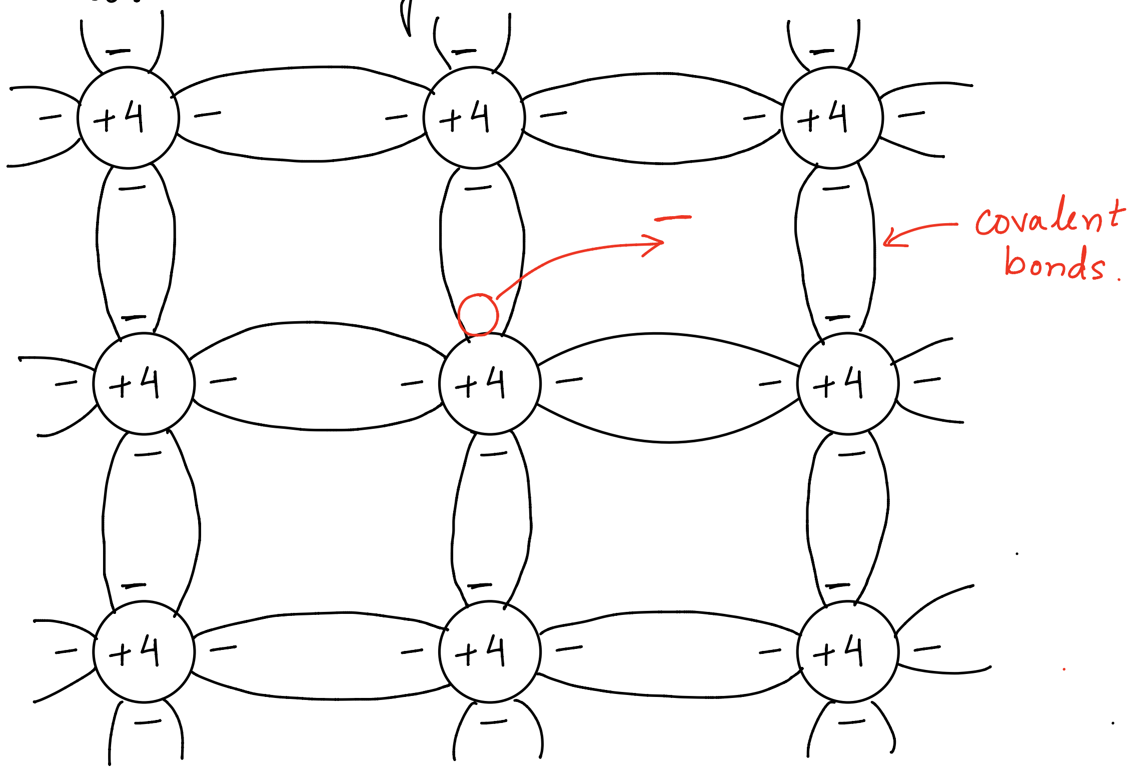
Semiconductor Devices.

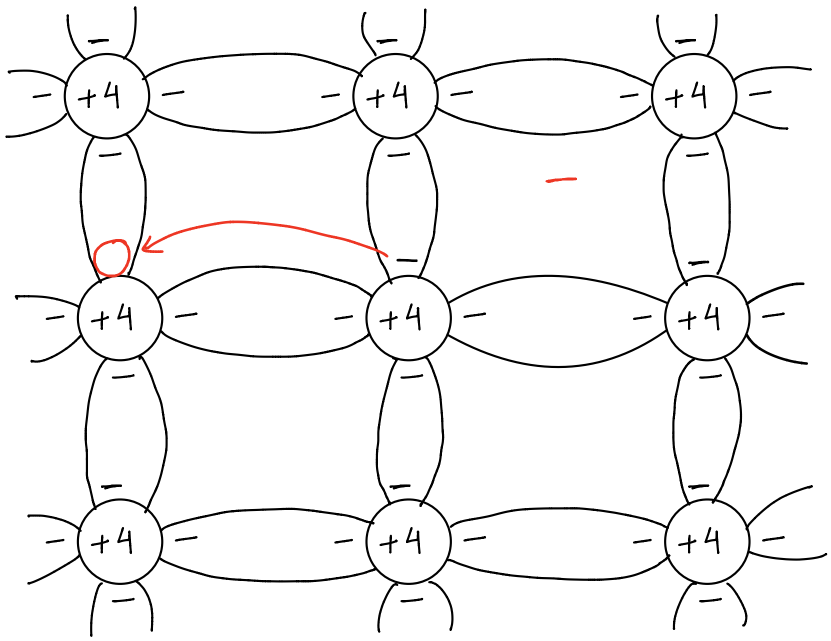
- ✓ It has a conductivity between conductor and insulator.
- ✓ Conductors: copper, aluminium, gold
- ✓ Insulators : Glass (SiO_2)
- ✓ Most commonly used semiconductor : Silicon



→ Pure silicon also called as intrinsic silicon is a bad conductor at 0K as all of its covalent bonds are intact.

→ As temperature increases, some of the covalent bond breaks generating holes and electrons.

Charge Movement by the electron and holes



→ There can be conduction of current by movement of free electrons and holes.

→ Movement of electrons is almost 2.5 times faster than that of holes.

Generation and Recombination

→ At a given temperature, number of electrons and holes are equal and constant per unit volume.

→ And at equilibrium condition

Rate of generation = rate of recombination

→ So, $\boxed{n = p = n_i}$

where n and p are concentration of electrons & holes, respectively (per unit volume). And

$$n_i = B\,T^{3/2}\,e^{-E_g/2kT}$$

where B: material dependent parameter and for silicon it is $7.3 \times 10^{15}\, cm^{-3} K^{-3/2}$

T: temperature in K

Eg: bandgap energy (1.12 eV for Si)

k: Boltzmann's constant (8.62×10^{-5} eV/K)

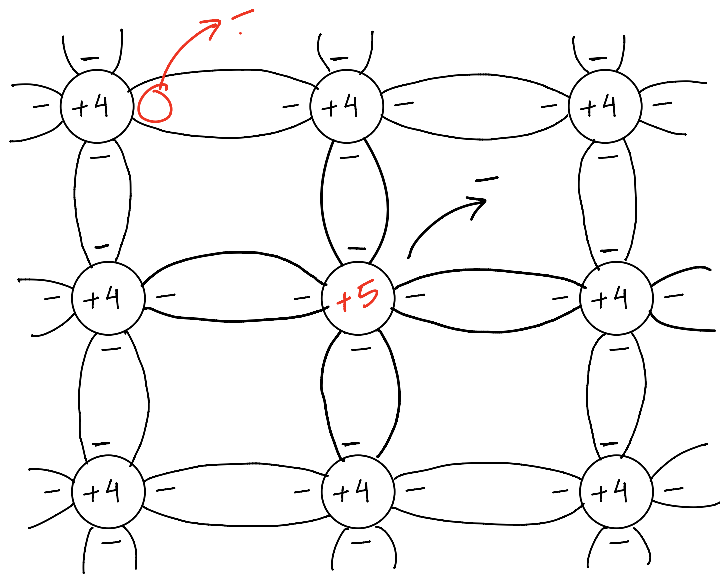
$n_i \simeq 1.5 \times 10^{10} / cm^3$ at room temperature ($T = 300\,K$)

$$\boxed{np = n_i^2}$$

* This is not high enough for considerable amount of current conduction.
* Temperature dependent parameter

n-type semiconductor

- ✓ It is a doped semiconductor.
- ✓ Element with valence 5 like phosphorus are added.



- ✓ n-type semiconductor is a netural material
- ✓ No change in silicon crystal structure.
- ✓ If concentration of donor atoms is N_D and if $N_D >> n_i$, then the free electrons in n-type material is

$$n_n \simeq N_D$$

concentration of electrons

n-type material

- ✓ So it is no more dependent on temperature.

$$\boxed{p_n n_n = n_i^2}$$

✓ The concentration of the holes from thermal generation at equilibrium can be still given by the above equation.

$$p_n = \frac{n_i^2}{n_n} \simeq \boxed{\frac{n_i^2}{N_D}}$$

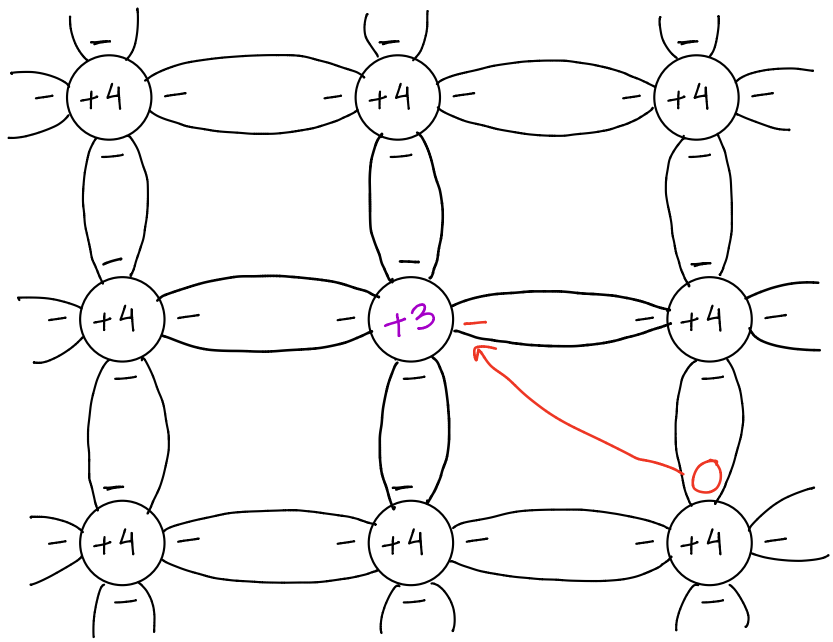
✓ Electrons are majority charge carrier.

✓ Holes are minority charge carrier.

n-type semi conductor

p-type semiconductor

- ✓ It is another type of doped semiconductor
- ✓ Element with valence 3 are added.



- ✓ If the concentration of acceptor atoms is N_A and $N_A \gg n_i$ then

by doping →
$$p_p \simeq N_A \quad \text{(majority charge carriers)}$$

by thermal generation →
$$n_p \simeq \frac{n_i^2}{N_A} \quad \text{(minority charge carriers)}$$

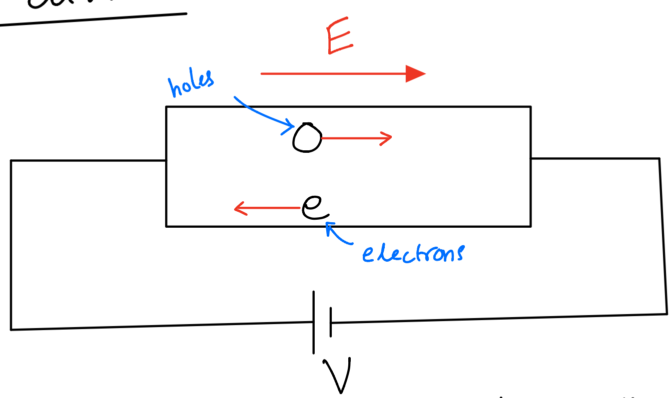
Current Flow in Semiconductor

- Drift current
- Diffusion current

Drift current is electric current due to the motion of charge carriers under the influence of an external electric field

Diffusion current is due to concentration gradient of charge carriers across the junction and it is due to majority charge carriers

Drift current



The velocity acquired by the holes is

$$v_{p\text{-drift}} = \mu_p E$$

where μ_p is a constant called hole mobility.
It's unit is $cm^2/V \cdot s$

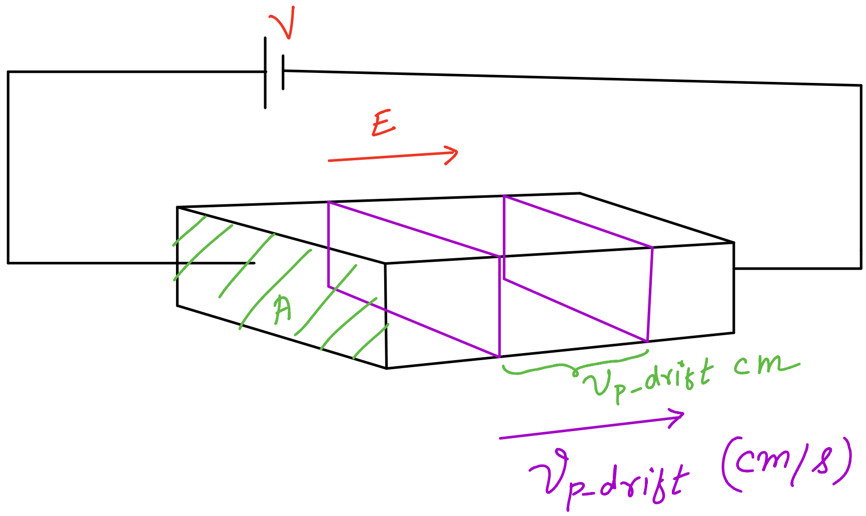
Similarly, the velocity of the electron is

$$v_{n\text{-drift}} = -\mu_n E$$

where μ_n is the mobility of the electrons.

$$\boxed{\frac{\mu_n}{\mu_p} = 2.5}$$

Drift current due to the holes & electrons.



Amount of charge in the box $= A v_{p\text{-drift}} p q$

$$I_p = A q p v_{p\text{-drift}} = A q p \mu_p E$$

So, the current density due to the holes is

$$\boxed{J_p = \frac{I_p}{A} = q p \mu_p E}$$

So, for electrons the current is given by

$$I_n = -A q n v_{n\text{-drift}} = A q n \mu_n E$$

$$\boxed{\therefore \quad J_n = \frac{I_n}{A} = q n \mu_n E}$$

$$\therefore \; J_{tot} = J_p + J_n = \underbrace{q(p\mu_p + n\mu_n)}_{} E$$

$$\sigma = q(p\mu_p + n\mu_n) \longrightarrow \text{conductivity.}$$

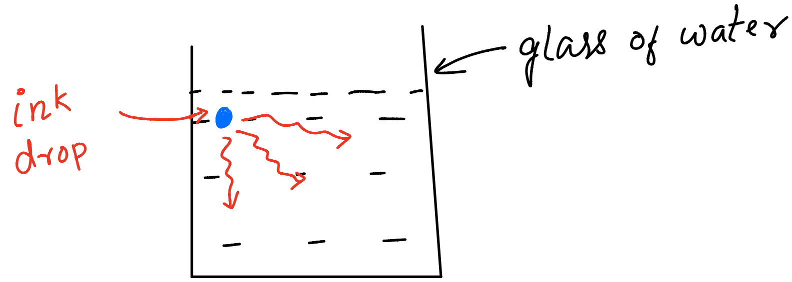
$$\rho = \frac{1}{\sigma} = \frac{1}{q(p\mu_p + n\mu_n)} \longrightarrow \text{resistivity.}$$

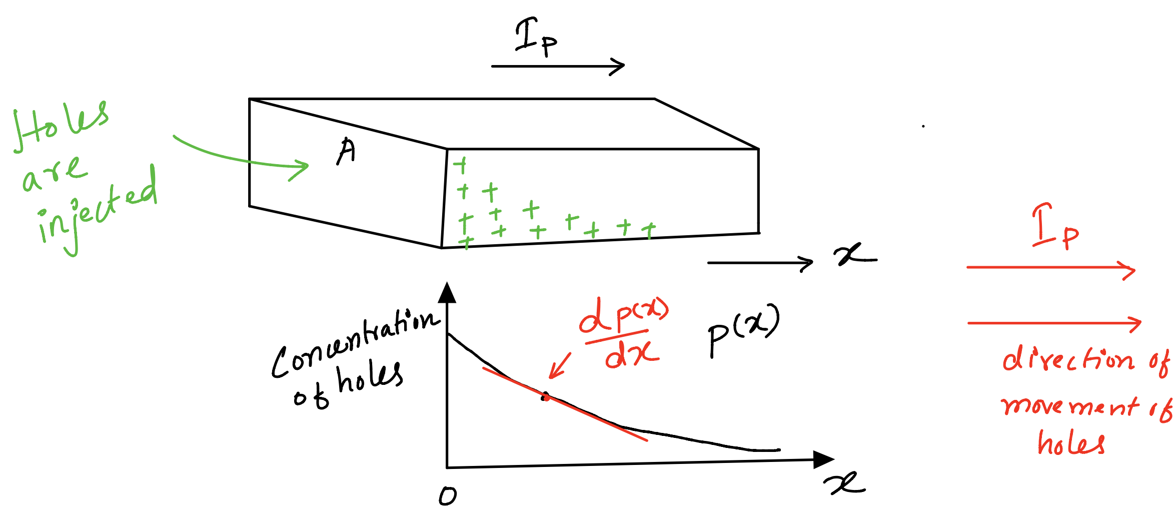
$$\boxed{J_{tot} = \frac{1}{\rho} E}$$

$$\frac{I_{tot}}{A} = \frac{1}{\rho} \frac{V}{L}$$

$$\Rightarrow \; V = \underbrace{\frac{\rho L}{A}}_{\text{Resistance}} I_{tot}$$

Diffusion currents due to holes and electrons.





✓ The magnitude of current at any point is proportional to the slope of concentration profile or gradient.

$$I_p \propto -\frac{dp(x)}{dx}$$

$$I_p \propto -Aq\frac{dp(x)}{dx}$$

$$\therefore I_p = -Aq D_p \frac{dp(x)}{dx}$$

$$\therefore \quad \boxed{J_p = \frac{I_p}{A} = -q D_p \frac{d\,p(x)}{dx}}$$

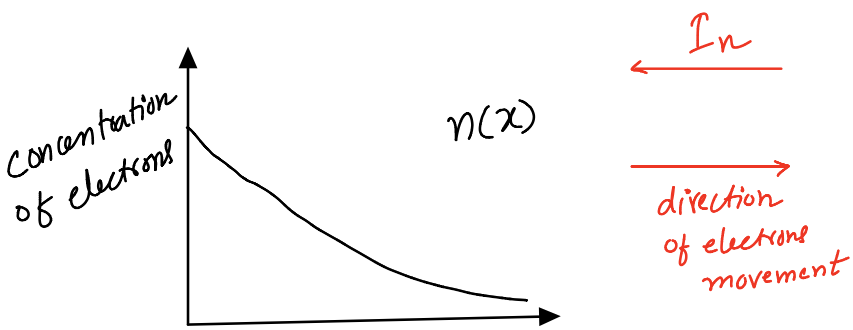
where $J_p \rightarrow$ diffusion current density (A/cm^2)

$q \rightarrow$ charge of holes

$D_p \rightarrow$ diffusion constant

$p(x) \rightarrow$ concentration of the holes at x

Diffusion current for electrons



$$J_n = q D_n \frac{d\,n(x)}{dx}$$

For holes and electrons the typical value of diffusion constant is

$$D_p = 12 \ cm^2/s$$

$$D_n = 35 \ cm^2/s$$

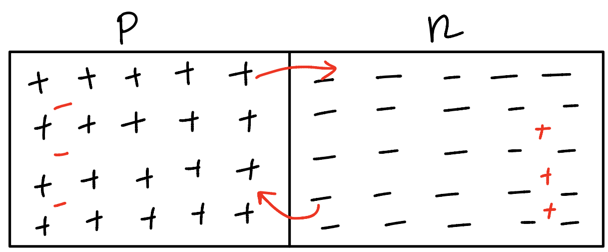
Einstien Relation

$$\boxed{\frac{D}{\mu} = \frac{kT}{q} = V_T}$$

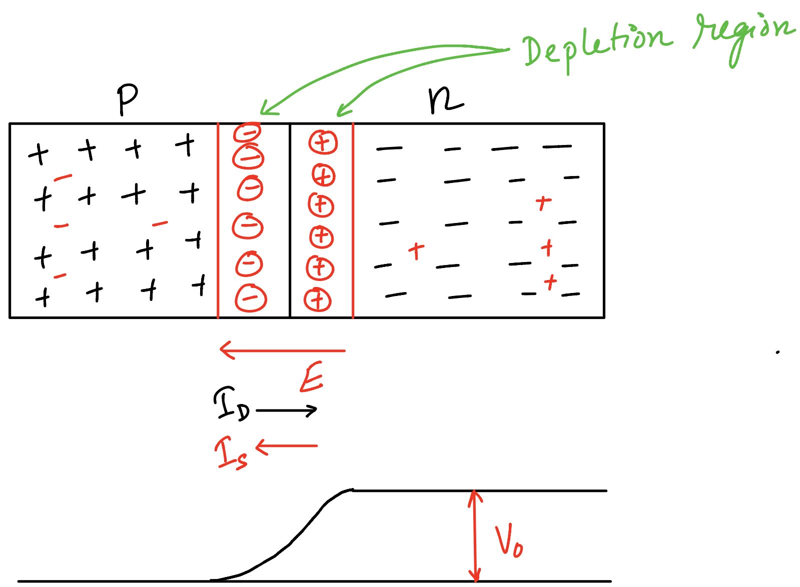
$V_T = 26mV$ at $T = 300K$

(room temp)

pn junction



So, in equilibrium $I_D = I_S$



- ✓ Carriers are depleted from the depletion region.
- ✓ An electric field E is created that prevents the diffusion of holes and electrons on either side.
- ✓ Also, it results in a barrier potential V_0 which decreases I_D to a great extent. And I_D is dependent on V_0.
- ✓ Minority charge carriers on both sides will result in a drift current.

However, it is not dependent on V_0. It is only dependent on temperature.

✓ In equilibrium,

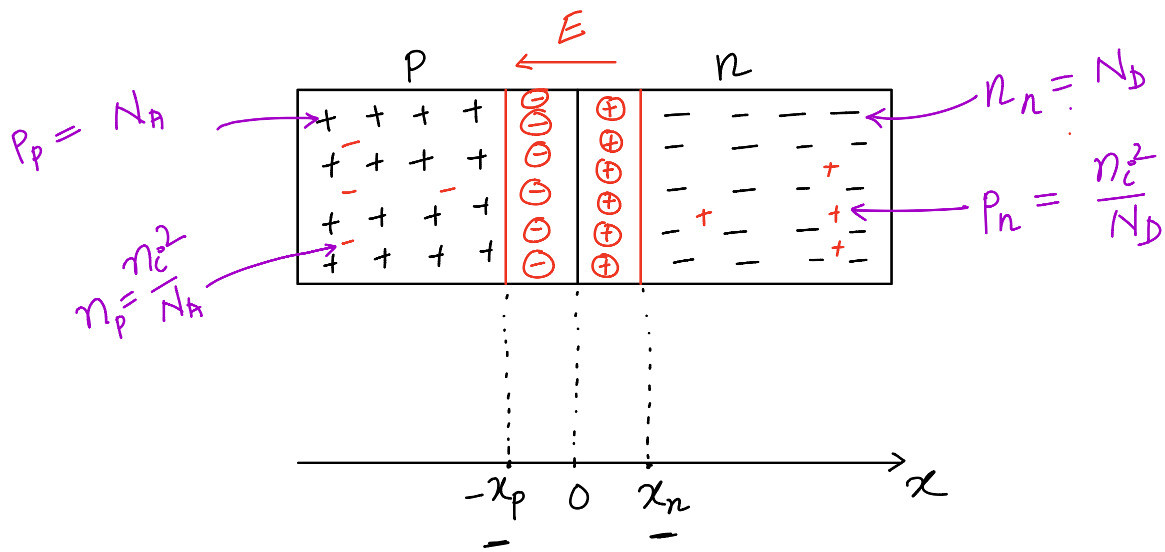
$$\boxed{I_D = I_S}$$

✓ So, $I_S \uparrow$ $I_D \uparrow$ $V_0 \downarrow$ / $I_S \downarrow$ $I_D \downarrow$ $V_0 \uparrow$

✓ $I_{drift,p} = I_{diff,p}$ | $I_{drift,n} = I_{diff,n}$

The barrier potential is the potential difference across the depletion layer between the p and the n regions of a semiconductor. It is known as the barrier potential since it opposes the flow of the charge carriers on either side of the semiconductor.

Derivation of barrier potential



$$I_{drift,p} = I_{diff,p}$$

$$\Rightarrow \cancel{q}\mu_p p(-E) = -\cancel{q} D_p \frac{dp}{dx}$$

Since, $E = -\frac{dV}{dx}$

$$\Rightarrow \mu_p p \frac{dV}{\cancel{dx}} = -D_p \frac{dp}{\cancel{dx}}$$

$$\Rightarrow \int_{-x_p}^{x_n} dV = -\frac{D_p}{\mu_p}\int_{p_p}^{p_n} \frac{dp}{p}$$

$$\Rightarrow \underbrace{V(x_n) - V(-x_p)} = -\frac{KT}{q} \ln p \Big|_{p_p}^{p_n}$$

$$\Rightarrow V_0 = \frac{KT}{q} \ln\left(\frac{p_p}{p_n}\right) \qquad \begin{cases} p_p = N_A \\ p_n = \dfrac{n_i^2}{N_D} \end{cases}$$

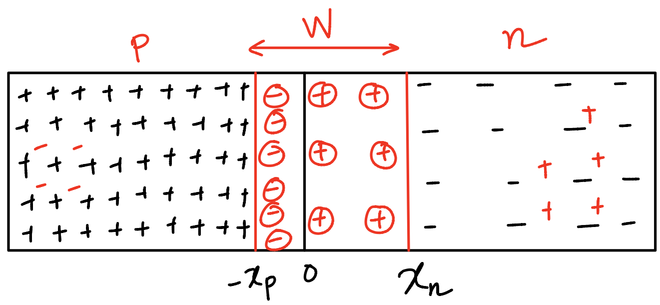
$$\therefore \quad \boxed{V_0 = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

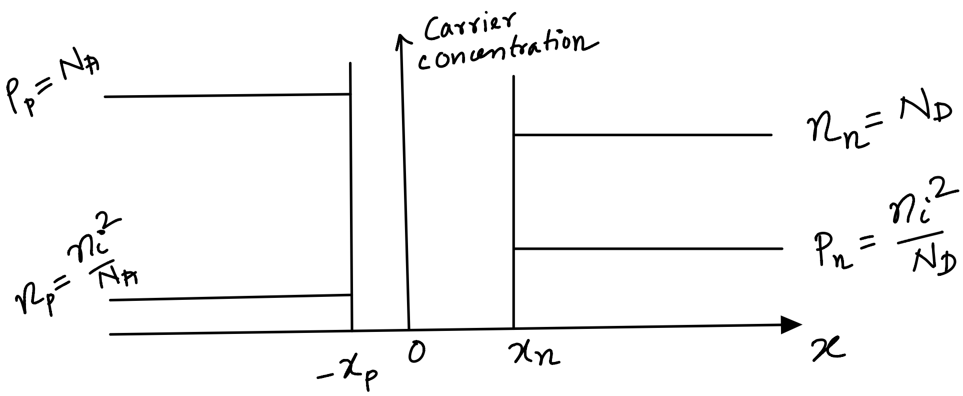
Where $N_A \longrightarrow$ doping concentration of p-side
$N_D \rightarrow$ " " " n-side

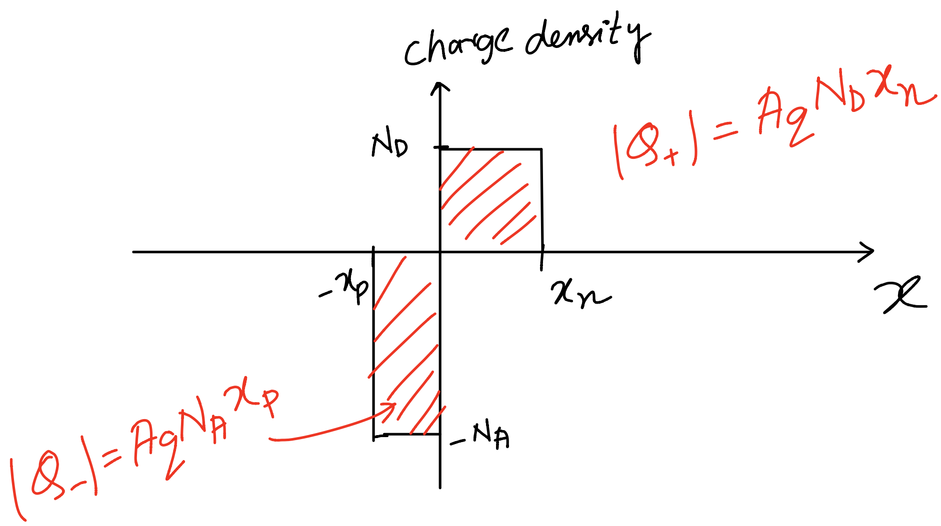
✓ For silicon at $T = 300K$, V_0 varies from 0.6V to 0.9V

Width of the depletion Region.

Consider $N_A > N_D$







$$|Q_-| = |Q_+|$$

$$\Rightarrow A q N_A x_p = A q N_D x_n$$

$$\boxed{\therefore \frac{x_n}{x_p} = \frac{N_A}{N_D}}$$

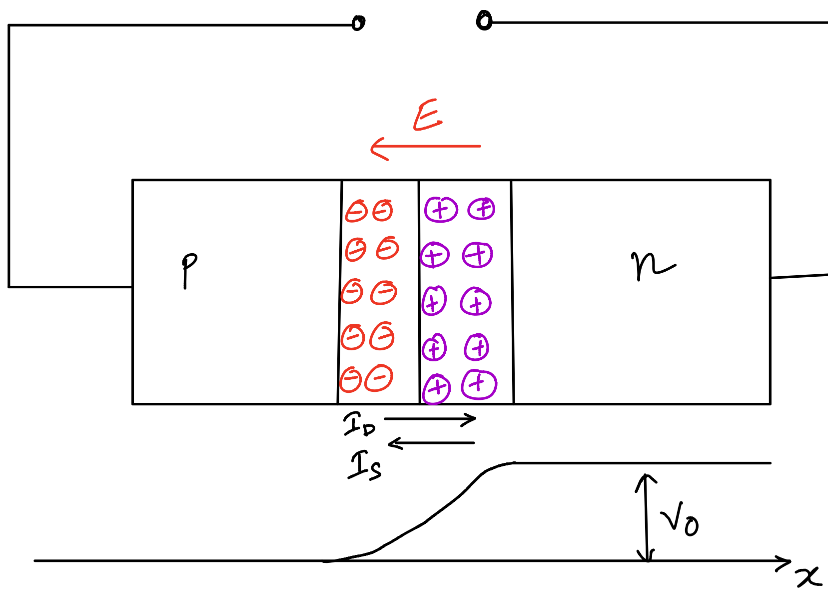
$$\boxed{W = x_n + x_p = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0}}$$

where $\epsilon_s \rightarrow$ electrical permittivity of silicon and it is $11.7\,\epsilon_0$

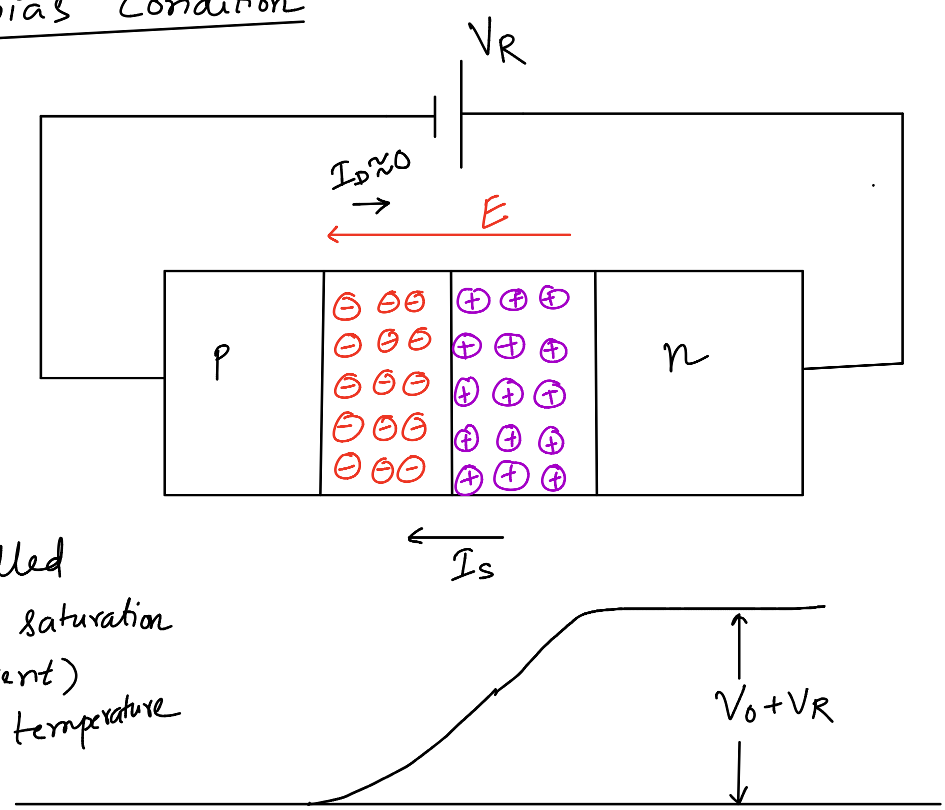
$$x_n = \frac{N_A}{N_A + N_D} W$$

$$x_p = \frac{N_D}{N_A + N_D} W$$

pn junction with applied voltage.



Reverse bias condition

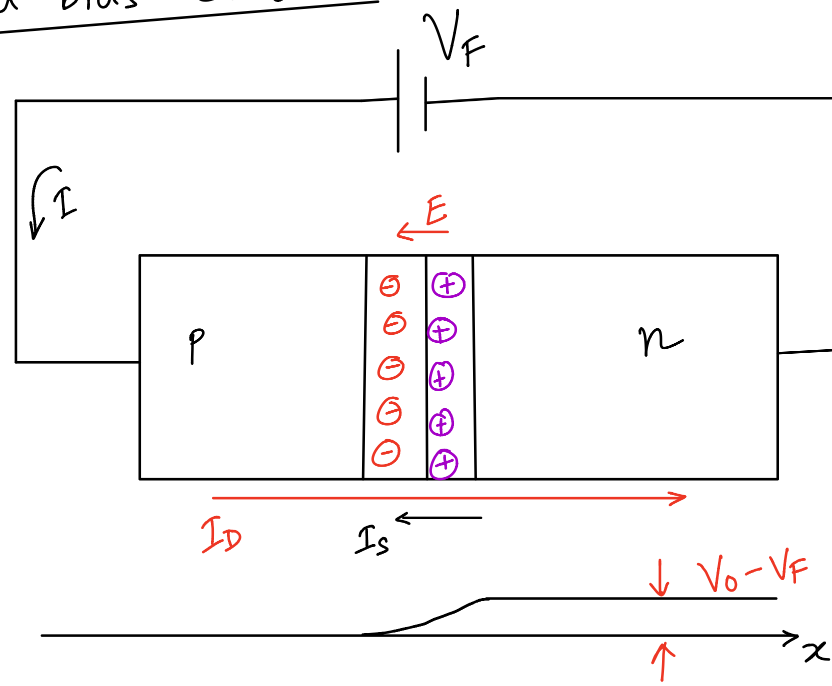


Current is

I_s (also called reverse saturation current)

✓ depends on temperature

Forward bias condition



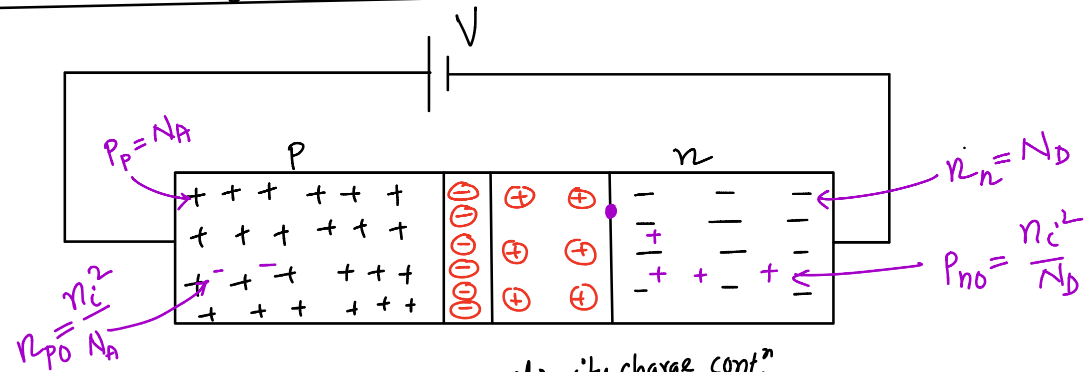
$$I = I_D - I_S$$

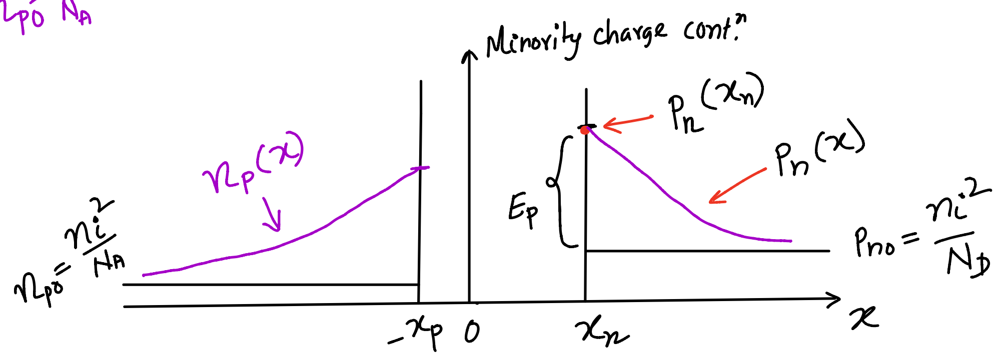
$$\approx I_D \quad (I_D \gg I_S)$$

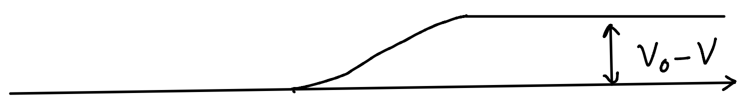
Width of depletion Region

Equilibrium	Reverse bias	Forward bias
$W = x_n + x_p$ $= \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)V_0}$	$W = x_n + x_p$ $= \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_0+V_R)}$	$W = x_n + x_p$ $= \sqrt{\frac{2\epsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_0-V_F)}$

Derivation of Diode Characteristic Equation







$$V(x_n) - V(-x_p) = V_T \ln\left(\frac{P_p(-x_p)}{P_n(x_n)}\right)$$

$$\Rightarrow V_0 - V = V_T \ln\left(\frac{N_A}{P_n(x_n)}\right)$$

$$\Rightarrow \frac{P_n(x_n)}{N_A} = e^{\frac{V-V_0}{V_T}}$$

$$\Rightarrow P_n(x_n) = \underbrace{N_A}_{} e^{V/V_T} \cdot \underbrace{e^{-\frac{V_0}{V_T}}}_{} \longrightarrow (i)$$

We know, $$V_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$\Rightarrow -V_0 = V_T \ln\left(\underbrace{\frac{n_i^2}{N_D}}_{p_{no}} \cdot \frac{1}{N_A}\right)$$

$$\Rightarrow p_{no} = N_A e^{-V_0/V_T} \longrightarrow (ii)$$

From (i) & (ii), we get

$$\boxed{p_n(x_n) = p_{no}\, e^{V/V_T}}$$

So, the excess minority carrier concentration is

$$E_p = p_{no} e^{V/V_T} - p_{no}$$
$$= p_{no}\left(e^{V/V_T} - 1\right)$$

This excess minority carrier will decay exp. and we can write $p_n(x)$ as

$$p_n(x) = \underline{p_{no}} + E_p e^{-(x-x_n)/L_p}$$

where L_p is a constant called diffusion length of the holes in n-type material.

So, this profile will lead to a diffusion current

$$J_p(x) = -q D_p \frac{d\, P_n(x)}{dx}$$

$$\Rightarrow J_p(x) = \frac{q D_p E_p}{L_p} e^{-(x-x_n)/L_p}$$

$$\therefore J_p(x) = q\left(\frac{D_p}{L_p}\right) P_{no} \left(e^{V/V_T} - 1\right) e^{-(x-x_n)/L_p}$$

So, $J_p(x)$ is max at $x = x_n$

$$\therefore J_p(x_n) = q\left(\frac{D_p}{L_p}\right) P_{no} \left(e^{V/V_T} - 1\right)$$

Similarly, on the p-side we will get

$$J_n(-x_p) = q\left(\frac{D_n}{L_n}\right) n_{po} \left(e^{V/V_T} - 1\right)$$

$$\therefore J = J_n(x_n) + J_n(-x_p)$$

$$\therefore I = A J$$

$$= Aq\left(\frac{D_p}{L_p}p_{n0} + \frac{D_n}{L_n}n_{p0}\right)\left(e^{V/V_T}-1\right)$$

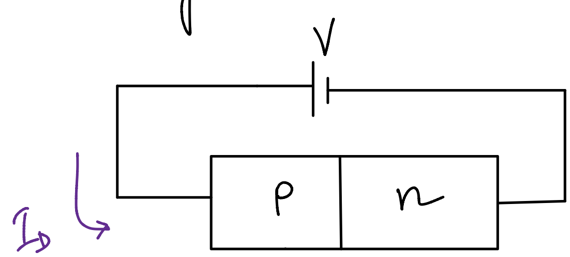
$\because$ $p_{n0} = \frac{n_i^2}{N_D}$ and $n_{p0} = \frac{n_i^2}{N_A}$

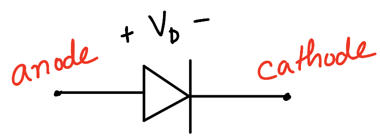
$$\therefore \boxed{I = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)\left(e^{V/V_T}-1\right)}$$

$$\boxed{I = I_s\left(e^{V/V_T}-1\right)}$$

where $I_s = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$

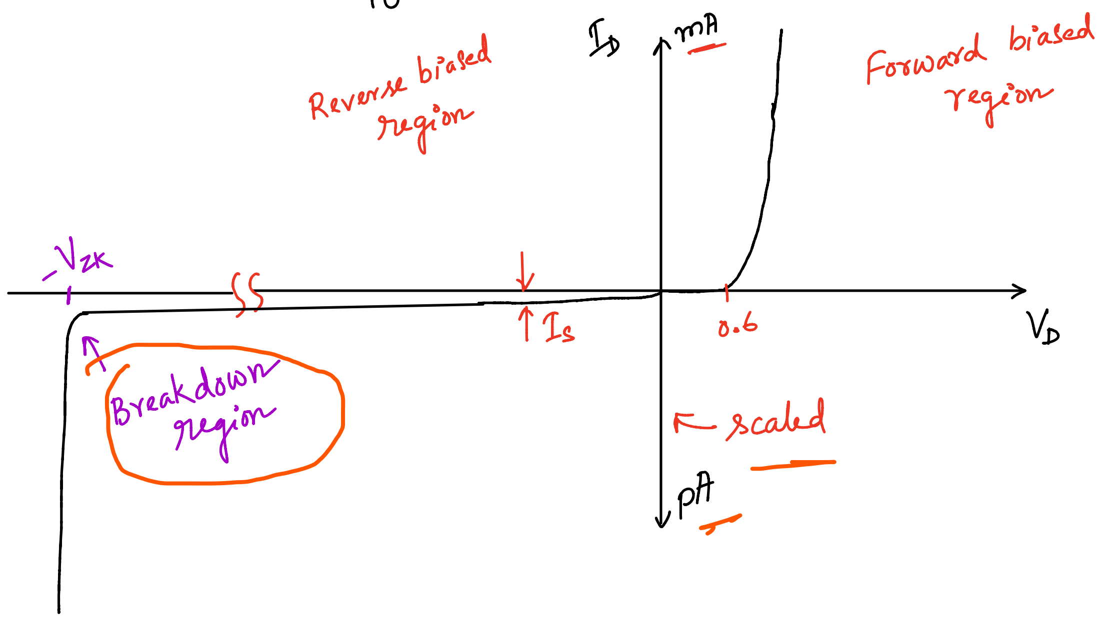
Solving Diode Circuits.





$$I_D = I_S \left(e^{V_D/V_T} - 1\right) \quad \text{where} \quad V_T = \frac{kT}{q}$$

I_S ↑ $10^{-12}A$

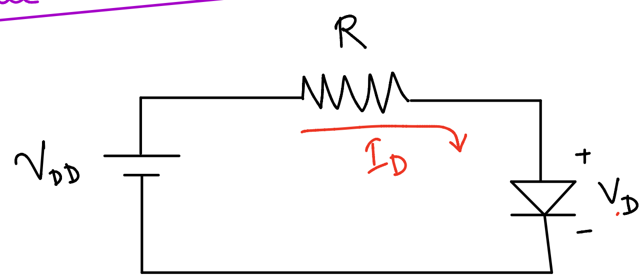


$$I_D = I_S\left(e^{V_D/V_T} - 1\right)$$

$$\Rightarrow I_D = I_S e^{V_D/V_T} - I_S$$

$$\boxed{\therefore I_D \simeq I_S e^{V_D/V_T}}$$

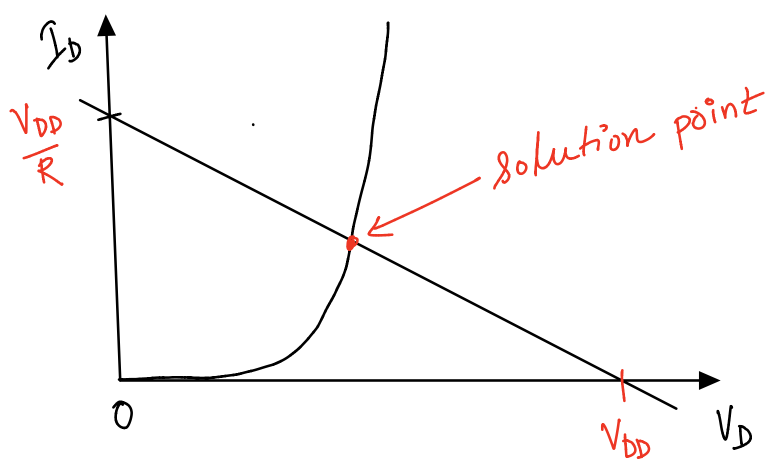
Solving diode circuit



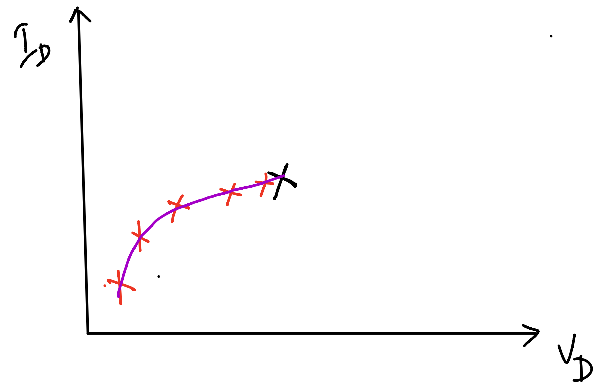
$$I_D = I_S e^{V_D/V_T} \longrightarrow (i)$$

$$I_D = \frac{V_{DD} - V_D}{R} \longrightarrow (ii)$$

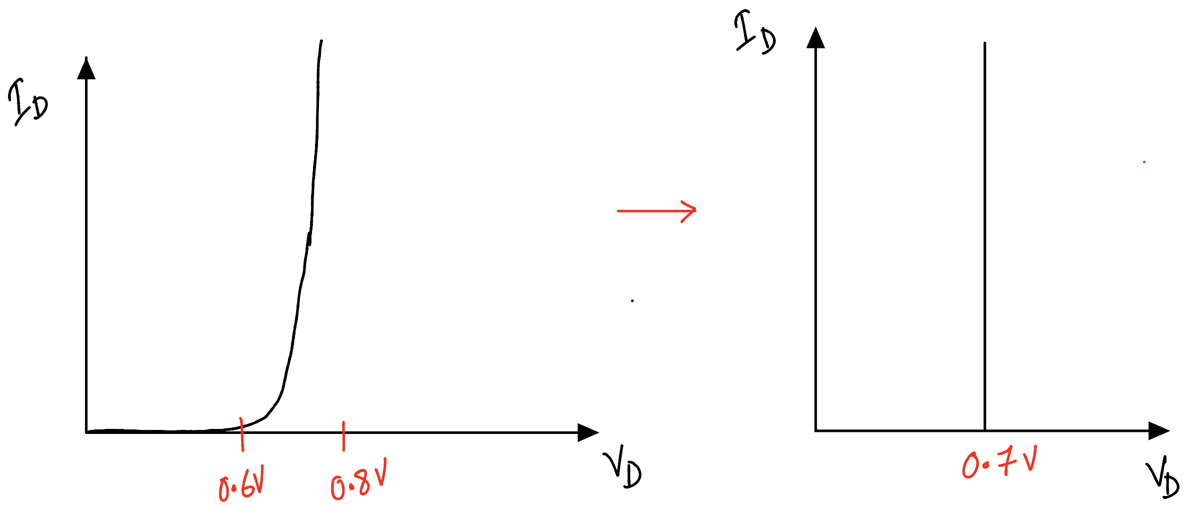
Graphical method

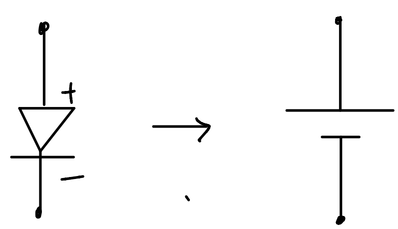


Numerical Method / Iterative Method



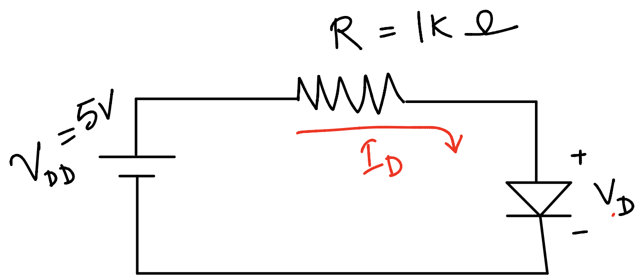
Constant Drop Model

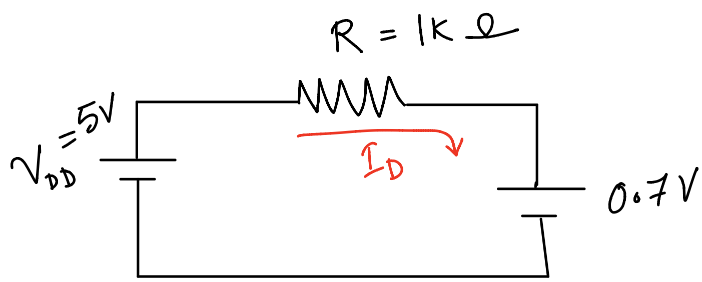




$V_D = 0.7V$

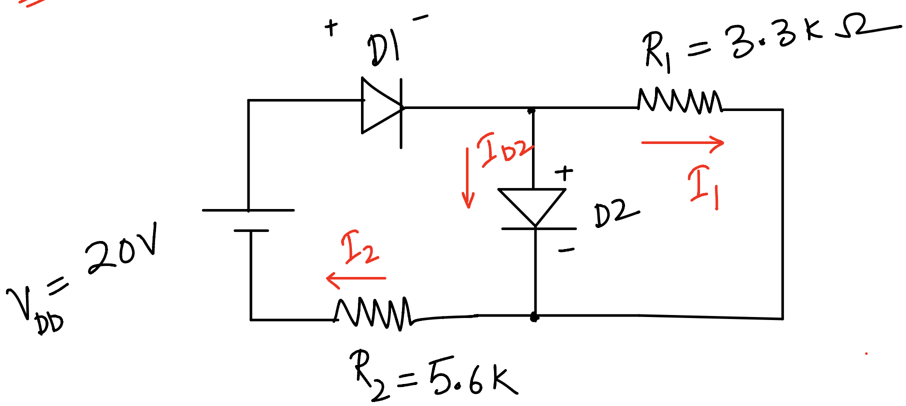
Q1: Find I_D in the following example





$$\therefore I_D = \frac{V_{DD} - 0.7}{R} = \frac{5 - 0.7}{1k} = 4.3mA$$

Q2: Find I_1, I_2 and I_{D2}



$$I_1 R_1 = 0.7\ V \Rightarrow I_1 = \frac{0.7}{3.3k} = 0.212mA$$

$$\therefore V_{DD} - V_{D1} - V_{D2} - I_2 R_2 = 0$$

$$\Rightarrow I_2 = \frac{V_{DD} - V_{D1} - V_{D2}}{R_2} = \frac{20 - 0.7 - 0.7}{5.6K}$$

$$= 3.32\ mA$$

$$\therefore I_2 = I_{D2} + I_1$$

$$\Rightarrow I_{D2} = I_2 - I_1 = 3.11mA$$

$I_1 = 0.\underline{212}mA$

$I_2 = 3.\underline{32}mA$

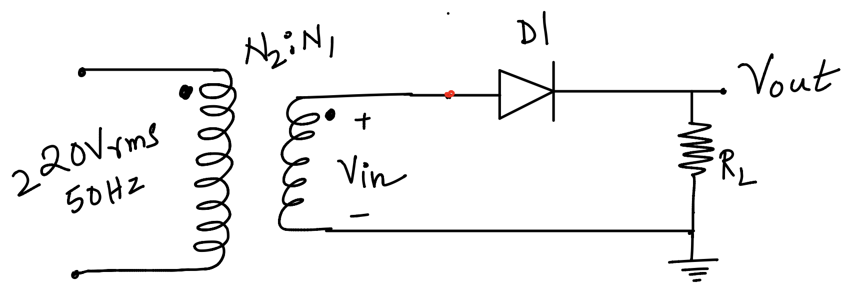
$I_{D2} = \underline{3.11}mA$

Rectifier Circuits.

- Half-Wave Rectifier
- Full-wave Rectifier
  - Bridge
  - Center tap.

Half-wave Rectifier

$V_D \approx 0.7V$

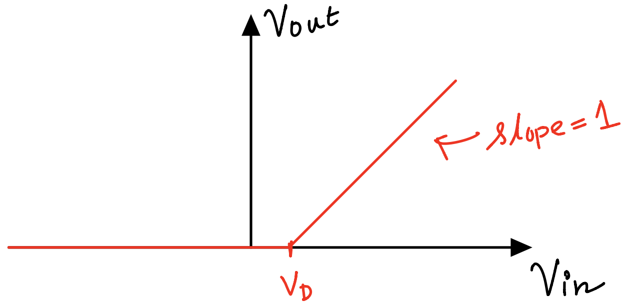


when $V_{in} < V_D$

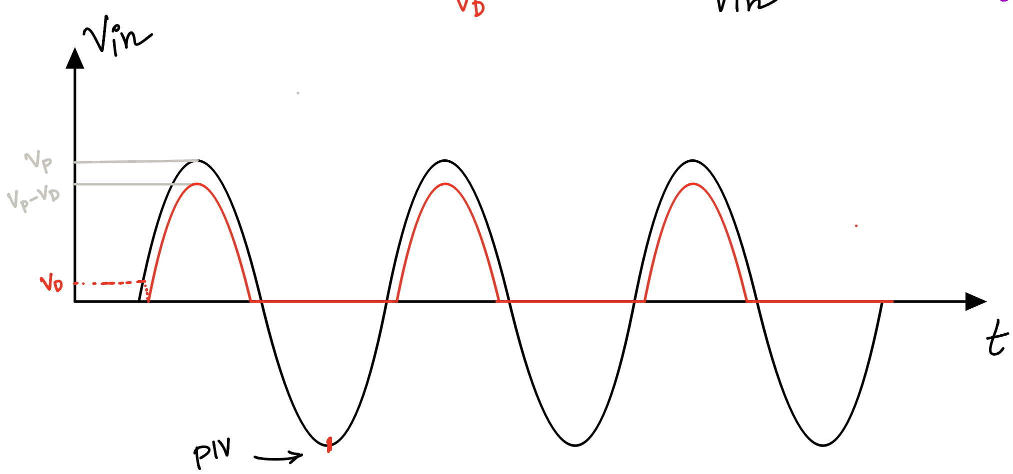
$V_{out} = 0$ (D1 is off)

$V_{in} > V_D$

$V_{out} = V_{in} - V_D$

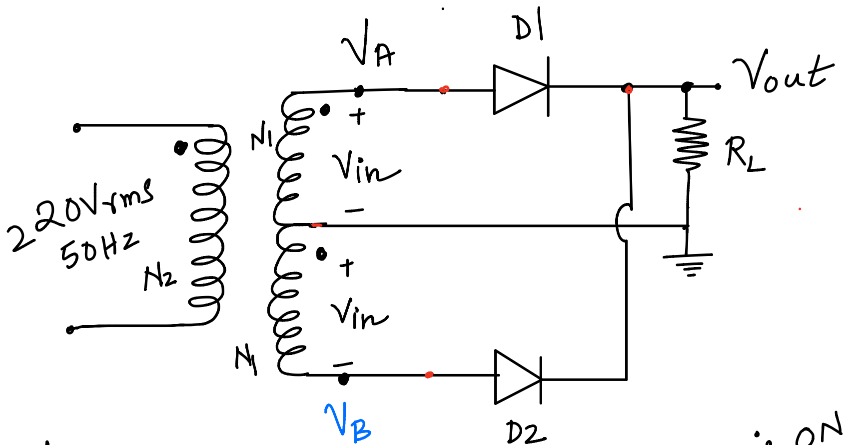


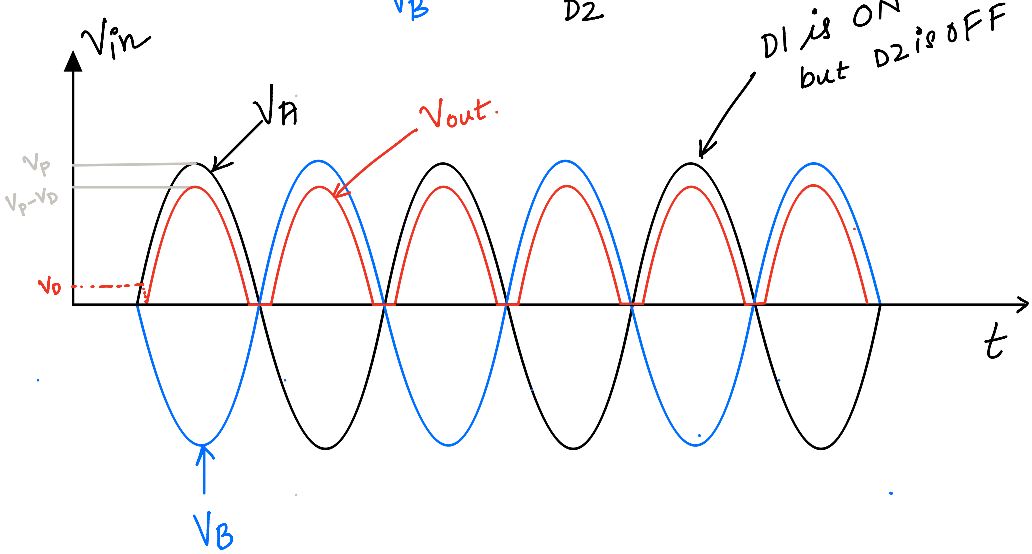
This is input-output characteristic of half-wave rectifier



Peak Inverse Voltage (PIV) = V_p

Full-Wave Rectifier (Center-tap)

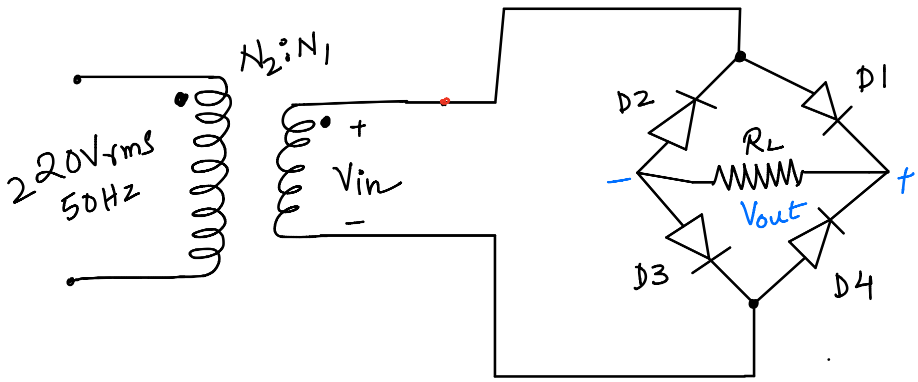


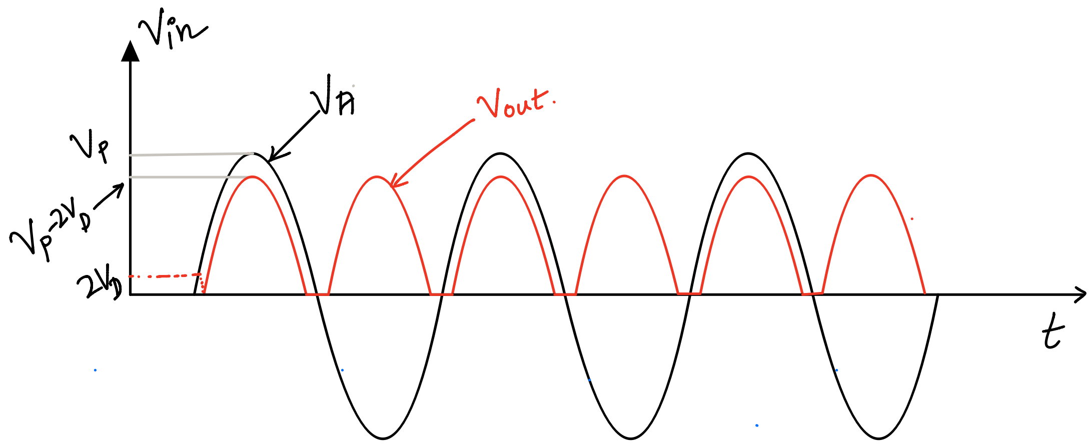


$\therefore \; PIV = 2V_p - V_D$

Peak inverse voltage is the maximum voltage a diode can withstand in the reverse-biased direction before breakdown.

Full-Wave Rectifier (Bridge)

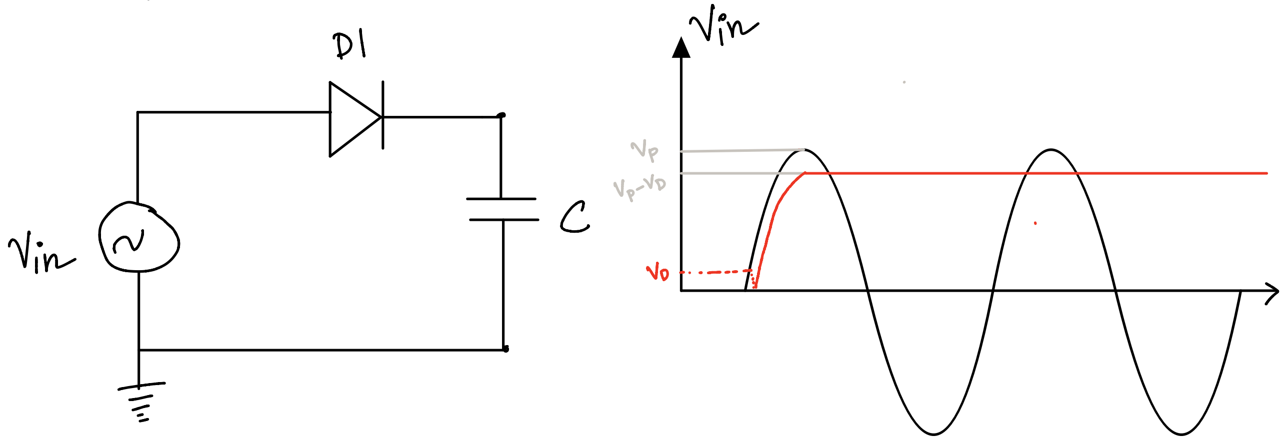


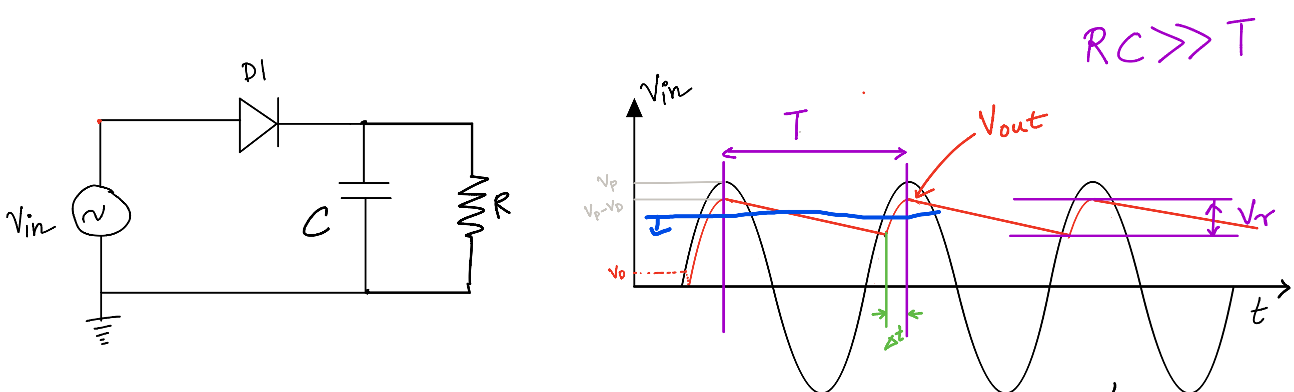


$$\therefore PIV = V_p - V_D \quad // \qquad 10 - 0.7$$

$$= \underline{\underline{9.3}}$$

Rectifier with a Filter Capacitor





$$V_{out} = (V_p - V_D)\,e^{-t/\tau} = (V_p - V_D)\,e^{-t/RC}$$

So, at the end of discharge, it will be

$$V_p - V_D - V_r = (V_p - V_D)\,e^{-\frac{(T-\Delta t)}{RC}}$$

$$\Rightarrow V_p - V_D - V_r \simeq (V_p - V_D)\,e^{-T/RC}$$

$$\because RC \gg T, \text{ so } e^{-T/RC} \simeq \left(1 - \frac{T}{RC}\right)$$

$$\Rightarrow V_p - V_D - V_r \simeq (V_p - V_D)\left(1 - \frac{T}{RC}\right)$$

$$\Rightarrow \cancel{(V_p - V_D)} - V_r = \cancel{(V_p - V_D)} - \frac{T(V_p - V_D)}{RC}$$

$$\Rightarrow V_r = \frac{T(V_p - V_D)}{RC}$$

Let $V_p - V_D = V_M$

Half-Wave Rectifier

$$\boxed{\therefore V_r = \frac{T V_M}{RC} = \frac{V_M}{f RC}}$$

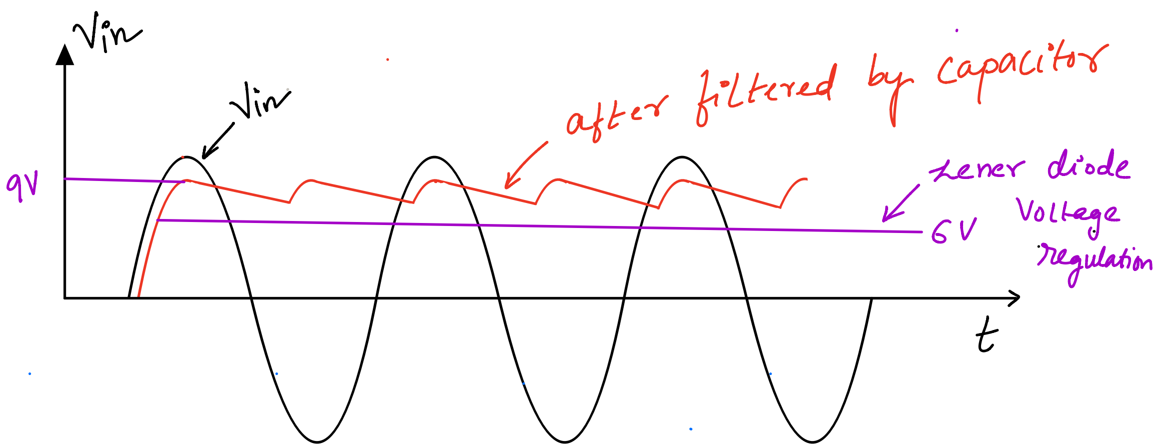
* 'C' cannot be very large because if it is too high, current required to charge it may exceed the max current allowed through the diode.

Full-Wave Rectifier

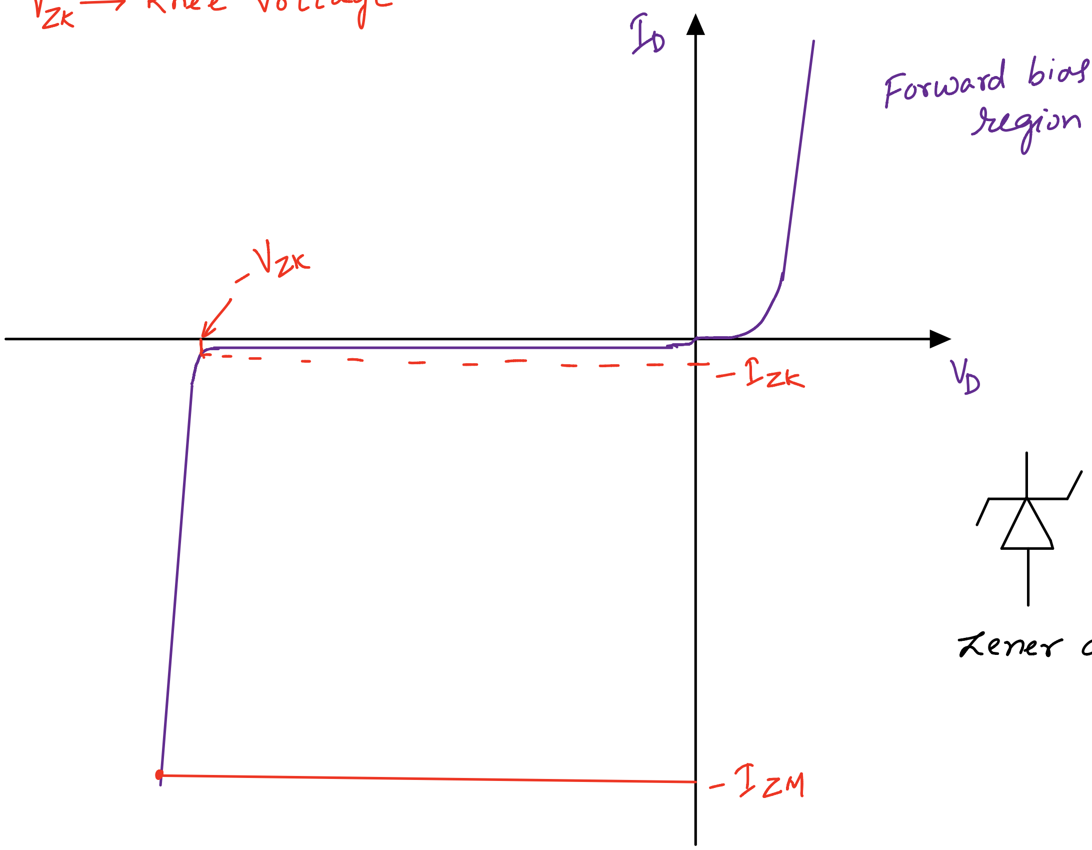
$$\boxed{\therefore V_r = \frac{T V_M}{2RC} = \frac{V_M}{2f RC}}$$

A ripple is defined as the fluctuating AC component in the rectified DC output. The rectified DC output could be either DC current or DC voltage. When the fluctuating AC component is present in DC current it is known as the current ripple while the fluctuating AC component in DC voltage is known as the voltage ripple.

Voltage Regulation by Zener Diode.



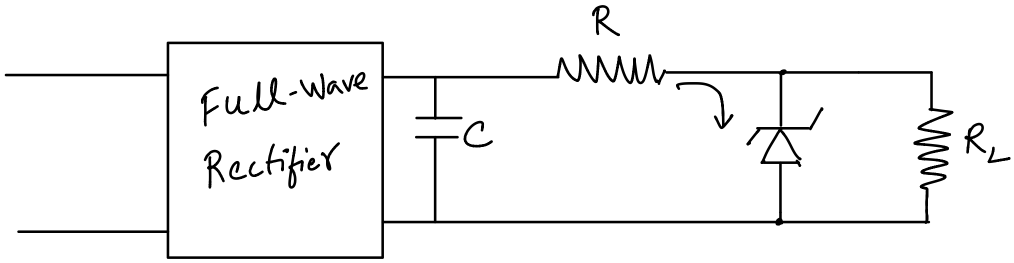
$V_{ZK} \rightarrow$ knee voltage

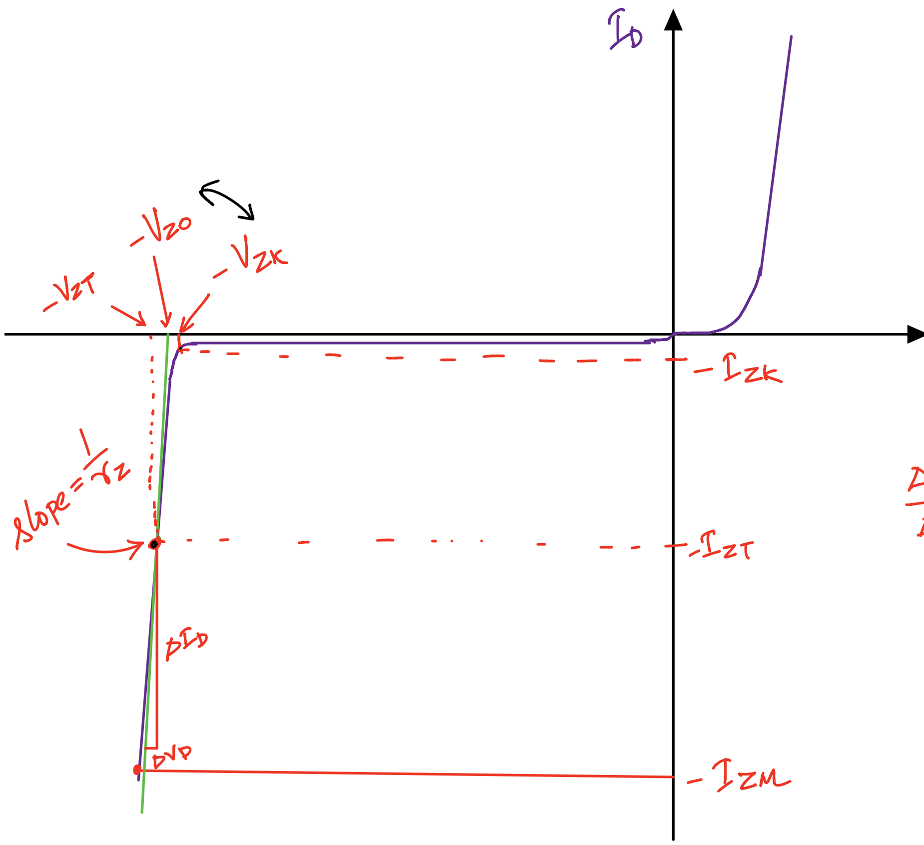


zener diode

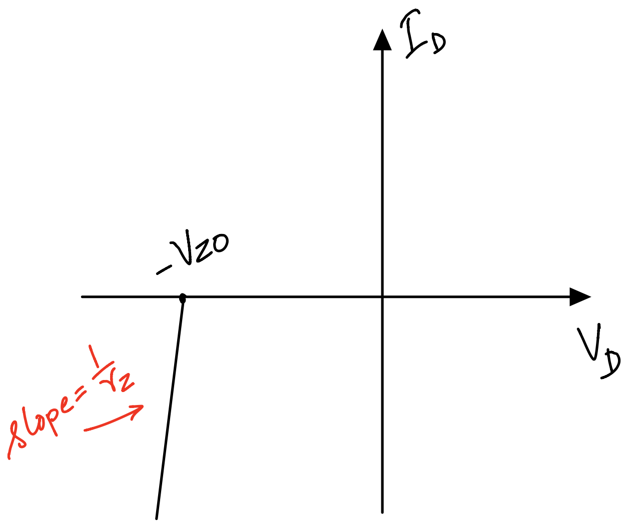
✓ Knee voltage can be varied by varying the doping concentration of the pn junction.

Block diagram of the zener regulation.





$$\frac{\Delta I_D}{\Delta V_D} = \frac{1}{r_Z} = \text{slope}$$



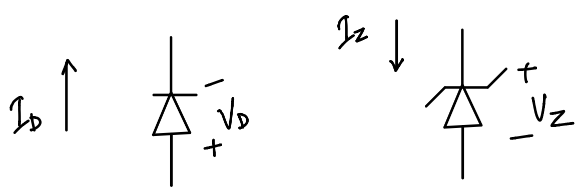
$y = mx + c$

$\Rightarrow I_D = \frac{1}{r_Z} V_D + c$

when $I_D = 0$, $V_D = -V_{Z0}$

$\Rightarrow c = \frac{V_{Z0}}{r_Z}$

$$\boxed{V_D = r_Z I_D - V_{Z0}}$$



So, for zener diode

$I_Z = -I_D$

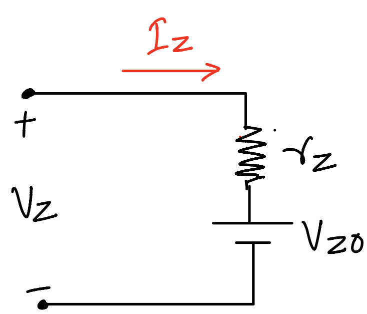
$V_Z = -V_D$

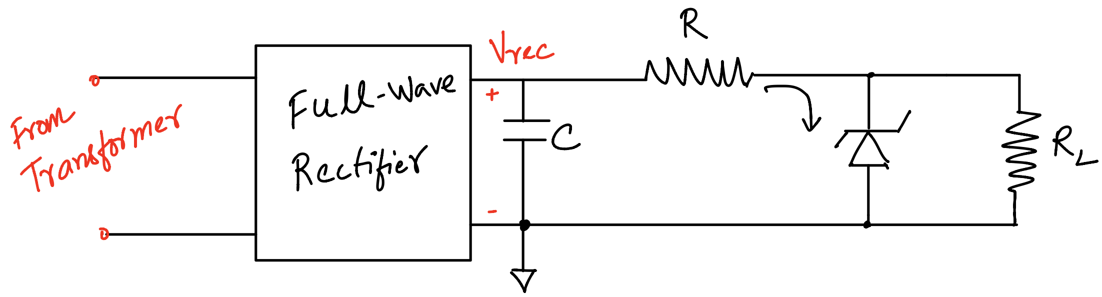
$\therefore -V_Z = r_Z(-I_Z) - V_{Z0}$

$\Rightarrow V_Z = r_Z I_Z + V_{Z0}$

So, for zener diode

$$\boxed{V_Z = r_Z I_Z + V_{Z0}}$$





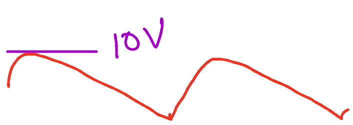
For the zener diode: $r_Z = 10\,\Omega$ at $I_{ZT} = 10mA$, $V_{ZT} = 6.3V$

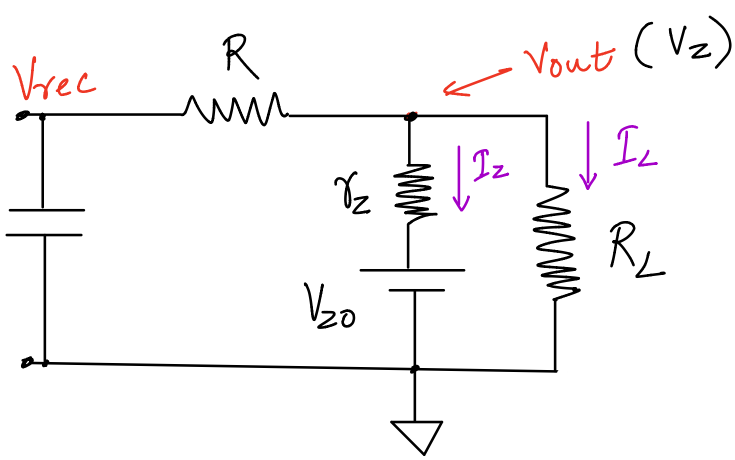
$I_{ZM} = 50mA$, $I_{ZK} = 0.2\,mA$

We know, $V_Z = V_{Z0} + I_Z r_Z$

$\Rightarrow 6.3 = V_{Z0} + 10mA \times 10\,\Omega$

$\Rightarrow V_{Z0} = 6.2\,V$





Finding the minimum value of R.

- To find the minimum value of R, we need to consider $I_L = 0$ or $R_L \longrightarrow \infty$.

- Current through zener will be maximum when V_{rec} is maximum

$$\therefore V_{Z(max)} = V_{out(max)} = V_{Z0} + I_{Z(max)} r_Z$$

$$= V_{Z0} + I_{ZM} r_Z$$

$$= 6.2 + 50mA \times 10$$

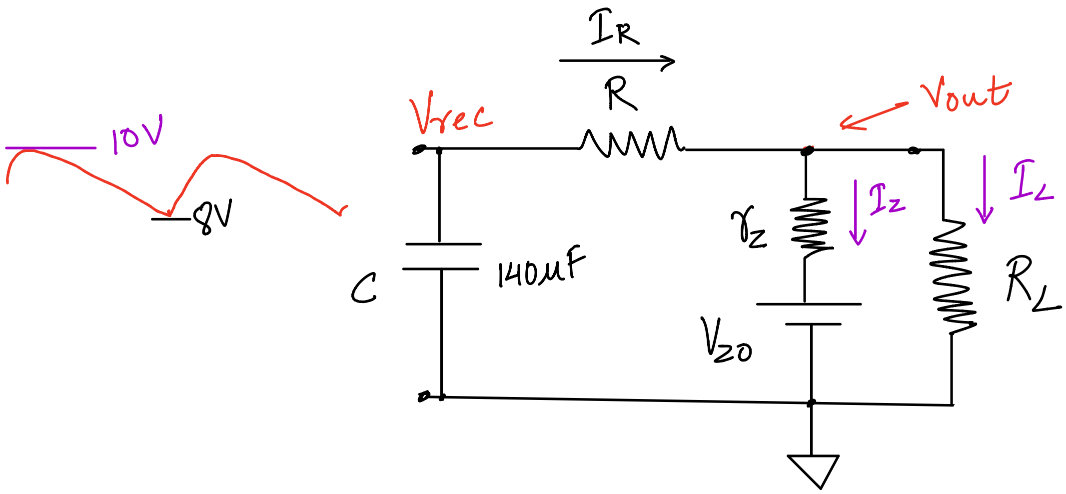
$$= 6.7 V$$

$$\therefore I_{ZM} = \frac{V_{rec(max)} - V_{Z(max)}}{R_{min}}$$

$$\Rightarrow R_{min} = \frac{10 - 6.7}{50mA} = 66 \Omega$$

$$\Rightarrow R_{min} = 66 \Omega$$

So, $R > 66 \Omega$



Let's consider, $R = 80\,\Omega$.

Finding out the R_L minimum

- $V_{out} = V_{zk} \approx V_{z0}$
- Current flowing through the zener is I_{zk}

$$\therefore \quad I_L = \frac{V_{out}}{R_L} = \frac{V_{z0}}{R_L}$$

- We need to consider V_{rec} minimum, because if it is breaking down at this voltage, it will definitely break down at higher voltage.

$$\therefore I_R = I_{ZK} + I_L = \frac{V_{rec(min)} - V_{Z0}}{R}$$

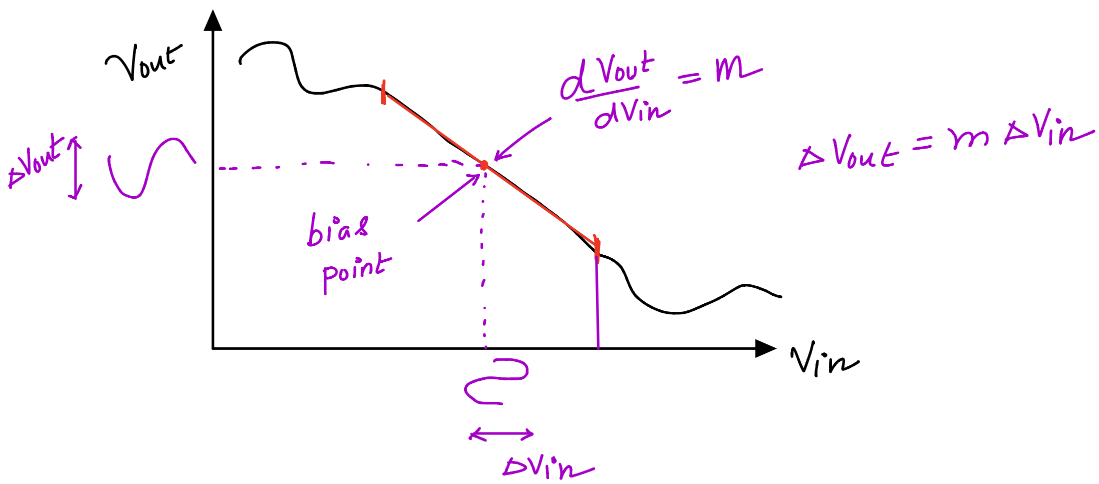
$$\Rightarrow 0.2\,mA + \frac{V_{Z0}}{R_L} = \frac{8 - 6.2}{80}$$

$$\Rightarrow \frac{6.2}{R_L} = 22.3\,mA$$

$$\therefore R_L = 278\,\Omega$$

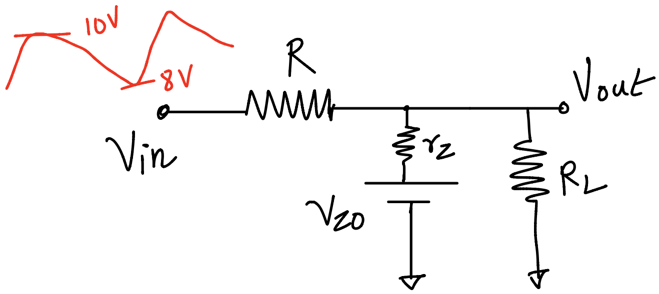
$$\therefore R_L > 278\,\Omega \quad //$$

Small Signal Analysis.

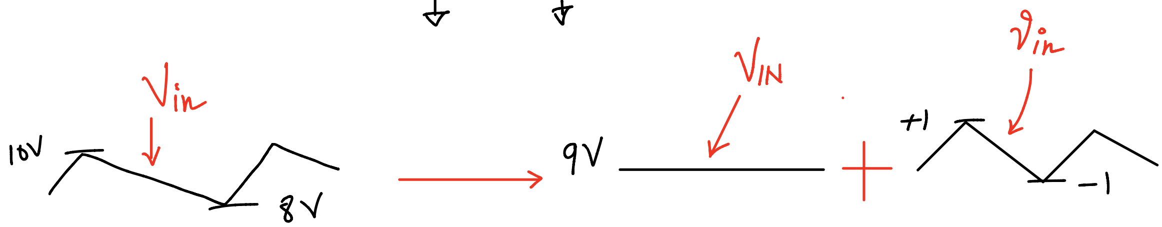


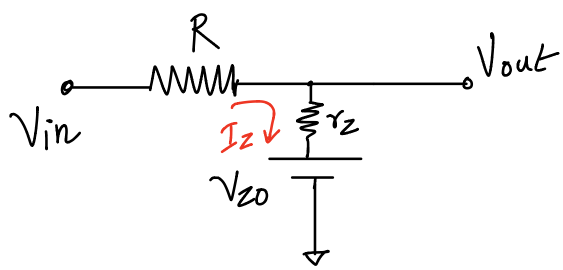
The operating point of a device, also known as bias point, quiescent point, or Q-point, is the DC voltage or current at a specified terminal of an active device (a transistor or vacuum tube) with no input signal applied. A bias circuit is a portion of the device's circuit that supplies this steady current or voltage.

Small-Signal Analysis for Zener based regulator



$V_{in} = V_{IN} + v_{in}$





$$I_z = \frac{V_{in} - V_{zo}}{R + r_z}$$

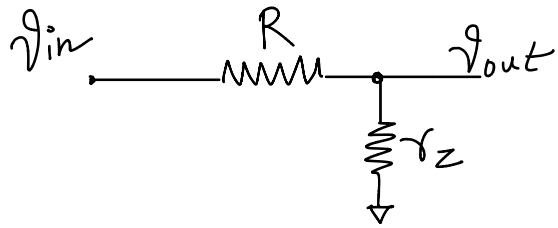
$$V_{out} = V_{zo} + I_z r_z$$

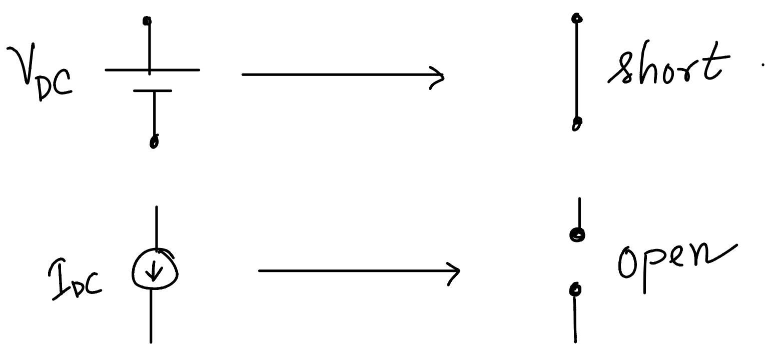
$$\Rightarrow V_{out} = V_{zo} + \left(\frac{V_{in} - V_{zo}}{R + r_z}\right) r_z$$

$$\Rightarrow V_{out} = V_{zo} - \frac{r_z V_{zo}}{R + r_z} + \frac{r_z}{R + r_z} V_{in}$$

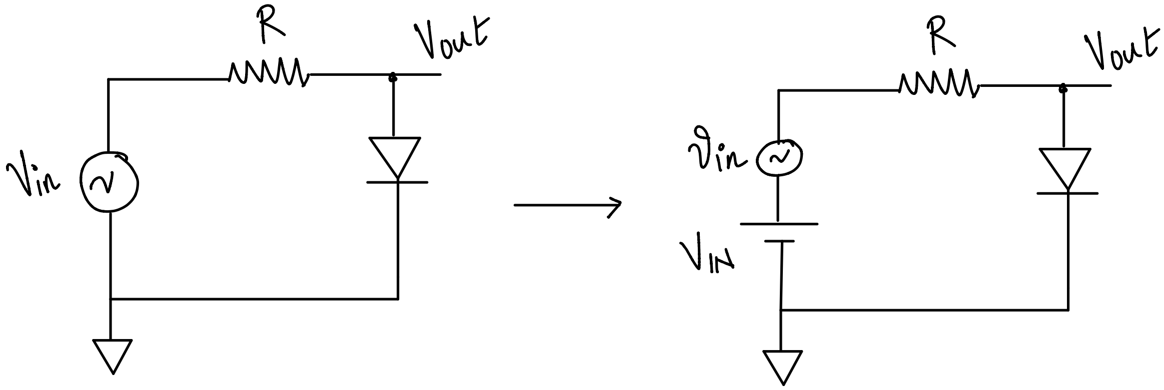
$$\therefore \frac{dV_{out}}{dV_{in}} = \frac{r_z}{R + r_z}$$

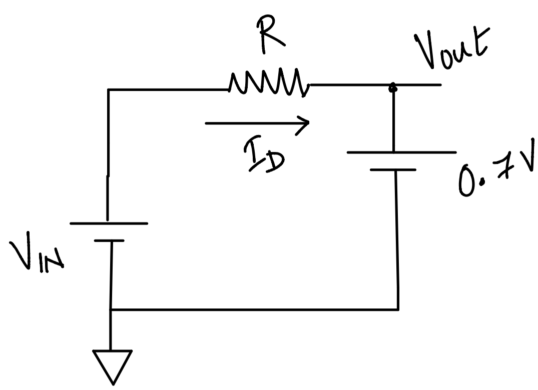
$$\frac{v_{out}}{v_{in}} = \frac{r_z}{R+r_z} \Rightarrow v_{out} = \frac{r_z}{R+r_z} v_{in}$$





Small Signal Analysis for diode cicuits.

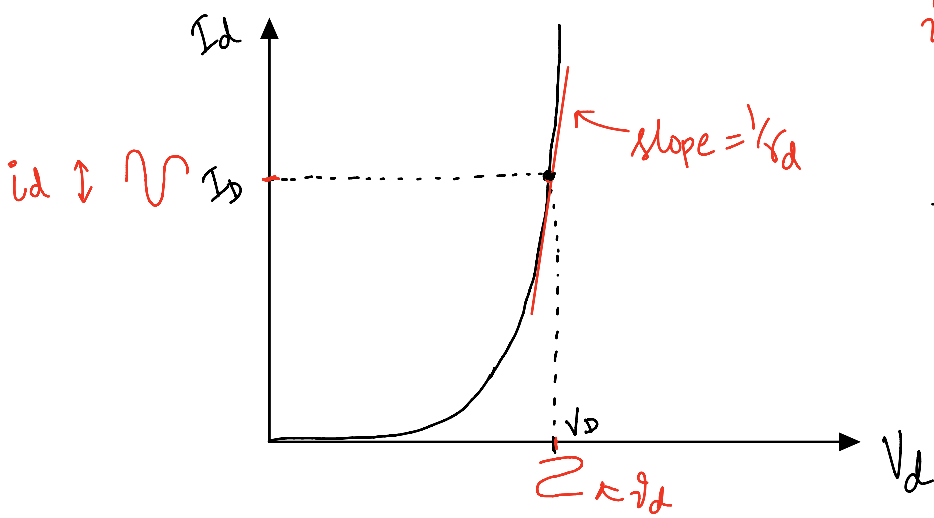




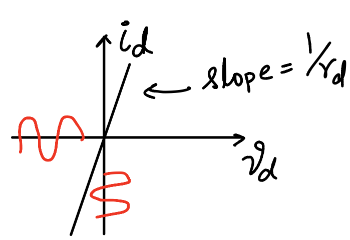
$$I_D = \frac{V_{IN} - 0.7}{R}$$

$$I_D = \frac{3 - 0.7}{1k\Omega}$$

$$= 2.3mA$$



$v_d = i_d r_d$



$$i_d = \frac{v_d}{r_d}$$

$$I_d = I_s\, e^{V_d/V_T}$$

$$\Rightarrow I_D + i_d = I_s\, e^{(V_D+v_d)/V_T} = \underbrace{I_s\, e^{V_D/V_T}}_{I_D} \cdot e^{v_d/V_T}$$

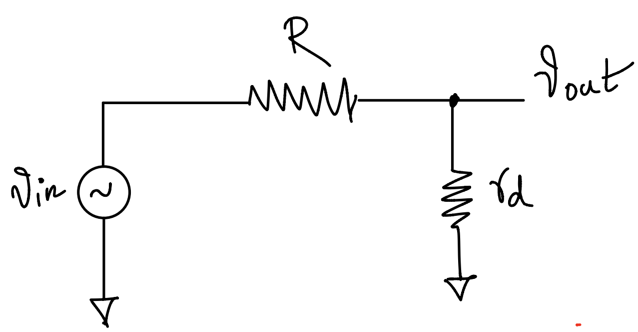
$$\Rightarrow I_D + i_d = I_D\, e^{v_d/V_T}$$

If $v_d/V_T \ll 1$, $e^{v_d/V_T} \approx 1 + \frac{v_d}{V_T}$

$$\Rightarrow I_D + i_d = I_D\left(1 + \frac{v_d}{V_T}\right)$$

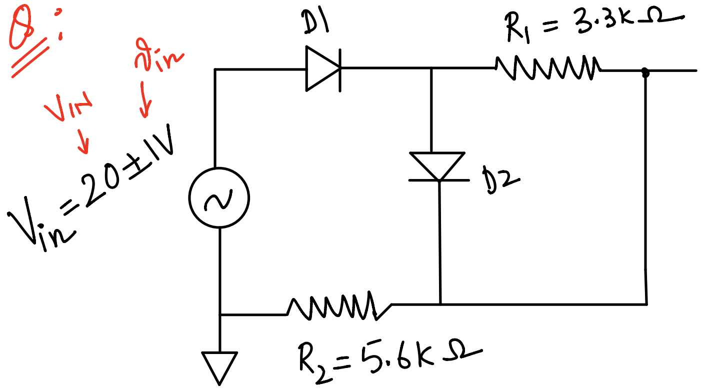
$$\Rightarrow \cancel{I_D} + i_d = \cancel{I_D} + \frac{I_D}{V_T} v_d$$

$$\Rightarrow i_d = \frac{I_D}{V_T} v_d = \frac{v_d}{r_d}$$ where $\boxed{r_d = \frac{V_T}{I_D}}$



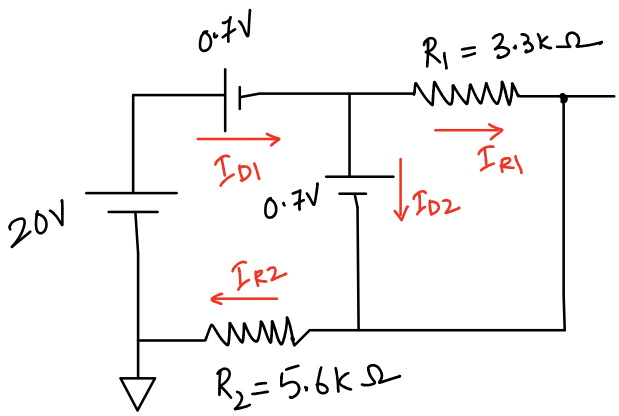
$$v_{out} = \frac{r_d}{R + r_d} v_{in}$$

Q:



$V_{out} = V_{OUT} + v_{in}$

DC Analysis / Operating point analysis



$$I_{R1} = \frac{0.7}{R1} = \frac{0.7}{3.3k} = 0.21mA$$

$$I_{D1} = I_{R2} = \frac{20 - 0.7 - 0.7}{R2}$$

$$= 3.32\ mA$$

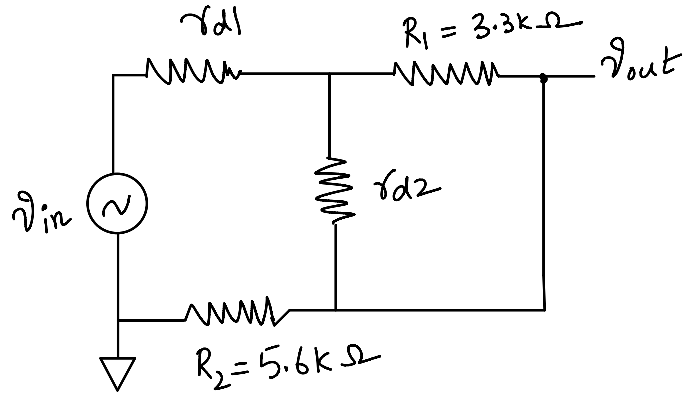
$$I_{R2} = I_{D2} + I_{R1}$$

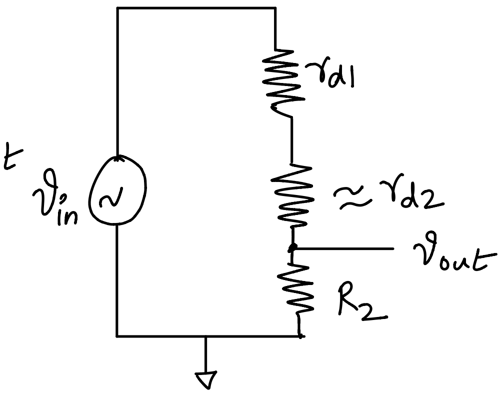
$$\Rightarrow I_{D2} = 3.11mA$$

$$\therefore r_{d1} = \frac{V_T}{I_{D1}} = 7.8\Omega$$

$$r_{d2} = \frac{V_T}{I_{D2}} = 8.36\Omega$$

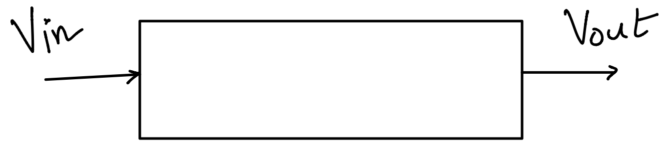
Small-Signal Analysis.

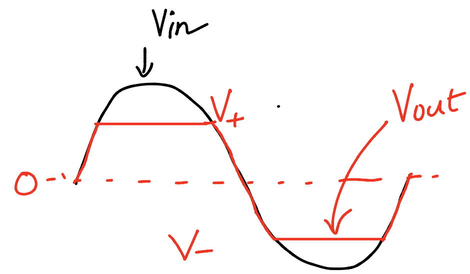


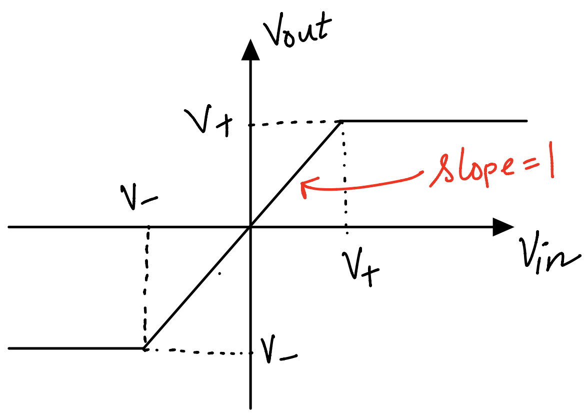


$$\therefore v_{out} = \frac{R_2 v_{in}}{r_{d1} + r_{d2} + R_2}$$

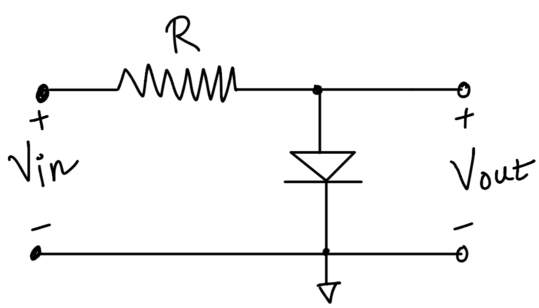
Clippers

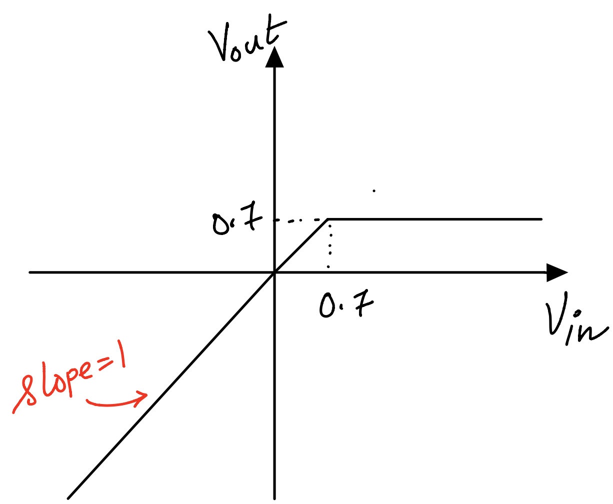


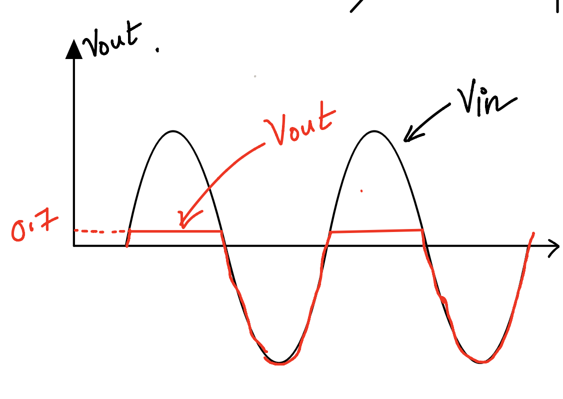




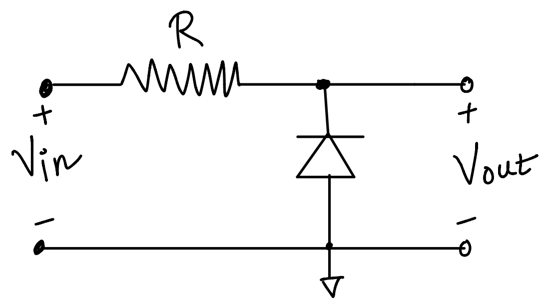
Upper Clipper

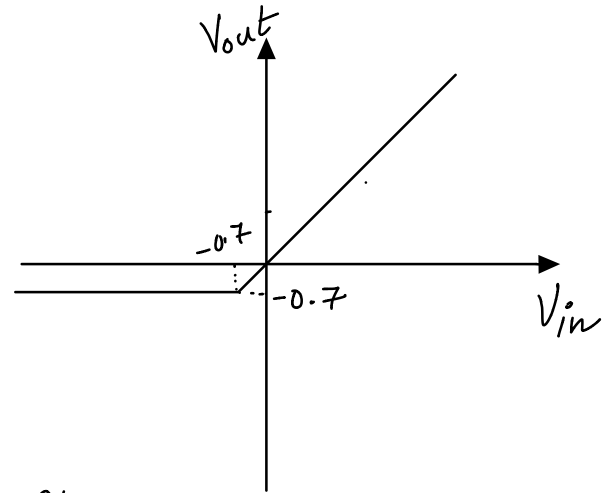




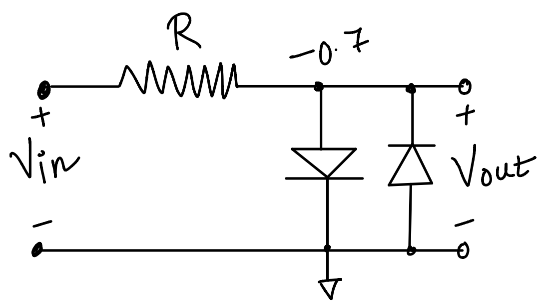


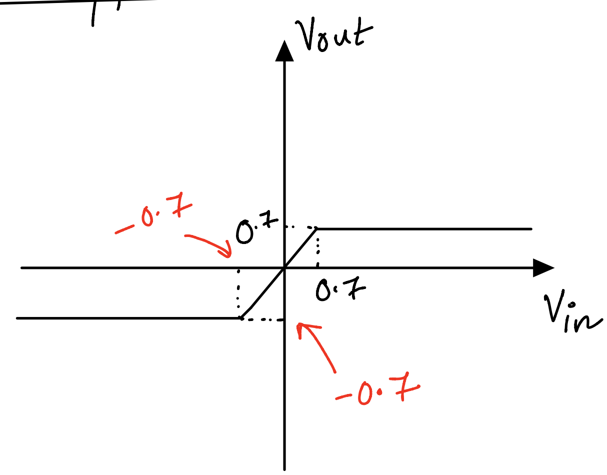
Lower Clipper

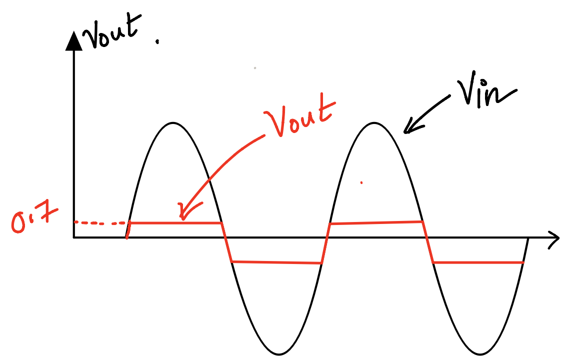




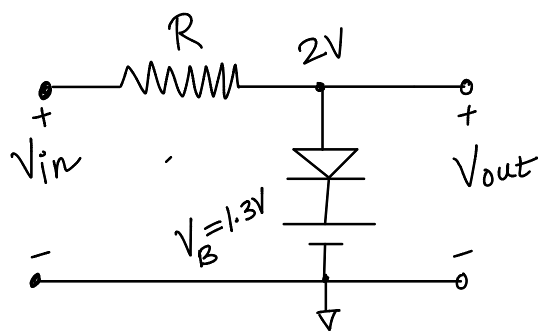
Combined lower and Upper Clipper

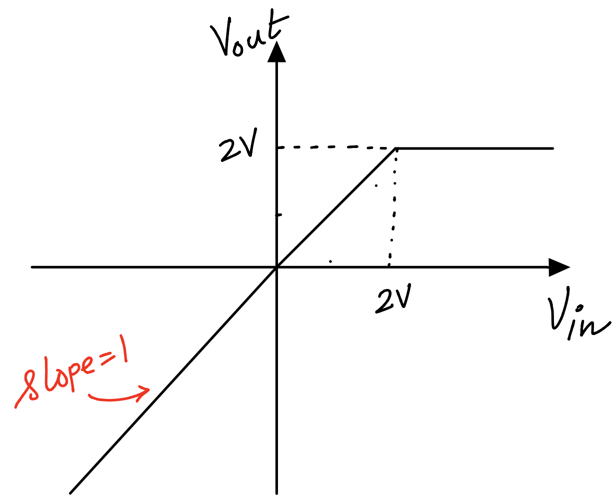




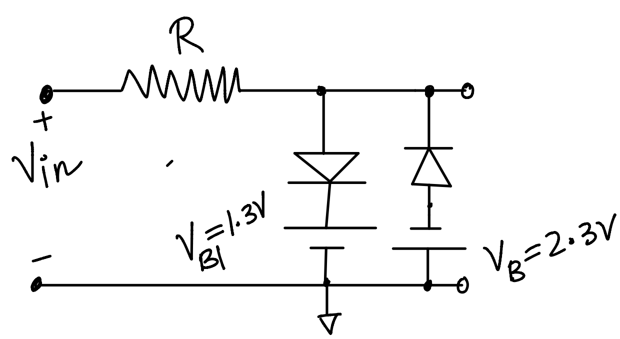


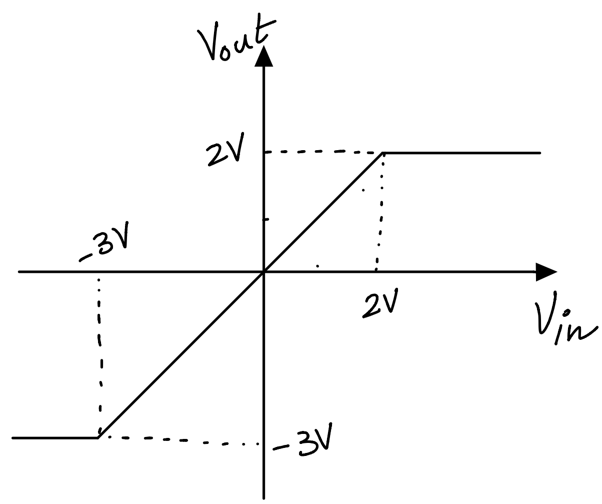
Upper Clipper with Offset



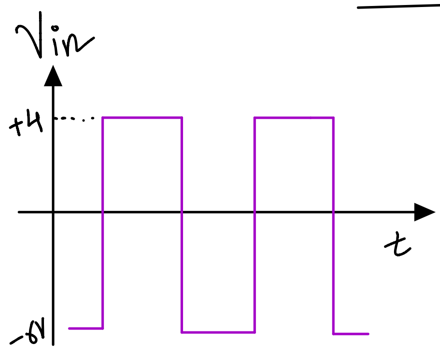


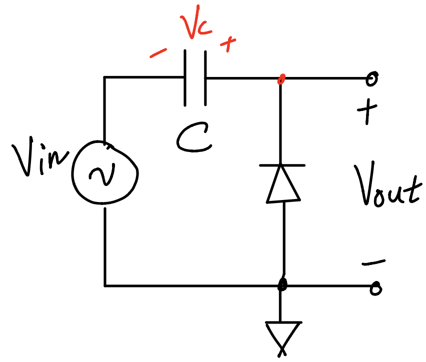
Combined Upper and lower Clipper with Offset

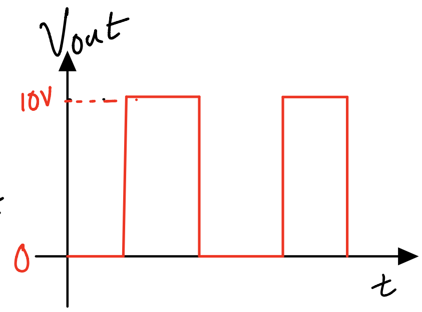


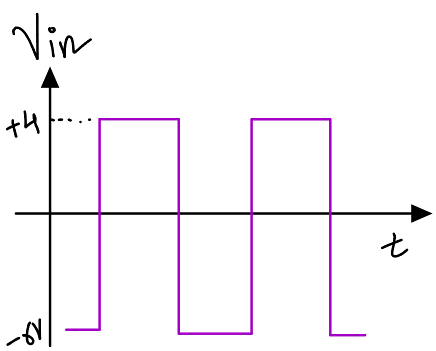


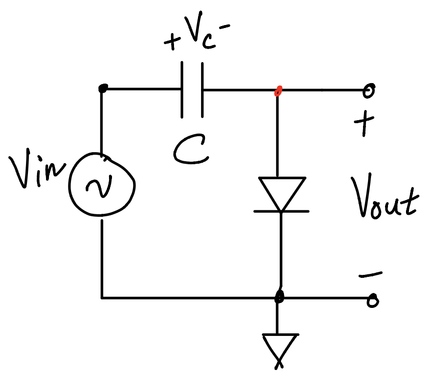
Clamper Circuits

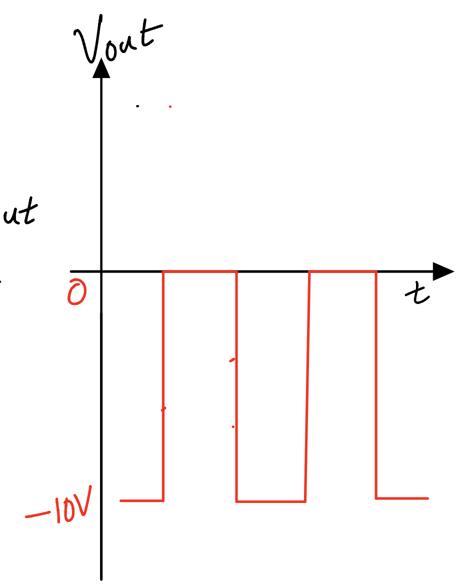




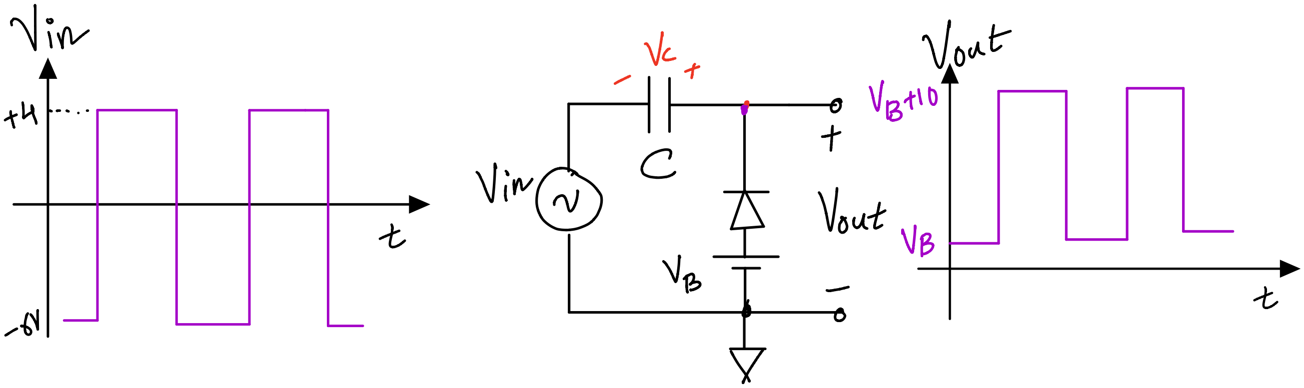




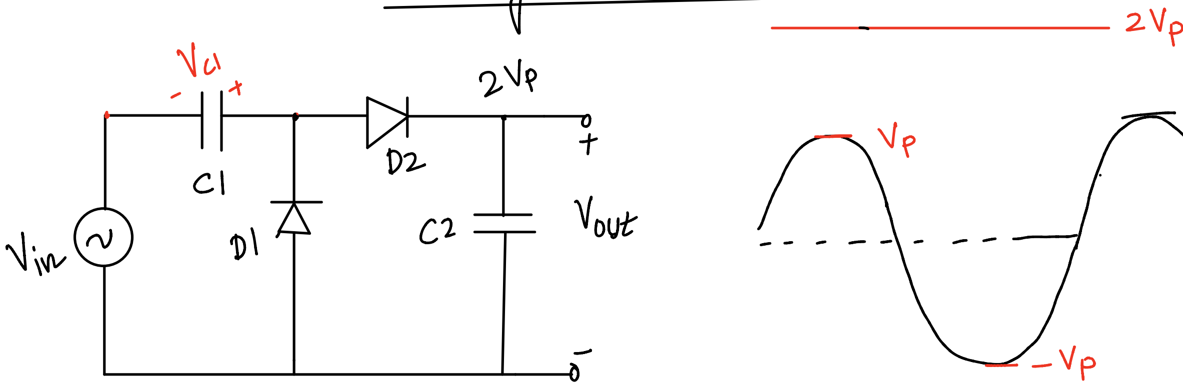




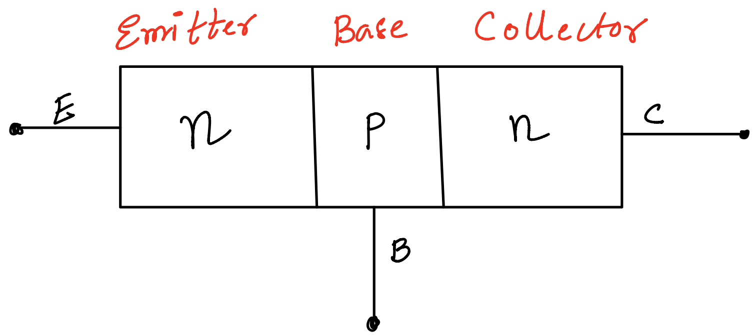
Clampers with Offset



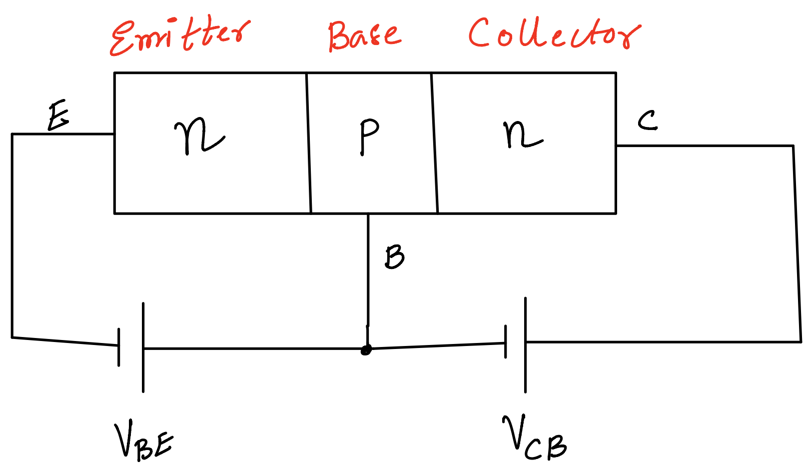
Voltage Doubler



Bipolar Junction Transistors (BJT)



* There are two types of BJTs : npn & pnp



* Base and emitter will always be in forward bias region

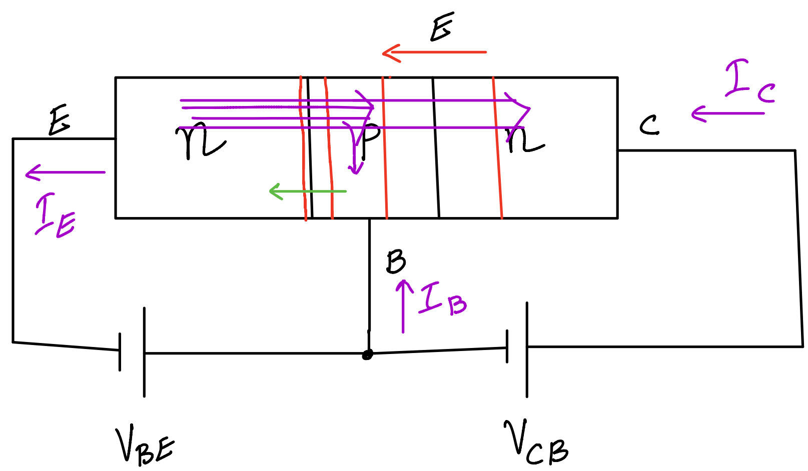
* Base and collector " " " reverse " "

* Based on value of V_{BE} and V_{CB} there will be three different region of operations.

3 regions of operation

Cut-off — Active — Saturation

Active Region



$$I_C = \beta I_B \qquad \beta \rightarrow 50 \sim 350$$

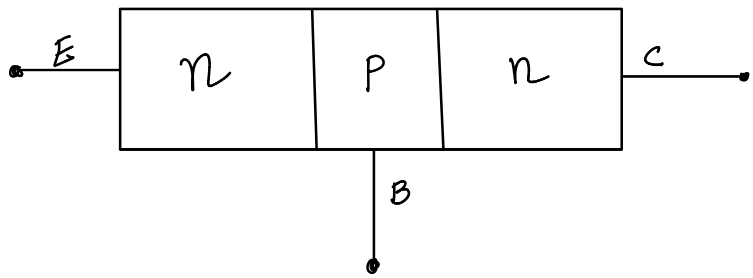
$$I_E = I_B + I_C$$

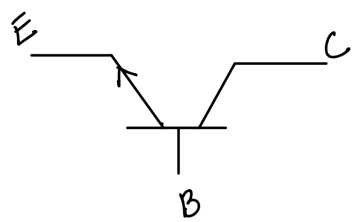
$$I_B = I_s' e^{V_{BE}/V_T}$$

$$\therefore I_C = \beta I_s' e^{V_{BE}/V_T}$$

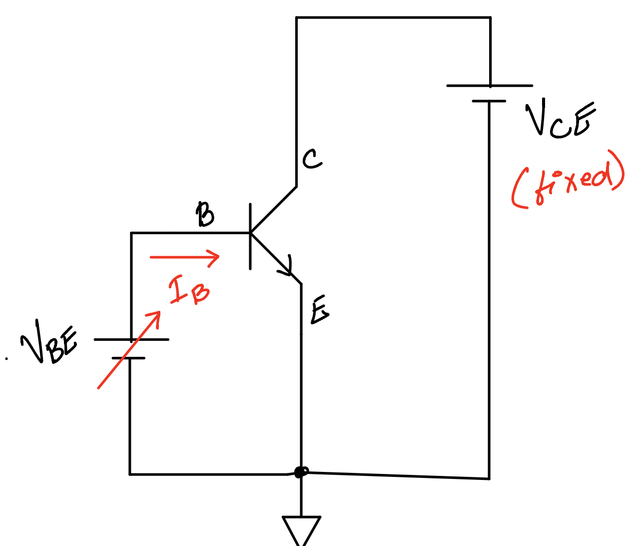
$$\Rightarrow I_C = I_s e^{V_{BE}/V_T}$$

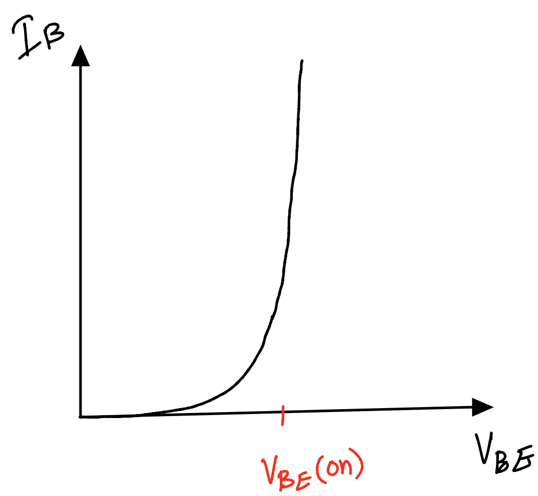
Symbol of BJT





Characteristic of BJT (I_B Vs V_{BE})



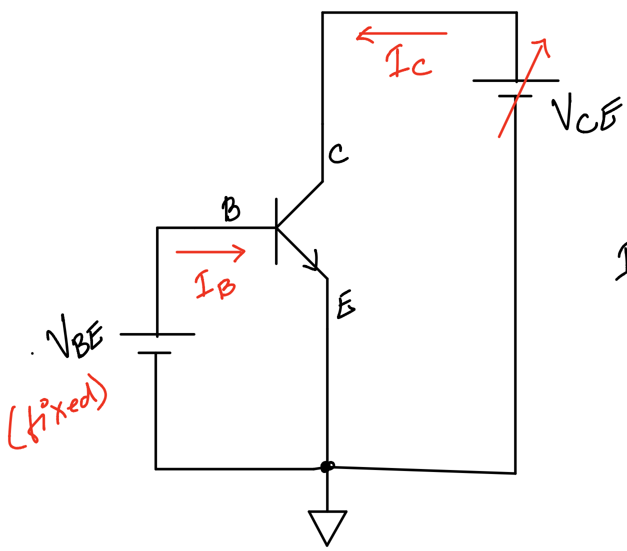


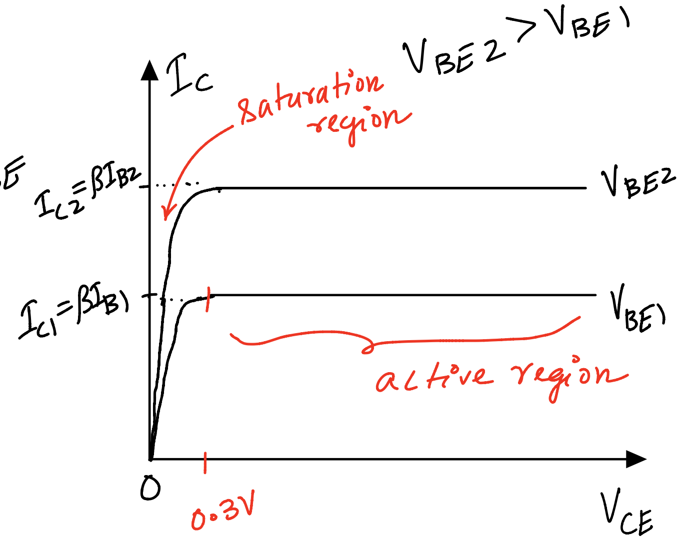
$V_{BE}(on) = 0.7$

$$I_B = I_s' e^{V_{BE}/V_T}$$

When $V_{BE} < 0.6V$, $I_B \approx 0$ (cut-off region)

Characteristic of BJT (I_C Vs V_{CE})





$$I_C = \beta I_B = \beta I_s' e^{V_{BE}/V_T}$$

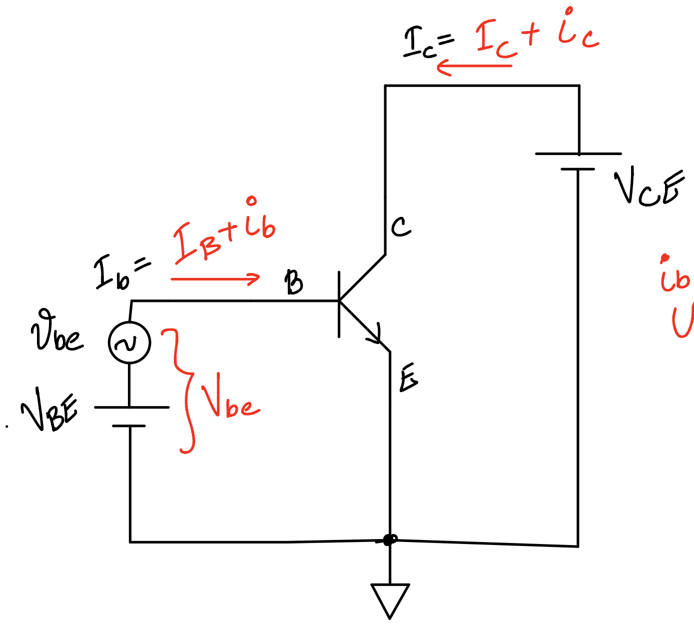
Cut-off-region : $V_{BE} < 0.6V$

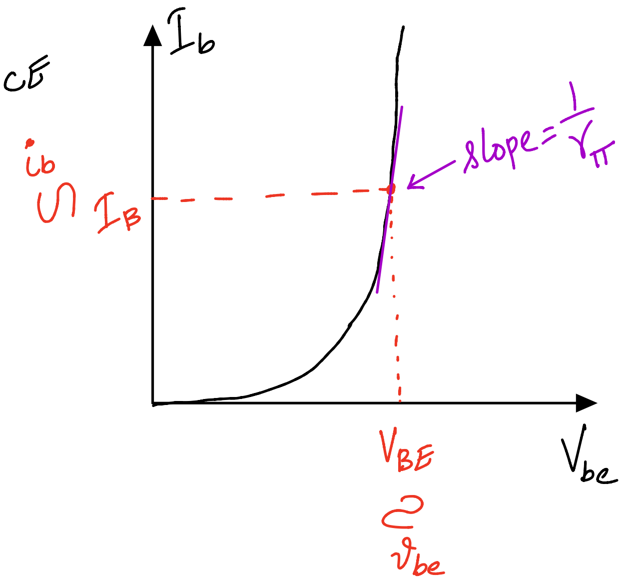
Saturation region : $V_{CE} < 0.3V$

Active region : $V_{BE} > 0.6$ & $V_{CE} > 0.3V$

Small Signal Model of BJT

$$i_c = \beta i_b$$

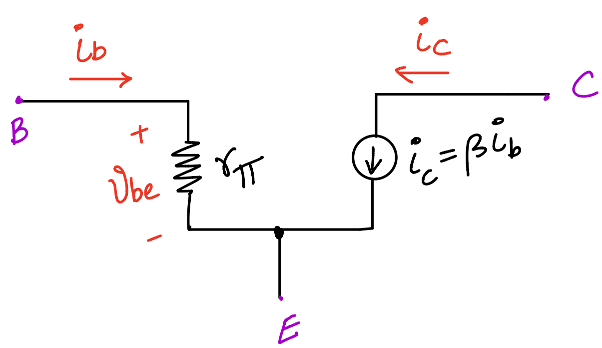




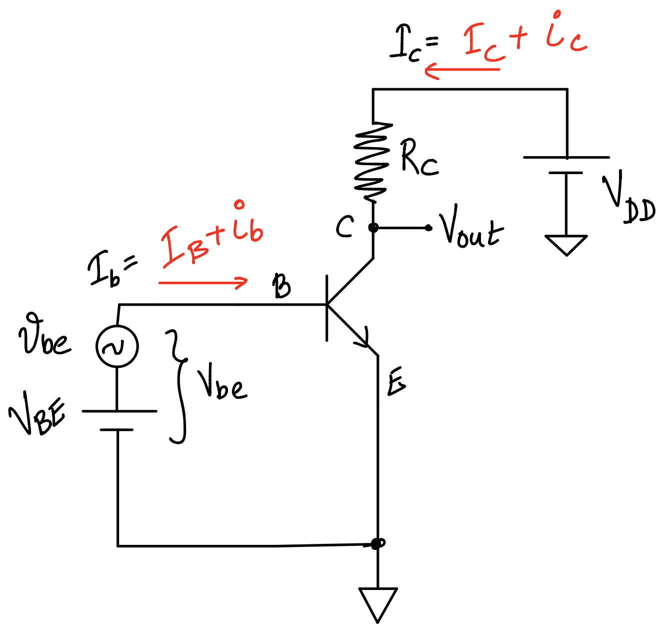
$$r_\pi = \frac{V_T}{I_B} \quad , \quad i_b = \frac{v_{be}}{r_\pi}$$

⇐ r_π for BJT is similar to r_d of diode.

$$i_b = \frac{v_{be}}{r_\pi} \quad \text{and} \quad i_c = \beta i_b$$



Amplifier Design

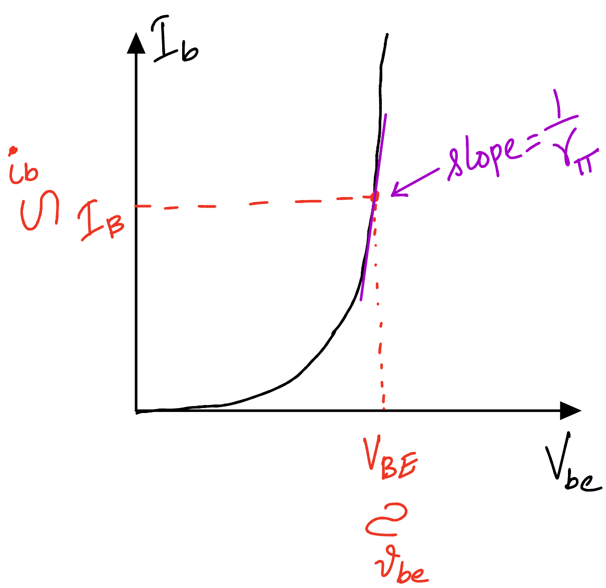


$$V_{out} = V_{DD} - I_c R_c$$
$$= V_{DD} - \beta I_b R_c$$

$$\therefore \frac{dV_{out}}{dV_{be}} = 0 - \beta R_c \frac{dI_b}{dV_{be}}$$

$$\Rightarrow \frac{dV_{out}}{dV_{be}} = -\beta R_c \left.\frac{dI_b}{dV_{be}}\right|_{I_b = I_B}$$

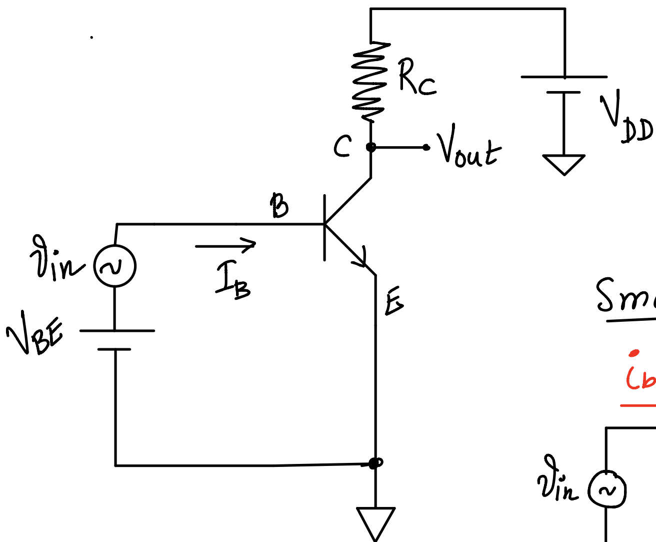
$$\Rightarrow \frac{v_{out}}{v_{be}} = -\beta R_c \frac{1}{r_\pi}$$
$$= -\beta R_c \frac{I_B}{V_T}$$
$$= -\frac{I_C R_C}{V_T}$$



If $v_{be} = v_{in}$

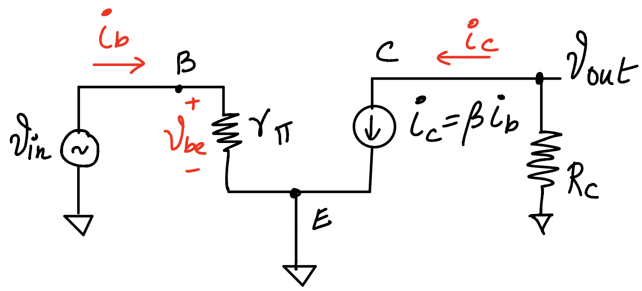
$$A_v = \frac{v_{out}}{v_{in}} = -\frac{I_C R_C}{V_T}$$

Common Emitter Amplifier (CE Amplifier)



$$A_v = \frac{v_{out}}{v_{in}} = -\frac{I_C R_C}{V_T}$$

Small-Signal Analysis



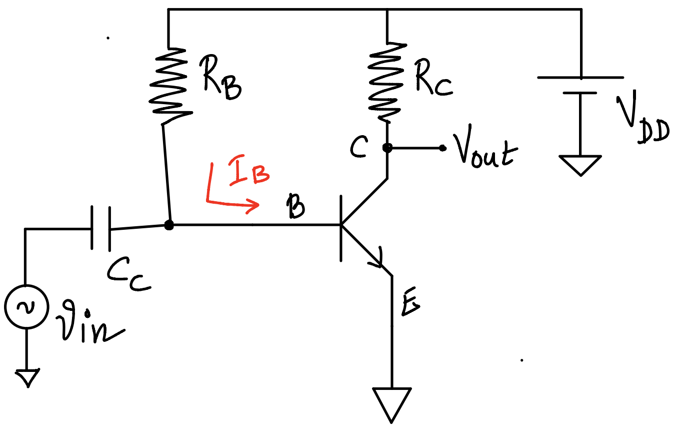
$$\therefore v_{out} = -i_c R_C$$

$$= -\beta i_b R_C$$

$$= -\beta R_C \frac{v_{be}}{r_\pi} = -\beta R_C \frac{v_{in}}{r_\pi}$$

$$\therefore A_v = \frac{v_{out}}{v_{in}} = -\beta R_C \frac{I_B}{V_T} = -\frac{I_C R_C}{V_T} \quad //$$

Self-Biasing of CE Amplifier

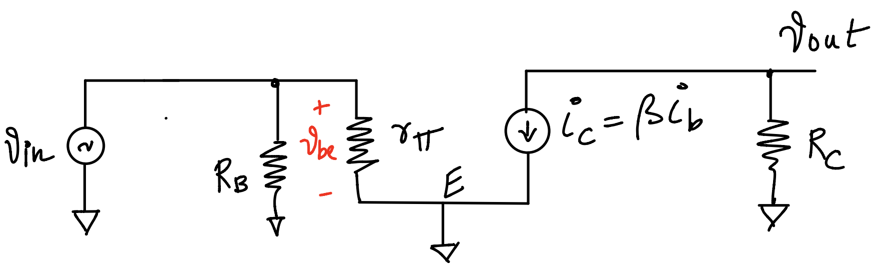


$$\frac{V_{DD} - V_{BE(on)}}{R_B} = I_B$$

0.7

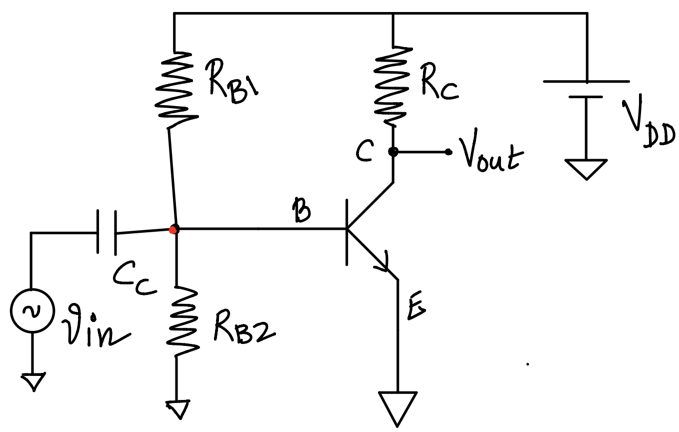
$$\Rightarrow I_B = \frac{V_{DD} - 0.7}{R_B}$$

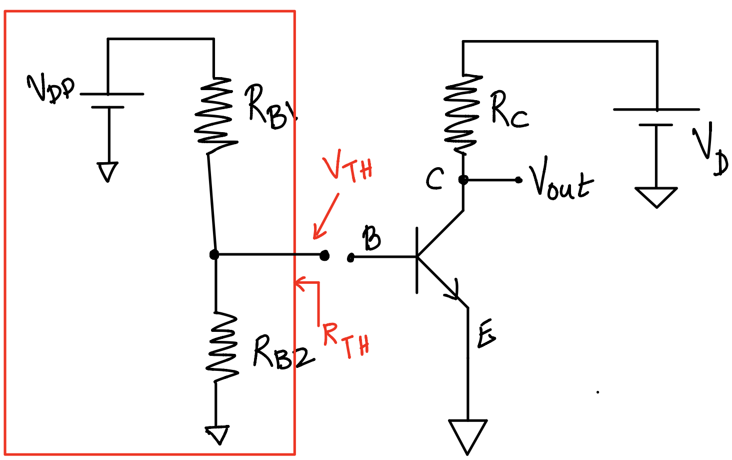
Small signal Analysis



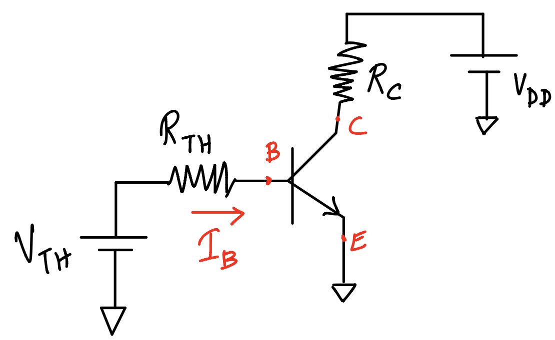
$$A_v = -\frac{I_C R_C}{V_T}$$

Resistive Divider Biasing Technique



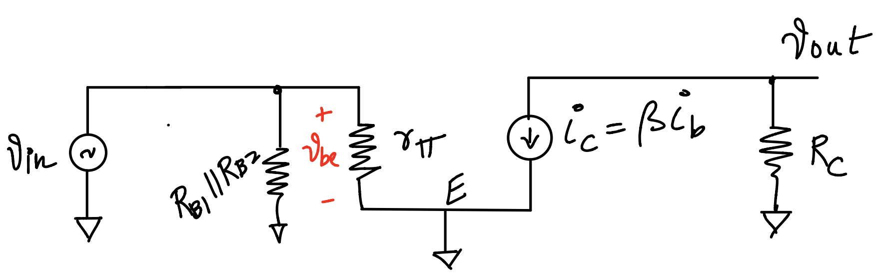


$$V_{TH} = \frac{V_{DD} R_{B2}}{R_{B1} + R_{B2}}, \quad R_{TH} = R_{B1} \| R_{B2}$$

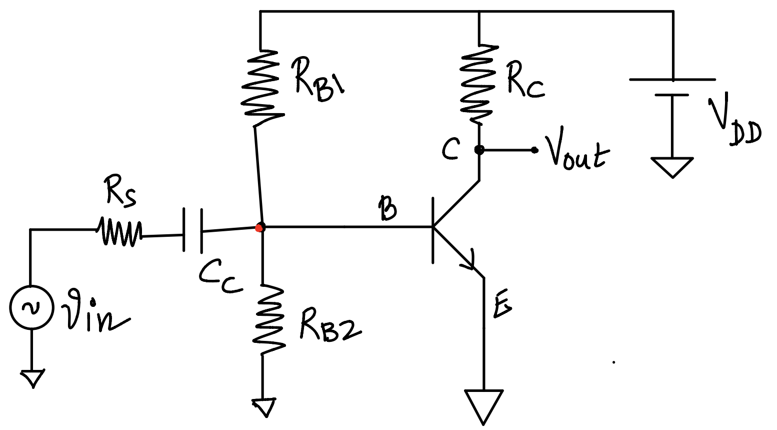


$$I_B = \frac{V_{TH} - V_{BE(on)}}{R_{TH}}$$

Small signal Analysis



Example Problem:



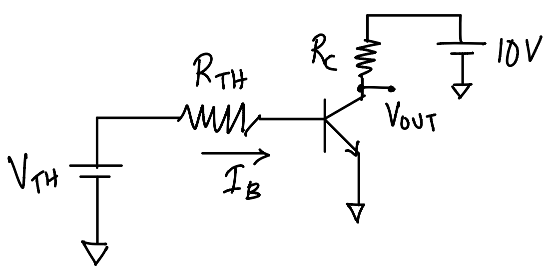
$\beta = 295$

$R_{B1} = 186\,k\Omega$

$R_{B2} = 15\,k\Omega$

$R_C = 3\,k\Omega$

$R_S = 2\,k\Omega$



$R_{TH} = R_{B1} \| R_{B2} = 13.88\,k\Omega$

$$V_{TH} = \frac{V_{DD} R_{B2}}{R_{B1} + R_{B2}} = 0.746\,V$$

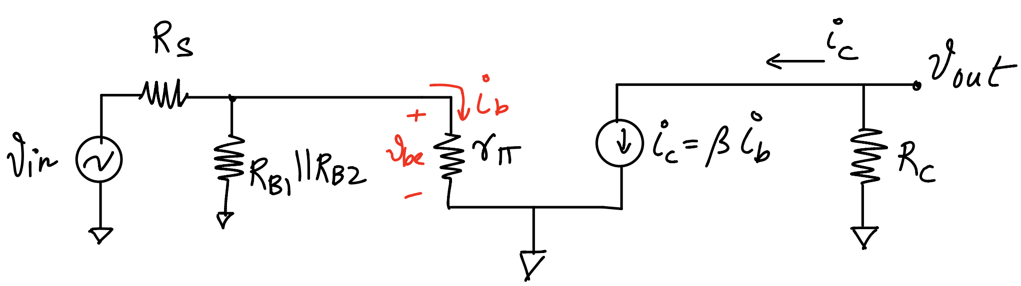
$$\therefore I_B = \frac{V_{TH} - 0.7}{R_{TH}} = \frac{0.746 - 0.7}{13.88\,k\Omega}$$

$\Rightarrow I_B = 3.33\,\mu A$ //

$I_C = \beta I_B = 0.98\,mA$

$V_{CE} = V_{OUT} = V_{DD} - I_D R_C = 10 - 0.98mA \times 3k\Omega$

$\approx 7V$



$$v_{be} = \frac{v_{in}(r_\pi \| R_{B1} \| R_{B2})}{R_S + r_\pi \| R_{B1} \| R_{B2}} \longrightarrow (i)$$

$$r_\pi = \frac{V_T}{I_B} = \frac{26mV}{3.3\mu A} = 7.87\,k\Omega$$

$$\therefore\ i_b = \frac{v_{be}}{r_\pi} \longrightarrow \text{(ii)}$$

$$v_{out} = -i_c R_c = -\beta i_b R_c$$

$$= -\beta \frac{v_{be}}{r_\pi} R_c \quad \text{from (ii)}$$

$$= -\frac{\beta R_c}{r_\pi} \cdot \frac{(r_\pi \| R_{B1} \| R_{B2})\, v_{in}}{R_s + r_\pi \| R_{B1} \| R_{B2}}$$

$$\therefore\ A_v = \frac{v_{out}}{v_{in}} = -\frac{\beta R_c}{r_\pi} \cdot \frac{r_\pi \| R_{B1} \| R_{B2}}{R_s + r_\pi \| R_{B1} \| R_{B2}}$$

$$= -\frac{295 \times 3K}{7.87K} \cdot \frac{5K}{2K + 5K}$$

$$\approx -80$$