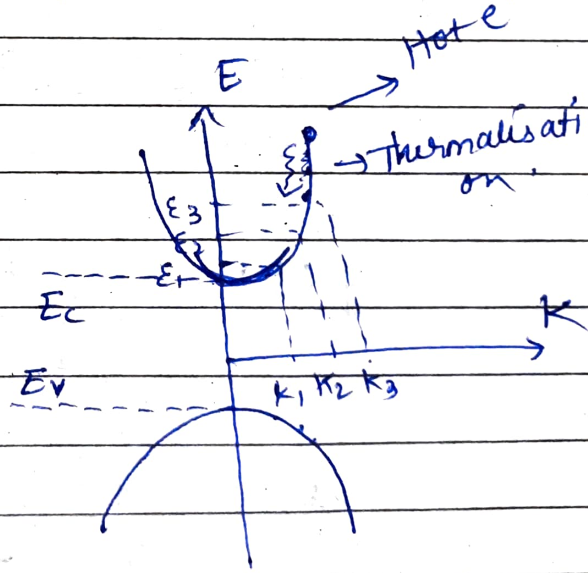
$$n = \int_{E_c}^{\infty} n(E)\,dE = \int_{E_c}^{\infty} g(E)\,f(E)\,dE$$

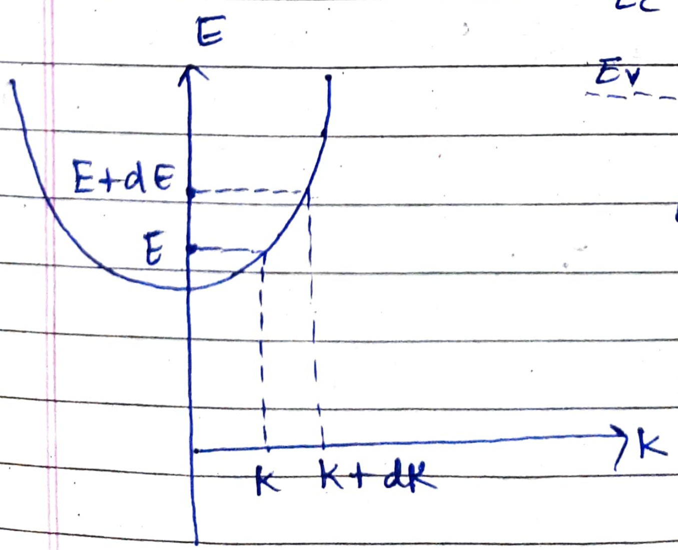
$$p = \int_{-\infty}^{E} p(E)\,dE = \int_{-\infty}^{E_v} g(E).[1-f(E))\,dE$$

→ **Density of states**

→ $\dfrac{\text{no. of allowed energy level}}{\text{Volume}}$

$$g(E)\,dE = g(K)\,dK$$
$\hookrightarrow \dfrac{K^2}{\pi^2}$





(max^m e^- will lie on the bottom of C.B)

$$E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

Parabolic approximation
$$\begin{cases} E = E_c + \dfrac{\hbar^2 k^2}{2m_c} & \longrightarrow \text{For C.B} \\ E = E_V - \dfrac{\hbar^2 k^2}{2m_v} & \longrightarrow \text{For V.B.} \end{cases}$$

m = effective mass.

$m_c \rightarrow$ effective mass in C.B

$m_v \rightarrow$ effective mass in V.B

$$\rho(E)\,dE = \rho(k)\,dk$$

$$\rho(E) = \frac{\rho(k)}{\left(\frac{dE}{dk}\right)} \quad — (1)$$

$$E = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$\frac{dE}{dk} = \frac{2\hbar^2 k}{2m_c} \quad — \text{put in (1)}$$

$$\rho_c(E) = \frac{\rho(k)\, m_c}{\hbar^2 k}$$

$$\rho(E) = \frac{k^2}{\pi^2}$$

$$\rho_c(E) = \frac{k^2}{\pi^2}\,\frac{m_c}{\hbar^2 k}$$

$$\rho_c(E) = \frac{1}{\pi^2}\,\frac{m_c}{\hbar^2}\cdot k$$

Now from (1)

$$k = \left(\frac{2m_c}{\hbar^2}\right)^{1/2} (E - E_c)^{1/2}$$

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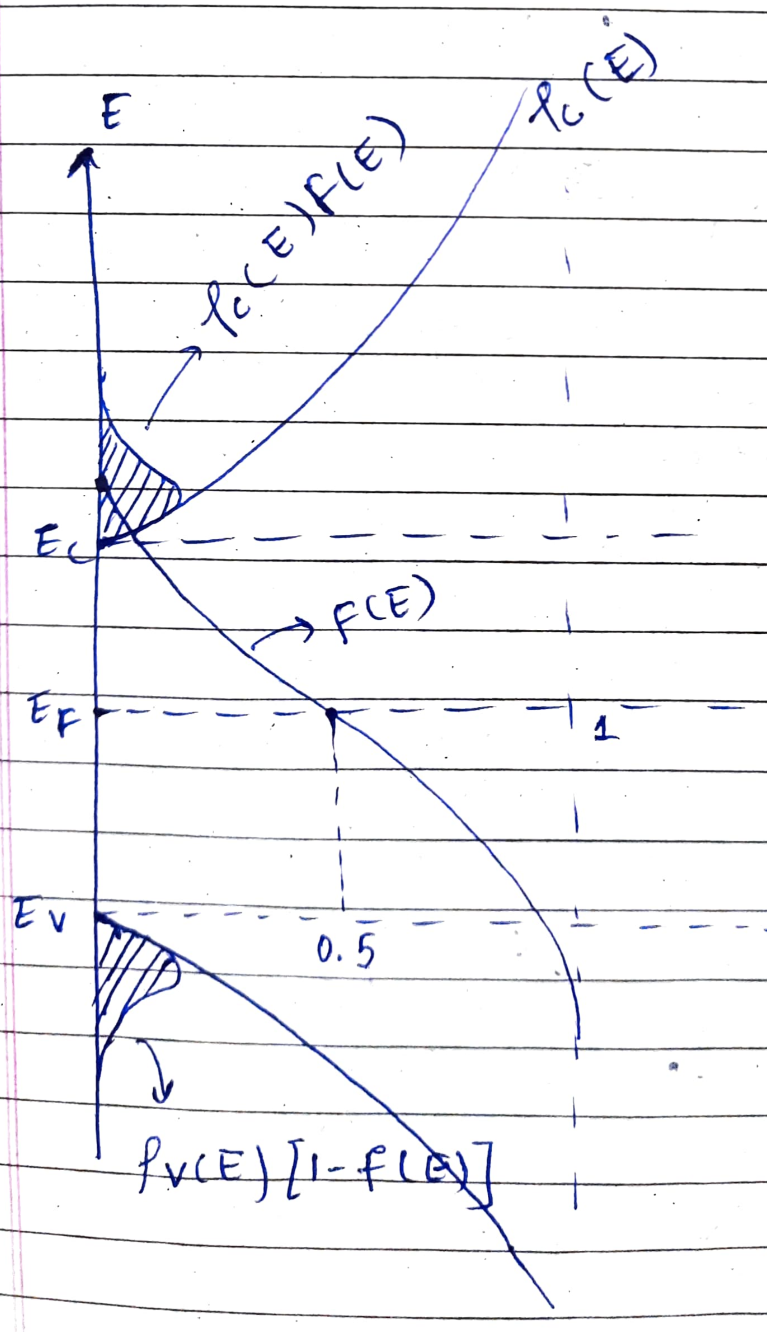
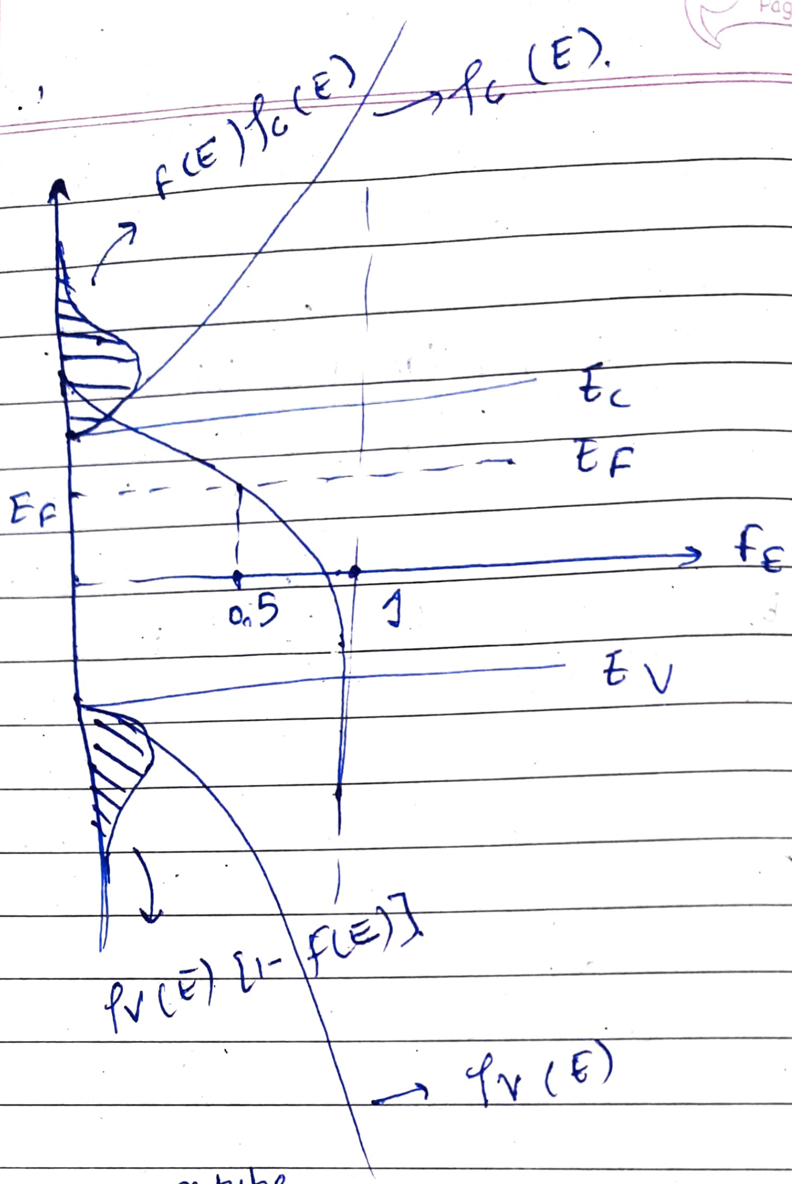
$$\rho_c(E) = \frac{1}{2\pi^2} \frac{2m_c}{\hbar^2} \left(\frac{2m_c}{\hbar^2}\right)^{1/2} (E-E_c)^{1/2}$$

$$\boxed{\rho_c(E) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_c}{\hbar^2}\right)^{3/2} (E-E_c)^{1/2}}$$

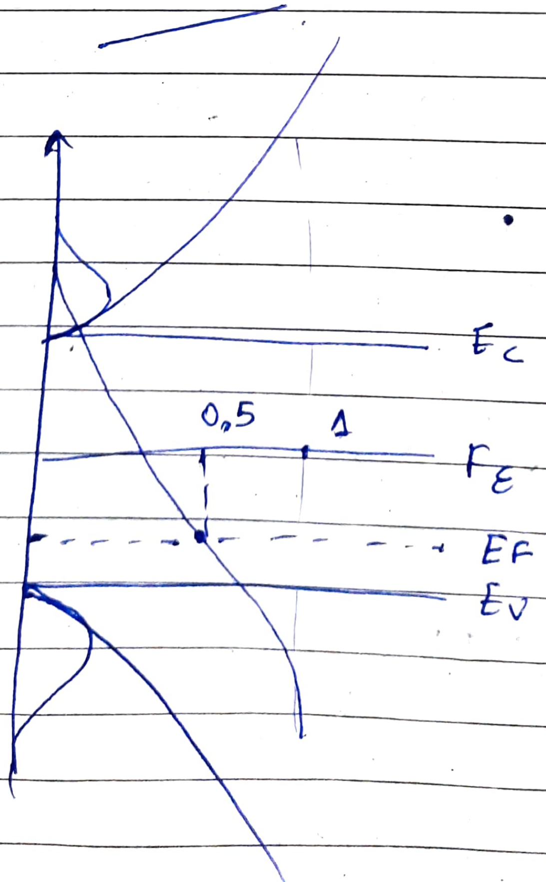
$$\boxed{\rho_v(E) = \frac{1}{2\pi^2} \cdot \left(\frac{2m_v}{\hbar^2}\right)^{3/2} (E_v-E)^{1/2}}$$



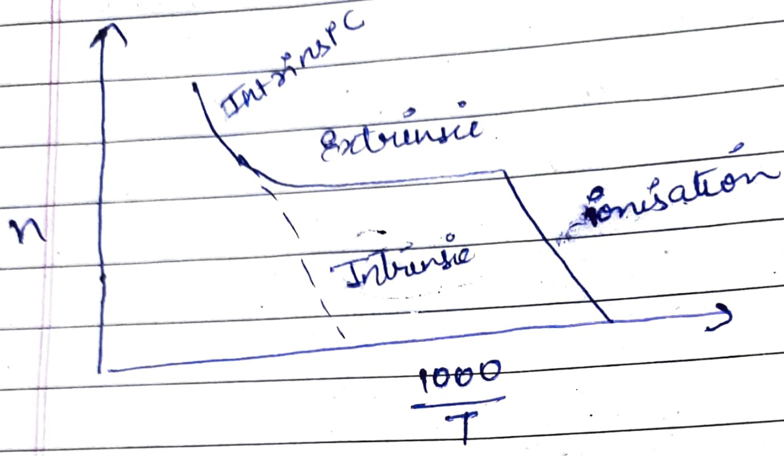
→ Intrinsic



n type



$$n_i = 2\left(\frac{2\pi K}{h^2}\right)^{3/2} (m_c m_v)^{3/4} T^{3/2} \cdot e^{-E_g/2KT}$$



→ for intrinsic s.c

$$n_i = N_c e^{-(E_c - E_i)/KT}$$

$$n = N_c e^{-(E_c - E_i + E_i - E_f)/KT}$$

$$= \underbrace{N_c e^{-(E_c - E_i)/KT}} \cdot e^{-(E_i - E_f)/KT}$$

$$n = n_i e^{-(E_i - E_f)/KT}$$

E_c

E_f and E_i (Intrinsic level)

E_v

$$\boxed{\begin{aligned} n &= n_i e^{(E_f - E_i)/KT} \\ p &= n_i e^{(E_i - E_f)/KT} \end{aligned}}$$

It is the relation of carrier concentration with intrinsic carrier concentration as the fermi level varies w.r.t. intrinsic level.

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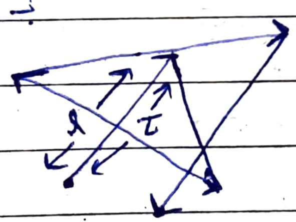
→ Carrier Transport

① Drift
② Diffusion
③ Tunneling

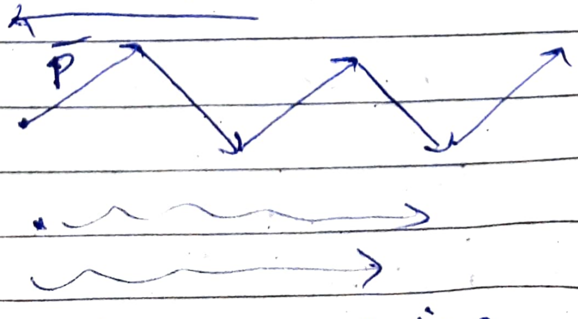
→ If the carriers moves under the influence of any electric field. it is known as drift.
→ If the carrier moves in a region where the concentration gradient exist eg - osmosis is known as diffusion.
→ The phenomenon due to which a carrier crosses the potential barrier. even if it does not have the sufficient energy is known as Quantum mechanical tunneling

① Drift :-



(Brownian motion).

l → mean free path.
τ → mean free time.



rate of change of momentum
$\frac{\bar{P}}{\tau}$

acc. Newton 2nd law -

$$\frac{d\bar{P}}{dt} = -nq\bar{E} = \frac{\bar{P}}{\tau}$$

Let momentum be $\bar{P}$.

$$\frac{\bar{P}}{\tau} = -nq\bar{E}$$

$$\bar{P} = -nq\tau\bar{E}$$

$$\langle \bar{P} \rangle = \frac{\bar{P}}{n} = -q\tau\bar{E}$$

$$m^* \langle v \rangle = -q\tau\bar{E}$$

$$\boxed{v_d = \langle v \rangle = \frac{-q\tau\bar{E}}{m^*}}$$

Drift Velocity

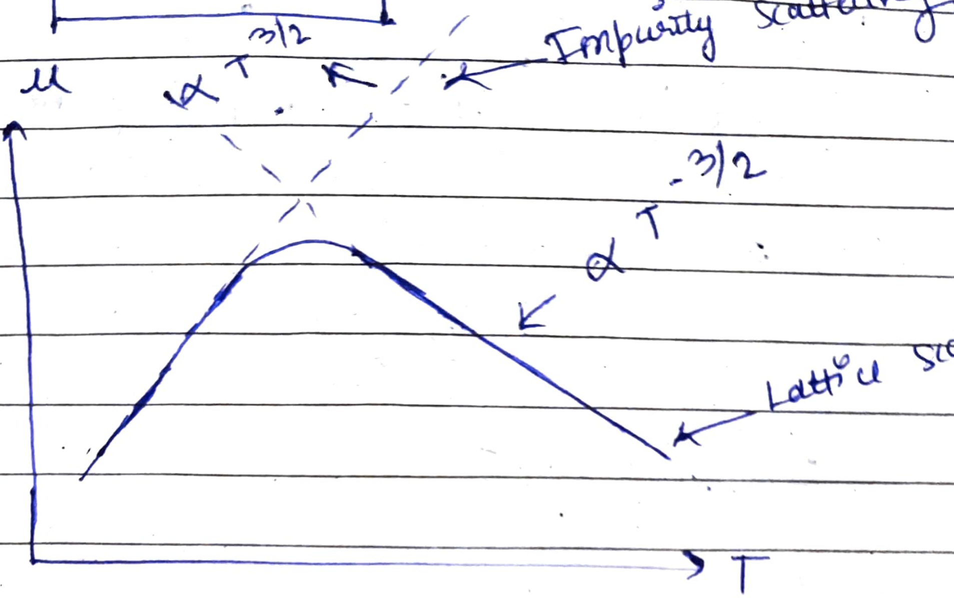
$$v_d \propto \bar{E}$$

$$\boxed{\bar{v}_d = \mu\bar{E}}$$

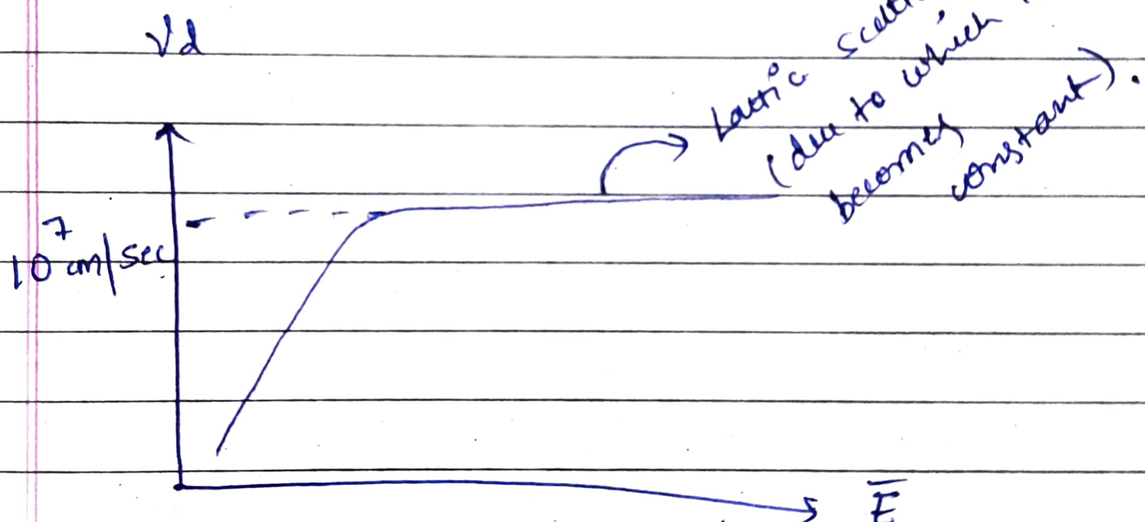
$$\mu = \frac{\bar{v}_d}{\bar{E}}$$

μ = mobility

$$\boxed{\mu = \frac{q\tau}{m^*}}$$



(Temperature dependence of mobility).



Dependence of Drift Velocity on Electric field.

→ J → Current density (A/m²).

$$\bar{J} = -qn\bar{V_d}$$

$$\frac{C}{s.m^2} = C.\ \frac{no.\ of\ e^-}{m^3} \cdot \frac{m}{s}$$

$$\bar{J} = -qn\left(\frac{-q\tau}{m^*}\right)\bar{E}$$

$$\boxed{\bar{J} = \left(\frac{nq^2\tau}{m^*}\right)\bar{E}}$$

$\bar{J} \propto \bar{E} \Rightarrow \boxed{\bar{J} = \sigma\bar{E}}$ ← point form of ohm's law.

$\sigma \rightarrow$ conductivity

$$\sigma = \frac{nq^2\tau}{m^*}$$

$$\bar{J}_n = \sigma \mu_n \bar{E}$$

$$\bar{J}_p = \sigma \mu_p \bar{E}$$

$$\boxed{\bar{J} = \left(\frac{nq^2\tau}{m^*}\right)\bar{E}}$$

$\bar{J} \propto \bar{E} \Rightarrow \boxed{\bar{J} = \sigma\bar{E}}$ ← point form of ohm's law.

$\sigma \rightarrow$ conductivity

$\bar{J}_{drift} = (J_{drift})_{(holes)} + J_{drift\,(e^-)}$ ~~$\sigma = \frac{nq^2\tau}{m^*}$~~

$pq\mu_p\bar{E} + nq\mu_n\bar{E}$ $\quad \bar{J}_n = \sigma_{m_n}\bar{E}$ $\quad \boxed{J_{drift} = nq\mu\bar{E}}$

$\bar{J}_p = \sigma_{mp}\bar{E}$

Que - Show that minimum conductivity of semiconductor occur when $n_0 = n_i\sqrt{\frac{\mu_p}{\mu_n}}$

also find the expression of minimum conductivity.

Que → A silicon bar of 0.1 cm long and 100 micro meter square in cross sectional area is dropped with $10^{17}/cm^3$ phosphorous atoms. find the current at 300K with 10V apply. [$\mu_n = 700\,cm^2/Vs$]

Que → A silicon sample is dopped with 10^{17} arsenic atoms / cm^3. what is the equilibrium hole concentration ε_0 at 300K. where is ε_f related to ε_i

Sol^n-1 → Total current density - $\bar{J} = \bar{J_n} + \bar{J_p}$

$$\bar{J} = nq\mu_n\bar{E} + pq\mu_p\bar{E}$$

$$\bar{J} = q[n\mu_n + p\mu_p]\bar{E}$$

$$\bar{J} = \sigma_{overall}\bar{E}$$

$$\sigma_{overall} = \sigma = q[n_o\mu_n + p_oq\mu_p]$$

$\bar{J} = \sigma\bar{E}$

$\bar{J} = nq\bar{E}\mu$

$\bar{J_n} = nq\mu_n E$

$\bar{J_p} = n_pq\mu_p\bar{E}$

at thermal equilibrium

$$n_op_o = n_i^2 = p_o = \frac{n_i^2}{n_o}$$

$$\sigma = q[n_o\mu_n + \frac{n_i^2}{n_o}\mu_p]$$

$$\frac{d\sigma}{dn_o} = q[\mu_n - \frac{n_i^2}{n_o}\mu_p]$$

for minimum conductivity $\frac{d\sigma}{dn_o} = 0$

$$q[\mu_n - \frac{n_i^2}{n_o^2}\mu_p] = 0$$

$$\mu_n = \frac{n_i^2}{n_o^2}\mu_p$$

$$n_o^2 = n_i^2\frac{\mu_p}{\mu_n}$$

$$\boxed{n_o = n_i\sqrt{\frac{\mu_p}{\mu_n}}}$$

$$n_op_o = n_i^2$$

$$p_o = \frac{n_i^2}{n_o}$$

$$\boxed{p_o = n_i\sqrt{\frac{\mu_n}{\mu_p}}}$$

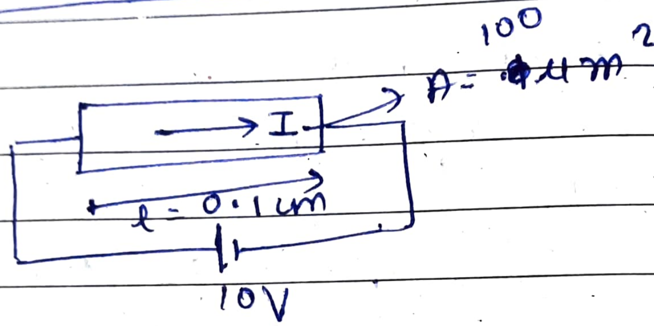
→ at $n_0 = n_i\sqrt{\frac{\mu_p}{\mu_n}}$ and $p_0 = n_i\sqrt{\frac{\mu_n}{\mu_p}}$.

$$\sigma = \sigma_{min} = q\left\{\mu_n n_i\sqrt{\frac{\mu_p}{\mu_n}} + n_i\sqrt{\frac{\mu_n}{\mu_p}}\,\mu_p\right\}$$

$$= n_i q\left\{\sqrt{\mu_n\mu_p} + \sqrt{\mu_n\mu_p}\right\}$$

$$\boxed{\sigma_{min} = 2n_i q\sqrt{\mu_n\mu_p}}$$

Solⁿ-2 →



$I = \frac{V}{R}$

$R = \rho\frac{l}{A} = \frac{L}{\sigma A}$

$I = \frac{V}{L}\cdot\sigma A$

$\sigma = nq\mu_n \qquad \mu_n = 700\ cm^2/V\text{-}s$

$\sigma = 10^{17}\times 1.6\times 10^{-19}\times 700 = 11.2$

$$I = \frac{10\times 11.2\times 10^{-6}}{0.1}$$

$I = 1.12\times 10^{-3} = 1.12\times 10^{-3}\,A$

$$\boxed{I = 1.12\times 10^{-3}A \text{ or } 1.12\,mA}$$

$Sol^n \rightarrow$ $N_d = 10^{17}/cm^3$

$n = 10^{17}/cm^3$

$n_i = 1.5 \times 10^{10}/cm^3 \rightarrow$ Standard Value

$n \cdot p_o = n_i^2$

$$p_o = \frac{n_i^2}{n}$$

$$= \frac{1.5 \times 10^{10} \times 1.5 \times 10^{10}}{10^{17}}$$

$p_o = 2.25 \times 10^3$ ans.

$\rightarrow$ $E_i \rightarrow$, $E_f \rightarrow$

$$\frac{KT}{q} \simeq 26mV$$

$$n = n_i e^{(E_f - E_i)/KT}$$

~~KT = 26 × 1.6 ×~~

~~KT = 41.6 × 10~~

$$KT \ln \frac{n}{n_i} = E_f - E_i$$

$$E_f - E_i = \cancel{41.6 \times 10^{-19}}\ .026 \ln \frac{10^{17}}{1.5 \times 10^{10}}$$

$$\cancel{E_f - E_i = 41.6 \times 10^{-19} \ln 6.6 \times 10^{6}}$$

$$E_f - E_i = 0.026 \ln \frac{10^{17}}{1.5 \times 10^{10}} = .407 eV$$

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Qu → A silicon sample is dopped with 10^{17} Boron atoms per cm^3. what is the e^- conc^n. n_o at 300K. What is the resistivity.

Qu → An unknown semiconductor has $E_g = 1.1eV$ and $N_c = N_v$. It is dopped with $10^{15}/cm^3$ donors where the donor level is .2 eV below E_c, given that E_f = .25eV below E_c Calculate n_i., concentration of e^- and holes in S.C ~~is~~ at 300 K

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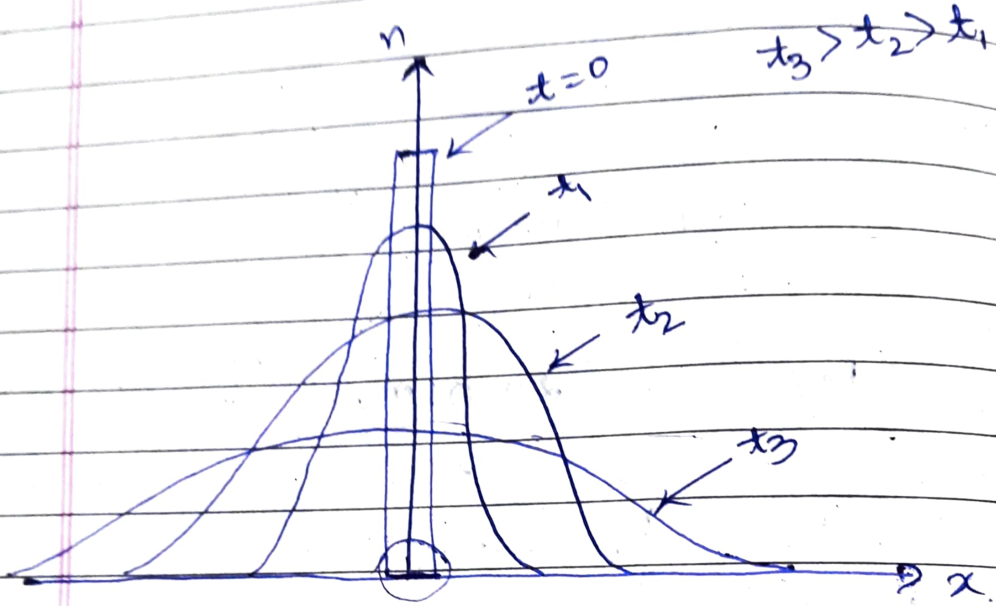
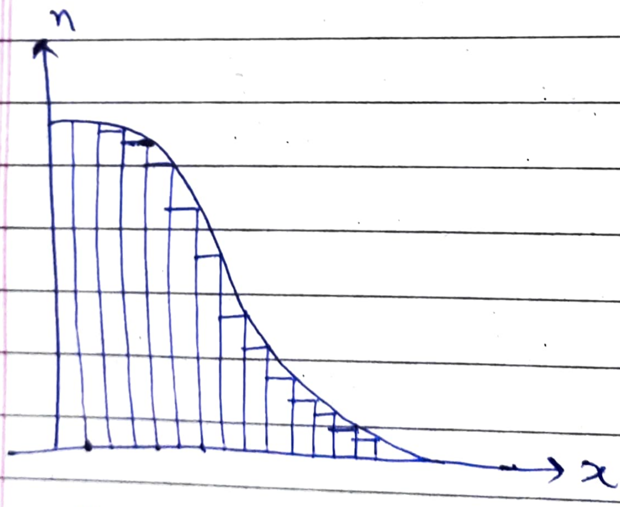
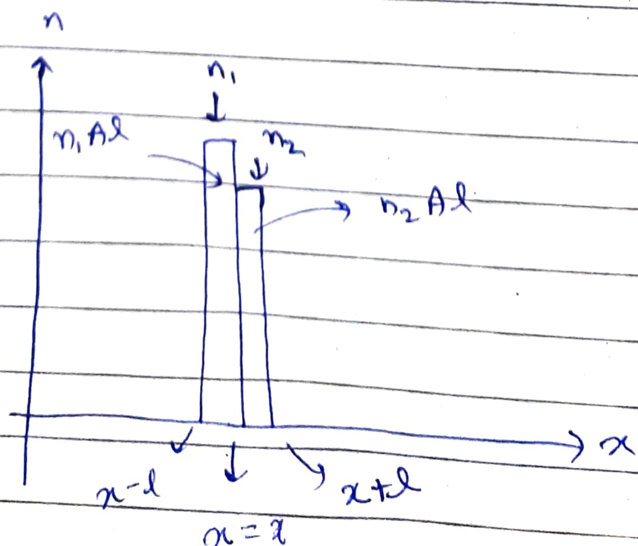
(2) Diffusion -







→ number of carriers crossing $x = x$
$= \frac{1}{2} n_1 A l - \frac{1}{2} n_2 A l$

→ number of carriers crossing $x = x$ per unit Area per unit time

$$= \frac{\frac{1}{2} \cancel{A} l \,(n_1 - n_2)}{\cancel{A} \tau}$$

$\tau \rightarrow$ ~~std~~ mean free time

$$\phi_n(x) = \frac{l}{2\tau}(n_1 - n_2)$$

From first principle of differentiation

$$f'(a) = \lim_{a \to 0} \frac{f(x) - f(x+a)}{a}$$

$$n_1 - n_2 = \frac{[n(x) - n(x+\Delta x)]}{\Delta x} \cdot l$$

$$\phi_n(x) = \frac{l^2}{2\tau}\left[\lim_{\Delta x \to 0} \frac{n(x) - n(x+\Delta x)}{\Delta x}\right]$$

l = mean free path

$$\boxed{\phi_n(x) = -\left[\frac{l^2}{2\tau}\right]\frac{dn}{dx}}$$

✓ ↳ for a fixed s.c it is constant

(constant of diffusion

$$D_n = \frac{l^2}{2\tau}$$

→ J_n (Diffusion current density)

$$\boxed{J_{diff} = -q D_n \frac{dn}{dx}}$$

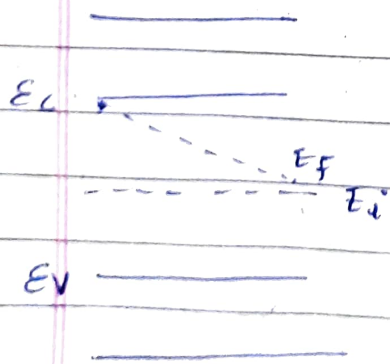
for e^- $= -(-q) D_n \frac{dn}{dx}$

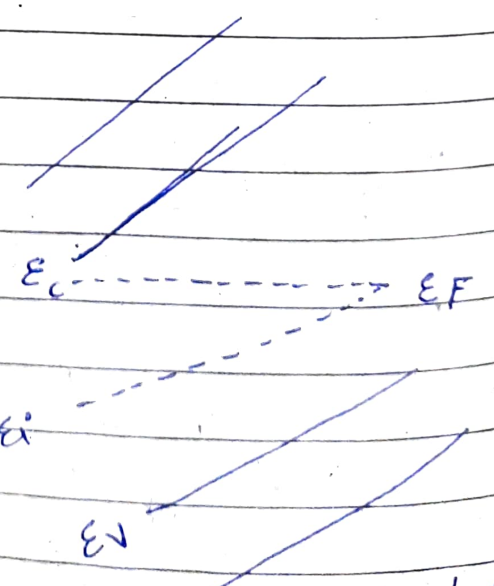
$$\boxed{\phi_n(x) = -D_n \frac{dn}{dx}}$$

$$\boxed{\phi_p(x) = -D_p \frac{dp}{dx}}$$

$$\left[\begin{aligned} J_n(diff) &= -(-q) D_n \frac{dn}{dx} = q D_n \frac{dn}{dx} \\ J_p(diff) &= -(+q) D_p \frac{dp}{dx} = -q D_p \frac{dp}{dx} \end{aligned}\right]$$

→ ~~Diffusion with Drift~~ -





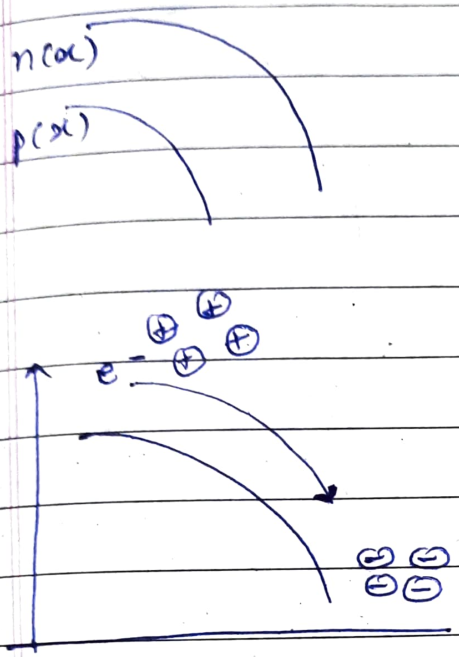
$n = n_i e^{(E_f - E)/kT}$

→ Band digram when light is incident

→ ~~Eqlt~~ Energy band diagram at equilibrium -

→ Diffusion with Drift -

$\xrightarrow{\mathcal{E}(x)}$



ϕ_p (drift) and ϕ_p (diffu) →

J_p (drift) and J_p (diff) →

ϕ_n (diff) →

J_n (diff) ←

ϕ_n (drift) ←

J_n (drift) →

→ Total Current Density

$$J_n = J_n(\text{Drift}) + J_n(\text{diff})$$

$$= nq\mu_n E + qD_n \frac{dn}{dx}$$

at thermal Equilibrium.

$$nq\mu_n E + qD_n \frac{dn}{dx} = 0 \quad \text{— (1)}$$

$$n = n_i e^{(E_F - E_i)/KT}$$

$$\frac{dn}{dx} = n_i e^{(E_F - E_i)/KT} \cdot \frac{1}{KT}\left[\frac{dE_F}{dx} - \frac{dE_i}{dx}\right]$$

$$\frac{dn}{dx} = n \cdot \frac{1}{KT} \cdot \left(-\frac{dE_i}{dx}\right)$$

$$F = \frac{K q_1 q_2}{r^2}$$

$$V = \frac{K q}{r^2} \qquad V = \frac{E}{q}$$

$$E = -\frac{\partial V}{\partial x}$$

$$= -\frac{\partial}{\partial x}\left[\frac{E_i}{(-q)}\right]$$

$$E = \frac{1}{q}\frac{dE_i}{dx}$$

from (1)

$$nq\mu_n\left(\frac{1}{q}\frac{dE_i}{dx}\right) + qD_n\left(\frac{-n}{KT}\cdot\frac{dE_i}{dx}\right) = 0$$

$$n\mu_n = qD_n \cdot \frac{n}{KT}$$

$$\mu_n = \frac{q}{KT} \cdot D_n$$

$\frac{KT}{q}$ = thermal voltage (V_T).

for e⁻ → $\boxed{\frac{D_n}{\mu_n} = \frac{KT}{q}}$ — It is always constant for a particular temperature

→ Known as Einstein's Relation

for holes → $\boxed{\frac{D_p}{\mu_p} = \frac{KT}{q} = V_T}$

$V_T \simeq 26\ mV$ at 300K

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$$\boxed{\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} \Rightarrow \frac{D_n}{D_p} = \frac{\mu_n}{\mu_p}}$$

$$D = \frac{l^2}{2\tau}$$

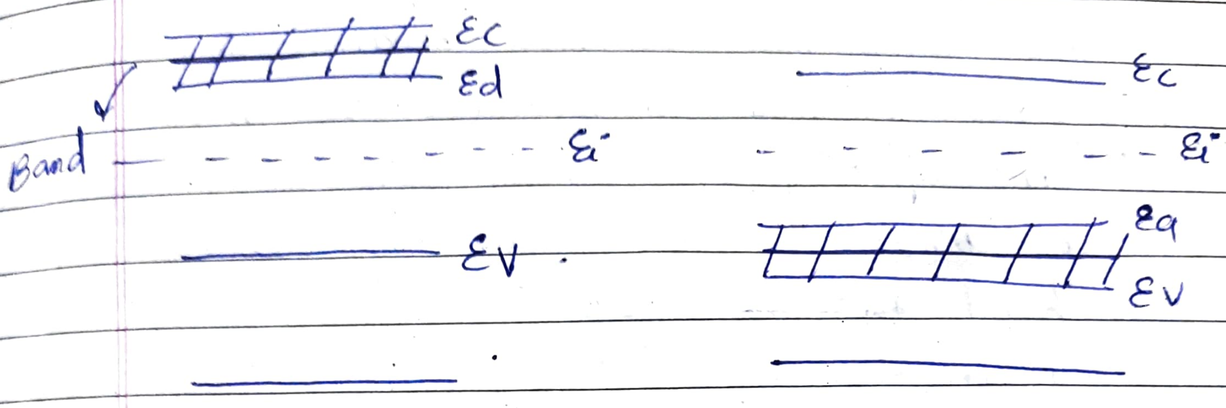
$$\mu = \frac{q\tau}{m^*}$$

Que → A silicon ~~bar of~~ sample is dopped with $10^{16}/cm^3$ Boron atoms at a certain no. of donors. The fermi level is 0.36 eV above E_i at 300 K. What is the donor concentration

(b) Silicon sample contains $10^{16}/cm^3$ Indium acceptor atoms and a certain no. of donors. The Indium acceptor level is 0.16 eV above E_V and E_f is 0.26 eV above E_V at 300K. How many indium atoms are unionised.

→ **De-generate Semiconductor.** -

n-type — p-type.

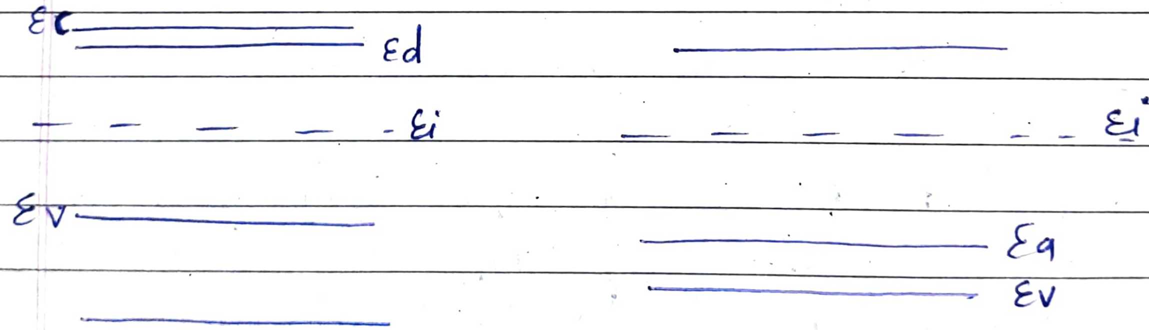


$n > N_C$

$p > N_V$

→ **Non-degenerate Semiconductor** -

n-type — p-type



$$\begin{cases} n << N_C \\ p << N_V \end{cases}$$

→ When doping concentration is very small the interatomic distance between impurity atoms is sufficiently large and we can assume that the impurity atoms are not interacting with each other and hence the donor energy level or acceptor energy level will discrete this ~~type~~ of

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Semiconductors are known as non-degenerate Semiconductors.

→ when the doping concentration is increased the interatomic distance between ~~interatomic~~ impurity atom continues to decrease this may lead splitting of single discrete acceptor or donor energy level into continuous band ~~this is called~~

when the doping concentration is further increased the continuous band of donor energy level or acceptor energy level may overlap with conduction band or Valance band respectively. these type of S.C. are known as Degenerate S.C.

→ Compensated semiconductor –

① $N_d > N_a \Rightarrow$ n-type Compensated S.C.
② $N_d < N_a \Rightarrow$ p-type Compensated S.C.
③ $N_d = N_a \Rightarrow$ Exact compensated S.C.
or
Intrinsic

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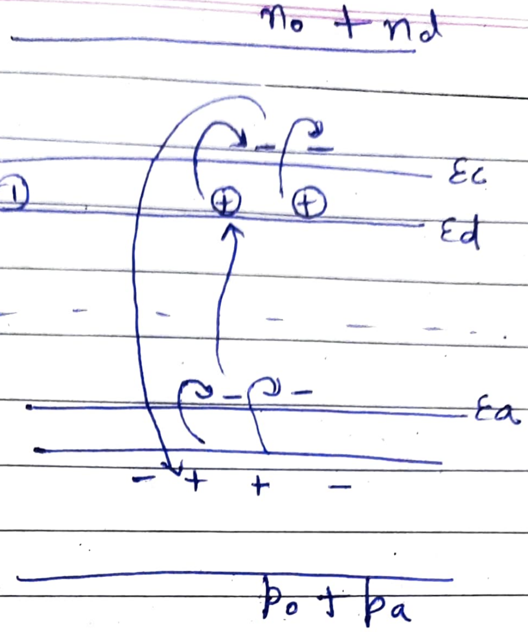
→ Neutrality condition -

$p + N_d = n + N_a$

$n = (N_d - N_a) + p$ — (1)



Law of mass action

$np = n_i^2$

$p = \frac{n_i^2}{n}$

put in (1)

$$n = (N_d - N_a) + \frac{n_i^2}{n}$$

$$n^2 - (N_d - N_a)n - n_i^2 = 0$$

from quadratic eq^n -

$$n = \frac{(N_d - N_a) \pm \sqrt{(N_d - N_a)^2 + 4n_i^2}}{2}$$

we will not take (-) ve because the conc^n will become (-)ve.

$$\boxed{n = \left[\frac{N_d - N_a}{2}\right] + \sqrt{\frac{(N_d - N_a)^2}{4} + n_i^2}}$$

for holes - $p^n = \frac{n_i^2}{p}$ — put in (1)

$$\boxed{p = \left[\frac{N_a - N_d}{2}\right] + \sqrt{\frac{(N_a - N_d)^2}{4} + n_i^2}}$$

Unit - 3

Excess carriers -

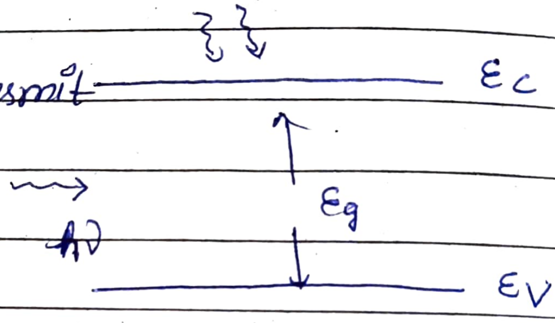
- → Carrier absorption
- → Electron Bombardment
- → Carrier Injection.

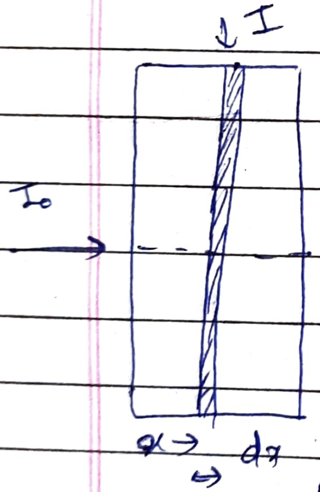
① Optical Absorption -

$h\nu < E_g \rightarrow$ Transmit

$h\nu > E_g$

Absorption





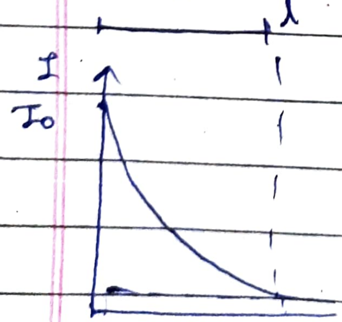
$$-\frac{dI}{dx} = \alpha I$$

α → Absorption coefficient

$$\int_{I_0}^{I} \frac{dI}{I} = -\alpha \int_0^x dx$$

$$\left| \ln I \right|_{I_0}^{I} = -\alpha x$$

$$\boxed{I = I_0 e^{-\alpha x}}$$



$$E = h\nu = \frac{hc}{\lambda}$$

$$\boxed{E(eV) = \frac{1.24}{\lambda}}$$

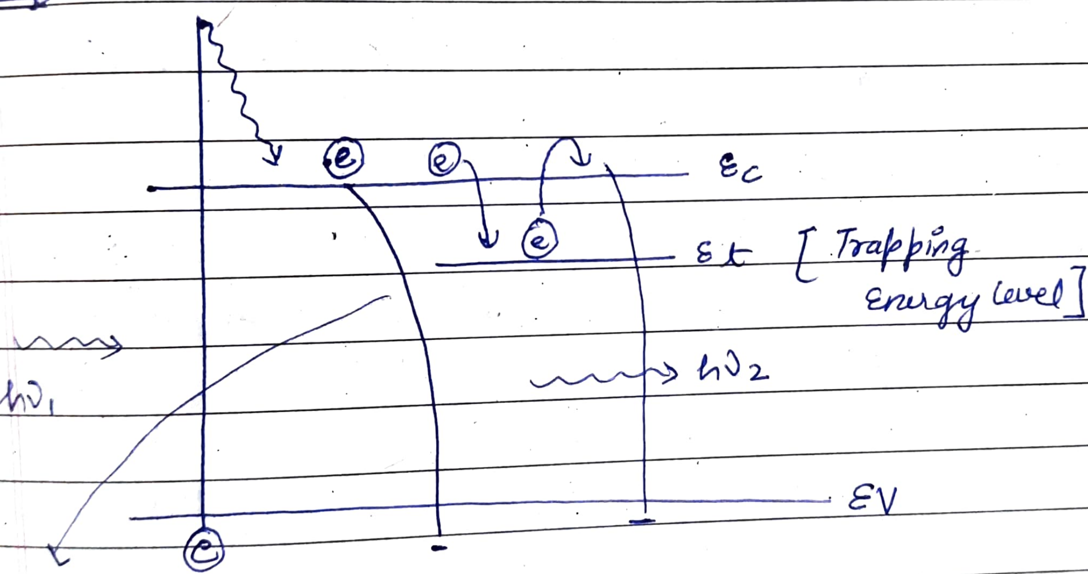
Luminescence -

Property of any material to generate or emit the light.

- → Photoluminescence (optical Absorption)
- → Cathodo luminescence (Electron Bombardment)
- → Electro luminescence (Carrier injection or current)

⇓

Excitation methods.



Direct recombination.

① Direct Recombination -

⇓

fast process (10^{-8} sec)

⇓

fluorescence

Indirect Recombination

⇓

Slow process

⇓

phosphorescence

→ Direct Recombination →

$$\frac{dn}{dt} = \alpha_r n_i^2 - \alpha_r n(t)\,p(t)$$

$$n = \underbrace{n_0}_{\text{equilibrium}} + \underbrace{\delta n}_{\text{Excess}}$$

$$p = \underbrace{p_0}_{\text{equilibrium}} + \underbrace{\delta p}_{\text{Excess}}$$

$$\rightarrow \frac{d\delta n(t)}{dt} = \alpha_r n_i^2 - \alpha_r\left[(n_0 + \delta n(t))(p_0 + \delta p(t))\right]$$

$$\delta n(t) = \delta p(t)$$

$$n_0 \approx 0 \quad [p\text{-type}]$$

$$\frac{d\delta n(t)}{dt} = \cancel{\alpha_r n_i^2} - \cancel{\alpha_r n_i^2} - \alpha_r(\cancel{n_0} + p_0)\,\delta n(t) - \underbrace{\delta n^2(t)}_{\text{neglected [due to low level injection]}}$$

$$\frac{d\delta n(t)}{dt} = -\alpha_r p_0\,\delta n(t)$$

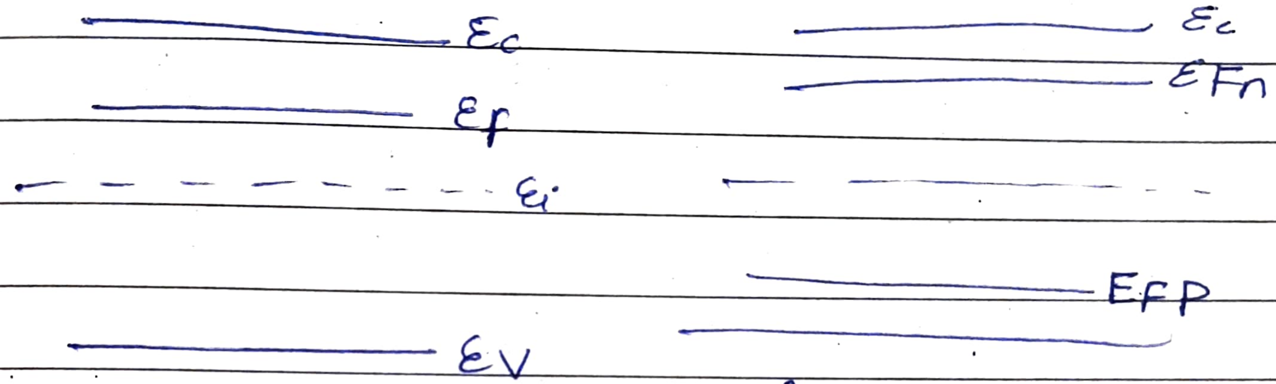
$$\int \frac{d\delta n(t)}{\delta n(t)} = -\alpha_r p_0 \int dt$$

$$\delta n t = \Delta n e^{-\alpha_r p_0 t}$$

$$\delta n(t) = \Delta n e^{-\alpha_r p_0 t} = \Delta n e^{-t/\tau}$$

$$\boxed{\tau = \frac{1}{\alpha_r p_0}} \rightarrow \text{minority carrier life time}$$

→ Quasi fermi level -



Eq^n cond

Quasi fermi level.