Aug 09, 2021

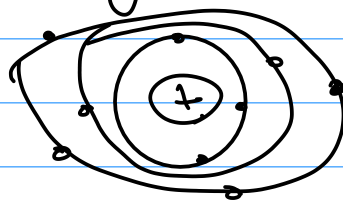
EC 261 : A1

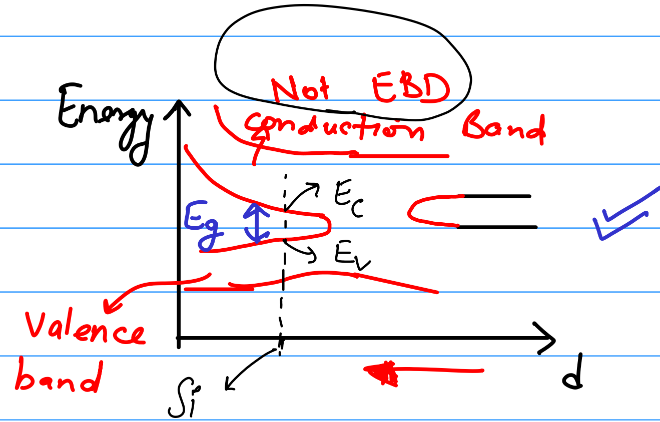
ANALOG ELECTRONICS

- Microelectronics — Jacob Millman, Arvin Grabel
- (or) Microelectronic — Millman, Halkias
- Sedra & Smith

→ **Energy Band Diagrams (EBD)**

isolated
↓
d = v.v. large





d = inter atomic distance

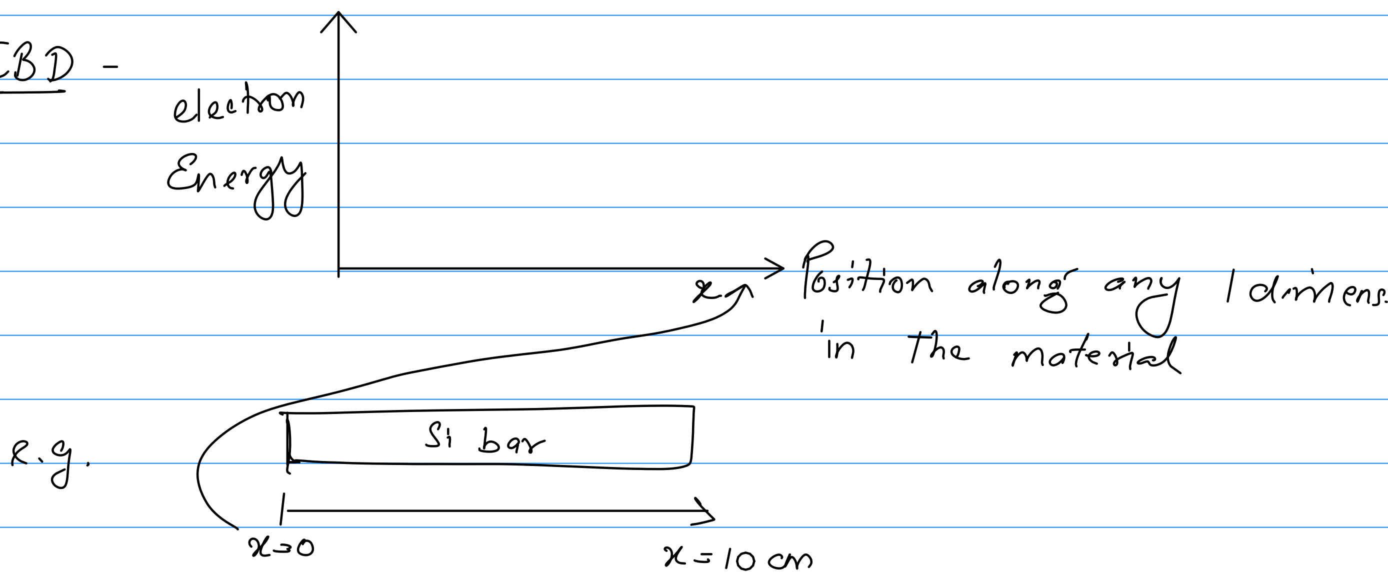
E_g = Forbidden energy gap. (band gap)

what if d ↓

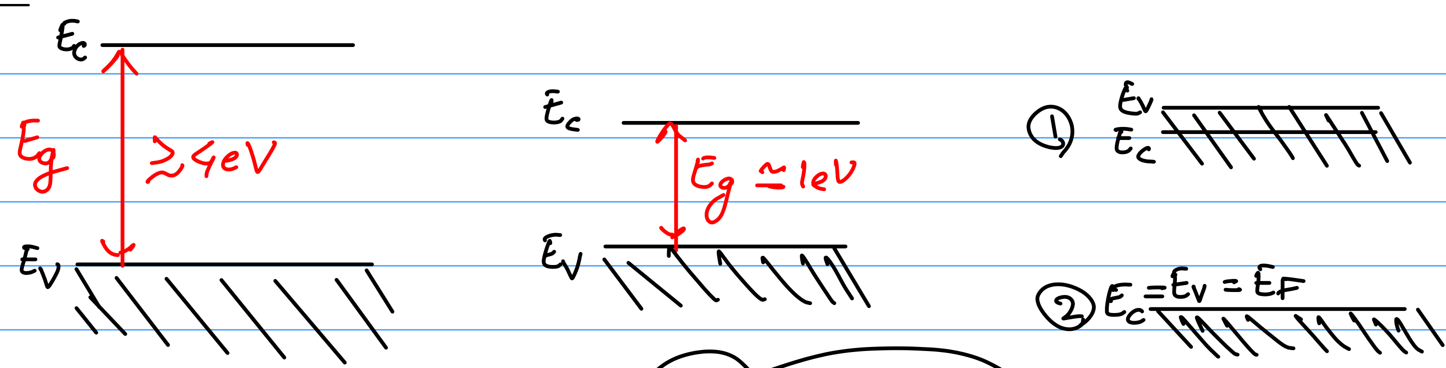
⊙ as d ↓, E_g ↑. For constant d (1 material), E_g = constant

⊙ For 1 material, d is fixed (constant) under constant external condition, e.g. T (temperature)

- EBD -



3 types of materials | Insulator | Semi Conductor | Conductor



- What is eV? $1\,eV = 1.6 \times 10^{-19}\,C \times 1\,V = 1.6 \times 10^{-19}\,J$ (energy)

$\boxed{1\,eV = 1.6 \times 10^{-19}\,J}$

$1\,e$ = mag. of charge of $1\,e^-$
$= 1.6 \times 10^{-19}\,C$

energy Joules, $1\,J = 1\,C \times 1\,V$

$W = Q.V$

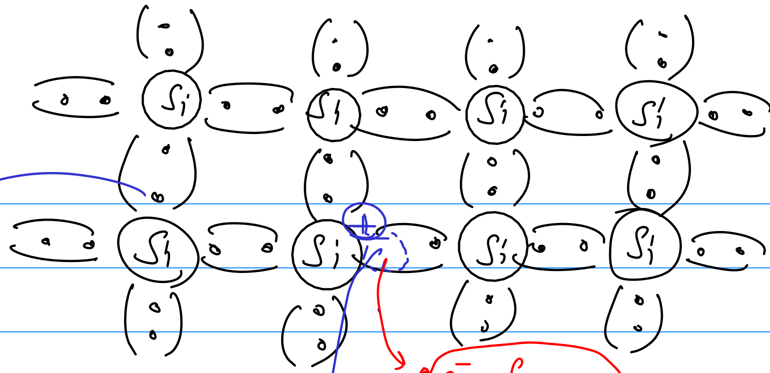
- <u>What is conduction band</u> →
  Energy levels available to be occupied by e^-s which are free of bonds (free to move anywhere in the material).
  Hence these e^-s are conducting e^-s.

- <u>What is valence band</u> –
  Energy levels occupied by e^-s that are bonded (not free to move except around their nucleus)

→ <u>Semiconductors</u> – Silicon (Si, Z = 14 (atomic no.)), Ge, GaAs

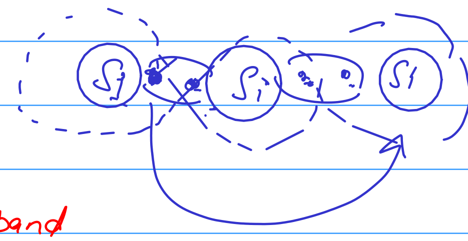
$14 e^-s \rightarrow \underbrace{1s^2 2s^2 2p^6}_{10}$

$+ 4$ valence



Valence band e^-s

e^- free e^-



Give some energy to valence e^-

$\hookrightarrow \geq E_g$

Conduction band e^-

This +ve charged vacancy is called "hole"

* holes are vacancies in valence band

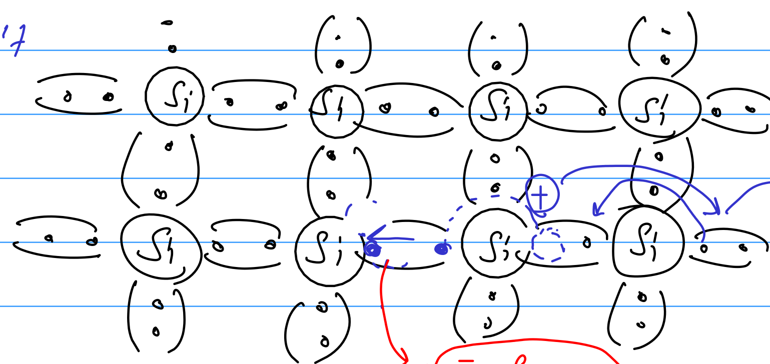
They are free to move in the valence band.

* free e^-s are in cond. band & they are free to move

So, there are 2 types of charge carriers in a semi-conductor.

Si. Nucleus doesn't move

All e^-s feel $\vec{E}$ force



$\oplus$ hole motion

e^- free e^-

$\vec{F} = q\vec{E}$

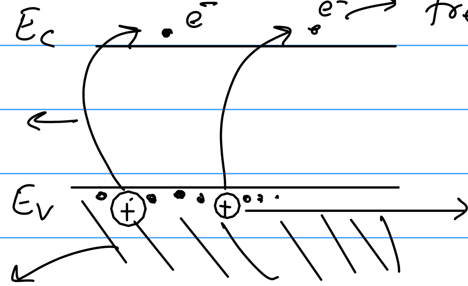
-ve for e^-

So, dir of $\vec{F}$ & $\vec{E}$ are opp. for e^-

$\vec{E}$ $\longrightarrow$ $\longleftarrow$ e^-

E_c e^- e^- $\rightarrow$ free to move above E_c

EHP generation



E_v $\rightarrow$ free to move below E_v

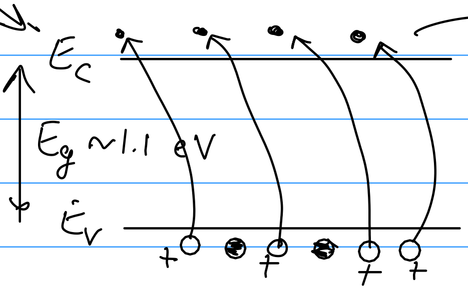
Shading means lots & lots of e^-s (but not free to move)

AUG 11)

→ Types of s.c. –

1. **Intrinsic semi cond.** – Pure, no impurities (or doping)

Silicon (Si) at Room Temp



Thermally generated Electron-hole pairs (EHPs)

e.g. in Si,
Let n = no of e^-s cm^{-3}
p = " " holes cm^{-3}

at room temp, $n = p = n_i \cong 1.5 \times 10^{10}\ cm^{-3}$

n_i → intrinsic carrier conc.

Atomic Density of Si $\cong 5 \times 10^{22}\ cm^{-3}$

So, $n_i <<$ atomic density

* Intrinsic semi cond. have very low conductivity.

* $n_i \uparrow$ if $T \uparrow$
* $n_i \downarrow$ if $E_g \uparrow$

$$\boxed{n_i = A \exp\left(\frac{-E_g}{2kT}\right)}$$

where $A \propto T^{3/2}$

$$n_i = A\, e^{(-E_g/2kT)}$$

k = Boltzmann's constant

$$\boxed{kT = \frac{T}{11600}\ eV}$$

where T is in Kelvin

at room temp ($T = 300$ K)

$$\boxed{kT \cong 26\ meV}\ *$$

unit of energy

$1\ eV = 1 \times 1.6 \times 10^{-19} \times C \times V = 1.6 \times 10^{-19}$ Joules

$C \times V = J$

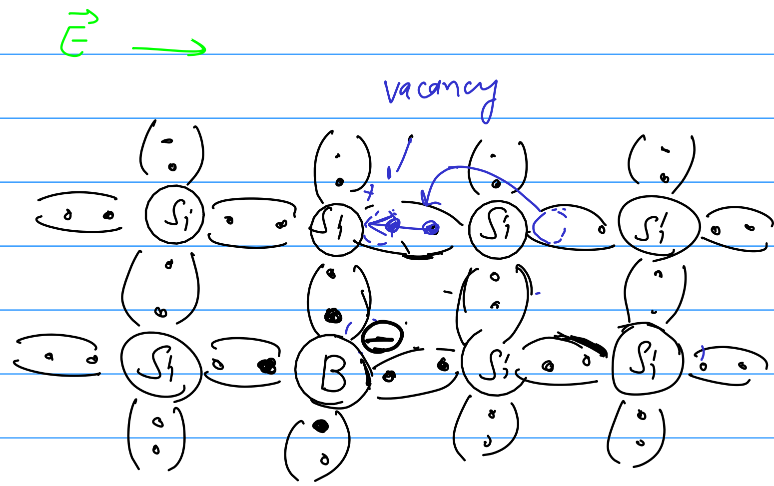
→ **Extrinsic Semi-cond.** - impure (or doped)

Trivalent Group 3 or acceptor type dopant (impurity)	Group 3	Group 4	Group 5
	B	C	N
	Al	Si	O
	Ga	Ge	P
	In	Sn	As
	Tl	Pb	Bi

S.C.

P → Phosphorous, As → arsenic → Group 5 or Pentavalent (or) Donor type impurities

Trivalen dopant Like B makes p-type semi-conductor



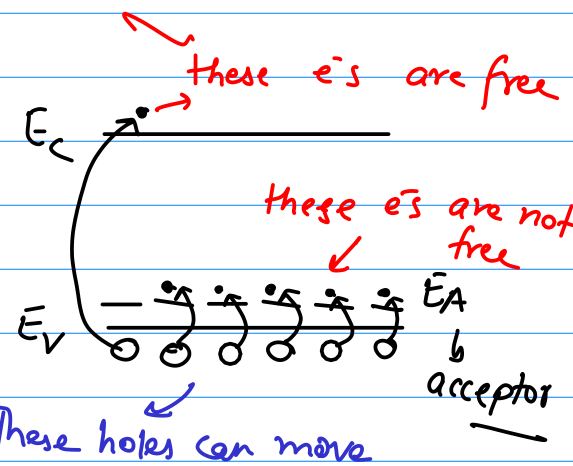
as a result, 1 B atom causes creation of 1 hole (without any free e^- generation)

(any dopant ion)

* B^- 1 charge is immobile
* Si^+ → hole can move.

E_A is v. close E_V

$E_A - E_V \sim 0.05\,eV$



Si has 5×10^{22} cm^{-3} atoms at room temp

If there 1 B atom per 10^8 Si atoms

then B concentration = $N_A = 5\times10^{14}$ cm^{3}

acceptor

At room temp. every B atom gives 1 hole & 0 e's.

So hole conc. = $p = N_A$ + (thermal Generated) as we saw $n_i = 1.5 \times 10^{10}\ cm^{-3}$ → hole conc. before doping

$N_A = 5 \times 10^{14}\ cm^{-3}$

↳ doping.

$p = N_A +$ thermal gen.

$N_A \gg n_i$, $\boxed{p \simeq N_A} = 5 \times 10^{14}\ cm^{-3}$

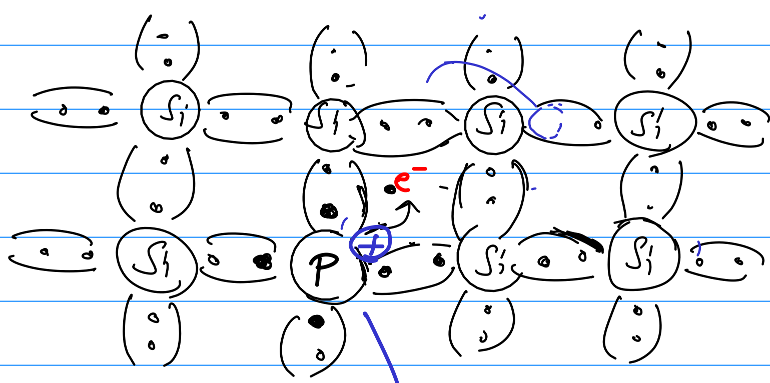
→ In p-type s.c. $p \gg n$ & $p \gg n_i$

So, we say that holes are the 'majority carriers'

→ In any extrinsic s.c., Maj. Carrier conc. $\cong$ Doping conc. (at room temp.)

→ N-Type s.c. → Dopants → P or As → Pentavalent

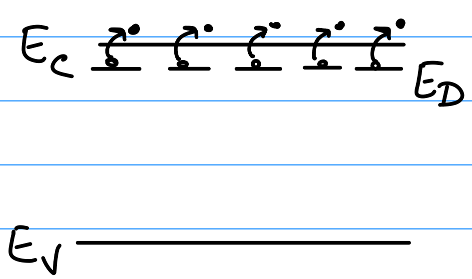
+ve charge on P^+ is 'immobile'



P is a Donor

N-type

an extra e^- was created (without any new hole generation)



$E_c - E_D \sim 0.05\ eV$

At room temp, every Donor atom releases 1 e^- into conduction band.

Let Phos. conc. = N_D = 5×10^{14} cm^{-3}
Donor

then $n = N_D +$ (thermally gen.)

$n_i \sim 1.5 \times 10^{10}$ cm^{-3} $\quad N_D >> n_i$

So, $\boxed{n \simeq N_D} \simeq 5 \times 10^{14}$ cm^{-3}

→ Donor impurity makes n-type s.c.

→ In n-type s.c., electrons are majority carriers ($\because$ $n >> p$ & $n >> n_i$)

→ In any extrinsic s.c, majority conc. ≃ Doping conc. (at room temp.)

→ Law of Mass action – Under thermal equilibrium,

$$\boxed{n.p = n_i^2}$$ → valid for both intrinsic & extrinsic s.c.

→ Minority conc. – Law of mass action is used to find this

let's take p-type s.c. $\boxed{p = N_A}$

then e^- conc. n under equilibrium can be found from $np = n_i^2$

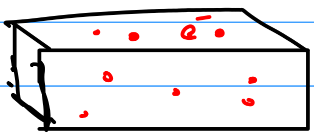
$$\boxed{n = \frac{n_i^2}{p} \simeq \frac{n_i^2}{N_A}}$$

Similarly, for n type s.c.,

Majority $\rightarrow$ $\boxed{n \simeq N_D}$ & $\boxed{p = \frac{n_i^2}{n} \simeq \frac{n_i^2}{N_D}}$ $\leftarrow$ minority

$\rightarrow$ <u>Charge conservation in s.c.</u> - Total charge in material is always conserved.

So, $\underbrace{\text{sum of all charges}}$ = 0 $\rightarrow$ Charge Neutrality.



<u>-ve charges</u> - free e^-s $\rightarrow n$

Acceptor ions $\rightarrow N_A^- \simeq N_A$ (at room temp)

<u>+ve charge</u> - holes $\rightarrow p$

Donor ions $\rightarrow N_D^+ \simeq N_D$ (at room temp)

let the s.c. be doped with both donors & acceptors (General Case)

Charge Neutrality $\rightarrow$ (total +ve charges) + (total -ve charges) = 0

$$\cancel{q}(p + N_D^+) - \cancel{q}(n + N_A^-) = 0$$

where $q = +1.6 \times 10^{-19}$ C

$$p + N_D^+ = n + N_A^-$$

at room temp

$\downarrow$

$$\boxed{p + N_D = n + N_A} \quad **$$

if $N_A >> N_D$ & $N_A >> n_i$

$$p + \cancel{N_D}_{\to 0} - n - N_A = 0$$

Also, even $n \sim n_i$ (which it isn't),

$$p - \cancel{n}_{\to 0} - N_A = 0, \quad p - N_A = 0 \Rightarrow p = N_A$$

If $N_A >> n_i$ but $N_A > N_D$ (not too large)

$$p + N_D - \cancel{n}_{\to 0} - N_A = 0 \Rightarrow p - (N_A - N_D) = 0$$

$$\Rightarrow \boxed{p = N_A - N_D} \rightarrow \text{maj. conc in p-type}$$

Similarly if $N_D >> n_i$, $N_D > N_A$

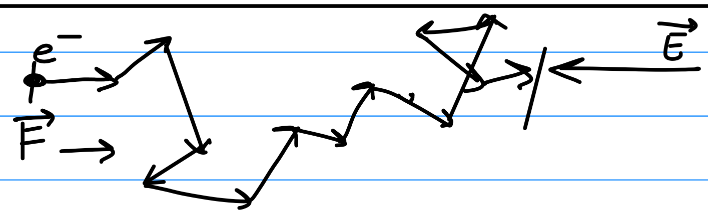
then p is neglected, & $\boxed{n = N_D - N_A}$

maj conc. in n-type s.c

* Now minority conc. can be found from Law of mass action.

→ <u>Conduction in s.c.</u> – <u>2 processes</u>

1. Drift



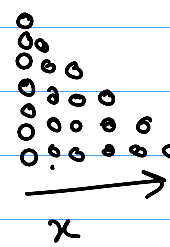
Collisions ⇒ Scattering

e^-s don't have Newtonian vel.
they have v_d (Drift velocity)

$$v_d \propto |\vec{E}| = \mathcal{E} \Rightarrow \boxed{v_d = \mu \mathcal{E}}$$

μ = Mobility

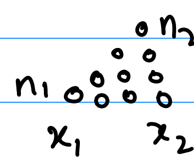
2. Diffusion



conc. changes with x → <u>Conc. Gradient</u>

particles move from high conc. to low conc.

<u>for e^-s</u>, – if $\frac{dn}{dx} = +ve$



$n_2 > n_1$, $x_2 > x_1$ $\quad \frac{n_2 - n_1}{x_2 - x_1} \simeq \frac{dn}{dx}$ → +ve

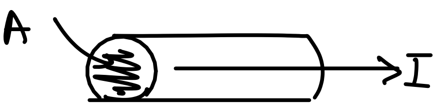
e^-s will move in $-x$ direction
I will be in $+x$ direction

Diffusion - $J_{n\text{-}diff} \propto \frac{dn}{dx}$

Current density due to e^-s

$q = +1.6 \times 10^{-19}$ C

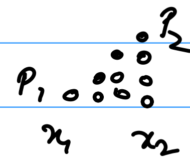
$$\boxed{J_{n\text{-}diff} = q D_n \frac{dn}{dx}}$$



Current density

$J = \frac{I}{A}$ Amp/cm^2

for holes - if $\frac{dp}{dx} = +ve$



$p_2 > p_1$ $\quad$ $x_2 > x_1$ $\quad$ $\frac{p_2 - p_1}{x_2 - x_1} = \frac{dp}{dx} = +ve$

holes will move in $-ve$ x direction
& I will be in $-ve$ x dir.

D_n, D_p Diffusion Constants

So, $$\boxed{J_{p\text{-}diff} = -q D_p \frac{dp}{dx}}$$

$q = +1.6 \times 10^{-19}$ C

Drift Current - Caused by electric field (force, pot. diff)

$J_{drift} \propto \mathcal{E}$

$\mathcal{E}$ → electric field

$\boxed{J_{drift} = \sigma \mathcal{E}}$ ← $\boxed{\text{Ohm's law}}$

σ → conductivity

Ohm's law - $V = IR$ $\qquad$ $I = \frac{1}{R} V$

$\text{Amp} = \frac{1}{\text{Ohm}} \times \text{Volts}$

Resistance

$R = \rho \frac{l}{a}$ $\quad$ l → length, a → cross section area

ρ → resistivity

$\rho = \text{Ohm} \cdot \text{cm}$

$\frac{1}{\rho} = \sigma = \frac{1}{\text{Ohm} \cdot \text{cm}}$

Divide both sides by area (cm^2)

$$\frac{\text{Amp}}{cm^2} = \left(\frac{1}{\text{Ohm} \cdot \text{cm}}\right)\left(\frac{\text{Volt}}{\text{cm}}\right)$$

$\frac{\text{Amp}}{cm^2}$ → Current density

$\frac{1}{\text{Ohm} \cdot \text{cm}}$ → conductivity (σ)

$\frac{\text{Volt}}{\text{cm}}$ → electric field

$$\boxed{J = \sigma \cdot \mathcal{E}}$$

→ Conductivity – $\sigma = \frac{1}{\rho}$ $\sigma \to \frac{1}{\Omega cm}$

$\rho \to$ resistivity (Ωcm)

$\sigma_n \propto n$; $\sigma_n \propto \mu_n$ $\because$ $\sigma_n \propto \frac{1}{scattering}$ $\mu \propto \frac{1}{scattering}$

$$\boxed{\sigma_n = q n \mu_n}$$

Similarly $\boxed{\sigma_p = q p \mu_p}$

Total conductivity for any s.c. –

$$\boxed{\sigma = \sigma_n + \sigma_p = q n \mu_n + q p \mu_p}$$

Intrinsic Conductivity (for intrinsic s.c.) →

$n = p = n_i$

so, $\boxed{\sigma_i = q n_i (\mu_n + \mu_p)}$

if for n-type s.c., $n >> p$ then $n\mu_n >> p\mu_p$

So, $\sigma \simeq q n \mu_n$ (total conductivity)

Since $n \simeq N_D$ then $\sigma \simeq q N_D \mu_n$

if for p-type s.c., $p >> n$ then $p\mu_n >> n\mu_n$

& $\sigma \simeq q p \mu_p$

since $p \simeq N_A$ So, $\sigma \simeq q N_A \mu_p$

Conduction equations – Total current density, $J = J_n + J_p$

where $J_n = J_{n\,drift} + J_{n-diff}$

& $J_p = J_{p\,drift} + J_{p\,diff}$.

So,

$$\boxed{\begin{aligned} J_n &= q n v_{dn} + q D_n \frac{dn}{dx} \\ J_p &= q p v_{dp} - q D_p \frac{dp}{dx} \end{aligned}}$$

& $\boxed{J = J_n + J_p}$

$v_{dn} = \mu_n \mathcal{E}$

$v_{dp} = \mu_p \mathcal{E}$

→ Einstein's Relation – $\boxed{\dfrac{D}{\mu} = \dfrac{kT}{q}}$

$kT = \dfrac{T}{11{,}600}$ → in Kelvin

$\simeq 26\,meV$ at room temp

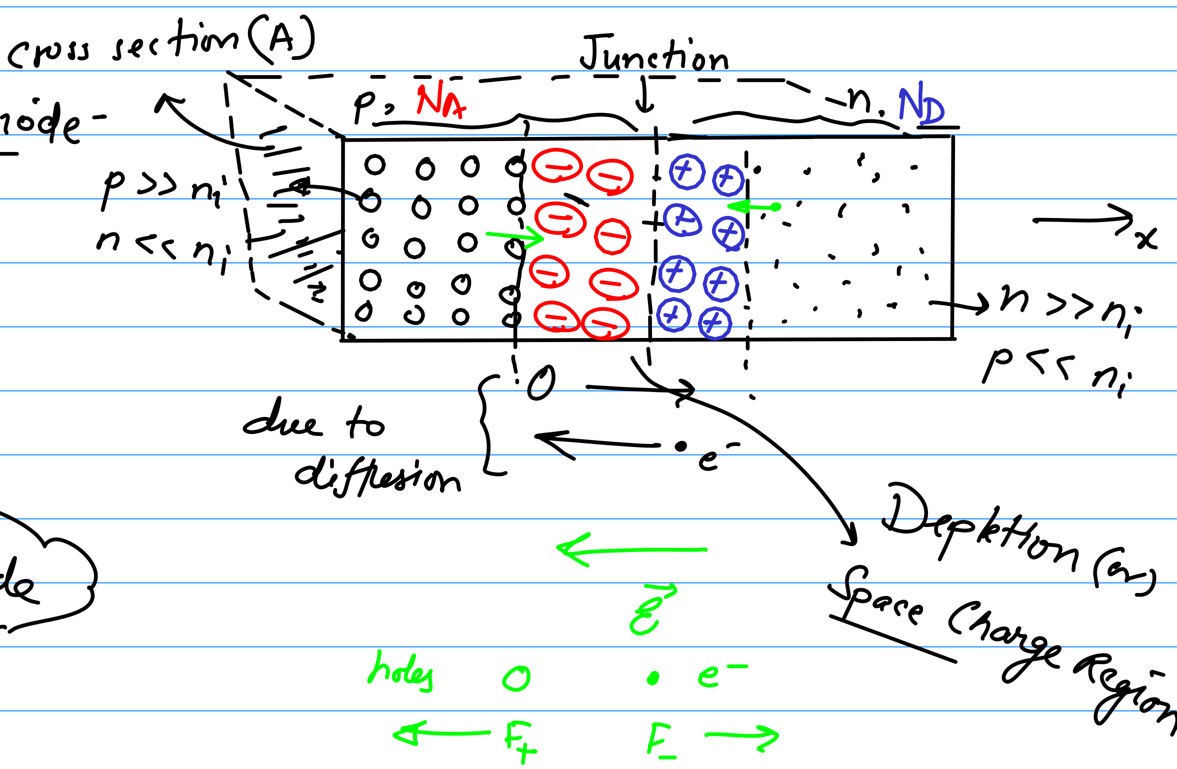
D = Diffusion constant (cm^2/s)

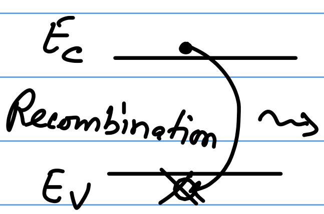
μ = mobility (cm^2/Vs)

$\dfrac{kT}{q} = V_T \cong 26\,mV$ at room temp.

V_T → Thermal voltage

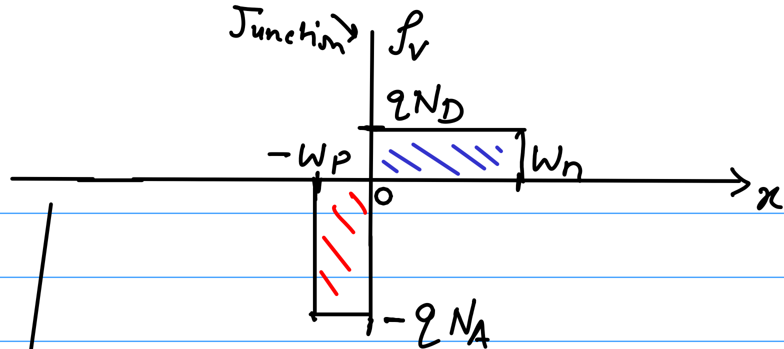
→ P-N Junction Diode –





Unbiased diode

ρ_V = Volume Charge density (C/cm^3)



if $N_A > N_D$, Depletion spreads more in n side than p side

$W_n > W_p$

assume → $N_A > N_D$

(N_A & N_D are present in different region)

∴ Charge conservation –

Total exposed Charge on p side (red rectangle) $= -qN_A(A\,W_p)$ (Volume)

Total charge exposed on n side $= +qN_D(A\,W_n)$

by charge conservation →

$$|-qN_A A W_p| = |+qN_D A W_n|$$

$$\Rightarrow \boxed{N_A W_p = N_D W_n} \quad ** \quad \begin{pmatrix}\text{Red rectange} \\ \text{area}\end{pmatrix} = \begin{pmatrix}\text{Blue Rect.} \\ \text{area}\end{pmatrix}$$

→ Plot $\vec{\mathcal{E}}$ & V in this device – "Poisson's Equation"

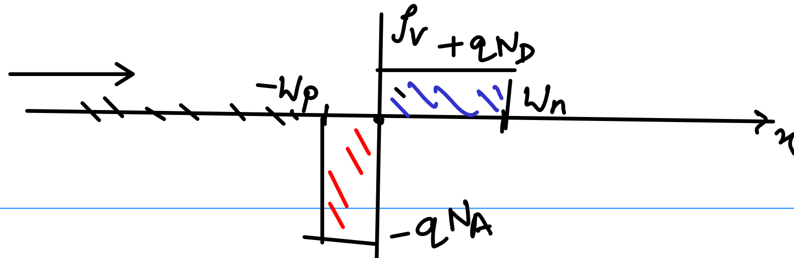
$$\boxed{\nabla^2 V = -\frac{\rho_V}{\epsilon}}$$

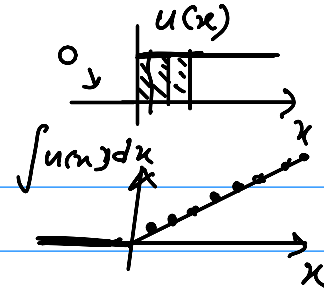
$$\boxed{\frac{d^2V}{dx^2} = -\frac{\rho_V}{\epsilon}} \rightarrow \frac{d}{dx}\left(\frac{dV}{dx}\right) = -\frac{\rho_V}{\epsilon}$$

Also, $\boxed{\vec{\mathcal{E}} = -\frac{dV}{dx}}$

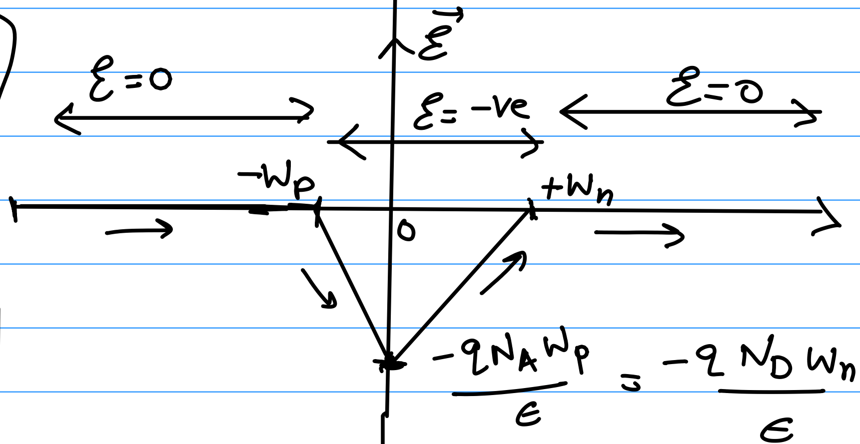
$$\Rightarrow \boxed{\frac{d\mathcal{E}}{dx} = \frac{\rho_V}{\epsilon}}$$

$$\frac{d\mathcal{E}}{dx} = \frac{\rho_v}{\epsilon}$$





So, $\boxed{\mathcal{E} = \int \frac{\rho_v}{\epsilon} dx}$



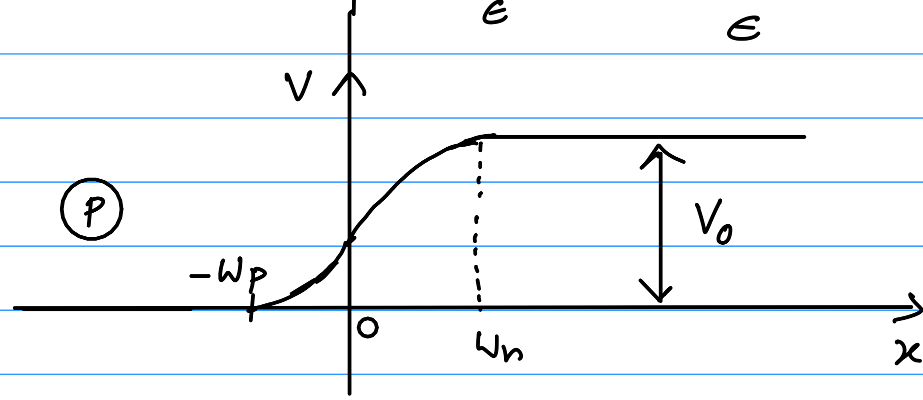
$(\because N_A W_p = N_D W_n)$

$V(x) = ?$

$$\vec{\mathcal{E}} = -\frac{d\vec{V}}{dx}$$

$$V = -\int \mathcal{E} dx$$

let metal p contact be at $V=0$ (reference)



* V_0 = Built-in Potential.
* Naturally appears (without external bias)

* V_0 is $-ve$ of total area under $\vec{\mathcal{E}}$ curve.

$$\text{Area under } \vec{\mathcal{E}} = \frac{1}{2} \times (\text{altitude}) \times (\text{base})$$

$$= \frac{1}{2} \times \left(\frac{-qN_AW_p}{\epsilon}\right) \times (W_p + W_n)$$

or

$$= \frac{1}{2}\left(\frac{-qN_DW_n}{\epsilon}\right)(W_p + W_n)$$

So, $$\boxed{V_0 = \frac{1}{2}\left(\frac{qN_AW_p}{\epsilon}\right)(W) = \frac{1}{2}\left(\frac{qN_DW_n}{\epsilon}\right)(W)}$$

where $W = W_p + W_n$ = Total Depletion width.

We have $\quad W = W_p + W_n \quad \text{— (1)}$

$$N_A W_p = N_D W_n \quad \text{— (2)} \qquad \text{(Charge Conservation)}$$

Solving for W_p & W_n →

$$\boxed{W_p = \left(\frac{N_D}{N_A+N_D}\right) W} \quad \& \quad \boxed{W_n = \left(\frac{N_A}{N_A+N_D}\right) \cdot W}$$

$W_p \propto N_D$ $\qquad$ $W_n \propto N_A$

So, if $N_A > N_D$ then $W_n > W_p$

Replacing W_p or W_n in V_0 expression,

$$V_0 = \frac{1}{2}\left(\frac{q N_A}{\epsilon}\right)\underbrace{\left\{\left(\frac{N_D}{N_A+N_D}\right)W\right\}}_{W_p} W$$

$$V_0 = \frac{q}{2\epsilon}\left(\frac{N_A N_D}{N_A+N_D}\right) W^2$$

{ Relation between V_0 & W

Solve for W

$$W = \sqrt{\frac{2\epsilon}{q}\left(\frac{N_A+N_D}{N_A N_D}\right) V_0}$$

$$\boxed{W = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right) V_0}}$$

** [used to find W if N_A, N_D, V_0 are known]

V_0 can be found from → $\boxed{V_0 = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$ **

where $\frac{kT}{q} = V_T = \frac{T}{11600} = 26\text{mV}$ (at $300k$)

(kelvin)

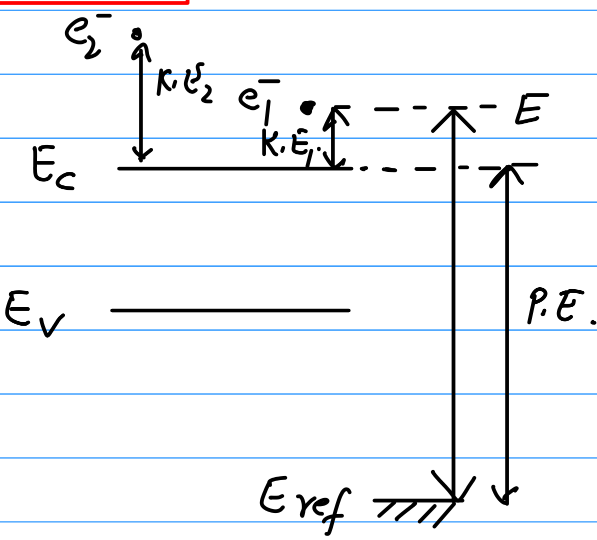
$$V_0 = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = \frac{kT}{q} \ln\left(\frac{N_D}{\{n_i^2/N_A\}}\right)$$

N_D → maj. e^- conc. on n-side (n_n)

$\{n_i^2/N_A\}$ → minority e^- conc. on p-side (n_p)

So, $$\boxed{V_0 = \frac{kT}{q} \ln\left(\frac{n_n}{n_p}\right) = \frac{kT}{q} \ln\left(\frac{p_p}{p_n}\right)}$$

→ Revisiting EBD —



Let e^- in cond. band have total energy E

E = P.E. + K.E.

where

P.E. = $E_c - E_{ref}$

So, K.E. = E − P.E. = $E - (E_c - E_{ref})$

Let $E_{ref} = 0$

then K.E. = $E - E_c$ (height of e^- over E_c)

↳ $\left(\frac{1}{2}mv^2\right)$

* e^- at E_c has zero velocity ($\because$ KE = 0)

* higher an e^- in cond. band, faster it moves.

* $E_c - E_{ref}$ = $\boxed{\text{P.E.} = E_c}$ (if $E_{ref} = 0$)

* P.E. = (Charge) × (Potential)

in EBD, vert. axis is e^- energy

So, $\boxed{E_c = -qV}$ where $-q$ = e^- charge

EBD of p-n junction diode -

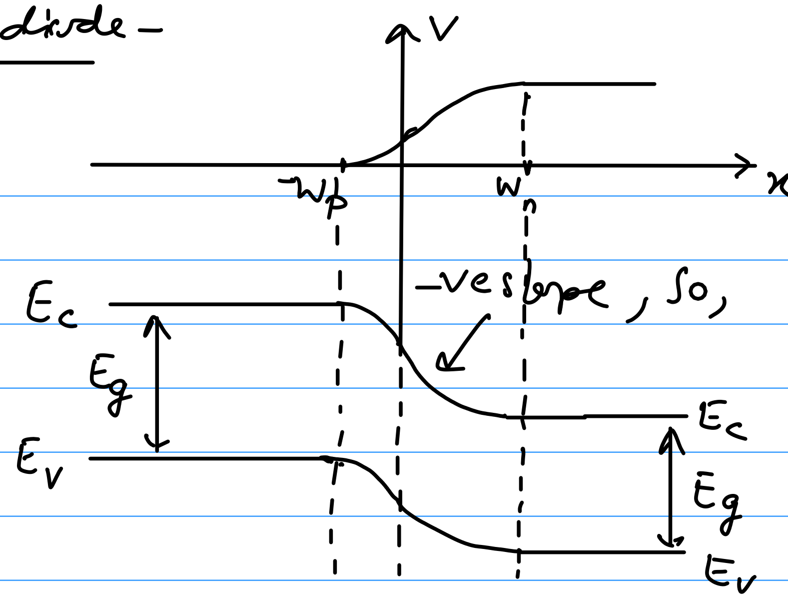
$E_c = -qV$

$\vec{\mathcal{E}} = -\frac{dV}{dx}$

$\mathcal{E} = -\frac{d}{dx}\left(\frac{-1}{q}E_c\right)$

$$\boxed{\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx}}$$

So, $\boxed{E_c = q\int \mathcal{E}\,dx}$



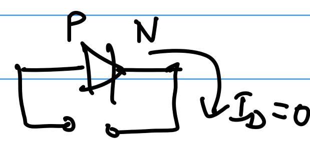
(or V)

* if $\mathcal{E}$ is known then E_c can be found.
* E_v will be E_g below E_c

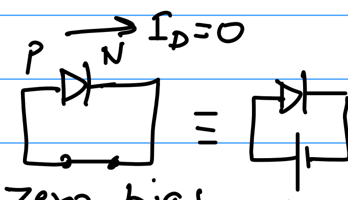
* $\vec{\mathcal{E}}$ is always in the direction of rise of E_c

→ Biasing a P-N Junction - (i) No Bias } Equilibrium, $I_D = 0$
(ii) Zero Bias
(iii) Forward Bias } Non Equilibrium, $I_D \neq 0$
(iv) Reverse Bias

i) & ii) Zero & No bias -

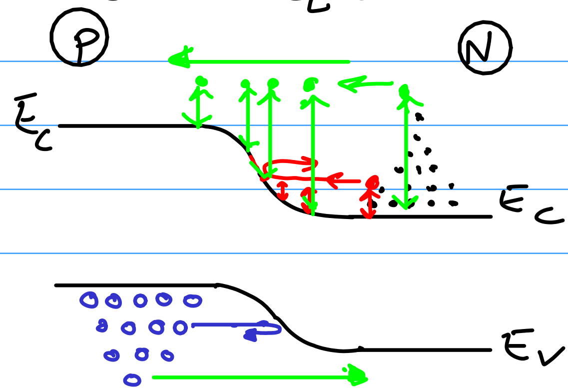


No bias



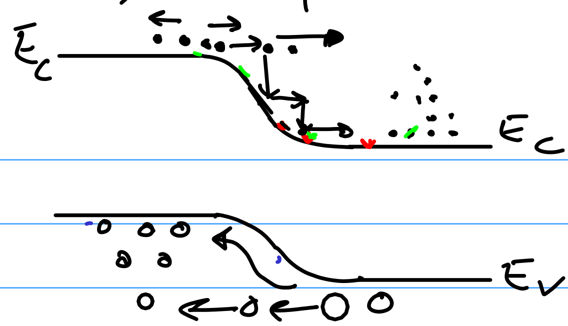
Zero bias

Diode under Eqlbm. & $I_D = 0$

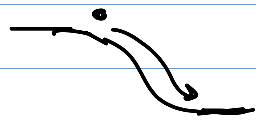


* e^- conc. reduces exponentially as we go up in cond. band.
* hole conc. reduces exponentially as we go down below E_v.

from P side, min. e's if come into dep region, they get swept away to N side



Similarly for min. holes on N-side.



carriers can roll down the hill

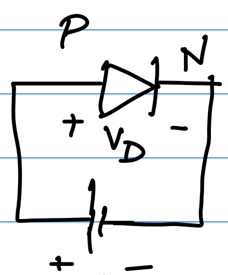
* Under Equlbm, No. of min. e⁻s going from P-N (drift) is same as no maj. e⁻s going from N-P over the barrier (diffusion).

So, $J_n = \underset{(+ve)}{J_{n\,diff.}} + \underset{(-ve)}{J_{n\,drift}} = 0$

* Similarly $J_p = \underset{(+ve)}{J_{p\,diff}} + \underset{(-ve)}{J_{p\,drift}} = 0$

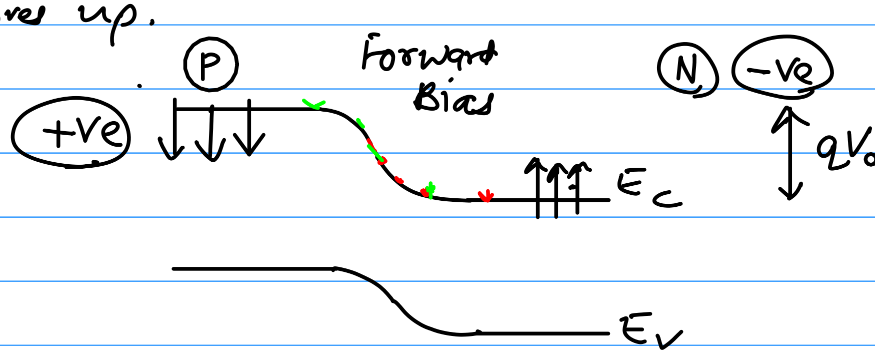
* So, $J = J_n + J_p = 0$ [zero bias & no bias]

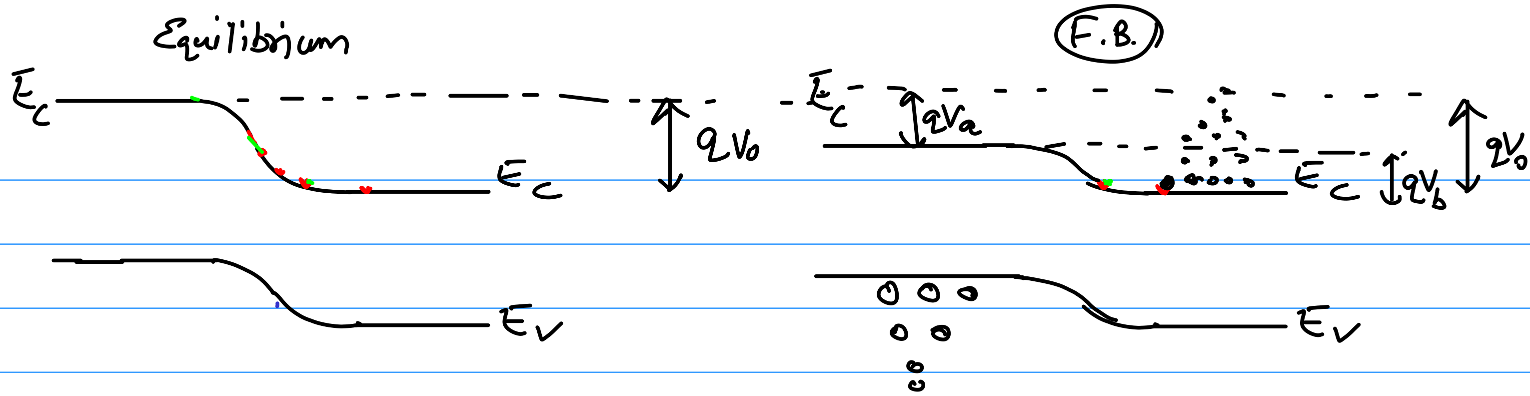
(iii) Forward Bias - * The side with +ve (or higher pot.) moves down in EBD. ∵ $E_c = P.E. = -qV$ if $V(+ve)$, -ve P.E. gets added. If $V = -ve$, +ve P.E. is added & EBD moves up.



(applied bias)

here, $V_D = V_a$





If N side contact (metal – S.C. contact) is taken as reference, then E_c on side can be taken at same level, w.r.t. it, P side E_c moves down by an amount of $qV_D = qV_a$

* By F.B., barrier height reduces.

$$qV_b = qV_0 - qV_D$$

* Now there are several (exponential) maj. carriers on both side that can go over the barrier.

* But minority carriers crossing to other side are still same in number. ∵ height of barrier never mattered to them

* So, there is imbalance. Min. e^-s drifting from P to N can no longer cancel Maj. e^-s diffusing from N to P.
  So, J_n = non zero (+ve x dir ∵ e^- N to P)

* Similarly due to imbalance in hole motion
  J_p = non zero (+ve x dir. ∵ holes, P to N)

* So, $J = J_n + J_p$ = non zero (from P to N)

* $I_D \propto \exp.(V_D)$ $\boxed{I_D = I_0\left(e^{\frac{qV_D}{\eta kT}} - 1\right)}$ *

η = Ideality factor. It should be 1 ideally but practically $1 < \eta$

typically $1 < \eta \leq 2$

$\frac{kT}{q} = V_T = \frac{T^{(\text{Kelvin})}}{11,600} \simeq 26\ mV$ at 300 K.

* if $V_D \gg 3V_T$ then $e^{\frac{V_D}{\eta V_T}} \gg 1$

& $\boxed{I_D = I_0 \exp\left(\frac{V_D}{\eta V_T}\right)}$

* I_0 = Reverse Saturation Current or thermal current
Min. carrier current

$$\boxed{I_0 = qA\left[\frac{D_p}{L_p} P_{n_0} + \frac{D_n}{L_n} n_{p_0}\right]}$$

$D_p, D_n \rightarrow$ Diffusion constants

$L_p \rightarrow$ minority hole diffusion length (in n type s.c.)

$L_n \rightarrow$ min e^- diffusion length (in p-type s.c.)

9 <u>Min. Diffusion Length (L)</u> $\rightarrow$ Average distance for which a min. carrier can diffuse into a sea of maj. carriers, before it gets recombined.

$p_{no} \rightarrow$ min. hole conc. on n side at equilibrium

$$p_{no} = \frac{n_i^2}{N_D}$$

$n_{po} \rightarrow$ min e^- conc. on p-side at equilibrium

$$n_{po} = \frac{n_i^2}{N_A}$$

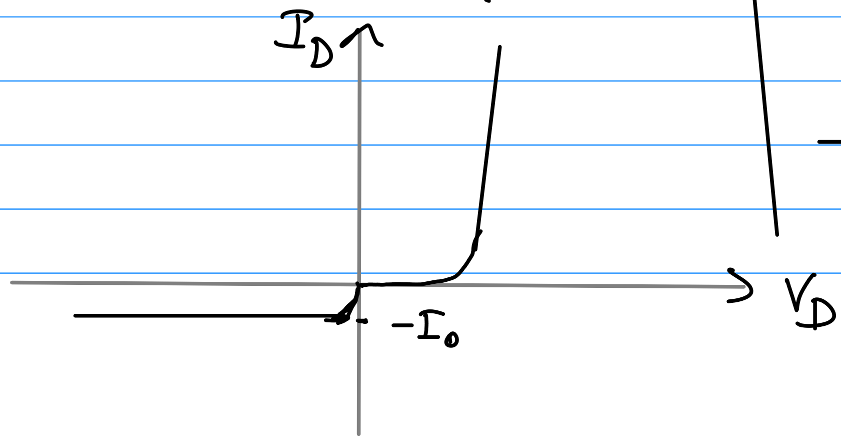
* $\sqrt{D_p L_p} = \tau_p$ & $\sqrt{D_n L_n} = \tau_n$

where τ_p & τ_n are minority carrier Lifetime for holes & e^-s resp.

<u>Min. carrier Lifetime</u> – Average Lifetime of min. carriers from generation to recombination.

→ <u>IV characteristics of P-N J^n diode</u> –

$$I_D = I_0\left(\exp\left(\frac{V_D}{\eta V_T}\right) - \cancel{1}\right)_0$$



$\frac{V_D}{\eta V_T} >> 1$ $(V_D = +ve)$

$$I_D = I_0 \exp\left(\frac{V_D}{\eta V_T}\right)$$

if $V_D = -ve$
exp. term becomes negligible
& $I_D = -I_0$

Depletion Width under F.B −

$$W = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_b)}$$

actually

V_b → barrier potential

(at equil., $V_b = V_0$)

* $V_b = V_0 - V_D$

So,

$$\boxed{W = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V_D)}}$$ *

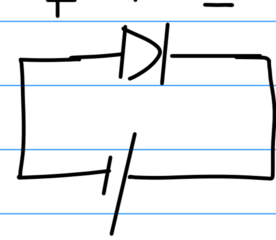
if V_D = +ve (F.B.), $W < W_0$

W_0 = W at equilibrium

If V_D = −ve (R.B.), $W > W_0$

→ Reverse Bias p-N Jn −

V_D = −ve

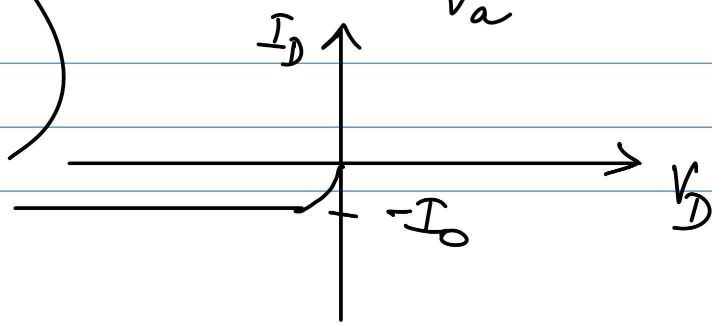


$$I_D = I_0\left(\exp\left(\frac{V_D}{\eta V_T}\right) - 1\right)$$

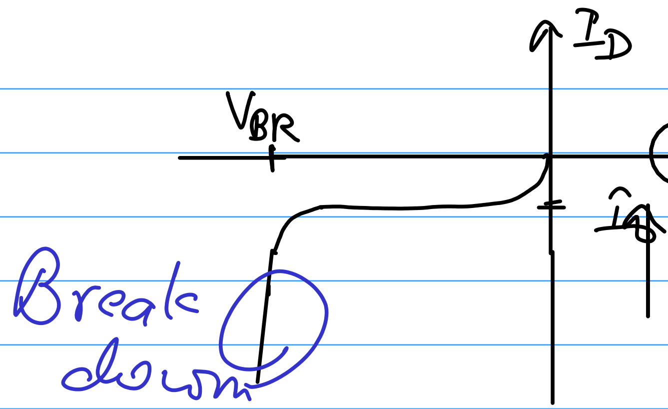
$$= I_0\left(\frac{1}{\uparrow \exp\left(\frac{|V_D| \uparrow}{\eta V_T}\right)} - 1\right)$$

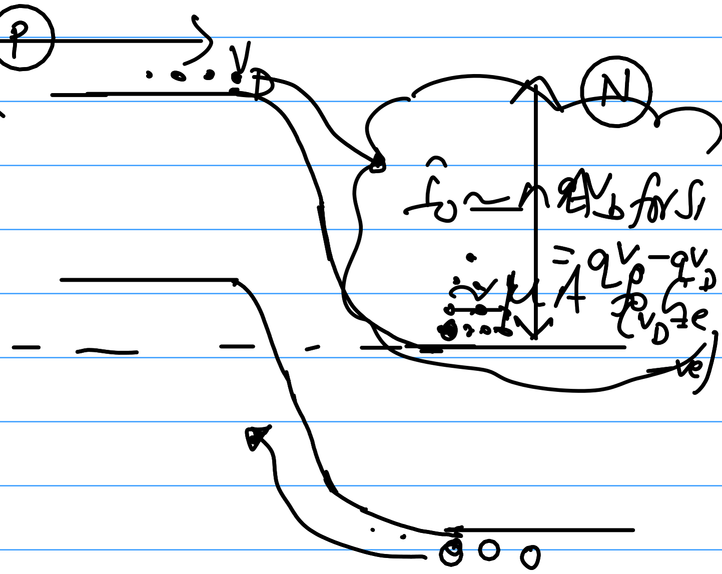
as $|V_D|$ ↑↑, → 0

$$I_D = I_0(0 - 1)$$



* If we keep ↑ R.B., Diode breaks down



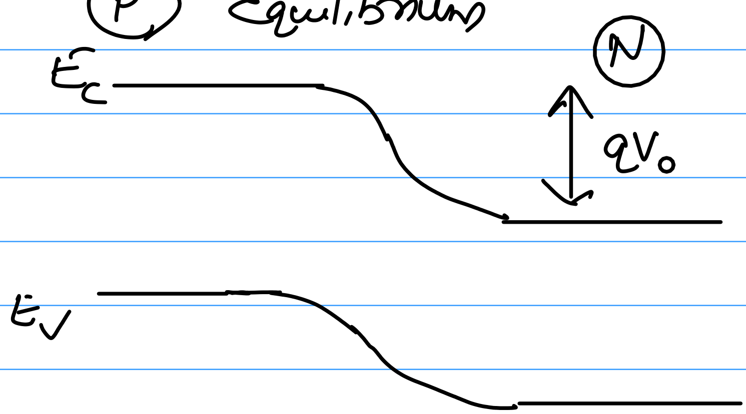


→ Breakdown Mechanisms -

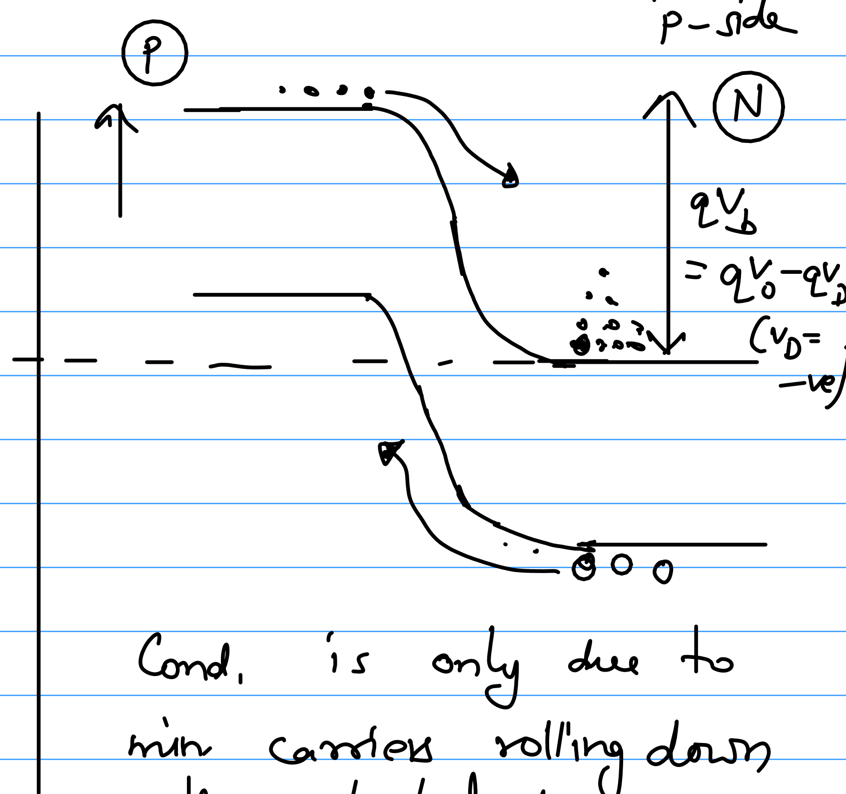
- Avalanche Breakdown
- Zener Breakdown

→ R.B. E.B.D.

P Equilibrium

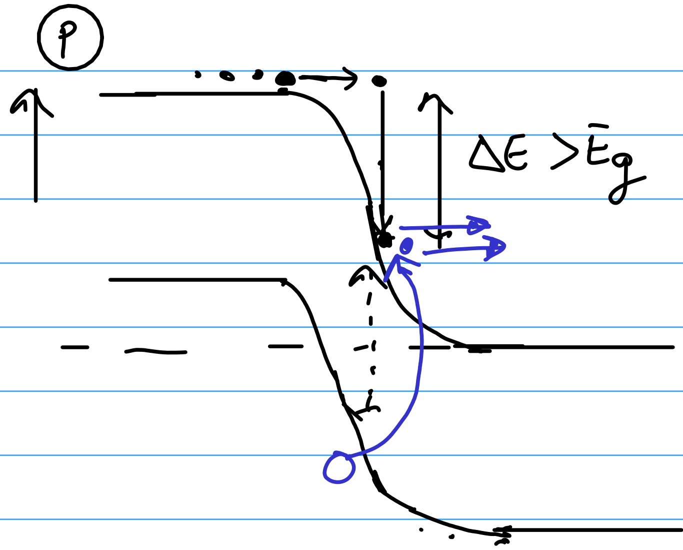


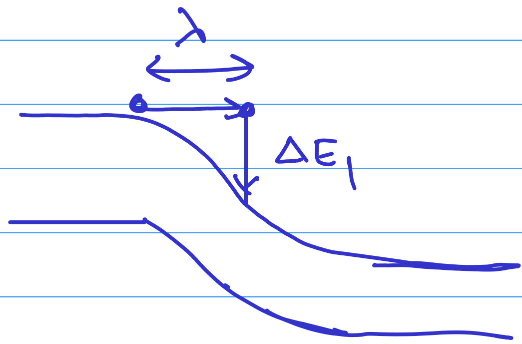
R.B. → -ve pot at p-side

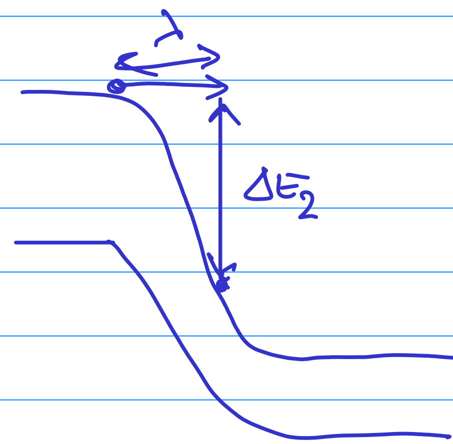


Cond. is only due to min carriers rolling down the potential hill.

Avalanche — (Impact Ionisation)







$$\Delta E_2 > \Delta E_1$$

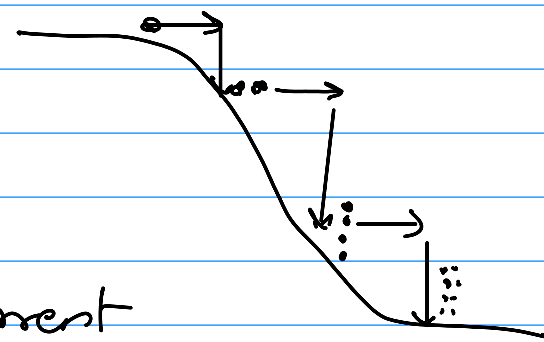
* $\uparrow$ Steepness of band in dep. Region. $\Delta E \uparrow$
for same λ (mean free path → avg. dist b/w 2 collision → free path)

* Steepness / slope of $E_c = \vec{\mathcal{E}}$ (electric field)

* So, $\uparrow \mathcal{E}$ in dep. $\uparrow \Delta E$ on collision

So, chances of Impact Ionisation are more if $\vec{\mathcal{E}}$ is more.

* If dep region is wide (large W), then a single e^- could undergo several I.I. events (say m events). So every e^- causes generation of m new EHPs as it passes W.



* Avalanche happens.
& a large R.B. current flows in the device.

* for Avalanche breakdown, W should be large i.e. it happens if dopings are low $\left(W \propto \frac{1}{N}\right)$

* But large $\vec{\mathcal{E}}$ is also needed. So it happens for large R.B voltages (V_{Br} = large)
($\because$ under R.B., $|V_D| \uparrow \rightarrow \vec{\mathcal{E}} \uparrow$, $V_b \uparrow$

→ Zener breakdown – happens due to "Tunneling" (for thin barriers)

* It happens if dopings are large. (small W) $\left(W \propto \frac{1}{N}, \text{ large } N\right)$

* It happens at smaller V_{BR} as compared to Avalanche breakdown.

* as $T\uparrow$, V_{BR} (avalanche) increases (+ve temp coeff-)

* as $T\uparrow$ V_{BR} (zener) decreases (-ve temp coeff)

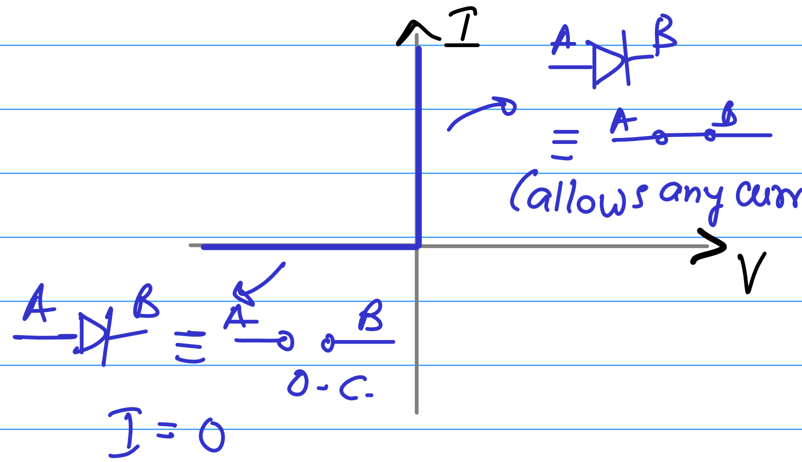
→ <u>Diode circuits</u> – why? → Rectification

↓

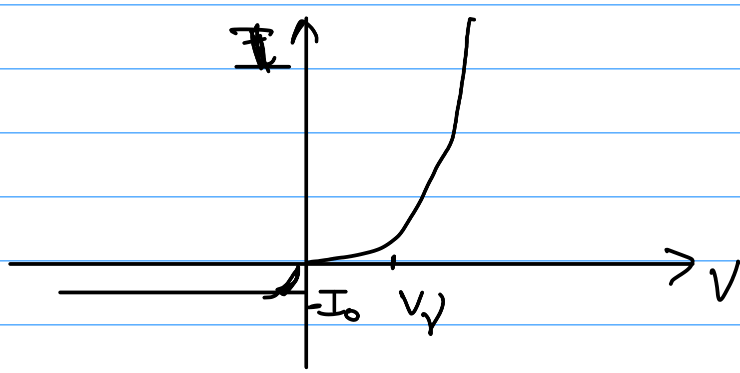
uni-directional conduction

* What we want from diode is

* Ideal Rectifier? →



Practically →



In ckts, a diode can be replaced by a model.

→ **Large Signal Model of diode -**

Large signal → DC bias vol.

can be changed

Small signal → ($\sim$ + large DC) → applied to device

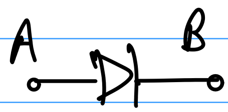
signal to be processed

bias

(large signal)

<< large signal

ent)



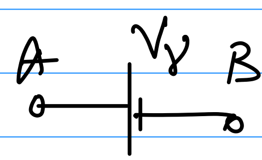
Replaced by →

(i) F.B. case

V_γ → cut in vol.

R_f = forward bias resistance (small)

even simpler model



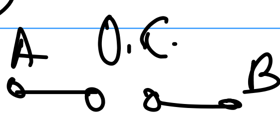
$(R_f \to 0)$

(ii) R.B. case

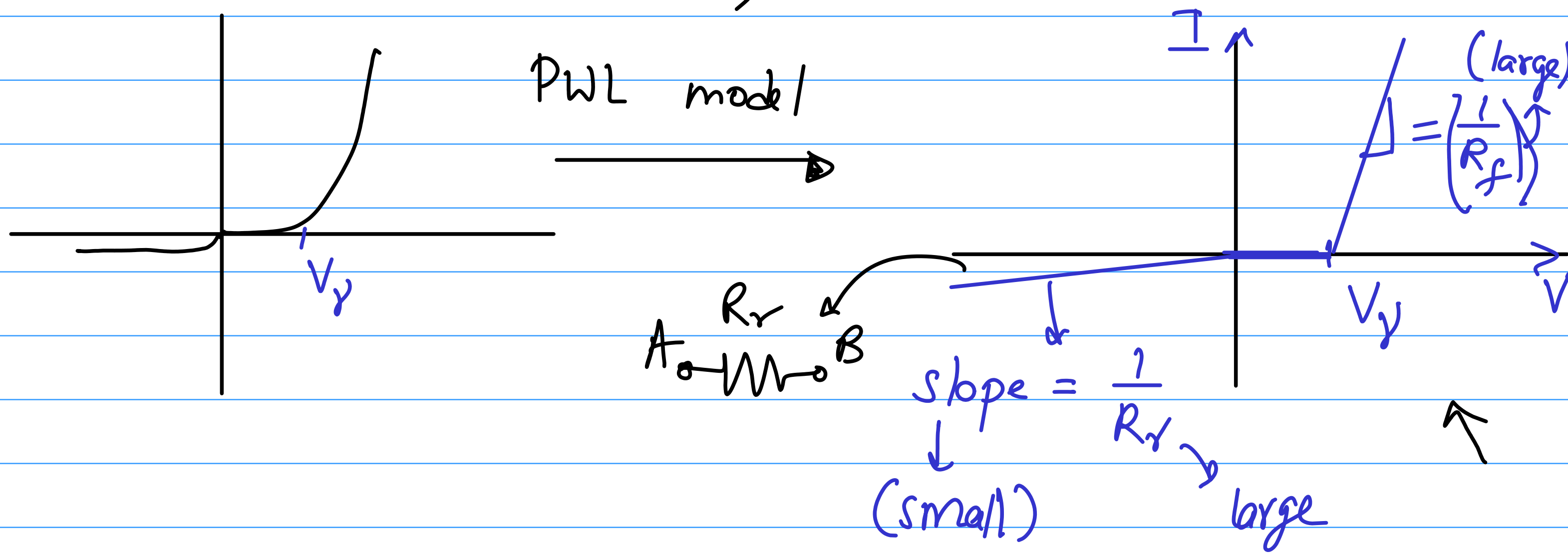
R_r = Reverse Resistance (large)

↓ simpler

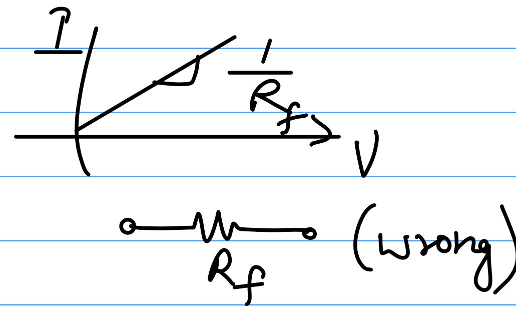
$(R_r \to \infty)$



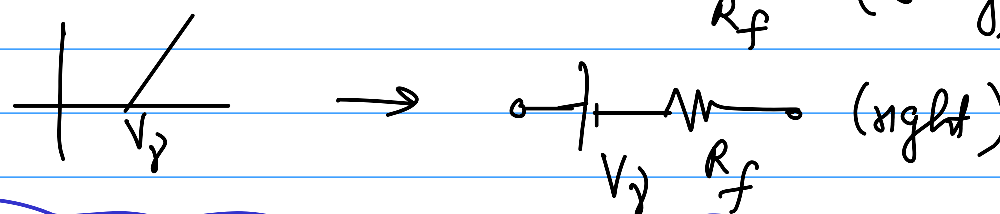
Graphically (Piece-wise Linear Model) (PWL)



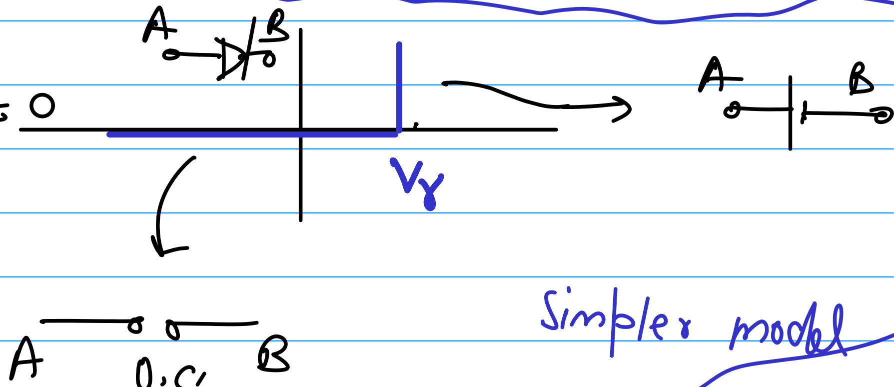
from PWL model, F.B →



but actually,



if $R_f = 0$



Simpler model

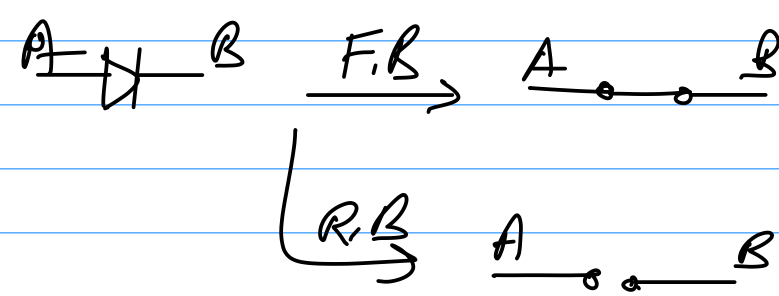
* for Si, $V_\gamma \cong 0.7$ V

Ge $V_\gamma \cong 0.2$ V

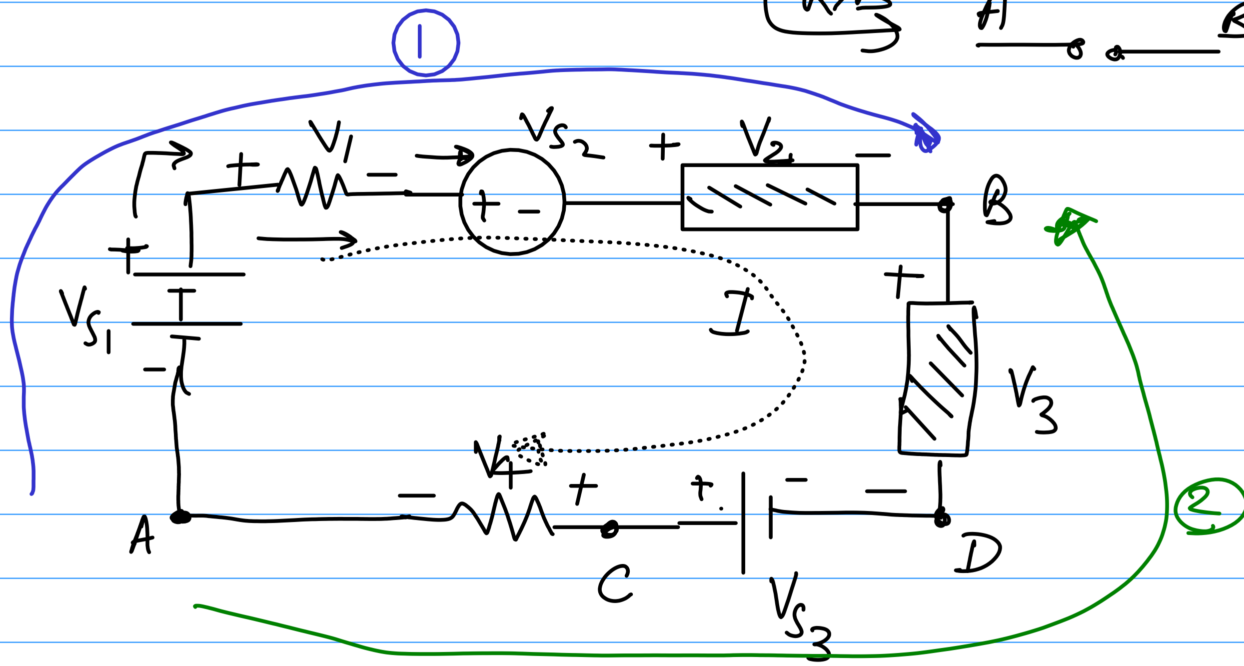
$$\boxed{\frac{dV_\gamma}{dT} = -2.5 \text{ mV}/^\circ C}$$

→ If ideal diode is mentioned,

$V_\gamma = 0$



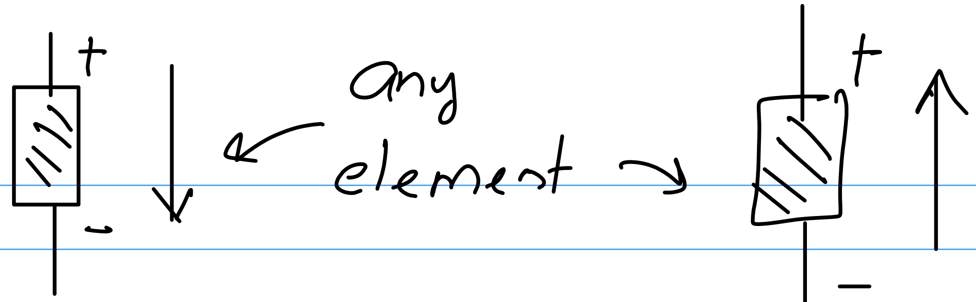
→ KVL :



(1) KVL can be applied from any node to any other node in ckt (loop is not necessary, it is only a special case where the starting & end points are same)

(2) You can assume any dir. for current & any polarities for all the potential drops (voltage or pot. diff.)

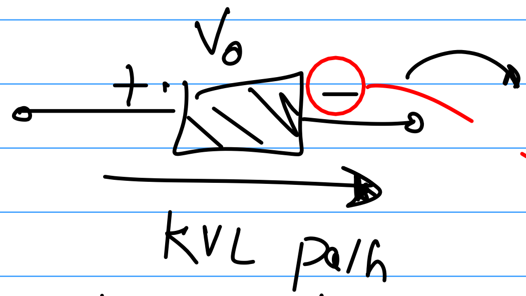
[for resist. I always flows from higher to lower pot. through the resistance)



(absorbing/consuming power) (Delivering power)

(3) To write KVL, start with pot. at beginning node (e.g. V_A). Then write every pot. drop along the path with sign taken from the terminal where path exits the element

e.g.



in KVL, use $-V_0$

Finally, equate it all to potential at end node.

<u>example path</u> ① →

$$\boxed{V_A + V_{S_1} - V_1 - V_{S_2} - V_2 = V_B} \quad \text{(KVL)} \text{ — } ①$$

Now Pot. diff b/w B & A $= V_B - V_A = V_{BA}$

from ①, $$\boxed{V_B - V_A = V_{BA} = V_{S_1} - V_1 - V_{S_2} - V_2} \text{ — } ②$$

Along path 2 —

$$V_A + V_4 - V_{S_3} + V_3 = V_B \quad \text{— (3)}$$

$$V_B - V_A = V_{BA} = V_4 - V_{S_3} + V_3 \quad \text{— (4)}$$

from (2) & (4)

$$V_4 - V_{S_3} + V_3 = V_{S_1} - V_1 - V_{S_2} - V_2 \quad \text{— (5)}$$

Along loop → (A → B → D → C → A)

$$\cancel{V_A} + V_{S_1} - V_1 - V_{S_2} - V_2 - V_3 + V_{S_3} - V_4 = \cancel{V_A}$$

$$\boxed{V_{S_1} - V_1 - V_{S_2} - V_2 - V_3 + V_{S_3} - V_4 = 0} \quad \text{— (6)}$$

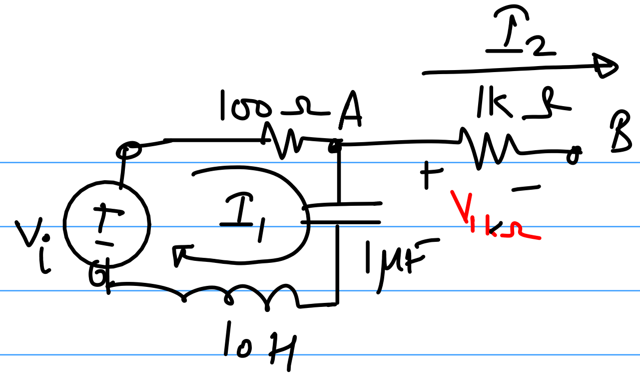
eq. (5) & (6) are same !!

example — V_A is known, & we want V_D

Use KVL from A to D

$$V_D = V_A + V_4 - V_{S_3}$$

Ex problem →



$V_A = 10\ V$

$V_B = ?$

Use KVL – $V_A - V_{1k\Omega} = V_B$

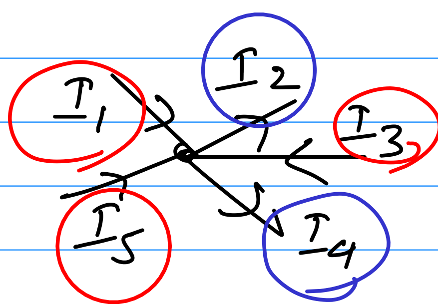
$10 - V_{1k\Omega} = V_B$

∵ c/t at B is not complete, $I_2 = I_{1k\Omega} = 0$

So, $V_{1k\Omega} = R \times I = 1k\Omega \times 0 = 0$

So, $10 - 0 = V_B \Rightarrow \boxed{V_B = V_A = 10\ V}$

→ KCL –



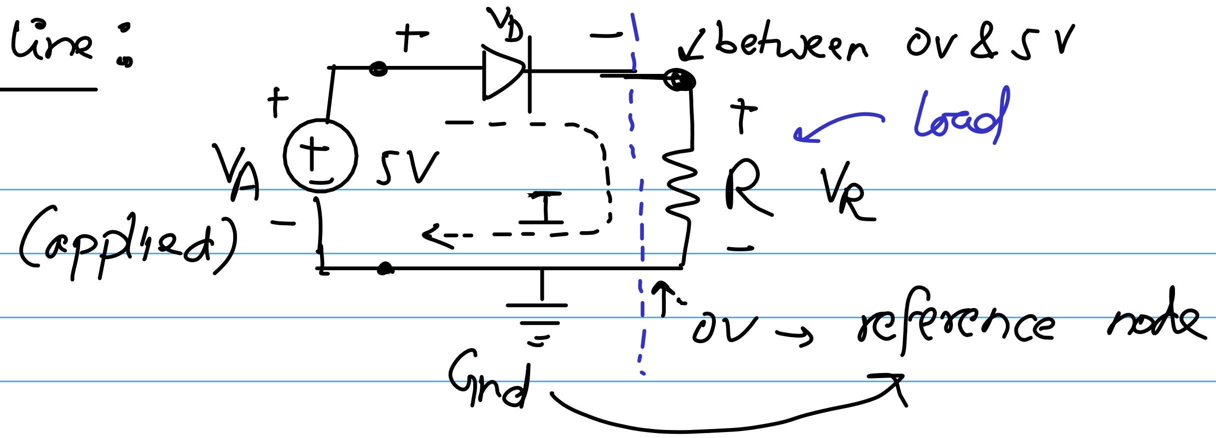
(i) Assume dir. of unknown currents.

(ii) Use ^opposite signs^ for incoming currents & outgoing currents in algebraic sum.

Let incoming currents = +ve, outgoing = −ve

$I_1 - I_2 + I_3 - I_4 + I_5 = 0$ KCL

→ Load line:



Apply KVL in the loop –

$$+V_A - V_D - V_R = 0 \Rightarrow V_A = V_D + V_R$$

$$V_R = IR \quad \text{(Ohm's law)}$$

$$V_A = V_D + IR \Rightarrow \boxed{I = -\frac{1}{R}V_D + \frac{1}{R}V_A} \quad (1)$$

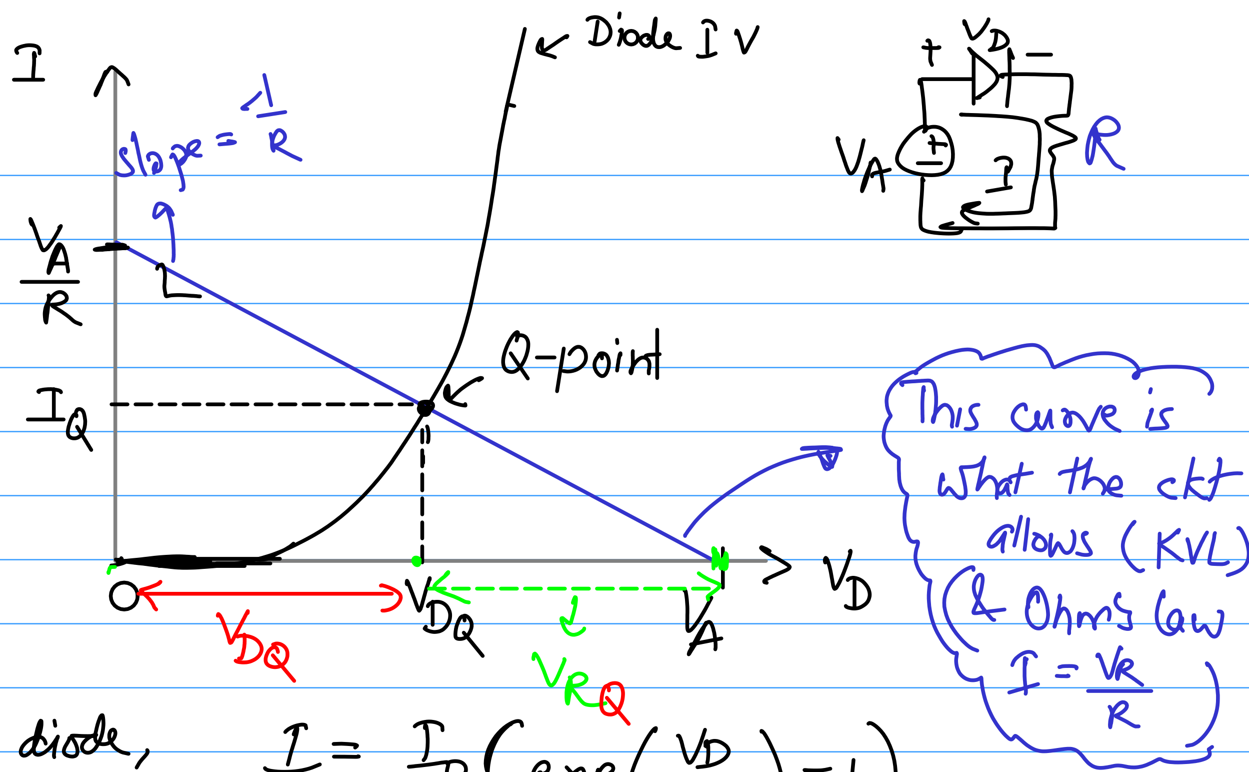
(Load line)

* Eq (1) relates ckt current I to diode vol V_D. (assuming R & V_A to be constants)
* Eq (1) is a straight line ($y = mx + c$)

So, slope $= -\frac{1}{R}$ (−ve)

vert. axis intercept $= \frac{V_A}{R}$

* Slope of this line changes with R (load in this ckt)



* But for diode, $I = I_0\left(\exp\left(\frac{V_D}{\eta V_T}\right) - 1\right)$

* Both curves should be satisfied.

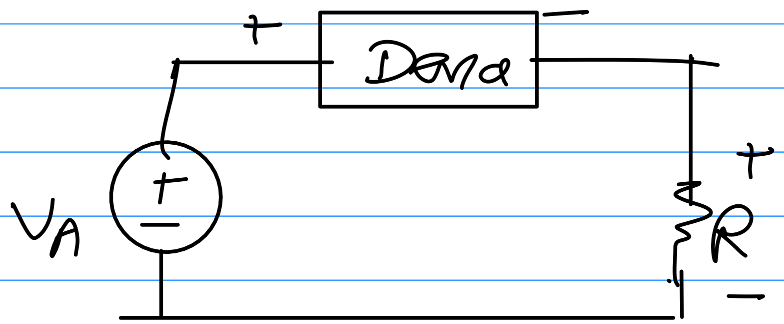
* Q-point = Opertating point (Acutally the ckt operates at this ~~vo~~ current (I_Q) & this diode vol. (V_{DQ})

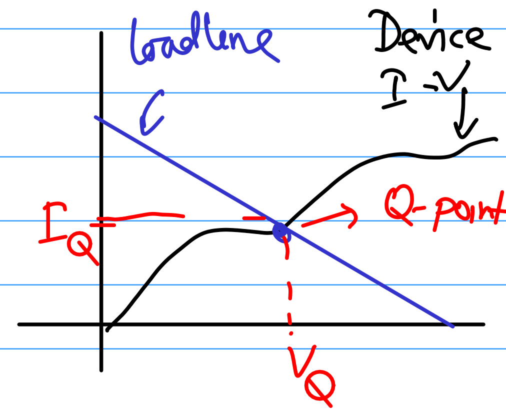
* Load line concept is applicable to any device ckt. to find operating point.

* Q-point → V_{DQ} is the vol that actually forward biases the diode in the ckt & I_Q is the actual f.b. current.

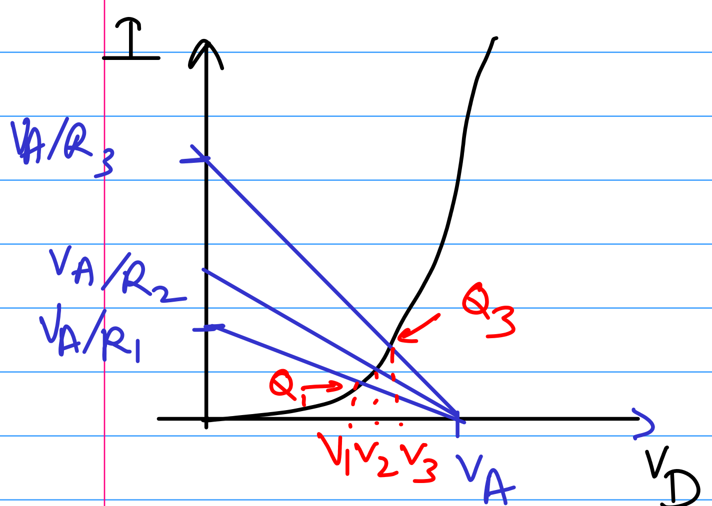
* V_{DQ} & I_{DQ} or I_Q are the actual operating vd & current in the ckt.

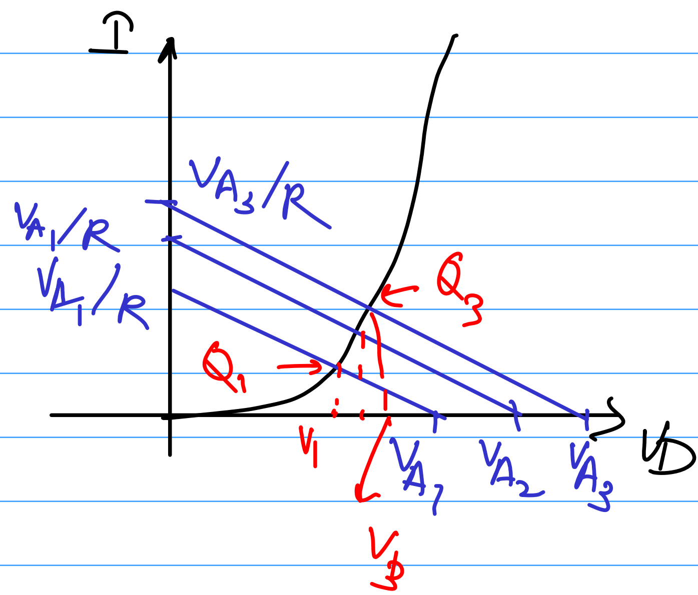
* Load line concept can be applied to any device in ckts to find the operating point.





→ Load line vs R & V_A —





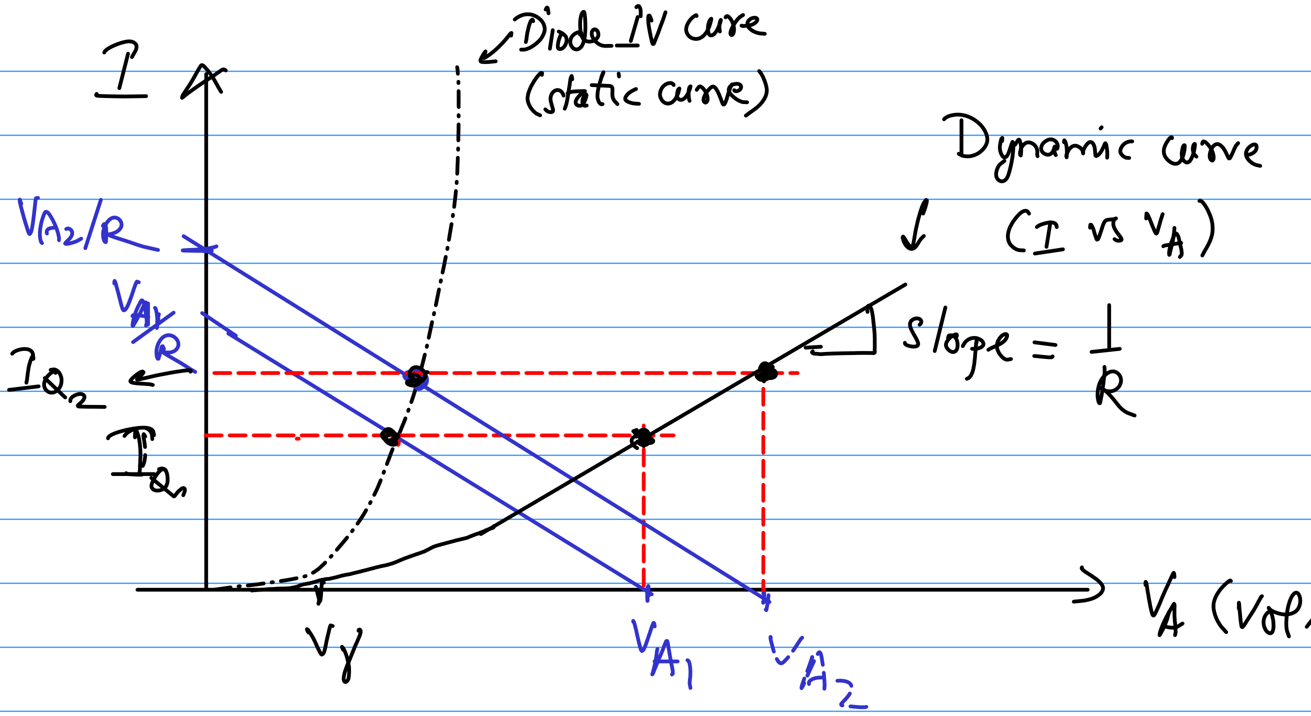
$R_1 > R_2 > R_3$

$V_1 < V_2 < V_3$

$V_{A_1} < V_{A_2} < V_{A_3}$

$V_1 < V_2 < V_3$

→ Dynamic (I - V) curve – (ckt current I vs applied vol. V_A)



from ~~load line~~ KVL →

$$I = \frac{V_A - V_D}{R} \Rightarrow \boxed{I = \frac{1}{R} V_A - \frac{1}{R} V_D} \quad \text{——} (2)$$

if I vs V_D is plotted from (2), then we get the load line (blue)

& if I vs V_A is plotted, we get the dynamic curve

So, slope $= + \frac{1}{R}$

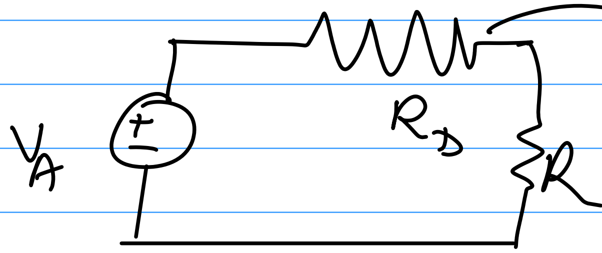
* At low V_A, V_D will also be small. ($V_A < V_\gamma$

So, $V_D < V_\gamma$)

if $V_D < V_\gamma$ then diode barrier is large.

So, diode is less conductive or diode resist. Is large (R_D = large)

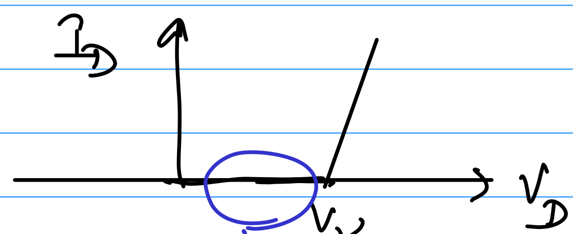
So, ckt can be modelled as



Just for understanding

here $R_D >> R$

Remember



here I_D is v. small

or R_D is v. high

So, by KVL & potential division

$$V_D = \left(\frac{R_D}{R_D + R}\right) V_A$$

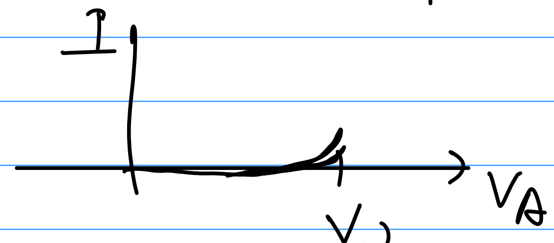
$\because R_D >> R$, $\quad V_D \simeq \dfrac{\cancel{R_D}}{\cancel{R_D}} V_A \Rightarrow \boxed{V_D \simeq V_A}$

* So if $V_A < V_\gamma$, then $\boxed{V_D \simeq V_A}$ (Diode controls the current)

Since I vs V_D is exponential (diode IV)

I vs V_A also is exponential ($\because V_D \simeq V_A$)

So

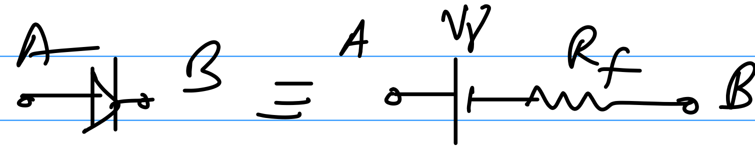


but this I is very small $\because R_D$ large

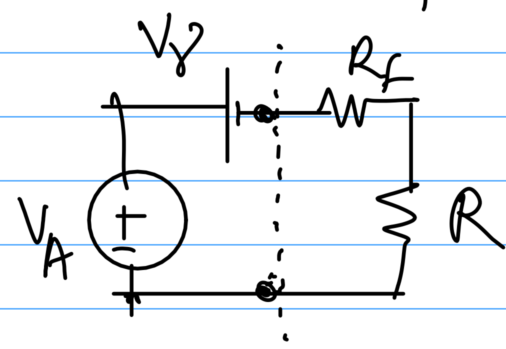
* As $V_A \uparrow$ ($V_A > V_\gamma$), diode "turns-on".

barrier $\to$ negligible, $R_D \to R_f$ (small)

&



for $V_A > V_\gamma$



$R_f \ll R$

by KVL,

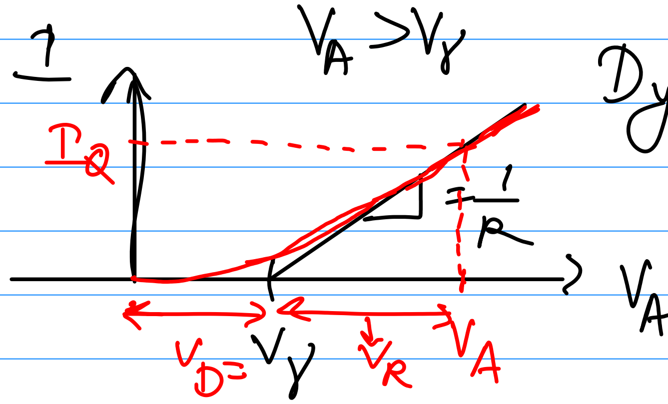
$$V_R = (V_A - V_\gamma)\left(\frac{R}{R+R_f}\right)$$

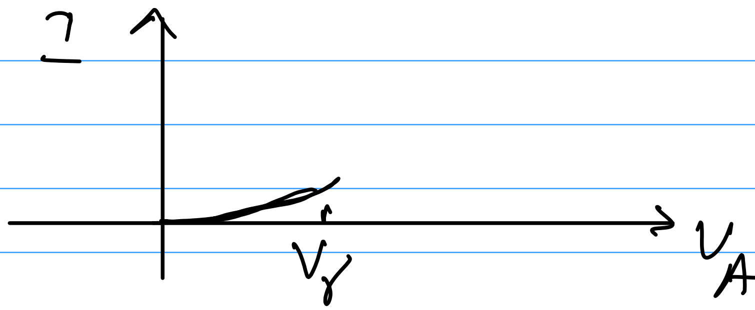
as $R \gg R_f$, $\boxed{V_R = V_A - V_\gamma} = IR$

Now $I = \dfrac{V_A - V_\gamma}{R}$ $\Rightarrow$ $\boxed{I = \dfrac{1}{R}V_A - \dfrac{V_\gamma}{R}}$ *

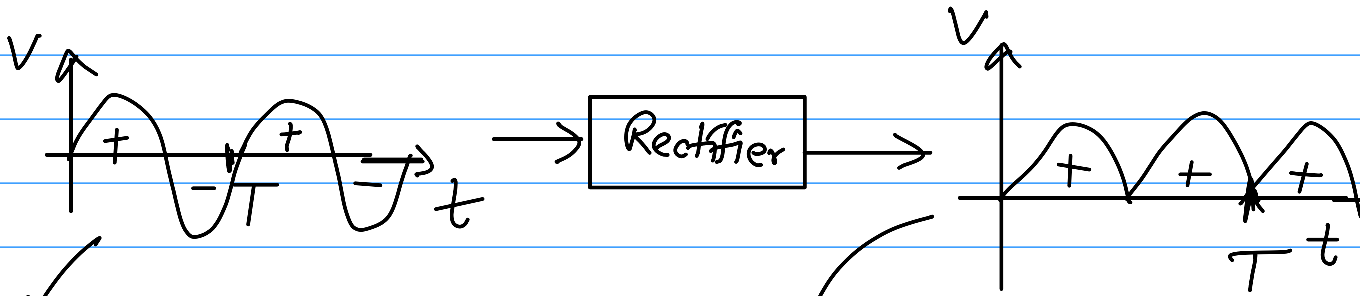
$V_A > V_\gamma$

Dynamic curve





→ Rectifiers –

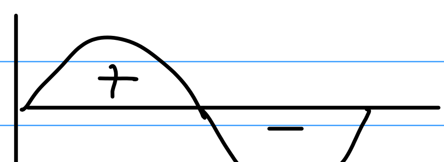


In ac signal
avg. vol. = 0

$$\boxed{V_{avg} = \frac{1}{T}\underbrace{\int_0^T V(t)\,dt}}$$

area under vol. curve

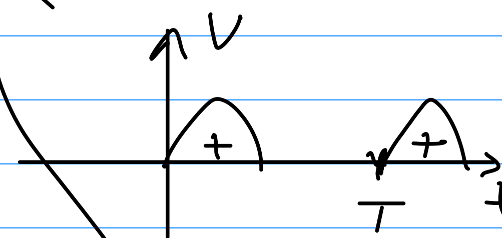
(+ve area + (−ve) area)



So, total area = 0

So, $\boxed{V_{avg} = 0}$

(or)



$V_{avg} = +ve$

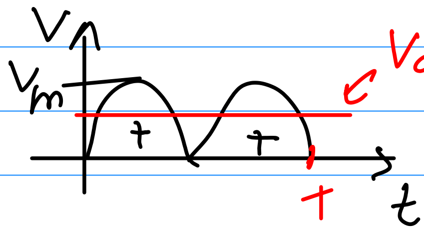
∵ +ve area + 0

or +ve area + (+ve) area

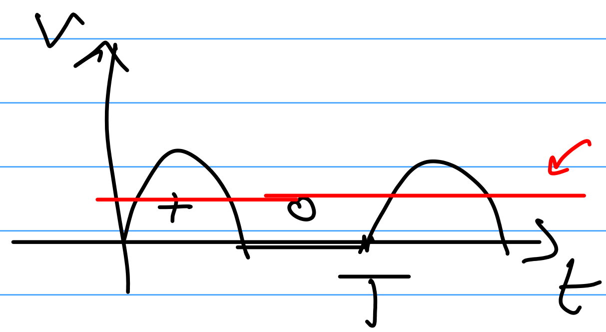
* So, Rectifier is used to get +ve avg vol. or current from a zero avg vol. or current signal (Symmetric ac)

* (Or) rectifier increases the avg vol. or current in a signal.

* Avg vol can also be called 'dc' vol.

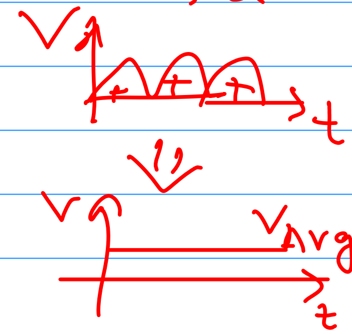


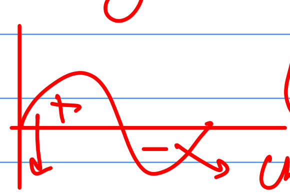
$V_{avg} = \frac{2V_m}{\pi}$ = DC vol.



$V_{Avg} = \frac{V_m}{\pi}$

* Avg vol. is that DC vol which if applied to a resistance will cause same amount of charge transfer as the original non constant signal



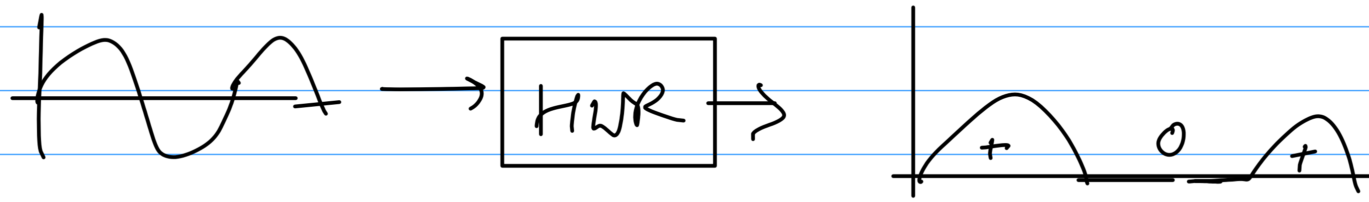


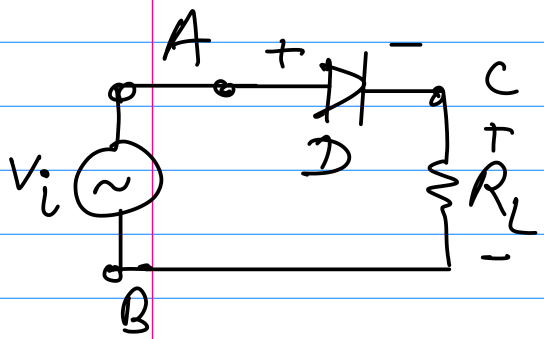
So total = 0

+ charge in one dir

charge Xfer in opp dir.

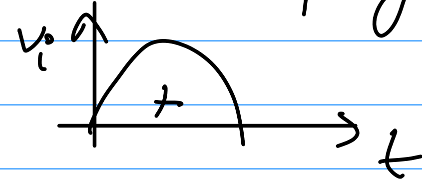
→ <u>Half wave Rectifier</u> (HWR) -





HWR

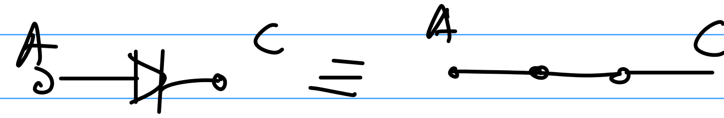
(i) for +ve half cycle of V_i



$V_A > V_B$

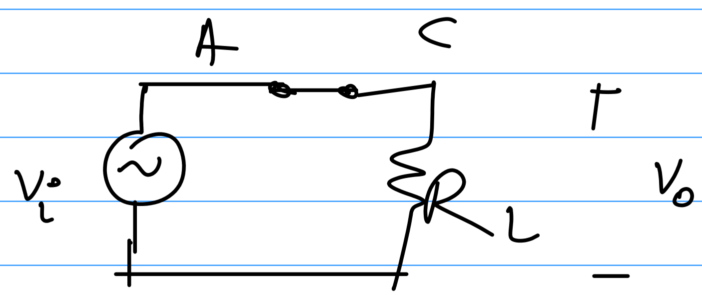
$V_A > V_C > V_B$

So, Diode D is F.B.



(assuming ideal diode)

So ckt



By KVL, $V_i = V_o$