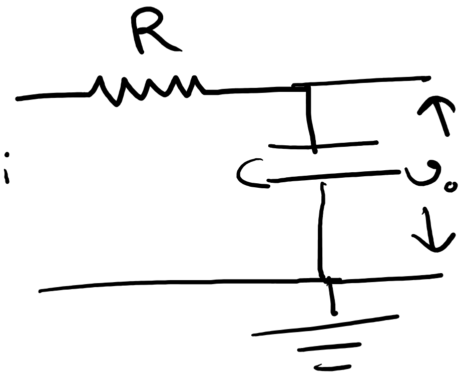
Class-5



$$v_i = \underbrace{IR}_{v_R} + \underbrace{\frac{\int_0^t I\,dt}{C}}_{v_o}$$

$$\frac{v_i}{R} = I + \frac{\int_0^t I\,dt}{CR}$$

$$= I + \frac{I}{j\omega CR}$$

If $j\omega CR >> 1$, $I \cong \dfrac{v_i}{R}$

$$I = Ae^{j\omega t}$$

$$\int_0^t I\,dt = \frac{Ae^{j\omega t}}{j\omega}$$

$$= \frac{I}{j\omega}$$

$$v_o = \frac{\int_0^t I\,dt}{C} = \int_0^t \frac{v_i\,dt}{RC}$$

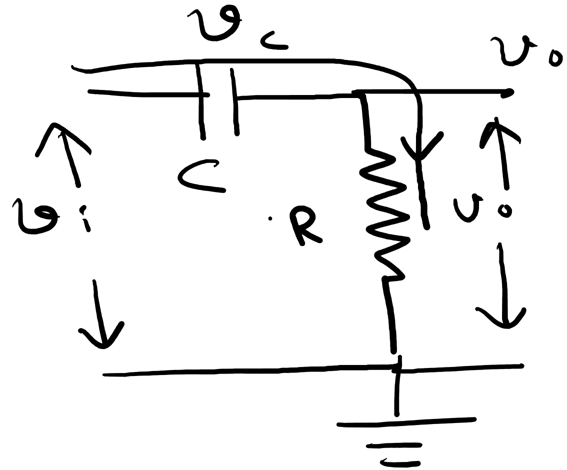
$$= \frac{1}{RC}\int_0^t v_i\,dt$$

$$v_i = v_o + v_c$$

$$v_o = IR$$

$$v_c = \frac{1}{C} \int_0^t I \, dt$$

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



If $R << \frac{1}{j\omega C}$ or, $j\omega CR << 1$

$$v_i = v_o + v_c$$

$$v_o = IR$$

$$v_c = \frac{\int I\,dt}{C} = \frac{1}{j\omega C} I$$

If $v_o << v_c$.

$$v_i \cong v_c = \frac{\int_0^t I\,dt}{C}.$$

$$\Rightarrow \int_0^t I\,dt = C v_i$$

$$\Rightarrow I = C \frac{dv_i}{dt}$$

$$v_o = RI$$

$$= RC \frac{dv_i}{dt}$$

Law of Mass-Action.

$$n_i p_i = n p$$

total hole conc in Valence Band

intrinsic electron conc in the CB

total electron concentration in CB

intrinsic hole conc in valence Band

Q: Semiconductor: Si

$N_D = 10^{15}/cm^3$.

what is the value of n and p?

$n_i = p_i = 1.5 \times 10^{10}/cm^3$ at $T = 300K$.

$N_D = 10^{15}/cm^3$

$N_D \gg n_i$

$n \cong N_D = 10^{15}/cm^3$.

$n_i p_i = np$

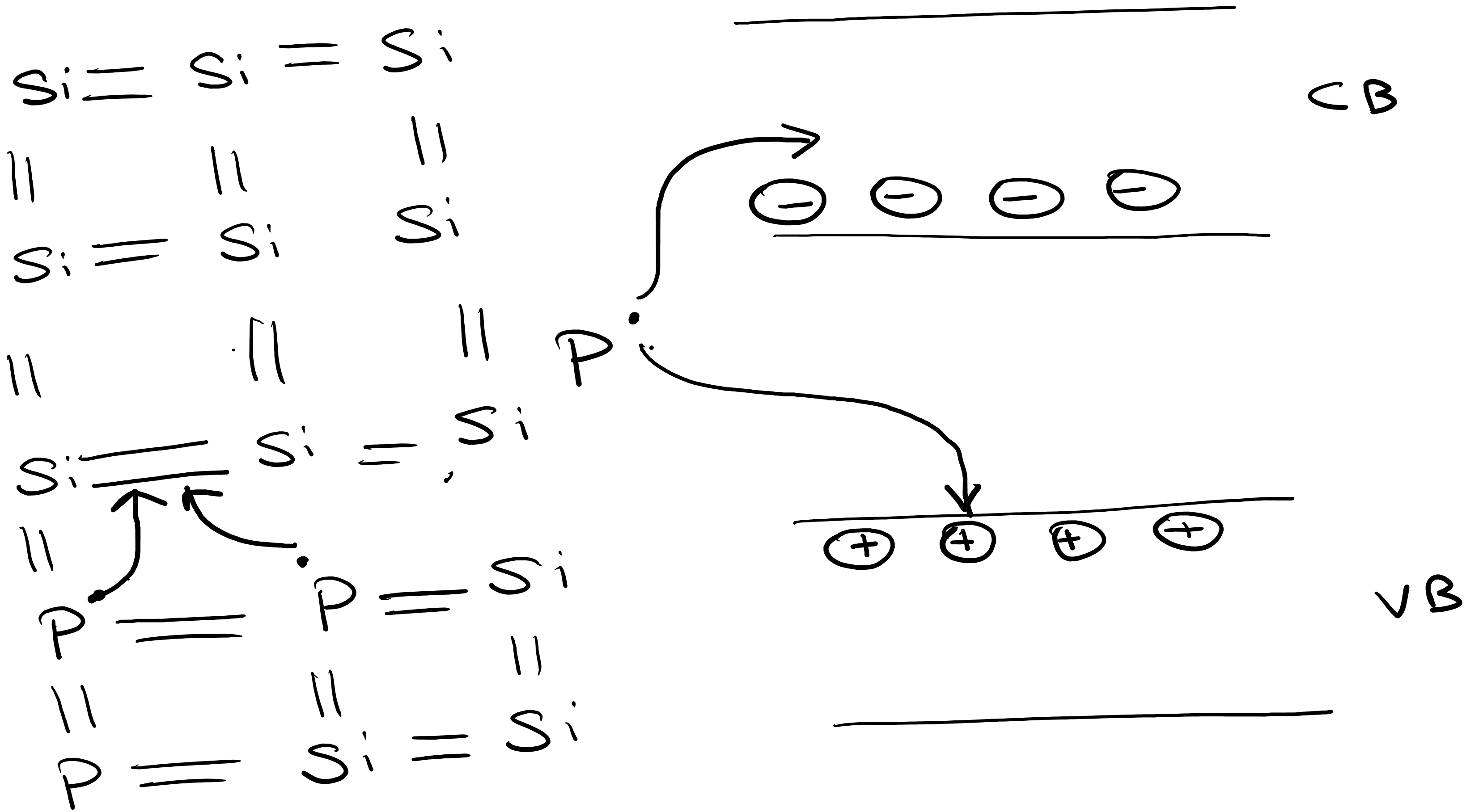
$$p = \frac{n_i p_i}{n}$$

$$= \frac{(1.5\times10^{10})^2}{10^{15}} /cm^3$$

$$= 2.25\times10^5 /cm^3$$

$n = 10^{15}/cm^3$ and $p = 2.25\times10^5/cm^3$.

$$\underbrace{p}_{2.25\times10^5/cm^3} << \underbrace{p_i}_{1.5\times10^{10}/cm^3}$$


Si = Si = Si
Si = Si
Si
P
Si = Si = Si
P = Si
P =
P = Si = Si
CB
VB

Since n-type and p-type doping enhances the number of electrons in the conduction band and the number of holes in the valence Band respectively, introducing dopant impurities enhance the conductivity of semiconductors.

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

n-type semiconductor:- Semiconductors containg n-type or donor type impurities

P-type semiconductor:- Semiconductors containing P-type or acceptor type dopants.

$$N_D = 10^{15}/cm^3 \text{ of P}$$

$$N_A = 3\times10^{15}/cm^3 \text{ of B.}$$

What type of semiconductor is this?

This semiconductor is p-type because there are more acceptor type impurities compared to donor type impurities.

$$p \cong \underbrace{N_A - N_D} \cong 2\times10^{15}/cm^3.$$

This process of introducin both acceptor and donor type impurities in a Semiconductor is known as compensation doping.

$10^{15}/cm^3$ $\rightarrow$ extra el due to N_D

$\rightarrow 3\times10^{15}/cm^3 \rightarrow$ vacancy due to N_A

what remain is $2\times10^{15}/cm^3$ vacancy $\longrightarrow$ p

Current flow in Semiconductor

Drift current.

* Driving agent is the electric field. Electrons and holes flow in the opposite and same direction as the electric field respectively.

Diffusion current.

Electrons or holes flow from the point of high concentration to the point of low concentration. This flow occurs due to a difference in carrier concentration or a gradient in carrier concentration

$$J_{drift} = \underbrace{e(n\mu_n + p\mu_p)}_{\sigma}E$$

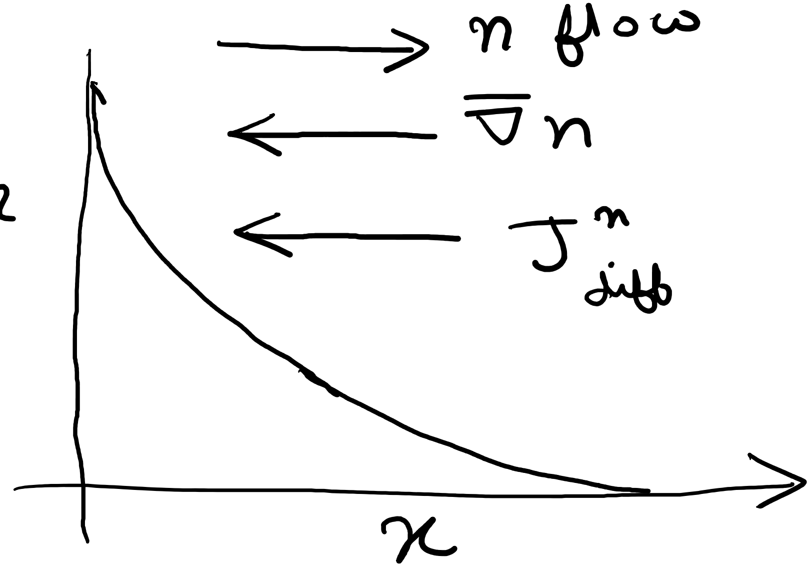
Diffusion current: $\overline{\nabla} n$ or $\overline{\nabla} p$

$$n = Ae^{-\alpha x}$$

$$\overline{\nabla} n = \frac{\partial}{\partial x}(n)\hat{i} + \cancel{\frac{\partial}{\partial y}(n)\hat{j}}\ n$$

$$\cancel{+ \frac{\partial}{\partial z}(n)}\hat{k}.$$

$$= -A\alpha e^{-\alpha x}\hat{i}$$

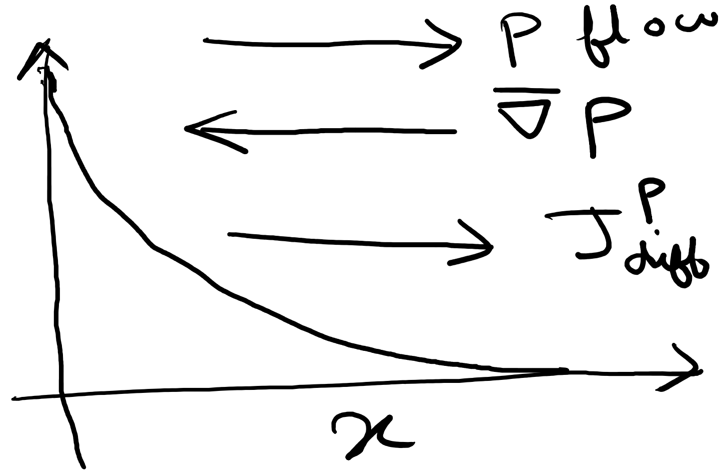


$$\overline{J}^{n}_{diff} = q D_n \overline{\nabla} n$$

→ diffusion co-efficient for electrons.

$$J^{p}_{diff} = q D_p \left(- \overline{\nabla} p \right)$$

→ diffusion coefficient for holes

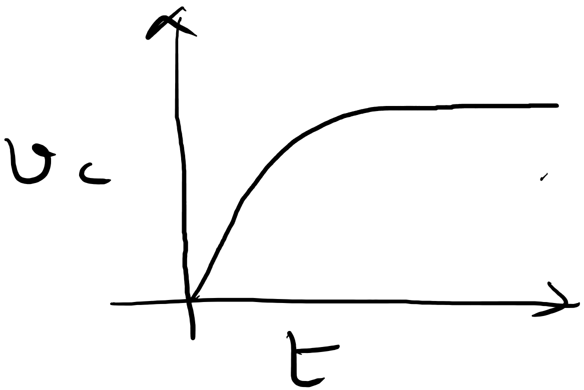


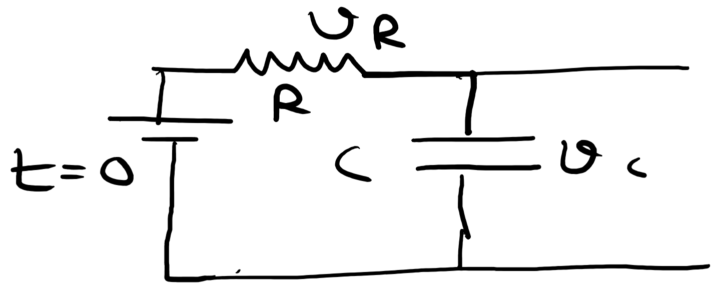
$$J_{diff} = q D_n \overline{\nabla} n - q D_p \overline{\nabla} p$$

Equilibrium: No external sources of excitation except the thermal energy in the surrounding environment. No charge inside the semiconductor. No generation or dissipation of energy.

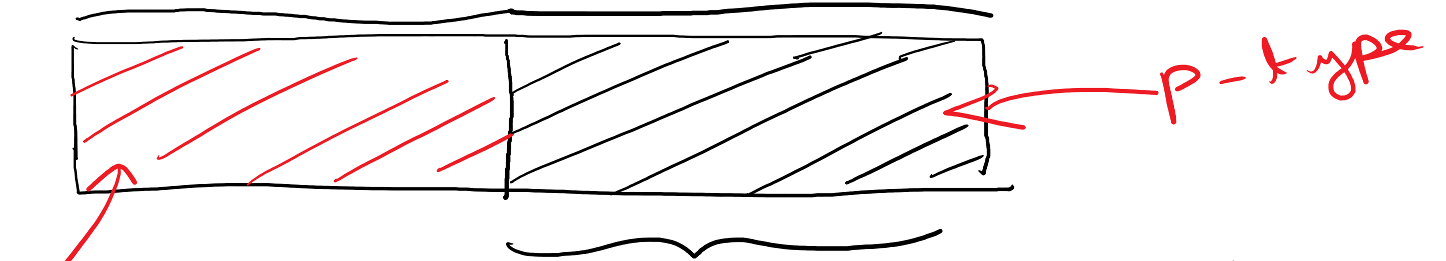
$$np = n_i p_i \rightarrow \text{valid only in equilibrium}$$

Steady state: There is no change in the device measurables with time. However, there can be dissipation or generation of energy.





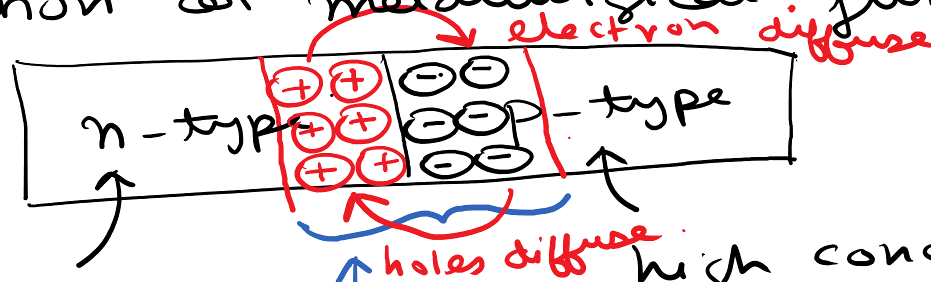
Class-6 $\quad N_D = 10^{15}/cm^3$



$2\times10^{15}/cm^3$ of p-type

$N_A = 2\times10^{15}/cm^3$

p-n junction or metallurgical junction.

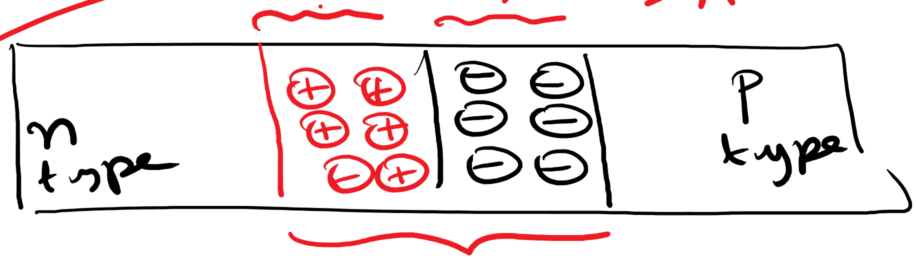


high conc of elec in CB but no holes in VB

high conc of holes in VB but no electrons in CB.

Region of accumulated charge is known as the space-charge region or the depletion region.

All holes in this region have flowed towards the n-type semiconductor

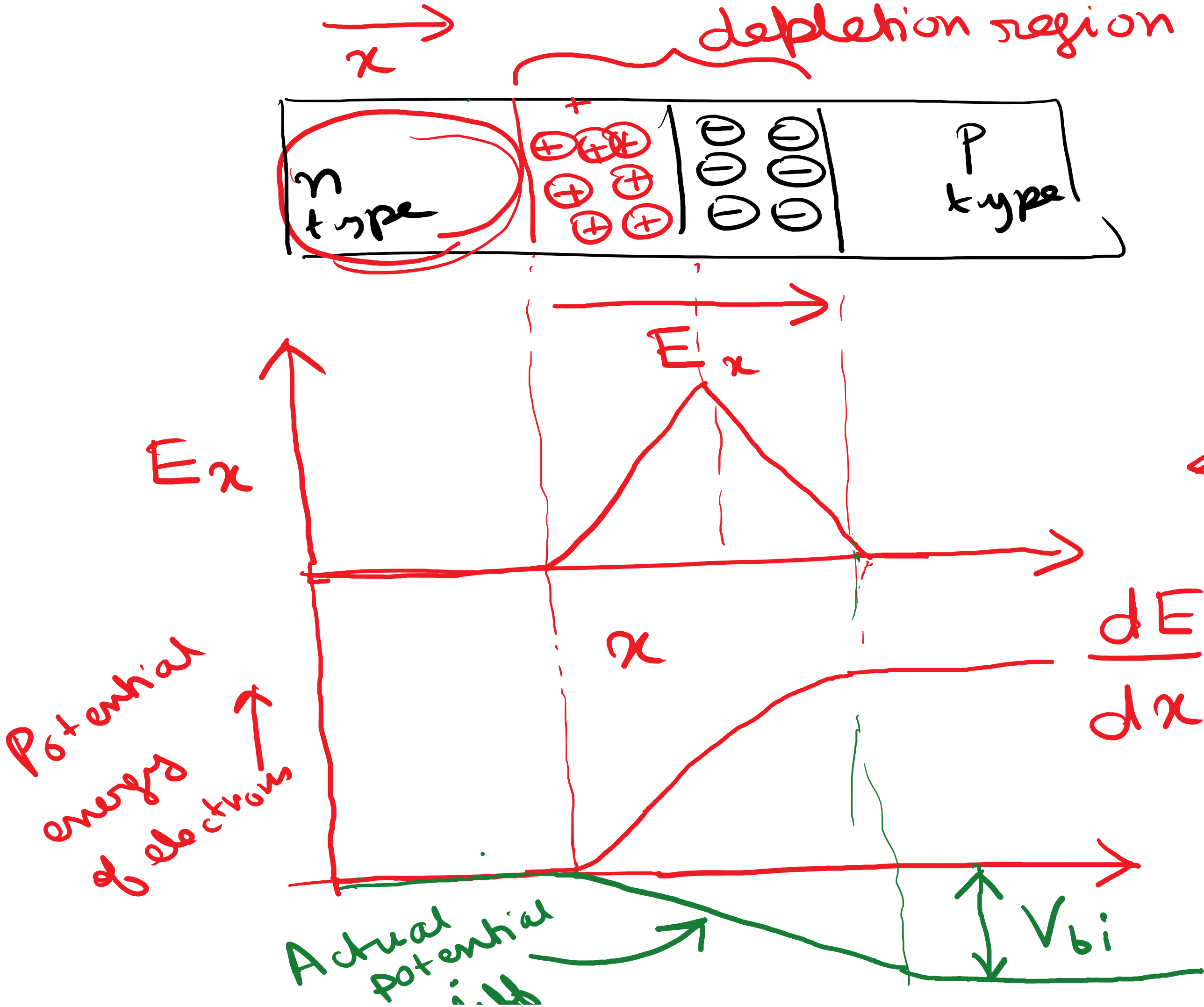


All electrons in this region has flowed towards the p-type material

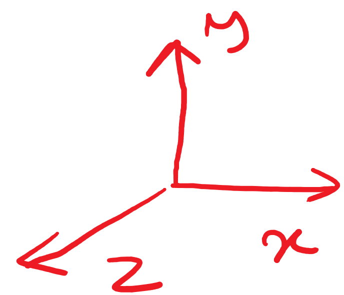
depletion region

$\xrightarrow{\quad\quad} E$

$\oplus \longrightarrow \ominus$



$$\bar{\nabla} \cdot \bar{E} = \frac{\rho}{\varepsilon}$$



$$\frac{dE_x}{dx} = \frac{\rho}{\varepsilon}$$

$$V_{ab} = -\int_a^b E(x)\,dx$$

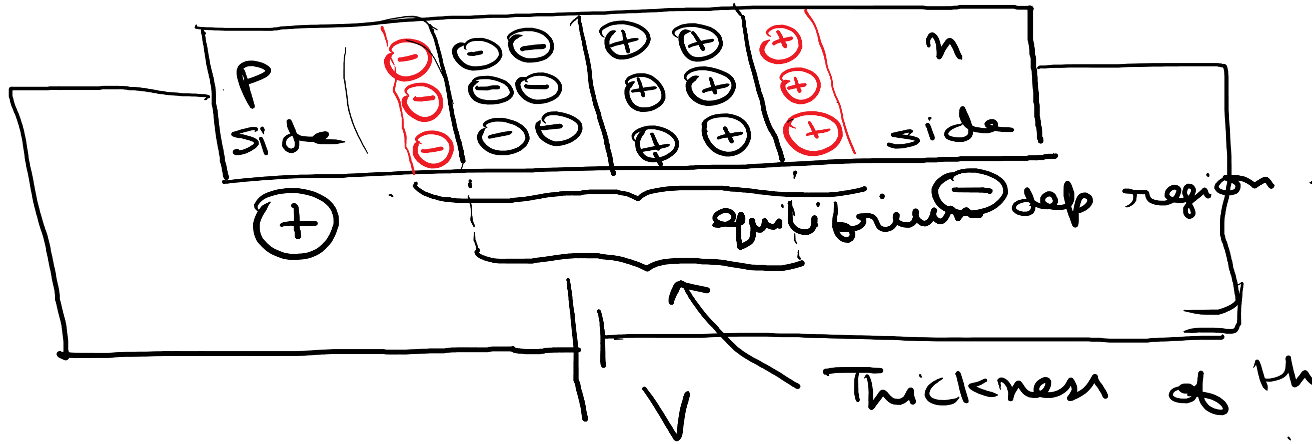

diff
Vbi

Due to electric field at the junction, a potential difference is created between the p-side and the n-side. This potential difference is called built-in potential (V_{bi})

$$V_{bi} = \frac{kT}{q} \ln \frac{N_A N_D}{n_i^2}$$

p-n junction.

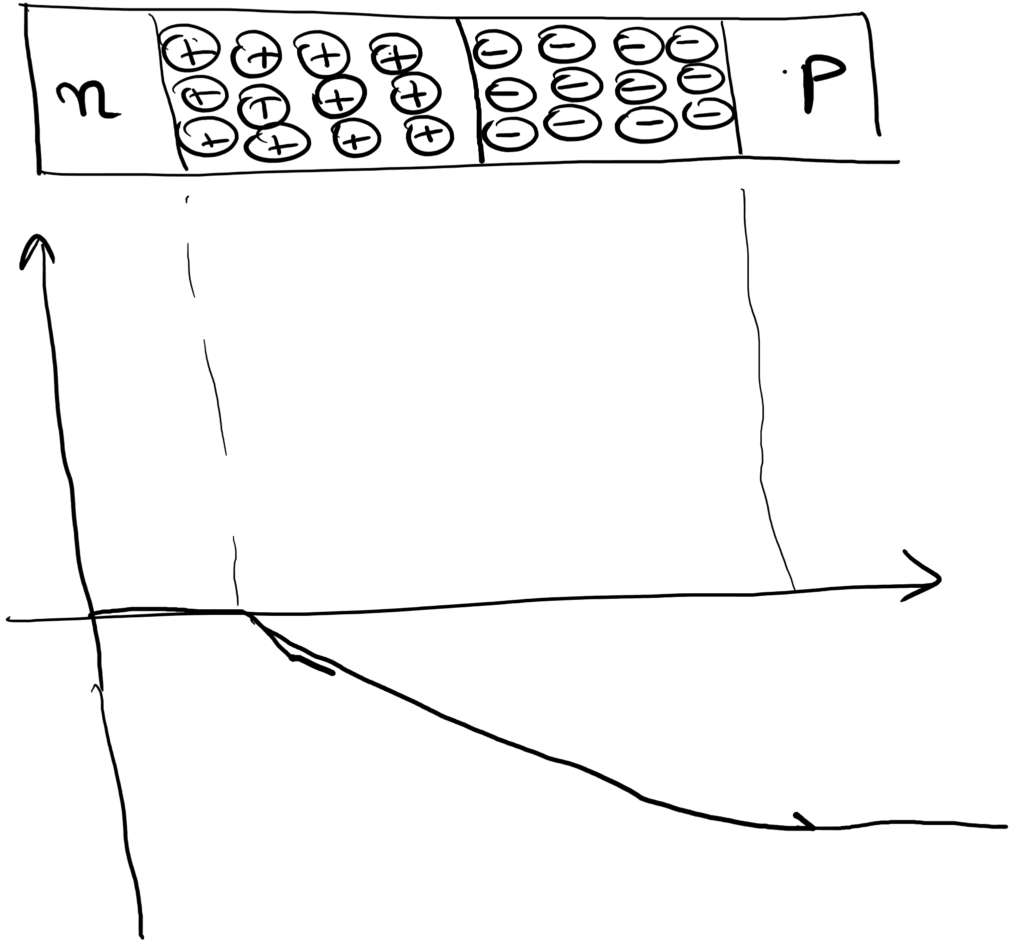
- Electrons and holes diffuse towards the p-side and n-side respectively.
- A charge accumulation builds up and the depletion region is created.
- An electric field builds up in the depletion region due to accumulation of spatial charge
- A potential diff builds up between ~~p-ty~~ p-side and the n-side.



Thickness of the depletion region under application of the voltage bias.

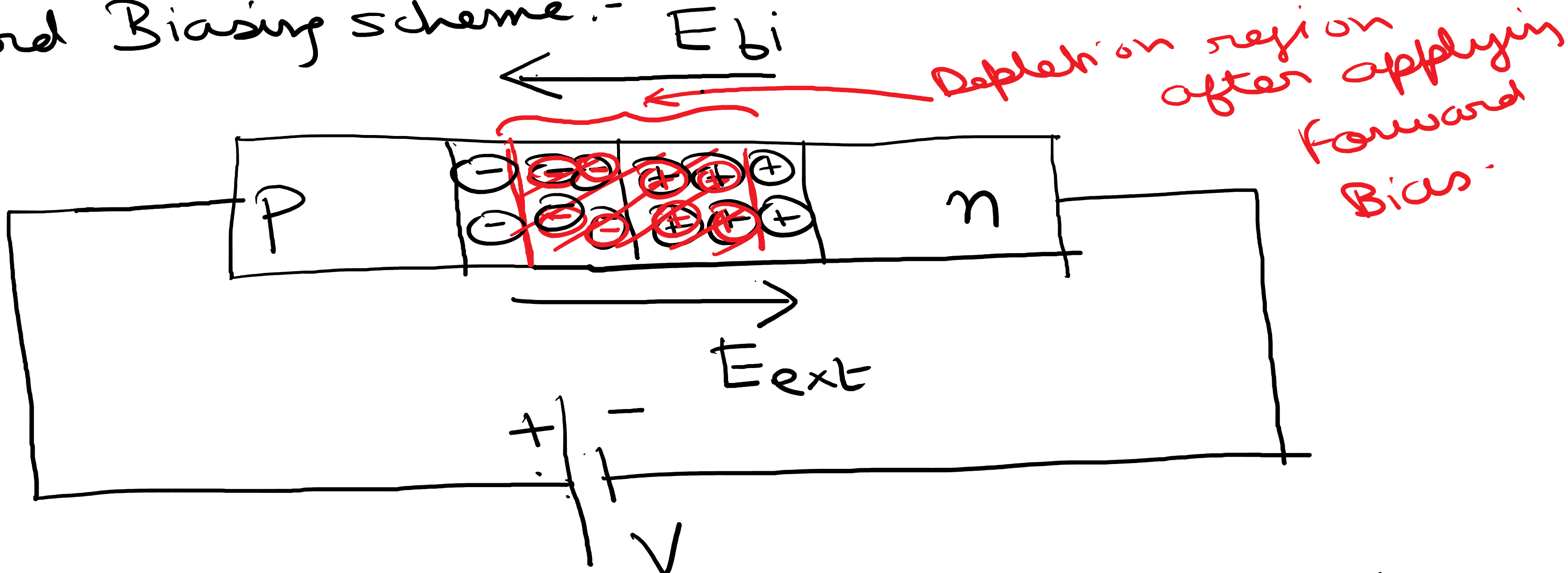
$$V_{bi} = \frac{KT}{q} \ln \frac{N_A N_D}{n_i^2}$$

The total potential difference between the p-side and the n-side now reduces to $(V_{bi} - V)$


n
p

Class-7

Forward Biasing scheme:-



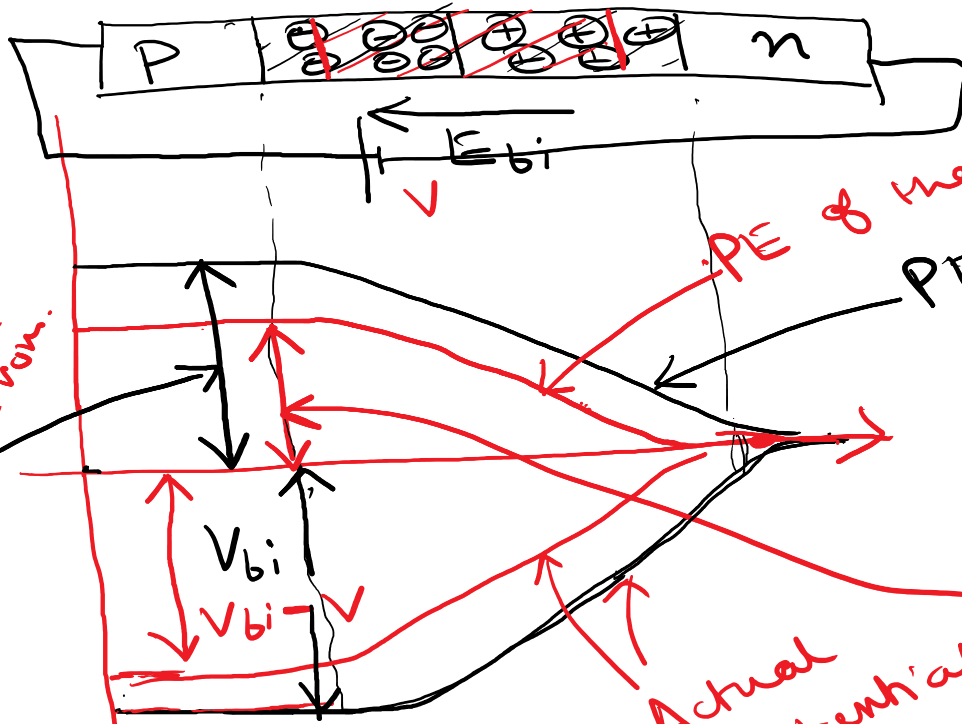
The external voltage source reduces the electric field at the junction

Since any electric field must be supported by unbalanced charge, a reduction in the electric field at the junction implies a reduction in the total unbalanced charge at the junction. A reduction in unbalanced charge implies a reduction in thickness of the depletion region.

Since the potential diff is negative of the integral of the Electric field in space, the magnitude of

$$V_{ab} = -\int_a^b \vec{E} \cdot d\vec{x}$$

V_{bi} also reduces.



Potential energy of the electron.

This is the potential V_{bi} the barrier that the electron has to cross when it diffuses from n side to p-side under no bias.

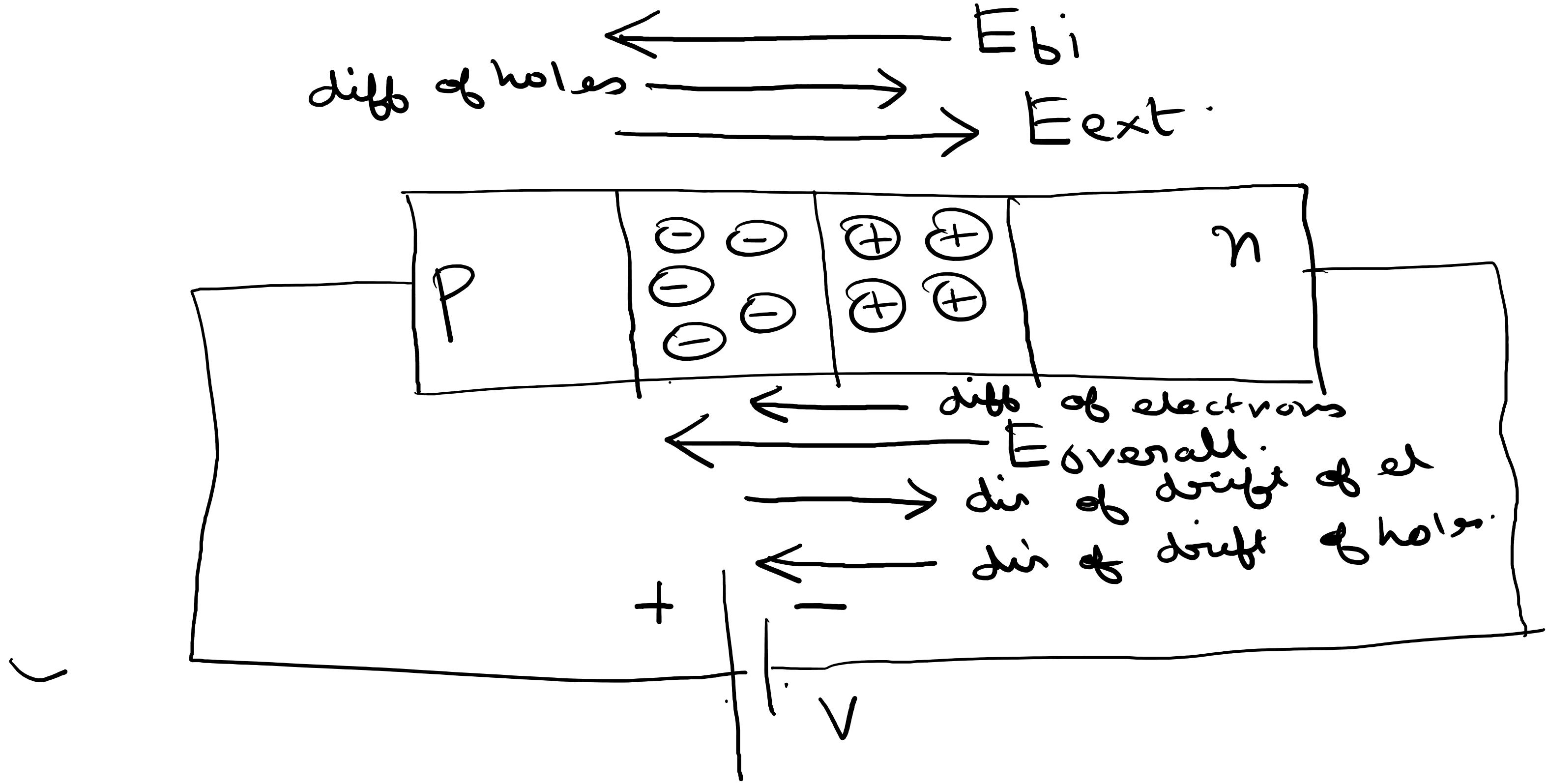
PE of the el under FB

PE of the electrons under no Bias.

Actual potential.

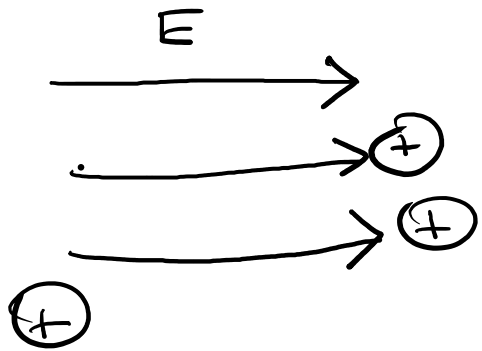
Under forward bias the potential barrier that the electrons have to cross while diffusing from n to p side reduces

Since the potential Barrier has reduced more electrons can now diffuse from the n-side to the p-side. So, the diffusion rate of electrons increases. The diffusion rate of electrons actually increase exponentially with reduction in amount of potential barrier that the electrons have to cross. The diffusion component of the current therefore increases exponentially with applied bias voltage.



Ebi
diff of holes
Eext.
p
n
diff of electrons
Eoverall.
dir of drift of el
dir of drift of holes.
+
−
V

The drift current at the junction is limited by very less number of electrons in the p-side and very less number of holes in the n-side. So, the drift current doesn't change much with change in strength of the electric field.



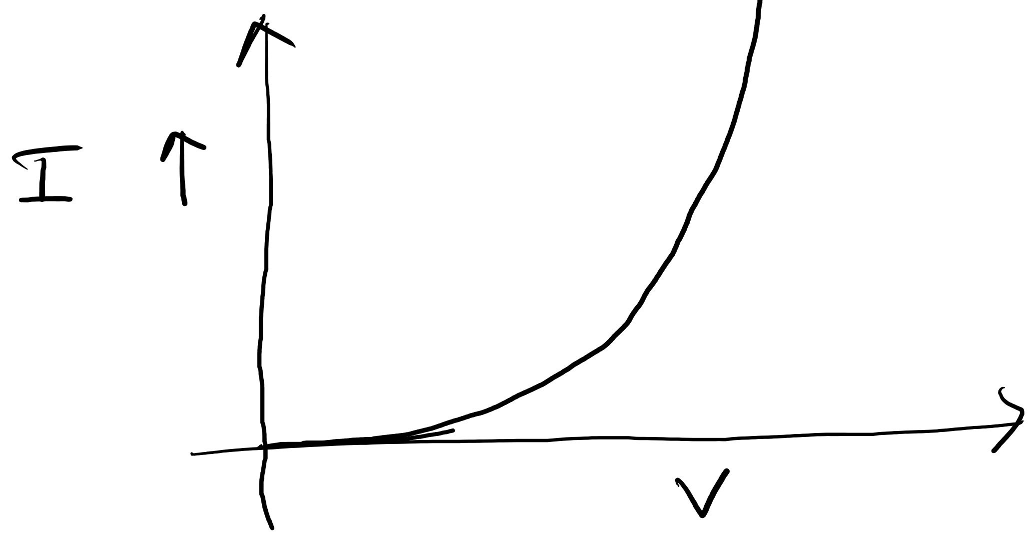
$\eta \rightarrow$ ideality factor.
from $1 \rightarrow 2$
$1 \rightarrow$ for ideal diode.

$$I = I_S \left[\underbrace{\exp\left\{ \frac{V}{\eta V_T} \right\}}_{\text{diffusion component}} - \underbrace{1}_{\text{drift component}} \right]$$

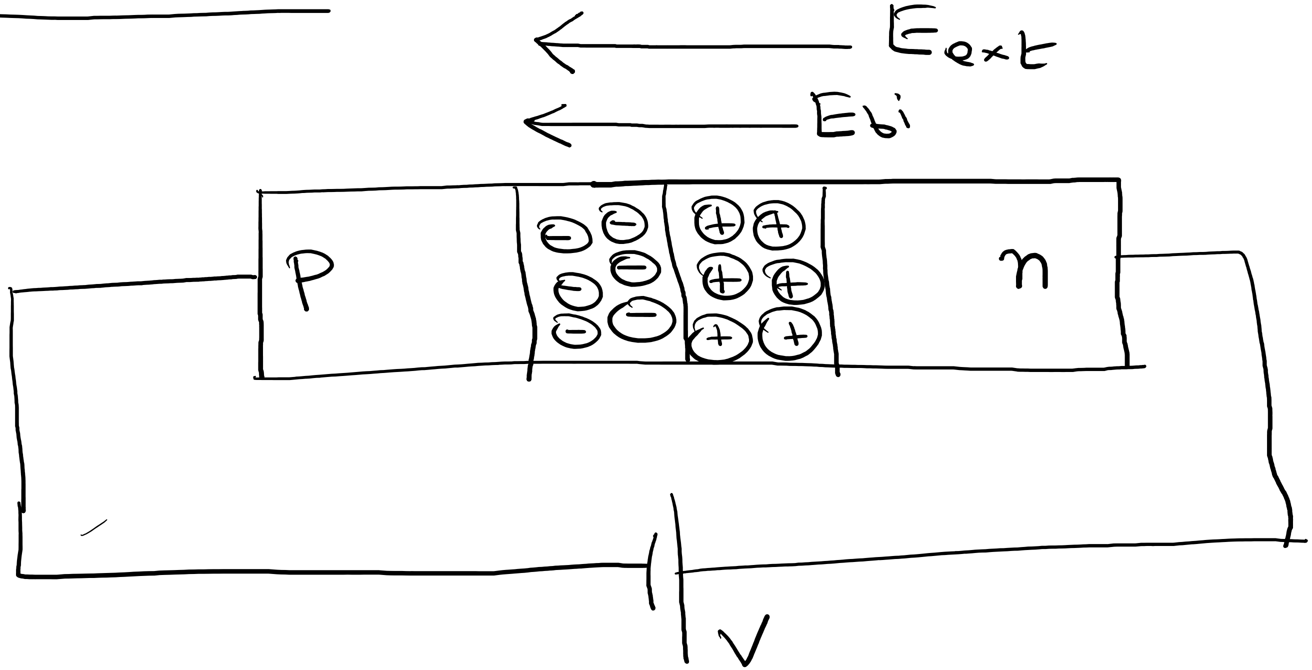
I_S → dependent on material and constant for a given material.

$V_T = \frac{KT}{q} \simeq 25.9\ meV$ at $T = 300K$

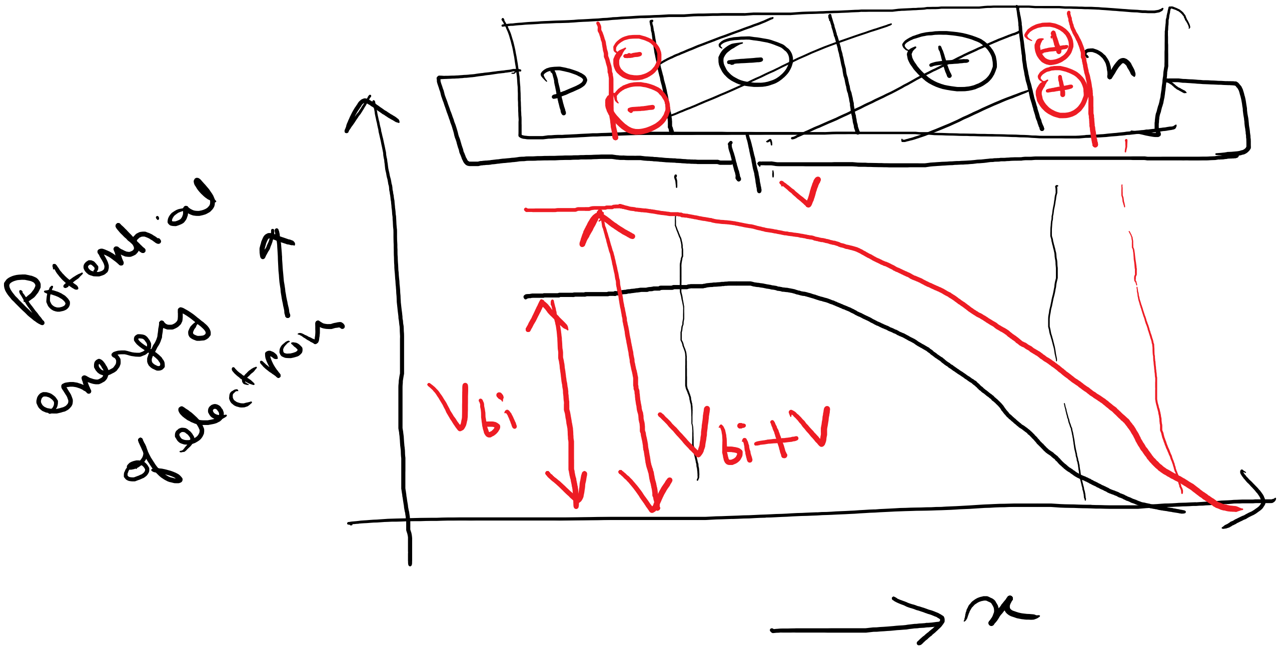
In equilibrium the drift and diffusion current components are equal and opposite. So, the total current is zero. On applying a forward bias voltage the diffusion component increases exponentially with bias voltage. But the drift component remains unchanged. So the total current increases exponentially with the bias voltage.



Reverse Bias:



So, the external voltage source increase the overall electric field at the junction



P
n
V
Potential energy of electron
Vbi
Vbi+V
x

The external potential source now aids the built in potential. and increases the overall potential difference between the p and n side. So, now, the electrons have to cross a higher potential barrier while diffusing from the n-side to the p-side.

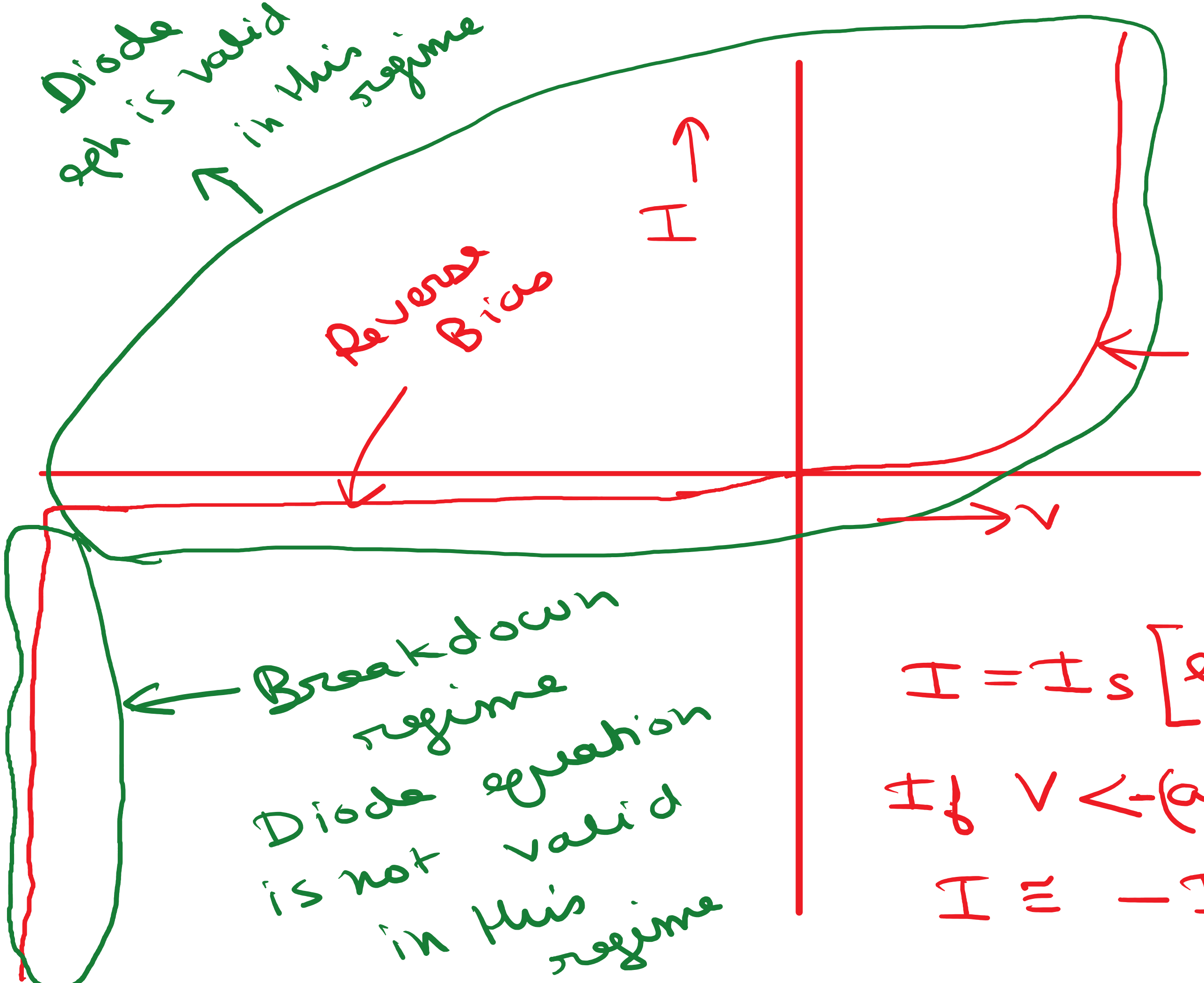
So, the rate of diffusion of electrons decreases rapidly with the increase in reverse bias voltage

Although the electric field at the junction increases, the drift current doesn't change. This is because drift current at the junction is limited by less availability of electrons in the p-side and less availability of holes in the n-side

$$I = \underbrace{I_{diff}} + \underbrace{I_{drift}}.$$

reduces to approximately zero on increasing the reverse bias voltage.

remains unchanged with increasing reverse bias voltage.



I_s = reverse saturation current

$V_T \cong 25.9\,\text{mV}$ at $T = 300\,\text{K}$

$$I = I_s\left[\exp\left\{\frac{V}{\eta V_T}\right\} - 1\right]$$

If $V < -(\text{a few } V_T)$

$$I \cong -I_s$$

Breakdown of diodes:-

<u>Avalanche Breakdown</u>: High electric field breaks the bonds to release electron-hole pairs and these electron-hole pairs are then accelerated to very high kinetic energy by the large electric field. The high KE carriers collide with other atoms to further break bonds and release more electron-hole

pairs. So, a large number of electron-hole pairs are created which increase conductivity and hence current. The process of creation of a large number of electron-hole pairs in this way is called Avalanche multiplication.

Zener Breakdown: This occurs in highly doped p-n junction due to a process called quantum tunnelling.

Class - 8

Capacitance of a p-n junction:

Majority carriers: These are basically the carriers that dominate inside the material. Electrons for n-type semiconductors and holes for p-type semiconductors.

Minority carriers: These are carriers that are available in limited numbers inside the material. Eg: electrons in p-type semiconductors and holes in n-type semi conductors.

Minority carriers can be derived from the following equation:-

$$p \cong \frac{n_i^2}{N_D} \quad \text{(for n-type semiconductors)}$$

$$n \cong \frac{n_i^2}{N_A} \quad \text{(for p-type semiconductors)}$$

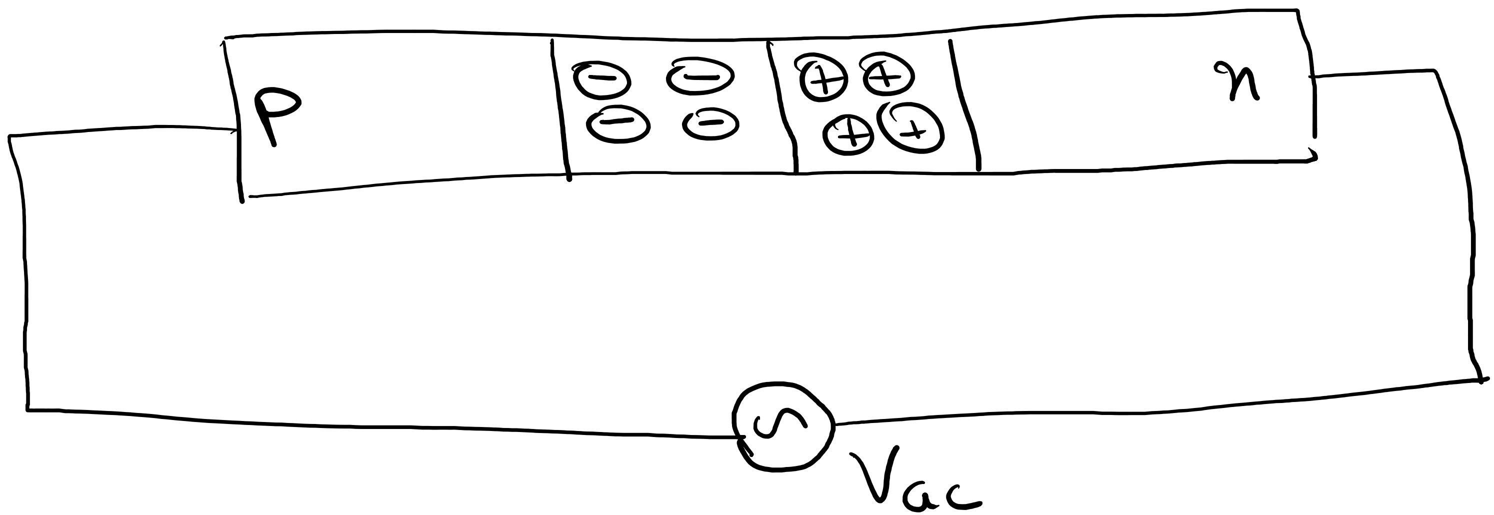
Capacitance of p-n junction

Depletion capacitance

$$C_{dep} = \frac{dQ_{dep}}{dV}$$

Diffusion capacitance

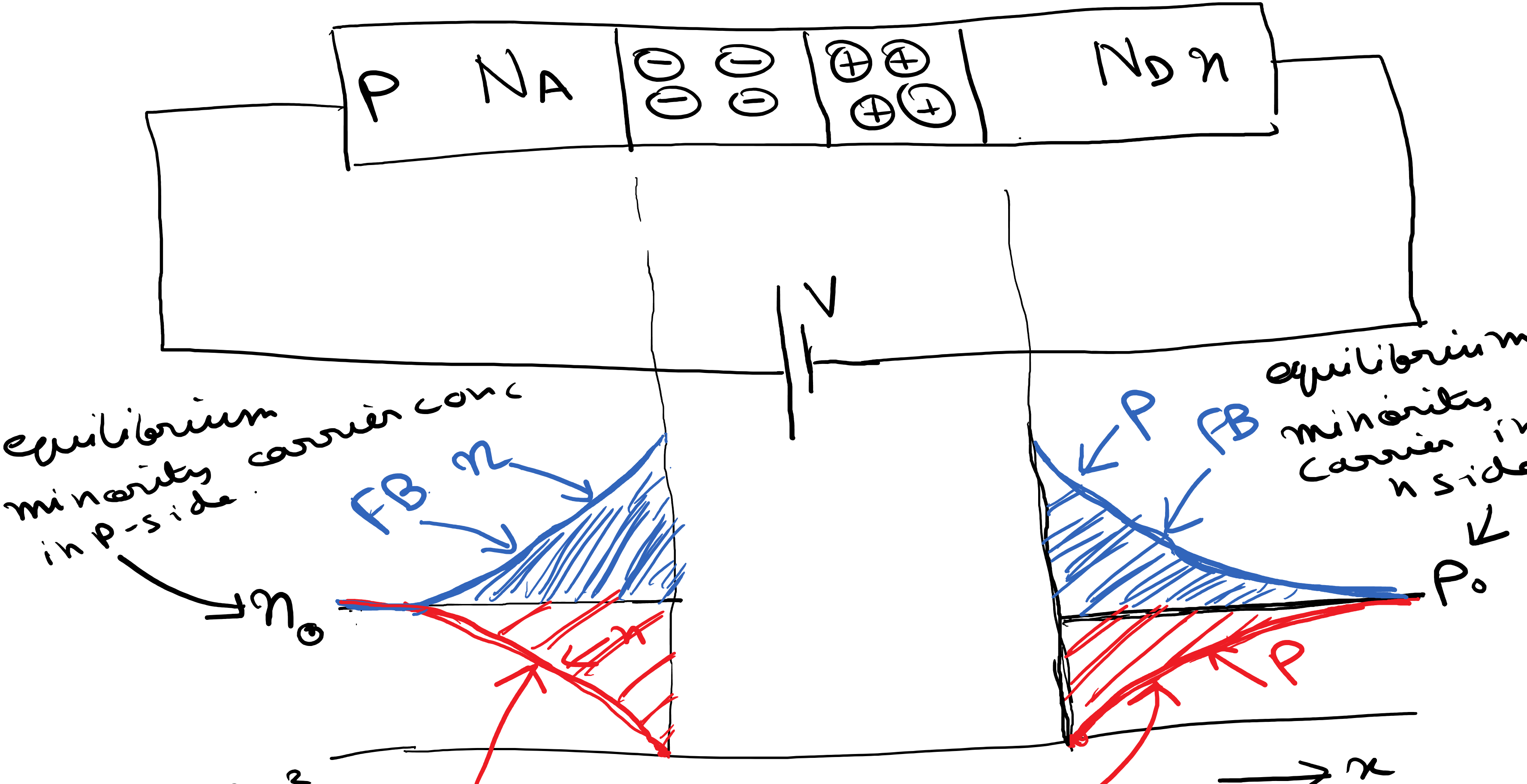
$$C_{diff} = \frac{dQ_{diff}}{dV}$$



Since the stored charge in the depletion region changes in response to a change in the applied voltage, this gives rise to a capacitor like behaviour. This capacitor like behaviour is modeled mathematically by defining the depletion capacitance.

$$C_{dep} = \frac{dQ_{dep}}{dV}$$

$Q_{dep} \rightarrow$ magnitude of the charge stored in each side of the depletion layer.

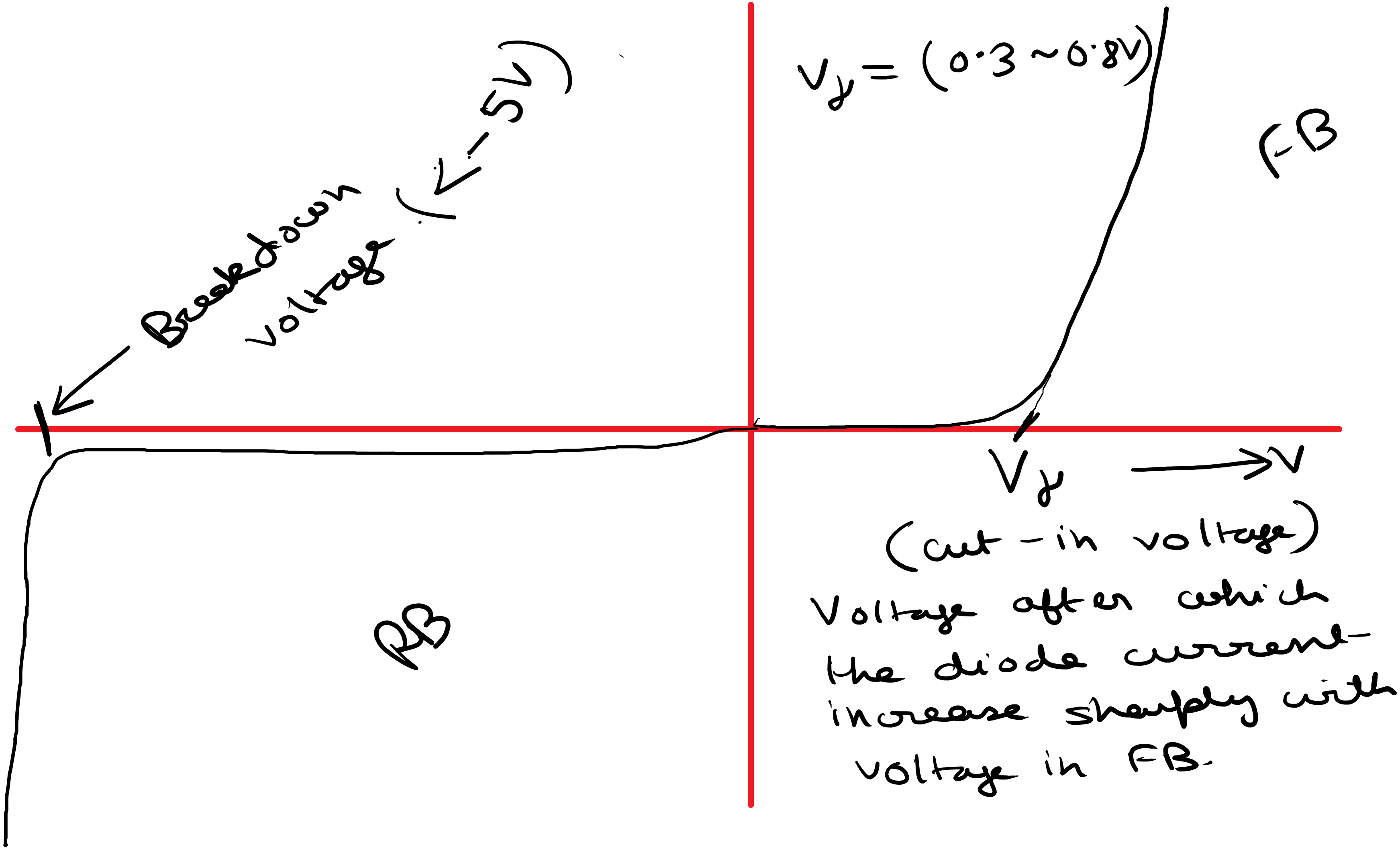


$$n_0 = \frac{n_i^2}{NA}$$

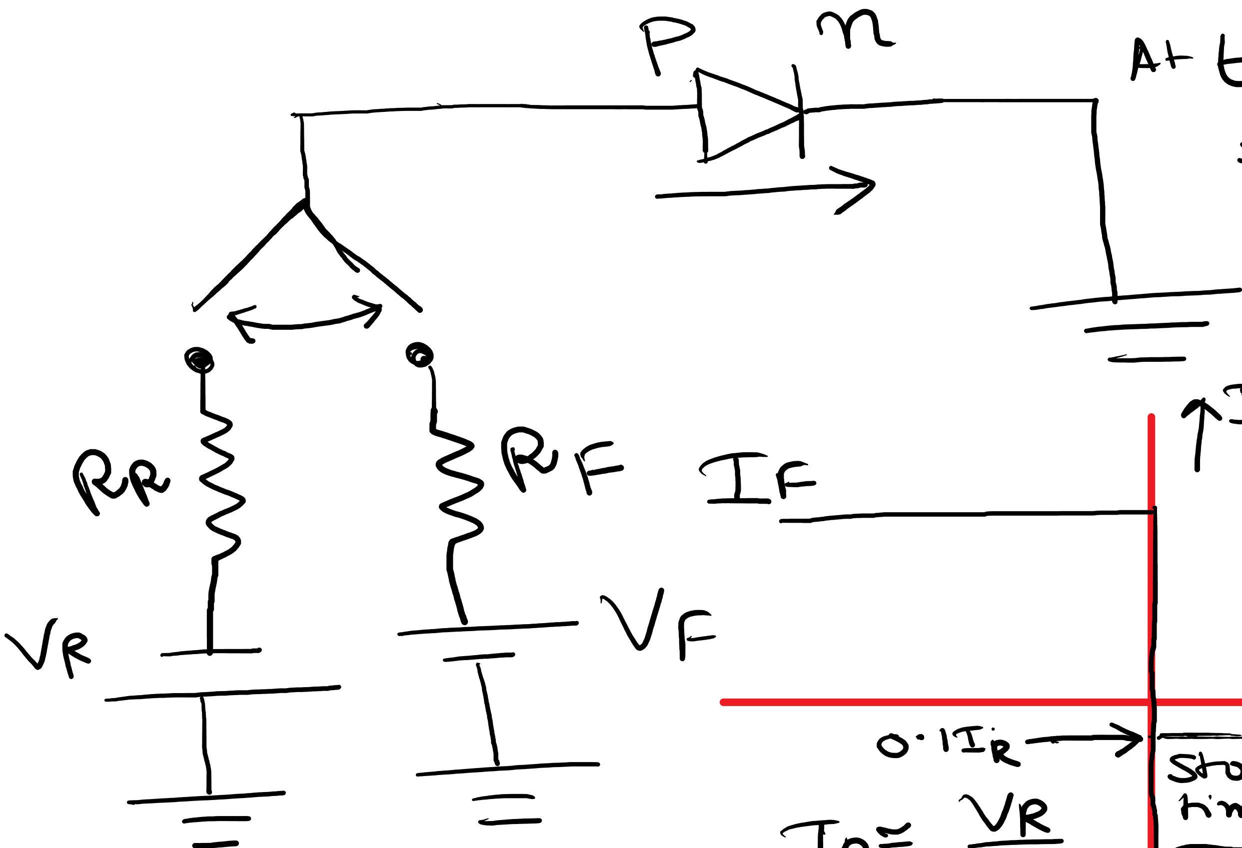
$$P_0 \simeq \frac{n_i^2}{N_D}$$

$$C_{diff} = \frac{dQ_{diff}}{dV}$$

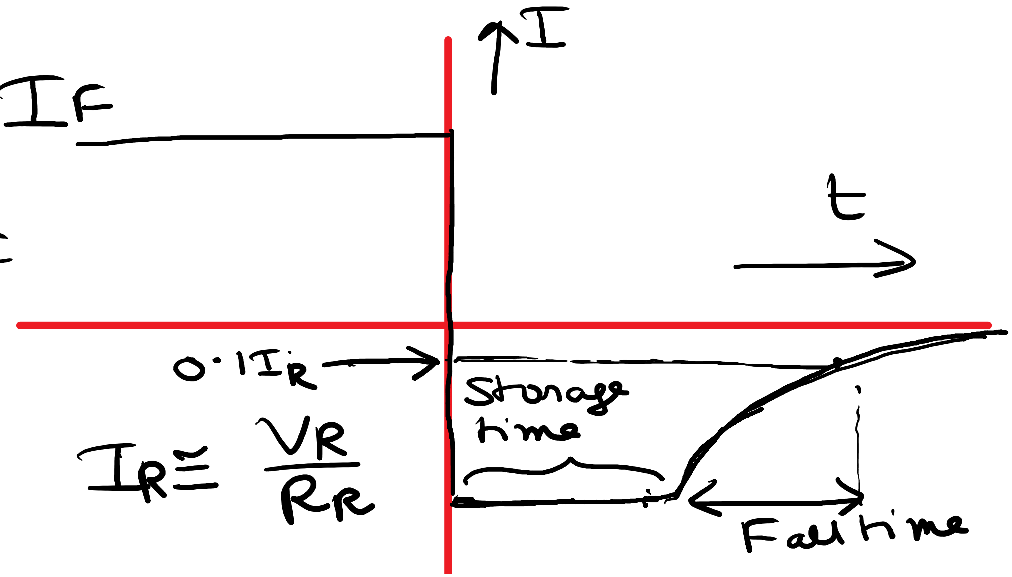
$Q_{diff} \rightarrow$ magnitude of the charge due to accumulation of excess minority carriers just outside the depletion region


Breakdown voltage (<-5V)
$V_\gamma = (0.3 \sim 0.8V)$
FB
RB
V_γ
V
(cut-in voltage)
Voltage after which the diode current increase sharply with voltage in FB.

Switching behaviour of p-n junction:-



At $t=0$, the switch is rotated.



$$I_R \simeq \frac{V_R}{R_R}$$


RR
Fall time

Turn-off time = Storage time + Fall time

(Approximate time required to bring the diode from forward Biased State to reverse Biased state)

Turn-on time $\simeq$ Storage time + $\underbrace{\text{Rise time}}$

Time during which the current increases to 90% of the Steady state value in Forward Bias

Class-9

Diode model:

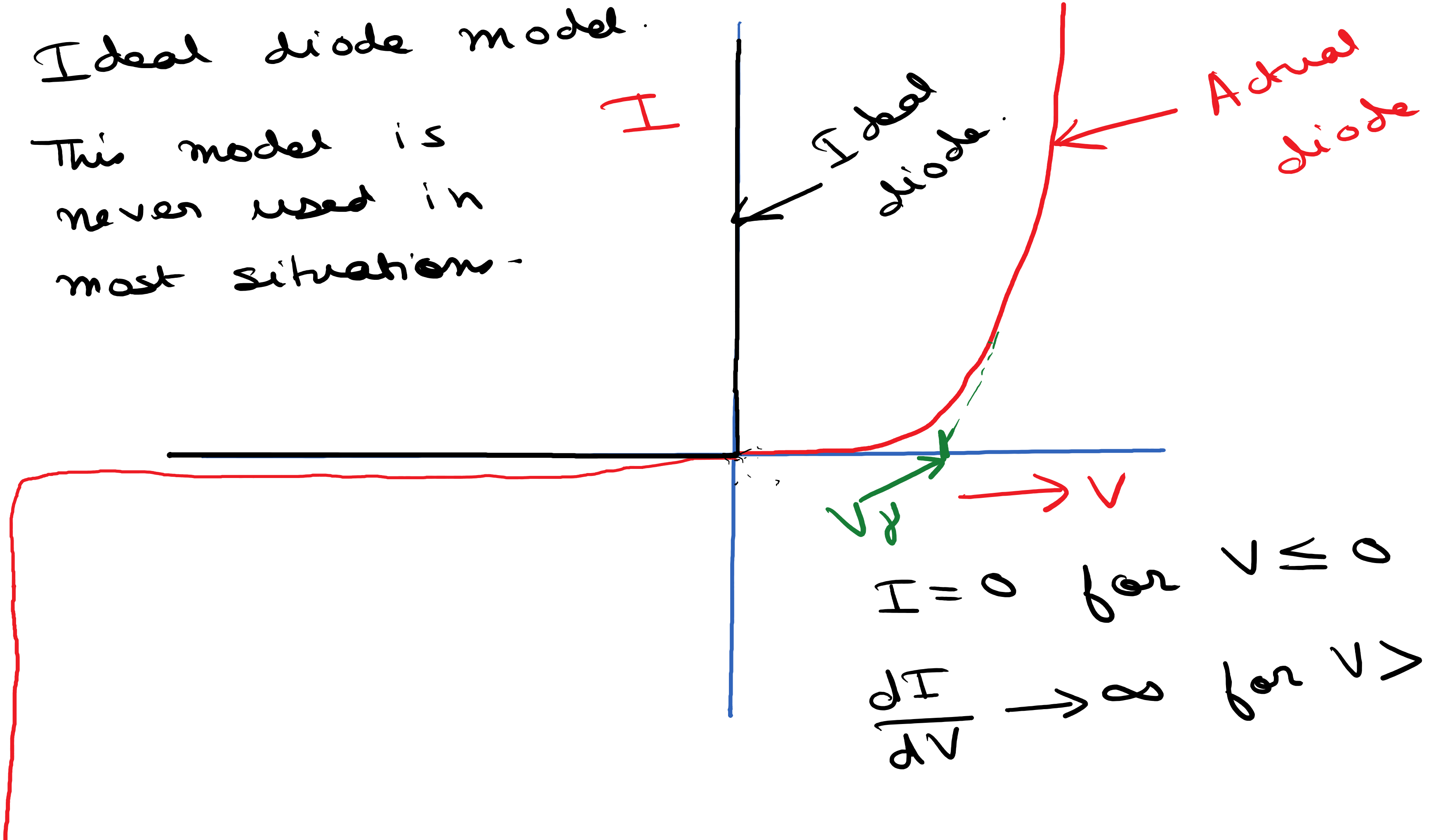
Diode → device which conducts in the forward Bias state and doesn't conduct in the reverse Bias state.

Low resistance state in FB and high resistance state in reverse bias.

→ exclude the Breakdown regime.

Ideal diode model.

This model is never used in most situations.

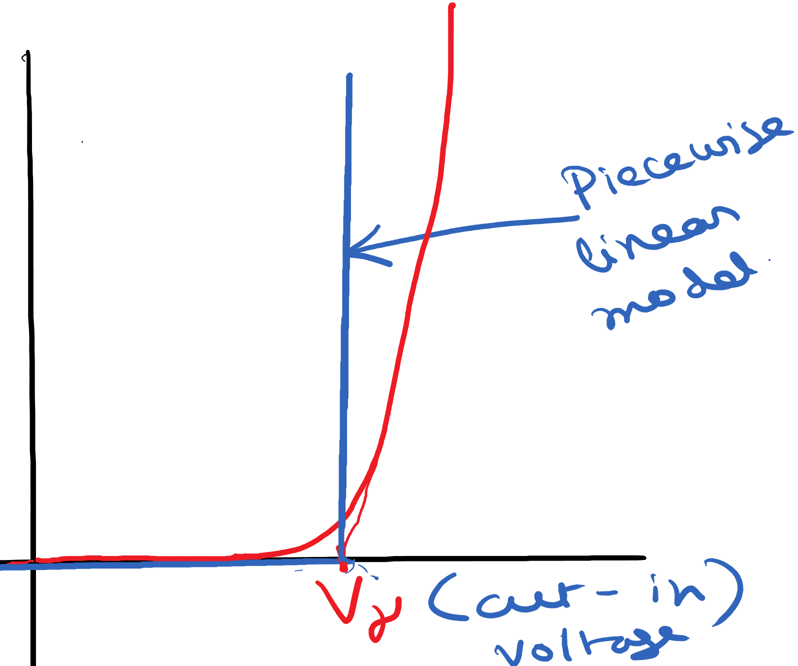


$I = 0$ for $V \leq 0$

$\frac{dI}{dV} \to \infty$ for $V > 0$

Piecewise linear model:

Unless otherwise stated, we would be using this model for most calculations.

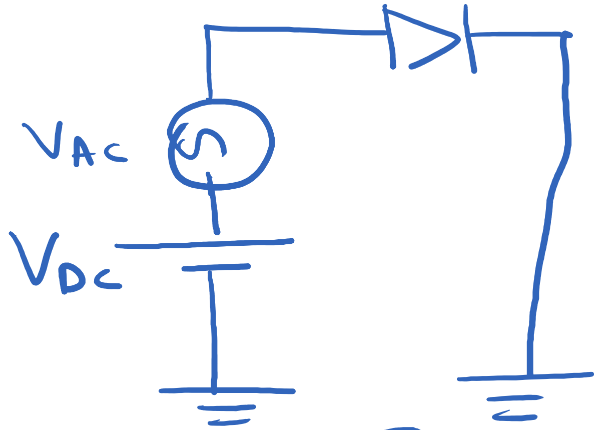


* The voltage across the diode can't exceed V_γ for practical purposes.
* For any finite value of current the voltage across the diode is fixed at V_γ.

$$\begin{cases} \text{For } V < V_\gamma, & I = 0 \\ \text{For } V \geq V_\gamma, & \dfrac{dI}{dV} \to \infty \end{cases}$$

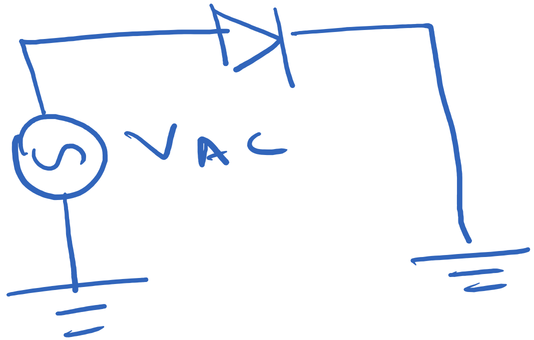
Small signal AC model: A model that ties a relation only between the AC components of the voltage and current.

$V_{AC} << V_{DC}$

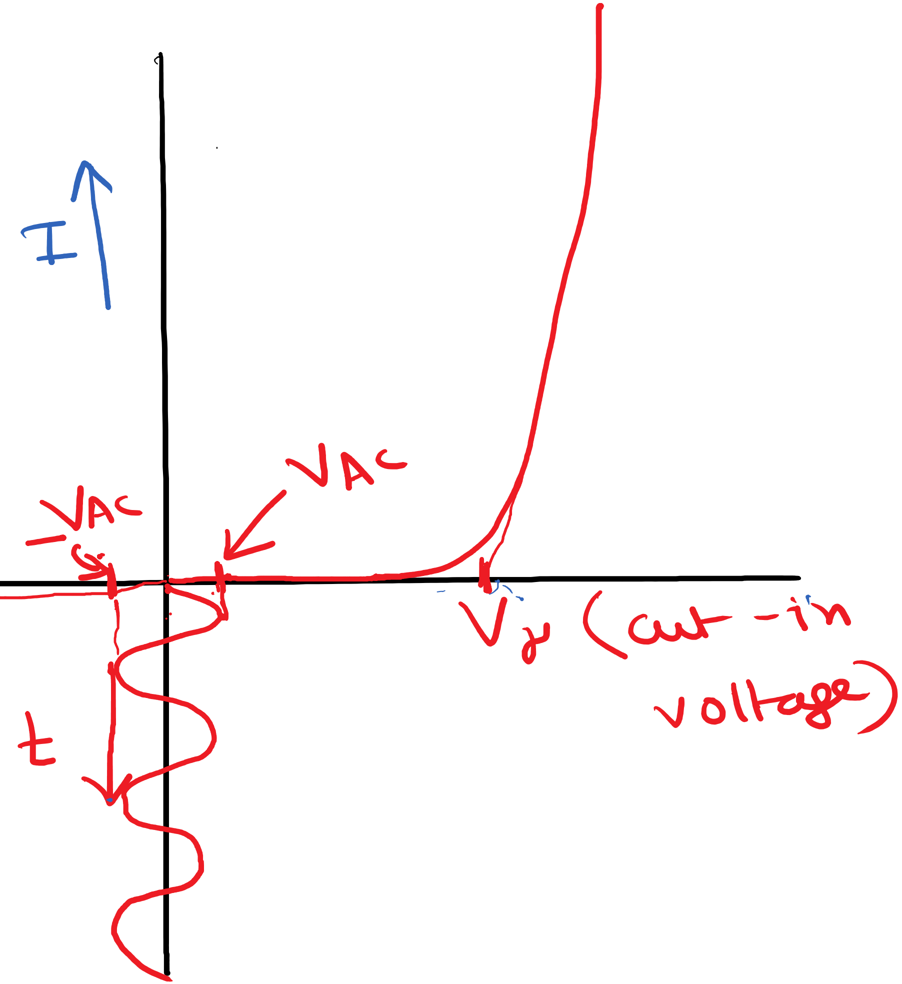


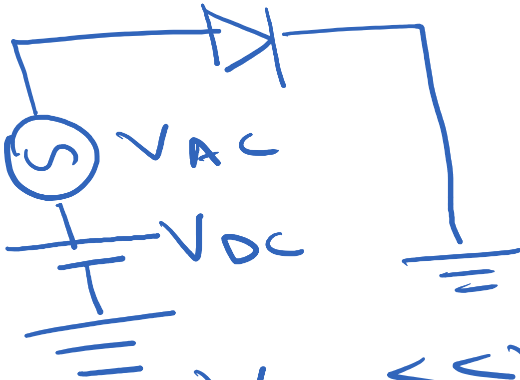
$V_{tot} = V_{DC} + V_{AC}$

$I_{tot} = I_{DC} + I_{AC}$



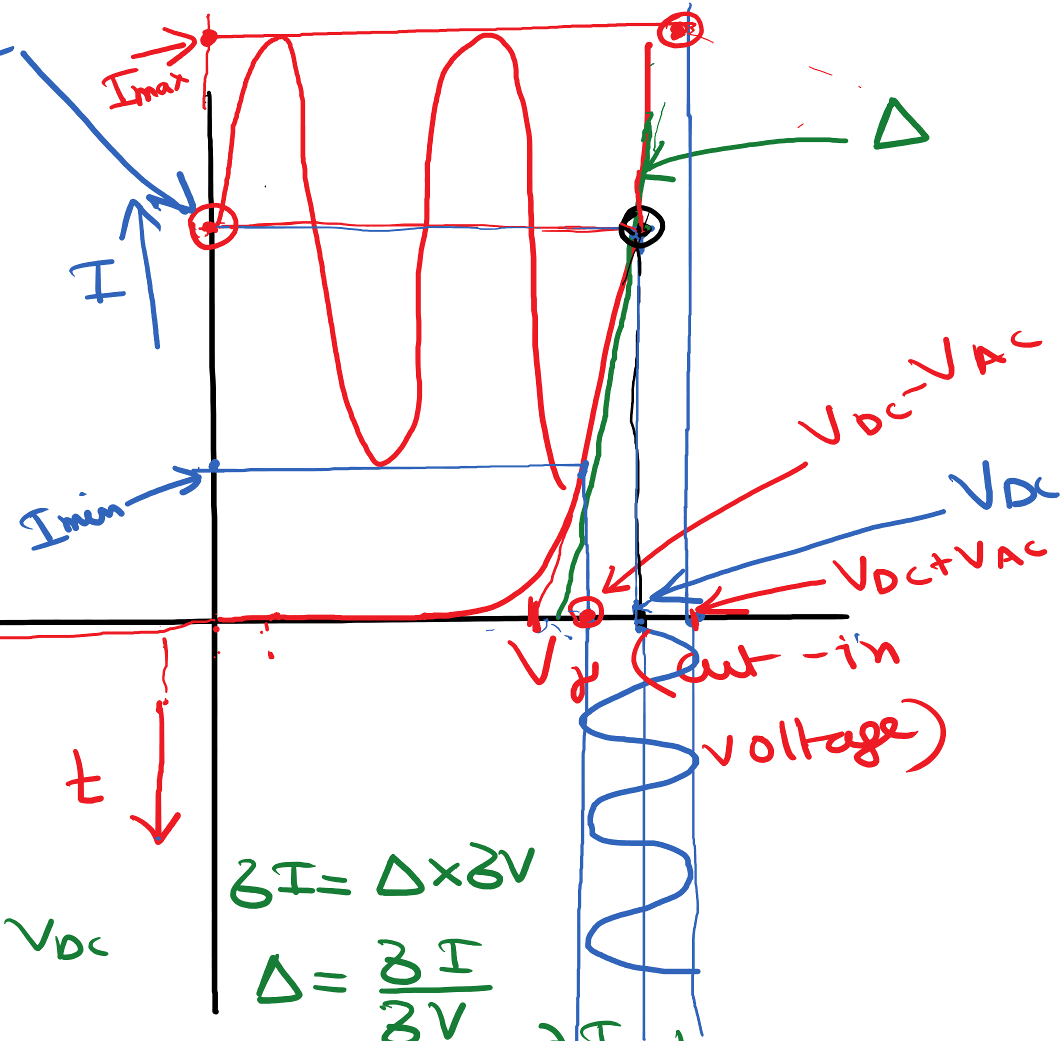
$V_{AC} << V_\gamma$





$V_{AC} << V_\gamma$

$V_{DC} > V_\gamma$



$V_{tot} = V_{DC} + V_{AC}$

Δ = slope of the I-V curve at $V = V_{DC}$

$$= \left.\frac{\partial I}{\partial V}\right|_{V=V_{DC}}$$

$$\delta I = \Delta \times \delta V$$

$$\Delta = \frac{\delta I}{\delta V} = \left.\frac{\partial I}{\partial V}\right|_{V=V_{DC}}$$

$$= \frac{\partial I}{\partial V}\Big|_{V=V_{DC}}$$

∂V

$$= \frac{\partial I}{\partial V}\Big|_{V=V_{DC}}$$

The DC voltage basically takes the diode to a low resistance regime where there is a large variation in the current with a small variation in the applied voltage. So, the function of the DC voltage is to cross the cut-in voltage V_γ or to bring the operation of the diode to the low resistance regime.

$$g_d = \Delta = \left.\frac{\partial I}{\partial V}\right|_{V=V_{DC}} = \text{small signal conductance or the diffusion conductance.}$$

$$\underbrace{\partial I = \Delta \times \partial V}$$

↳ gives us the information only about the AC-components

$$g_d = \left.\frac{\partial I}{\partial V}\right|_{V=V_{DC}} = \frac{\partial}{\partial V}\left[I_s \exp\left\{\frac{V}{V_T}\right\} - 1 \right]\Bigg|_{V=V_{DC}}$$

$$= \frac{I_s}{V_T} \exp\left\{\frac{V_{DC}}{V_T}\right\} \simeq \frac{I_{DC}}{V_T}$$

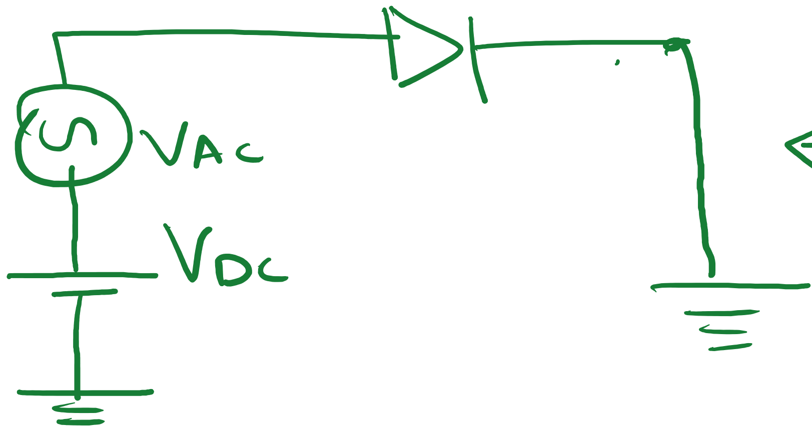
$$I_{DC} = I_S\left[\exp\left\{\frac{V_{DC}}{V_T}\right\} - 1\right]$$

$$V_T \cong 25.9\ mV \quad \left(V_T = \frac{KT}{q}\right)$$

at $T = 300K$

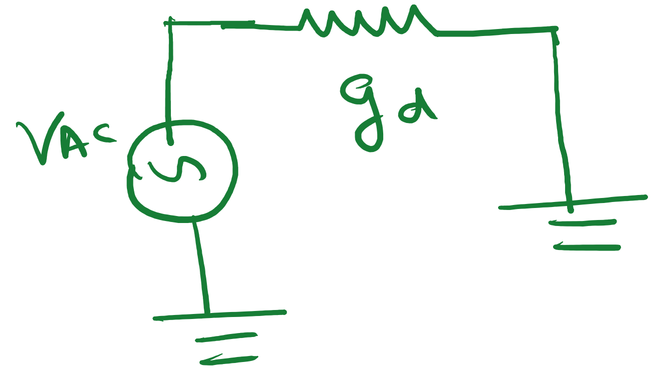
If $V_{DC} \gg V_T$,

$$I_{DC} \cong I_S \exp\left\{\frac{V_{DC}}{V_T}\right\}$$

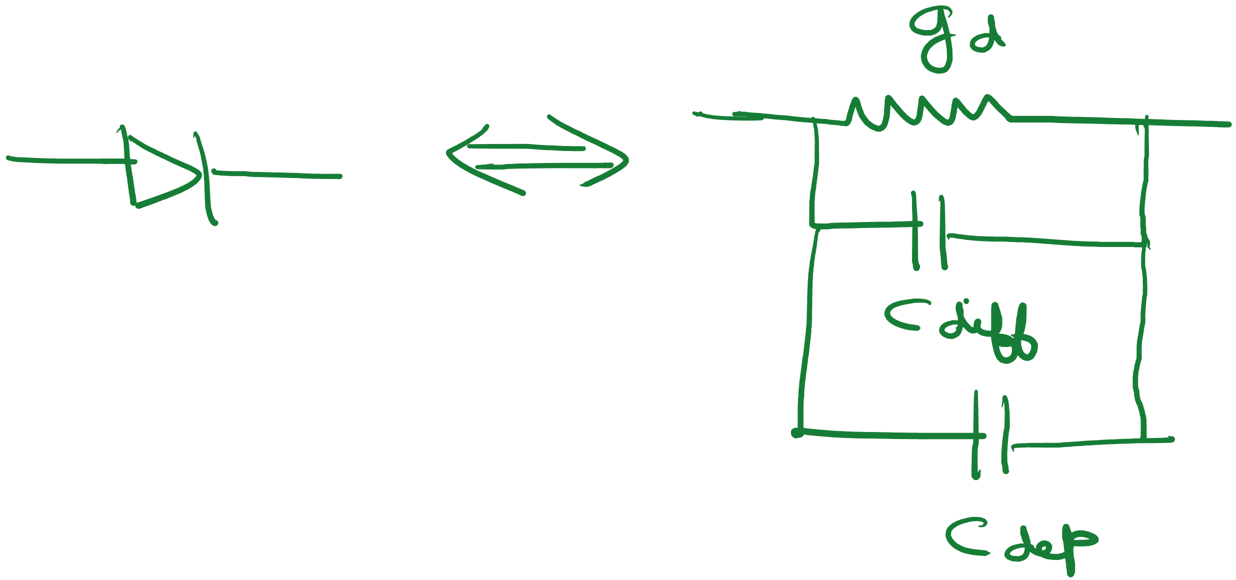


Real circuit

$\Longleftrightarrow$



Small signal AC model for low or moderate frequency.

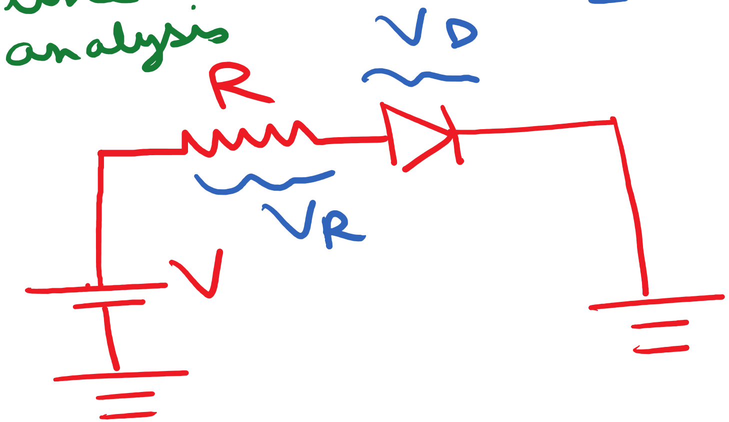


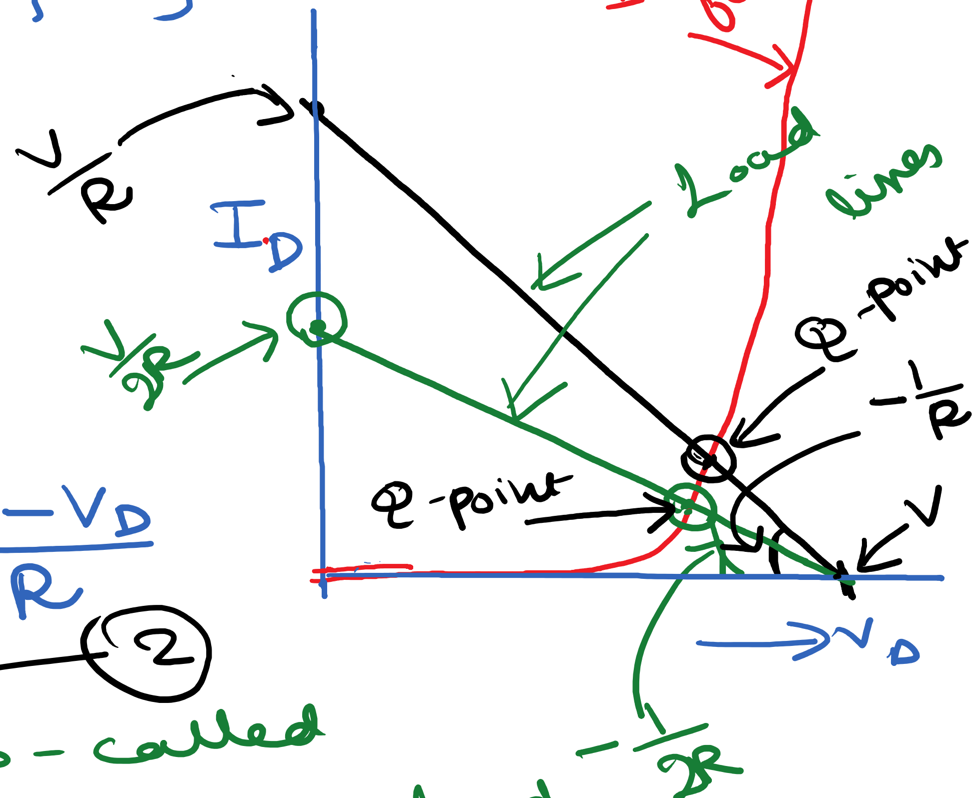
Small signal AC model of the diode for moderately high frequency or high frequency.

The process of bringing the diode or other devices to low resistance state by applying a DC voltage is known DC biasing.

Load line analysis

$$I_D = I_S\left[\exp\left\{\frac{V_D}{V_T}\right\}-1\right] \quad (1)$$





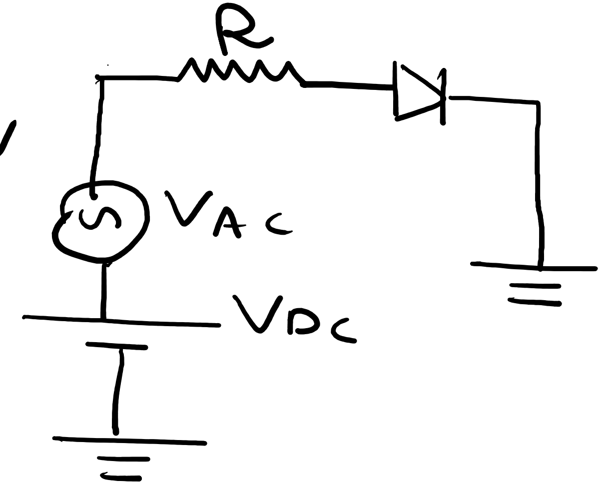
$$I_R = I_D = \frac{V_R}{R} = \frac{V-V_D}{R} \quad (2)$$

The load-line is so-called because it depends on the load resistor R.

For a particular load resistor we have a particular Q-point or quiescent-point.

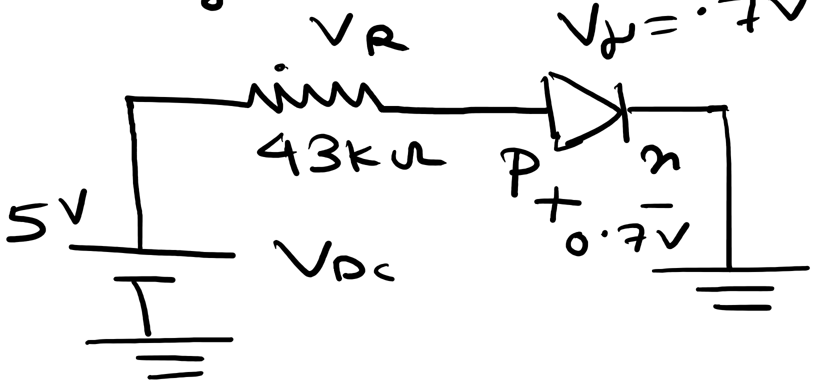
$V_{DC} = 5V$, $R = 43\,k\Omega$,

$V_\gamma = 0.7V$, $V_{AC} = 5 \sin \omega t \; mV$



I_{DC}? $V_{AC} = ?$

Equivalent circuit for DC analysis:-



$V_R = 5V - V_\gamma$

$= 5V - 0.7V$

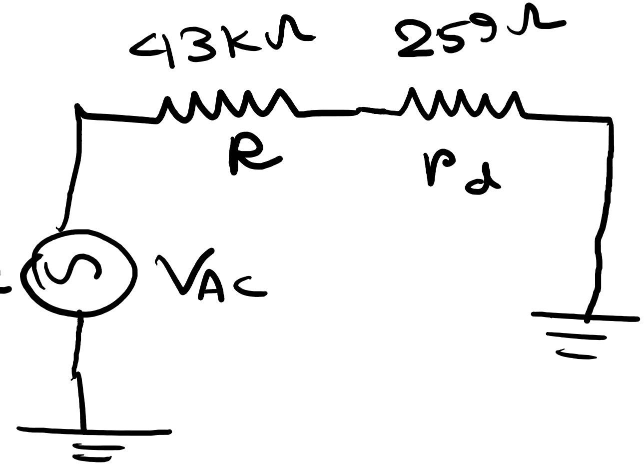
$= 4.3V$.

$$I_{DC} = I_R = \frac{V_R}{R} = \frac{4.3V}{43k\Omega} = 0.1mA$$

$$I_{DC} = 0.1\,mA. \qquad T = 300K.$$

$$g_d = \frac{I_{DC}}{V_T} = \frac{0.1\,mA}{25.9\,mV} = \frac{1}{259}\,\Omega^{-1}$$

$$r_d = g_d^{-1} = 259\,\Omega$$



$$I_{AC} = \frac{V_{AC}}{R + r_d} = \frac{5\sin\omega t\ mV}{43K\Omega + .259K\Omega}$$

$$= 0.1156\ \sin(\omega t)\ \mu A$$

$$v_D^{AC} = I_{AC} \times r_d = 0.1156 \times 259\ \sin(\omega t)\ \mu V$$

$$= 29.94\,(\sin\omega t)\,\mu V$$