

Semiconductors

Intrinsic - Pure form of semiconductors

Extrinsic - Doped semiconductor

n type

p type

most metal oxides are n type

Crystal : Periodic arrangement of atoms in space

Crystal = Lattice + Basis

$$\vec{p} = \frac{\hbar}{\lambda} \approx \frac{\hbar \times 2\pi}{2\pi/\lambda} = \hbar \vec{k} \quad \vec{k} \text{ is wave vector (number)}$$

\vec{k} has unit m^{-1}

To study electron, we've to convert real space into reciprocal space

for simple cubic lattice, $\vec{a}_1 = a\hat{i}$ $\vec{a}_2 = a\hat{j}$ $\vec{a}_3 = a\hat{k}$

in reciprocal space
reciprocal vectors are given by $\vec{b}_1, \vec{b}_2, \vec{b}_3$ resp

$$\vec{b}_1 = \frac{(\vec{a}_2 \times \vec{a}_3) 2\pi}{a_1 \cdot (a_2 \times a_3)}$$

$$\vec{b}_2 = \frac{2\pi (\vec{a}_3 \times \vec{a}_1)}{a_1 \cdot (a_2 \times a_3)}$$

$$\vec{b}_3 = \frac{(\vec{a}_1 \times \vec{a}_2) 2\pi}{a_1 \cdot (a_2 \times a_3)}$$

$a_1 \cdot (a_2 \times a_3)$ is vol. of lattice

for 2D with parameter a_1 & a_2 ,

$$\vec{b}_1 = \frac{2\pi a_2}{a_1 \times a_2} \quad \& \quad \vec{b}_2 = \frac{a_1 2\pi}{a_1 \times a_2}$$

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primitive
for BCC,

$$\vec{a}_1 = \frac{1}{2} a (-\hat{i} + \hat{j} + \hat{k})$$

$$\vec{a}_2 = \frac{1}{2} a (\hat{i} - \hat{j} + \hat{k})$$

$$\vec{a}_3 = \frac{1}{2} a (\hat{i} + \hat{j} - \hat{k})$$

same formula to find
 b_1, b_2, b_3

primitive
for FCC,

$$\vec{a}_1 = \frac{1}{2} a (\hat{j} + \hat{k})$$

$$\vec{a}_2 = \frac{1}{2} a (\hat{k} + \hat{i})$$

$$\vec{a}_3 = \frac{1}{2} a (\hat{i} + \hat{j})$$

→

Simple cubic cell in real space will be simple cubic in reciprocal space

Surf

BCC in real space will be FCC in reciprocal space

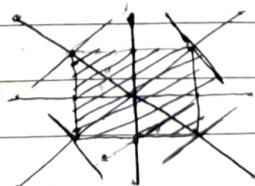
FCC in real space will be BCC in reciprocal space

* Primitive cell

A unit cell containing only one lattice point.

Creating a primitive cell -

The shaded part is called
primitive cell



~~imp~~ when primitive cell in real space is of length a , its length in reciprocal space will be $2\pi/a$

$$\Psi = e^{ik_x x} \text{ for } +x \text{ direction}$$

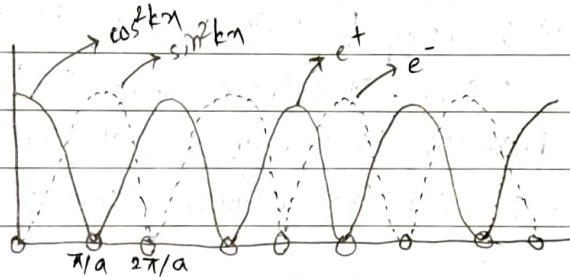
$$\Psi = e^{-ik_x x} \text{ for } -x \text{ direction}$$

$$\Psi_{(+)} = e^{ik_x x} + e^{-ik_x x} = 2 \cos(k_x x)$$

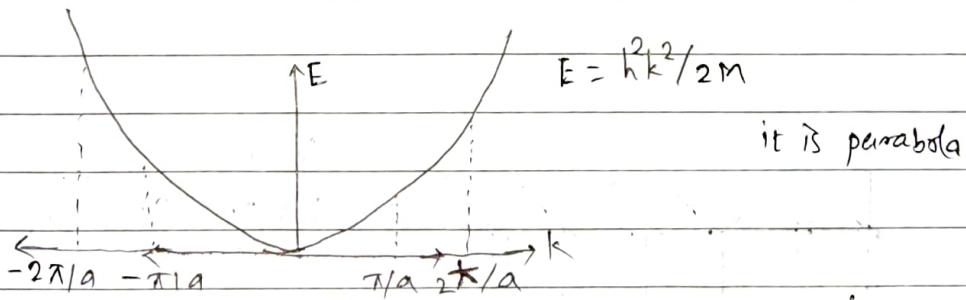
$$\Psi_{(-)} = e^{ik_x x} - e^{-ik_x x} = 2i \sin(k_x x)$$

$$e_+ = |\Psi_+|^2 \propto \cos^2 k_x x$$

$$e_- = |\Psi_-|^2 \propto \sin^2 k_x x$$



at points meeting X axis, $f(e) = 0$



* Fermi Dirac State

$$f(E) = \frac{1}{1 + e^{(E-E_f)/kT}} \quad \text{if } E = E_f, \quad f(E) = 1/2$$

Density of States tells us how many states exist at a given energy E . $f(E)$ is the probability of finding the electron i.e. $f(E)$ is the equilibrium condition, specifies the probability of an available state of an energy E will be occupied by an electron. It is a probability distribution function.

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

here, E_f - fermi energy level

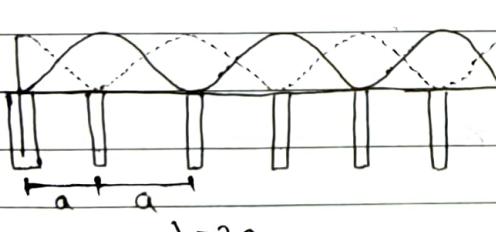
k = Boltzmann constant

$$= 1.38 \times 10^{-23} \text{ J/K} = 8.6 \times 10^{-5} \text{ eV/K}$$

T = absolute temperature in K

The amount of energy for which probability is $1/2$, $f(E) = 1/2$ is called fermi energy. It is the case when $E = E_f$

$f(E)$ is probability that a quantum state at E is filled with electron
 $1 - f(E)$ is probability that a quantum state at E is empty



k-wave no

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{2a} = \pi/a$$

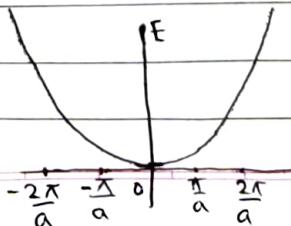
for constructive interference,
 $\Psi = e^{ikx} + e^{-ikx}$
 $= A \cos(kx)$

$$|\Psi|^2 = \text{prob}(e^-/\text{vol})$$

for destructive interference,
 $\Psi = e^{ikx} - e^{-ikx}$

$$= B \sin(kx)$$

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

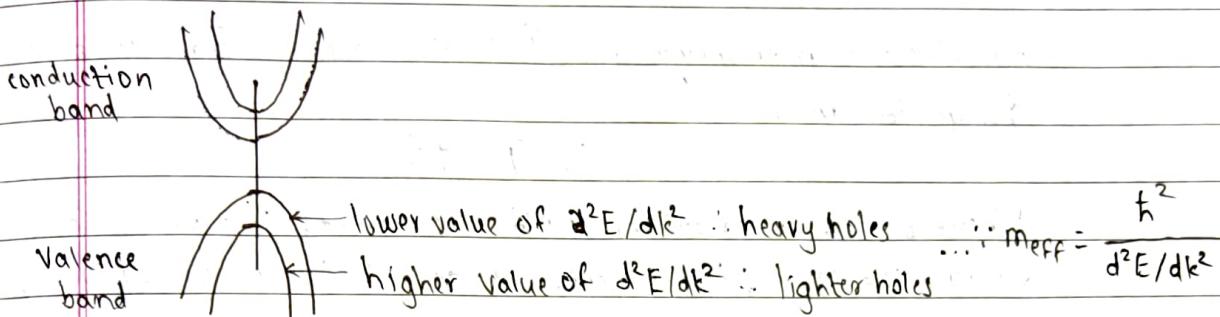


$$\frac{dE}{dk} = \frac{\hbar^2 k}{m} \quad \frac{d^2 E}{dk^2} = \frac{\hbar^2}{m_{\text{eff}}}$$

$$\therefore m_{\text{eff}} = \frac{\hbar^2}{\frac{\partial}{\partial k_x} \cdot \frac{\partial}{\partial k_y} E}$$

* Brillouin zone

* The primitive cell in reciprocal lattice space is called as Brillouin zone.



* Charge carrier density in intrinsic semiconductor

$$n = \int_{E_c}^{\infty} D_e(E) f_e(E) dE \quad p = \int_{-\infty}^{E_v} D_h(E) f_h(E) dE$$

$D(E)$ = density of states

= no. of available states per unit energy per unit volume

n = no. of electron per unit volume

p = no. of holes per unit volume

$f_e(E)$ = probability of finding electron

$f_h(E)$ = probability of finding holes

$$D_e(E) = \frac{1}{2\pi^2} \left(\frac{2m_e^*}{\hbar^2} \right)^{3/2} (E - E_c)^{1/2}$$

$$D_h(E) = \frac{1}{2\pi^2} \left(\frac{2m_h^*}{\hbar^2} \right)^{3/2} (E_v - E)^{1/2}$$

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

$$kT = 25 \text{ meV}$$

$$3kT = 75 \text{ meV}$$

$$\text{if } E - E_f > 3kT \quad f_e(e)$$

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

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

An electron maintaining its \vec{k} vector signifies that it doesn't change its momentum

$$\therefore \vec{P} = \hbar \vec{k}$$

Whenever the momentum isn't maintained, i.e. when initial & final one isn't the same, the momentum is said to be conserved by phonon

$$P_{\text{phonon}} = \vec{P}_{e-\text{VB}} - \vec{P}_{e-\text{CB}}$$

VB - valence band

CB - conductⁿ band

$$n = \int_{E_c}^{\infty} D_e(E) f_e(E) dE$$

$$n = \int_{E_c}^{\infty} A(E-E_f)^{v_2} e^{-(E-E_f)/k_B T} dE$$

$$P = \int_{-\infty}^{E_V} D_h(E) f_h(E) dE$$

$$= \int_{-\infty}^{E_V} (E_V - E)^{v_2} e^{-(E_f - E)/k_B T} dE$$

$$n = \int_{E_c}^{\infty} A(E-E_f)^{v_2} e^{-[E-E_f-E_c+E_c]/k_B T} dE$$

$$n = \int_{E_c}^{\infty} A(E-E_f)^{v_2} e^{-(E_c-E_f)/k_B T} e^{-(E-E_c)/k_B T} dE$$

$$n = A e^{-(E_c - E_f)/k_B T} \int_{E_c}^{\infty} (E - E_f)^{1/2} e^{-(E - E_f)/k_B T} dE$$

$$\frac{E - E_c}{k_B T} = x \quad dE = dx \cdot k_B T \quad \text{When } E = E_c, x = 0 \\ E = \infty, x = \infty$$

$$n = A e^{-(E_c - E_f)/k_B T} \int_0^{\infty} (k_B x)^{1/2} e^{-x} k_B T \cdot dx$$

$$n = A e^{-(E_c - E_f)/k_B T} (k_B T)^{3/2} \int_0^{\infty} x^{1/2} e^{-x} dx$$

$$n = A e^{-(E_c - E_f)/k_B T} (k_B T)^{3/2} \frac{\sqrt{\pi}}{2}$$

now, we know, $A = \frac{1}{2\pi^2} \left(\frac{2m_e^*}{h^2} \right)^{3/2}$

$$\therefore n = \frac{1}{2\pi^2} \left(\frac{2m_e^*}{h^2} \right)^{3/2} (k_B T)^{3/2} \frac{\sqrt{\pi}}{2} e^{-(E_c - E_f)/k_B T}$$

$$= \frac{1}{4} \left(\frac{2m_e^* k_B T}{h^2 \pi} \right)^{3/2} e^{-(E_c - E_f)/k_B T}$$

$$n = 2 \left(\frac{k_B m_e^*}{2\pi h^2} \right)^{3/2} e^{-(E_c - E_f)/k_B T}$$

similarly,

$$p = 2 \left(\frac{k_B T m_h^*}{2\pi h^2} \right)^{3/2} e^{-(E_f - E_v)/k_B T}$$

when $n = p$,

$$1 = \left(\frac{m_e^*}{m_h^*} \right)^{3/2} e^{(E_f - E_c - E_v + E_f)/k_B T}$$

$$1 = \left(\frac{m_e^*}{m_h^*} \right)^{3/2} e^{(-E_c - E_v)/k_B T} \cdot e^{2E_f/k_B T}$$

$$\therefore e^{-2E_f/k_B T} = \left(\frac{m_e^*}{m_h^*} \right)^{3/2} e^{-(E_c + E_v)/k_B T}$$

$$\therefore e^{(E_c + E_V)/k_B T} = \left(\frac{m_e^*}{m_h^*}\right)^{3/2} e^{2E_f/k_B T}$$

$$\frac{E_c + E_V}{k_B T} = \ln\left(\frac{m_e^*}{m_h^*}\right)^{3/2} + \frac{2E_f}{k_B T}$$

$$E_c + E_V - k_B T \cdot \ln\left(\frac{m_e^*}{m_h^*}\right)^{3/2} = 2E_f$$

$$\therefore \frac{E_c + E_V}{2} - \frac{k_B T}{2} \ln\left(\frac{m_e^*}{m_h^*}\right)^{3/2} = E_f$$

$$\begin{aligned} \therefore E_f &= \frac{E_c + E_V}{2} - \frac{k_B T}{2} \ln\left(\frac{m_e^*}{m_h^*}\right)^{3/2} \\ E_f &= E_{\text{midgap}} - \frac{3k_B T}{4} \ln\left(\frac{m_e^*}{m_h^*}\right) \end{aligned}$$

no. of intrinsic carrier = n_i

$$n_i^2 = n_p n_n$$

$$\boxed{n_o = n_p n_c e^{-(E_c - E_f)/k_B T}, n_c = \frac{2(2\pi m_e^* k_B T)^{3/2}}{h^3}}$$

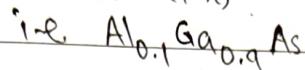
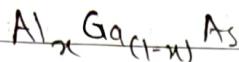
$$\boxed{P_o = P_V e^{-(E_f - E_V)/k_B T}, P_V = \frac{2(2\pi m_h^* k_B T)^{3/2}}{h^3}}$$

$$\boxed{n_i^2 = n_c P_V e^{-(E_c - E_V)/k_B T}}$$

$$\boxed{n_i = \sqrt{n_c P_V} e^{-(E_c - E_V)/2k_B T}}$$

- * To get the intermediate properties of 2 semiconductors, their alloys are made
- * To get Comⁿ for 2 semiconductors to be eligible for alloy form.
- 1) Comparable electronegativity
 - 2) Comparable oxidation state (same)
 - 3) As less as possible mismatching properties.

ex. Aluminium Arsenide & Gallium Arsenide



i.e. Al is mixed w/ GaAs

for any lattice parameter a , & alloy $\text{A}_x \text{B}_{1-x} \text{C}$,

$$a_{\text{A}_x \text{B}_{1-x} \text{C}} = x a_{\text{AC}} + (1-x) a_{\text{BC}}$$

$$E_g_{\text{A}_x \text{B}_{1-x} \text{C}} = x E_g_{\text{AC}} + (1-x) E_g_{\text{BC}}$$

* Mobility of charge carriers in semiconductors depends on:

- 1) Dynamics of lattice
- 2) Impurities in crystals

$$\tau = \text{mean collision time} \Rightarrow \frac{1}{\tau} = \frac{1}{\tau_{\text{lattice}}} + \frac{1}{\tau_{\text{impurity}}}$$

$$\text{mobility} (\mu) \propto \frac{1}{\tau}$$

$$\frac{1}{\mu} = \frac{1}{\mu_{\text{lattice}}} + \frac{1}{\mu_{\text{impurity}}}$$

$$\frac{1}{\mu} = \frac{1}{\mu_{\text{lattice}}} + \frac{1}{\mu_{\text{impurity}}}$$

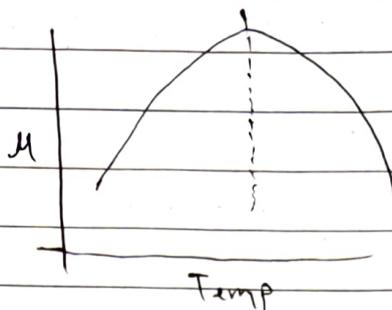
$$\mu_{\text{lattice}} \propto T^{3/2}$$

$$\mu_{\text{impurity}} \propto T^{-3/2}$$

... T is temperature

μ = drift velocity per electric field

$$\mu = \frac{V_d}{E} = \frac{eET}{m_e E} = \frac{eT}{m_e}$$



$$\mu_{\text{lattice}} \propto T^{3/2}$$

$$\mu_{\text{impurity}} \propto T^{-3/2}$$

At low temperature there are lesser no. of phonons \therefore Very less possibility of collision i.e. very low mobility i.e. very less drift velocity

At higher temp., there are very high no. of phonons
 \therefore Too many collisions & thereby μ & V_d .

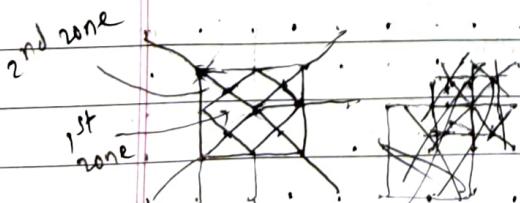
Draw the reciprocal lattice of a 2D crystal with lattice parameter $3A^\circ$ & $2A^\circ$ with angle of 90° & draw Brillouin zone

$$a_1 = 3A^\circ \quad a_2 = 2A^\circ$$

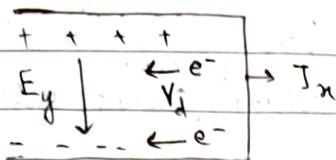
$$\vec{a}_1 = 3\hat{i} \quad \vec{a}_2 = 2\hat{j}$$

$$\vec{b}_1 = \frac{2\pi a_2}{a_1 \times a_2} = \frac{2\pi \times 2}{3 \times 2 \times \sin 90^\circ} = \frac{2\pi}{3A^\circ} \hat{i}$$

$$\vec{b}_2 = \frac{2\pi a_1}{a_1 \times a_2} = \frac{2\pi}{2A^\circ} \hat{j}$$



B.Z. of a square lattice will be square
& that of a rectangular lattice will be a rectangle



$$\text{Lorentz force} = F_L = eV_d B_z$$

$$eE_y = eV_d B_z$$

$$E_y = V_d B_z$$

$$J_x = -neV_d$$

$$\therefore \frac{E_y}{B_z} = -\frac{J_x}{ne}$$

$$\therefore E_y = -\frac{1}{ne} J_x B_z$$

$$\therefore R_H = \text{Hall's coefficient} = \frac{E_y}{J_x B} = -\frac{1}{ne}$$

n type semiconductors - trivalent impurity is added
p type semiconductors - pentavalent impurity is added

* Gradient of impurities in extrinsic semiconductors

diffusion current is due to majority carriers

drift current \rightarrow minority \leftarrow

\leftarrow diffusion current
 \rightarrow drift current

Electric field is created due to

diffusion current

for n

$e^- e^- e^- \rightarrow e^-$

current density total $= J_T = J_{\text{diffuse}} + J_{\text{drift}}$

type

semiconductor $e^- e^- e^- e^-$

$J_T = 0$ \because No external voltage is applied

$$\therefore 0 = qD_n \frac{dN_D}{dx} + N_D q u_e E_x = 0 \quad \text{--- (1)}$$

$I_{\text{diffusion}} \propto \frac{dN_D}{dx}$

E_x - electric field q - charge of carrier u_e - mobility

$J_{\text{diffusion}} = D_n \frac{dN_D}{dx} q$ N_D - no. of donors per vol. D_n = diffusion constant

D_n is diffusion const.

for greater no. of donor atoms (N_D value), fermi energy level for ext.

~~n-type~~ S.C. goes nearer to the conductⁿ band

for greater no. of acceptor atoms, $\text{energy value level}$ goes nearer to the valence band

$$N_D = N_i e^{-2 \left(\frac{m_e^* K_B T}{2\pi \hbar^2} \right)^{3/2} e^{(E_f - E_c)/K_B T}}$$

$$N_D = 2 \left(\right)^{3/2} e^{(E_f - E_c + E_{if} - E_{if})}$$

E_{if} - intrinsic S.C. at fermi level

D - donor

$$N_A = 2 \left(\right)^{3/2} e^{(E_{if} - E_c)/K_B T} e^{(E_f - E_{if})/K_B T} \quad \text{A-acceptor}$$

$$\text{similarly, } N_A = 2 \left(\right)^{3/2} e^{(E_V - E_{if})/K_B T} e^{(E_{if} - E_f)/K_B T} \quad \text{--- (2)}$$

$$\text{--- (1)} \times \text{--- (2)} \Rightarrow N_D \times N_A = n^2$$

$$\therefore \text{from (1), } N_D = N_i e^{(E_f - E_{if})/K_B T} \quad n_i \text{ is written as } N_i$$

$$\text{from (2), } N_A = N_i e^{(E_{if} - E_f)/K_B T}$$

$$\text{from (1), } E_f - E_{if} = K_B T \ln(N_D/N_i)$$

$$\therefore -\frac{dE_{if}}{dn} = K_B T \times N_i \times \frac{1}{N_D} \times \frac{dN_D}{dn} \quad \text{--- (4)}$$

$$\text{now, we know, } qE_x = \frac{dE_{if}}{dn} \quad \therefore E_x = \frac{dE_{if}}{qdn} \quad \text{--- (5)}$$

E_x is total electric field

from (4) & (5),

$$E_x = \frac{-K_B T}{qN_D} \times \frac{dN_D}{dn}$$

putting this value in (1),

$$qD_n \frac{dN_D}{dn} = n q u_e \frac{K_B T}{qN_D} \frac{dN_D}{dn}$$

here n is vol. conc. of donor atoms (electrons)
i.e. $n = N_D$

for n-type S.G., $\boxed{\frac{D_n}{u_e} = \frac{k_B T}{e}}$... when charge is an electron

D_n = diffusⁿ const for

for p-type S.C.

$$\boxed{\frac{D_h}{u_h} = \frac{k_B T}{q}} \quad \text{... for hole}$$

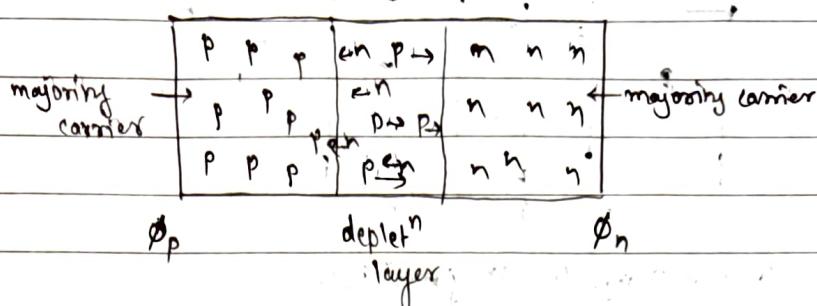
u_h = mobility of holes

This is known as Einstein relation

for no external electric field

nsic

* PN junction



Generated electric field \vec{E} will oppose the further movement of majority charge carriers (diffusion)

It will promote the already diffused charge

here also, total current density = 0

$$J_T = q \mu N_A E_x - q D_p \frac{dN_A}{dx} = 0$$

promotes

opposes

carriers

N - no. of charge per volume

$$\frac{q}{D_p} \frac{dN_A}{dx} = \frac{1}{N_A} \frac{d\phi}{dx}$$

we know, $E_x = \frac{d\phi}{dx}$

$$\frac{\mu}{D_p} \times \frac{-d\phi}{dx} = \frac{1}{N_A} \frac{dN_A}{dx}$$

ϕ is potential

$$\frac{q}{k_B T} \frac{d\phi}{dx} = \frac{1}{N_A} \frac{dN_A}{dx}$$

we are going from p region to n

$$\int_{\phi_p}^{\phi_n} d\phi = \int_{P_o}^{P_v} \frac{dN_A}{N_A}$$

$$\frac{-q}{k_B T} (\phi_n - \phi_p) = \ln \frac{P_o}{P_v}$$

$$P_v = N_A$$

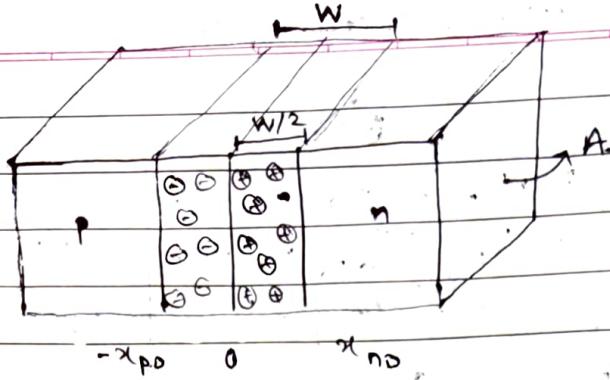
$$N_A N_D = N_i^2$$

$$n_0 n_0 = N_i^2$$

$$\therefore V_0 = \frac{k_B T}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

$$n_0 n_0 = n_i^2$$

V_0 = potential at junct?



Overall charge on pn junction is 0

$$\text{Q}_{\text{in } p} + \text{Q}_{\text{in } n} = 0$$

$$-WqA\chi_{p0}N_A + qA\chi_{n0}N_D = 0$$

$$\chi_{p0} = \frac{N_A}{N_p + N_D}, \chi_{n0} = \frac{N_D}{N_A + N_D}$$

$$\chi_{p0}N_A = \chi_{n0}N_D$$

V

By Maxwell's eqn,

$$\frac{d\vec{E}_n}{dx} = \frac{q}{\epsilon_0} (p - n + N_D - N_A) x \quad \text{"axis fract" of charge carriers}$$

There is no mobility in depletion region $\therefore p = n = 0$

$$\frac{d\vec{E}_n}{dx} = \frac{q}{\epsilon_0} (N_D - N_A) x$$

M for n region, $\frac{d\vec{E}_n}{dx} = \frac{q}{\epsilon_0} N_A \chi_{n0}, \quad 0 < x < \chi_{n0}$

$$\int d\vec{E}_n = \frac{qN_A}{\epsilon_0} \int_{-W/2}^{W/2} N_A \chi_{n0} dx \Rightarrow \vec{E}_n = \frac{WqN_A \chi_{n0}}{\epsilon_0}$$

P for p region, $\frac{d\vec{E}_n}{dx} = \frac{-q}{\epsilon_0} N_D \chi_{p0}, \quad 0 < x < -\chi_{p0}$

$$\int d\vec{E}_n = \frac{-qN_D}{\epsilon_0} \int_{-W/2}^{W/2} N_D \chi_{p0} dx \Rightarrow \vec{E}_n = \frac{-WqN_D \chi_{p0}}{\epsilon_0}$$

for half part of depletion region, $V_o = \frac{\vec{E}_n W}{2}$

$$\vec{E}_n = \frac{Wq\chi_{p0}N_D}{\epsilon_0}$$

$$\therefore V_o = \frac{1}{2} \frac{qN_D \chi_{p0} W^2}{\epsilon_0}$$

$$300k_B = 0.0259 \text{ eV}$$

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$$\chi_{pd} = \frac{N_A}{N_D + N_A}$$

$$\therefore V_0 = \frac{q N_D N_A W^2}{2 \epsilon_0 (N_D + N_A)}$$

here $q N_D = S_D$

$$W = \left(\frac{2 \epsilon_0 V_0}{q} \left[\frac{1}{N_D} + \frac{1}{N_A} \right] \right)^{1/2}$$

$$q N_A = S_A$$

S is charge density

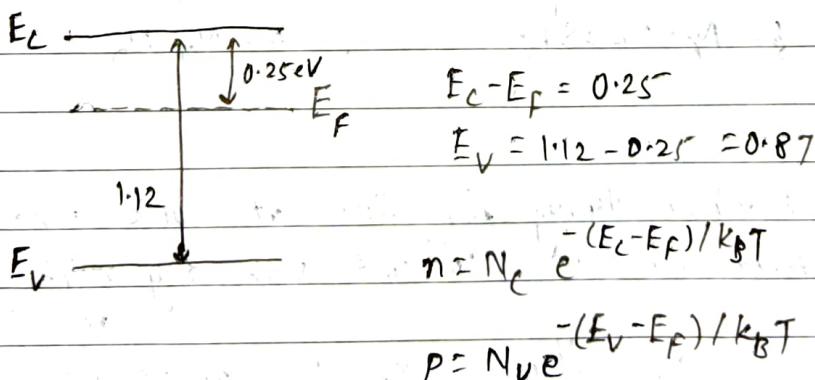
if N_D is very small, $\Rightarrow W$ is very large

$\Rightarrow V_0$ is very less

N_D is very large $\Rightarrow W$ is small

$\Rightarrow V_0$ is large

- 1) Calculate thermal equi. conc. of e^- , holes in a silicon conductor at temp 300K. Density of states in valence & conductn band is $1.04 \times 10^{19} \text{ cm}^{-3}$ & $2.8 \times 10^{19} \text{ cm}^{-3}$. Bandgap of Si is 1.12 eV & Fermi energy is 0.25 eV below conductn band.



$$N_c = 2.8 \times 10^{19} \quad N_V = 1.04 \times 10^{19}$$

2) prove that donor conc in an extrinsic semiconductor

$$n = \frac{N_D^2 - N_A^2}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$p + N_D = N_A + n \quad np = n_i^2$$

$$\frac{n_i^2}{n} + N_D = N_A + n$$

$$n_i^2 + nN_D = nN_A + n^2$$

$$n^2 + n(N_A - N_D) + n_i^2 = 0$$

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

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

Similarly, $p = \frac{N_A + N_D}{2} + \sqrt{\left(\frac{N_A + N_D}{2}\right)^2 + n_i^2}$

$$\text{for } N_D - N_A \gg n_i$$

$$\text{for heavily doped SC, } n = N_D - N_A$$

$$\text{for } N_A - N_D \gg n_i, \quad p = N_A - N_D$$

3) find e⁻ & hole density for silicon at 300K when donor conc is 10^{16} cm^{-3} without any acceptor conc

$$N_D = 10^{16} \text{ cm}^{-3} \quad N_A = 0 \quad n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$$

use above formulae to find n & p

~~Imp~~ for 300K, $k_B T = 0.0259 \text{ eV}$

Date _____

Page _____

- 4) for σ type silicon at 300K, Fermi energy is 0.2 eV below conduct band $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ $N_c = 2.8 \times 10^{19}$. Find donor ion conc for S.C to be n type $N_A = 10^{16}$

$$n = N_c e^{-(E_C - E_F)/k_B T}$$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

$$N_A \gg n_i \therefore n = N_D - N_A$$

$$N_D - N_A = N_c e^{-(E_C - E_F)/k_B T}$$

N_D can be calculated

- 5) Donor impurity conc $= 8 \times 10^{15} \text{ cm}^{-3}$ & acceptor impurity conc is $5 \times 10^{15} \text{ cm}^{-3}$ for silicon $N_c = 2.10 \times 10^{19}$ $n_i = 1.5 \times 10^{10}$ at 300K $N_D = 8 \times 10^{15}$ $N_A = 5 \times 10^{15}$

Find diff in Fermi energy & conductn band energy for conductor to be n type

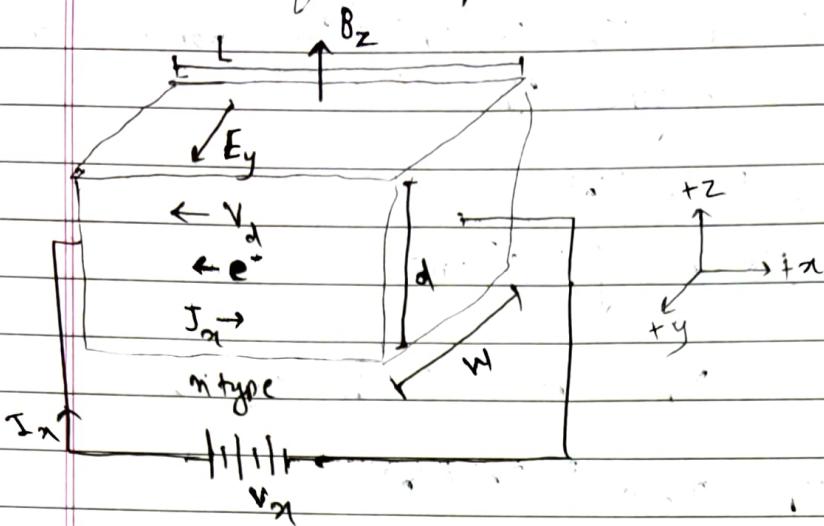
$$N_D - N_A \gg n_i$$

$$-(E_C - E_F)/k_B T$$

$$\therefore n = N_D - N_A = N_c e^{-(E_C - E_F)/k_B T}$$

All is given find $E_C - E_F$

* External field is present



$$eE_y = B_z eV_d \quad \text{for n type}$$

$$J_x = -nev_d \quad V_d = -J_x / ne$$

$$E_y = B_z \left(\frac{-J_x}{ne} \right)$$

$$\boxed{\frac{E_y}{B_z J_x} = \frac{-1}{ne}}$$

n type

$$\boxed{\frac{E_y}{B_z J_x} = \frac{1}{pe}}$$

p type

$$E_y = V_y / w$$

$$\boxed{\frac{V_y}{w B_z J_x} = \frac{-1}{ne} = R_H}$$

R_H = Hall coefficient

V_y = Hall voltage

$$J_x = I_x / A$$

$$= I_x / (W d)$$

$$J = nev_d = ne \frac{V_d \cdot E_x}{E_x} = nev_d \frac{V_d}{L}$$

$$M = \frac{V_y}{V_x B_z} \cdot \frac{L}{W}$$

$$V_y = -\frac{WB_2J_y}{ne} - \frac{-B_2I_y}{ned}$$

$$\text{putting } J_y = \pi neu \frac{V_x}{L}$$

$$\mu = \frac{V_y}{V_x B_z W}$$

1] Si at 300K $N_D = 2 \times 10^{16} \text{ cm}^{-3}$

↓ it is n in completely ionized con?

$$d = 10^{-2} \text{ cm} \quad L = 1 \text{ cm} \quad W = 10^{-1} \text{ cm} \quad I_m = 1.2 \text{ mA}$$

$$B = 500 \text{ Gauss} = 5 \times 10^{-3} \text{ T}$$

$$1 \text{ Gauss} = 10^{-4} \text{ T}$$

find V_y & E_y

$$V_y = -\frac{B_2 I_y}{ned} = -179.64 \text{ V}$$

$$E_y = \frac{V_y}{W} = -179640 \text{ V/m}$$

$$V_y = -\frac{wB_z I_n}{n e} - \frac{-B_z I_n}{n e d}$$

putting $I_n = \frac{n e u V_x}{L}$

$$u = \frac{V_y}{V_x B_z} \frac{L}{w}$$

1] Si at 300K $N_D = 2 \times 10^{16} \text{ cm}^{-3}$

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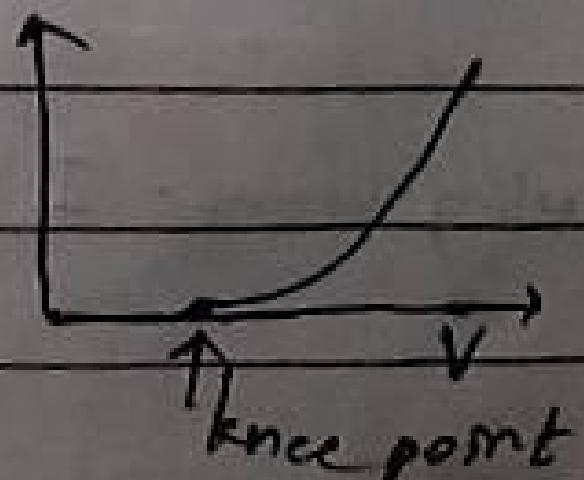
$$E_y = \frac{V_y}{w} = -179640 \text{ V/m}$$

* Diode

for forward bias, width of depletion region is small

for reverse \rightarrow large

Until the external potential is less than junction potential, diode doesn't conduct electricity. After a certain value it'll start to conduct electricity.



from $(E_F - E_C) \propto T$

$$n = N_C e^{-\frac{E_F - E_C}{k_B T}}$$

$$E_C - E_F = k_B T \ln \left(\frac{N_C}{N_D} \right)$$

N_C - effective density of states of conduction band

N_D - donor atom conc

if $N_C = N_D$, $E_C = E_F$

if $N_D > N_C$, RHS < 0

$\therefore E_C < E_F$

E_F

E_C

from $(E_F - E_V) \propto T$

$$p = N_V e^{-\frac{E_F - E_V}{k_B T}}$$

$$E_F - E_V = k_B T \ln \left(\frac{N_V}{N_A} \right)$$

N_V - effective density of states of valence band

$N_V = N_A$, $E_F = E_V$

N_A - Acceptor atoms conc

$N_A > N_V$, RHS < 0

$E_F < E_V$

E_V

E_F



Diode



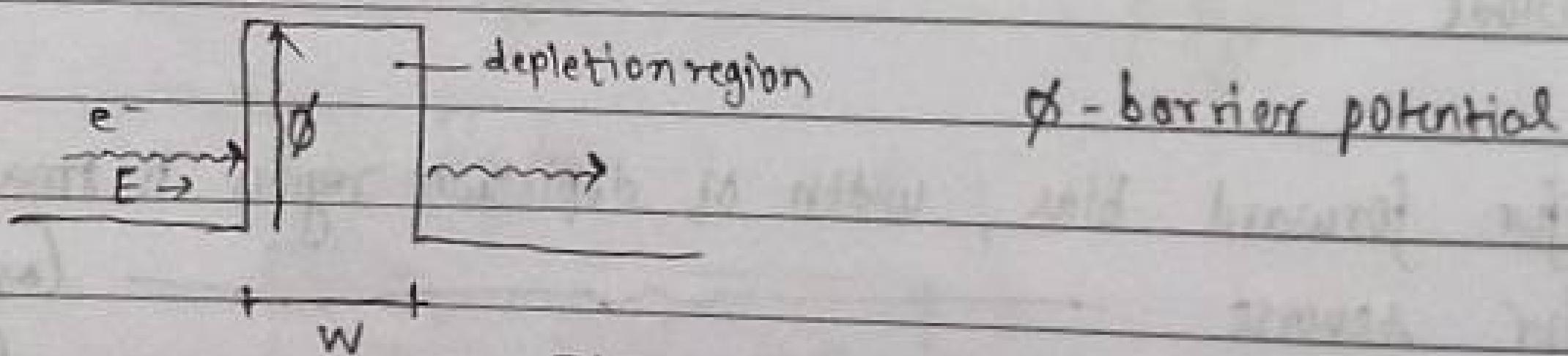
Zener diode



Tunnel diode

Very high doping than zener diode

* Tunnelling effect



If particle energy is less than the barrier then there is a finite probability of finding the particle on other side

$$\text{Tunnelling current} = I \propto e^{2kW}$$

$$k = \frac{\sqrt{2m(\phi - E)}}{\hbar}$$

ϕ - barrier potential

w - width of depletion region

E - energy that we are providing

m - effective mass of electron

* Zener diode : mostly used in reverse bias

Zener diode is heavily doped & hence depletion width is very small. Consequently electric field is so high.

$$V_0 = \frac{k_B T}{q} \ln(N_A N_D / n_i^2)$$

$$(depletion width) \quad W = \left(\frac{2 \epsilon_0 \epsilon_r V_0}{q} \left[\frac{1}{N_D} + \frac{1}{N_A} \right] \right)^{1/2} \quad \epsilon_r = \epsilon$$

$$(electric field developed in depletion region) \quad E = \frac{V_0}{W}$$

Imp When doping is very high $\Rightarrow N_A \& N_D$ is very high $\Rightarrow W$ is very low
 $\Rightarrow E$ is very high

When semiconductor is highly doped with donor atoms, conduct band has very large no. of donor atoms i.e. very large no. of e^- are present there energy level when E_f is probability of finding majority charge carriers is $1/2$. Since large no. of e^- are present in conduct band, E_f level will be closer to conduct band.

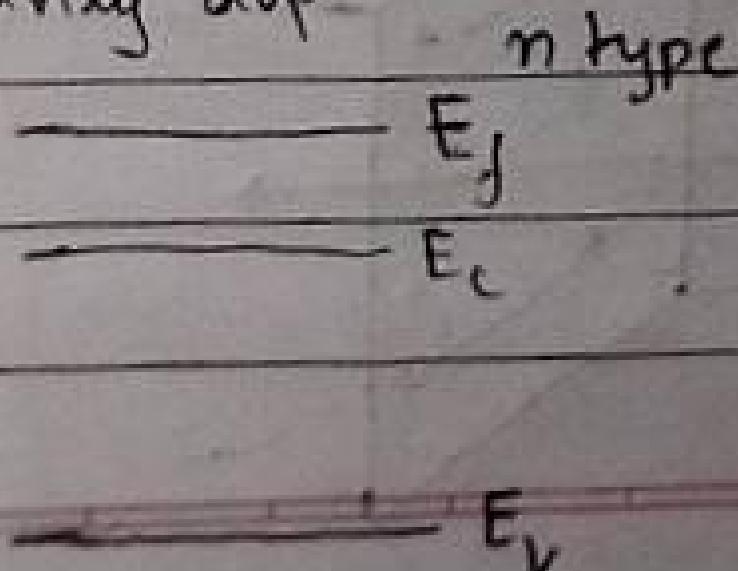
Imp When semiconductor is doped with acceptor atoms, valence band has very large no. of acceptor atoms i.e. very large no. of holes are present there.

E_f is energy level when prob of finding majority charge carrier is $1/2$.

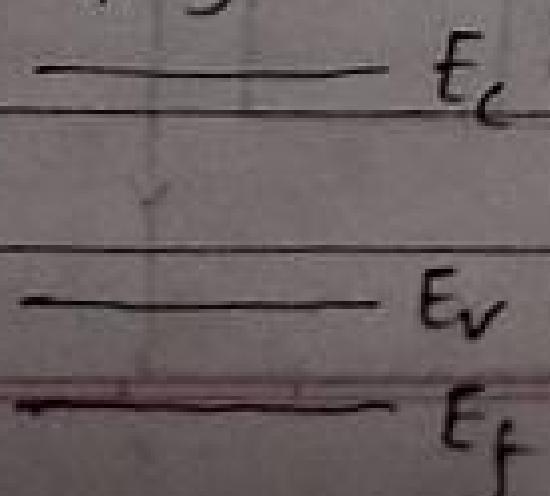
Since large no. of holes are present in valence band, E_f level will be closer to valence band.

In intrinsic, E_f is in b/w $E_c \& E_v$. But for heavy doped semiconductor it may be below E_v or above E_c for p & n type respectively.

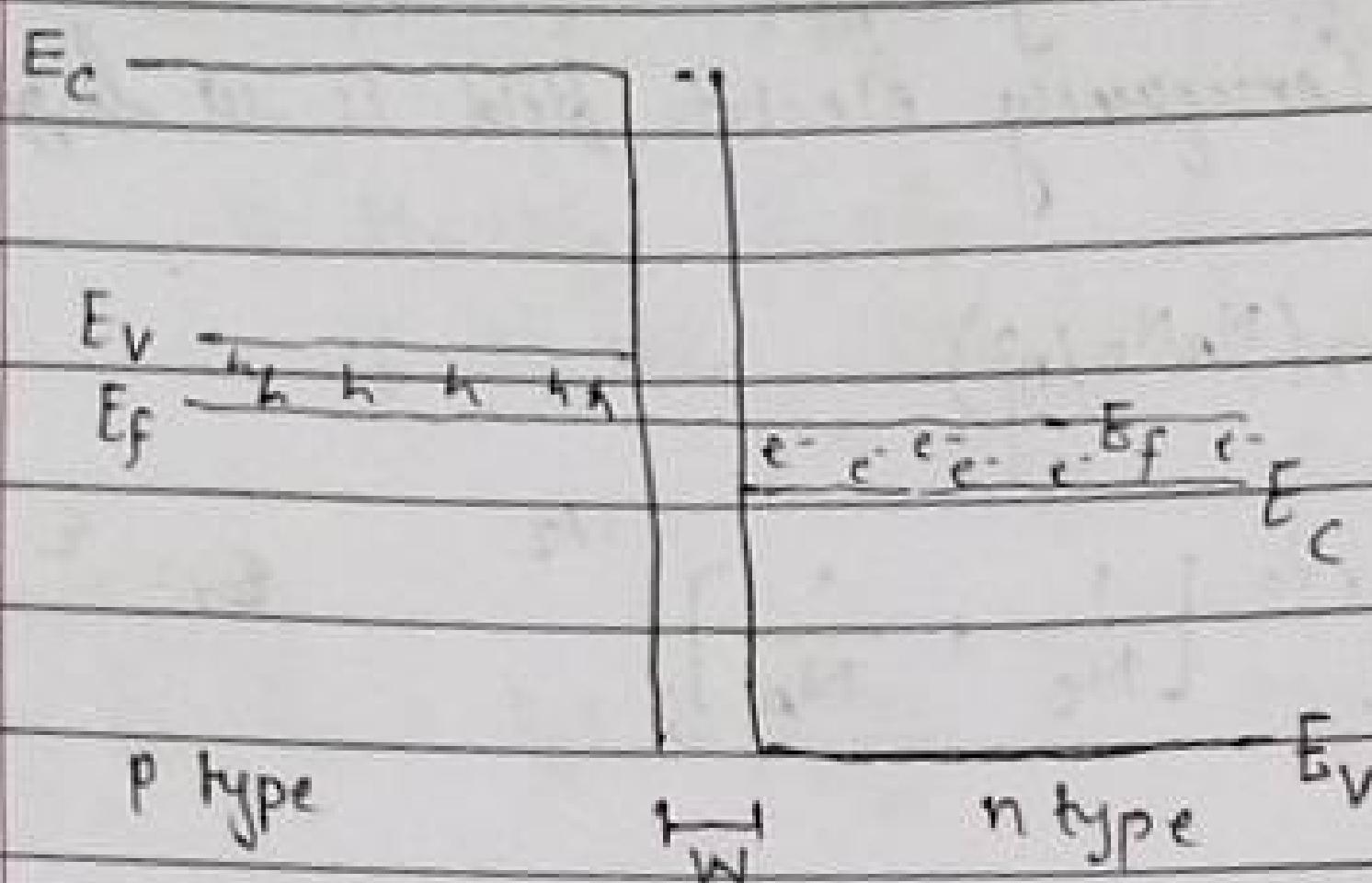
Heavily dop-



p type



* Tunneling effect



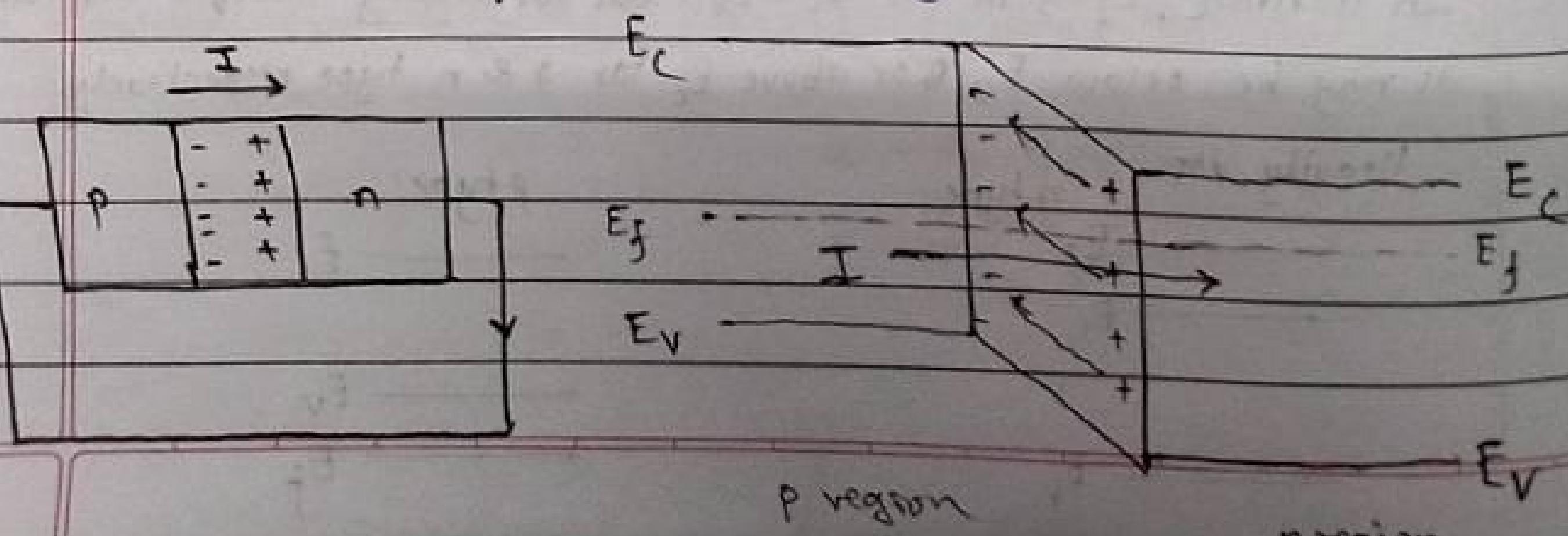
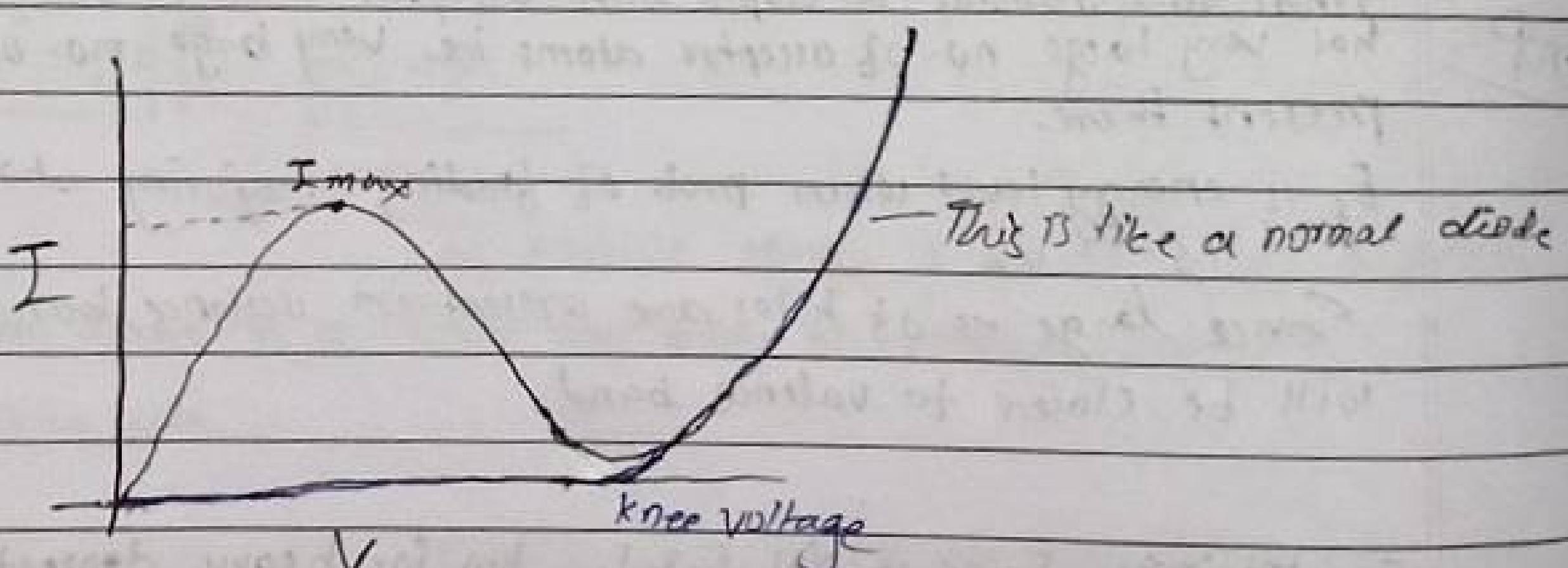
Tunnel diode in absence of any bias

energy of e^- increases (-ve pole will repel e^-) so it moves up
& energy of hole increases (+ve pole will repel h) so it moves down

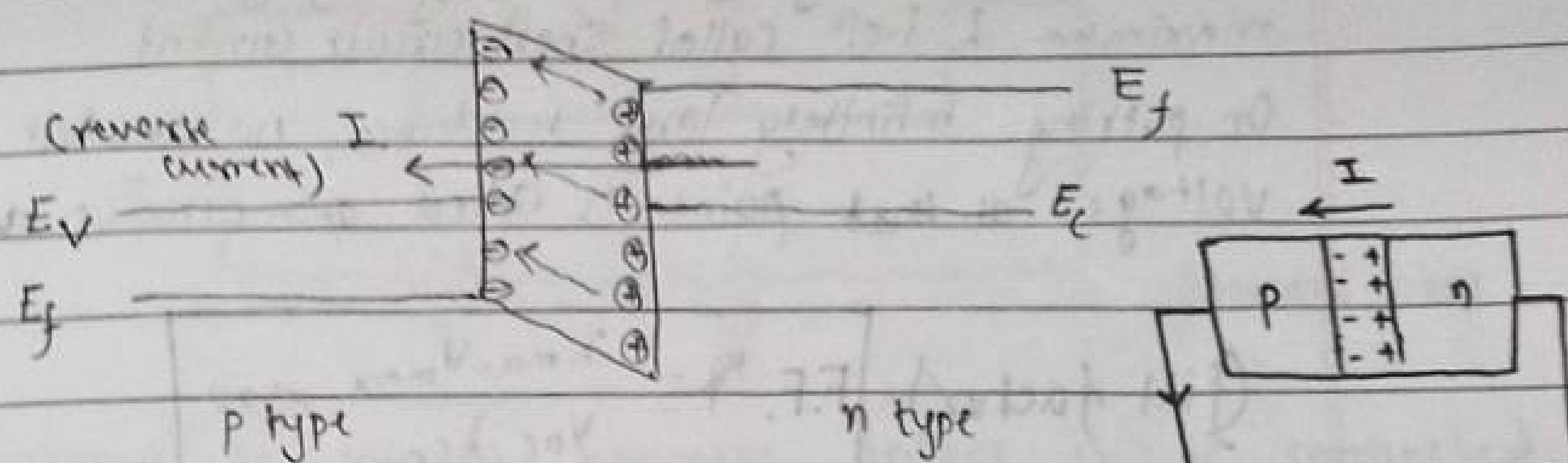
forward bias

In forward bias, E_f of p type moves downward & that of n type moves upward. After some time both will exactly match & at that time tunneling current is maximum.

further increasing potential again, the same process continues & it acts as a normal diode

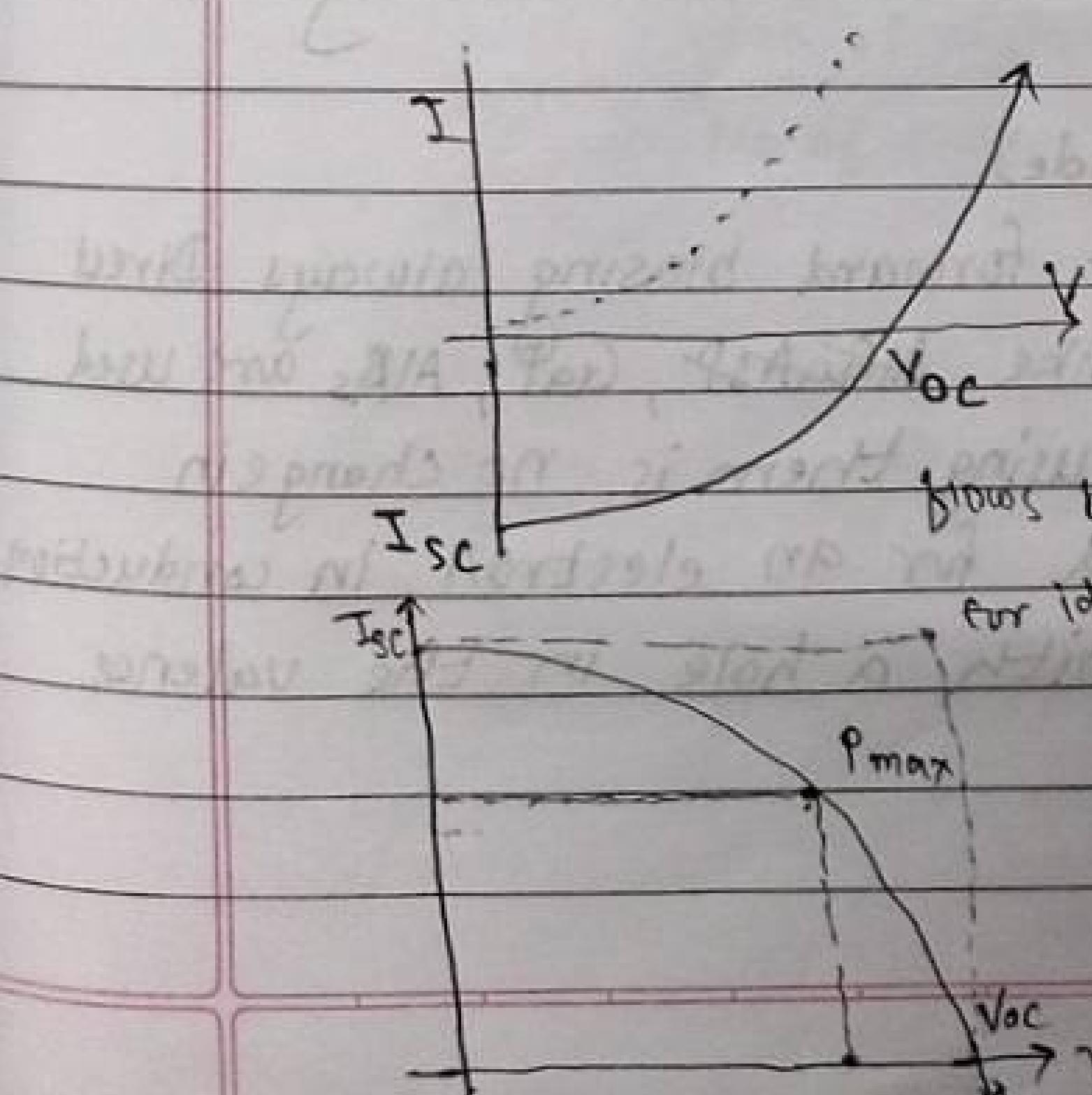
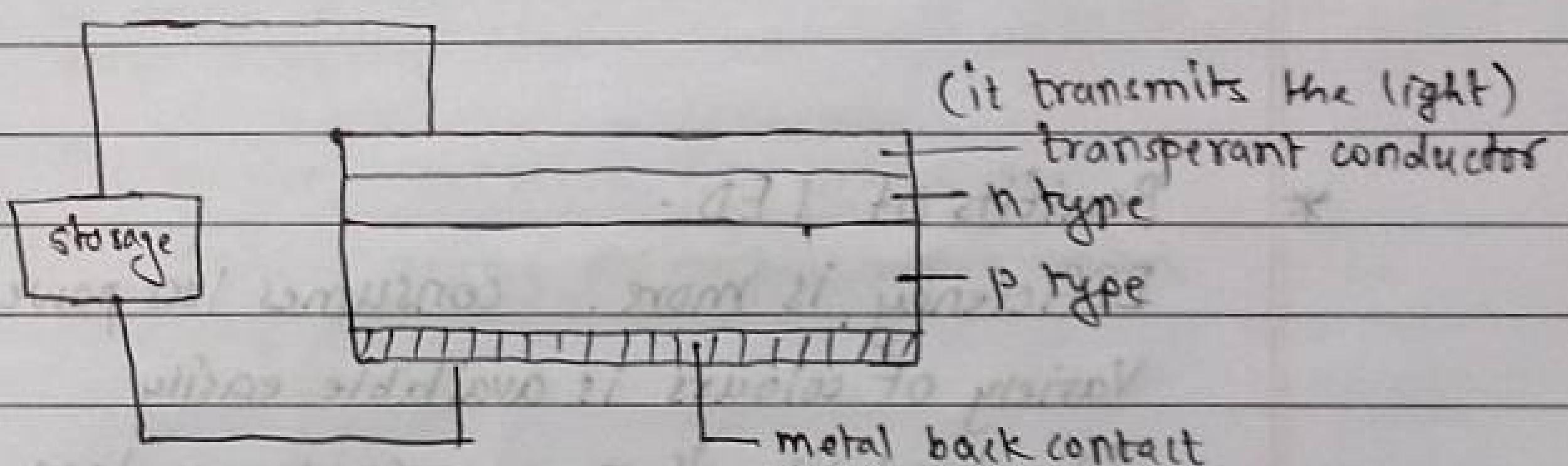
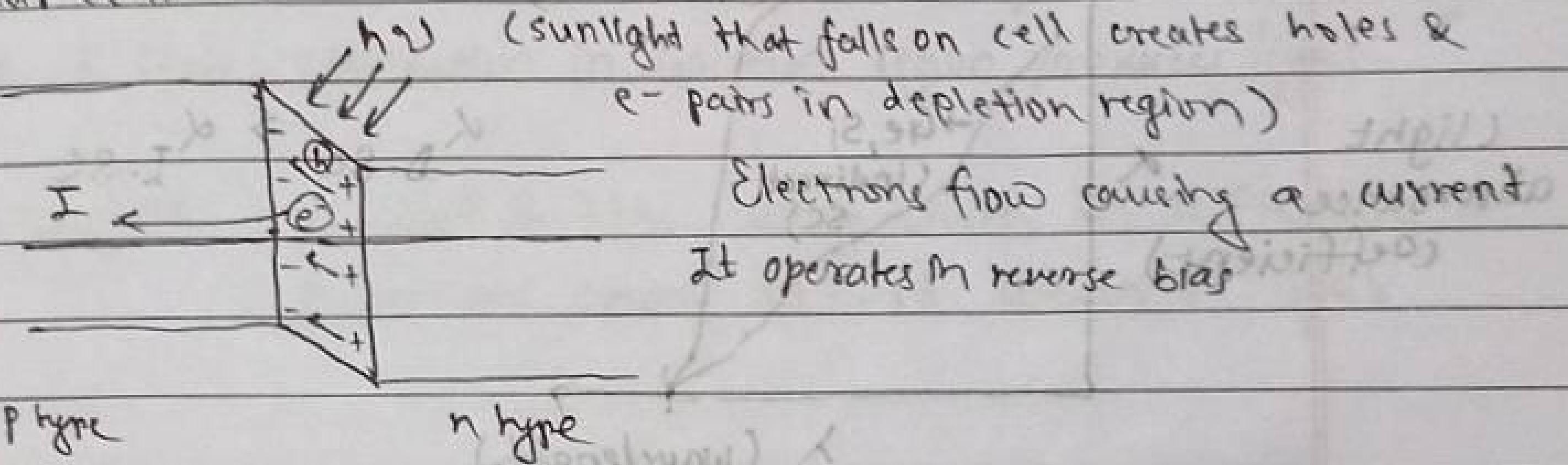


Reverse bias



In reverse bias, current flows in reverse direction

* Solar cell



dotted one shows for general diode in solar cell, when e- & hole pair is generated, e- moves & a current is developed even before reverse current produced when applied external voltage

On passing the ext. voltage current flows but in reverse direction

for ideal device P_{max} was expected to be $I_{sc} \times V_{oc}$
but now it lies on curve of
Some different values of I & V . let
Values be I_{max} & V_{max}

$$P_{max} = I_{max} \times V_{max}$$

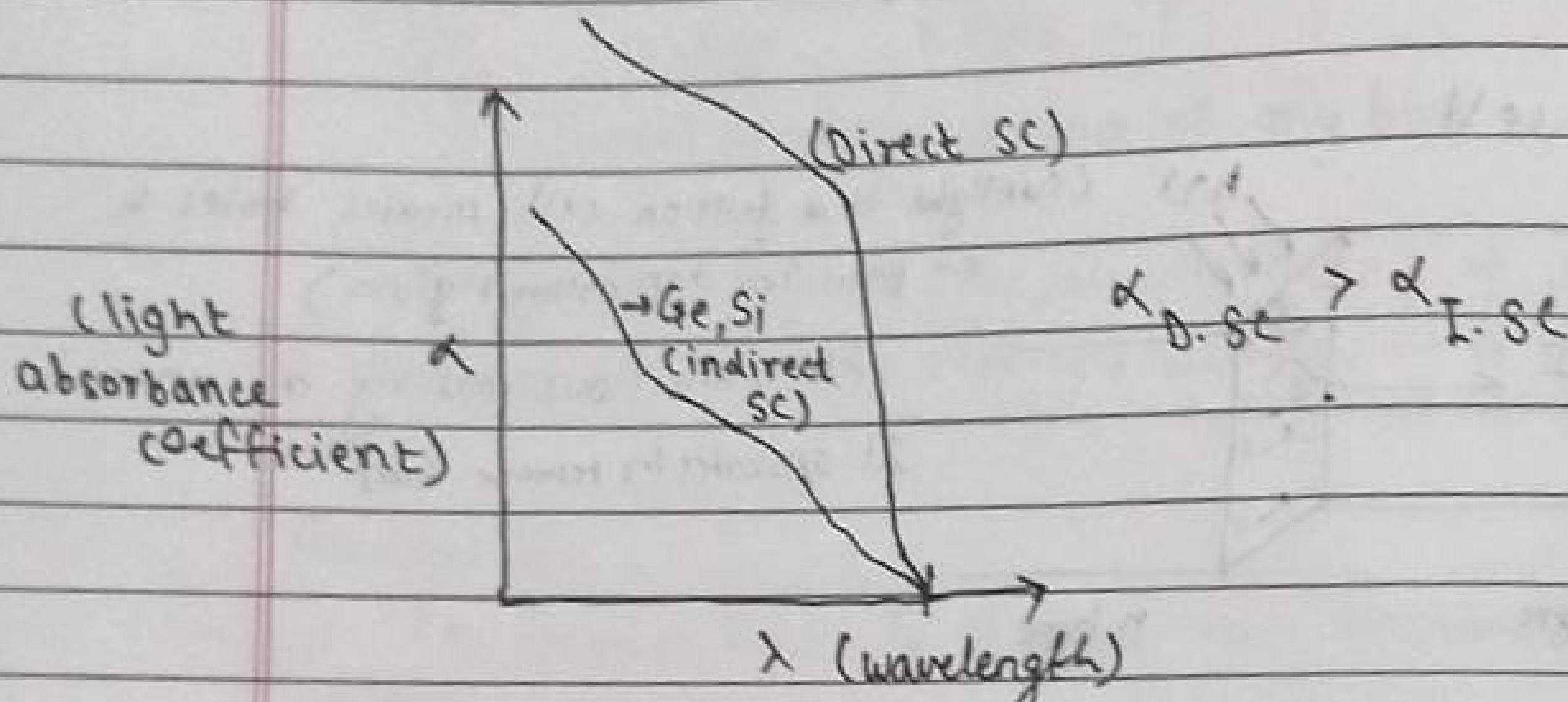
$$P_{ideal} = I_{sc} \times V_{oc}$$

On short circuiting by connecting by just a wire, we get maximum I i.e. called short circuit current

On putting infinitely large resistance, no current will flow then voltage at that point is called open circuit voltage

(fill factor)

$$F.F. \eta = \frac{I_{max} V_{max}}{V_{oc} I_{sc}} \times 100$$



* Benefits of LED -

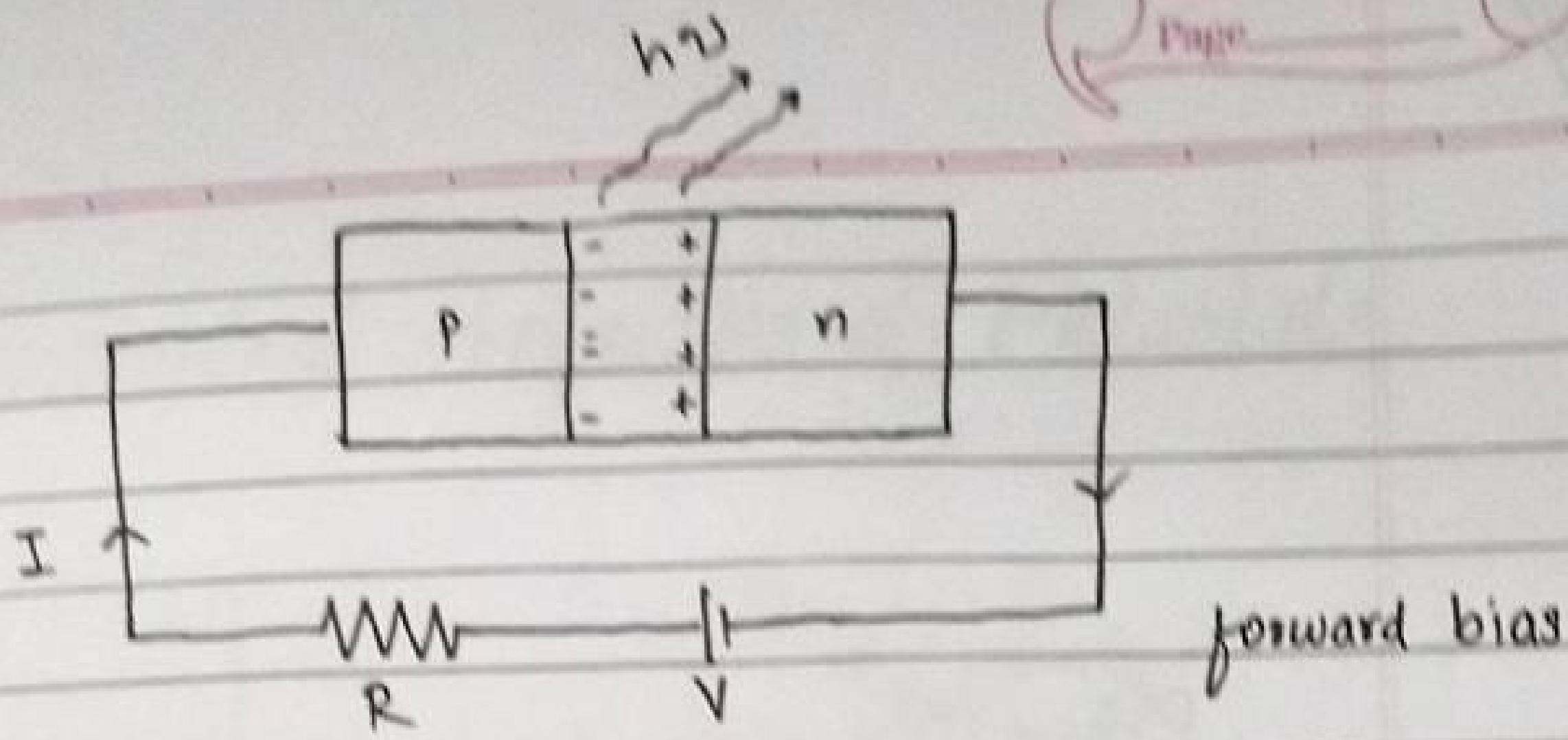
Efficiency is more. consumes less power

Variety of colours is available easily

Its durability is more. consumes less electricity

* LED (light emitting diode)

LED makes use of forward biasing always. Direct band gap semiconductor like $AlGaAsP$, GaP , AlS are used in LED. Reason behind using them is no change in momentum is required for an electron in conduction band to recombine with a hole in the valence band.



Resistance is present because unless it is connected, very large amount of current will flow which will damage the device.

Electrons & holes are pushed in from n & p region resp & their combination in depletion region produces light.

AlGaAsP

Gap & AlAs using them in different proportions create different colours of light

Efficiency

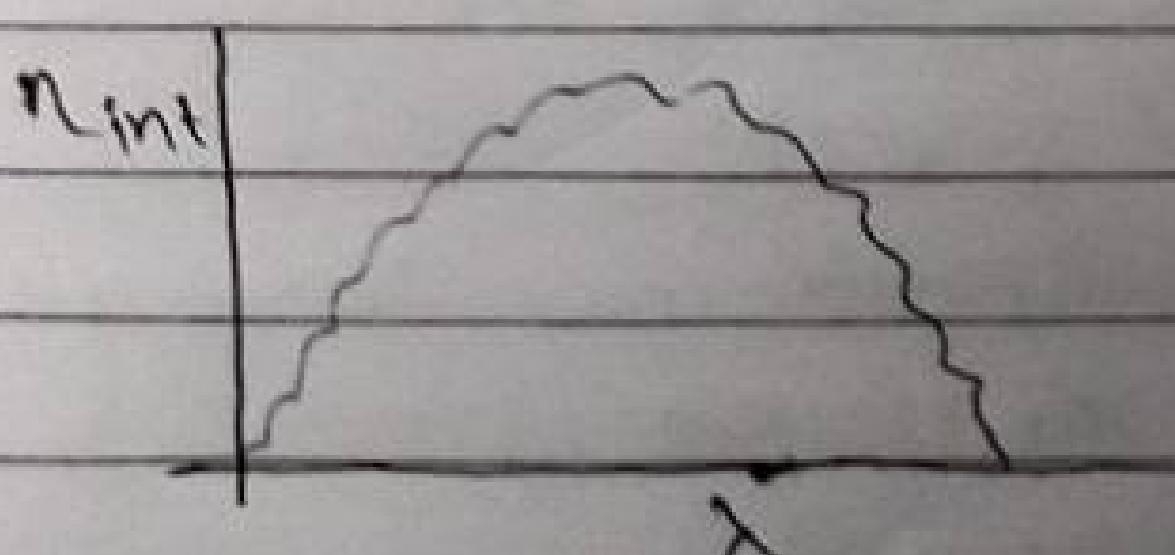
$$\eta_{\text{total}} = \eta_{\text{int}} \cdot \eta_{\text{ext}}$$

$$\eta_{\text{int}} = \frac{\text{no. of } e^- \text{ emitted per sec from active region}}{\text{no. of } e^- \text{ passing per sec from active region}}$$

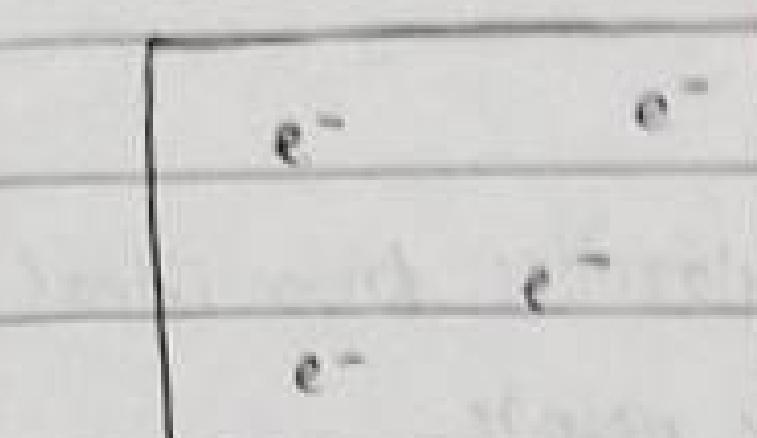
$$= \frac{P_{\text{int}} / h\nu}{I/e}$$

$$\eta_{\text{ext}} = \frac{\text{No. of photons coming from LED}}{\text{No. of photons coming from active region}} = \frac{P/h\nu}{P_{\text{int}}/h\nu} = P/P_{\text{int}}$$

$$\eta_{\text{total}} = \frac{P/h\nu}{I/e} = \frac{Pe}{h\nu I}$$

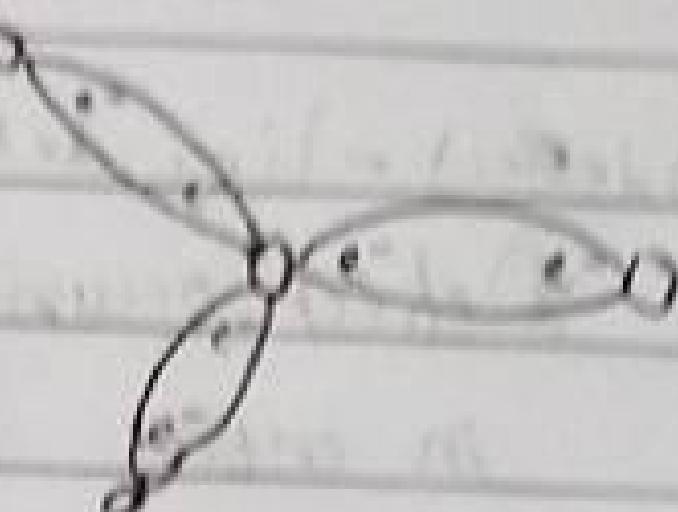


Mechanical Properties of Materials



metals / conductors

free electrons



Insulators

no free electrons (comparable
(covalent solids) ^{not so} _{electron-gathering})

ionic solids - no free electrons, (notable diff. in electronegativity)

* Defect

DD effect - point defect

Vacancy, interstitial, Schottky, Frankel

Vacancy point defects are irregularities or deviations from ideal arrangement around a point or an atom in a crystalline substance

Vacancy: When some of the lattice sites are vacant, crystal is said to have vacancy defect. decreases density

Interstitial: Some constituent particles (atoms or molecules) occupy an interstitial site. This is known as interstitial defect. increases density

Frankel: Shown by ionic solids. Smaller ion (usually cation) is usually dislocated from its normal sites to an interstitial site. It creates a vacancy defect at original site & an interstitial defect at new locⁿ. Frankel defect is also called dislocation defect

Shown by ions having large diff. in size

ex. ZnS, AgCl, AgBr, AgI
doesn't change density

Schottky : It is vacancy defect in ionic solids. In order to maintain electronic neutrality, the number of missing cations & anions are equal, decreases density.

1. O defect - line defect

Defect occurring due to irregularities from ideal arrangement in entire rows of lattice points.

$$\text{Capacitance in vacuum } C_{\text{vac}} = \epsilon_0 \frac{A}{d} \quad A - \text{area of capacitor plates}$$

$$C_d = \epsilon_r \epsilon_0 \left(\frac{A}{d} \right)$$

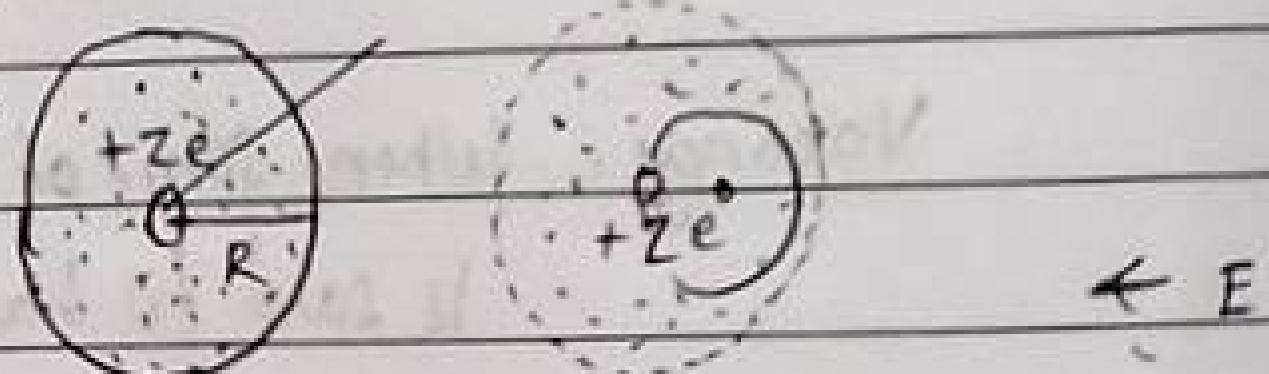
$$\text{dielectric const. } \epsilon_r = \frac{C_d}{C_{\text{vac}}} = \frac{A/d}{d}$$

Two types of polarization:

- 1) deformational / distortional
- 2) orientational / dipolar

deformational polarizability:

electronic : \rightarrow
ionic



on applying electric field, +ve charge is going in opp. direct. of field & -ve charge is in dir. of field.

$$\text{charge density } (\beta) = \frac{-Ze}{\frac{4}{3}\pi R^3}$$

$$\mu_e = \kappa_e E$$

μ_e - electronic dipole moment

κ_e - electronic polarizability

$$P_e = N \mu_e$$

N - no. of dipoles

$$= N \kappa_e E$$

P_e - electric polarization

$$= E \epsilon_0 (\epsilon_r - 1)$$