



Subject:- Elements of Electronics
(EC-1500)

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NIT Patna



← Conductors - have large number of free e^- s

Insulator - have small number of free e^- s or no free e^- s

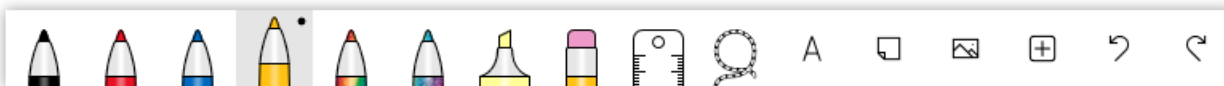
Conductors

metals

Insulators

wood, plastics

Semiconductor - have conductivity in between conductors & insulators.



Semiconductors → Intrinsic & Extrinsic



Pure form of
Semiconductor
material.

less conductivity

Impure S.C.
materials.

more Conductivity

Ex - Si, Ge, GaAs

Si₁₄ Ge₃₂

Si₁₄ → 2, 8, 4.

Ge₃₂ ⇒ 2, 8, 18, 4

Extrinsic Semiconductors.



Impurities

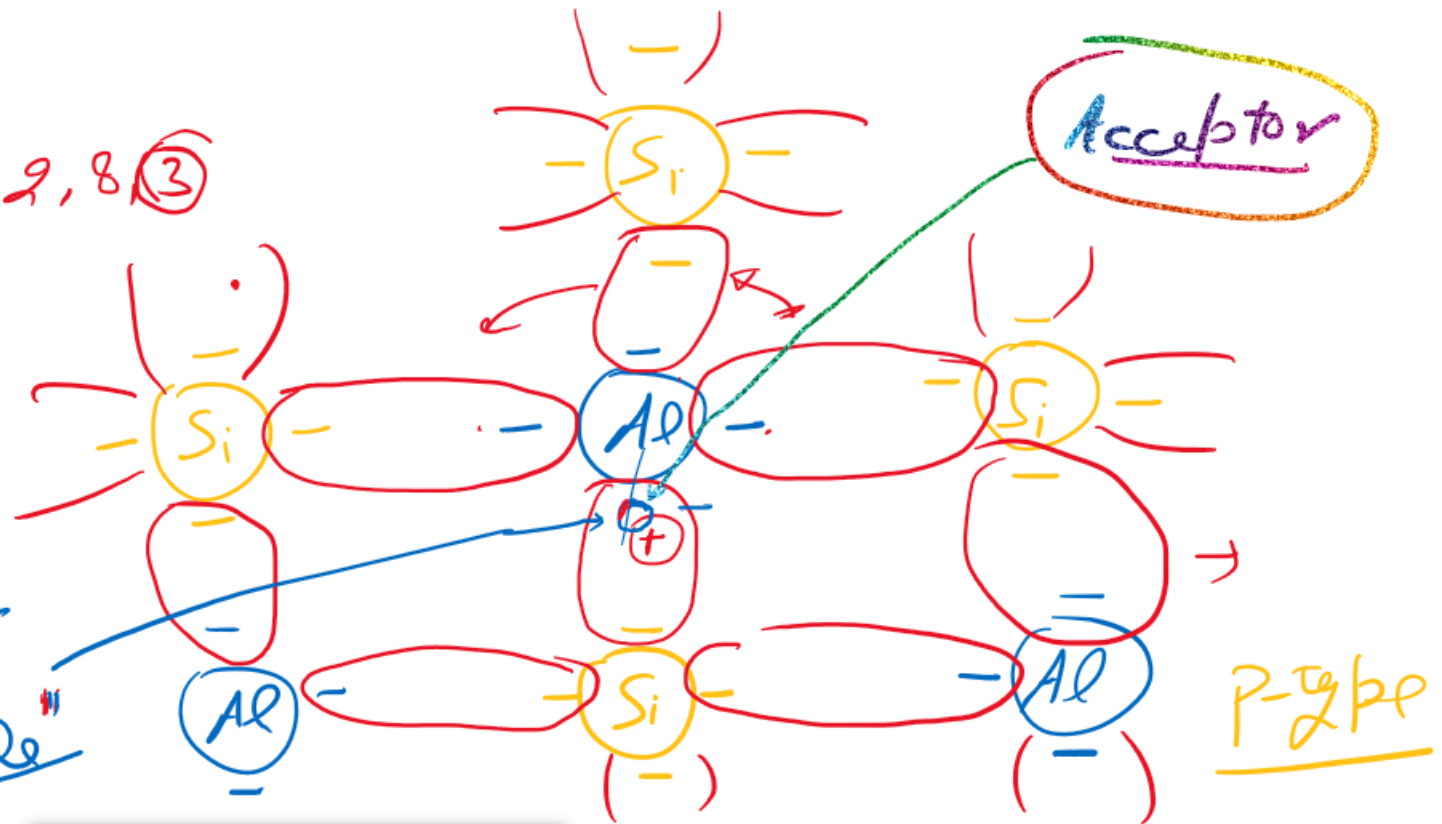
Trivalent materials $\rightarrow$ III - Grp $\rightarrow$ B, Al
 Pentavalent materials $\rightarrow$ V - Grp $\rightarrow$ Sb, P

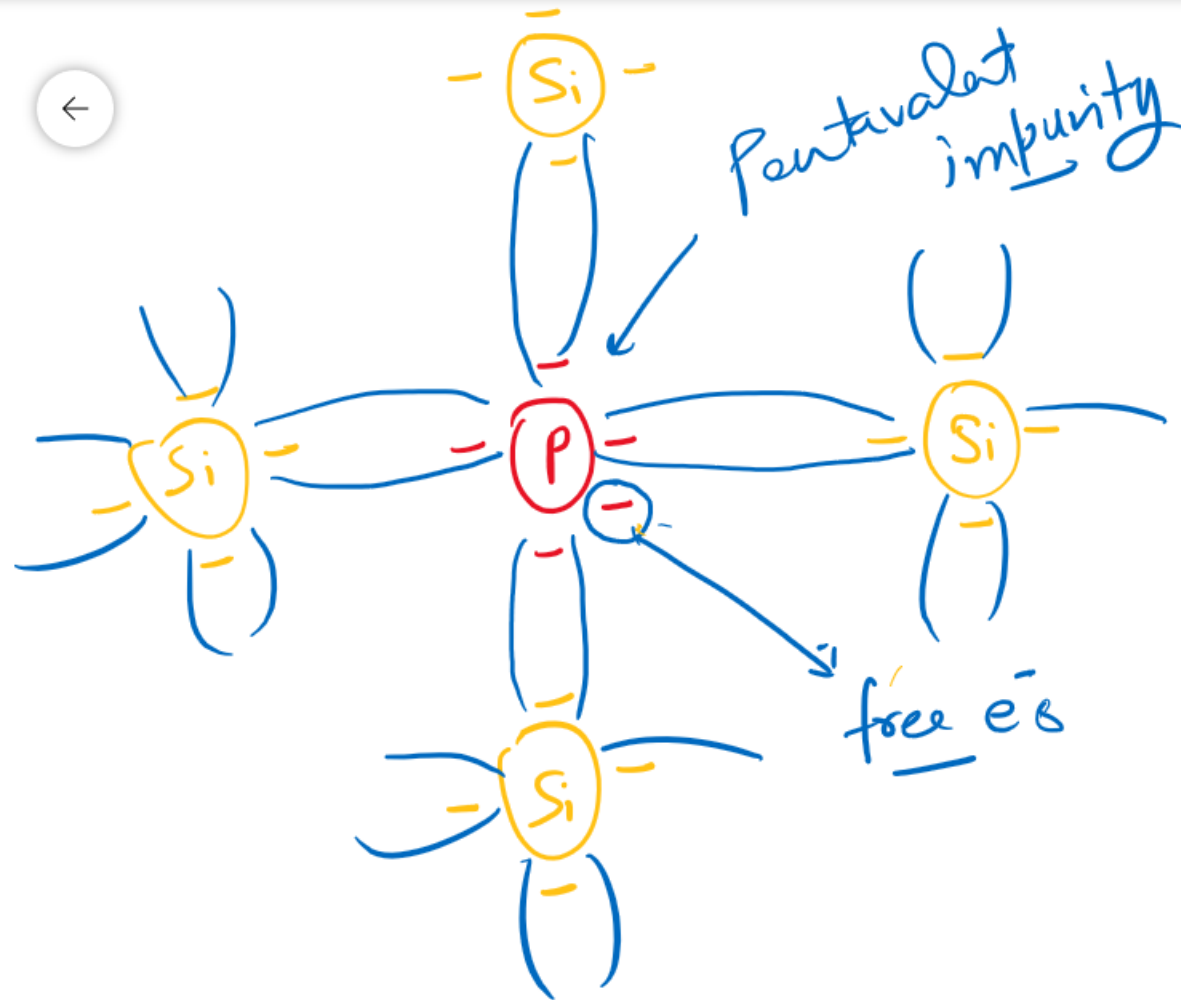
Increases Conductivity
 of Pure S.C

$Al_{13} \rightarrow 2, 8, \textcircled{3}$

* Semiconductors
 are having
 Covalent bonds

Deficiency of e^-
 "hole"





Tendency of Donating
its e^-

Donor

N-type of Extrinsic
material



P-Type Semiconductor → large number of "holes" → majority
less no. of e^- → minority

N-type material → large number of e^- → majority
less "holes" → minority

majority

Charge carrier

minority charge

carrier



Semiconductors

Intrinsic (Pure)
Si, Ge, GaAs

Extrinsic (Impure)

N-type

free (e^-) (Extra e^-)

formed by Pentavalent Impurity

Donor

e^- - majority c.c. holes - minority c.c.

P-type

free-holes

Deficiency of e^-

Trivalent imp.

Acceptor

holes - majority c.c.
 e^- - minority c.c.



Temperature coefficient of Resistance

Conductors - $T \uparrow \rightarrow R \uparrow \rightarrow \sigma \downarrow$
conductivity

Semiconductors - $T \uparrow \rightarrow e_s \uparrow \rightarrow R \downarrow \rightarrow \sigma \uparrow$

↳ negative temperature coefficient of Resistance.



Energy band diagram -



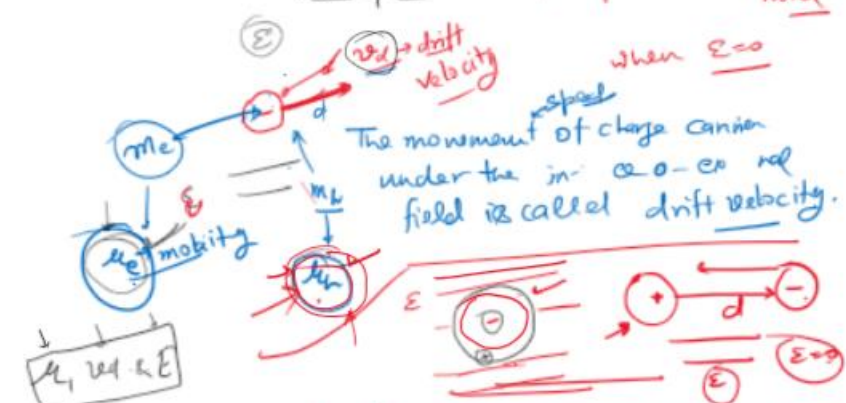
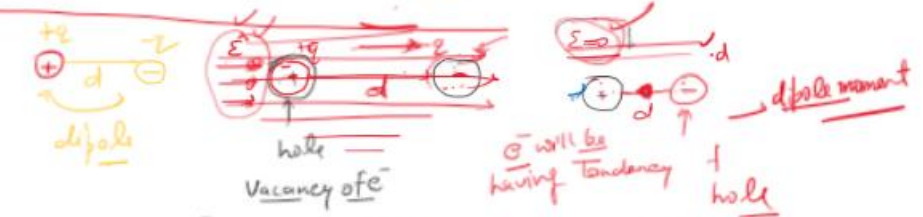
- ① Conductors $\rightarrow \frac{\sigma}{\epsilon} \approx \infty$, very large
 - ② Insulators $\rightarrow \frac{\sigma}{\epsilon} \approx 0$, very small.
- $\epsilon < \epsilon_s < \epsilon$

Conduction
Valence
Good

work function (ψ)

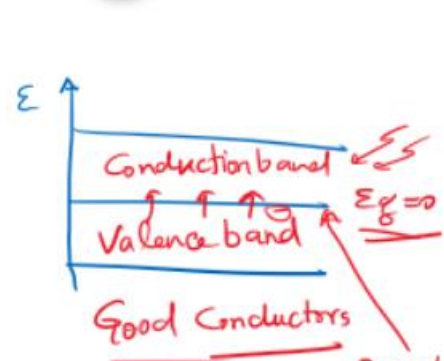
- ① $E > E_v$ but $E \leq E_g$ e^- moves from valence to conduction band
- ② $E > E_g$ e^- will move to conduction band

Dipole Dipole moment

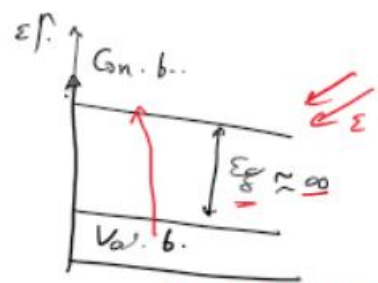


$$\mu = \frac{v_d}{E} \Rightarrow v_d = \mu E$$

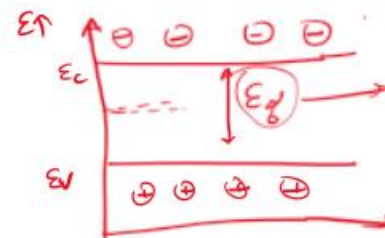
What is the meaning of hole's mobility?



Overlapping Energy bands.



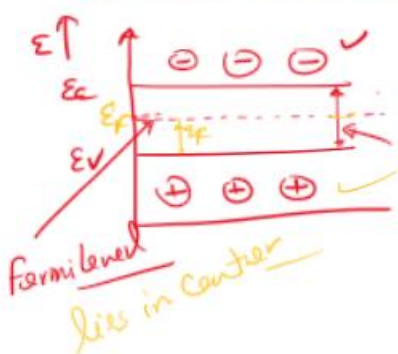
Perfect Dielectric



Can be changed using doping
 $\ominus \rightarrow$ Acceptor
 $\oplus \rightarrow$ Donor.

close to Conduction band

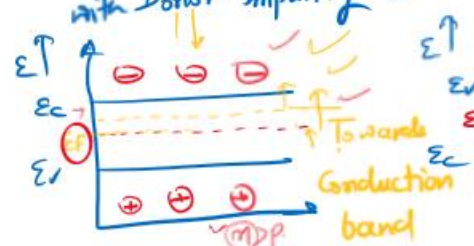
Intrinsic Semiconductors pure



no. of $e^- =$ no. of holes

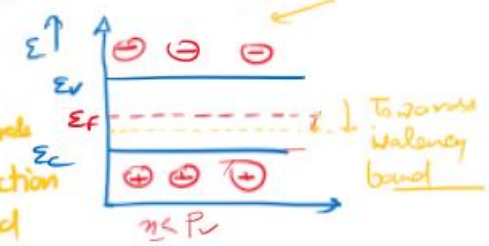
Fermi Gap

Extrinsic S.C. with Donor Impurity (s)



$n \approx p$

with Acceptor Im (s)

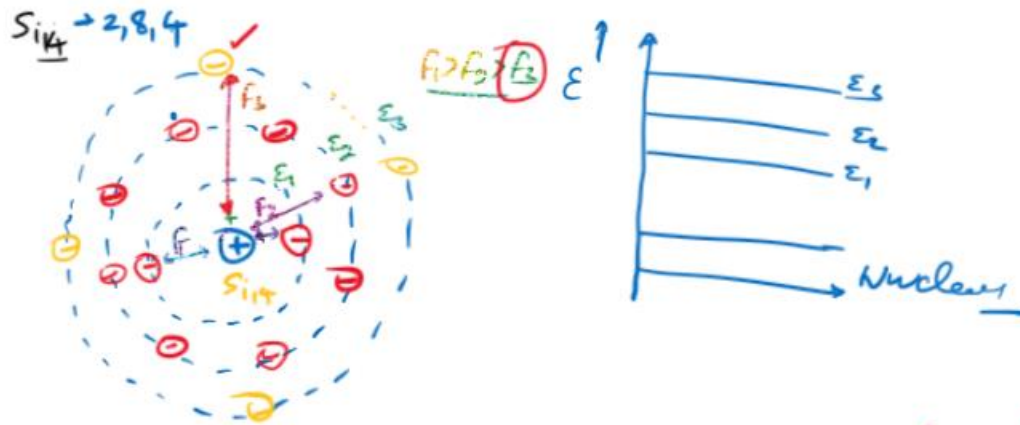


$n \ll p$



Tendency
towards

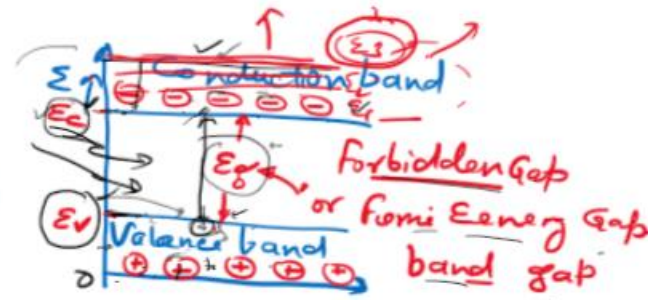
Fermi Energy / Fermi level -



① Conductors

② Insulators/Dielectrics

③ Semi conductors.



Work function (\$\psi\$) \$\rightarrow\$

$\epsilon \rightarrow e^-$

$$E_g = E_c - E_v \rightarrow \text{Fermi Energy.}$$

$\epsilon > E_g \rightarrow$ To jump in conduction band

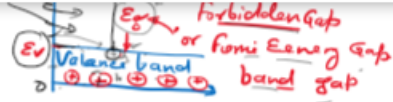
$\epsilon < E_g \rightarrow e^-$ will not move to G.B.

$\epsilon > E_c \rightarrow e^-$ will leave the surface

$\epsilon \uparrow$ Conductors

Semi conductors

- ① Insulators/Dielectrics
- ② Semiconductors



Work function (ϕ) $\rightarrow$

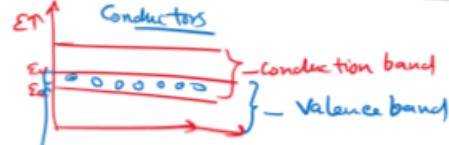
$$E \rightarrow e \uparrow$$

$$E_g = E_c - E_v \rightarrow \text{Fermi Energy}$$

$E > E_g \rightarrow$ To jump in conduction band

$E < E_g \rightarrow e^-$ will not move to C.B.

$E > E_s \rightarrow e^-$ will leave the surface $\leftarrow$



overlapping bands, $E_g = 0$

Conductivity, $\sigma \approx \infty$, or very high

$$R \approx 0$$



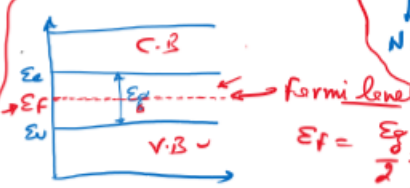
$$E_g > 5 \text{ eV, or } \infty$$

$$\sigma \approx 0$$

$$R \approx \infty$$

Semiconductors

Intrinsic (Pure)



no. of $e^- (n) = \text{no. of holes } (p)$

Pure Semiconductors

Extrinsic (Impure)

(5) N (Donors) (e^-) (3) P (Acceptors) (holes)

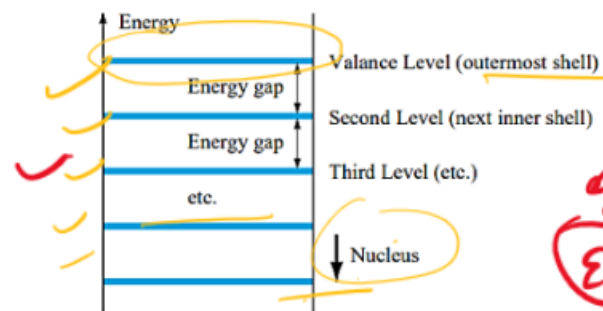


E_g can be changed by amount of dopant at time of manufacturing

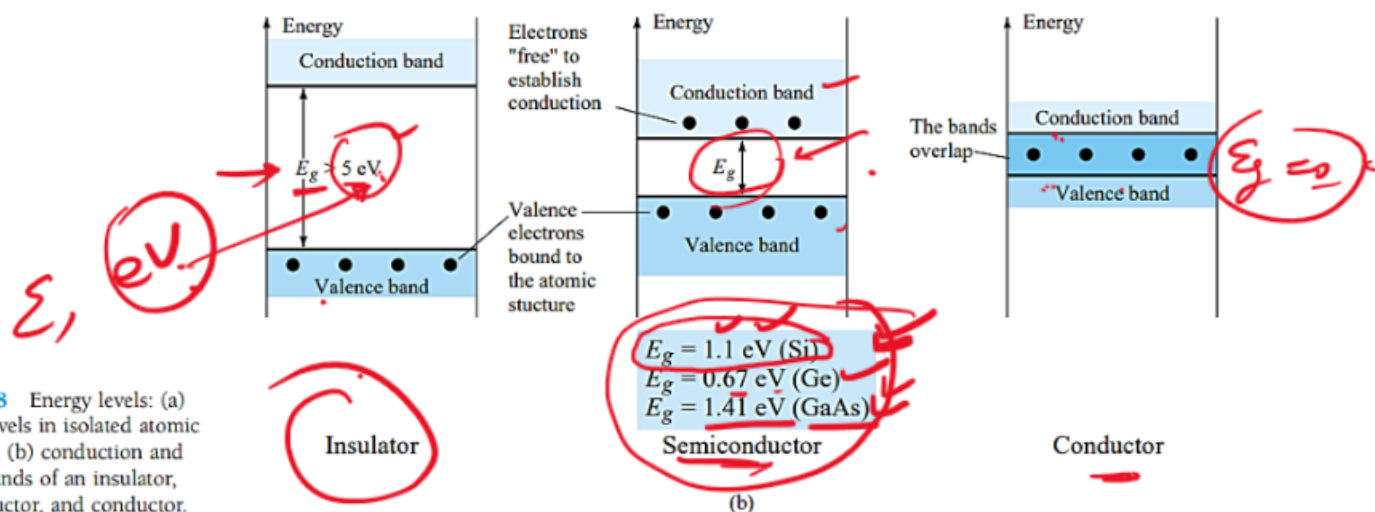
Study - Graphene



mi level



(a)



Currents

Conductors

Conduction Current

$$J_c = \sigma E$$

Current density $\rightarrow$ J_c
 $\uparrow$ σ Conductivity
 $\uparrow$ E Electric field

$$J_c = \frac{I}{A}$$

$\leftarrow$ Current I
 $\leftarrow$ Area A

Insulator
Convection Current

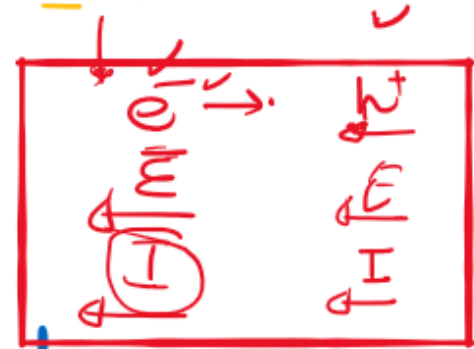
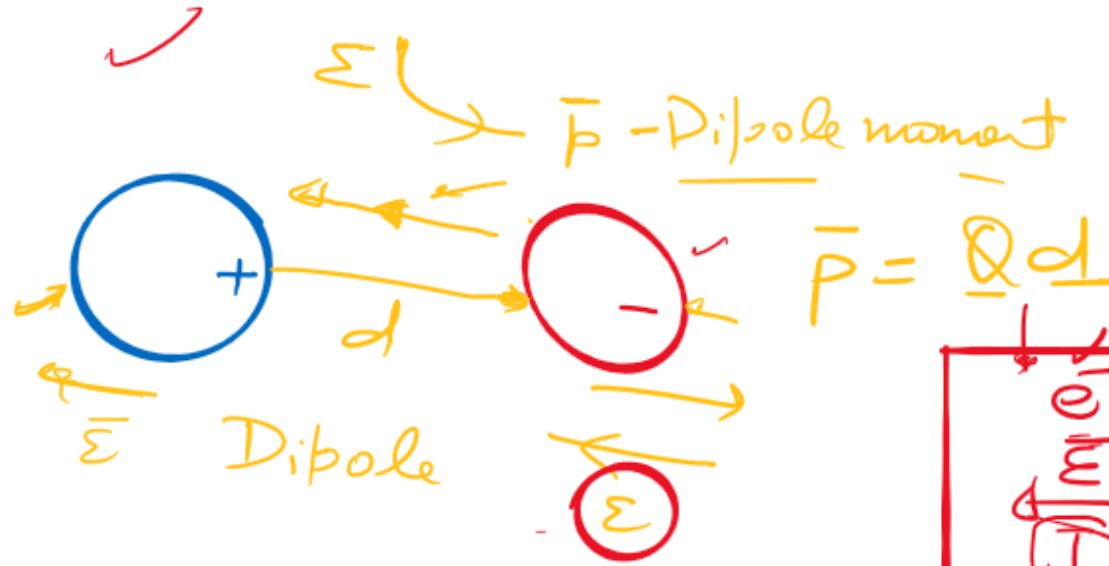
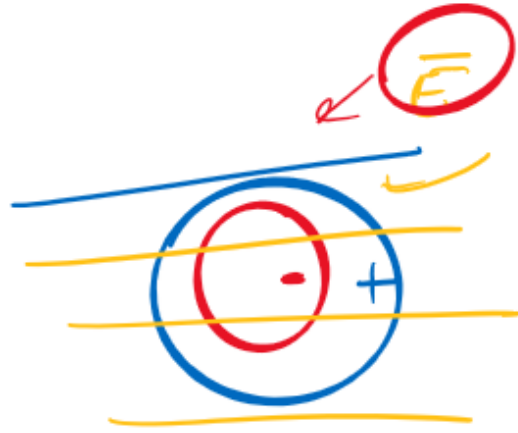
Semiconductors

① Drift current

② Diffusion current

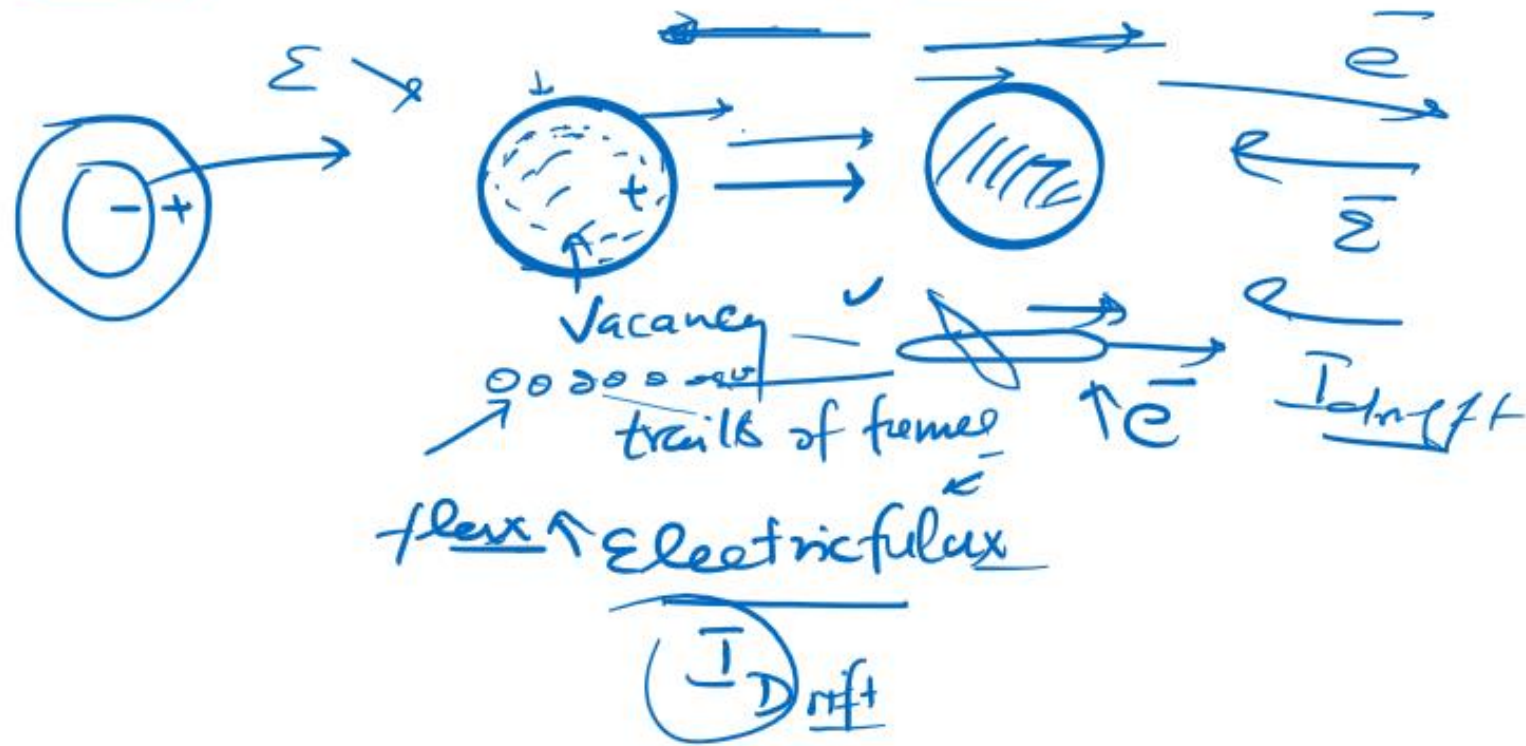
Q. What is convection?

② ① Drift Current →



- ① keep any material in the electric field. ✓
- ② This will create dipoles or there will be a motion of charge carriers
- ③ The motion of charge carriers provides a current. "Drift current"

③ ① What is hole? → Difficiency of e^-



Drift Current - ① Holes.

④



① $+Q \rightarrow$ charge in the volume

② $\rho \rightarrow$ charge density = Q/V

③ holes are moving with a uniform velocity
 $v_{dp} \rightarrow$ (drift velocity of holes).

no. of holes $\Rightarrow p$
 " " $e^- \Rightarrow n$

$$\textcircled{4} \quad J_{p|drift} = \rho v_{dp} \quad \textcircled{1}$$

$$\rightarrow \rho = e p$$

$\uparrow$ electronic charge
 $\downarrow$ no. of holes

$$J_{p|drift} = (ep) v_{dp} \quad \textcircled{2}$$

⑤ $\vec{v}_d \rightarrow$ Drift velocity

$\mu_p \rightarrow$ mobility

$$v_d = \mu_p \cdot E$$

$$J_{p|drift} = (ep) \cdot \mu_p E \quad \text{--- ③}$$

⑥ for $\bar{e}$ $\rightarrow$

$$J_{n|drift} = (-en) v_{dn} \quad \text{--- ④}$$

$$\vec{v}_d \propto \vec{E}$$

$$v_d = \mu E$$

$\uparrow$ mobility

$$\begin{array}{c} m, p, n \\ \downarrow \\ e_{p,n} \frac{v_d}{E} \end{array}$$

$$J_{ndrift} = (-en) v_{dn} \rightarrow v_{dn} = \underline{-\mu_n E}$$

$$J_{ndrift} = (-en)(-\mu_n E)$$

$$J_{ndrift} = (en)\mu_n E \quad (5)$$

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

$\vec{E} \rightarrow$
 $\leftarrow \vec{v}_{dn}$
 e^-

Total drift current -

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

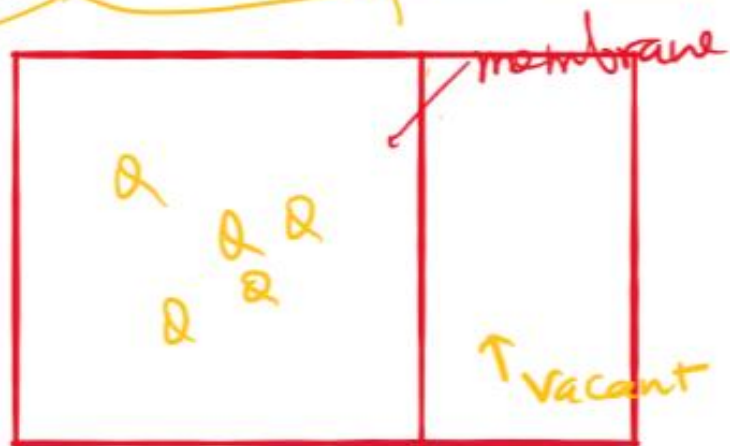
$$J_{drift} = J_{pdrift} + J_{ndrift} = (ep)\mu_p E + (en)\mu_n E$$

$$J_{drift} = e(p\mu_p + n\mu_n)E \quad (6)$$

$$J_c = \sigma E$$

	μ_n (cm ² /V-s)	$\frac{\text{room temp}}{T}$	μ_p (cm ² /V-s)
① Silicon (Si)	1350		480
② GaAs ✓	8500 ✓		400
③ Ge ✓	3900		<u>1900</u> ✓

② Diffusion Current



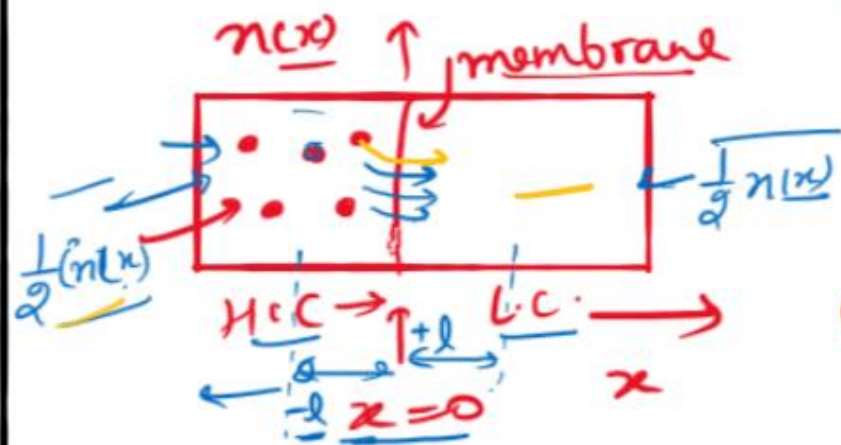
The current that flows due to movement of charge from higher to lower concentration.

↑ left side has higher concentration of charge

② Right side has lower "

③ Charge is moving from higher to lower concentration.

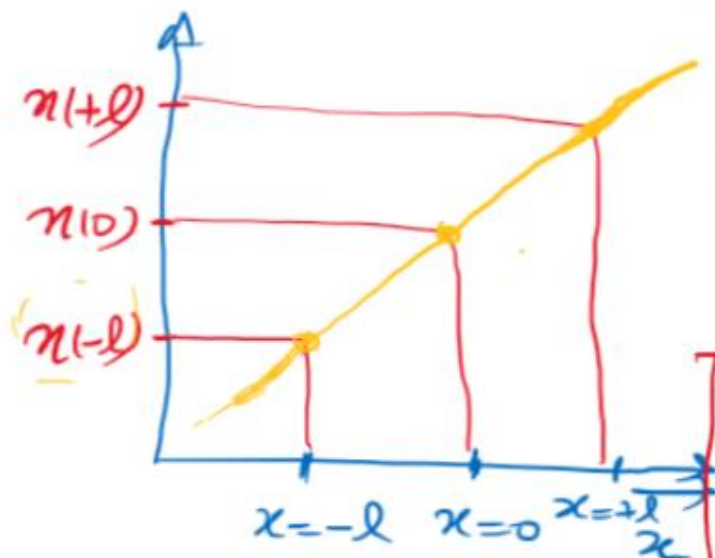
③ Diffusion current -



① There is flow of charge carriers from higher to lower concentration side.

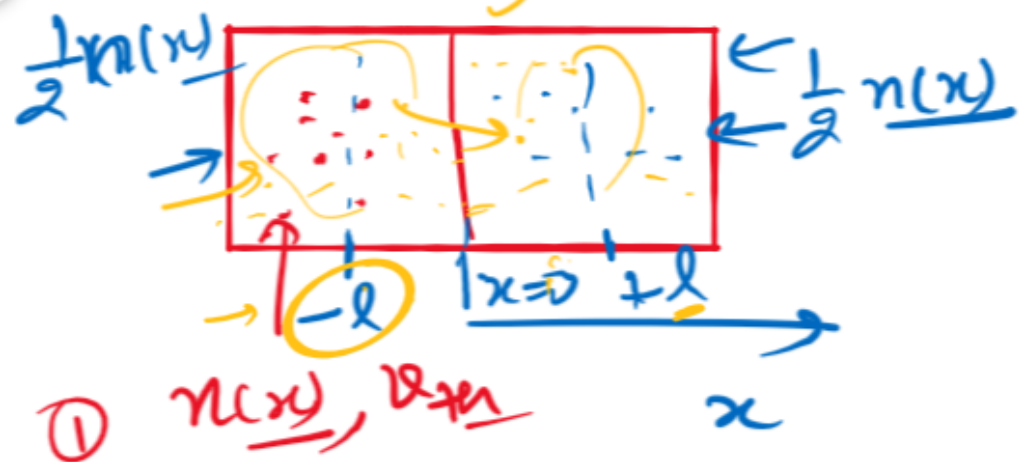
② The motion of charge particles generates a current which is called "Diffusion current".

① $\overline{n(x)}$, $\overline{v_{th}}$



② net flow of charge f_n

$$f_n = \frac{1}{2} n(-l) v_{th} - \frac{1}{2} n(+l) v_{th} \quad \text{--- (1)}$$



no flow of charge

$$F_n = \left(\frac{1}{2} n(-l) v_m - \frac{1}{2} n(l) v_m \right)$$

$$F_n = \frac{1}{2} [n(-l) - n(l)] v_m$$

→ ① membrane is not broken

② membrane is broken

→ (i) flow of charge from H.C. to L.C.

(ii) After some time charge will come under steady state or (uniformly distrib.)

using one dimensional Taylor's series expansion.

$$\eta(l) = \eta(0) + L \frac{d\eta}{dx} + \frac{L^2}{2} \frac{d^2\eta}{dx^2} + \dots$$

$$\eta(-l) = \eta(0) - L \frac{d\eta}{dx} + \frac{L^2}{2} \frac{d^2\eta}{dx^2} - \dots$$

Ignore the higher order terms -

$$f_n = \frac{1}{2} \psi_n \left[\left\{ \eta(0) - L \frac{d\eta}{dx} \right\} - \left\{ \eta(0) + L \frac{d\eta}{dx} \right\} \right]$$

$$f_n = \frac{1}{2} \psi_n \left[-2L \frac{d\eta}{dx} \right] = -L \psi_n \frac{d\eta}{dx}$$

$$\boxed{f_n = -L \psi_n \frac{d\eta}{dx}} \quad \text{--- (3)}$$

① For e's -

$$F_n = - \underbrace{124n}_{D_n} \frac{dn}{dx} \quad \text{--- (3)}$$

$D_n \rightarrow$ diffusion coefficient

$n \rightarrow$ no. of e's

$$J_{n|diff} = \underbrace{e}_{\substack{\leftarrow \\ I}} D_n \frac{dn}{dx} \quad \text{--- (4)}$$

② For holes -

$$F_p = - \underbrace{124p}_{D_p} \frac{dp}{dx} \Rightarrow p \Rightarrow \text{no. of holes.}$$

$D_p \rightarrow$ Diffusion coeff.

$$J_{p|diff} = -e D_p \frac{dp}{dx} \quad \text{--- (5)}$$

⑤ Total diffusion current -

$$J_{diff} = J_{pdiff} + J_{ndiff}$$

$$J_{diff} = -e D_p \frac{dp}{dx} + e D_n \frac{dn}{dx} \quad \text{--- (6)}$$

Total current in semiconductor $\rightarrow$

$$J = J_{drift} + J_{diff}$$

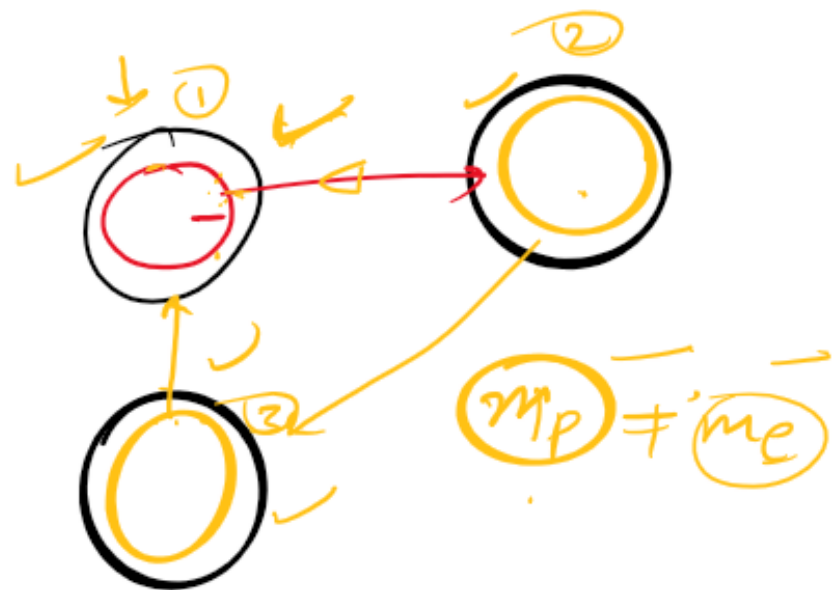
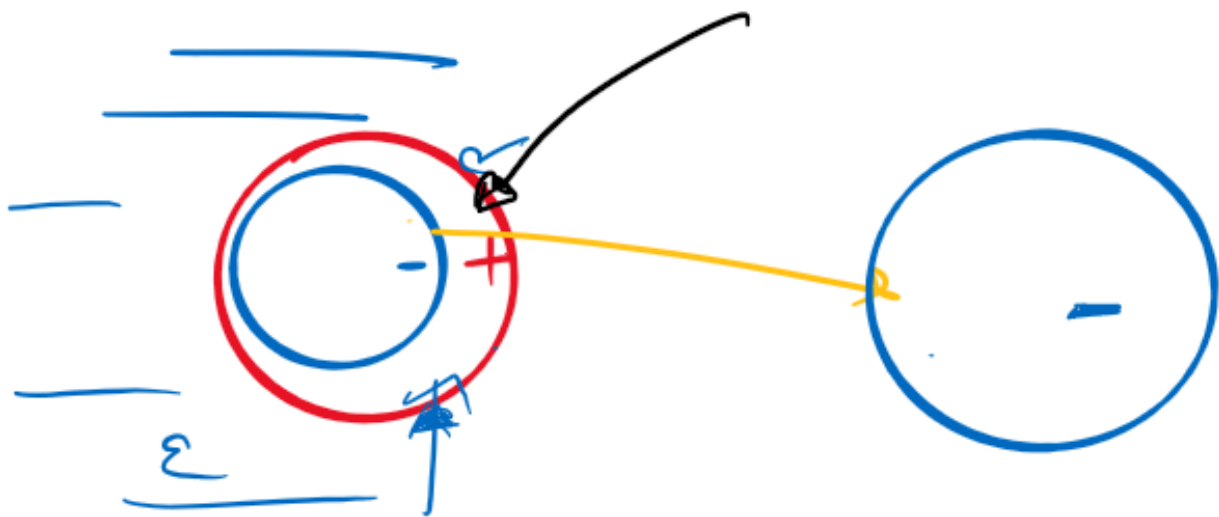
$$\boxed{D_p = \frac{2}{3} \mu_p}$$
$$\boxed{D_n = \frac{2}{3} \mu_n}$$

$$J = e(n\mu_n + p\mu_p)\bar{E} + e D_n \frac{dn}{dx} - e D_p \frac{dp}{dx} \quad \text{--- (7)}$$

Hole mobility

$$v_d \propto E \Rightarrow$$

$$v_d = \underline{\mu} E$$



⑬ Fermi-Dirac distribution function -

- ① particles are indistinguishable.
- ② one particle can only be permitted in one energy state.

Ex - E_s in any crystal, semiconductors.

Any distribution function defines the probability of finding particles in different energy states.

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

at $T=0\text{K}$, $E > E_F$

$$f(E) = \frac{1}{1 + \exp\left(\frac{+}{0}\right)} = \frac{1}{1 + \exp(+\infty)}$$

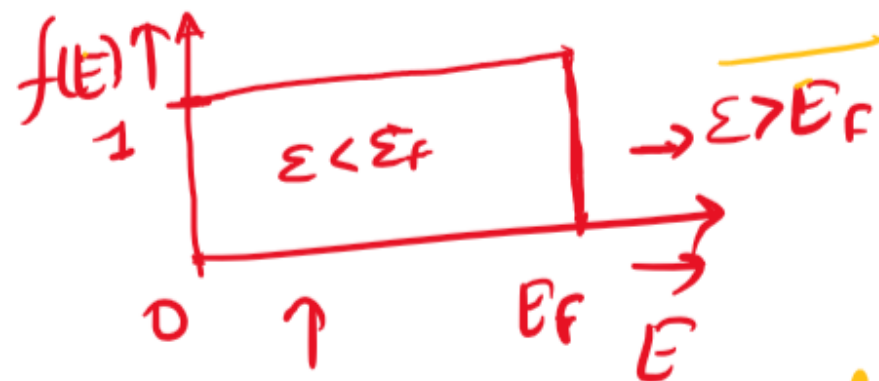
$$f(E) \approx 0$$

alt) $T=0\text{K}$, $E < E_F \Rightarrow$

$$f(E) = \frac{1}{1 + \exp(-\infty)} = 1$$

③ $\tilde{E} = \tilde{E}_F$ $f(E) = \frac{1}{2}$ ✓

$T > 0\text{K}$



→ There is high probability of finding e^- s in the lower energy state.

no. of e^- in conduction band -

$$n_0 = \int_{E_c}^{E_{cv}} \underbrace{g_c(E)} \cdot \underbrace{f(E)} \cdot dE$$

$$\underline{g_c(E)} = \frac{4\pi (2m_n^*)^{3/2}}{h^3} \sqrt{E - E_c} \leftarrow \text{density state function.}$$

$$n_0 = \underbrace{N_c}_{\uparrow} \exp \left[- \frac{(E_c - E_F)}{kT} \right]$$

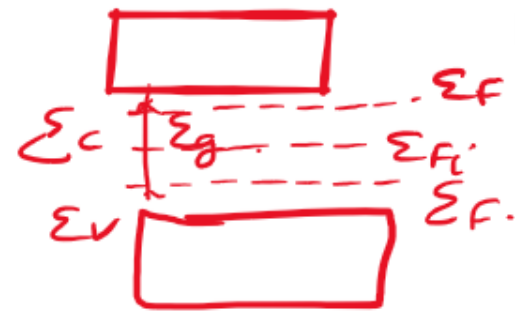
effective density function.

$$N_c = 2.5 \times 10^{19} \text{ /cm}^3$$

at $T = 300\text{K}$

no. of holes in valence band -

$$p_0 = N_v \exp \left[- \frac{(E_F - E_v)}{kT} \right]$$



$N_v \approx 10^{19} / \text{cm}^3$ at $T = 300 \text{ K}$

for pure semiconductors -

$$n_0 = n_i = N_c \exp \left[- \frac{(E_c - E_{Fi})}{kT} \right]$$

$$p_0 = p_i = n_i = N_v \exp \left[- \frac{(E_{Fi} - E_v)}{kT} \right]$$

$$p_0 \cdot n_0 = n_i^2 = N_c N_v \exp \left[- \frac{(E_c - E_v)}{kT} \right] = N_c N_v \exp \left[- \frac{E_g}{kT} \right]$$

Built-in barrier potential →

$$V_{bi} = |\phi_{fn}| + |\phi_{fp}| \quad \text{--- (1)}$$

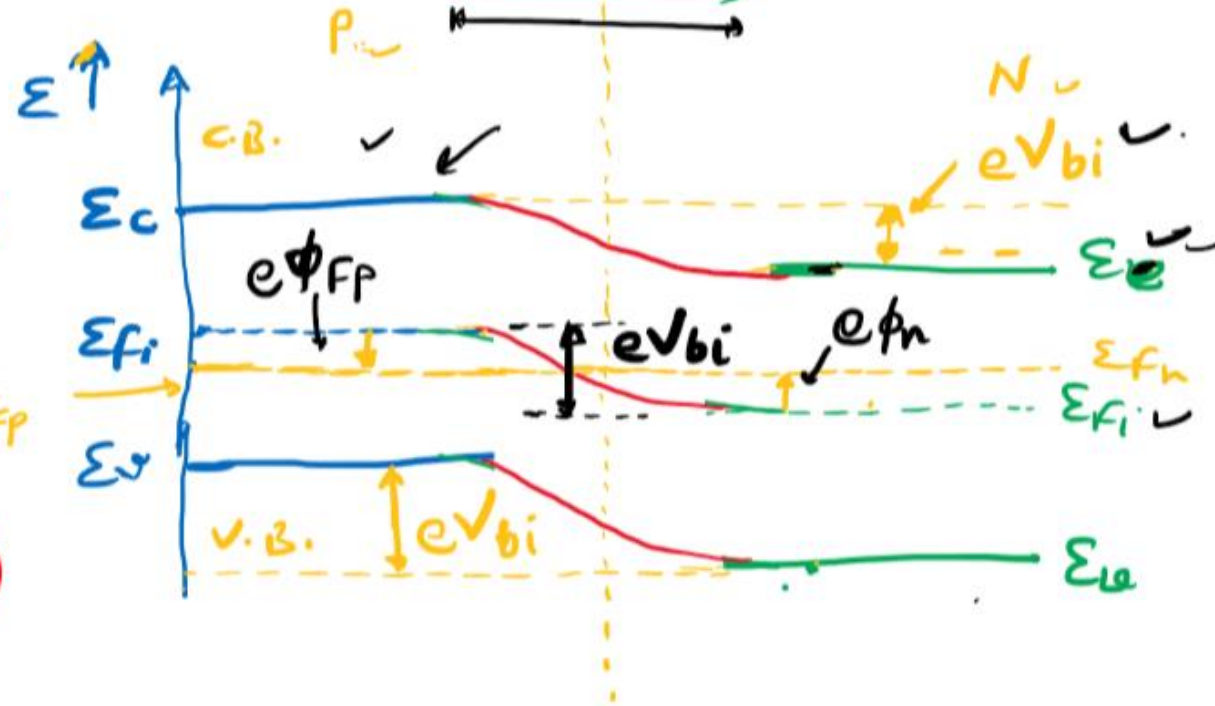
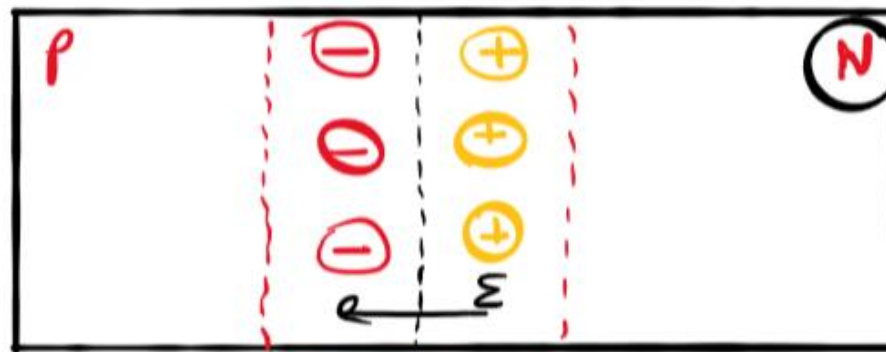
Concentration of $\bar{e}$ s in the conduction band (in n-region) →

$$n_0 = N_c \exp \left[\frac{-(E_c - E_f)}{kT} \right] \quad \text{--- (2)}$$

It can also be written as -

$$n_0 = n_i \exp \left[\frac{E_f - E_{fi}}{kT} \right] \quad \text{--- (3)}$$

$$e\phi_{fn} = E_{fi} - E_{fn} \quad \text{--- (4)}$$



$$\Rightarrow \underline{E_{fn} = E_{fp}}$$

$$n_d = \frac{n_0}{n_i} = n_i \exp \left[-\frac{(e \phi_{fn})}{kT} \right] \quad \text{--- (5)}$$

$$\boxed{E_{fp} = E_{fn} = E_f}$$



taking natural antilog at both sides -

$$\phi_{fn} = -\frac{kT}{e} \ln \left(\frac{N_d}{n_i} \right) \quad \text{--- (6)}$$

donor concentration = n_d

acceptor concentration

for p-region -

the concentration of holes $\rightarrow$

$$p_0 = n_g = n_i \exp \left[\frac{E_{fi} - E_{fp}}{kT} \right] \quad \text{--- (7)}$$

$$e \phi_{fp} = E_{fi} - E_{fp} \quad \text{--- (8)}$$

$$n_g = n_i \exp \left[\frac{e \phi_{fp}}{kT} \right] \quad \text{--- (8)} \Rightarrow \quad \phi_{fp} = +\frac{kT}{e} \ln \left(\frac{n_g}{n_i} \right) \quad \text{--- (9)}$$

$$V_{bi} = \frac{kT}{e} \ln \left[\frac{N_a N_d}{n_i^2} \right]$$

$$V_{bi} = V_T \ln \left[\frac{N_a N_d}{n_i^2} \right]$$

$$V_T = \frac{kT}{e}$$

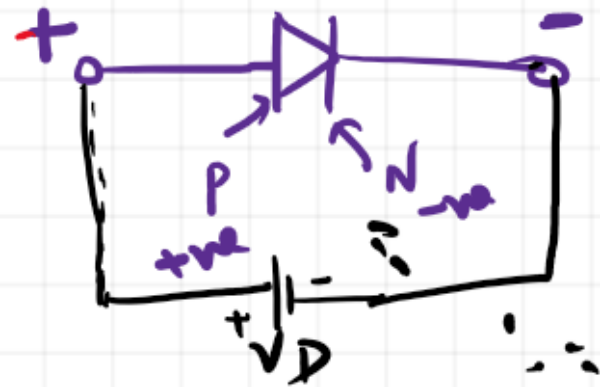


Thermal voltage

at $T = 300 \text{ K} \rightarrow$

$$\underline{\underline{V_T = 26 \text{ mV}}}$$

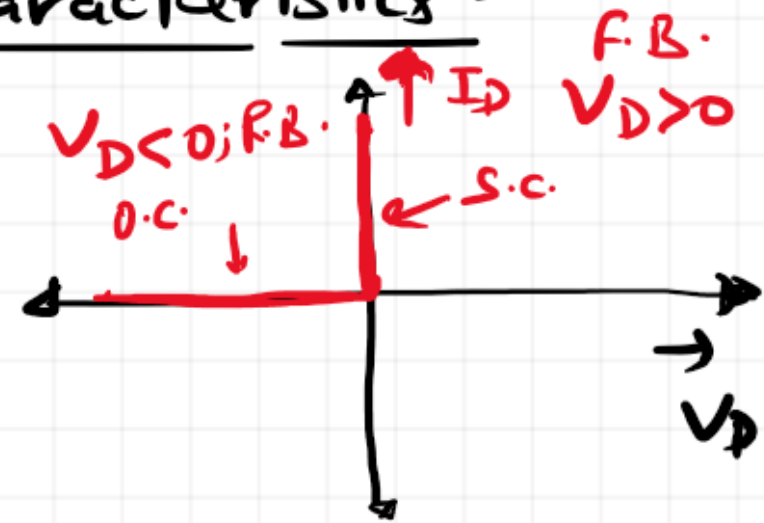
Ideal PN-Junction diode -



① forward bias - (F.B.) -

S.E.
 $R = 0 \Omega \Rightarrow I = \frac{V}{R} = \infty \text{ Amp.}$

Characteristics -

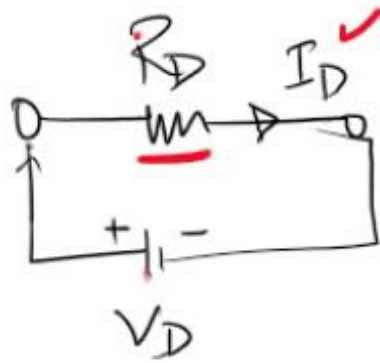


② Reverse bias - (R.B.) -

O.C.
 $R = \infty \Omega \Rightarrow I = 0 \text{ Amp}$

Ideal PN-junction diode acts as a perfect 'switch'

Practical PN-Junction diode -

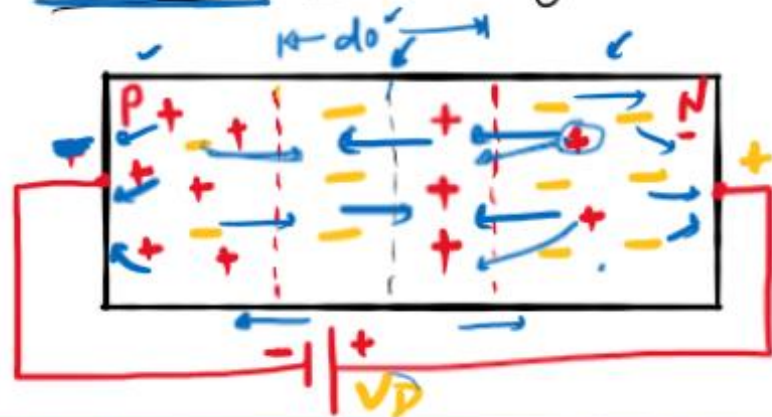


$$V_f = I_D \cdot R_D$$

Knee Voltage or threshold Voltage
or cut-in voltage.

→ minimum value of the voltage required after which diode starts providing current.

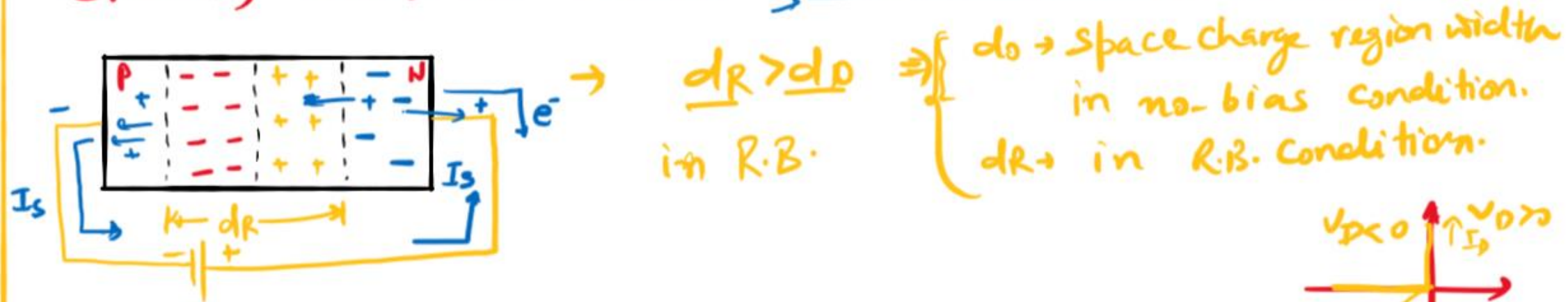
① Reverse biasing →



Biasing → way of application of power supply to any device.

→ In reverse biasing, minority Charge carriers are crossing the junction due to applied external voltage

→ Current is generated by flow of minority charge Carriers, which is called reverse saturation current

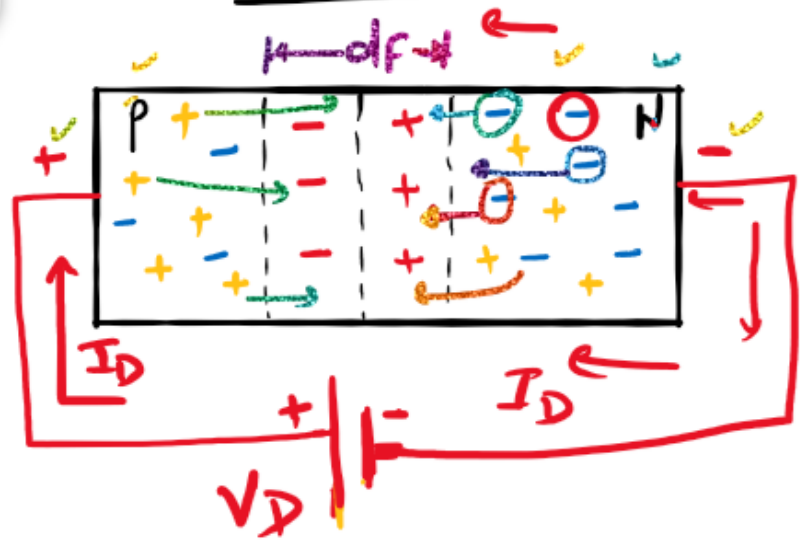


$I_S \rightarrow$ Reverse saturation current.

→ The order of I_S is "micro Amp" →

for some Si-Diodes → "nano Amp"

Forward biasing →



① In F.B., majority carriers cross the junction.

② This generates a current called diode current, I_D

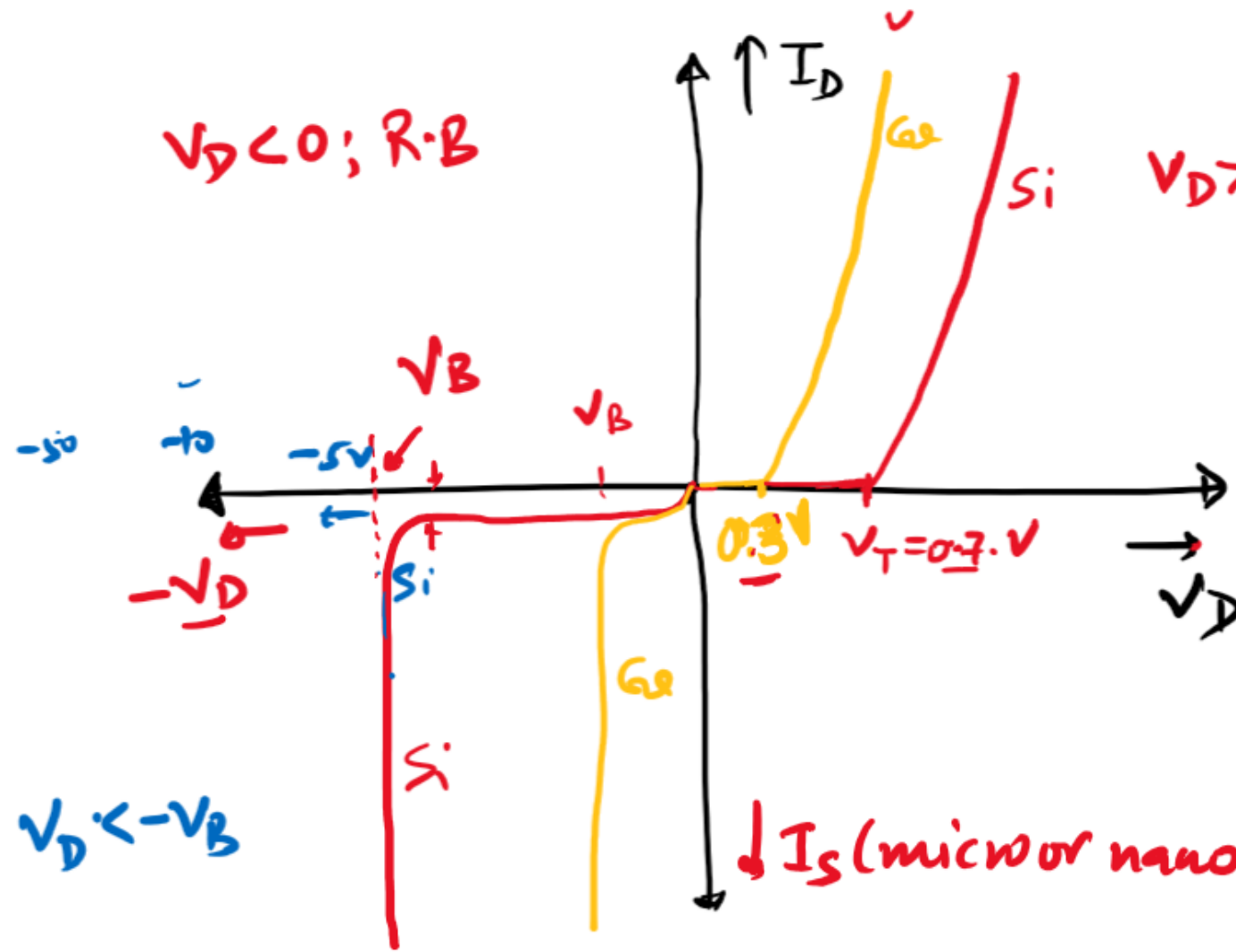
③ In F.B., $df < do$

$$\underline{df < do < dR}$$

$\left\{ \begin{array}{l} df \rightarrow \text{width of space charge} \\ \text{region in F.B.} \end{array} \right.$

Diode characteristics -

$$V_T = \begin{cases} \text{Si} \rightarrow 0.7V \\ \text{Ge} \rightarrow 0.3V \end{cases}$$



$V_B \rightarrow$ Breakdown Voltage.

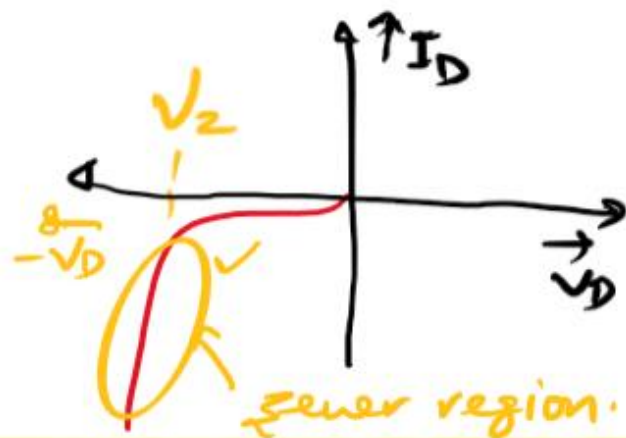
This is the -ve voltage applied on diode at which large no. of minority carriers start crossing the junction abruptly.

Diode Breakdown -

- ① Zener breakdown
- ② Avalanche breakdown.

① Zener breakdown -

→ At low value of reverse voltage, heavy electric field is created ~~across~~ the junction. This causes the flow of large no. of minority carriers and breakdown occurs, which is called Zener breakdown.



In breakdown, large no. of minority carriers flow and cross the junction that provides heavy reverse saturation current.

→ Zener diode works on the phenomena of Zener breakdown.

② Avalanche breakdown -

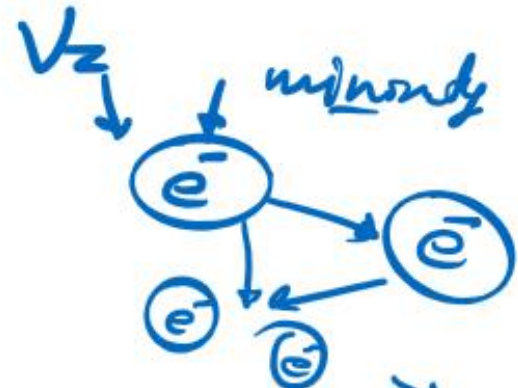
→ A large value of reverse voltage, the speed of minority carriers increases.

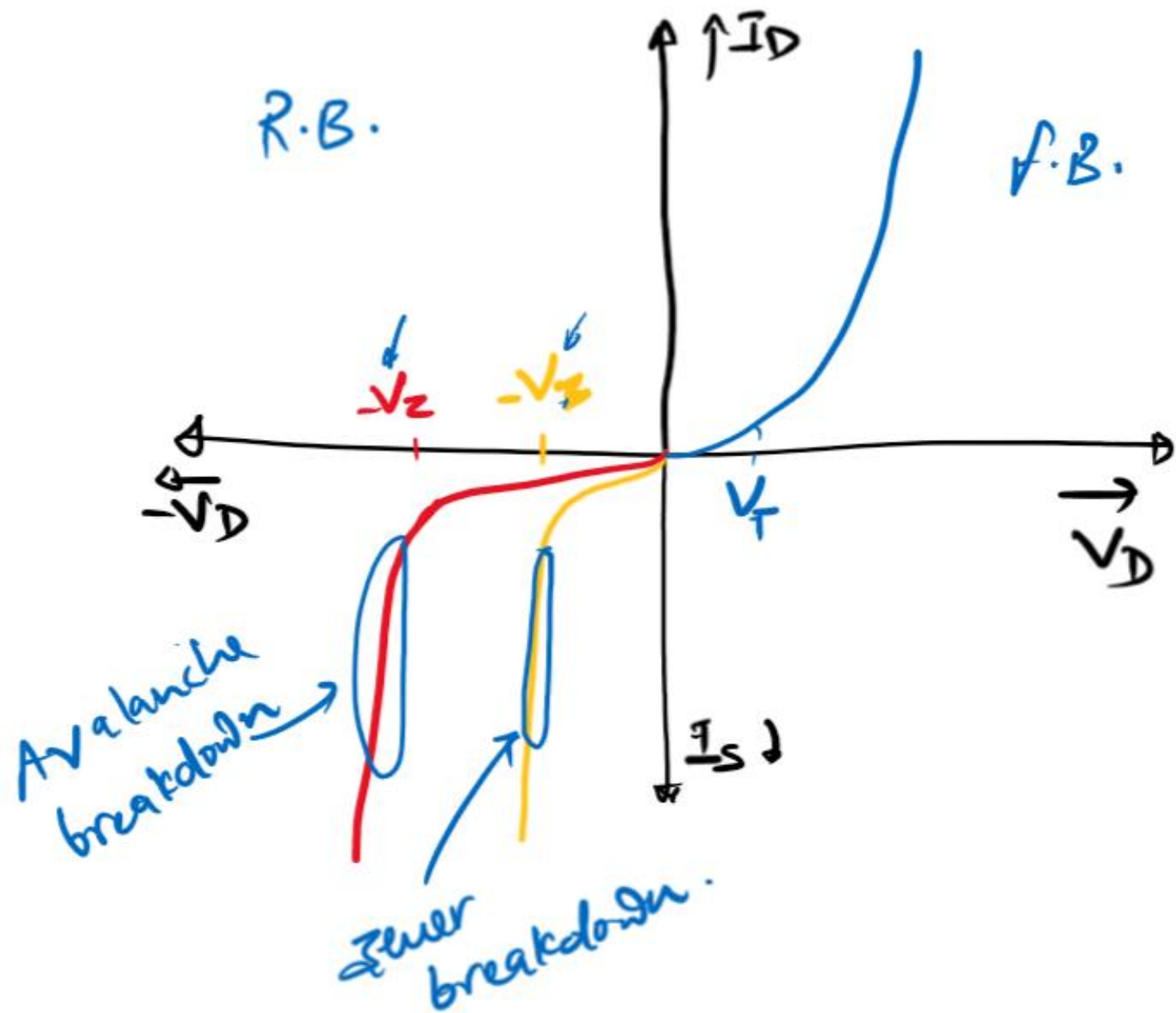
→ They collide with other particles and e^- s are knocked out by breaking of bonds.

→ The knocking out of e^- s after collision is known as "Impact Ionization"

→ Each time the no. of free particles is getting doubled, this is called "Avalanche multiplication"

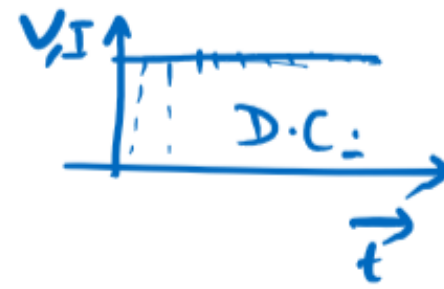
→ The phenomena of avalanche multiplication causes the flow of large minority carriers across the junction. This is called Avalanche breakdown.





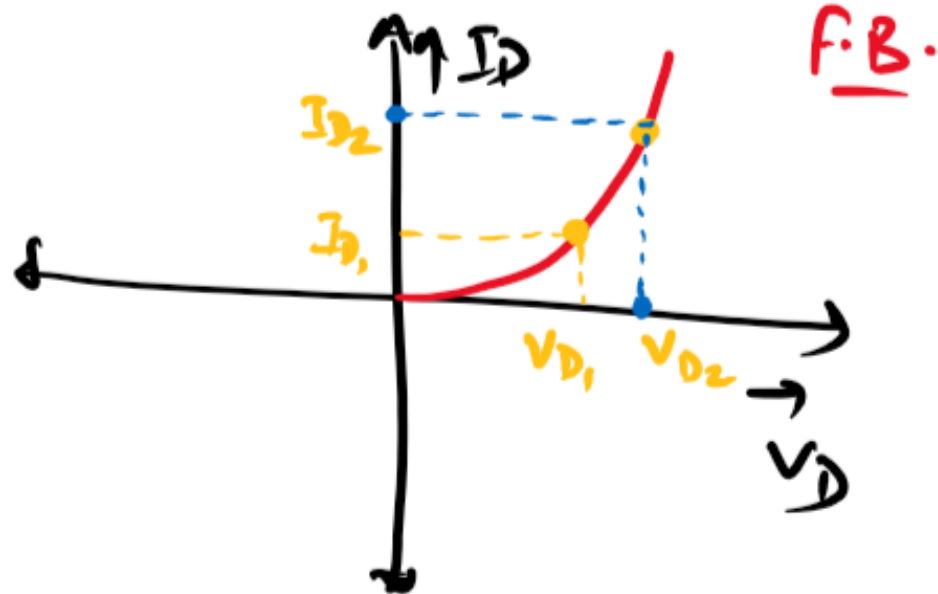
Diode Resistance →

- ① Static or D.C. resistance.
- ② Dynamic or A.C. resistance
- ③ Average A.C. resistance.



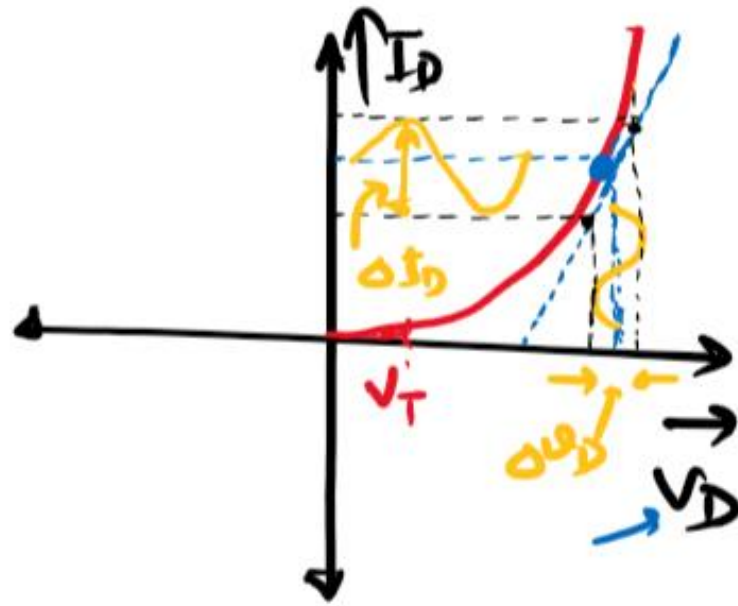
① D.C. resistance →

$$R_D = \frac{V_D}{I_D} \Rightarrow \text{Point resistance.}$$



⇒ R_D is non-varying
or it is a constant,
at each point.

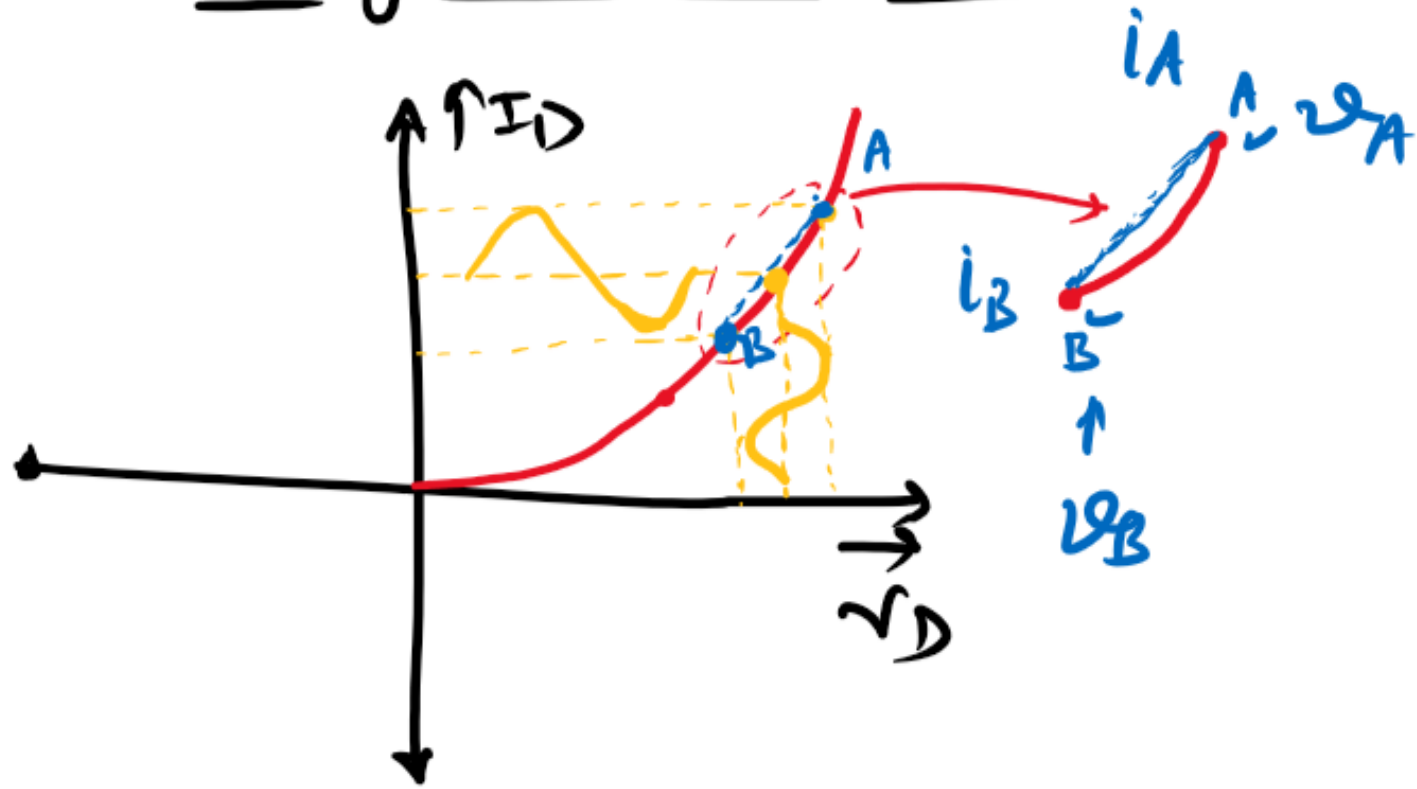
② AC / Dynamic resistance -



$$r_d = \frac{\Delta V_D}{\Delta I_D}$$

→ Draw a tangent at any point on the diode characteristics
↪ find the dynamic resistance

② Average AC resistance -

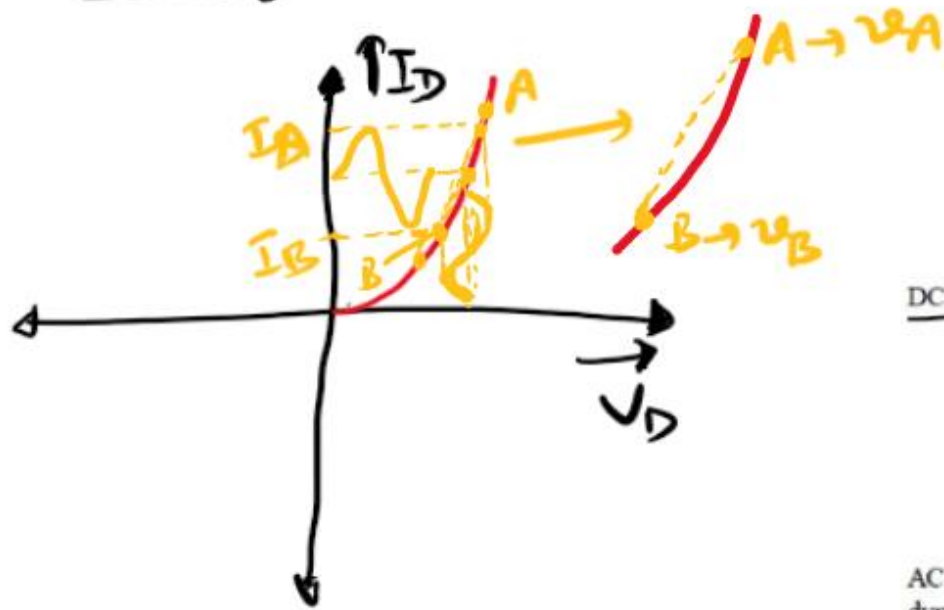


$$r_d = \frac{v_A - v_B}{i_A - i_B} \underline{r}$$

Solve → Example → 1.1, 1.2, 1.3, R. Boy lasted

Average AC Resistance -

$$r_d = \frac{v_A - v_B}{i_A - i_B}$$



DC or static

$$R_D = \frac{V_D}{I_D}$$

Defined as a point on the characteristics

AC or dynamic

$$r_d = \frac{\Delta V_d}{\Delta I_d} = \frac{26 \text{ mV}}{I_D}$$

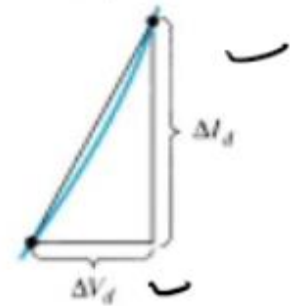
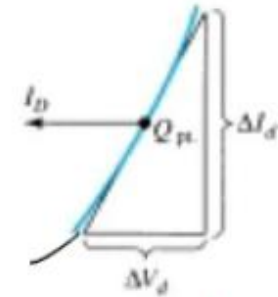
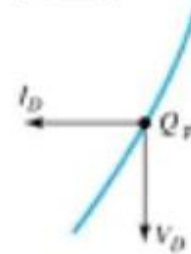
Defined by a tangent line at the Q-point

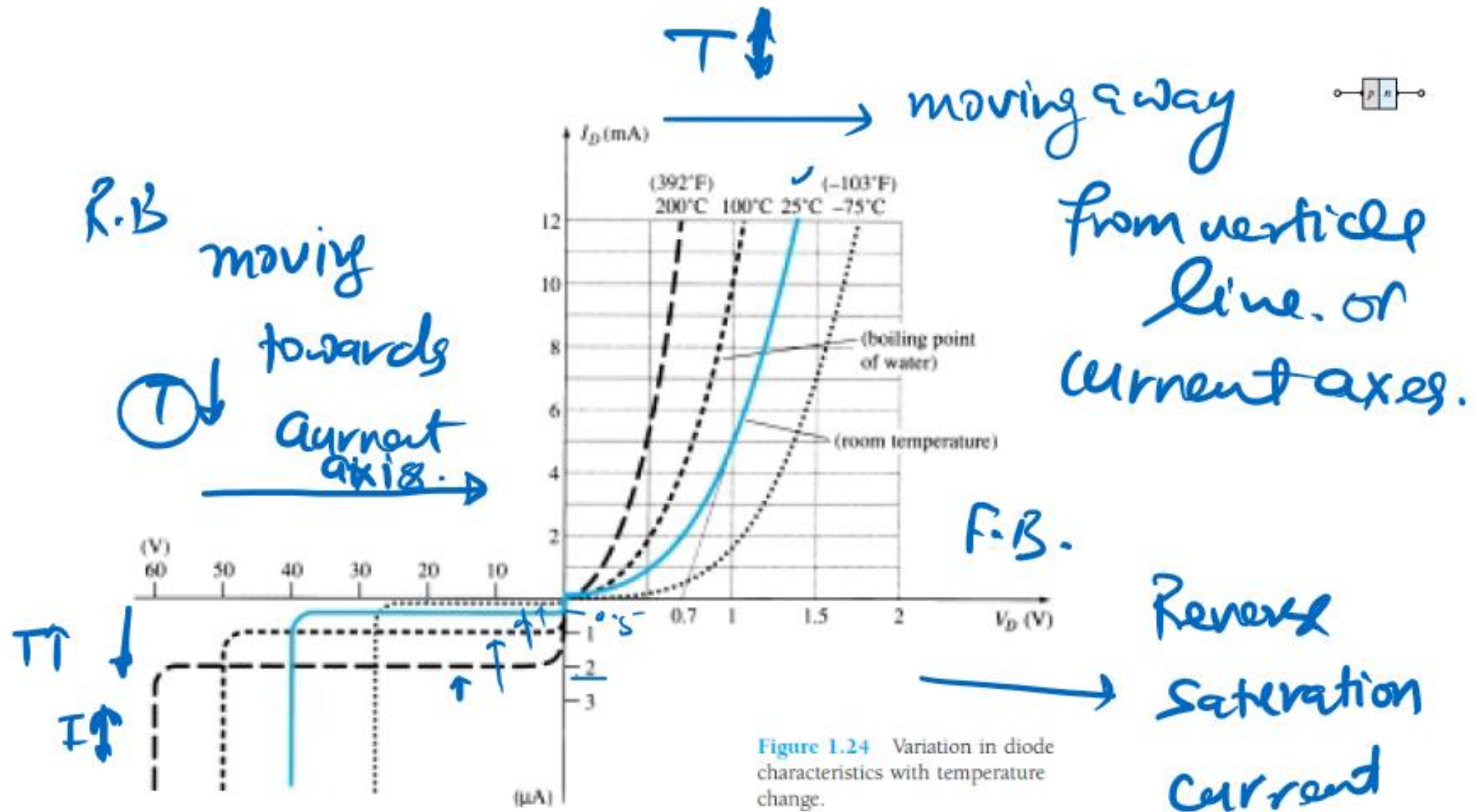
Average ac

$$r_{av} = \frac{\Delta V_d}{\Delta I_d \text{ pt. to pt.}}$$

Defined by a straight line between limits of operation

F.B.



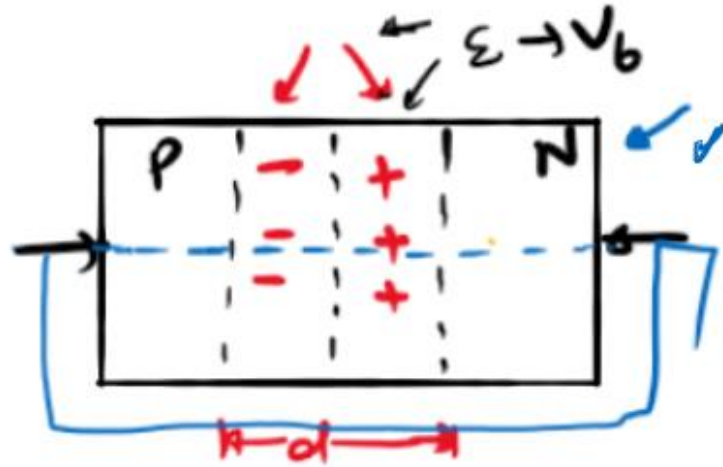


It is not uncommon for a germanium diode with an I_s in the order of 1 or 2 μA at 25°C to have a leakage current of 100 $\mu\text{A} = 0.1 \text{ mA}$ at a temperature of 100°C. Current levels of this magnitude in the reverse-bias region would certainly question our desired open-circuit condition in the reverse-bias region. Typical values of I_s for

Diode capacitances -

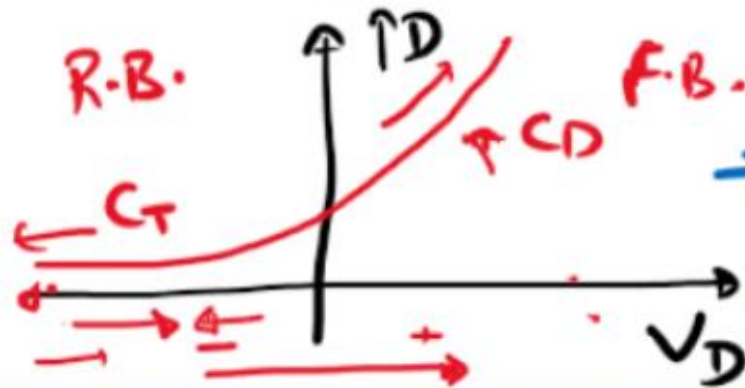
① Transition capacitance $\rightarrow (R.B.)$, C_T

② Diffusion capacitance $\rightarrow (F.B.)$, C_D



$$C = \frac{\epsilon A}{d} \Rightarrow \begin{matrix} \downarrow C \\ \uparrow d \end{matrix} \Rightarrow \begin{matrix} V_{R.B.} \uparrow \\ \rightarrow C_T \downarrow \end{matrix}$$

$$C = \frac{q A I_D}{V_F} \Rightarrow \begin{matrix} \uparrow C \\ d \downarrow \end{matrix} \Rightarrow \begin{matrix} V_F \uparrow \\ F.B. \uparrow \rightarrow C_D \uparrow \end{matrix}$$



$\rightarrow$ at Low frequency $\rightarrow$

$\rightarrow$ At high frequency $\rightarrow$

$$X_C = \frac{1}{2\pi f C} \Rightarrow \begin{matrix} \uparrow \infty \cdot 0 \cdot C \\ \rightarrow \end{matrix} \begin{matrix} \text{Capacitive reactance} \\ \downarrow \\ \text{Capacitive Resistance} \end{matrix}$$

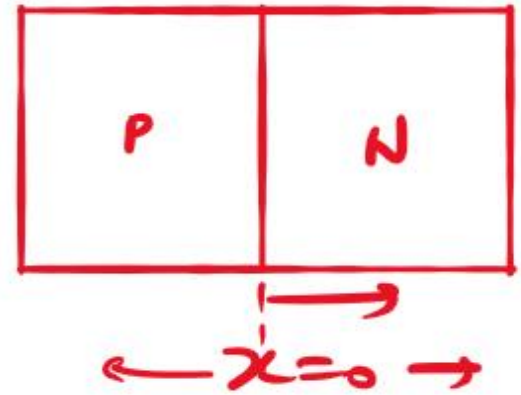
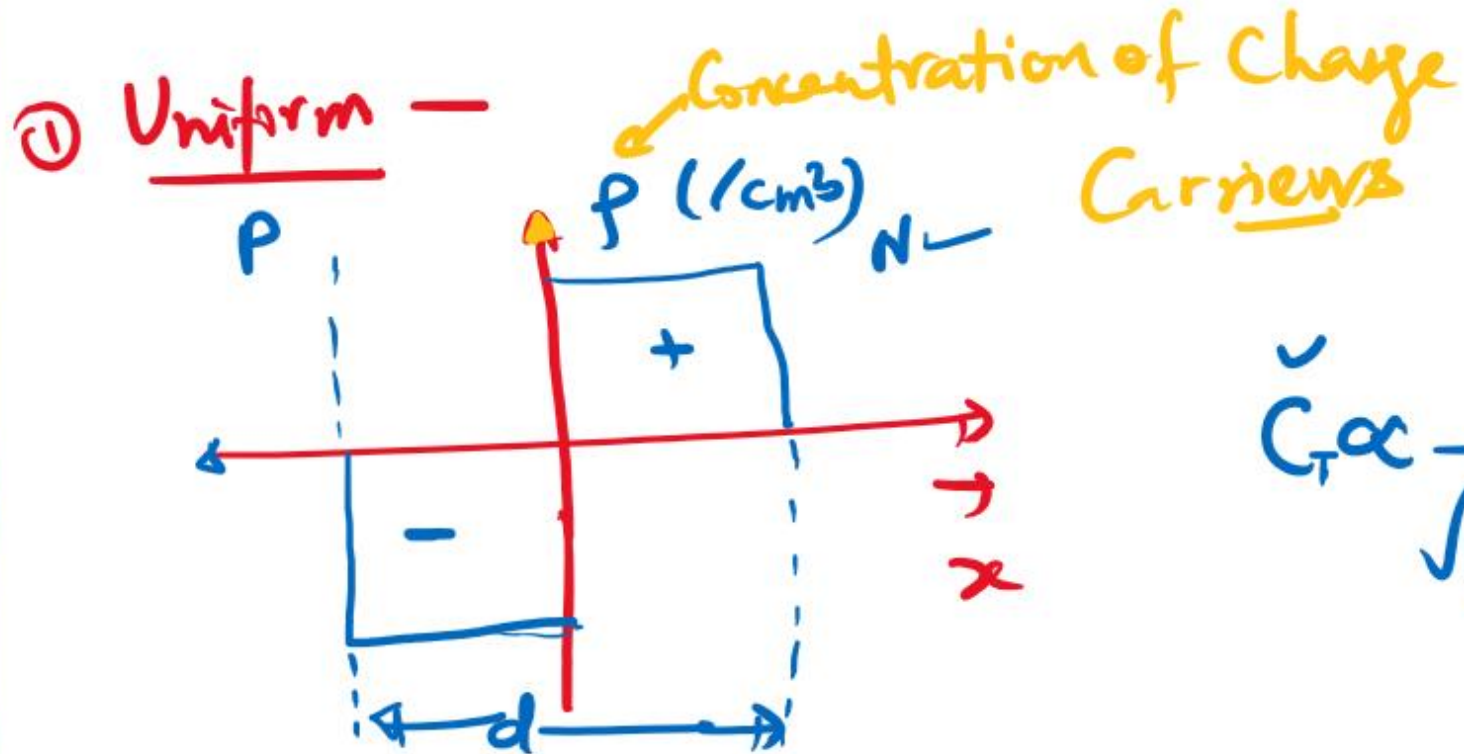
$\rightarrow$ At high frequency $\rightarrow X_C \approx 0 \Omega \rightarrow S.C.$

Types of PN-Junction & Capacitance -



① Uniformly doped PN-Junction

② Non-uniformly doped PN-Junction → [Linearly graded
Abrupt



$$\check{C}_T \propto \frac{1}{\sqrt{(V_{bi} + V_R)}}$$

$$\text{or } \check{C} \propto (V_{bi} + V_R)^{-1/2}$$

Non-Uniform $\Rightarrow$

① Linearly Graded $\Rightarrow$



$$\underline{C \propto (V_{bi} + V_R)^{-1/3}}$$

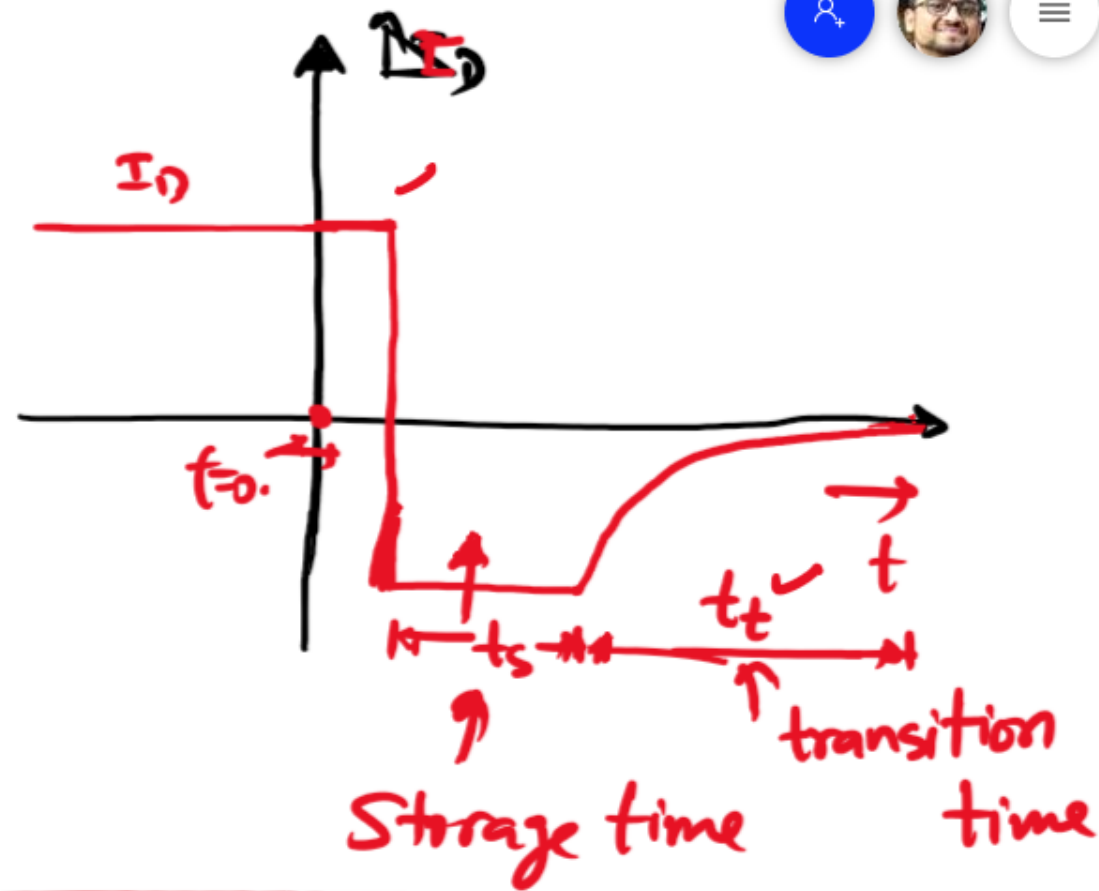
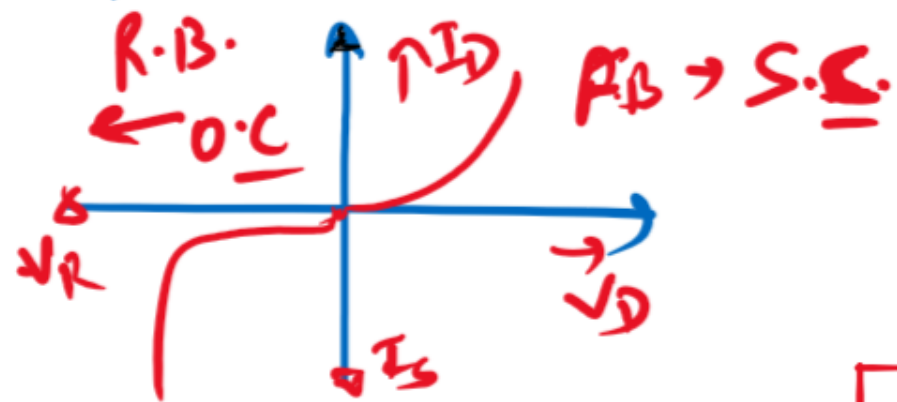
③ Abrupt / Hyperabrupt $\Rightarrow$

$$\underline{C} = (V_{bi} + V_R)^{-1/(\underline{m}+2)}$$

depends on doping concentration

Reverse-recovery time (t_{rr}) →

If any diode is in f.B.
and suddenly we remove the
battery or source.



$$t_{rr} = \underline{t_s} + t_t$$

Storage time $\rightarrow t_s \rightarrow$ This is time in which

minority carriers are stored near the junction and for a large depletion region.

Transition time $\rightarrow t_t \rightarrow$ This is time in which

the movement of charge carriers is totally reduced to zero & there is no current across the junction.

Diode Equation / Current equation / Shockley's eqn

$$I_D = I_S \left(e^{KV_D/V_T} - 1 \right) \quad (1)$$

reverse saturation
Current

① F.B. →

$$I_S \ll I_S e^{KV_D/V_T}$$

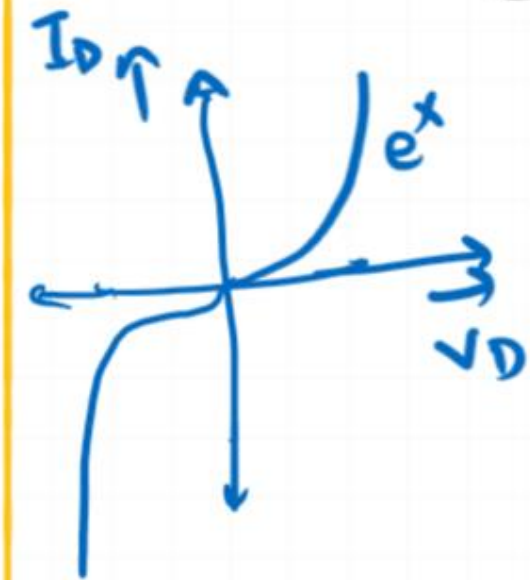
$$I_D \approx e^x$$

② I.R.B. →

$$I_S \gg$$

$$K = \frac{11,600}{\eta}, \quad \begin{cases} \eta = 1; \text{ Ge} \\ \eta = 2; \text{ Si} \end{cases}$$

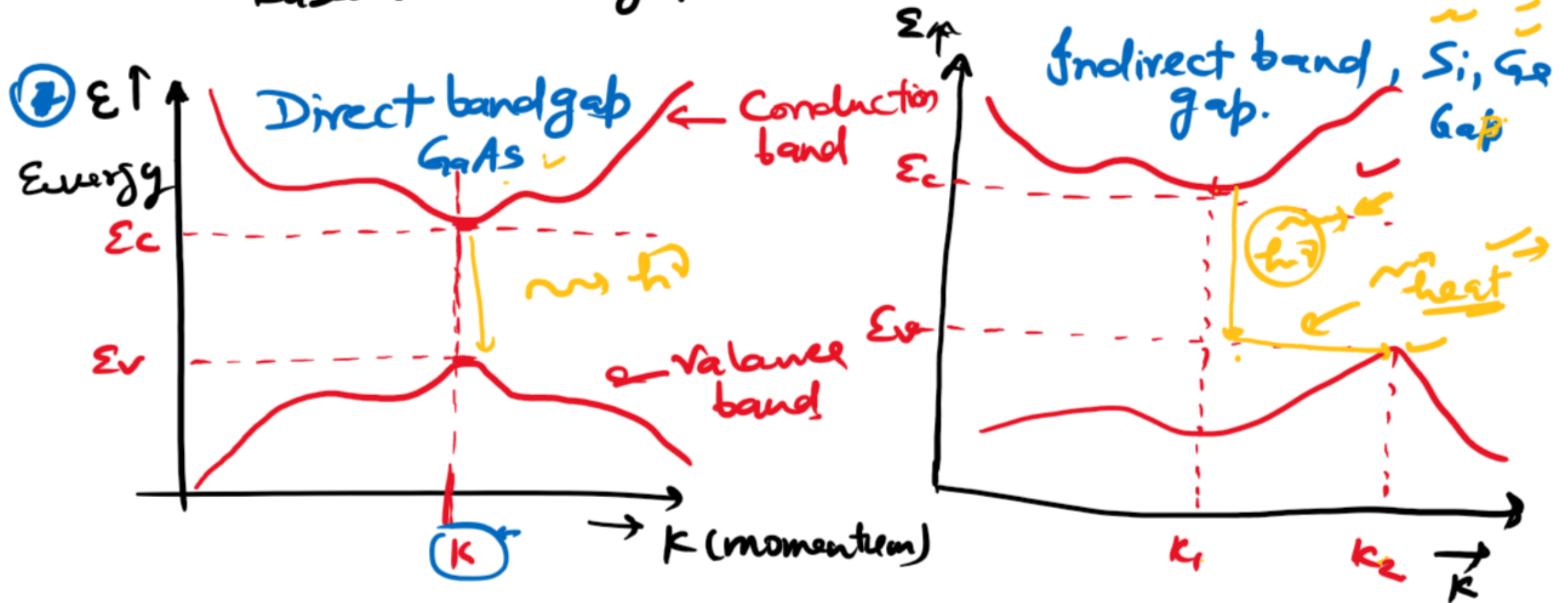
$$V_T = 25.9 \text{ mV} (\approx 26 \text{ mV}) = \frac{kT}{e}$$



Light Emitting diodes →

Types of semiconductors - $\bar{P}$, $\bar{N}$ →

Based on bandgap →



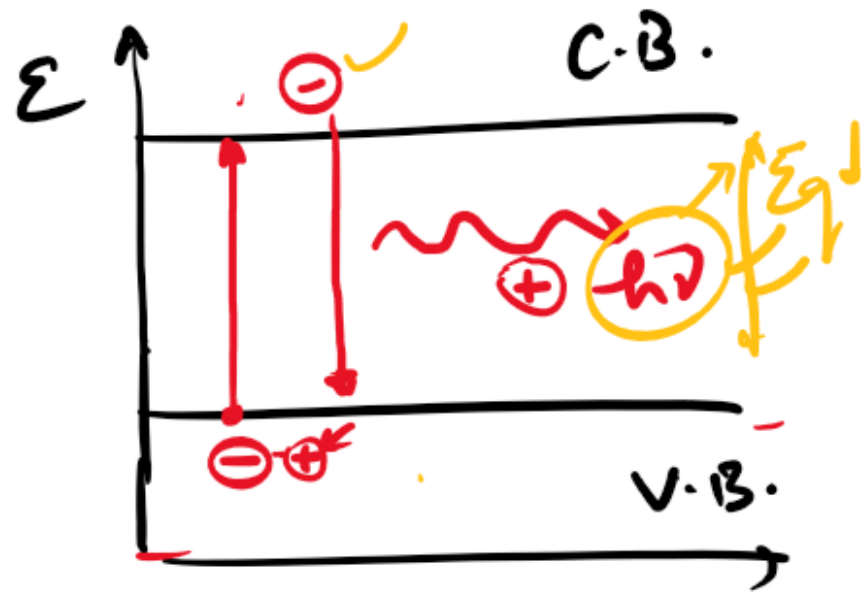
Some materials with Direct/Indirect B.G.



	Material	Direct / Indirect Bandgap	Band Gap Energy at 300 K (eV)
Elements	C (diamond)	Indirect	5.47
	Ge	Indirect	0.66
	Si	Indirect	1.12
	Sn (grey)	Direct	0.08
Groups III-V compounds	GaAs	Direct	1.42
	InAs	Direct	0.36
	InSb	Direct	0.17
	GaP ✓	Indirect ✓	2.26 ✓ → <u>LED's</u>
	GaN	Direct	3.36
	InN	Direct	0.70
Groups IV-IV compounds	α -SiC	Indirect	2.99
Groups II-VI compounds	ZnO	Direct	3.35
	CdSe	Direct	1.70
	ZnS	Direct	3.68

Data from R.E. Hummel, Electronic Properties of Materials, 3rd edition, Appendix 4, p. 413.

Operating principle of LED →



① e^- moves from V.B. to C.B. when energised.

② After residing in C.B., e^- returns back to V.B. and recombines with hole.

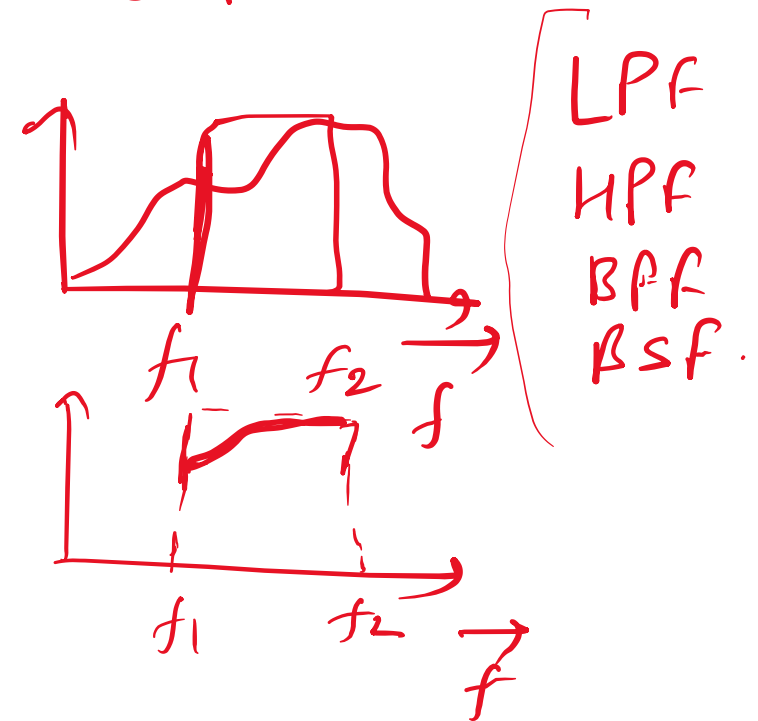
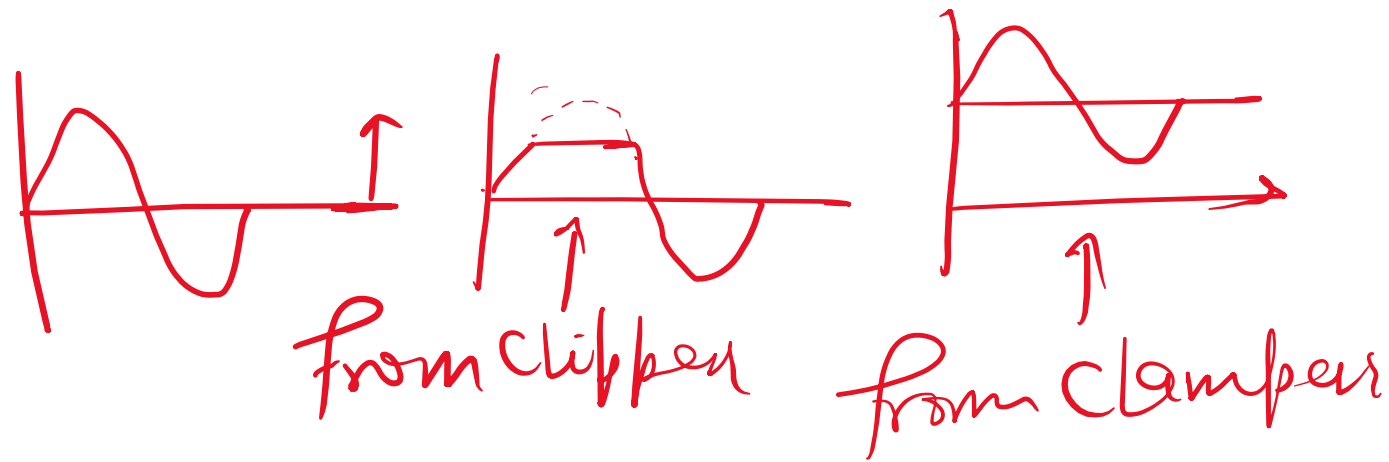
③ During return e^- releases Energy in form of visible light (photon).

$$\underline{E = h\nu}$$

→ LED operates in f.b. region only.

Applications of Diode →

- ① Rectifiers → AC to DC
- ② Clippers → clips the portion of any AC waveform.
- ③ Clampers → Shift the reference level of the A.C.
- ④ Filters → frequency selective device.

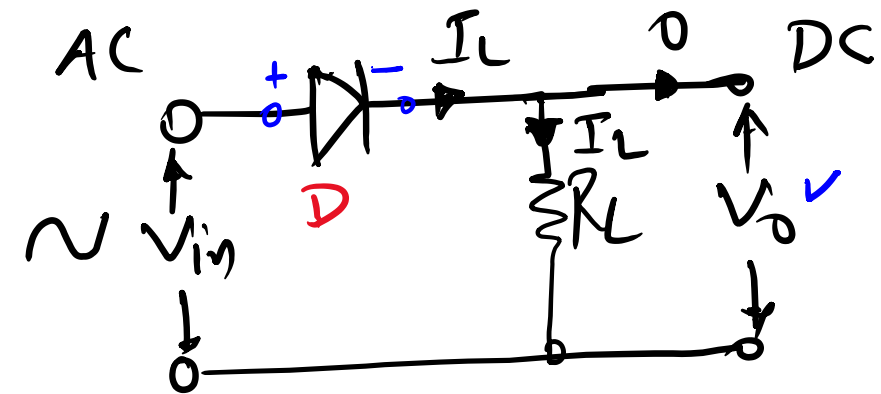


Rectifiers →

- ① Half wave Rectifier
- ② Full wave Rectifier →

Centre tap FWR.
Bridge Rectifier.

① Half wave Rectifier →



Operation →

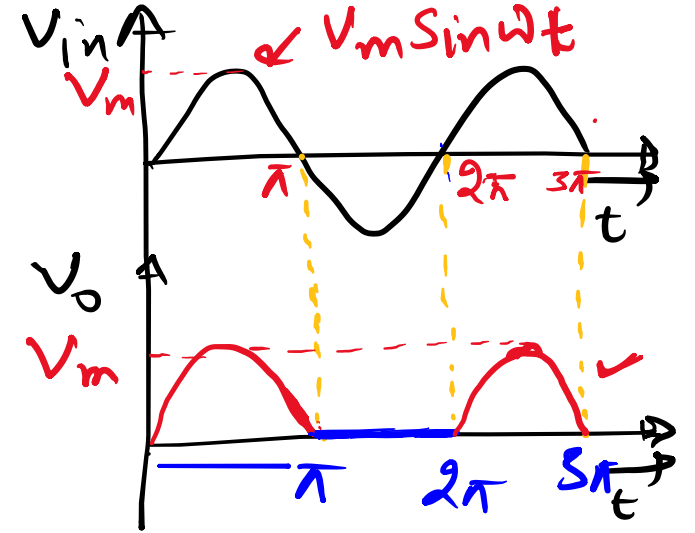
① positive half cycle at input - $(0 \rightarrow \pi)$

$$D \rightarrow \text{S.C.} \Rightarrow V_L = I_L \cdot R_L = V_{in} = V_o$$

(F.B.)

② negative half cycle → $(\pi \rightarrow 2\pi)$

$$D \rightarrow \text{O.C. (R.B.)} \Rightarrow V_o = 0$$
$$I_L = 0$$



→ Performance parameters -

$$\underline{\omega = 2\pi/T} \Rightarrow \underline{T = 2\pi}$$

① Average output voltage (DC voltage) →

$$V_{DC} = \frac{1}{T} \int_0^T v_o(t) \cdot dt = \frac{1}{2\pi} \left[\int_0^{\pi} V_m \sin \omega t \cdot dt + \int_{\pi}^{2\pi} (0) \cdot dt \right]$$
$$V_{DC} = \frac{1}{2\pi} \left\{ -V_m \frac{\cos \omega t}{\omega} \right\}_0^{\pi} = -\frac{1}{2\pi} \left\{ -V_m - V_m \right\} = + \frac{2V_m}{2\pi} = \frac{V_m}{\pi}$$

$$\boxed{V_{DC} = \frac{V_m}{\pi}}$$

② Root mean Square value (RMS) →

$$V_L = \sqrt{\frac{1}{T} \int_0^T v_o^2(t) \cdot dt} = \sqrt{\frac{1}{2\pi} \int_0^{\pi} V_m^2 \sin^2 \omega t \cdot dt} = \frac{V_m}{2}$$

$$\boxed{V_{rms} = \frac{V_m}{2}}$$

③ DC current →

$$I_{DC} = \frac{V_{DC}}{R_L} = \frac{V_m}{\pi \cdot R_L}$$

④ I_{rms} current →

$$I_L = \frac{V_{rms}}{R_L} = \frac{V_m}{2 \cdot R_L}$$

⑤ Form factor →

F.f. tells about the performance of any rectifier in terms of its efficient utilization.

$$f.f. = \frac{V_{rms}}{V_{DC}} = \frac{V_m/2}{V_m/\pi} = \frac{\pi}{2}$$

⑥ Efficiency →

$$\eta = \left(\frac{1}{ff} \right)^2 = \left(\frac{V_{DC}}{V_{rms}} \right)^2$$

$$\eta = \left(\frac{V_m/\pi}{V_m/2} \right)^2 = \frac{4}{\pi^2} = 0.405$$

$$\boxed{\eta = 40\%}$$

⑦ Ripple factor →

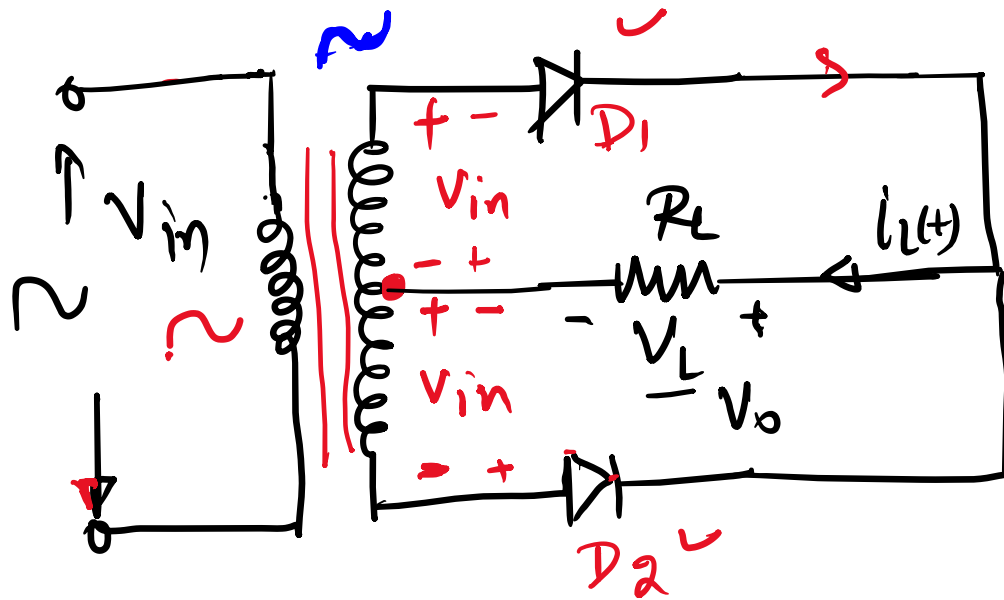
$$Rf = \sqrt{ff^2 - 1} = 1.21$$

The AC components present in the output of any rectifier.

Transformer utilization factor $\rightarrow$

$$TUF = \frac{P_{DC}}{\text{Effective Transformer } \underline{VA} \text{ rating.}} = \underline{0.286} \text{ (HWR)}$$

Full Wave Rectifier $\rightarrow$ ① Centre Tap



Transformer

240 $\rightarrow$ 5V
220 $\rightarrow$ 5V

① +ve half cycle

$D_1 \rightarrow F.B.$, $D_2 \rightarrow R.B.$

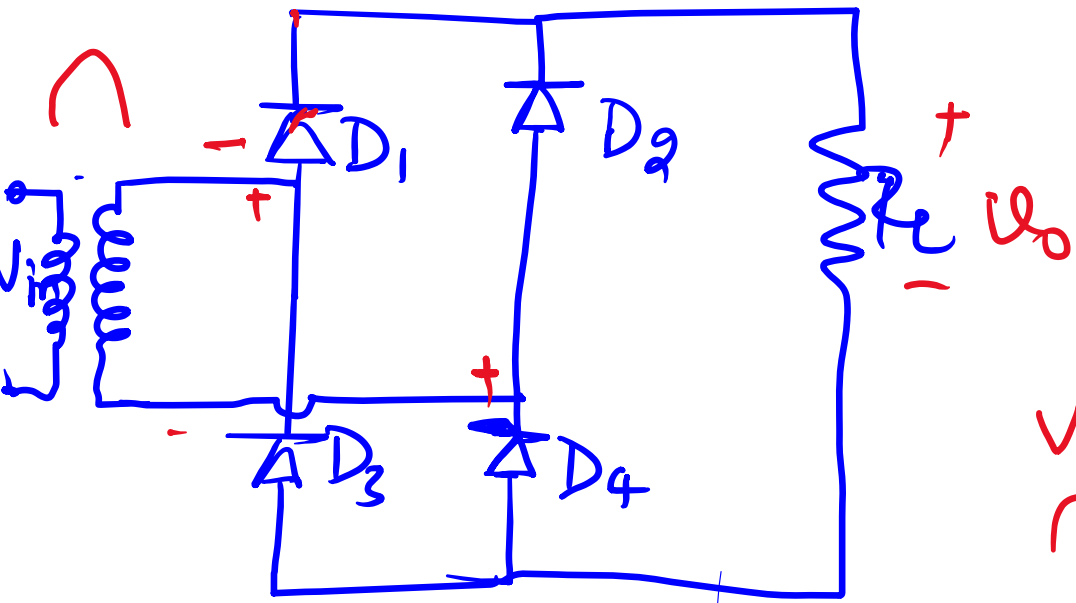
$$+V_L - V_{in} = 0 \Rightarrow V_L = V_{in} = V_0$$

② -ve half cycle

$D_1 \rightarrow R.B.$, $D_2 \rightarrow F.B.$

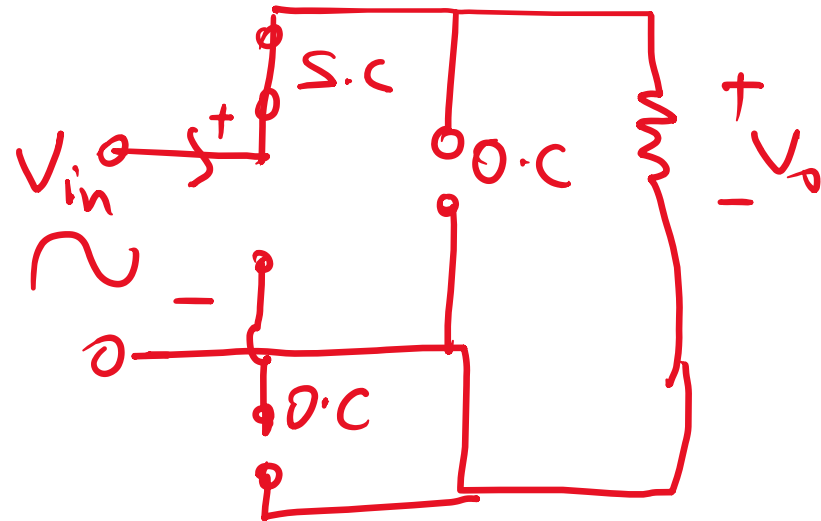
$$+V_L + V_{in} = 0 \Rightarrow \underline{V_L = -V_{in}}$$

Full wave bridge rectifier $\rightarrow$ +ve half cycle $\rightarrow$



$D_1 \rightarrow \text{S.C}$ $D_3 \rightarrow \text{O.C}$

$D_2 \rightarrow \text{O.C}$ $D_4 \rightarrow \text{S.C}$

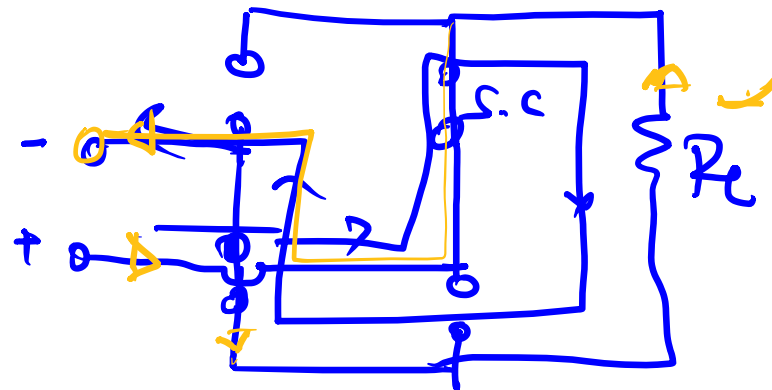


$$V_o = V_{in}$$

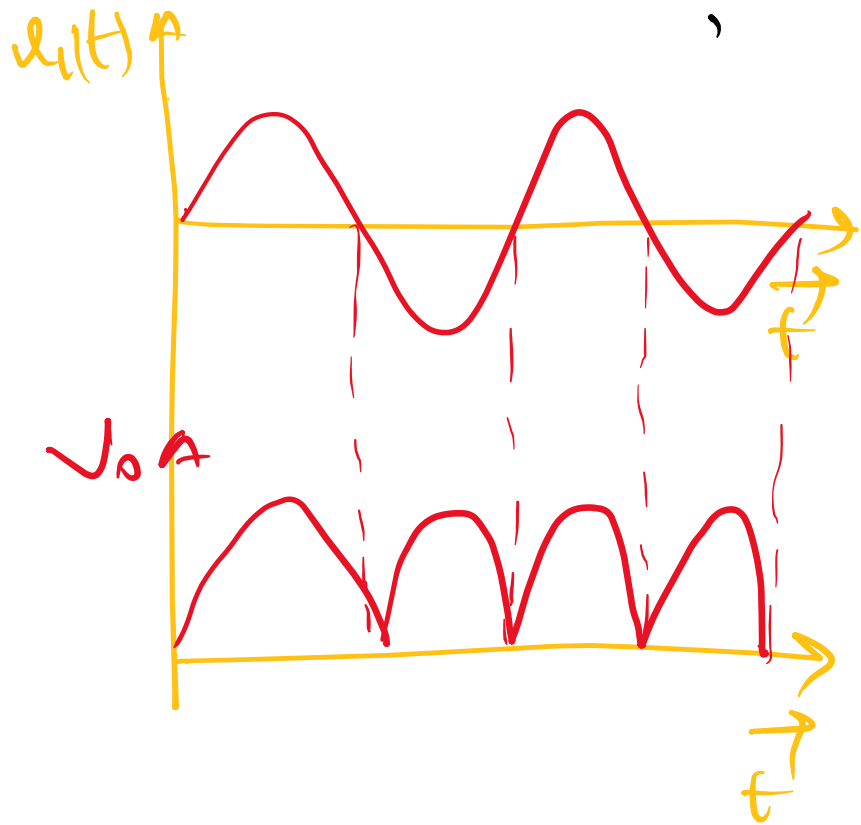
-ve half cycle $\rightarrow$

$D_1 - \text{O.C}$ $D_2 - \text{S.C}$

$D_3 - \text{S.C}$ $D_4 - \text{O.C}$



$$\Rightarrow V_o = -V_{in}$$

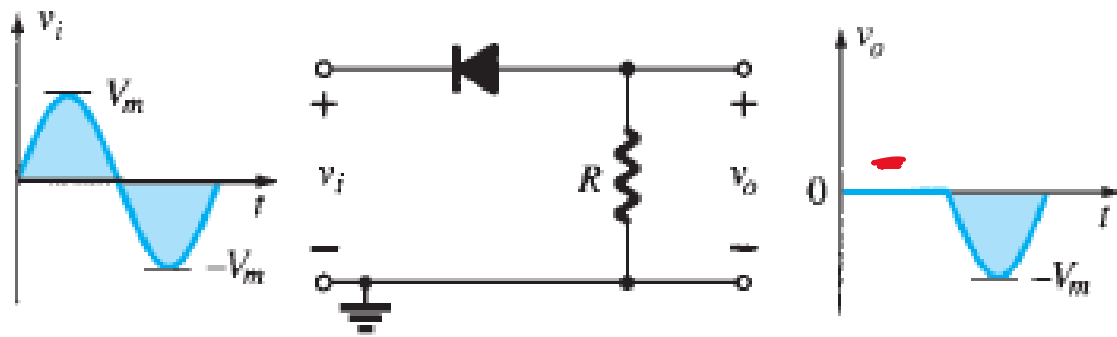


Comparison Table

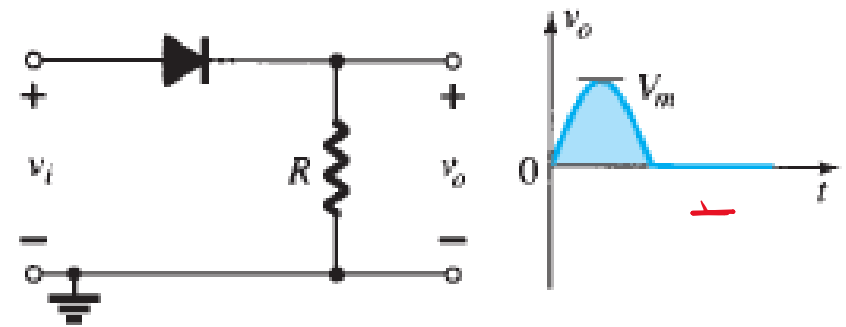
Properties	Half Wave Rectifier	Full Wave Rectifier	
		Center Tap	Bridge
No. of Diodes	1	2	4
Center Tap Necessity	No	Yes	No
Efficiency	40.6% ✓	81.2% ✓	81.2% ✓
Ripple Factor	1.21	0.482	0.482 ✓
Peak Inverse Voltage →	V_m ✓	$2V_m$	V_m ✓
Output Frequency	f_i ✓	$2f_i$ ✓	$2f_i$ ✓
RMS Current	$I_m/2$ ✓	$I_m/\sqrt{2}$ ✓	$I_m/\sqrt{2}$ ✓
Average Current	I_m/π	$2I_m/\pi$	$2I_m/\pi$

Simple Series Clippers (Ideal Diodes)

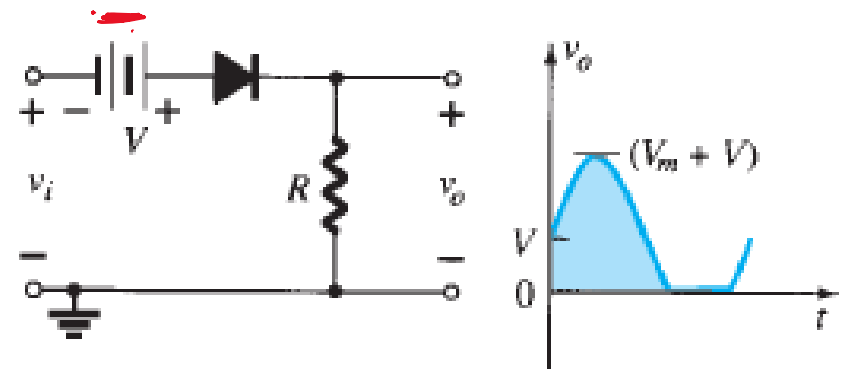
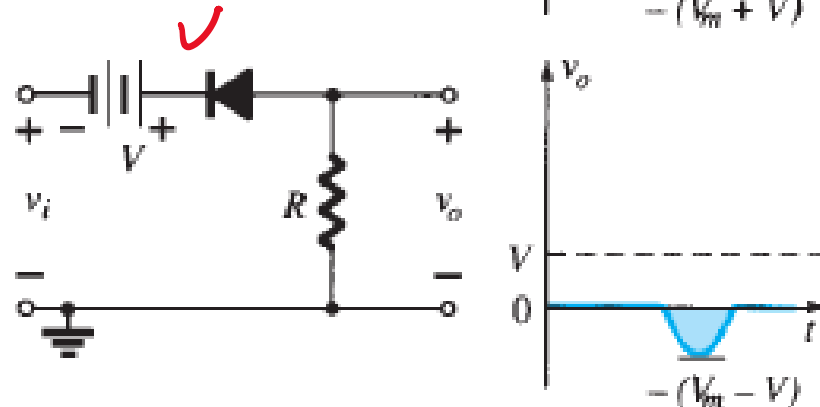
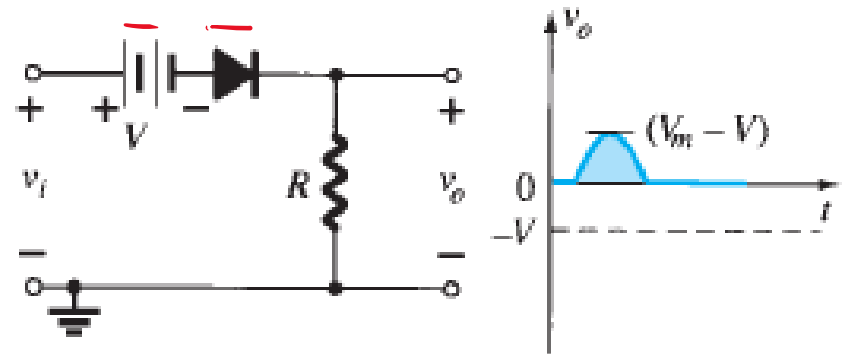
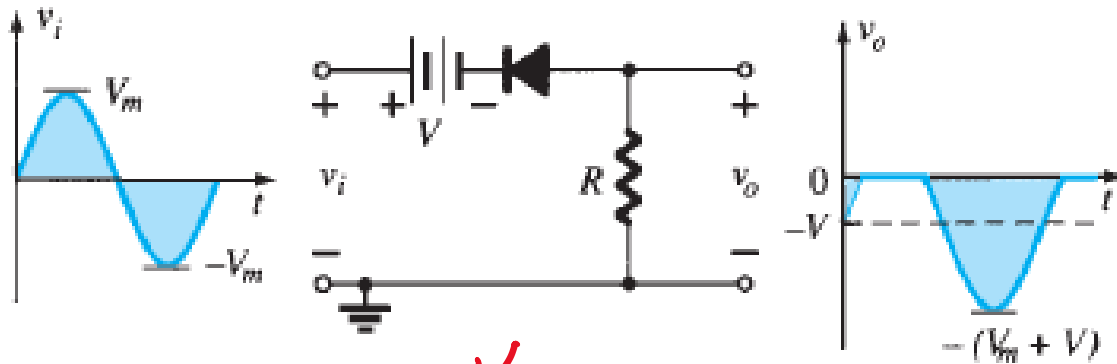
POSITIVE ✓



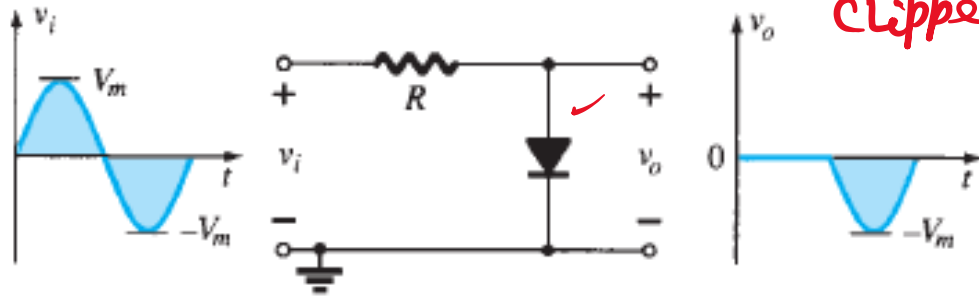
NEGATIVE ✓



Biased Series Clippers (Ideal Diodes)

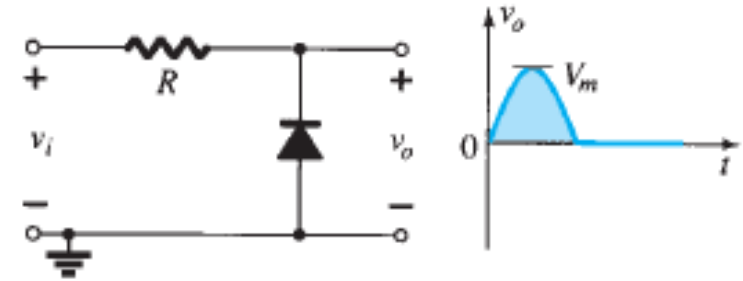


Simple Parallel Clippers (Ideal Diodes)

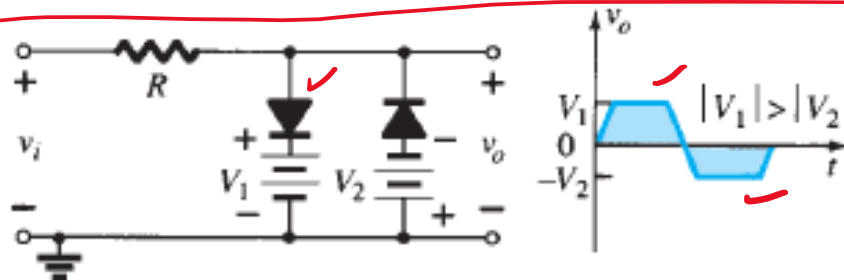
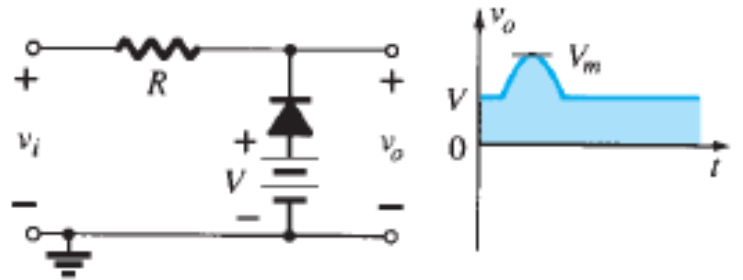
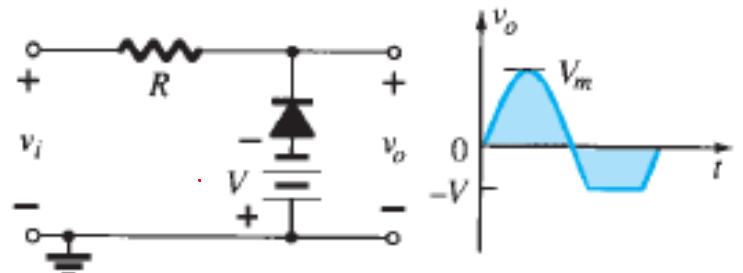
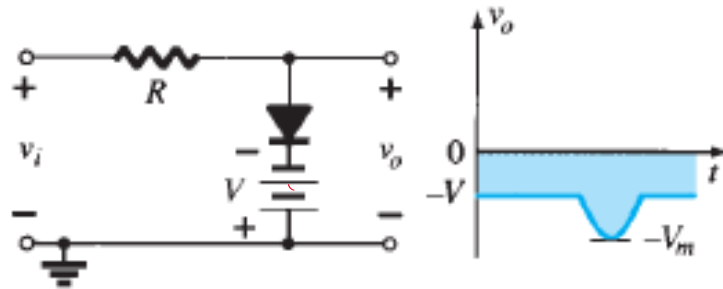
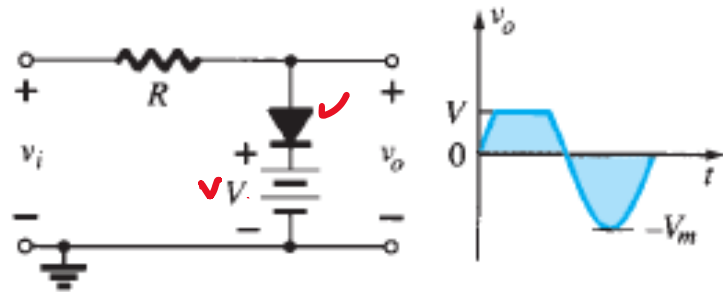


Positive
clipper

Negative clipper

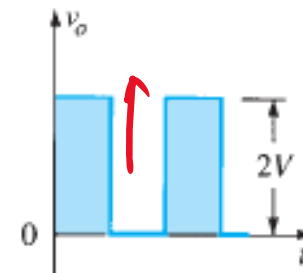
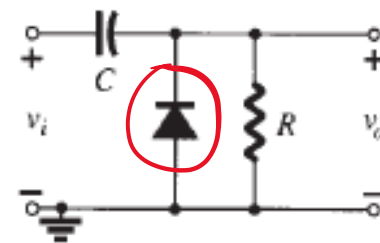
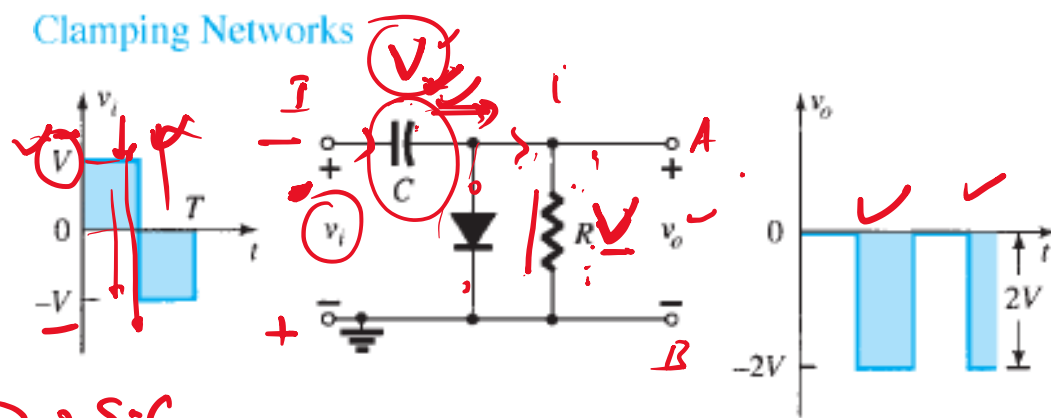


Biased Parallel Clippers (Ideal Diodes)



Dual peak clipper.

Clamping Networks



Clampers
→ Shift the level of reference line.

+ve $\rightarrow$ D $\rightarrow$ S.C.

$v_o = 0V$.

-ve $\rightarrow$ D $\rightarrow$ O.C.

$v_i \Rightarrow$ — v

$-v_i + v + iR = 0$

$+V + V = V_o$

$v_o = +V + 2V$

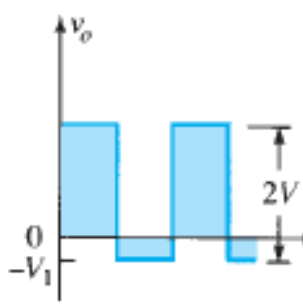
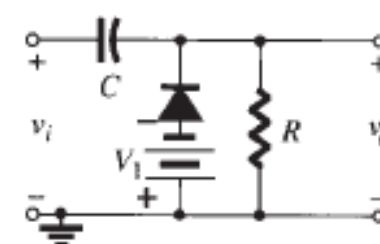
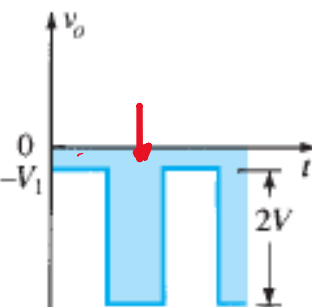
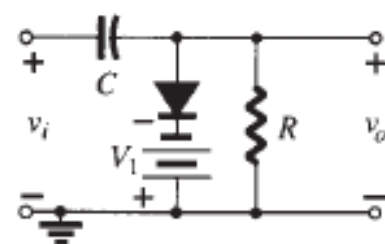
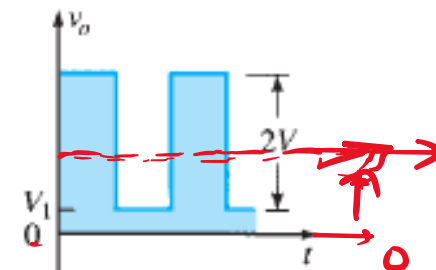
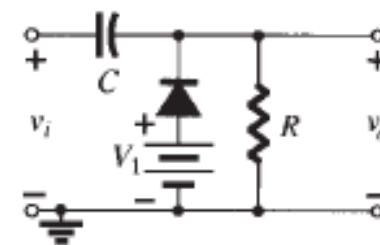
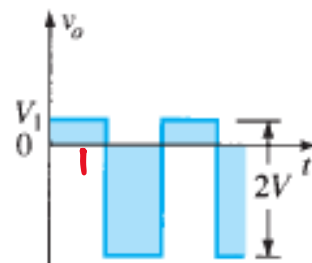
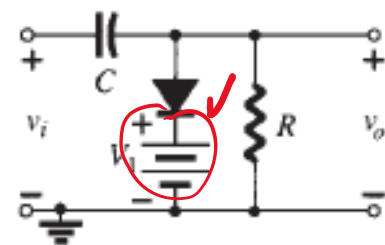
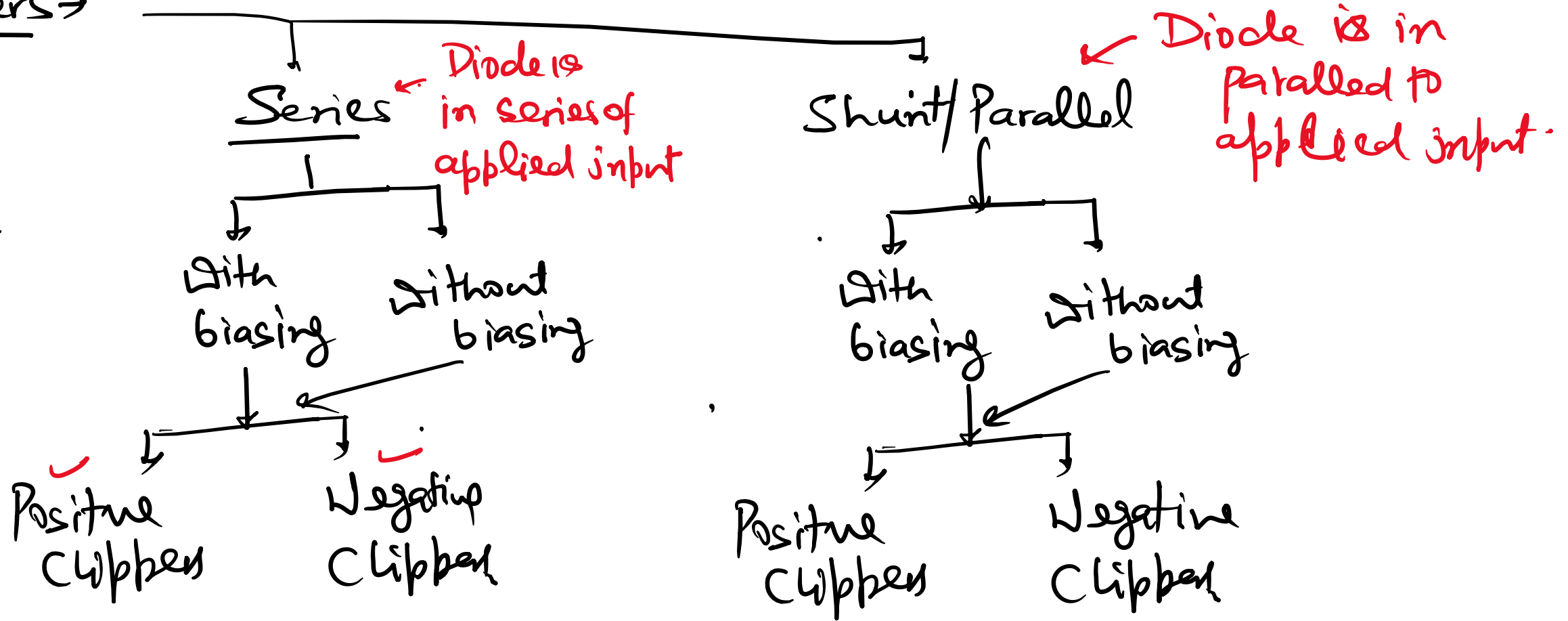


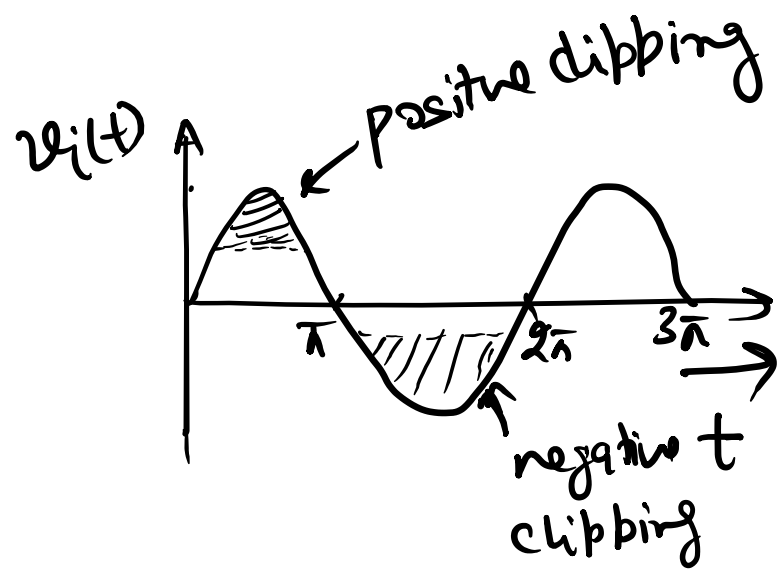
FIG. 2.100

Clamping circuits with ideal diodes ($5\tau = 5RC \gg T/2$).

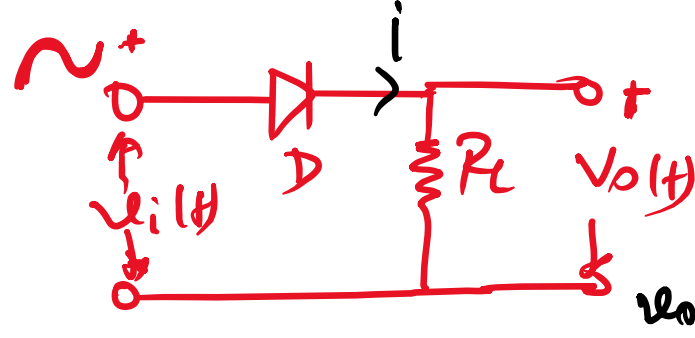
Clippers →



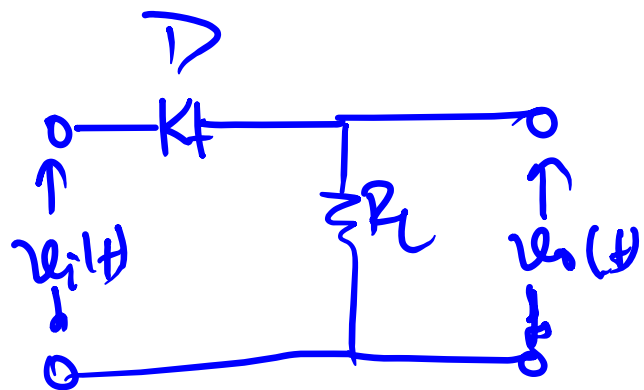
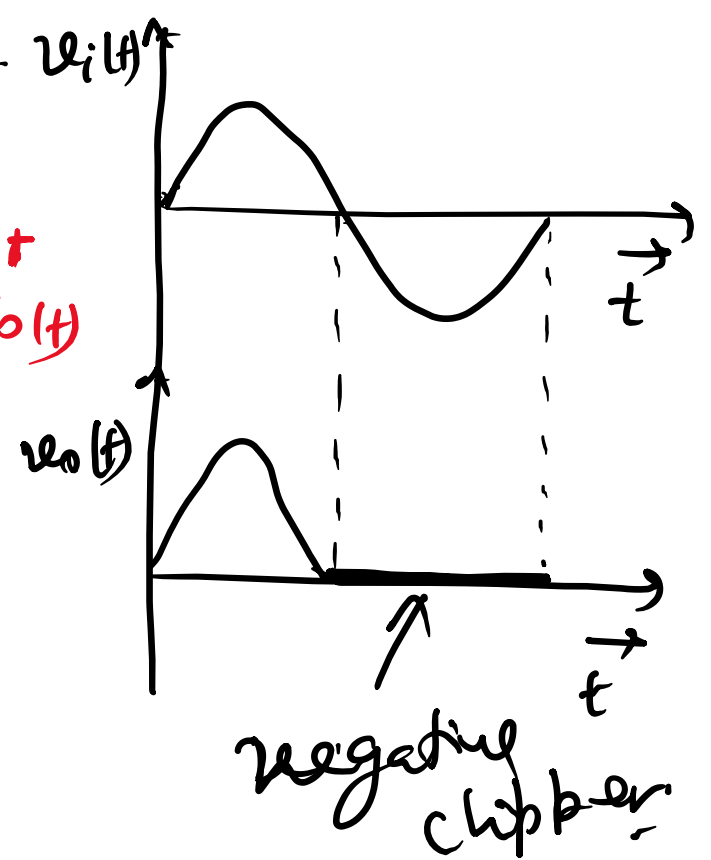
Clippers → This can clip or remove the specific portion of any wave or signal. This is electronic circuit made by using diode & basic components.



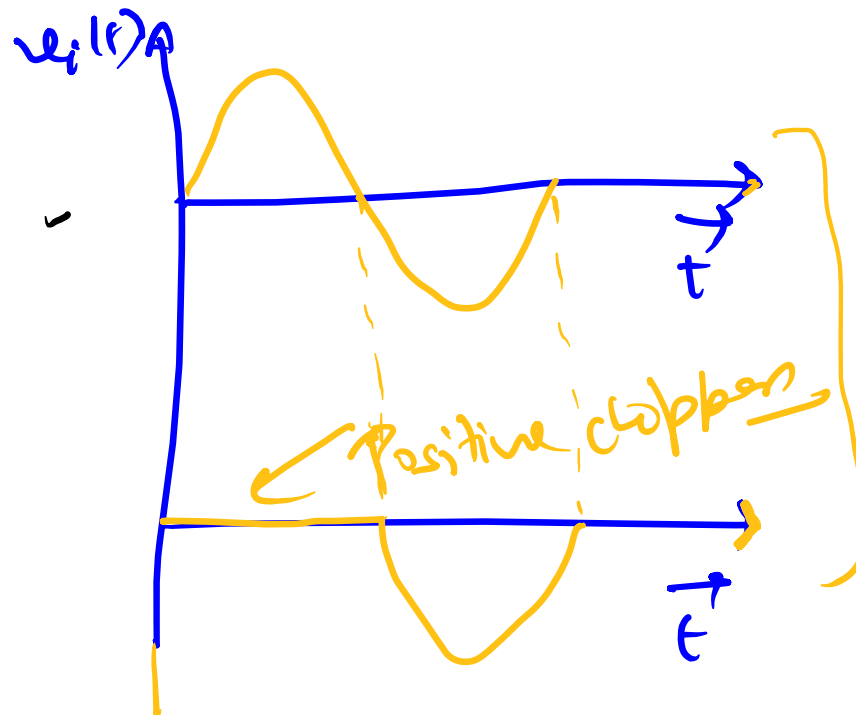
Series clipper - $v_i(t)$



$$\begin{aligned} \text{+ve } v_o(t) &= i R_L = v_i(t) \\ \text{-ve } v_o(t) &= 0 \end{aligned}$$

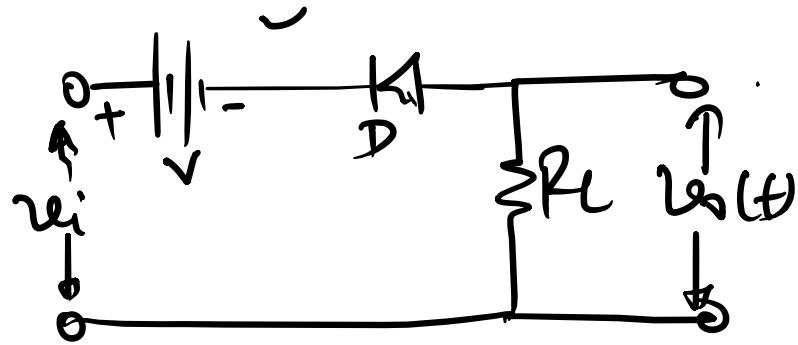


un biased clipper

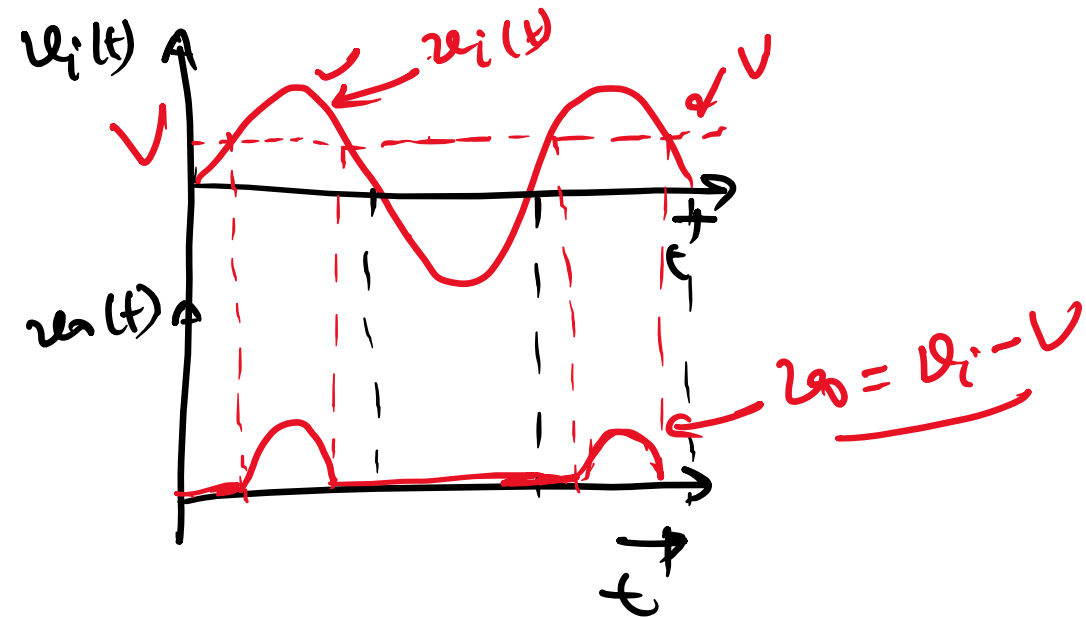


Q. What is the difference between rectifier & clippers?

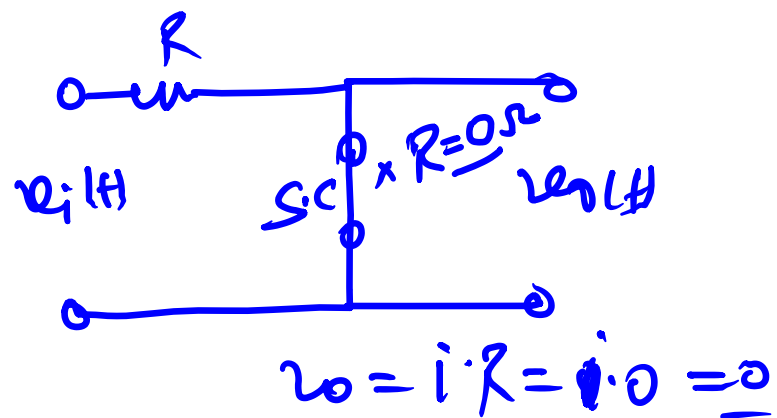
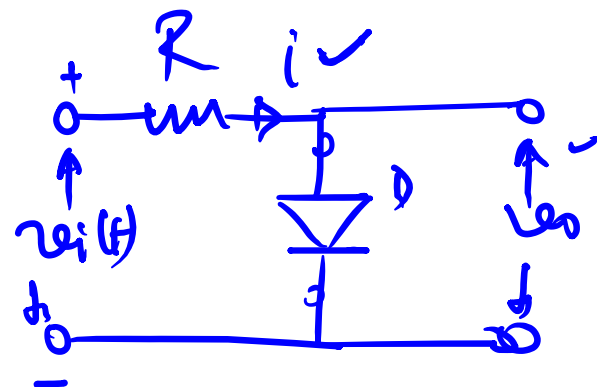
Biased Series clipper -



$$\begin{aligned}
 -v_i + V + v_o &= 0 \\
 v_i &= \overset{\text{bias Voltage}}{\underline{V}} + \underline{v_o} \\
 \underline{v_o} &= \underline{v_i - V} \quad \text{I}
 \end{aligned}
 \quad \left| \quad \begin{aligned}
 -v_i - V + v_o &= 0 \\
 v_i &= \underline{v_o - V} \\
 \underline{v_o} &= \underline{v_i + V} \\
 &\quad \text{II}
 \end{aligned}$$

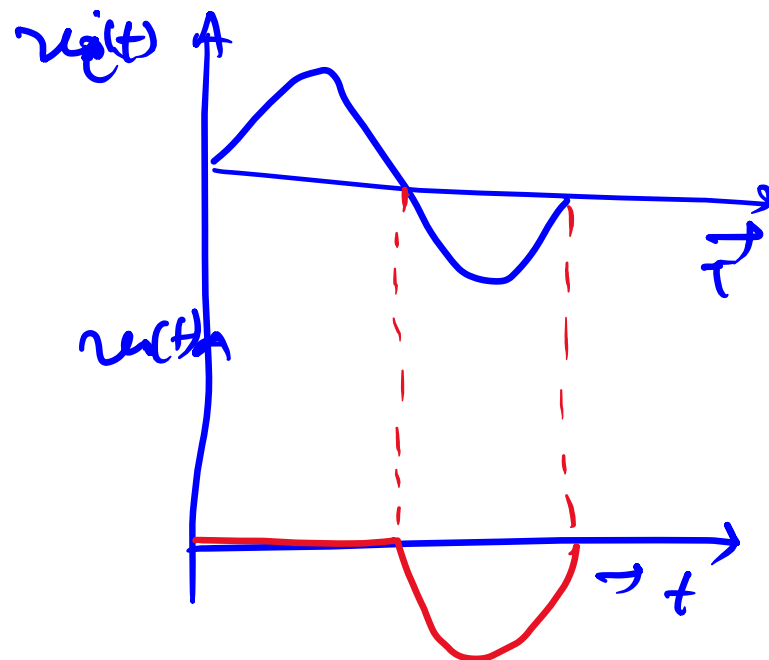


Parallel clippers -

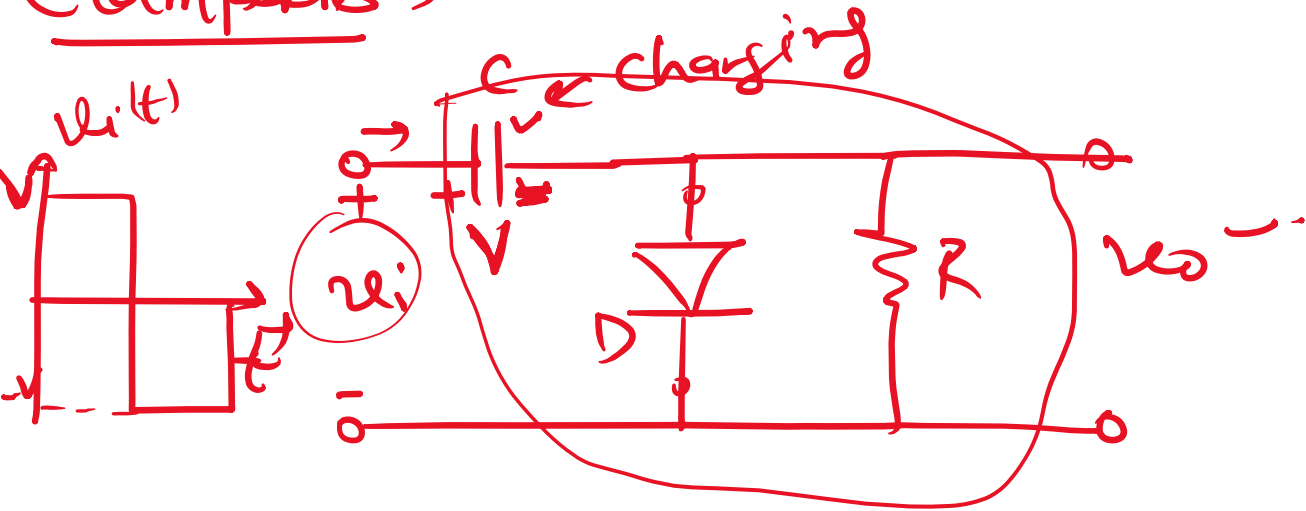


$+ve \rightarrow D \rightarrow S.C. \rightarrow v_o = 0$

~~$+ve$~~ $\rightarrow D + S.C. \rightarrow v_o = \underline{v_i}$



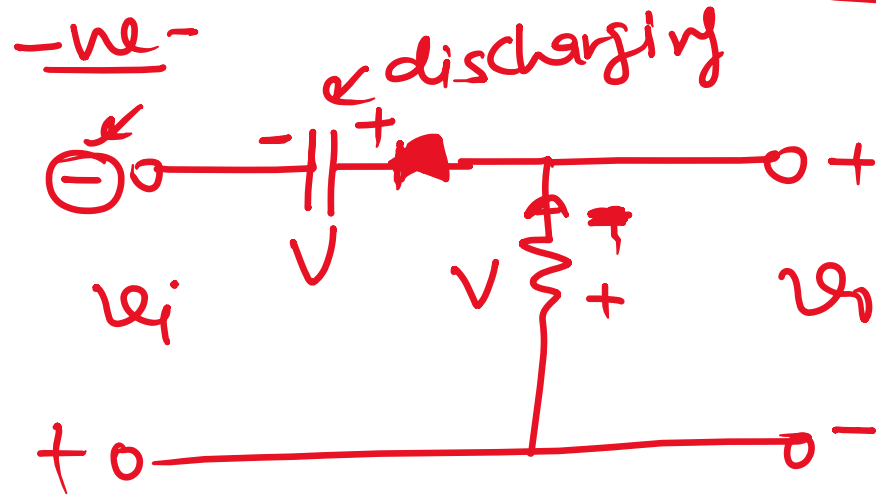
Clamper →



+ve → ① C → starts charging up to (V) volts.

② D → S.C.

③ $V_o = 0$



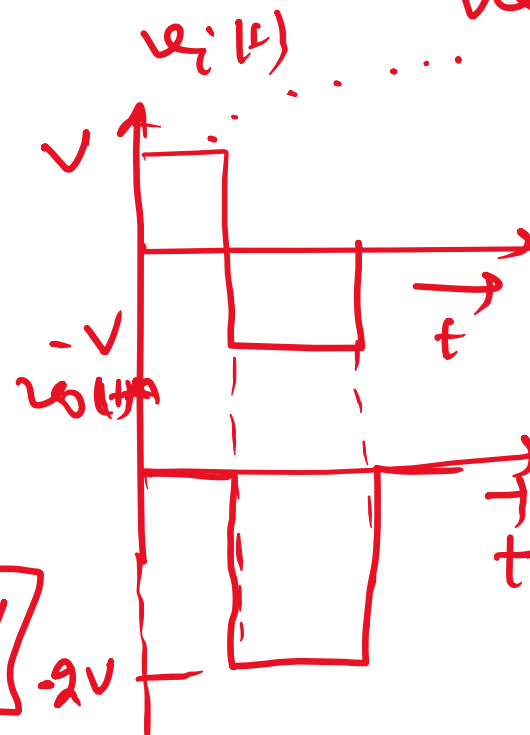
-ve → ① D → O.C.

② Capacitor provides current ~~the~~ and charge of capacitor is dissipated across R.

③ R → (V) ← Potential drop

$$+V_i - V - V = V_o$$

$$V_o = -2V$$

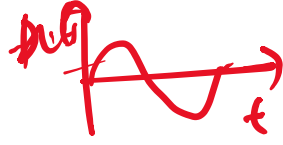


Filters → ① low pass filter (LPF)

② High pass filter (HPF)

③ Band pass filter (BPF)

④ Band stop filter (BSF) / Band reject filter / Notch filter.

Frequency Spectrum → 

Time domain

$$x(t) = A \sin(\omega t)$$

Frequency domain

$$X(\omega) = \pi [\delta(\omega) - \delta(-\omega)]$$

Time domain → Frequency domain Fourier Transform $\omega = 2\pi f$

→ $\left[\begin{array}{l} \text{Laplace Transform} \\ \text{Fourier Transform} \\ \text{Z-Transform} \end{array} \right] \rightarrow \text{Continuous time signal}$

Laplace Transform

Time
 $V_i(t) = V_i(s)$
 $V_o(t) = V_o(s)$
 $I(t) = I(s)$

Frequency

$R \rightarrow$

R

$\frac{1}{sC} = \frac{1}{j\omega C}$

$L \rightarrow$

$sL = j\omega L$

$s \Rightarrow$ Complex frequency.

$s = \sigma + j\omega$

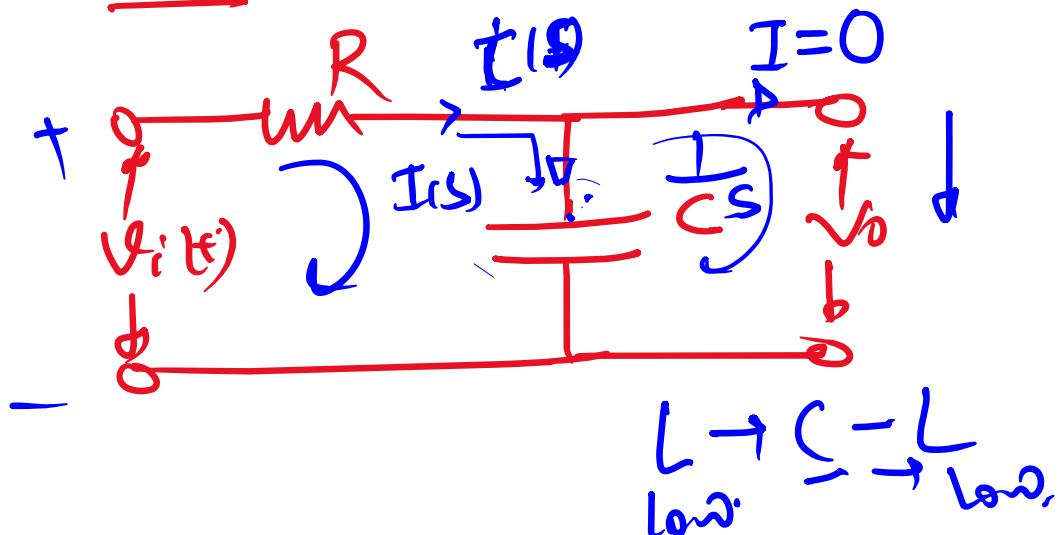
↑
real

frequency

↑
Imaginary
frequency.

($\sigma \approx 0$)

① Low Pass filter



$$\left. \begin{aligned} - V_i + I(s)R + \frac{1}{Cs} \cdot I(s) &= 0 \\ V_i &= I(s) \left(R + \frac{1}{Cs} \right) \quad \text{--- ①} \\ V_o &= I(s) \cdot \frac{1}{Cs} \quad \text{--- ②} \end{aligned} \right\}$$

$$\left[\frac{V_o(s)}{V_i(s)} = \frac{1/sC}{R + 1/sC} = \frac{1}{1 + sRC} \Rightarrow \text{Transfer function.} \right.$$

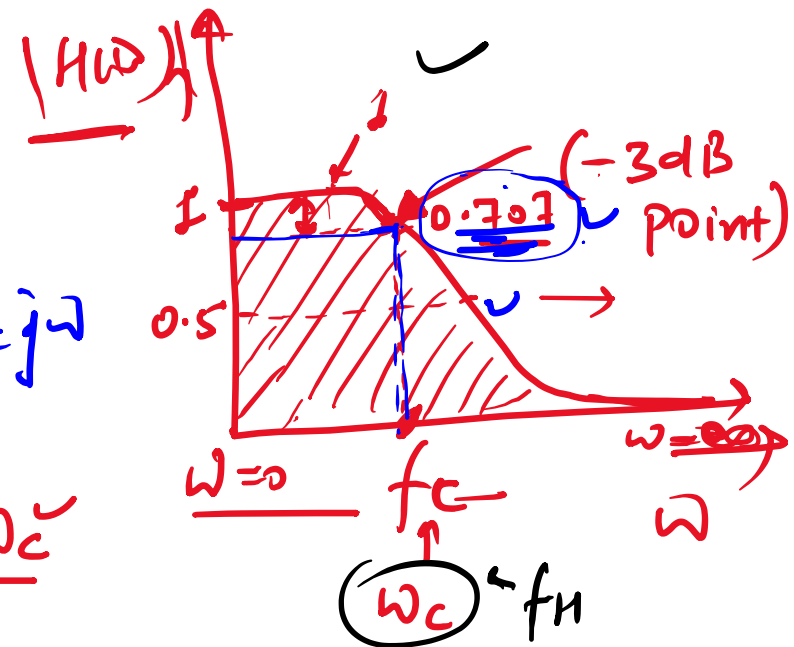
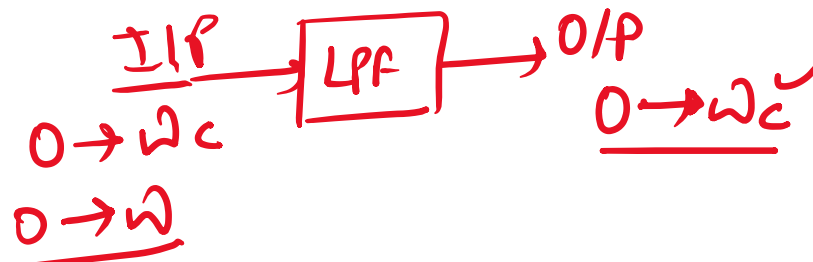
$$\text{Gain} = \frac{V_o(t)}{V_i(t)}$$

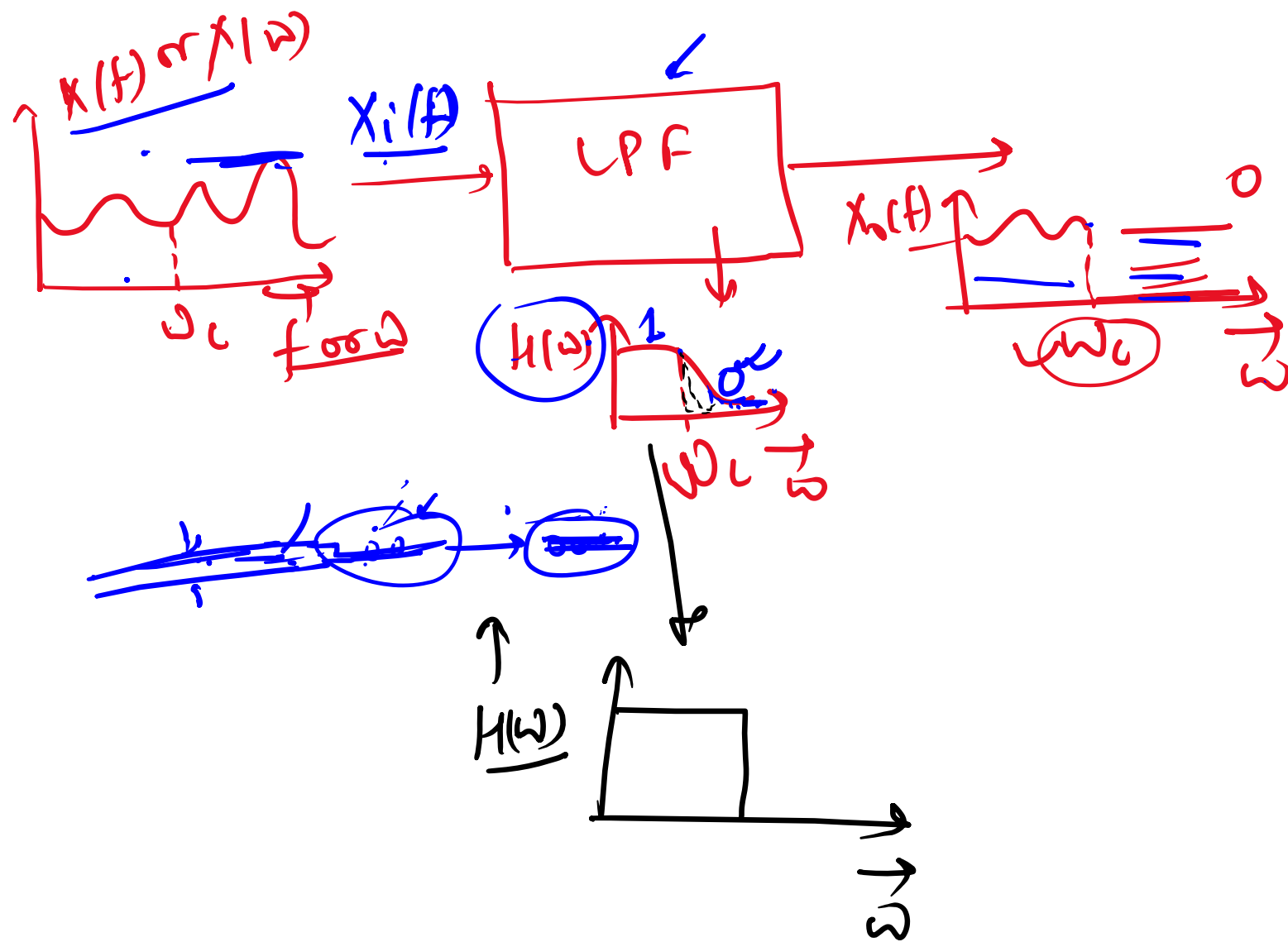
Transfer function

$$\underline{T.f.} = \frac{V_o(s)}{V_i(s)} = H(s)$$

$$H(s) = \frac{V_o(s)}{V_i(s)} = \frac{1}{1 + sRC} \Big|_{s=j\omega}$$

$$\begin{aligned} \rightarrow \omega = 0 ; H(\omega) &= 1 \\ \rightarrow \omega = \infty ; H(\omega) &= 0 \end{aligned}$$

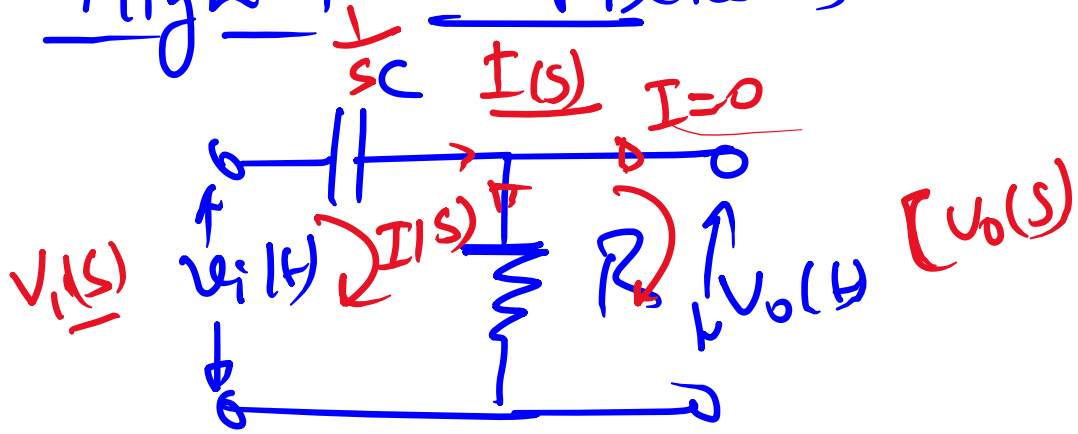




$$X_o(f) = H(f) \cdot X_i(f)$$

A Filter is
a frequency
selective device

High Pass Filter →



$$-V_i(s) + \frac{I(s)}{sC} + I(s) \cdot R = 0$$

$$V_i(s) = \left(R + \frac{1}{sC} \right) I(s) \quad \text{--- ①}$$

$$-I(s) \cdot R + V_o(s) = 0$$

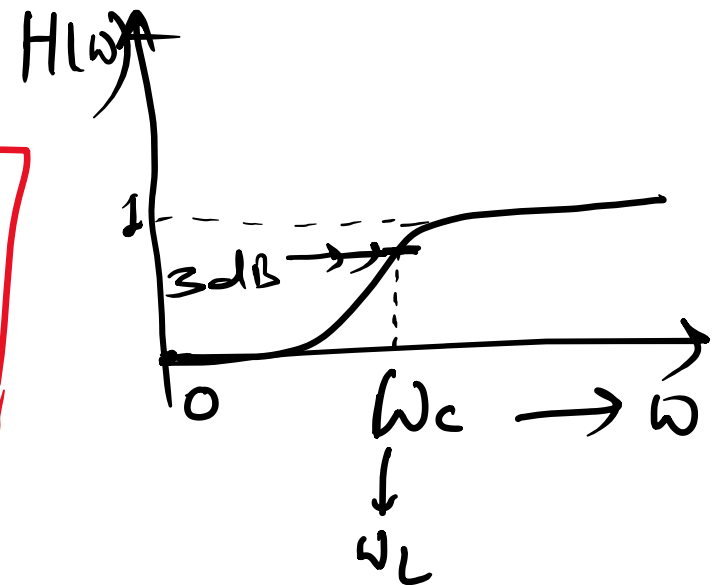
$$V_o(s) = I(s) \cdot R \quad \text{--- ②}$$

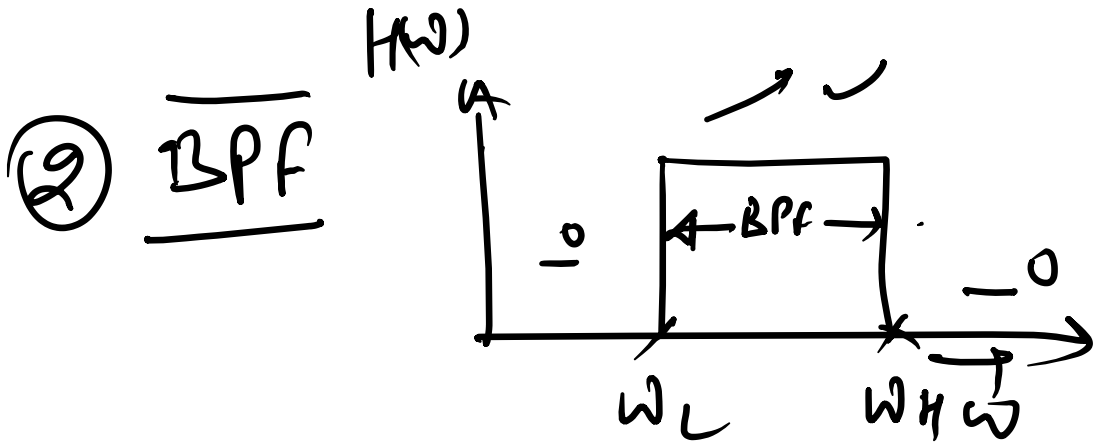
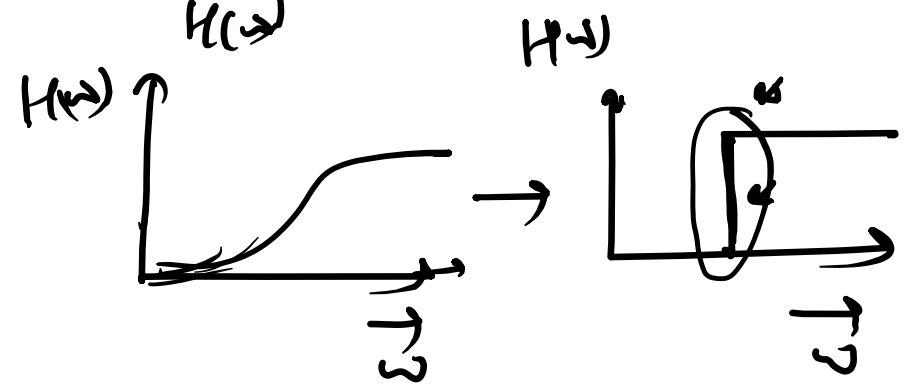
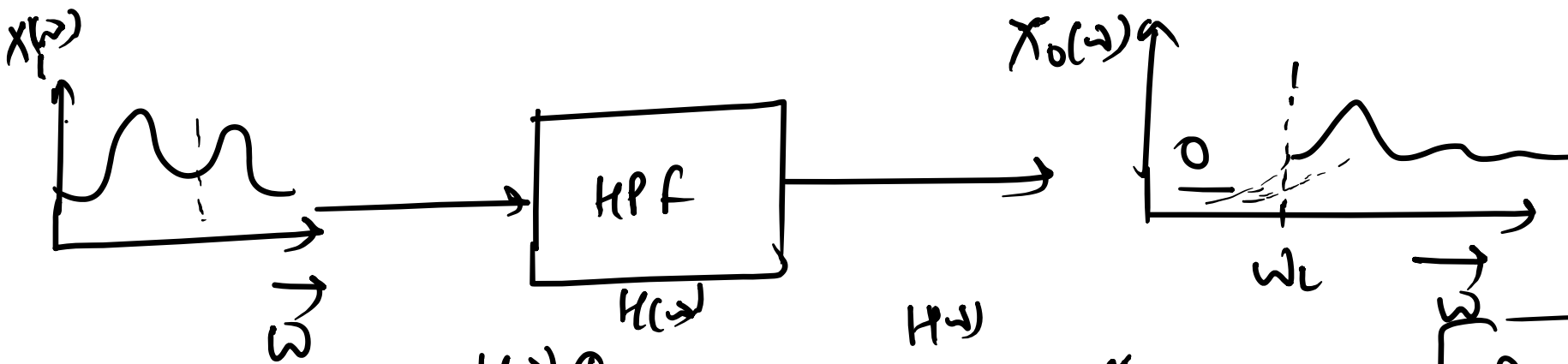
$$\frac{V_o(s)}{V_i(s)} = \frac{R}{R + 1/sC} = \frac{sCR}{1 + sCR} \quad \text{--- ③}$$

$$H(\omega) = \frac{j\omega CR}{1 + j\omega RC} \quad \text{--- ④}$$

$$\text{① } \omega = 0; H(\omega) = 0$$

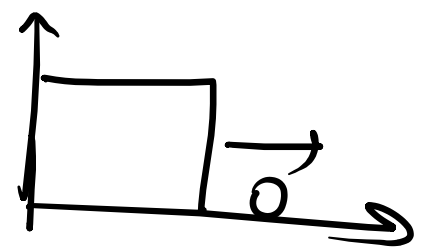
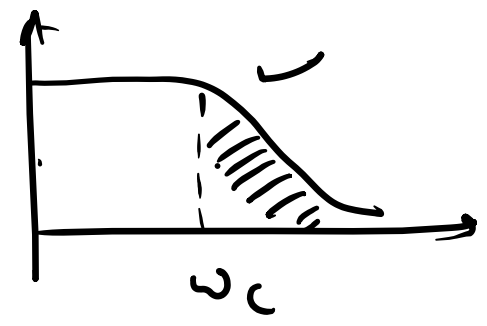
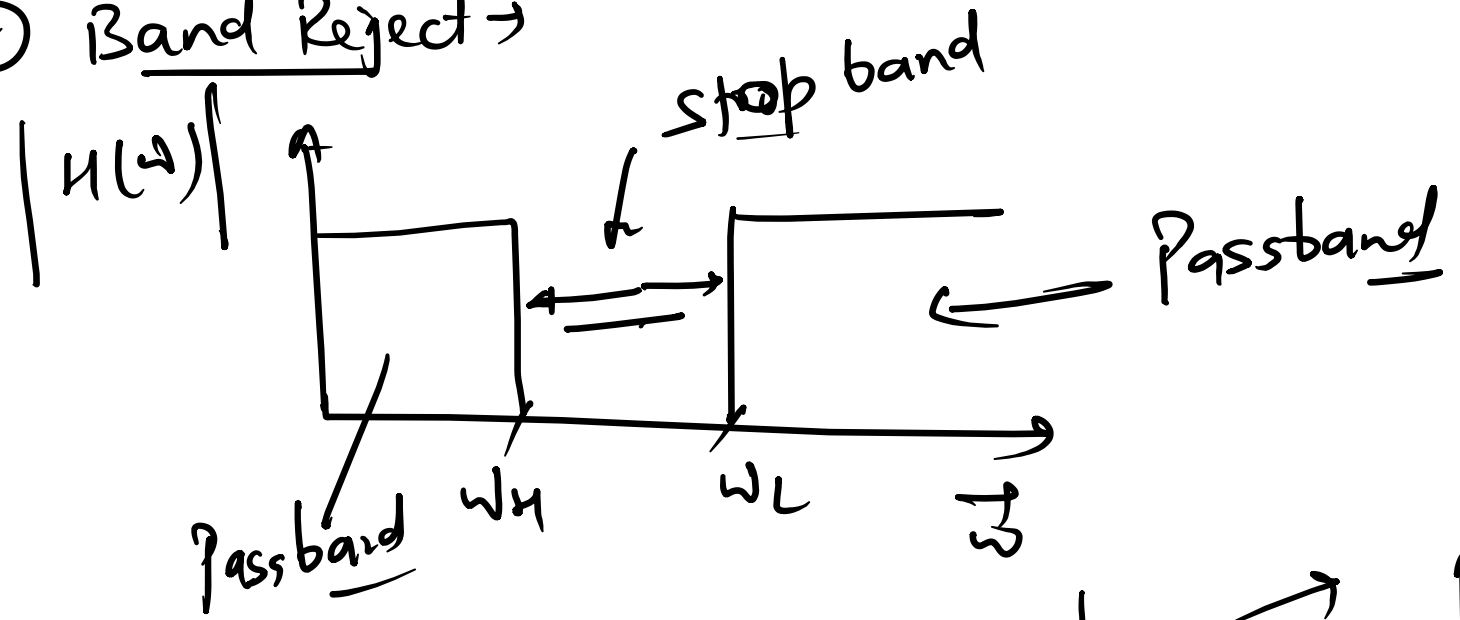
$$\text{② } \omega = \infty; H(\omega) = 1$$



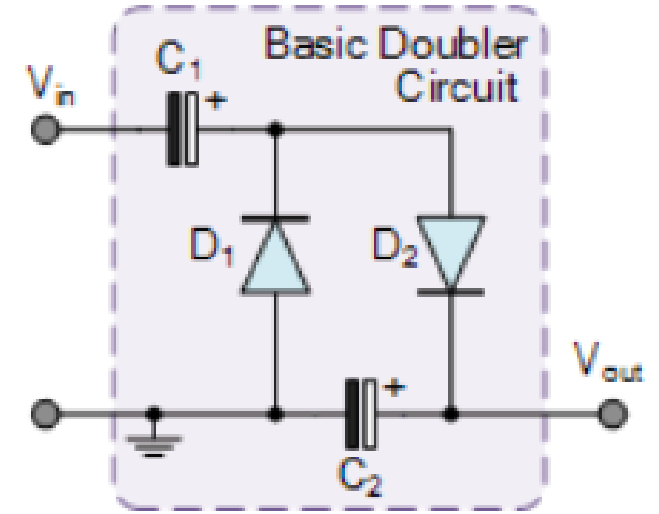
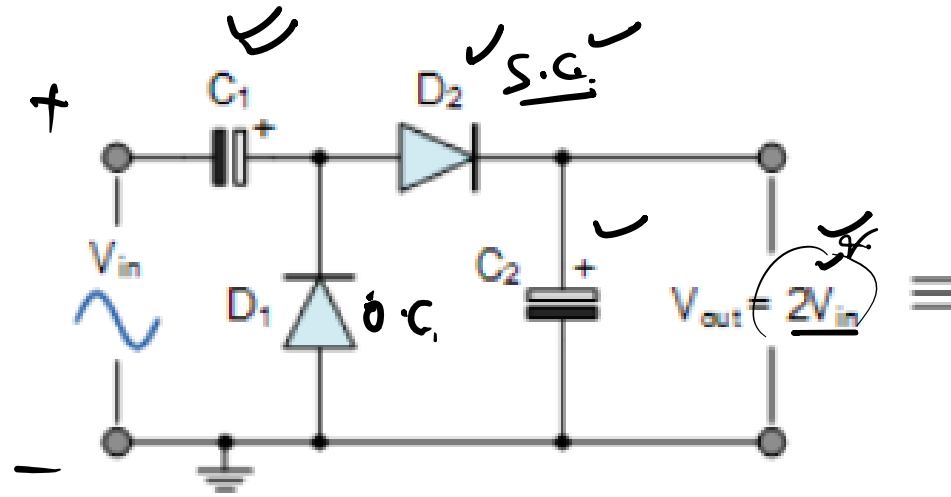


Q. How can we obtain the Sharp decay in Filter Characteristics.

④ Band Reject →

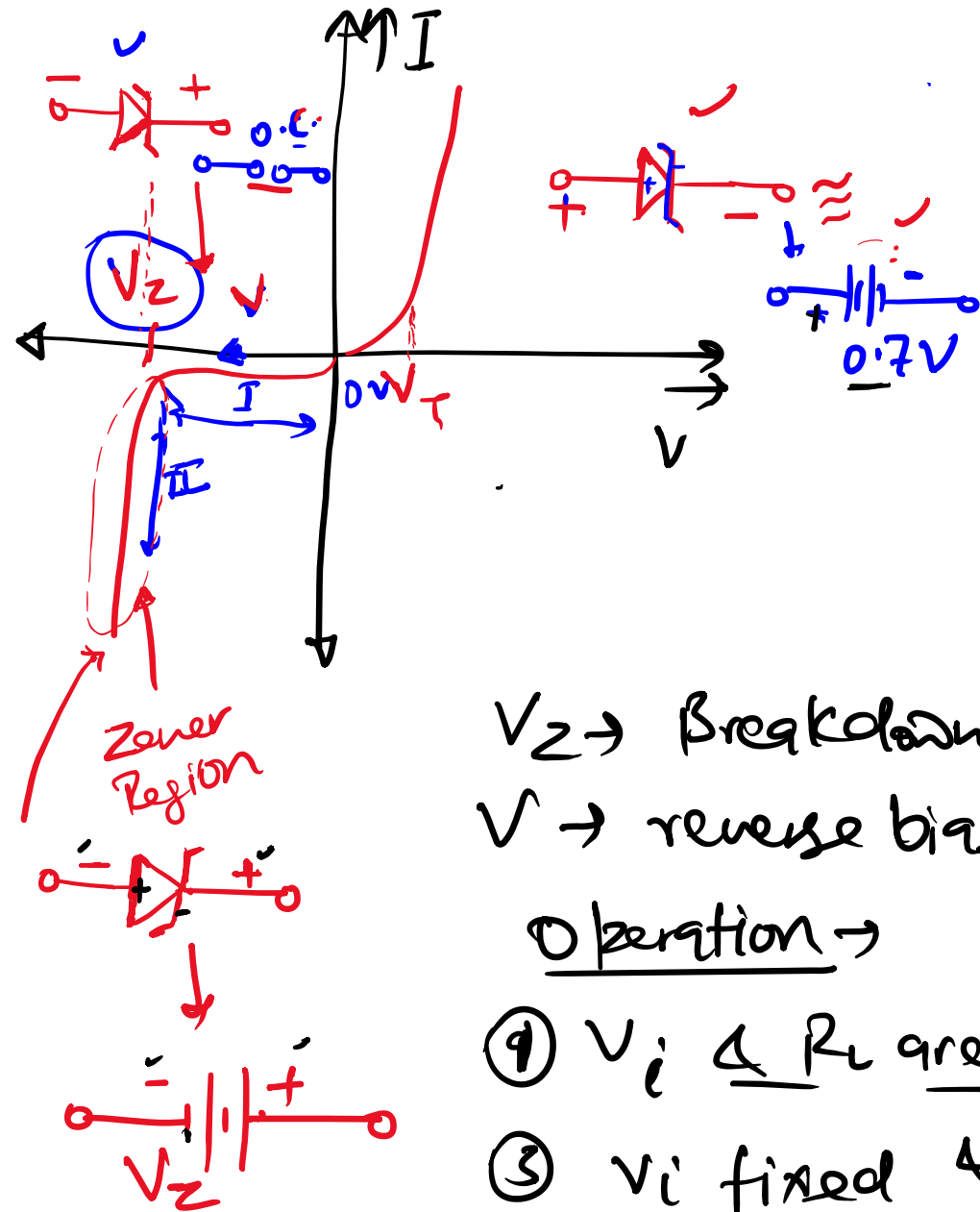


DC Voltage Doubler Circuit



Q write the operation of voltage doubler circuit.

Zener Diode →



① Works in reverse breakdown region called as "Zener" region.

② In F.B. region it operates as battery of Threshold voltage.

③ In reverse bias region →

① $V < V_Z \rightarrow$ Zener Diode acts as O.C.

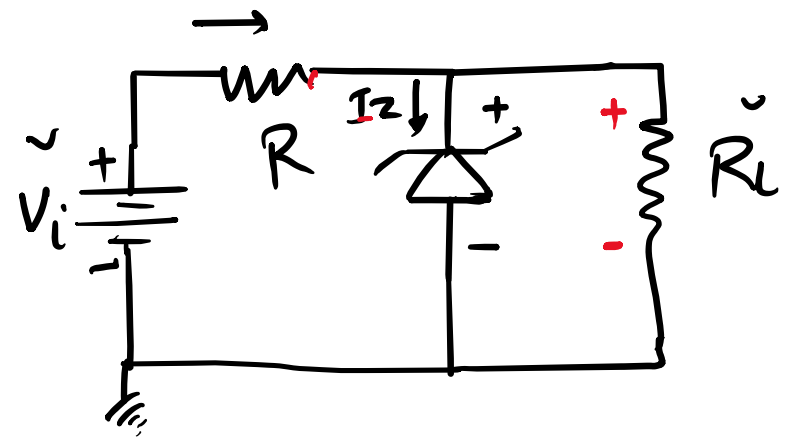
② $V > V_Z \rightarrow$ Zener diode acts as a voltage source of voltage across it as ' V_Z '.

$V_Z \rightarrow$ Breakdown Voltage
 $V \rightarrow$ reverse biased voltage

Operation →

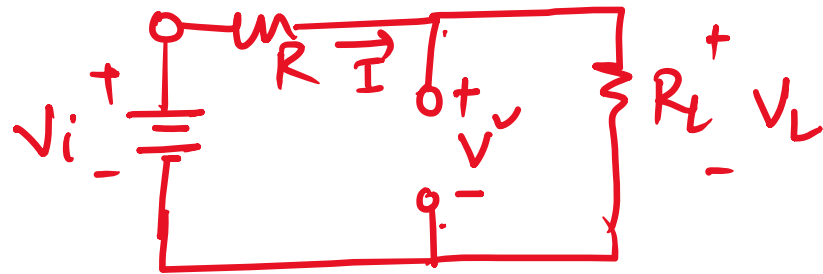
- ① V_i & R_L are fixed
- ② V_i variable and R_L fixed
- ③ V_i fixed & R_L variable.

① V_i & R_L are fixed



① Step 1

Remove Zener diode & apply a voltage source of voltage ' V '

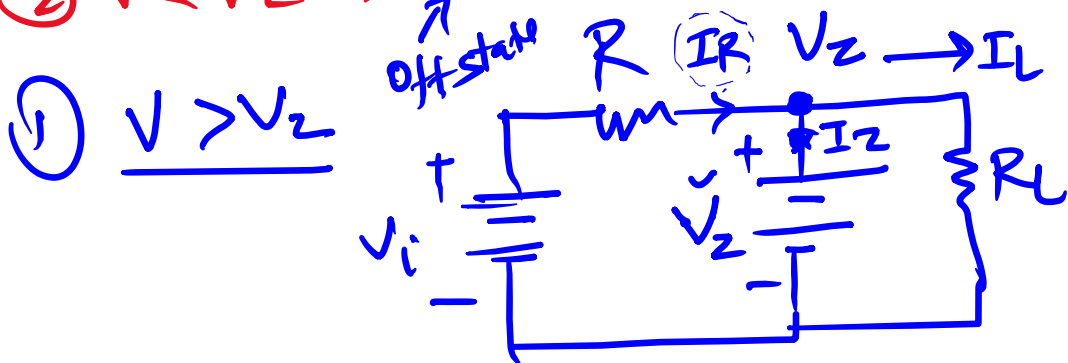


$$-V_i + IR + R_L I = 0$$

$$I = \frac{V_i}{R + R_L} \quad \text{--- ①}$$

$$\boxed{V = V_L = I \cdot R_L = \frac{V_i R_L}{R + R_L}}$$

① $\underline{V} > \underline{V}_Z \rightarrow$ Diode $\rightarrow \underline{V}_Z$ ↙ on state
 ② $\underline{V} < \underline{V}_Z \rightarrow$ Diode $\rightarrow$ O.C



$$I_L \neq I_Z = I_R \Rightarrow \boxed{I_Z = I_R - I_L}$$

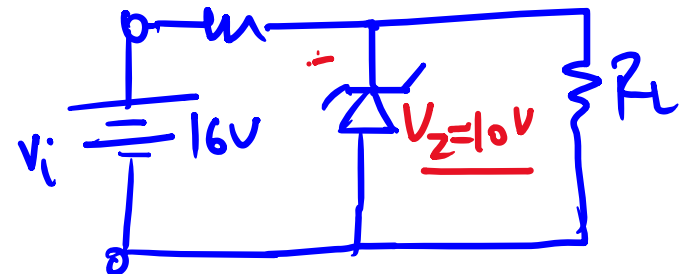
$$\boxed{I_Z = \frac{V_i - V_Z}{R} - \frac{V_Z}{R_L}}$$

$$\boxed{P_Z = V_Z I_Z}$$

Power dissipated by Zener Diode.

Example 3

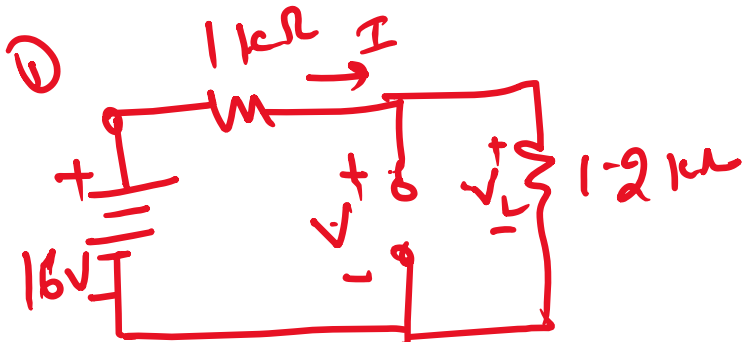
$R = 1 \text{ k}\Omega$



① Determine V_L , V_R , I_Z & P_Z for $R_L = 1.2 \text{ k}\Omega$

② " " " " " " $R_L = 3 \text{ k}\Omega$

①. check the voltage across the diode.



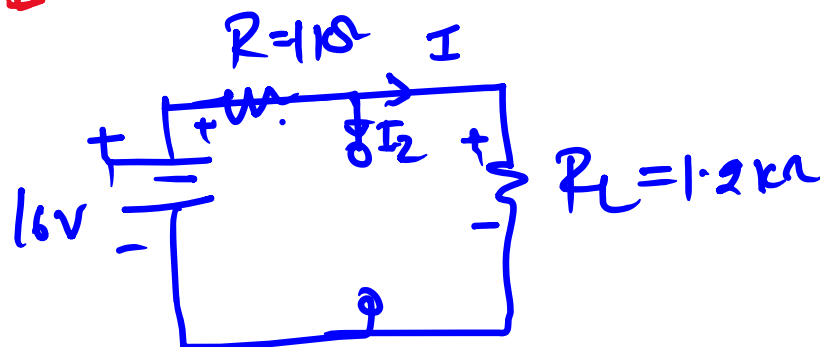
$$-16 + I(1 \times 10^3) + I(1.2 \times 10^3) = 0$$

$$I = \frac{16}{2.2 \times 10^3} = \frac{16}{2.2} \times 10^{-3} \text{ Amp.}$$

$$V = V_L = I \cdot R_L = \frac{16}{2.2} \times 10^{-3} \times 1.2 \times 10^3 = \frac{16 \times 1.2}{2.2} = \frac{96}{11} = 8.73$$

$$\boxed{V = 8.73 \text{ V}}$$

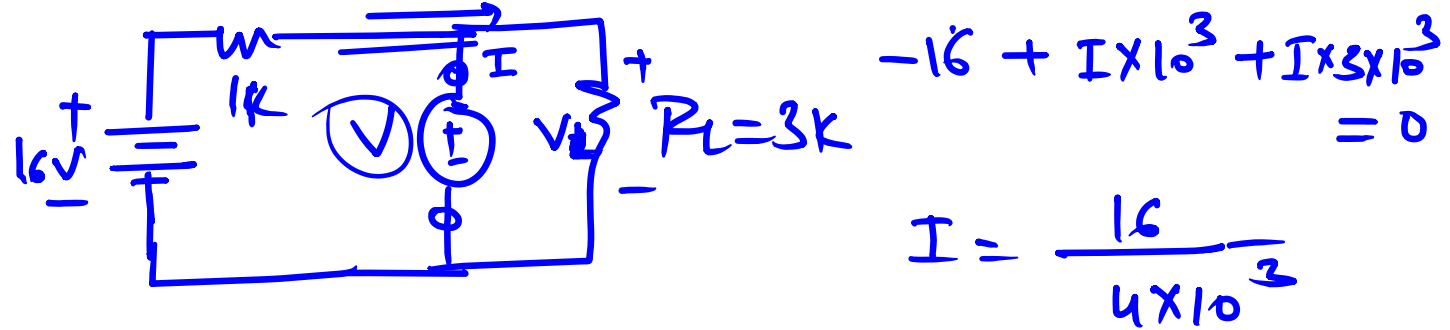
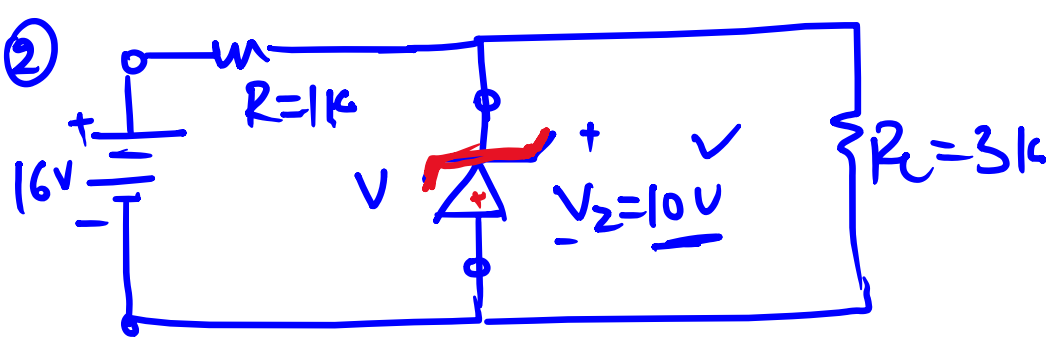
$V < V_Z \rightarrow \text{Diode} \rightarrow \text{O.C.}$



$$\begin{aligned} V_L &= I \cdot R_L \\ V_R &= I \cdot R \end{aligned}$$

$$I_Z = 0 \text{ Amp}$$

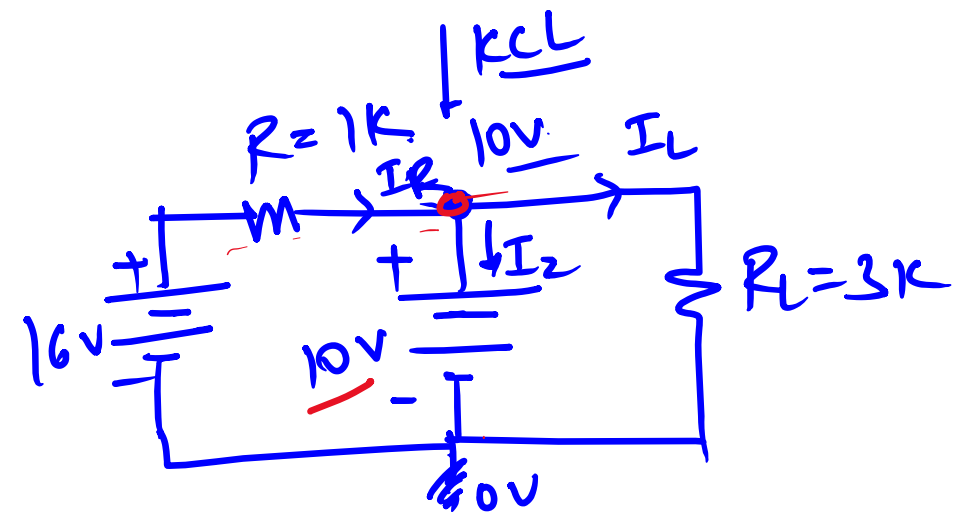
$$P_Z = V_Z \cdot I_Z = 0 \text{ W}$$



$$I = \frac{16}{4 \times 10^3}$$

$$I = 4 \times 10^{-3} \text{ Amp.}$$

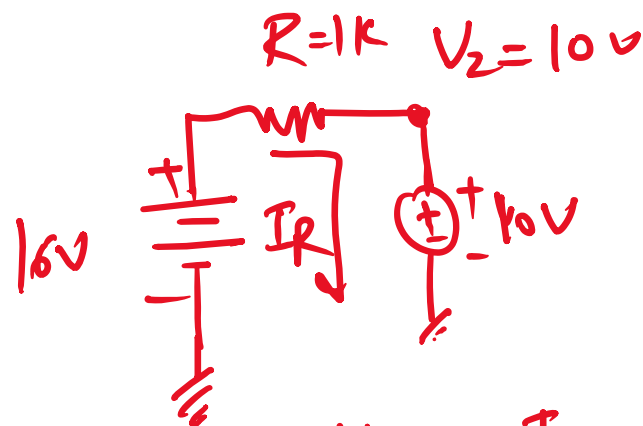
$$\rightarrow \text{V} = V_L = I \cdot R_L = \underline{\underline{12V}}$$



$$-I_R = \tilde{I}_L + \tilde{I}_Z \quad P_2$$

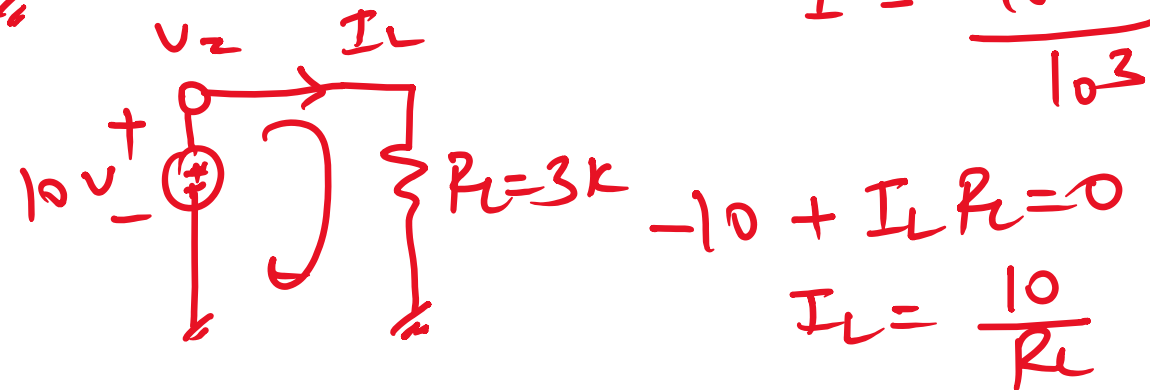
$$I_Z = \textcircled{I_R} - \textcircled{I_L}$$

$$\textcircled{I_Z} = \frac{16-10}{10^3} - \frac{10}{3 \times 10^3} =$$



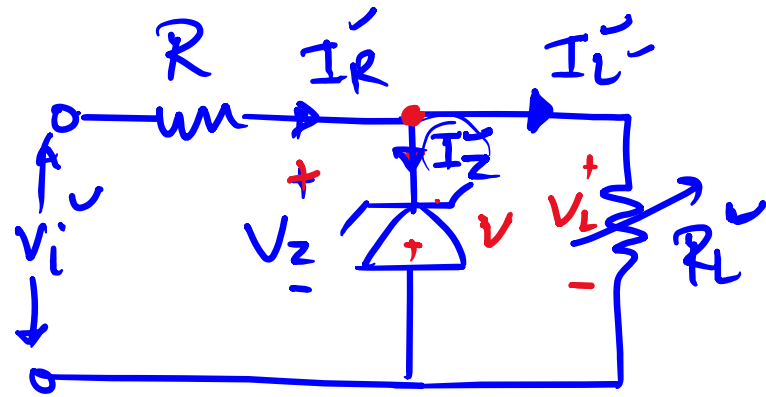
$$-16 + I \times 10^3 + 10 = 0$$

$$I = \frac{16-10}{10^3}$$



Zener diode as voltage regulator or regulated Power supply by using Zener diode -

② Fixed V_i & Variable R_L → ① $V < V_Z \rightarrow$ Z.D. will be O.C.



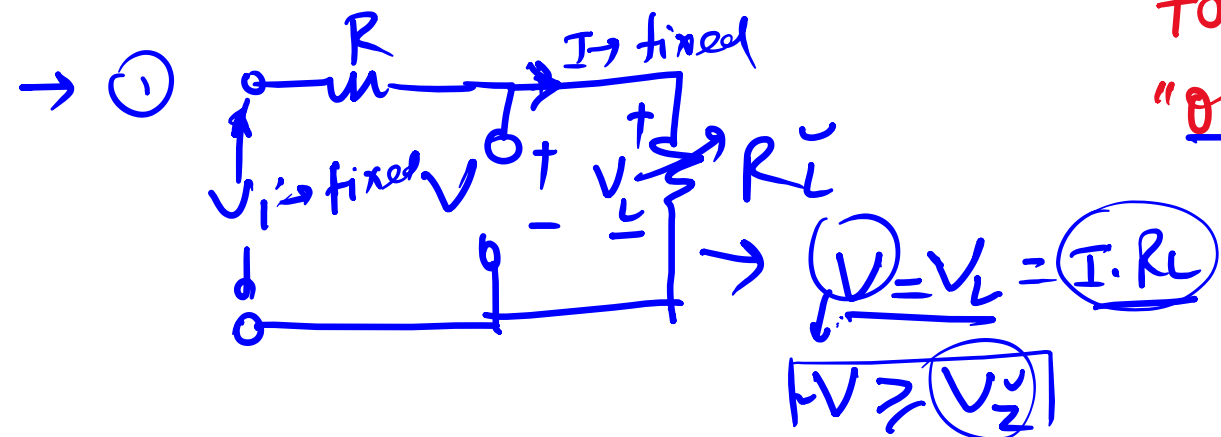
② $R_L \rightarrow$ variable resistance → ① R_{min}
② R_{max} } $[V \geq V_Z]$

$R_{min} \rightarrow$ minimum value of load resistance which makes the potential drop across it sufficient to bring the Zener diode in

"on state". → If $R_L < R_{min} \rightarrow$ Z.D. O.C.

for on state of Z.D. $R_L \geq R_{min}$
So that $V = V_Z = I R_L$

$V_i \rightarrow$ fixed $\rightarrow I_R \rightarrow$ fixed.



for "ON" state of Z.D $\rightarrow (R_L \geq R_{min})$

$$\underline{V} = \underline{V}_2 = \underline{V}_L = \frac{V_i R_L}{R + R_L} \Rightarrow$$

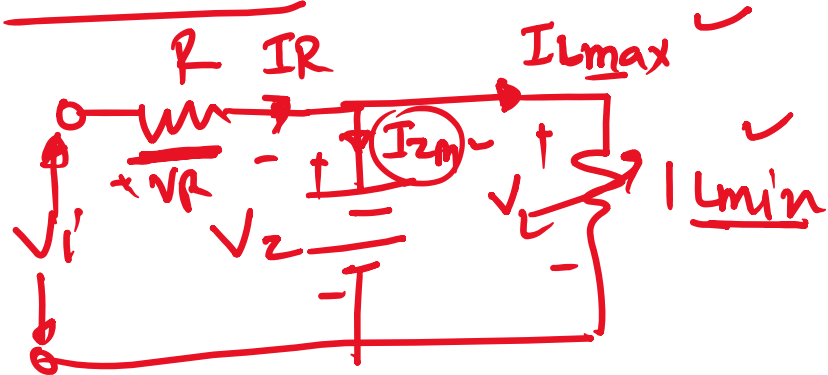
$$V_2 = \frac{V_i R_L}{R + R_L} \Rightarrow V_2 R + V_2 R_L = V_i R_L$$

$$V_2 R = (V_i - V_2) R_L$$

$$R_L = \frac{V_2 R}{V_i - V_2}$$

$$R_{min} = \frac{R V_2}{V_i - V_2}$$

for 'ON state' $\rightarrow$ Z.D $\rightarrow V_2$



$$I_{Lmax} = \frac{V_L}{R_{min}}$$

$$\rightarrow -V_i + \underline{I_R} R + V_2 = 0$$

$$V_R = V_i - V_2$$

$$I_R = \frac{V_R}{R}$$

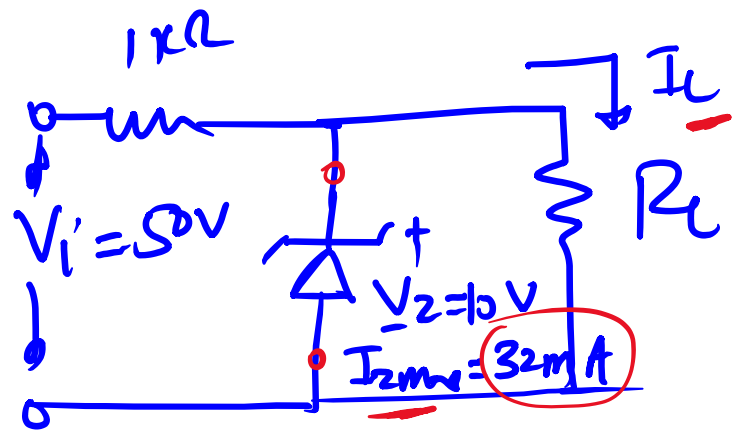
$$\underline{I_Z} = \underline{I_R} - \underline{I_{Lmax}}$$

Generally $I_{Z_{max}}$ is given in problems.
So we can find $I_{L_{min}}$

$$I_R = I_{Z_{max}} + I_{L_{min}} \Rightarrow \underline{I_{L_{min}}} = \underline{I_R} - \underline{I_{Z_{max}}}$$

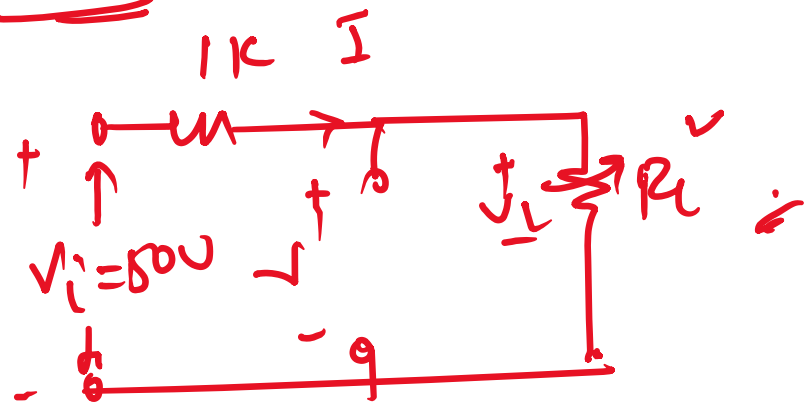
$$R_{L_{max}} = \frac{V_L}{I_{L_{min}}}$$

Q



- ① Determine the range of R_L & I_L that will result in V_{RL} being maintained at 10V.
- ② Determine the maximum wattage ratings of Z.D.

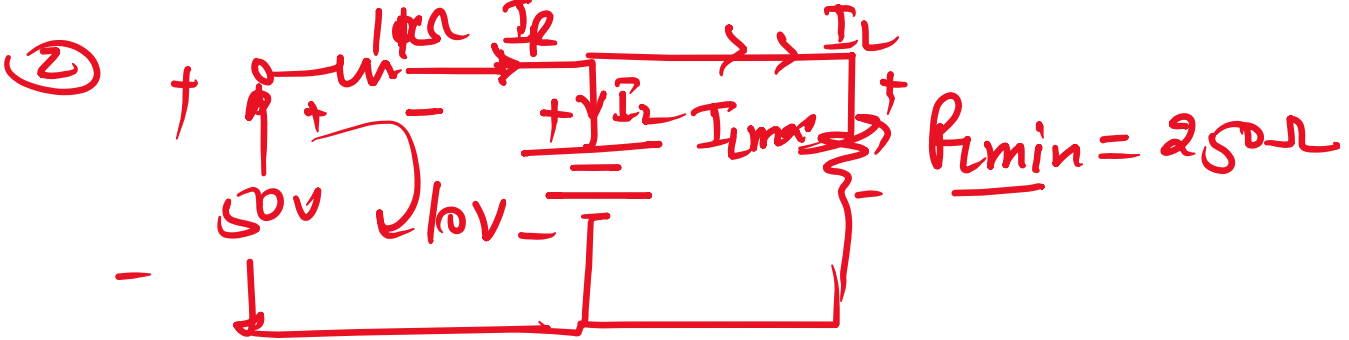
Solutions



$$V_L = \frac{V_i R_L}{R + R_L} \Rightarrow R_{Lmin} \Big|_{V=V_Z=V_L} = \frac{R V_Z}{V_i - V_Z}$$

$$R_{min} = \frac{10^3 \times 10}{50 - 10} = \frac{1}{4} \times 10^3 = 0.25 \text{ k}\Omega$$

$$\boxed{R_{min} = 250 \Omega} \rightarrow \text{makes Z.D. "ON"}$$



$$V_L = V_2 = 10V$$

$$I_{L\max} = \frac{V_L}{R_{\min}} = \frac{10}{250} = 0.04 A$$

$$\underline{I_{L\max} = 40 mA}$$

$$\rightarrow \underline{I_{L\max} = 32 mA} \rightarrow \underline{I_{L\min} \text{ \& } R_{L\max}}$$

$$I_L = \underline{I_R} - I_2$$

$$\underline{I_{L\min}} = \underline{I_R} - \underline{I_{2\max}}$$

$$I_{L\min} = 40 \times 10^{-3} - 32 \times 10^{-3}$$

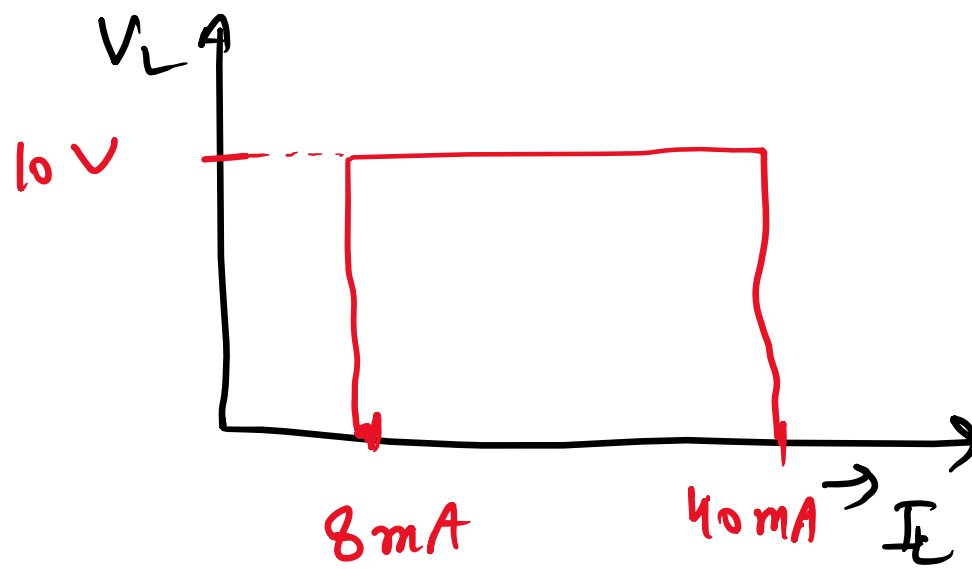
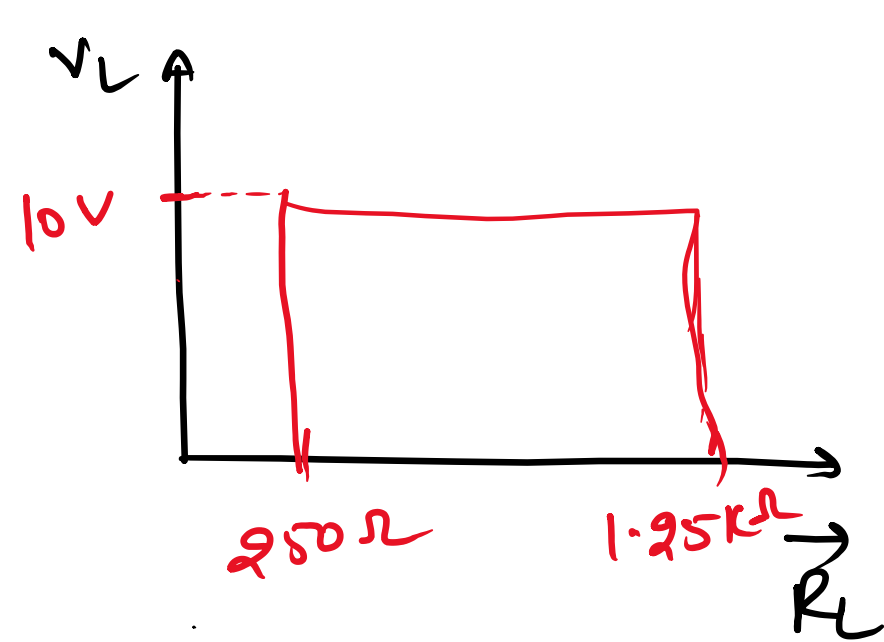
$$\underline{I_{L\min} = 8 mA}$$

$$I_R \Rightarrow -50 + I_R \times 10^3 + 10 = 0$$

$$I_R = \frac{40}{10^3} = 40 \mu A$$

$$R_{\max} = \frac{V_L}{I_{L\min}} = \frac{10}{8 \times 10^{-3}}$$

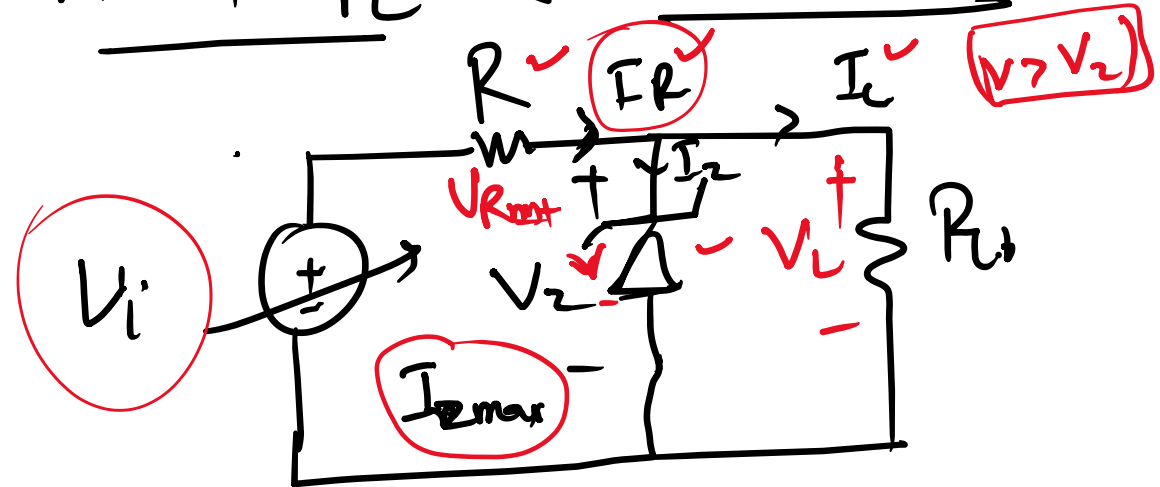
$$\underline{R_{\max} = 1.25 k\Omega}$$



(ii) $\rightarrow$ $\underline{P_{max}} = V_Z (I_{Zmax}) = 10 \times 32 \times 10^{-3}$
 $= \underline{320 \text{ mW}}$

Ans

③ Fixed R_L & Variable V_i



$V_L = V_Z \Rightarrow$ for 'ON state' of ZD

$$V_L = V_Z = \frac{V_i R_L}{R + R_L}$$

$$V_{imin} = \frac{V_Z (R + R_L)}{R_L}$$

q

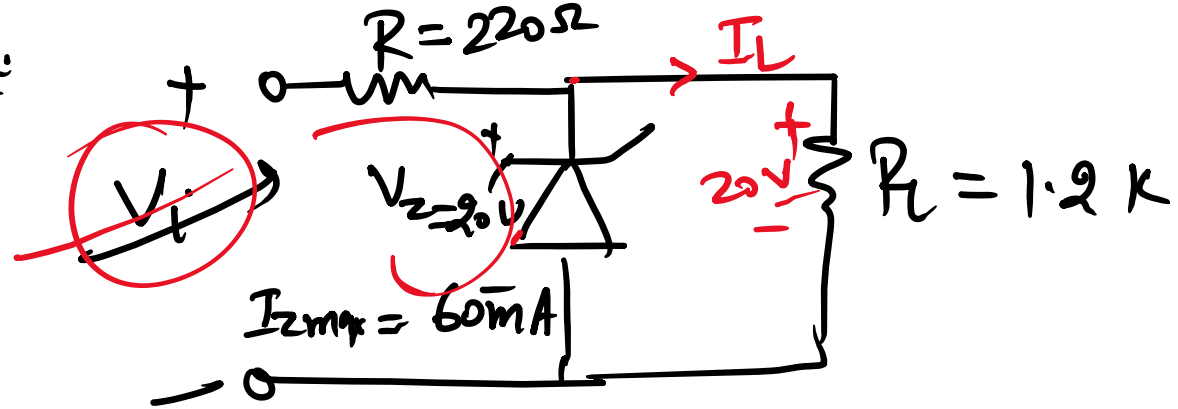
This is the minimum value of V_i that brings the ZD in 'ON state'.

$I_L \rightarrow$ fixed

$$I_R = I_Z + I_L \Rightarrow I_{Zmax} + I_L = I_{Rmax}$$

$$V_{imax} = V_{Rmax} + V_Z$$

Q.



Determine the range of V_i for which Z.D is maintained in "ON" state.

Solution $\rightarrow V_{i\min} = \frac{\bar{V}_z (\bar{R}_L + \bar{R})}{\bar{R}_L} = \frac{20 (1.2 \times 10^3 + 220)}{1.2 \times 10^3}$

$$V_{i\min} = 23.67 \text{ V}$$

$$I_{z\max} = 60 \text{ mA}$$

$$I_L = \frac{20}{1.2 \text{ k}} = \frac{20}{1.2} \times 10^{-3} = 16.67 \text{ mA}$$

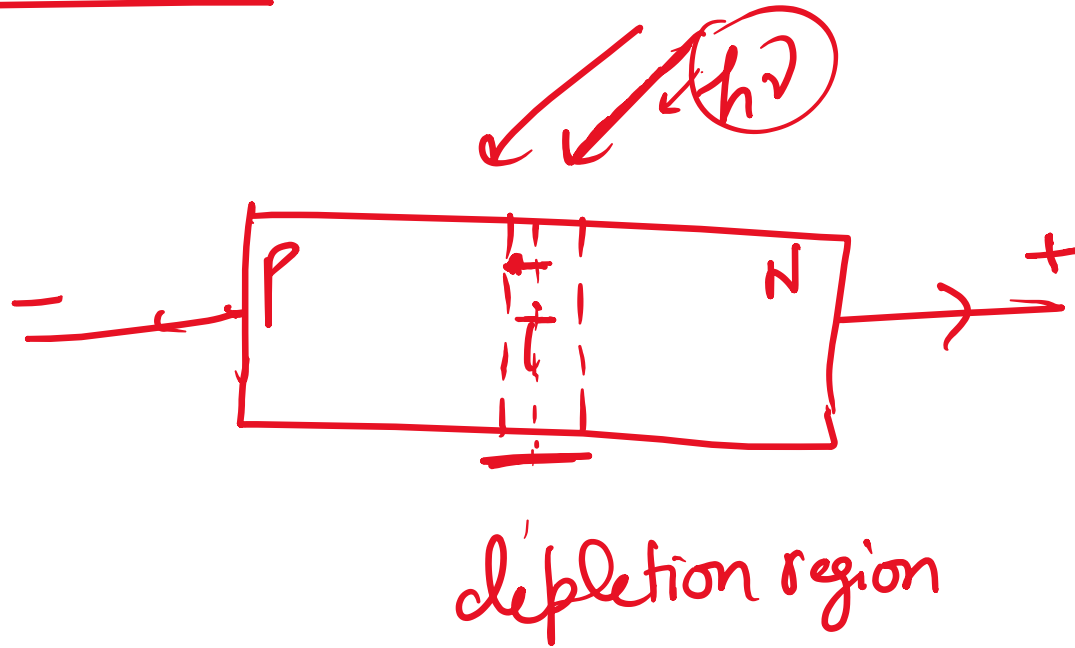
$$I_{z\max} = I_{R\max} - I_L$$

$$I_{R\max} = 60 \text{ mA} + 16.67 \text{ mA}$$

$$I_{R\max} = 76.67 \text{ mA}$$

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

Photo Diode



operates in R.B.

$$I = \underbrace{I_{\text{dark}}}_{\substack{\downarrow \\ \text{Without Photon} \\ \text{interaction}}} + \underbrace{I_{\text{terminal}}}_{\substack{\downarrow \\ \text{desired}}}$$

undesired

desired