Semiconductor Physics

Classical free e^- Theory (Drude Lorentz theory)

it assumes that atoms are present in sea of e^-. e^- are free to move within the crystal structure. Conductivity is mainly because of the free e^-. The collisions will be perfectly elastic. Random motion. Dependent on temperature.

$$\boxed{E = \frac{3}{2} KT} \rightarrow \text{Kinetic energy} \quad \langle \text{ideal gas} \rangle$$

e^- are moving through the uniform potential of +ve ions. ∴ In absence of electric field, e^- move randomly.
Talks about electrical conductivity.
Classical e^- → can have any value of energy.
In the presence of electric field, e^- are guided by the field.

Merits of the Theory:

→ Talks about conduction in metal → which is governed by Ohm's law. ∴ Ohm's law was explained by this theory.
→ Explained thermal & electrical conductivity & ratio b/w them.
→ Also explained optical properties & binding energy.

Limitations:

→ Could not explain Specific heat Cap.
→ Could not explain conductivity in semiconductor & insulator.
→ Could not explain paramagnetism, diamagnetism, quantum phenomena such as compton effect, photoelectric effect.

Band Theory:

Energy band: Group of energy levels having similar energy.
Size of energy band depends on interaction with neighbours.
★ depends on $2n$ $\quad n$ = no of neighbours.
Conduction Band: ~~Highest~~ Lowest empty energy band.
Valence Band: Highest filled energy band

Classification of Solids on the basis of Band Theory

★ Gap b/w highest valence band & lowest conduction band is known as Forbidden Energy Gap.

Conductors: Valence Band & conduction band overlap or partially filled ~~conduction~~ valence band.

Insulators: Empty conduction band, filled valence band & energy gap is very high.

Semiconductor: completely filled valence band, empty conduction band & energy gap is small.

Semiconductors:

pure form → intrinsic

conductivity shown by intrinsic semiconductor is totally dependent on temp. → not reliable.

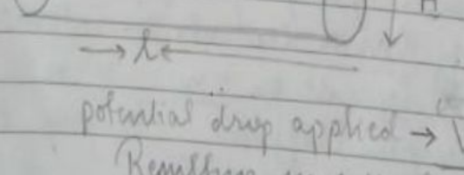
$0^\circ C$ → insulator

$50^\circ C$ → conductor

So intrinsic semiconductor is doped → extrinsic semiconductor

- ptype — trivalent
  {making & breaking of covalent bonds}
  → Mobility of hole < mobility of e^-
- ntype — pentavalent

Conductivity of a Conductor



potential drop applied → 'V'

Resulting in current 'I'

$$\boxed{I = nAeV_d}$$ → drift velocity

$$\boxed{V_d = \mu E}$$ → applied Electric field

$\rightarrow$ $I = n\mu EAe$

$$E = \frac{V}{l}$$

$\rightarrow$ $I = n\mu \frac{V}{l} A e$

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

$\rightarrow$ $$\boxed{R = \frac{l}{A} \cdot \frac{1}{ne\mu}}$$

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

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

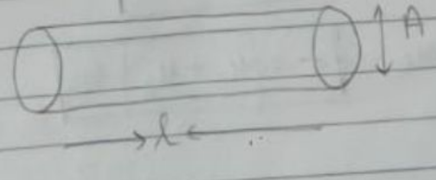
$$\boxed{\sigma = \frac{1}{\rho} = ne\mu}$$

& current density, $J = \frac{I}{A} = n\mu Ee$

$\rightarrow$ $$\boxed{J = \sigma E}$$

Conductivity of a Semiconductor

V → P.D.



Q1. Determine mobility (μ) in copper. each atom contributes 1 free e^- for conduction. $\rho = 1.7 \times 10^{-6}\ \Omega\ cm$

density of copper = 8.96 g/cc

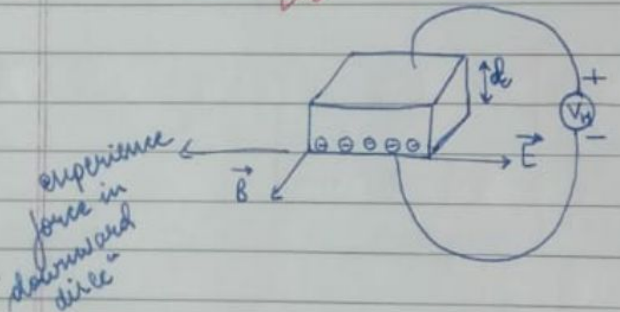
At wt of copper = 63.5

$N = 6.023 \times 10^{23}$ g/mol

→ $n = 6.023 \times 10^{23} \times \frac{8.96}{63.5} = 8.4 \times 10^{22}$ → no. of atoms = no. of e^-

→ $\mu = \frac{1}{n\rho e} = \frac{1}{1.7\times10^{-6} \times 8.4\times10^{22} \times 1.6\times10^{-19}} = 43.27\ cm^2/volt$

★ Hall Effect



direc^n of force is determined using Fleming's Left Hand Rule

Thumb → Force (F)
Index → Magnetic field (B)
Middle → Current (I)

★ $\boxed{F_E = eE}$

★ $\boxed{F_B = Bev}$

→ $Bev = eE_{int}$ {For Hall Effect}

internally developed electric field

$B\cancel{e}v = \cancel{e}\frac{V_H}{d}$

★ → $\boxed{V_H = Bv_d d}$

v_d → drift velocity

→ $I = neV_dA$ → $v_d = \frac{I}{neA}$

$$\boxed{I = \underbrace{I_e}_{\text{due to } e^-} + \underbrace{I_h}_{\text{due to holes}}}$$

$$I_e = nAeV_e$$

$$\boxed{V_e = \mu_e E}$$

$$I_e = n\mu_e EAe$$

$$E = \frac{V}{l}$$

$$\boxed{I_e = n_e\mu_e \frac{V}{l} Ae}$$

Similarly,

$$\boxed{I_h = n_h\mu_h \frac{V}{l} Ae}$$

$$I = I_e + I_h$$

$$I = n_e\mu_e \frac{V}{l} Ae + n_h\mu_h \frac{V}{l} \cdot Ae$$

$$\rightarrow I = \frac{V}{l}\{n_e\mu_e + n_h\mu_h\} Ae$$

$$\boxed{R = \frac{V}{I} = \frac{l}{A} \cdot \frac{1}{e\{n_e\mu_e + n_h\mu_h\}}}$$

$$\rightarrow \boxed{\rho = \frac{1}{e\{n_e\mu_e + n_h\mu_h\}}}$$

Conductivity, $\boxed{\sigma = e\{n_e\mu_e + n_h\mu_h\}}$

$$\boxed{\sigma = \sigma_e + \sigma_h}$$

Intrinsic: $n_e = n_h$ $\boxed{\sigma = \{\mu_e + \mu_h\} ne}$

$\rightarrow V_H = \dfrac{BId}{neA}$

$\bigstar$ A → area of face through which current passes

Hall Voltage, $\boxed{V_H = \dfrac{BId}{neA}}$ $\bigstar$

$J = \dfrac{I}{A}$ $\rightarrow \boxed{V_H = \dfrac{BJd}{ne}}$ $\bigstar$

R_H = Hall coefficient $= \dfrac{1}{ne}$

$\bigstar$ $\rightarrow \boxed{R_H = \dfrac{V_H}{BJd} = \dfrac{V_H A}{BId}}$

$\sigma = ne\mu$

$\bigstar$ $\boxed{R_H \sigma = \mu}$

Applications of Hall Effect

- → Helps determine 'n'
- → Helps determine drift velocity, mobility.
- → Type of semiconductor can be determined.

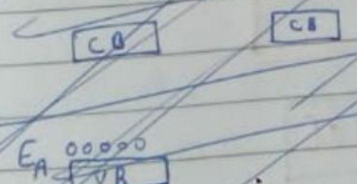
~~Diode : Device which permits current to flow only in one direc^n. Not all pn junctions are diode~~

~~Vacuum Diode~~

~~At high freq., triode valves & vacuum diodes are used.~~

~~$\bigstar$ Zener effect is reversible~~

~~Working of diode on basis of Band Theory~~



extrinsic:

p-type $\boxed{n_h >> n_e}$

→ $\boxed{\sigma = n_h \mu_h e}$

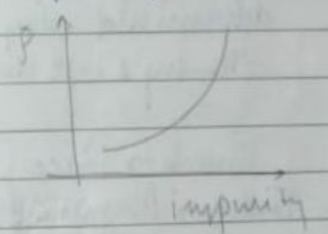
n-type: $\boxed{n_e >> n_h}$

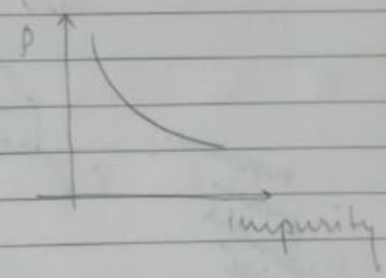
$\boxed{\sigma = n_e \mu_e e}$

Internal Factors affecting the conductivity

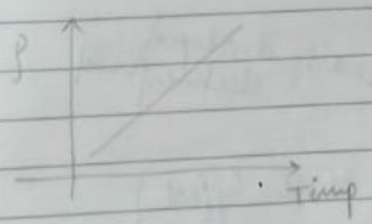
Conductor | Semiconductor

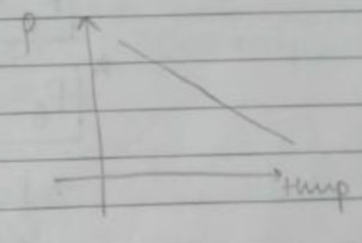
(1) Impurity



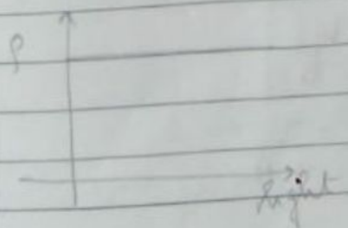


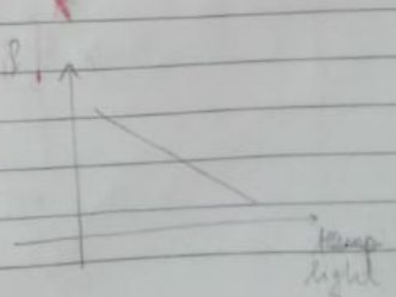
(2) Temperature





(3) Light





★ Fermi function & Fermi Level

The Fermi-Dirac probability function also known as Fermi function is:

★ $$\boxed{P(E) = \frac{1}{1 + e^{(E-E_f)/KT}}}$$

$P(E) \rightarrow$ probability of an e^- occupying the energy state E
$E_f \rightarrow$ Fermi energy
$K \rightarrow$ Boltzmann constant
$T \rightarrow$ Absolute temperature

★ Fermi Energy: Highest energy state e^- can occupy at 0 K

for $T > 0K$, if $E = E_f$

$$\boxed{P(E_f) = \frac{1}{2}}$$

i.e., the Fermi energy level represents the energy state with a 50% probability of being filled if forbidden gap does not exist as in the case of good conductors

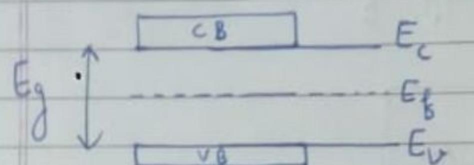
★ Probability of occupancy of energy levels below Fermi level decreases on increasing the temperature.
OR Probability of occupancy of energy levels above Fermi level increases on increasing the temperature.

★ at $T = 0K$, $E < E_f \rightarrow \boxed{P(E) = 1}$

at $T = 0K$, $E > E_f \rightarrow \boxed{P(E) = 0}$

Fermi energy represents weighted mean so it can be at the centre of forbidden energy gap.

★ Position of Fermi level in Intrinsic Semiconductor



$N = n_c + n_v$

$n_c = P(E_c)N$

$$\boxed{n_c = \frac{1}{1+e^{(E_c-E_f)/KT}} \cdot N}$$

Similarly,

$$n_v = \frac{1}{1+e^{(E_v-E_f)/KT}} \cdot N$$

$$\rightarrow \cancel{N} = \frac{\cancel{N}}{1+e^{(E_c-E_f)/KT}} + \frac{\cancel{N}}{1+e^{(E_v-E_f)/KT}}$$

$$\rightarrow \left(1+e^{(E_c-E_f)/KT}\right)\left(1+e^{(E_v-E_f)/KT}\right) = 1+e^{(E_v-E_f)/KT} + 1 + e^{(E_c-E_f)/KT}$$

$$\rightarrow 1 \cancel{+e^{(E_v-E_f)/KT}} \cancel{+e^{(E_c-E_f)/KT}} + e^{(E_c+E_v-2E_f)/KT} = 1 \cancel{+e^{(E_c-E_f)/KT}} \cancel{+e^{(E_v-E_f)/KT}}$$

$$\rightarrow e^{(E_c+E_v-2E_f)/KT} = e^0$$

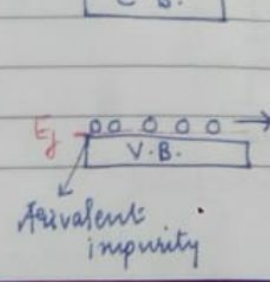
$$\rightarrow ★\ E_c+E_v-2E_f = 0$$

$$\rightarrow \boxed{\frac{E_c+E_v}{2} = E_f}$$

★ Hence, Fermi level lies at the centre of the forbidden band.

★ Position of Fermi level in Extrinsic Semiconductor

★ P-type → trivalent impurity



★ At 0 K, e^- are present in V.B. & acceptor level.

→ E_A (Acceptor level)
★ due to acceptor impurities

★ Effective Mass of an Electron

→ Related to conductivity.

→ An e^- in a crystal is not free.
So more force is req. to move the e^- when it is in bound state.
Effective mass takes this force required into consideration.

★ Effective mass of e^-, $\boxed{m^* = \dfrac{\hbar^2}{\left(\dfrac{d^2E}{dK^2}\right)}}$

★

→ The curvature $\dfrac{d^2E}{dK^2}$ of the energy band decides the effective mass ~~on~~ of an e^- in a crystal.

★ The curvature $\dfrac{d^2E}{dk^2}$ is $\boxed{\text{negative}}$ for an e^- at the top of the valence band & hence effective mass is negative.

★ The curvature $\dfrac{d^2E}{dk^2}$ is $\boxed{\text{positive}}$ at the bottom of conduction band & hence effective mass is positive.

★ Density of States

The density of states $\boxed{g(E)\,dE}$ is the number of allowed energy states in the energy range E & $E+dE$

★ $$\boxed{g(E)\,dE = \frac{8\sqrt{2}\,\pi}{h^3}\,E^{\frac{1}{2}}\,dE}$$

no. of available states/vol/dE

★ $$\boxed{N(E)\,dE = P(E)\,g(E)\,dE}$$

carrier concentration

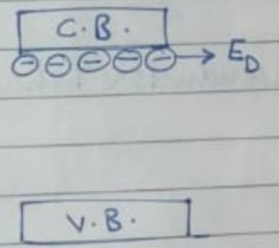
★ At 0K, the Fermi level lies midway b/w acceptor impurity levels & top of valence band.

★ On ↑ temperature, e^- travel from valence band to acceptor level. So E_f shifts upwards.

★ At room temperature, the position of the fermi level is in b/w acceptor level & E_f intrinsic level. (e^- are in conduc^n band leaving behind holes)
E_f can never reach E_f intrinsic level because in p type semiconductor, holes are greater in number & holes lie near valence band.

★ Greater the doping, lower will be the position of Fermi level compared to E_f intrinsic.

★ N-type → Pentavalent impurity



★ At 0K, the Fermi level lies midway b/w donor impurity level & bottom of conduction band.

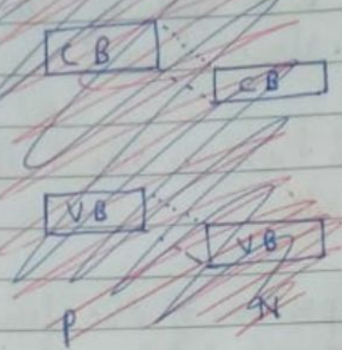
★ As temperature ↑, e^- will jump from E_D to conduction band.
★ → Fermi level come down

★★ At room temperature, Fermi level will lie b/w donor impurity level & E_f intrinsic level.

E_f can never reach E_f intrinsic level.

★ More the amount of doping, higher will be the position of E_f.

~~Potential Barrier~~



★ Effect of external parameters on E_f :

(i) Temperature

In $\boxed{\text{p-type}}$, as temperature ↑, Fermi level goes upwards. At very high temp, no. of e almost becomes equal to no. of holes & E_f reaches $E_{f\,(\text{intrinsic})}$

In $\boxed{\text{n-type}}$, as temperature ↑, Fermi level goes down. At very high temp. E_f reaches $E_{f\,(\text{intrinsic})}$

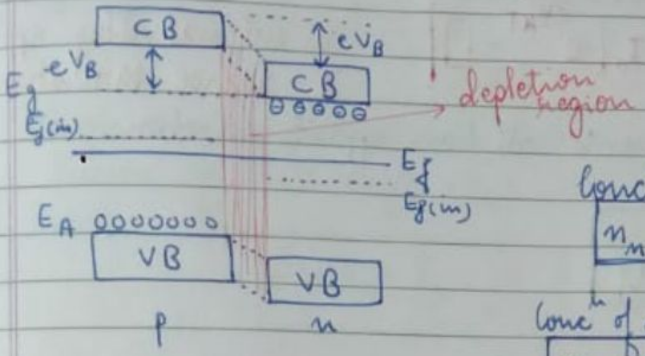
At high temperature, extrinsic semiconductors behave like intrinsic semiconductors.

(ii) Doping

In $\boxed{\text{p-type}}$, as doping ↑, Fermi level will come down ~~Ef will lie near acceptor levels.~~
~~In n-type, as doping ↑, Fermi level will go up~~
Valence band & Acceptor level merge & Fermi level lies ★ inside valence band.

In $\boxed{\text{n-type}}$, as doping ↑, Fermi level goes up. conduction band will merge with donor level so much so that the position of Fermi level will be ★ inside the conduction band.

Potential Barrier



Conc^n of e^- in C.B. on n side:

$$\boxed{n_n = {}^{D}N e^{-(E_g - E_f)/KT}} \quad -① $$

Conc^n of e^- in C.B. on p side:

$$\boxed{n_p = {}^{D}N e^{-(E_g + eV_B)/KT}} \quad -② $$

$\div$ ① & ②: $\frac{n_n}{n_p} = e^{eV_B/KT}$

taking log both sides: $\frac{eV_B}{KT} = \ln \frac{n_n}{n_p}$

$$\rightarrow \boxed{V_B = \frac{KT}{e} \ln \frac{n_n}{n_p}}$$

Let p_p = hole conc^n on p side $\qquad V_B = \frac{KT}{e} \ln \frac{n_n}{n_p} \cdot \frac{p_p}{p_p}$

At room temperature, all impurities are ionized $\rightarrow n_n = N_D \rightarrow$ donor impurity conc^n

& $p_p = N_A$ = acceptor impurity conc^n.

$\rightarrow n_p \cdot p_p = n_i^2$

$$\boxed{V_B = \frac{KT}{e} \ln \frac{N_D N_A}{n_i^2}}$$

$$\boxed{V_T = \frac{KT}{e}}$$

Potential Barrier $\leftarrow$ $\boxed{V_B = V_T \ln \frac{N_D N_A}{n_i^2}}$

$\boxed{V_B \propto \text{conc}^n \text{ of impurities}}$

Diode

Every pn junction is not a diode.
Diode is a device which allows flow of current only in one direction.

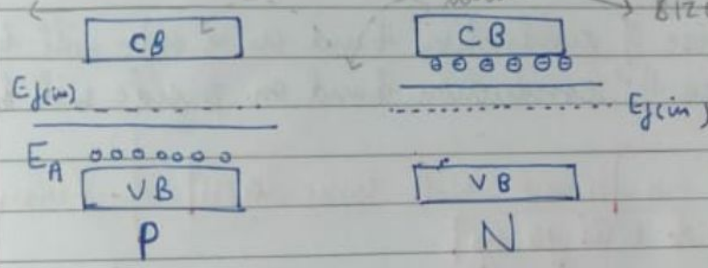
★ Vacuum diodes are better than pn junc^n because they don't allow current in other direc^n but vacuum diodes are big in size & very expensive so we prefer pn junction diode.
But at high frequency, pn junction cannot work properly so we use triode valve & vacuum diodes.

→ Avalanche Breakdown is irreversible effect.
→ Zener Breakdown is reversible effect.

★ WORKING OF DIODE ON THE BASIS OF BAND THEORY

gains e⁻ size of conduction band ↑

loses e⁻ → size of CB ↓



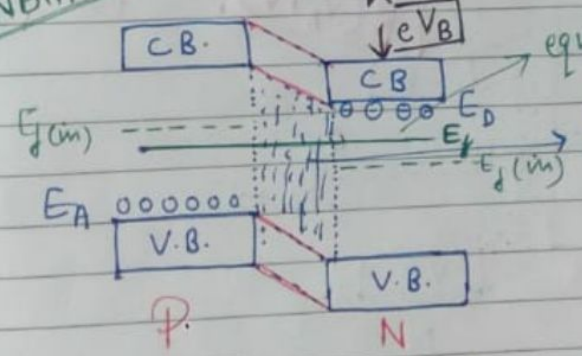
★ So Fermi level on n side goes down whereas Fermi level on p side goes up

UNBIASED:

★ drop in level of conduction band

equipotential surface

depletion layer

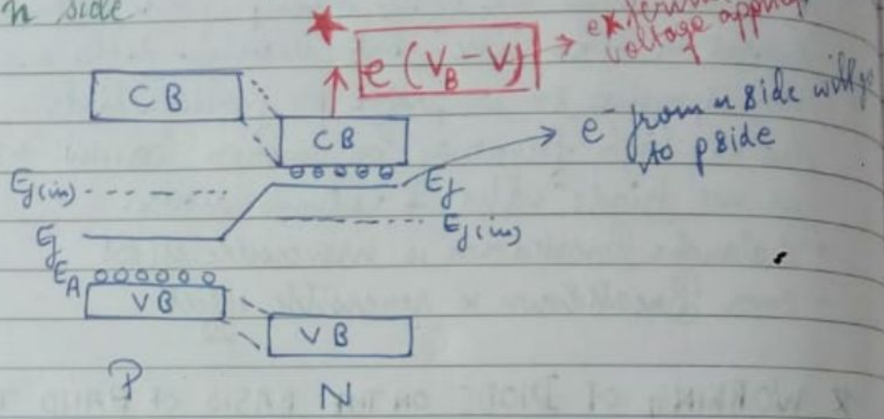


★ so no further movement of charge carriers is permitted

F.B.:
When diode is $\boxed{\text{F.B.}}$ width of depletion region ↓ → covalent bonds break. The generated e⁻ will come back to n side. So size of conduction band at n-side ↑ & size of conduction band at p-side ↓.
∴ On n side, Fermi level goes up & on p side, Fermi level goes down

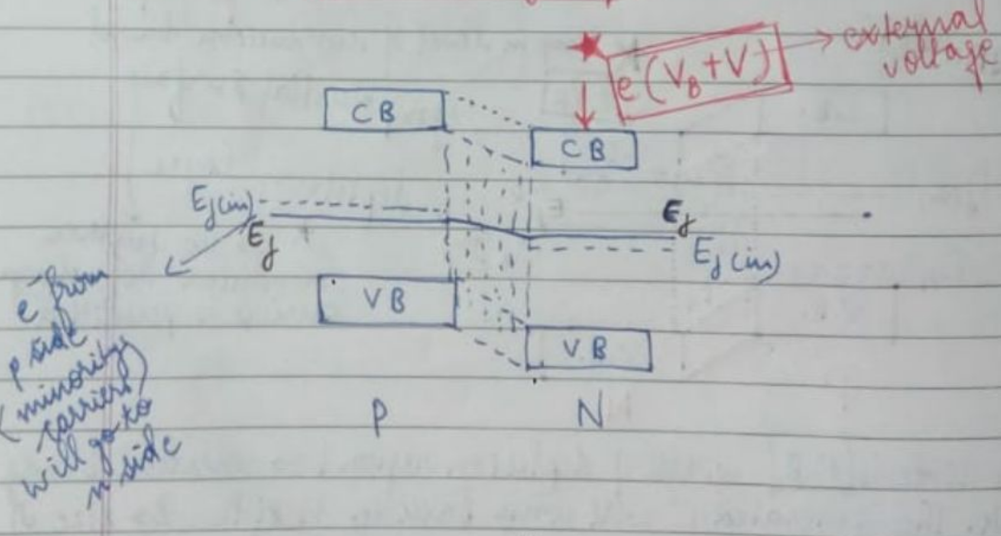
★ Potential Barrier can never become zero because there will always be some amount of recombination of e⁻ & holes

→ p side will always be at a higher potential compared to n side.



smaller ~~larger~~ In R.B, size of conduction band on n side will become larger ~~smaller~~ & size of conduction band on p side will become larger.

→ Fermi level on n-side will come down & Fermi level on p-side will go up



Semiconductors are made for room temperature → not very high temperature.

★ Ideal Diode Equation

★ $$\boxed{I = I_0\left[e^{eV/KT} - 1\right]}$$

V = external voltage applied

I_0 = reverse saturation current

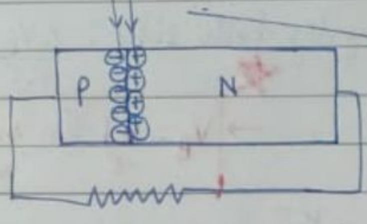
★ . F.B. & R.B. currents will have opposite direction.

★ Solar Cell

→ Semiconducting device.

→ Works on the principle of **Photo voltaic effect**

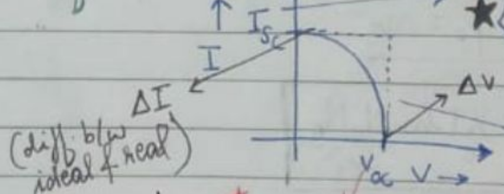
★ because of light, voltage is generated



→ When sunlight is incident, covalent bonds break & e^- are generated.
These e^- will go towards N side & current flows.

★ Efficiency, $\eta = \dfrac{\text{o/p power}}{\text{i/p power}}$

Fill factor



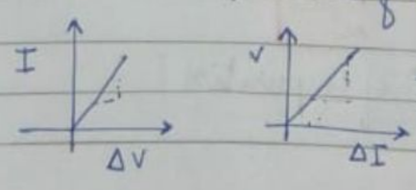
max. current ★ ⟨Short circuit current⟩ → when external or load resistance is 0

ΔI (diff. b/w ideal & real)

→ ideally relation should have been this but ★ (as current depends upon intensity of light)

★ Open circuit voltage $R \to \infty$

→ Due to internal resistance of cell, we get a curve.



→ Slope → internal resistance of cell.

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$$\boxed{\text{Fill factor} = \frac{I_m V_m}{I_{sc} V_{sc}}} = \frac{\text{real power}}{\text{Ideal power}}$$