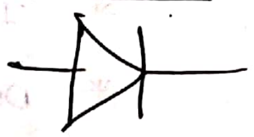
conducts current in (single direction only)

PN-Diode (or) "PN Junction Diode"

⇒ A Diode means ⇒ Di + electrodes
Two electrodes ⇒ Anode & cathode

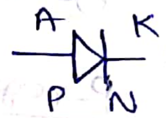


⇒ A Diode is a device which consists of two electrodes both Anode & cathode which conducts in single direction

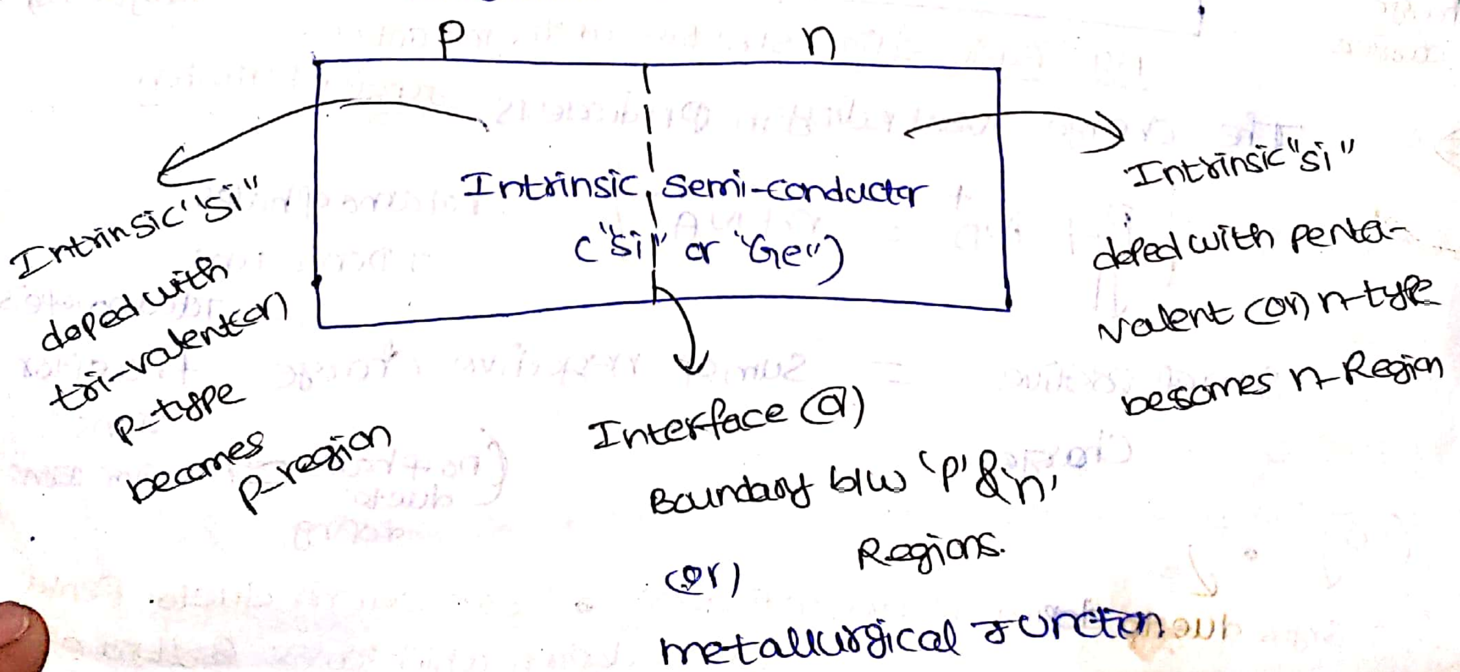
⇒ **PN-Junction diode :** (or) Basic structure of PN-Junction Diode

PN Junction diode is a semi-conductor device which is formed due to the doping of both 'N' type and 'P' type materials to an Intrinsic "si" (or) "Ge"

V.VImp
⇒ ☆ PN Junction diode is a device "which conducts current in single direction only" (From Anode to cathode)

[∴  ⇒ conventional current direction]

⇒ **PN Junction:** PN Junction is a boundary (or) interface between two types of semi-conductor materials, P-type & n-type in a single semiconductor crystal..



⇒ The P & n Regions are created by doping methods called

* Ion Implantation
* Diffusion of Dopants
* Epitaxy & Chemical vapour deposition

⇒ The P-Region has majority charge carriers as holes and minority charge carriers as electrons. The n-Regions has electrons as majority charge carriers & holes as minority charge carriers

* ⇒ The majority charge carriers are due to the Impurity atoms (or) doping & minority charge carriers are due to "Thermal generation."

⇒

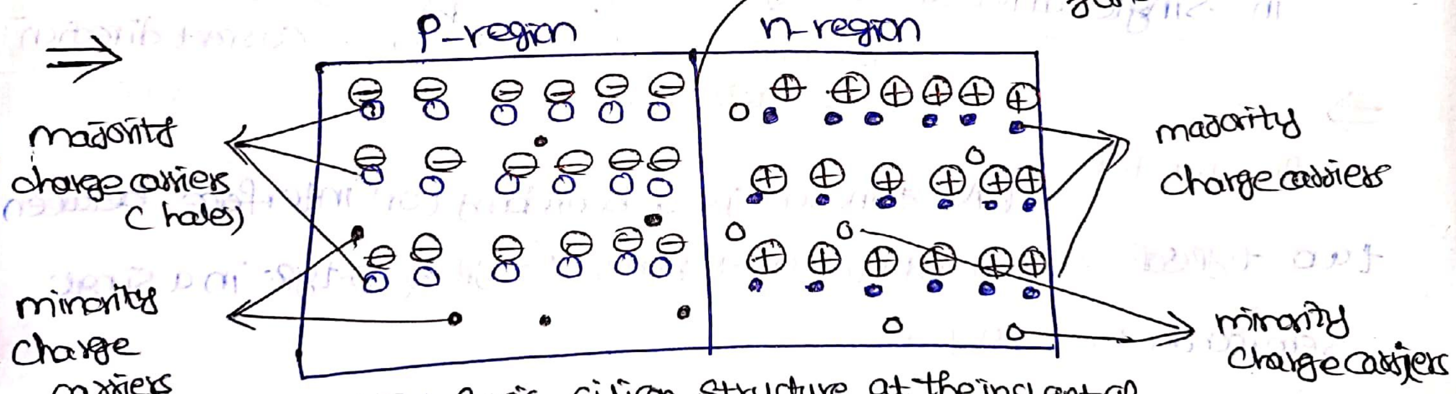


Fig: Basic silicon structure at the instant of Junction Formation

⇒ The charge Neutrality in Pn diode is

$$\boxed{P + N_D^+ = n + N_A^-}$$

Total no of holes + Donor Ions = Total no of e⁻'s + Acceptor Ions

⇓

Sum of positive Charge = Sum of negative Charge

(no of holes due to doping = Acceptor Ions)

$(\bar{o}$, $\overset{+}{\bullet}$ signs due to doping ie they indicates "•" ⇒ electrons due to Penta Valent doping which loses extra e⁻

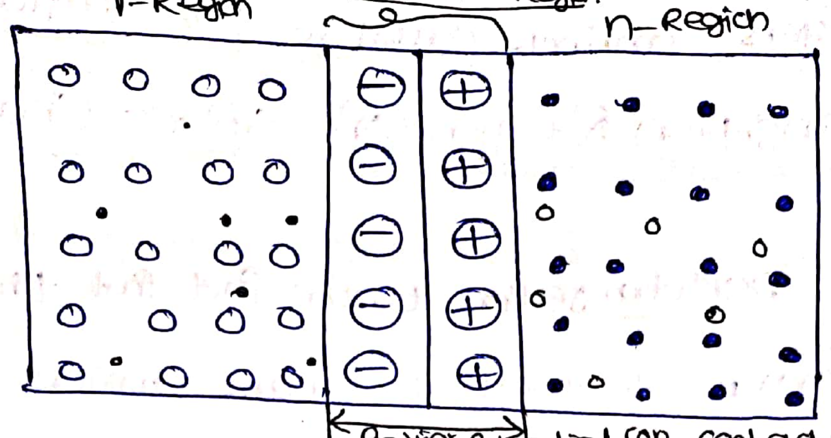


Fig (b) : Formation of Builtin Potential

⇒ The electrons in the n-region are high compared to electrons in the P-region, means the concentration gradient exists, so the electrons from n-sides diffuses from n-Region to P-Region and fall into the holes near the Junction in the P-Region similarly holes diffuses from P-Region to n-region [means the Valence electrons diffuses from n to P then the hole moves from P-Region to n-Regions, Becoz hole is an Imaginary Particle which will never move ⇒ Actual movement takes Place here is the electron movement through hole]

⇒ For every electron that diffuses across the junction, and combines with a hole, a positive charge is left in the n-Region & a negative charge is created in the P-region, forming a Barrier potential (or) Energy hill. This Region ~~is called~~ which consists of Immobile Ions (or) which creates a layer of negative charges (trivalent Ions) near the Junction & a layer of positive charges (Pentavalent ions) near the Junction in n-side

⇒ These two layers combinely called as Depletion Region (or) Transition Region (or) Space Charge Region

⇒ The term 'Depletion" refers to the fact that the region near the junction is depleted of charge carriers (depleted of majority charge carriers ie e⁻s & holes) due to diffusion across the junction.

[⇒ The term Space Charge Refers to the fact that, the Region (or) space which consists of only charge (Both +ve & -ve

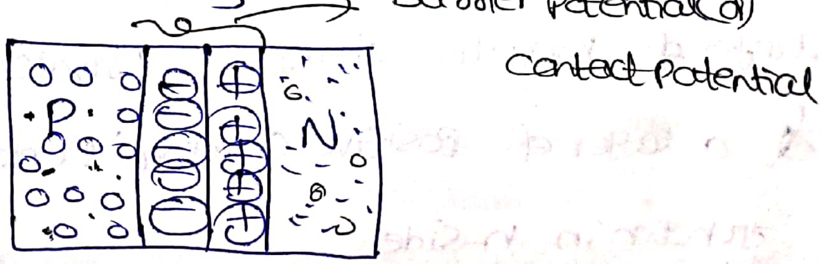
⇒ The term transition Refers to the fact that, the Region is formed becoz of the transition of e⁻s from n-side to P-side & holes from p-side to n-side]

* Barrier Potential (or) Contact Potential

⇒ The potential difference produced due to the positive and negative charges due to diffusion of charge carriers will acts as a Barrier to further movement of charge carriers from n-side to p-side & vice-versa. This opposition potential is called Barrier potential (or) Contact Potential

[Contact Potential ⇒ Becoz it is formed due to the contact of n-type with p-type]

⇒



⇒ Definitions of Barrier Potential

① It is the potential which opposes the movement of electrons & holes across the junction & permits the minority charge carriers to drift across the PN junction

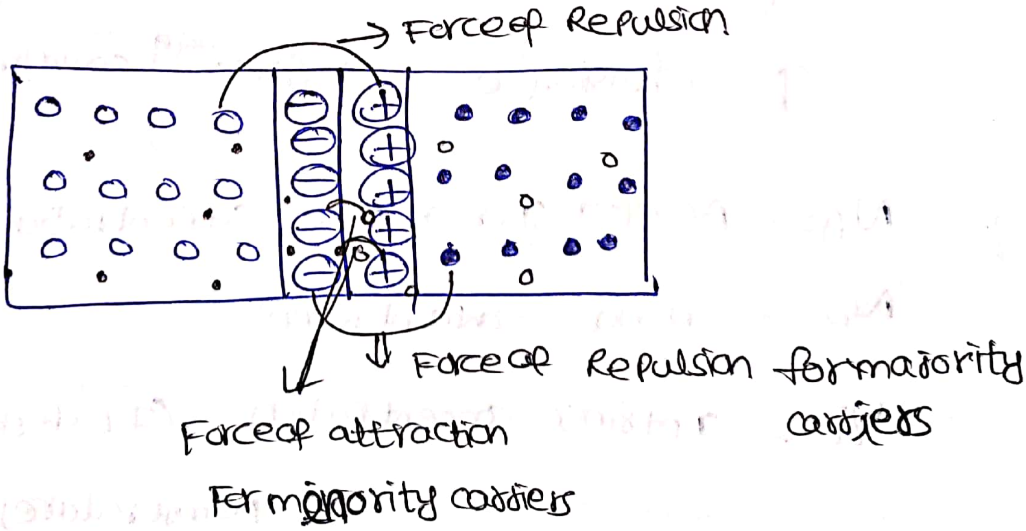
② The Potential Barrier in the Pn junction diode is the Barrier which does not allow charge flow across the junction

③ When a P-type material is brought in contact to an n-type material while forming a Pn junction (In Intrinsic Si),

Charge flow across the junction takes place due to concentration gradient between the two sides (n and P type); Then the immobile Ions are created near the contact which create electric Field, this Field opposes the Flow of current

⇒(Contact Potential)

This resistance to the flow of charge is known as Barrier Potential



⇒ The Forces b/w the opposite charges in the Depletion Region forms an electric Field, This is becoz of the Force acting on charges as described by coulomb's law

⇒ According to coulombs law Forces acting on charges is Known as electric Field $F = EQ$ (or) $\boxed{E = F/Q}$

⇒ This electric Field is a Barrier to the Free electrons in the n-region & an energy must be needed to move an electron through the electric Field. This potential difference is called Barrier Potential

⇒ $\boxed{\text{Barrier Potential } V_{bi} \text{ (or) } V_o = \frac{KT}{q} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)}$

(or)

$$V_{bi} \text{ (or) } V_o = V_T \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

V_T = Temperature equivalent voltage $= \frac{KT}{q} = 26\,mV$ at room Temp (T=300k)

K = Boltzman constant

$= 1.38 \times 10^{-23}$ J/K

T = Temperature

q = charge of e^- $= 1.6 \times 10^{-19}$ coulumbs

N_A = Accepter Ion (or) Atom concentration

N_D = Donor concentration

n_i = Intrinsic concentration (It depends on temperature)

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⇒ Barrier potential depends on several factors, they are

1. Type of Semi-conductor material ("Si" or "Ge") (ie n_i different for "Si" & Ge)
2. Doping concentration (or) amount of Doping (N_A & N_D)
3. Temperature

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

→ Doping concentration

Temperature

Type of material

$$\left.\begin{array}{l} n_i|_{Si} = 1.5\times10^{10} \\ n_i|_{Ge} = 2.5\times10^{13} \end{array}\right\} \text{At } T=300K$$

⇒ The typical Barrier potential for Pn diode madeup of Silicon is 0.7V & Germanium is 0.3V at room temperature

$$\boxed{\begin{array}{l} V_{bi} \text{ (or) } V_o = 0.7V \text{ For "Si"} \\ V_{bi} \text{ (or) } V_o = 0.3V \text{ For "Ge"} \end{array}}$$

⇒ Practical values of N_A & N_D in general are [For "Si"]

$N_A = 10^{17}$ & $N_D = 10^{16}$

$n_i = 1.5\times10^{10}$ then

$$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \Rightarrow (26mV)\times \ln\left(\frac{10^{16}\times10^{17}}{(1.5\times10^{10})^2}\right)$$

V_{bi} (or) $V_o \simeq 0.7$ Volts for "Si"

⇒ Units of Barrier Potential

$$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$$

$$\Rightarrow (\text{volts}) \ln\left(\frac{/cm^3 \times /cm^3}{(/cm^3)^2}\right)$$

$$\Rightarrow \text{volts (constant)}$$

$$V_{bi} \Rightarrow \text{Volts} \quad \left(\frac{KT}{q} \Rightarrow \frac{J/K \times K}{\text{coulomb}} \Rightarrow \frac{J}{C} \Rightarrow \frac{W}{Q} = V = \text{volts}\right)$$

NOTE:
Units of Barries potential is volts

⇒ Barrier Potential : why this name as Potential ?

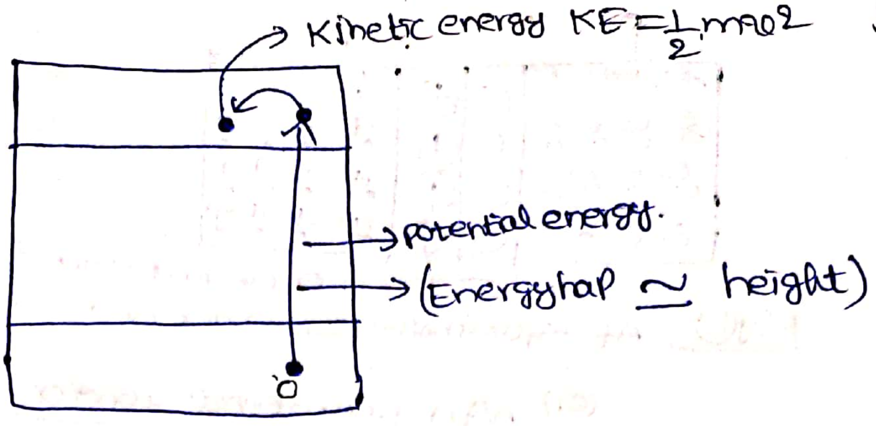
The energy required to take an e^- from one Band to another Band.

In General potential energy is work done against the gravitational Force (or) work done to move an object upto certain height "h" ie P.E = mgh

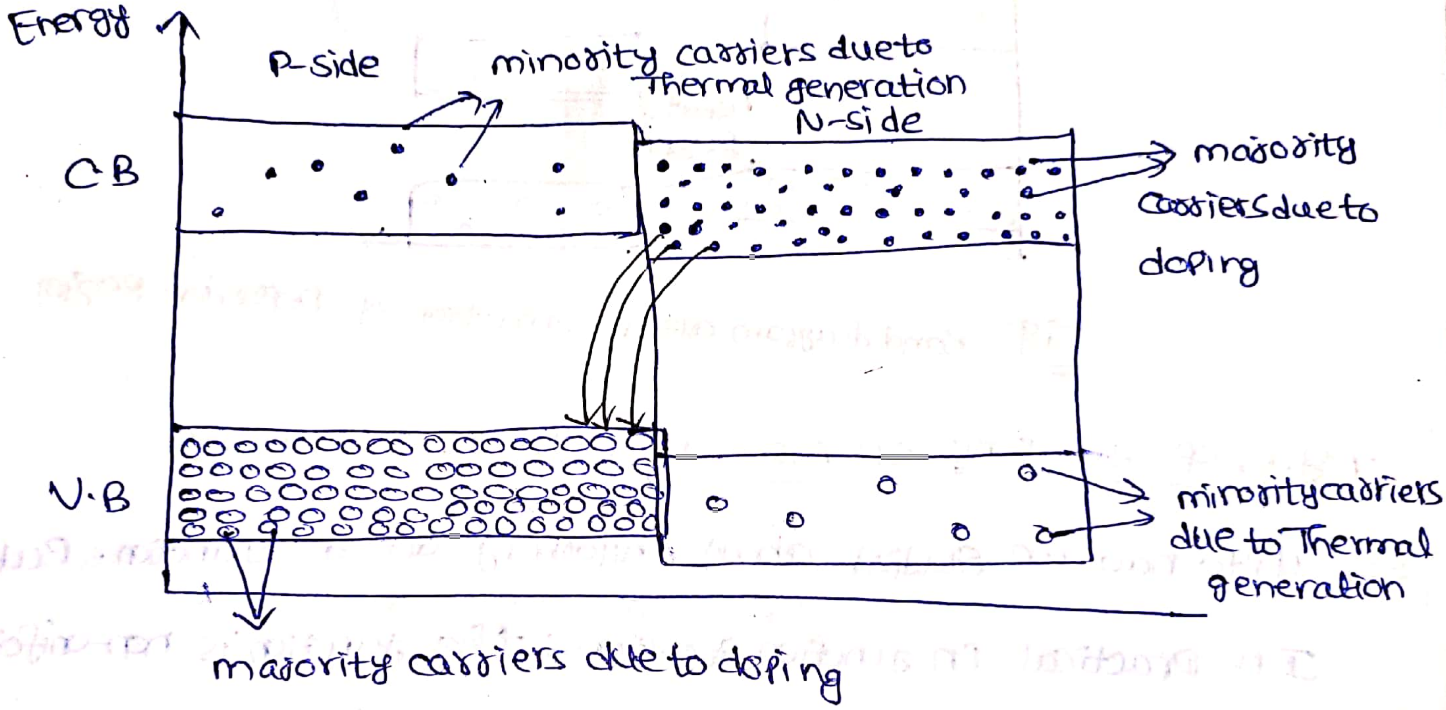
So Barrier potential is similar to potential energy so we named it as Barrier potential

[KE ⇒ Kinetic energy ⇒ Energy required to move an e^- ⇒ e^- acquired KE when it is in "CB" (ie free only)

⇒

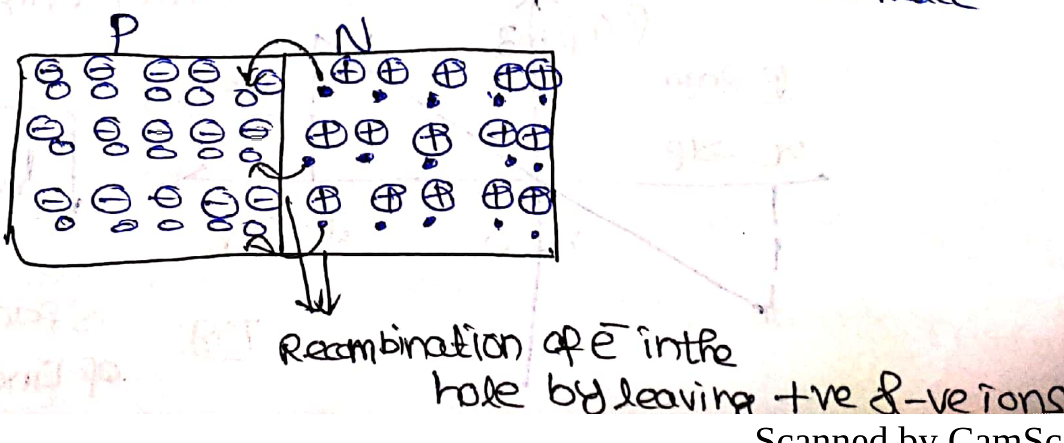


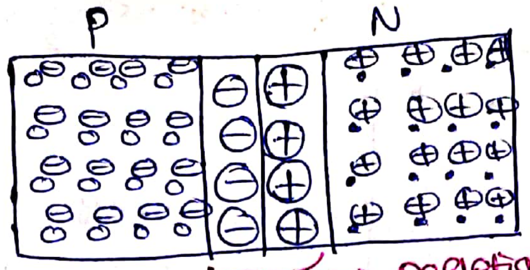
⇒ PN Junction at the instant of junction Formation:



Fig@ :- Band diagram at the Instant of junction Formation

⇒ The electron in the n-side diffuses becoz of the concentration gradient ie the concentration of electrons (or) majority carriers in n-side is ~~less~~ greater than in the p-side, due to this concentration gradient diffusion of electron from n-side to p-side takes place





Fig⑤ At equilibrium (or) under open ckt condition

(or) After Formation of Junction

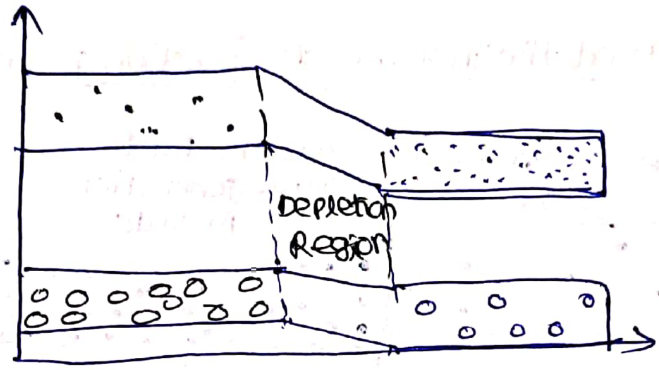


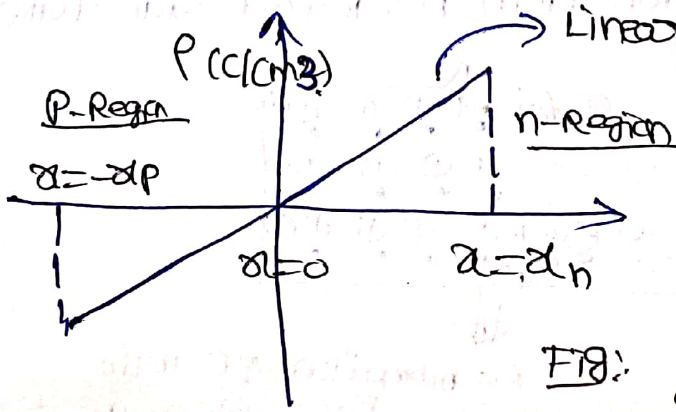
Fig: Band diagram after formation of Depletion Region

Types of Junctions (or) Non uniformly doped Junctions

⇒ upto now we studied about uniformly doped junction. But In practical pn junction structures the junction is non-uniformly doped

① Linearly graded Junctions:

The doping concentrations near the metallurgical junction may be approximated as a Linear function of distance from the metallurgical junction as shown below

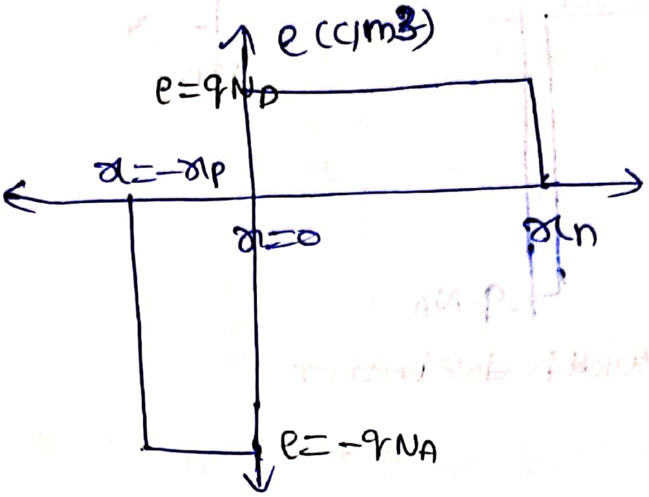


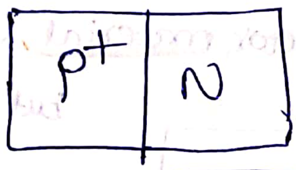
$$\boxed{W \propto V^{1/3}}$$

Fig: Space chargedensity of Linearly graded pn junction

Abrupt (or) Hyper abrupt Junctions

The doping concentrations are abruptly charges as a function of distance as shown below



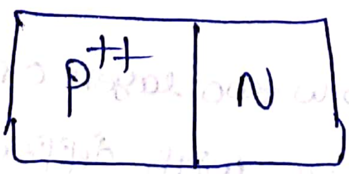


From the Formula $\boxed{N_D x_n = N_A \cdot x_p}$

If $N_A >> N_D$ then $x_n = \left(\frac{N_A}{N_D}\right) x_p$

If $N_A >> N_D$ then $x_n >> x_p$ means the width of the depletion Region moves more towards lightly doped side ($N_A >> N_D$)

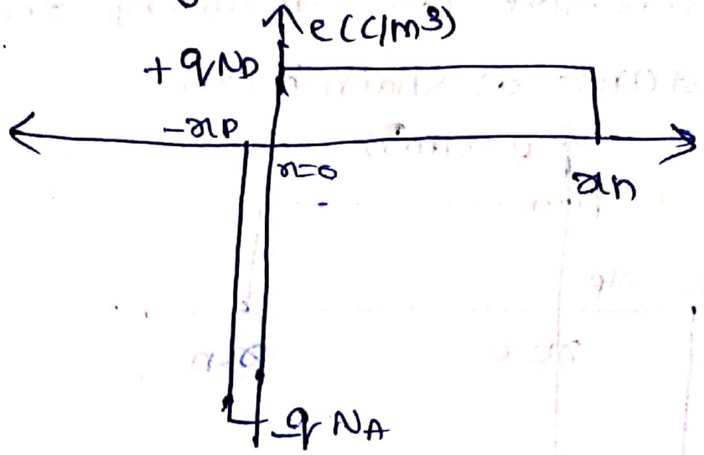
One-sided Junction:



then $N_D x_n = N_A \cdot x_p$

$N_A >>>> N_D$ then $x_n >>>> x_p$ that means the depletion Region almost moves towards n-side

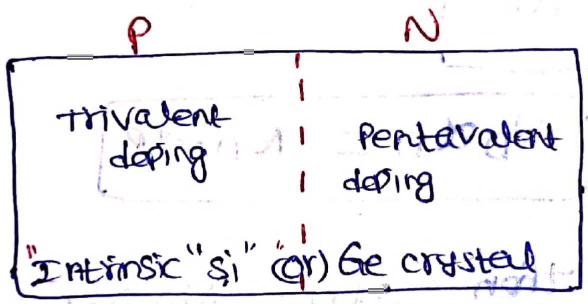
⇒ one-sided junction means Almost all the junction moves (or) present only one-side ie lightly doped side



~~Depletion Region width derivation~~

④ Homojunction :

Homojunction is a semi-conductor interface that occurs between layers of similar semi-conductor material, with different doping but with same bandgaps

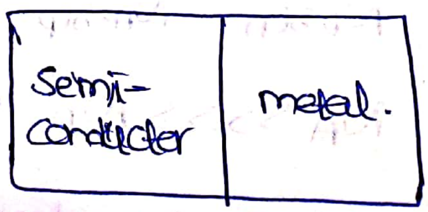


"PN junction is a homojunction", becoz It is the interface b/w Intrinsic "Si" crystal semi conductor but with different doping

⑤ Hetero junction:

Interface that occurs b/w two layers or regions of dissimilar crystalline semi-conductors with different band gaps

ex: used in Lasers



Built-in Potential & Analysis of Depletion Region

⇒

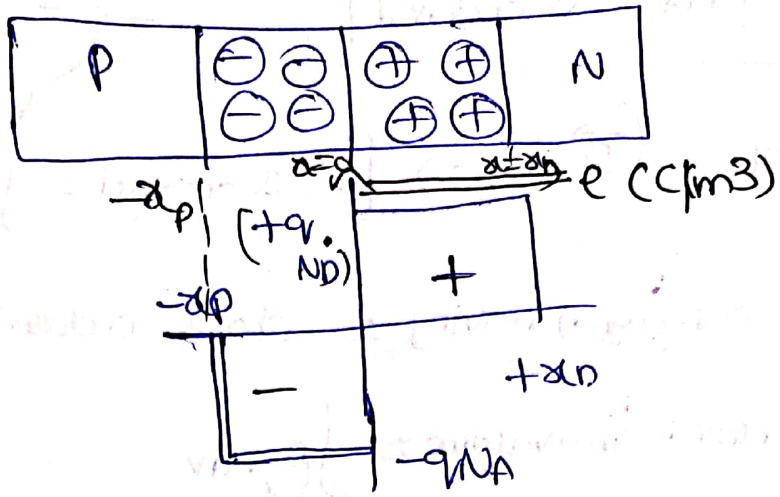
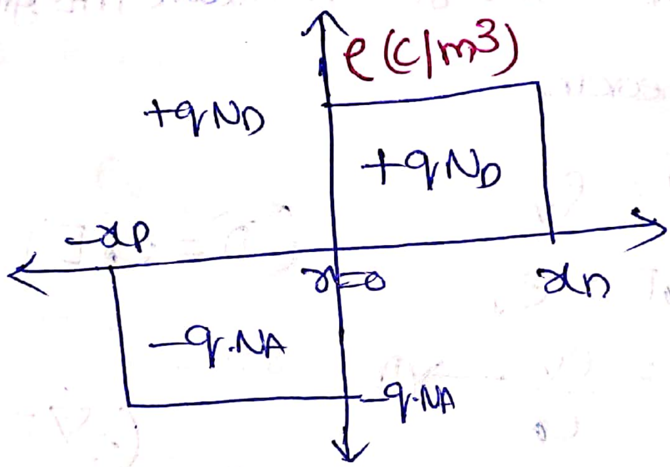


Fig: The space charge density in a uniformly doped pn junction assuming the abrupt junction approximation



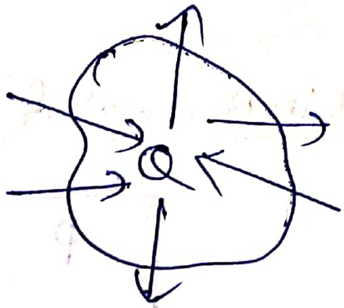
To analyse the depletion Region we are using the "Poission's equation"

$$\boxed{\frac{d^2V}{dx^2} = \frac{-\rho}{\epsilon}}$$

[Poission's equation will be obtained by using Gauss law

✲ Gauss law in electric Field

$$\boxed{\psi_{net} = Q_{enclosed}}$$



$$\psi_{net} = \int \vec{D} \cdot \vec{ds} \Rightarrow \left[\because Q_{enclosed} = \int \vec{D} \cdot \vec{ds} \right.$$

Flux entering (or) leaving = charge enclosed in that area.

$$Q_{enclosed} \text{ in a volume} = \int \rho_v \cdot dv$$

ρ_v = charge density

$$\oint \bar{D} \cdot \bar{ds} = \int \rho_v \cdot dv$$

To convert surface integral to volume integral, we use gauss-divergence theorem.

$$\nabla \cdot \bar{D} = \rho_v \qquad (\vec{D} = \epsilon_0 \cdot E)$$

$$\nabla \cdot \epsilon_0 E = \rho_v \qquad (\because \vec{D} = \epsilon E)$$

$$\nabla E = \frac{\rho_v}{\epsilon_0} \longrightarrow ① \qquad \left(\because \nabla = \frac{d}{dx}\right.$$

Charge density

$$\rho \Rightarrow \begin{cases} -qN_A, & -x_p < x < 0 \\ +qN_D, & 0 < x < x_n \end{cases}$$

$$\frac{d}{dx}(E) = \frac{\rho_v}{\epsilon_r \epsilon_0} \Rightarrow \frac{\rho_v}{\epsilon_r \epsilon_0} = \frac{\rho_v}{\epsilon}$$

$$\frac{dE}{dx} = \frac{\rho_v}{\epsilon_0} \longrightarrow ②$$

$$\frac{d}{dx}\left(-\frac{dV}{dx}\right) = \frac{\rho_v}{\epsilon}$$

$$-\frac{d^2V}{dx^2} = \frac{\rho_v}{\epsilon}$$ ⇒ This is called poission's law of equation

$$\frac{dE}{dx} = \frac{\rho_v}{\epsilon}$$

By applying integration on both sides to the above equation

$$\int \frac{dE}{dx} = \int \frac{\rho_v}{\epsilon}$$

$$E = \int \frac{\rho_v}{\epsilon}\, dx.$$

$$E = \frac{\rho_v}{\epsilon} x + C_1$$

To find the C_1 find 'E' at $x = -x_p$, $E = 0$

$$0 = \frac{\rho_v}{\epsilon}(-x_p) + C_1$$

$$C_1 = +\frac{\rho_v}{\epsilon} \cdot x_p$$

$$C_1 = -\frac{q \cdot N_A}{\epsilon} x_p$$

$$E = E_p = -\frac{qN_A}{\epsilon} x + \left(-\frac{qN_A}{\epsilon} x_p\right)$$

$$E_p = -\frac{qN_A}{\epsilon}(x_p + x); \quad -x_p < x < 0 \rightarrow \text{(A)}$$

Electric Field on n-side:

$$E = \int \frac{\rho}{\epsilon} dx$$

$$E = \frac{\rho}{\epsilon} x + C_2$$

$$E = +\frac{N_D q}{\epsilon} x + C_2$$

$$E = E_n |_{x = x_n} = 0$$

Electric Field on P-side at $x = x_n$

$$0 = \frac{N_D q}{\epsilon} x_n + C_2$$

$$C_2 = -\frac{N_D q}{\epsilon} x_n$$

$$E = E_n = \frac{N_D q}{\epsilon} x - \frac{N_D \cdot q x_n}{\epsilon}$$

$$E = E_n = -\frac{N_D q}{\epsilon} (x_n - x) \rightarrow (B)$$

$$\boxed{E_p = -\frac{q N_A}{\epsilon} (x_p + x)}$$

$$\boxed{E_n = -\frac{N_D q}{\epsilon} (x_n - x)}$$

To draw the graph at $x = -x_p$ on p-side.

$$E_p \Big|_{x = -x_p} = \frac{-q N_A}{\epsilon} (\cancel{+x_p} - \cancel{x_p}) = 0 \quad \Big| x = -x_p$$

$$E_p \Big|_{x=0} \Rightarrow E_p = -\frac{q N_A}{\epsilon} x_p \rightarrow (a)$$

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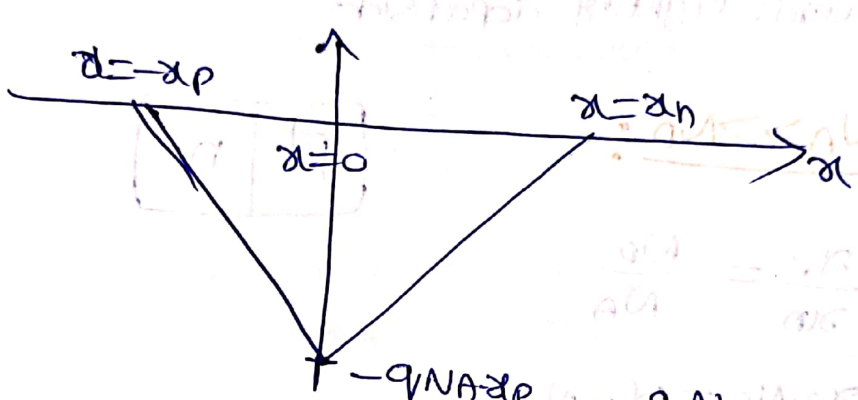
To draw the graph at $x=x_n$ on n-side

$$E_n\Big|_{x=x_n} = -\frac{N_D q}{\epsilon}(x_n - x) = -\frac{N_D q}{\epsilon}(\cancel{x_n} - \cancel{x_n}) = 0$$

$$E_n\Big|_{x=0} = -\frac{N_D q}{\epsilon}(x_n - x) = -\frac{N_D q}{\epsilon}(x_n - 0)$$

$$E_n = -\frac{N_D q}{\epsilon} x_n \rightarrow (b)$$



$$\boxed{E' = -\frac{qN_A x_p}{\epsilon} = \frac{-qN_D}{\epsilon} x_n}$$

The electric Field is a continuous waveform (or) function

continuous means Right Hand Limit = Left hand Side.

$$\frac{-qN_A \cdot x_p}{\epsilon} = \frac{-qN_D \cdot x_n}{\epsilon}$$

$$\boxed{N_A \cdot x_p = N_D \cdot x_n} \rightarrow (c)$$

This equation states that the no. of charges per unit Area in the p-region is equal to the no. of positive charges per unit

Area in the n-region

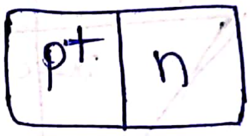
$$\boxed{\frac{x_p}{x_n} = \frac{N_D}{N_A}}$$

x_n = width of depletion layer in n-side

x_p = width of depletion layer in p-side.

⇒ * when one junction is heavily doped then the depletion layer moves towards lightly doped side.

If ① $N_A >> N_D$:-



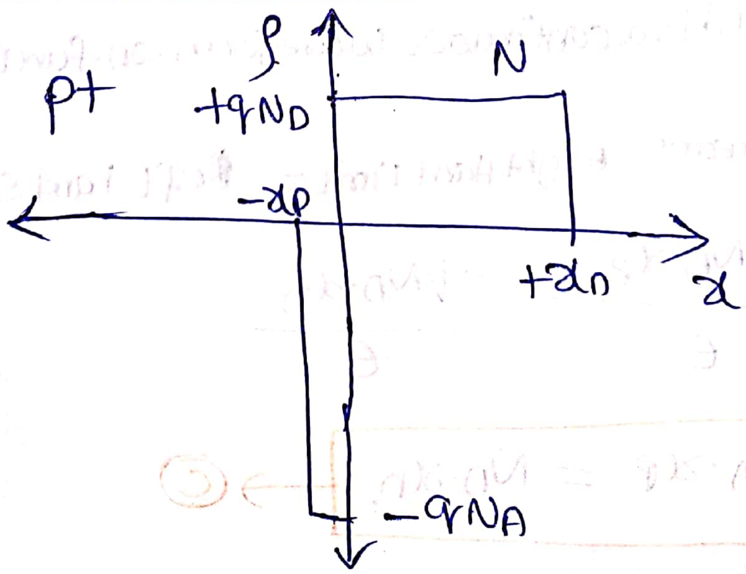
$$\frac{x_p}{x_n} = \frac{N_D}{N_A}$$

$$x_p \cdot N_A = x_n N_D$$

$$x_n = \frac{N_A}{N_D} \cdot x_p$$

$$\boxed{x_n >> x_p}$$

"Depletion Region moves towards lightly doped side"



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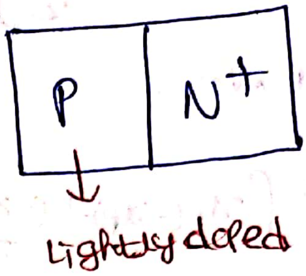
⇒ ② $N_D >> N_A$:



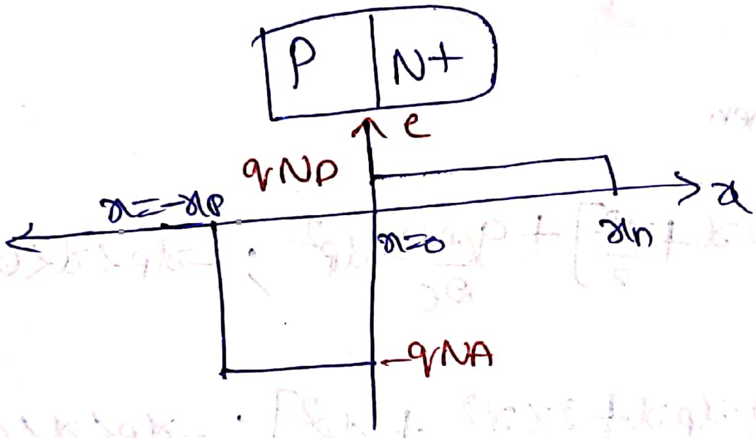
$$x_p \cdot N_A = x_n \cdot N_D$$

$$\frac{N_D}{N_A} \cdot x_n = x_p$$

$$x_p = \left(\frac{N_D}{N_A}\right) \cdot x_n$$

$$\boxed{x_p >> x_n}$$

"Depletion Region moves towards lightly doped side"



NOTE: Depletion width moves towards lightly doped Region

Potential ~~width~~ of P-N Junction :-

$$V = -\int E \cdot dx$$

Potential on P-Side:

$$V_p = -\int E_p \cdot dx \; ; \; -x_p < x < 0$$

$$V_p = -\int -\frac{q \cdot N_A}{\epsilon}(x_p + x) \; ; \; -x_p < x < 0$$

$$V_p = \frac{qN_A}{\epsilon}\left[x_p \cdot x + \frac{x^2}{2}\right] + c_1' \;; -x_p < x < 0$$

At $x = -x_p$, $V = 0$

$$0 = \frac{qN_A}{\epsilon}\left[x_p(-x_p) + \frac{(-x_p)^2}{2}\right] + c_1'$$

$$0 = \frac{qN_A}{\epsilon}\left[-x_p^2 + \frac{x_p^2}{2}\right] + c_1'$$

$$0 = \frac{qN_A}{\epsilon}\left[-\frac{x_p^2}{2}\right] + c_1'$$

$$c_1' = \frac{qN_A}{2\epsilon} x_p^2 \;; -x_p < x < 0$$

Sub c_1' in V_p then

$$V_p = \frac{qN_A}{\epsilon}\left[x_p x + \frac{x^2}{2}\right] + \frac{qN_A}{2\epsilon} \cdot x_p^2 \;; -x_p < x < 0$$

$$= \frac{qN_A}{2\epsilon}\left[2 \cdot x_p x + 2 \times \frac{x^2}{2} + x_p^2\right] ; -x_p < x < 0$$

$$V_p = \frac{q \cdot N_A}{2\epsilon}\left[2 \cdot x_p \cdot x + x^2 + x_p^2\right] ; -x_p < x < 0$$

$$V_p = \frac{q \cdot N_A}{2\epsilon}\left[x_p + x\right]^2 ; -x_p < x < 0$$

<u>Potential on n-side</u>:

$$V = -\int E \cdot dx \;; 0 < x < x_n$$

$$E = -\frac{qN_D}{\epsilon}(x_n - x) ; 0 < x < x_n$$

$$V = -\int -\frac{qN_D}{\epsilon}(x_n - x)\, dx ; 0 < x < x_n$$

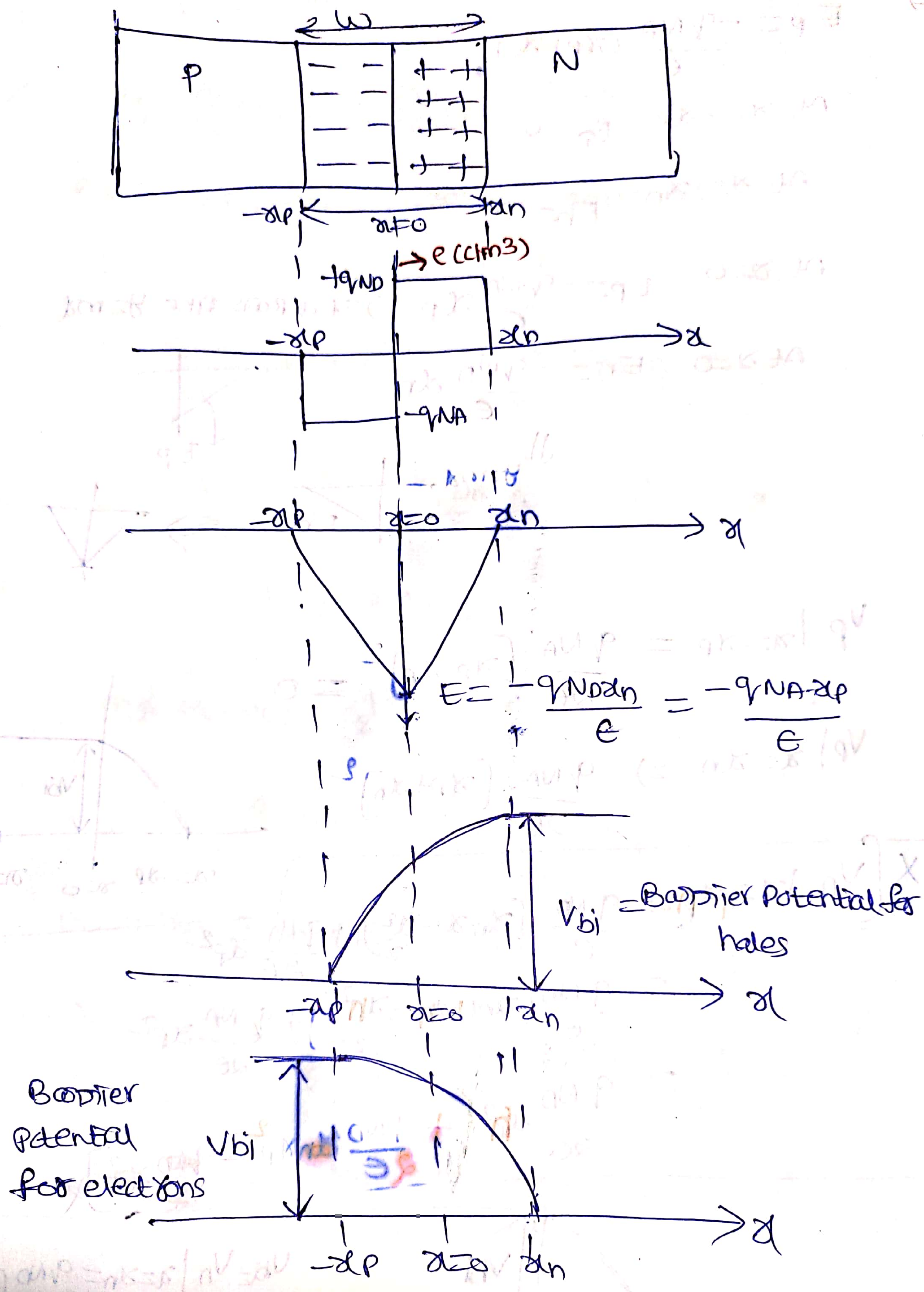


Fig:- Analysis of Depletion Region

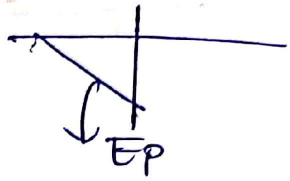
$\Rightarrow$ $$E_p = -\frac{qN_A}{\epsilon}(x_p + x)$$

At $x = -x_p$ $\quad E_p = 0$

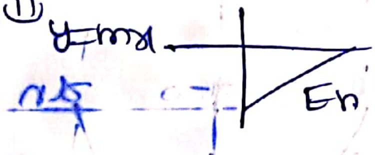
At $x = x_n$ $\quad E_n = 0$

At $x = 0$ $\quad E_p = -\frac{q N_A}{\epsilon} x_p$ $\Rightarrow$ It appears like $y = mx$

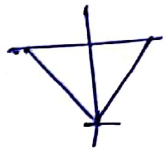
At $x = 0$ $\quad E_n = -\frac{q N_D}{\epsilon} x_n$



$\Downarrow$ $y = mx$

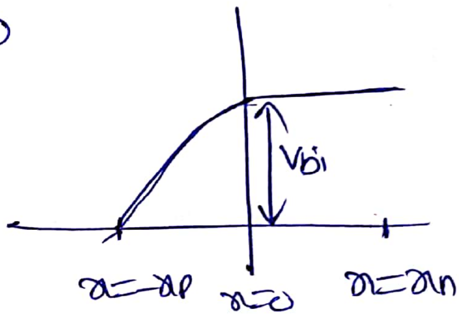


$\Rightarrow$



$\Rightarrow$ $$V_p\big|_{x=-x_p} = \frac{qN_A}{2\epsilon}[x_p - x_p]^2 = 0$$

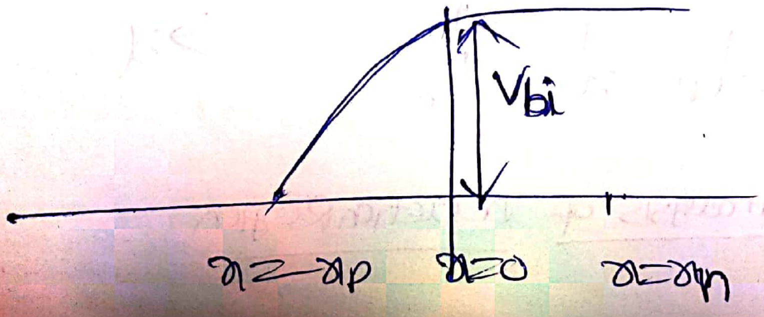
$$V_p\big|_{x=x_n} \Rightarrow \frac{qN_A}{2\epsilon}[x_p + x_n]^2$$



X $$\left[V_n\big|_{x=x_p} \Rightarrow \frac{qN_D}{\epsilon}\left[x_n x - \frac{x^2}{2}\right] + \frac{qN_A}{2\epsilon}x_p^2\right.$$

$$= \frac{qN_D}{\epsilon}\left[x_n(x_p) - \frac{x_p^2}{2}\right] + \frac{q N_A}{2\epsilon}x_p^2$$

$$= \frac{qN_D}{2\epsilon}x_p^2 + \frac{qN_D}{2\epsilon}x_n x_p^2 - \left.\frac{qN_D}{2\epsilon}x_p^2\right] \times$$



$$V_{bi} = V_n\big|_{x=x_n} = \frac{qN_D}{\epsilon}\left(x_n^2 - \frac{x_n^2}{2}\right) + \frac{qN_A}{2\epsilon}x_p^2$$

$$V_n = V_{bi} = \frac{qN_D}{2\epsilon}x_n^2 + \frac{qN_A}{2\epsilon}x_p^2$$

$$V_n = \int \frac{qN_D}{\epsilon}(x_n - x)\,dx \,; \quad 0 < x < x_n$$

$$V_n = \frac{qN_D}{\epsilon}\left(x_n \cdot x - \frac{x^2}{2}\right) + C_2' \rightarrow (D)$$

At $x=0$, Potential on p-side = Potential on n-side

ie voltage is a continuous function

$$\frac{qN_A}{2\epsilon}(x_p + 0)^2 \Big|_{x=0} = \frac{qN_D}{\epsilon}\left(x_n(0) - 0^2/2\right) + C_2'$$

$$\frac{qN_A}{2\epsilon} x_p^2 = \frac{qN_D}{\epsilon}(0-0) + C_2'$$

$$C_2' = \frac{qN_A}{2\epsilon} x_p^2$$

Sub the value of C_2' in eq (D)

$$V_n = \frac{qN_D}{\epsilon}\left(x_n \cdot x - \frac{x^2}{2}\right) + \frac{qN_A}{2\epsilon} x_p^2 \,; \quad 0 < x < x_n$$

At $x = x_n$; $V_0 = V_{bi}$ (max value)

$$V_0 = V_{bi} = \frac{q \cdot N_D}{\epsilon}\left[x_n \cdot x_n - \frac{x_n^2}{2}\right] + \frac{q \cdot N_A \cdot x_p^2}{2\epsilon}$$

$$V_0 = V_{bi} = \frac{qN_D}{2\epsilon} x_n^2 + \frac{qN_A}{2\epsilon} x_p^2$$

$$V_0 = V_{bi} = \frac{q}{2\epsilon}\left[N_D \cdot x_n^2 + N_A \cdot x_p^2\right]$$

we know that

$$N_A \cdot x_p = N_D \cdot x_n$$

$$x_p = \frac{N_D}{N_A} \cdot x_n$$

$$V_{bi} = \frac{q}{2\epsilon}\left[N_D \cdot x_n^2 + N_A\left[\frac{N_D}{N_A} \cdot x_n\right]^2\right]$$

$$V_{bi} = \frac{q}{2\epsilon}\left[\frac{N_D}{N_A}\right]\left[N_A + N_D\right] x_n^2$$

$$x_n^2 = \frac{2\epsilon}{q} \cdot V_{bi}\left[\frac{N_A}{N_D}\right]\left[\frac{1}{N_A+N_D}\right]$$

$$\boxed{x_n = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A+N_D}\right)}}$$

we know that $x_p \cdot N_A = x_n \cdot N_D$

$$x_n = x_p \cdot \frac{N_A}{N_D}$$

$$V_{bi} = \frac{q}{2\epsilon}\left[N_D\left[x_p \cdot \frac{N_A}{N_D}\right]^2 + N_A \cdot x_p^2\right]$$

$$= \frac{q}{2\epsilon}\left[N_D \cdot x_p^2 \cdot \frac{N_A^2}{N_D^2} + N_A \cdot x_p^2\right]$$

$$V_{bi} = \frac{q}{2\epsilon}\left[\frac{N_A}{N_D}\right]\left[N_A + N_D\right] x_p^2$$

$$x_p^2 = \frac{2\epsilon}{q}(V_{bi})\left[\frac{N_D}{N_A}\right]\left[\frac{1}{N_A+N_D}\right]$$

$$\boxed{x_p = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left(\frac{N_D}{N_A}\right)\left(\frac{1}{N_A+N_D}\right)}}$$

Width of Depletion Region: (W):

$$W = x_n + x_p$$

$$W = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left(\frac{1}{N_A+N_D}\right)}\left[\sqrt{\frac{N_D}{N_A}} + \sqrt{\frac{N_A}{N_D}}\right]$$

$$= \sqrt{\frac{2\epsilon}{q}(V_{bi})\left(\frac{1}{N_A+N_D}\right)}\left[\frac{N_D+N_A}{\sqrt{N_A}\cdot\sqrt{N_D}}\right]$$

$$W = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left[\frac{1}{\cancel{N_A+N_D}}\right)\frac{(N_D+N_A)^{\cancel{2}}}{N_A \cdot N_D}}$$

$$W = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left[\frac{N_D}{N_A N_D} + \frac{N_A}{N_A \cdot N_D}\right]}$$

$$\boxed{W = \sqrt{\frac{2\epsilon}{q}(V_{bi})\left[\frac{1}{N_A} + \frac{1}{N_D}\right]}}$$ Unbiased Junction

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

Forward Bias: $V_J = V_{bi} - V_f$

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

Reverse Bias: $V_J = V_{bi} + V_R$

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

F.B : As $V_f \Uparrow$ then $(V_{bi} - V_f) \Downarrow$

then $\Rightarrow$ $W \Rightarrow \Downarrow$ width of the depletion layer decreases

R.B : As $V_R \Uparrow$ then $(V_{bi} + V_R) \Uparrow$ then $W \Uparrow$

x_p (or) W_p = Depletion Region width on p-side

x_n (or) W_n = on n-side

W = Total width (or) Total Depletion Region width

N_A = Accepter concentration on p-side

N_D = Donor concentration on n-side.

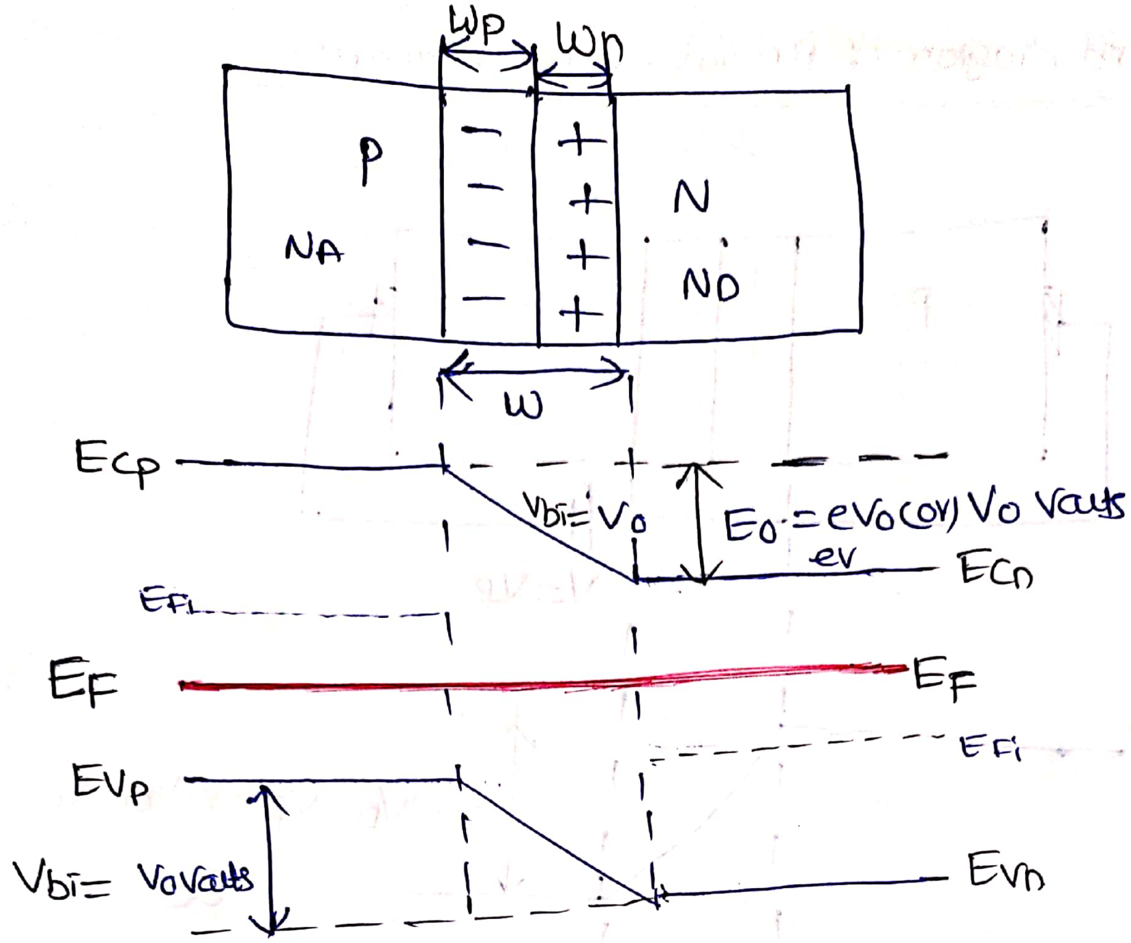
③ Invariance of Fermi-level at equilibrium (or) Band Diagram of pn diode

⇒ The Fermi-level of the PN-Junction diode is constant in Thermal equilibrium (or) until & unless If we apply a Forward (or) Reverse Bias

⇒ The Fermi level is constant
- (a) → Thermal equilibrium
- → open ckt condition

⇒ For p-type the Fermi-level is nearer to Valance Band

⇒ For n-type the Fermi-level is nearer to Conduction Band.



$$\boxed{V_0 = V_J = V_{bi}}$$

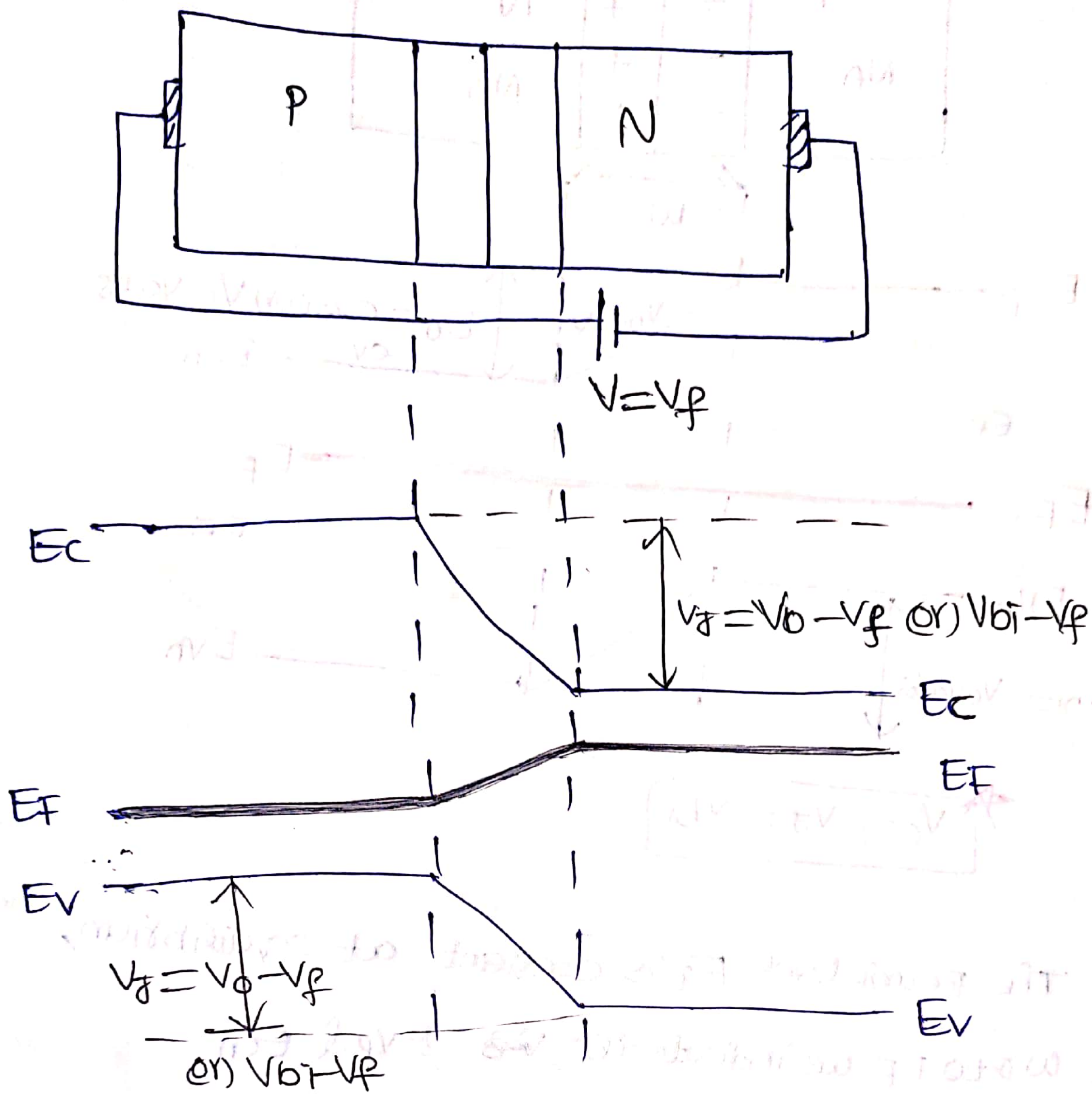
⇒ The Fermi-level E_F is constant at equilibrium, w.r.to E_F we indicate the ~~VB~~ E_{Vp} & E_{Cn}

⇒ "V_0" is the Barrier Potential (or) Contact Potential in volts

⇒ If we apply Biasing the Fermi-level changes. If we apply Forward Bias the contact potential ⇓ ~~with~~ ~~in the~~ by the amount of $V_{bi} - V_f$ (or) $V_0 - V_f$. If we apply the Reverse Bias the Contact potential ⇑ ~~with~~ by the amount of "$V_{bi} + V_R$" (or) "$V_0 + V_R$"

⇒ Band diagram of P-n diode under Forward Bias

⇒

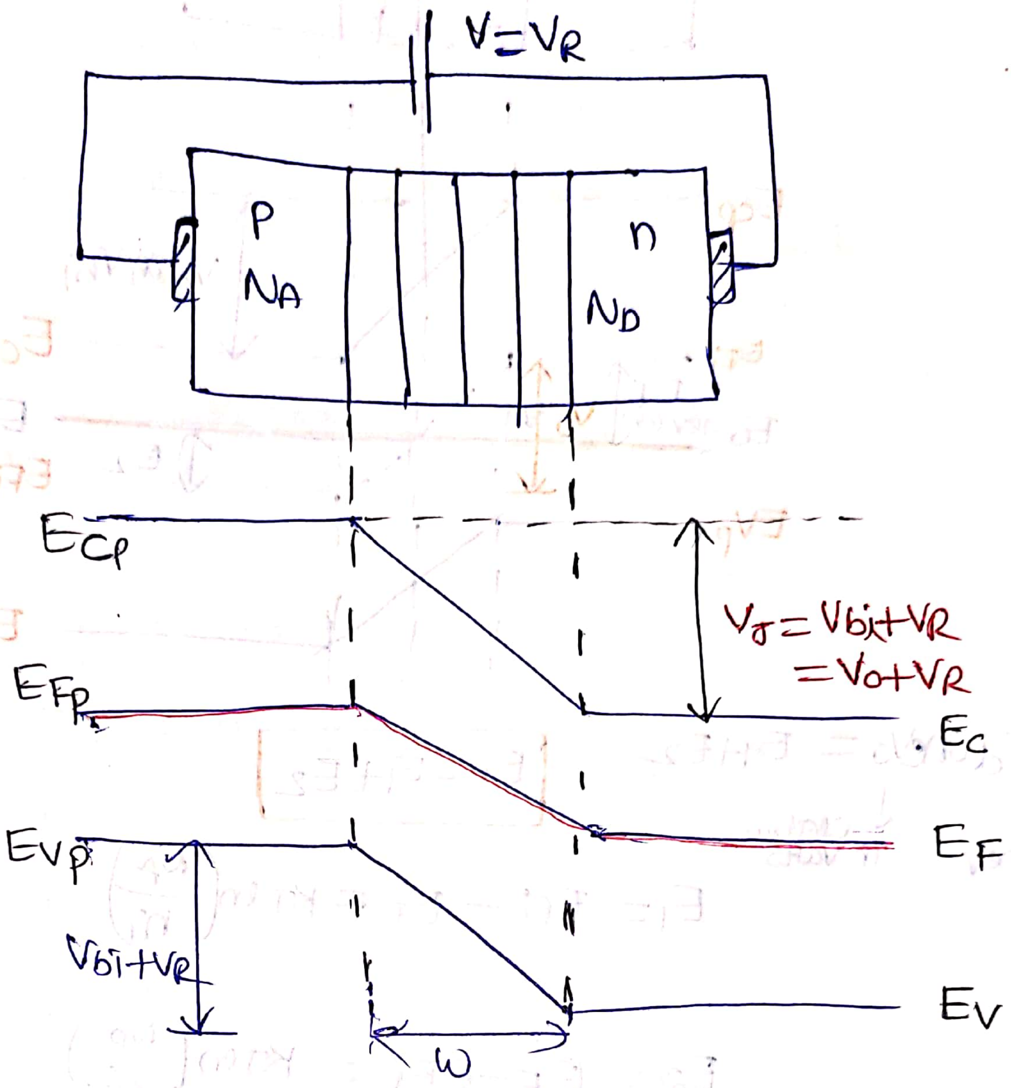


⇒ The built-in potential of the Barrier ⇓ becoz of the Forward Bias by the amount of "$V_{bi}-V_f$" volts

$$W = \sqrt{\frac{2\epsilon}{q}(V_{bi}-V_f)\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}$$

As V_f ⇑ ⇒ $V_{bi}-V_f$ ⇓ then W ⇓

Band diagram of Pn diode under ReverseBias :



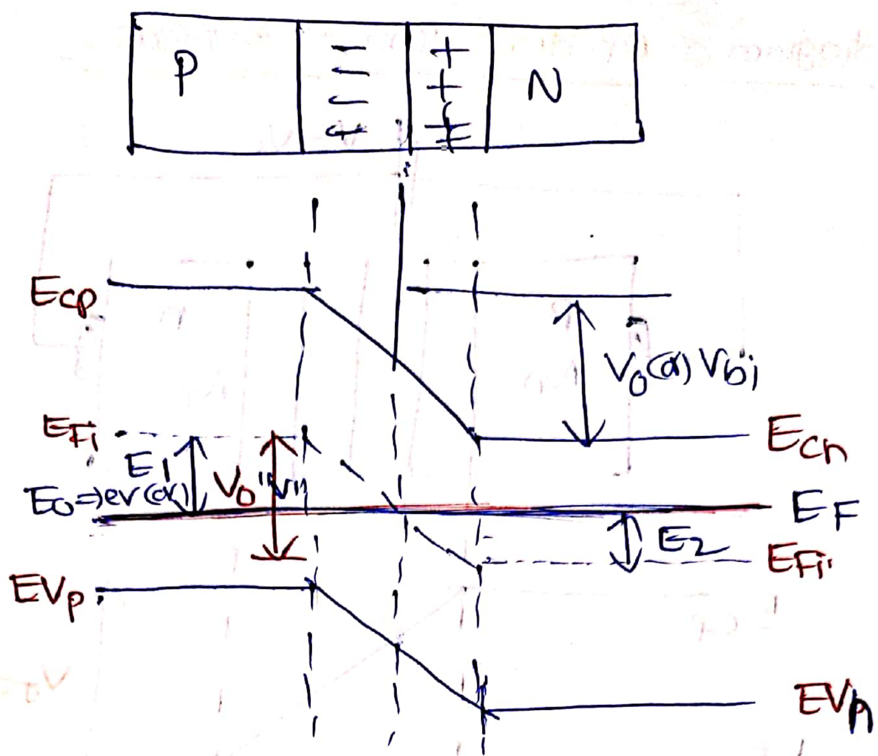
As $V_R \Uparrow$, $V_{bi} + V_R \Uparrow$, $w = \sqrt{\frac{2\epsilon}{q} (V_{bi} + V_R) \left[\frac{1}{N_A} + \frac{1}{N_D}\right]} \Uparrow$

$w \Uparrow$ then Depletion Region is high

Contact potential (or) Barrier potential

⇒ Read the definition in Page no:- 2

To Know the value of Contact Potential Let us Know the dependendency of the Contact potential on doping concentrations & any other Parameters



E_0 (or) $eV_0 = E_1 + E_2$

↓ in ev ↓ electron in volts

$$\boxed{E_0 = E_1 + E_2}$$

$$E_1 = E_{Fi} - E_F = KT\ln\left(\frac{N_A}{n_i}\right)$$

$$E_2 = E_F - E_{Fi} = KT\ln\left(\frac{N_D}{n_i}\right)$$

$$E_0 = KT\ln\left(\frac{N_A}{n_i}\right) + KT\ln\left(\frac{N_D}{n_i}\right)$$

$$E_0 = KT\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \text{ electronvolts}$$

$$V_0 = \frac{E_0}{q} = \frac{KT}{q}\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \text{ volts}$$

$$\boxed{V_{bi} = V_0 = \left(\frac{KT}{q}\right)\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right) \text{ Volts}}$$

$V_T = \frac{KT}{q}$ = Thermal equivalent Voltage

$\Rightarrow$ In n-type

$$n = N_c \exp -\left(\frac{E_c - E_F}{KT}\right) \rightarrow ①$$

$$n_i = N_c \exp -\left(\frac{E_c - E_{Fi}}{KT}\right) \rightarrow ②$$

$$\frac{①}{②} \Rightarrow \frac{\cancel{N_c}}{\cancel{N_c}} \exp\left(\frac{-\cancel{E_c} + E_F + \cancel{E_c} - E_{Fi}}{KT}\right) = \frac{n}{n_i}$$

$$\boxed{KT \ln\left(\frac{n}{n_i}\right) = E_F - E_{Fi}}$$

$n \simeq N_D$ in n-type

$$\boxed{E_2 = E_F - E_{Fi} = KT \ln\left(\frac{N_D}{n_i}\right)} \rightarrow ① \text{ (or) } \boxed{E_2 = E_{Fn} - E_{Fi} = KT \ln\left(\frac{N_D}{n_i}\right)}$$

$\Rightarrow$ In p-type:

$$p = N_v \exp -\left(\frac{E_F - E_v}{KT}\right) \rightarrow ③$$

$$n_i = N_v \exp -\left(\frac{E_{Fi} - E_v}{KT}\right) \rightarrow ④$$

$$\frac{③}{④} \Rightarrow \frac{p}{n_i} = \frac{\cancel{N_v}}{\cancel{N_v}} \exp\left(\frac{-E_F + \cancel{E_v} + E_{Fi} - \cancel{E_v}}{KT}\right)$$

$$KT \ln\left(\frac{p}{n_i}\right) = E_{Fi} - E_F$$

$p \simeq N_A$

$$\boxed{E_{Fi} - E_F = KT \ln\left(\frac{N_A}{n_i}\right)} = E_1$$

Maximum Electric Field:

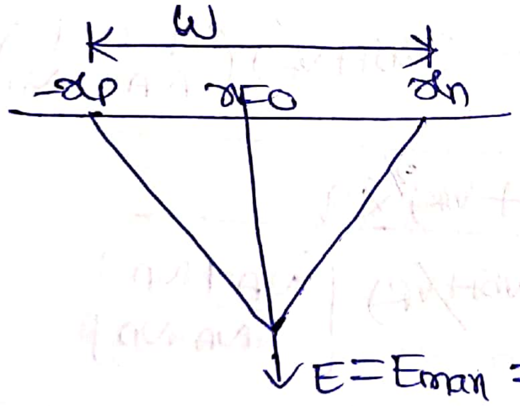
Maximum electric Field in PN Junction diode occurs at the metallurgical Junction

The magnitude of the Electric Field in the depletion Region increases with an applied Reverse-Bias.

The maximum electric Field$\big|_{x=0}$ $\Rightarrow E_{max} = E\big|_{x=0}$

$$E\big|_{x=0} = E_{max} = \frac{-qN_D x_n}{\epsilon} = \frac{-qN_A x_p}{\epsilon}$$

$E_{max} \Rightarrow \quad V = \int -E\,dx$



$E = E_{max} = \frac{-qN_D}{\epsilon} x_n = \frac{-qN_A \cdot x_p}{\epsilon}$

$$V = -\left[\int E \cdot dx\right]$$

$\Downarrow$

[Integration of Electric Field (or) Total Area of the waveform]

$$V = -\left[\frac{1}{2} \times W \times E\right]$$

$E = E_{max} \Rightarrow$ under Reverse Bias Condition ie

$V = V_{bi} + V_R$

$$V = V_{bi} + V_R = -\frac{1}{2} \times W \times E_{max}$$

$E = E_{max}$ when $V = V_{bi} + V_R$ (Reverse Bias)

$$(V_{bi} + V_R) = -\frac{1}{2} \times W \times E_{max}$$

$$\boxed{E_{max} = \frac{-2(V_{bi} + V_R)}{W}}$$

$$E_{max} = \frac{-2(V_{bi} + V_R)}{\sqrt{\frac{2\epsilon}{q}(V_{bi} + V_R)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}}$$

$$= \frac{\left(-\sqrt{(2(V_{bi} + V_R))^2}\right)}{\sqrt{\frac{2\epsilon}{q}(V_{bi} + V_R)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}}$$

$$= -\sqrt{\frac{4(V_{bi} + V_R)^{\cancel{2}} \times q}{2\epsilon\,(V_{bi} + \cancel{V_R})\left[\frac{N_A + N_D}{N_A N_D}\right]}}$$

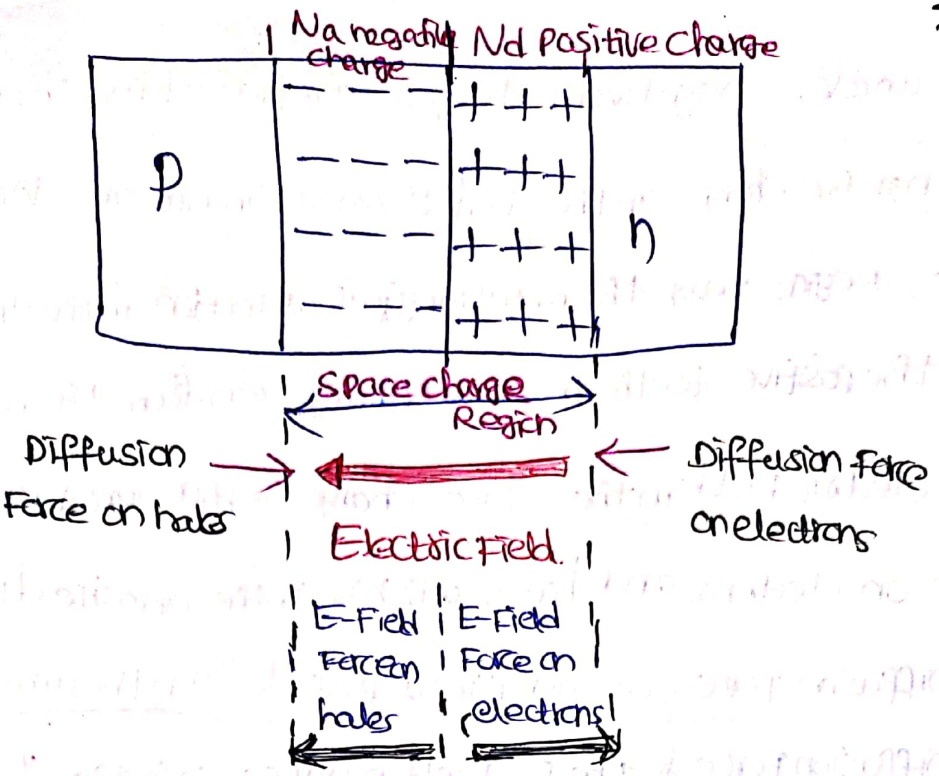
$$= -\sqrt{\frac{\cancel{4}^{2} q}{\cancel{2}\epsilon}(V_{bi} + V_R)\left(\frac{N_A N_D}{N_A + N_D}\right)}$$

$$\boxed{E_{max} = -\sqrt{\frac{2q}{\epsilon}\left(\frac{N_A N_D}{N_A + N_D}\right)(V_{bi} + V_R)}}$$

$$\boxed{|E_{max}| = \sqrt{\frac{2q}{\epsilon}\left(\frac{N_A N_D}{N_A + N_D}\right)(V_{bi} + V_R)}}$$

Scanned by CamScanner

⇒



⇒ Fig@: The space Charge Region, the electric Field & the Forces acting on the charged carriers

⇒ For simple analysis, consider a Step Junction in which the doping concentration is uniform in each Region and there is an abrupt change in doping at the junction

⇒ majority carrier electrons in the n-Region will begin diffusing into the P-region & majority carrier holes in the P-Region will begin diffusing into the n-Region

⇒ If there is no external connections to the Semi-conductor, then the diffusion process cannot continue further.

⇒ As e's diffuse from n-region, +vely Charged donor atoms are left behind, similarly as holes diffuse from the P-Region, they uncover negatively charged acceptor atoms. The net positive and negative charges in the 'n' & p Regions induce an electric Field in the Region near the metallurgical junction in the direction from the positive to the negative charge, (or) from the n to P Region.

⇒ The electric Field in the space charge region produces another Force on electrons and holes which is in the opposite direction to the Diffusion Force for each type of particle." In thermal equilibrium the Diffusion Force & the E-Field balance each other"

Operation of P-N Diode:

① PN Diode is a device which conducts current only in one direction from P to n (or) conventional current direction (or) Anode to cathode

Case ①

Under Zero applied Bias (or) open circuit condition :-

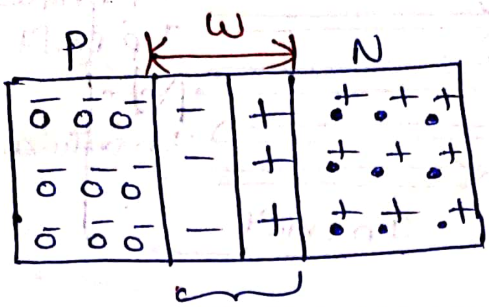
⇒ under Zero applied Bias (or) open circuit condition the current flow is zero, because no external excitation is applied.

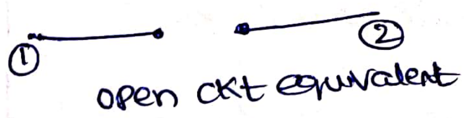
In open ckt condition the Built in potential is formed due to concentration gradient (or) Diffusion of e^- to P-side & holes to n-side by uncovering the immobile Ions by the amount of

For "Si" : $V_{bi} = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.7$ Volts

$\therefore$ For Si $\Rightarrow$ ($N_A = 10^{17}$ $N_D = 10^{16}$ Practically)

V_{bi} = Builtin potential Barrier = 0.7 Volts For "Si"
= 0.3 Volts For "Ge"





$$\boxed{V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$$

The charge Balanced equation in pn diode is

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

Total positive charge = Total negative charge

$p = 0 \Rightarrow$ hole concentration

$n = 0 \Rightarrow e^-$ " "

$+ \Rightarrow$ Immobile Donor ~~atom of~~ Ion

$- \Rightarrow$ Immobile Acceptor Ion

$\Rightarrow$ <u>Why current in open ckt is zero(A)?</u>

$\Rightarrow$ The Barrier Formed in pn junction will Further opposes the Diffusion of charge carriers so current Flow = 0,

$\Rightarrow$ There is no external electric Field (or) Biasing ~~is not there~~ in open circuit to overcome the Barrier so current = 0

($I_{Drift} = I_{Diffusion}$) In open ckt

n-side majority = e⁻s (Due to Doping)
n-side minority = holes (due to Thermal agitation)

Biasing: To provide external voltage to the PN-junction Diode
⇒ To provide Biasing we need to give ohmic contacts to the Diode

Ohmic contacts :- (or) metal contacts used to provide
(metal alloy junctions)

1. To provide Biasing
2. manufactured in such a way that they are "Non-Rectifying" means the contact potential across these metal-semiconductor junctions is approximately independent of the direction & magnitude of the current
3. If we neglect the 'p' & 'N' resistance the entire applied voltage will appear across the junction to change the height of the potential Barrier [Becoz ohmic contacts have less Resistance & P & N have less "]

⇒ Forward Bias means applying positive voltage to "p" & negative to "n" & Reverse Bias is Vice-versa

⇒ when a Forward-Bias voltage is applied to a PN junction, a current will be induced into the device after overcoming the Barrier potential

⇒ The applied Forward Bias will "overcomes the Force of Repulsion" between the equally charged (or) same type of charge carriers becoz positive charge on P-sides pushes holes towards "n" & negative charge on n-side repels (or) pushes e^- towards P-side n-side majority = e^-s (due to Doping)

n-side minority = holes (due to Thermal agitation)

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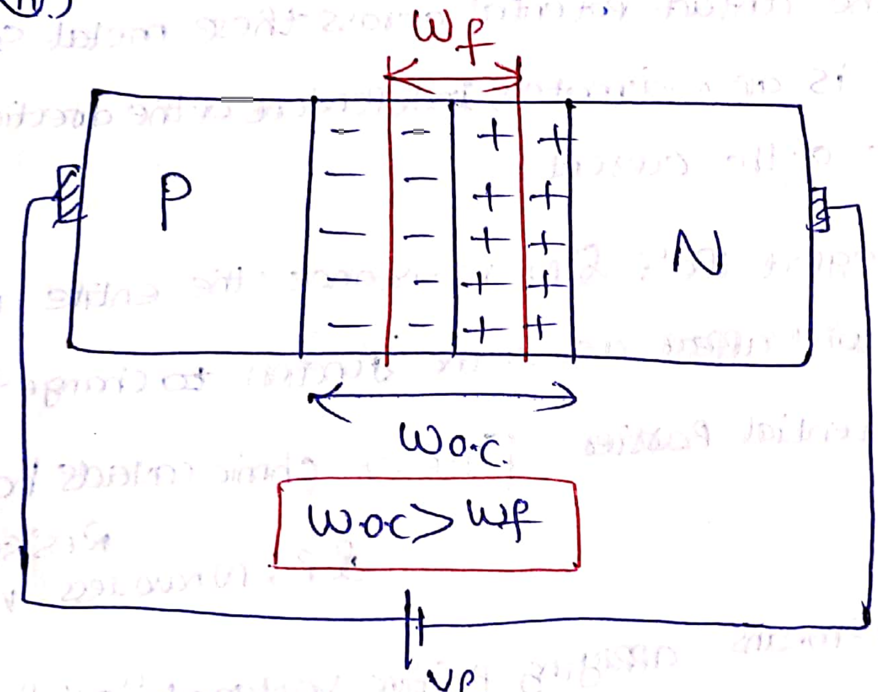
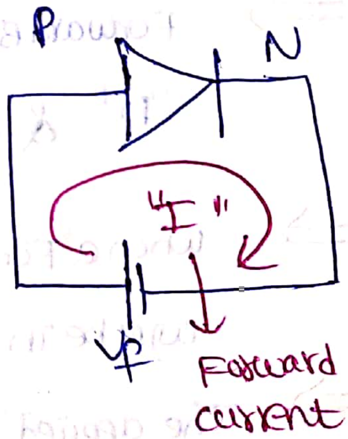
⇒ when the applied FB is equal to the cut-in voltage then the current starts to flow exponentially

⇒ when we apply FB, a more e^-s flow into the depletion Region & the no of positive Ions is reduced. and when holes "effectively" flow into the depletion Region the no. of negative Ions is reduced This reduction in positive and negative Ions during Forward Bias causes the depletion region narrow (or) width narrow ($W \Downarrow$)





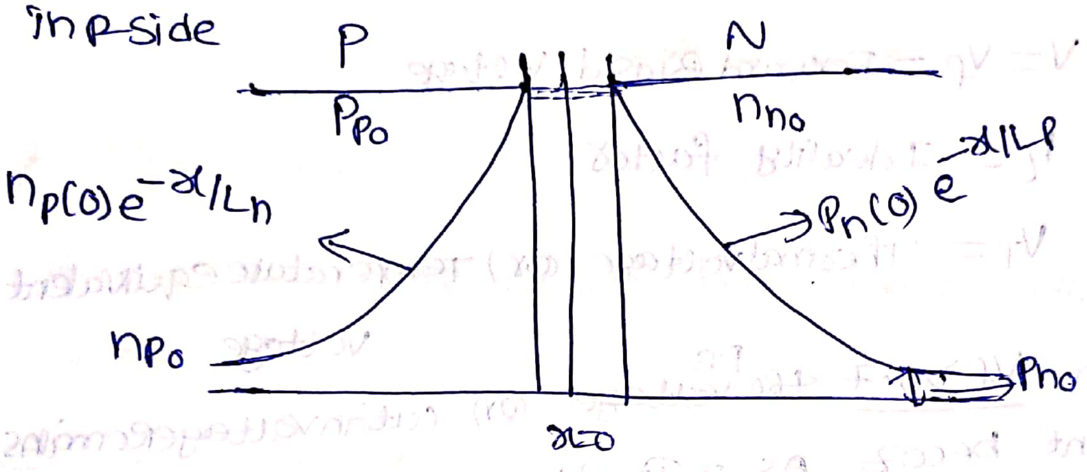
The reduce in depletion width is

$$W = \sqrt{\frac{2\epsilon}{q}(V_{bi} - V_f)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

when $V_f \Uparrow$ $(V_{bi} - V_f) \Downarrow$ & $W \Downarrow$ & flow of charge carriers takes place.

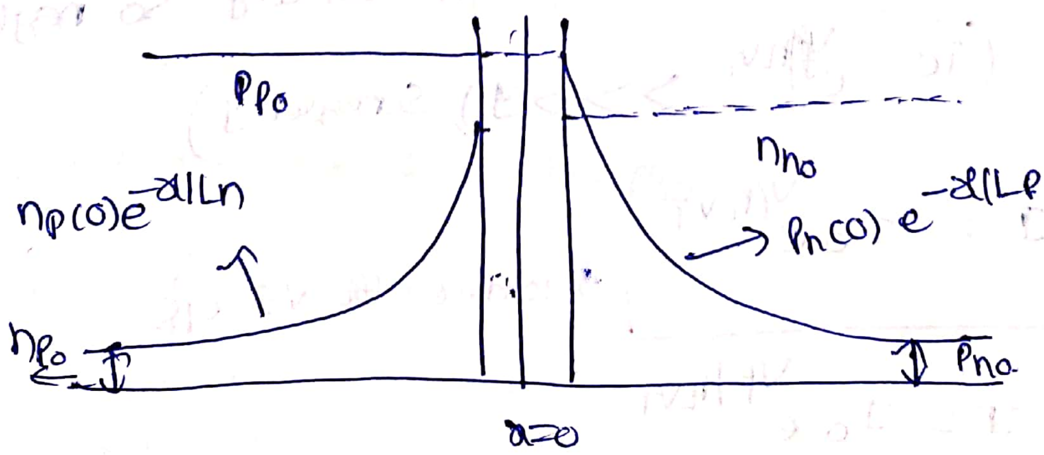
⇒ After overcoming the Barrier potential holes enters into the N-Region Becoz of Drift applied ie FB ie Due to applied electric Field the P-side charge carriers

⇒ Push into N-Region. The holes in n-Region becomes minority charge carriers then Diffusion dominates Drift & Diffusion of holes in n-Region takes place and electrons Diffusion takes in P-side



Fig(a): when P & N have uniform doping conc.

If $\boxed{P^+ | N}$ Diode then



Fig(b) P & N have different doping concentrations

If we derive the current equation, then the current in Forward Biased PN Junction is

$$\boxed{I = I_o(e^{V/\eta V_T} - 1)} \quad \boxed{I = I_o(e^{V_f/\eta V_T} - 1)}$$

I_o = Reverse Saturation current

I = Total current due to electrons & holes

$V = V_f$ = Forward Biased Voltage

η = Ideality factor

V_T = Thermal voltage (or) Temperature equivalent Voltage

⇒ when $V_f > 0.7$ the F.B voltage (or) cut in voltage remains constant becoz As $I\Uparrow$, $R\Downarrow$ total $V = (I\Uparrow R)\Downarrow$ remains constant

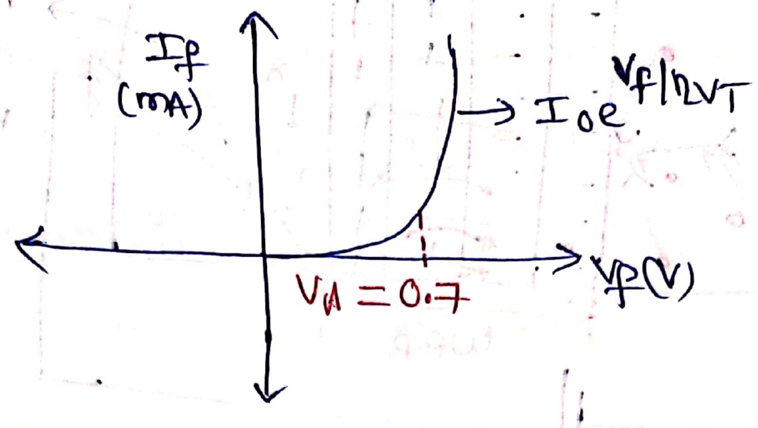
⇒ $I = I_o(e^{V_f/\eta V_T} - 1) = I_o(e^{V_f/\eta V_T} - 1)$

when $V_f > 0.7$ the current $\Uparrow$ rapidly so neglect '1' (ie $e^{V_f/\eta V_T} >>> 1$), So neglect 1)

$$\boxed{I = I_o e^{V/\eta V_T}}$$ ⇒ To draw the V-I c/s

$$I = I_o e^{V_f/\eta V_T}$$

⇒ VI Characteristics in F.B



V_γ = cut-in voltage $= 0.7$ For Si

$= 0.3$ For Ge

⇒ Reverse Bias :-

⇒ Reverse Bias is the condition that prevents current through the Diode

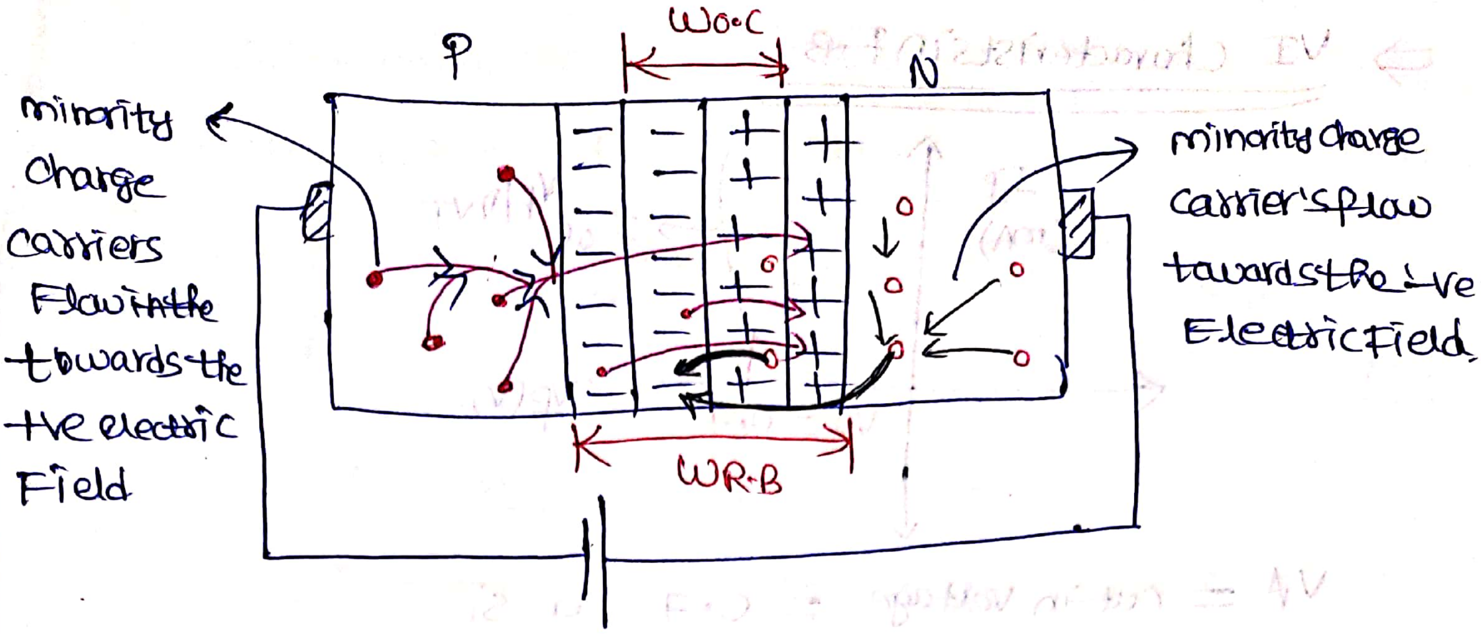
⇒ R.B ⇒ P ⇒ −ve Voltage

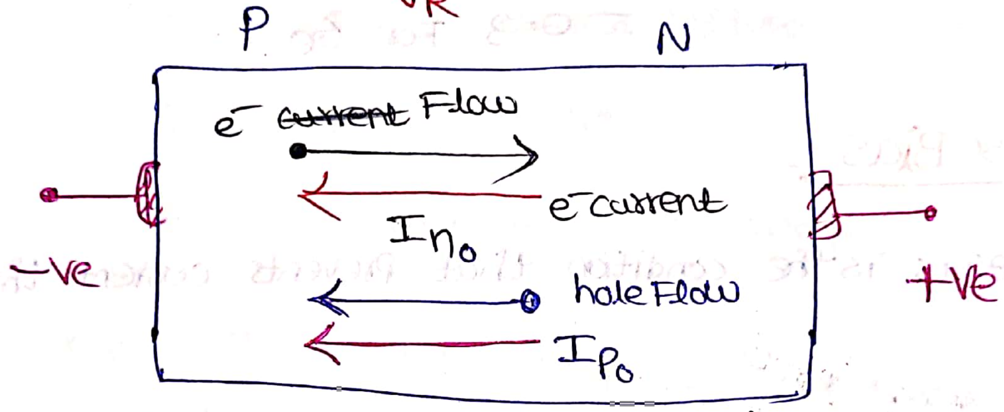
n ⇒ +ve Voltage

⇒ When we apply −ve voltage to the P-terminal then positively charged holes moves moves towards −ve potential & negati +ve voltage to the n-terminal then electrons moves towards positive potential by uncovering (or) leaving their Ions. Becoz of those immobile Ions the depletion Region width ⇈

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

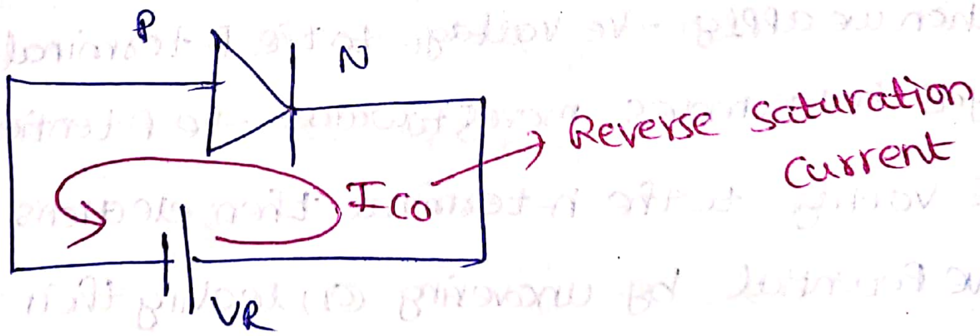
As V_R ⇈ $(V_{bi}+V_R)$ ⇈ then W ⇈





$$I_{Co} = \underbrace{I_{n_0}}_{\Downarrow} + \underbrace{I_{p_0}}_{\Downarrow}$$

due to minority charge carriers



Reverse-Saturation current:

The current Flows in Reverse direction (The Actual Flow in a diode is from P to N (or) in single direction) due to applied Reverse Bias is called Reverse saturation current

⇒ This current is called saturation current because the Reverse current is due to the minority carriers. Eventhough If we↑ the Reverse voltage the current saturates after certain maximum value because the minority carrier conc. Varies w.r.to Temperature only.

The current equation In Reverse Bias is

$$I = I_0\left(e^{V_R/\eta V_T} - 1\right)$$

$V_R \Rightarrow$ Is "$\underline{-ve}$" So exponential of "-ve" values far far less than 1

$(e^{-1} = 0.367 << 1$

$$I = I_0\left(e^{-(ve)} - 1\right)$$

"$V_R = -ve$"

$$I = I_0\left(e^{-ve} - 1\right)$$

$e^{-ve} << 1$ So neglect $e^{-(ve)}$ value (or) exponential term

$$I = I_0(-1)$$

$$\boxed{I = -I_0}$$

"Reverse saturation current 'I_0' does not depends on Reverse voltage It depends on Temperature.

As Temp ↑↑ I_0↑↑

For every 10°c raise in temp I_0 doubles

$$\boxed{I_0(T_2) = I_0(T_1) \cdot 2^{\frac{T_2 - T_1}{10}}}$$

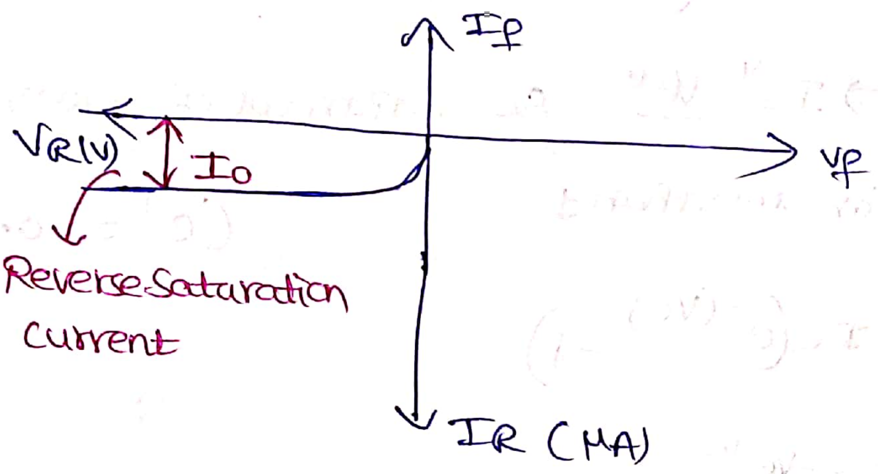
T_1 = Initial Temperature

T_2 = Increase in Temperature

$I_0(T_2)$ = Reverse Saturation current after ↑ in Temp

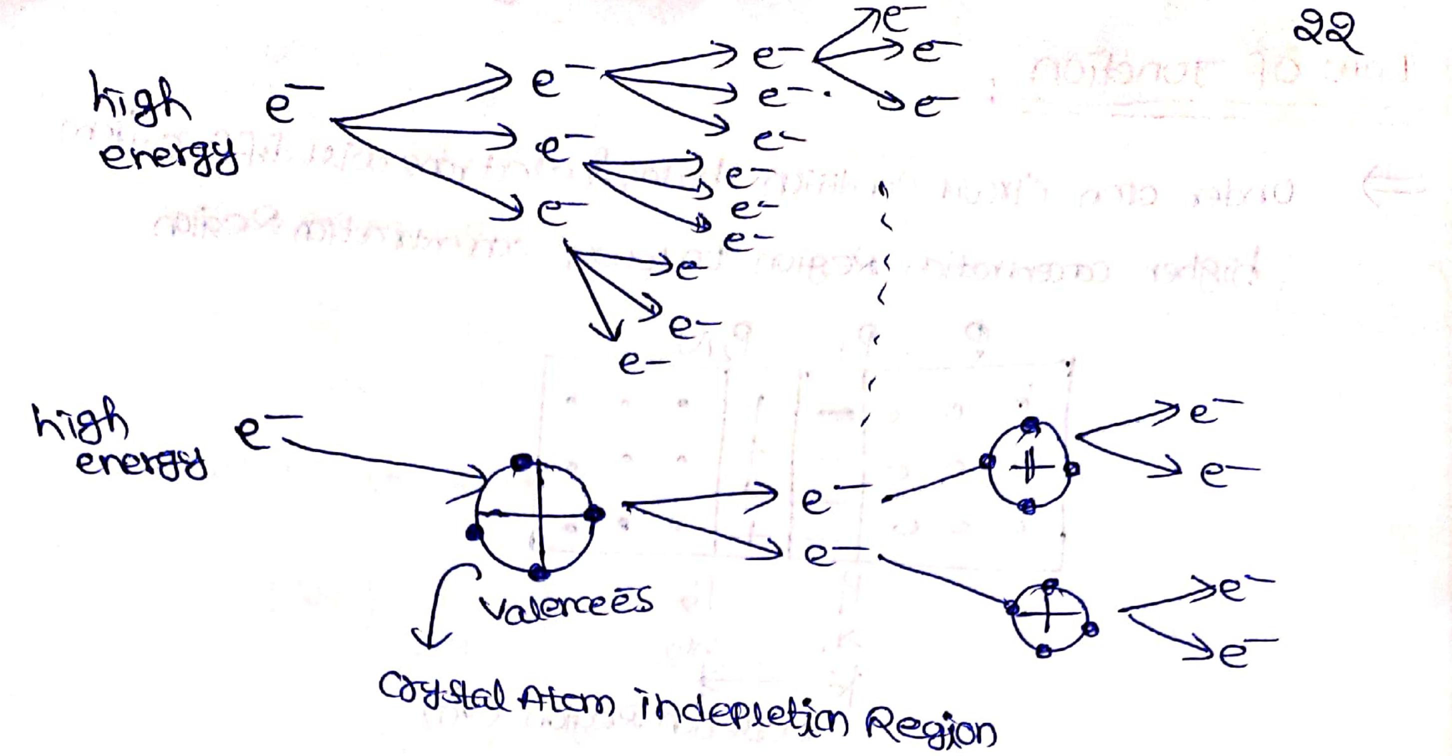
$I_0(T_1)$ = Reverse Saturation current in Initial Temperature

~~Reverse~~ V–I charectristics of P-N diode in R-B



⇒ ## Breakdown in Reverse Bias condition :-

When we are ↑ the V_R (or) Reverse voltage then the K.E (or) Kinetic energy of e^- ↑ and that high energy e^- collids with the atoms present in depletion Region due to this collision the atoms produces an $e^- - h^+$ pair in a cumulative Process. This $e^- - h^+$ pair generation ↑ as a Geometric progression. This multiplication of carriers ↑ in a cumulative manner so called cumulative multiplication

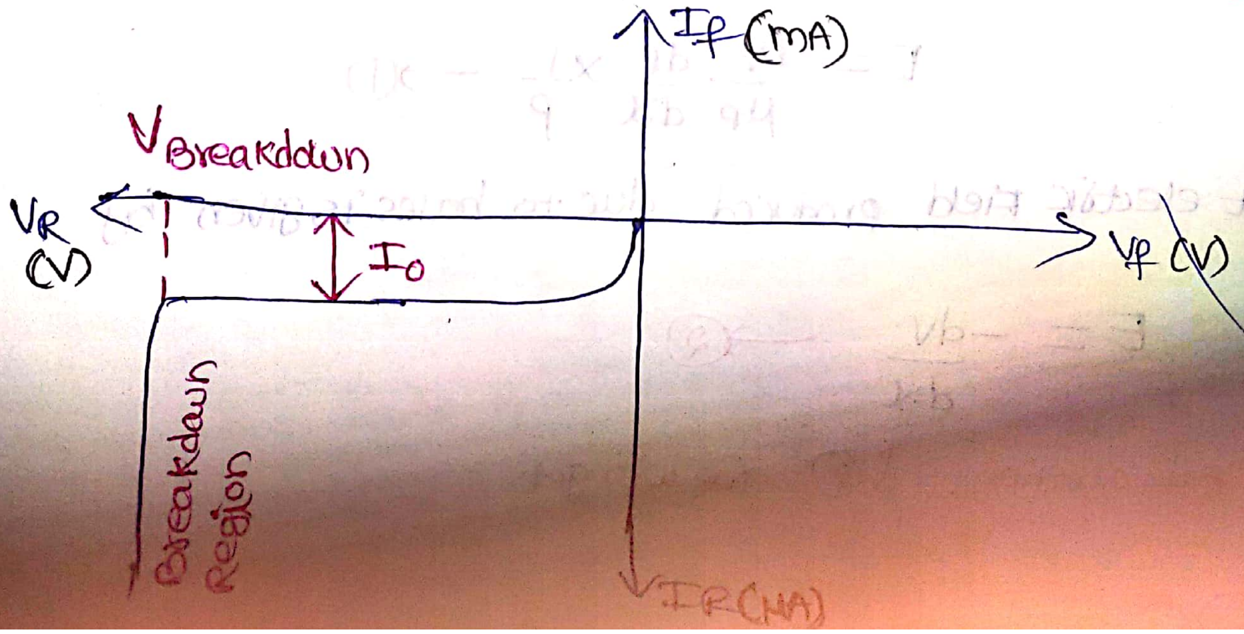


Avalanche multiplication

⇒ This cumullative multiplication is called Avalanche multiplication & Becoz of this rapid ⇑ in carrier concentration the current ⇑ abruptly (or) suddenly. this sudden breakdown of covalent bonds & rapid ⇑ in concentration causes "Avalanche Breakdown".

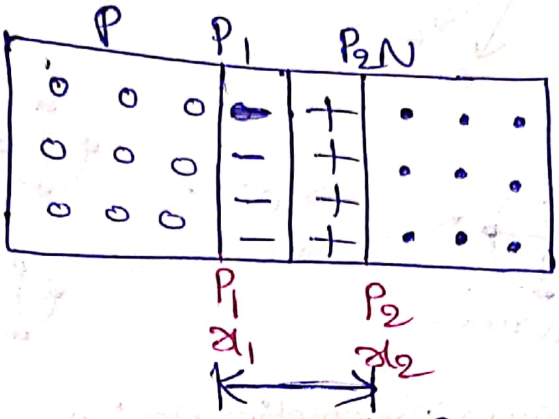
But for pn diode this Voltage is very high ie from 50V–1000V

But in pn diode after Breakdown the Diode will never recover



Law of Junction :-

⇒ Under open circuit condition holes & electrons will diffuse from higher concentration Region to Lower concentration Region



Depletion Region (V_0)

⇒ The Law of Junction provides a Relationship b/w the external applied voltage and the no. of carriers crossing the Junction

At open ckt condition, the diffusion current of holes & electrons is equal.

$$\boxed{I_{Drift} = I_{Diffusion}}$$

$$P.q\,\mu_p.E.A = q.D_p\frac{dp}{dx}.A$$

$$I_{Drift} = P.q\,\mu_p EA$$

$$I_{Diffusion} = q.D_p.\frac{dp}{dx}.A$$

$$P\cancel{q}\mu_p.E\cancel{A} = \cancel{q}D_p\frac{dp}{dx}.\cancel{A}$$

$$E = \frac{D_p}{\mu_p}.\frac{dp}{dx}\times\frac{1}{p} \longrightarrow (1)$$

But electric field produced due to holes is given by

$$E = -\frac{dV}{dx} \longrightarrow (2)$$

By equating (1) & (2) we will get

$$\left(\frac{D_p}{\mu_p}\right)\frac{dp}{dx}\times\frac{1}{p} = \frac{-dV}{dx} \rightarrow (3)$$

By Einstein Relation

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T \rightarrow (4)$$

Substitute (4) in (3)

$$(V_T)\frac{dp}{dx}\times\frac{1}{p} = \frac{-dV}{dx}$$

$$\frac{dp}{p} = \left(-\frac{1}{V_T}\right)dV$$

By variable seperable method.

$$\int\frac{dp}{p} = \int\left(\frac{-1}{V_T}\right)dV$$

$$\int_{P_1}^{P_2}\frac{dp}{p} = \frac{-1}{V_T}\int_{V_1}^{V_2}dV$$

$$\log P_2 - \log P_1 = -\frac{V}{V_T}\Big|_{V_1}^{V_2}$$

$$\log\left(\frac{P_2}{P_1}\right) = \frac{-1}{V_T}\left[V_2 - V_1\right]$$

$$\log\left(\frac{P_2}{P_1}\right) = \frac{-V_{21}}{V_T}$$

$$\frac{P_2}{P_1} = e^{-V_{21}/V_T}$$

$$P_2 = P_1 e^{-V_{21}/V_T}$$

$$\boxed{P_1 = P_2 e^{V_{21}/V_T}}$$

① under open ckt:

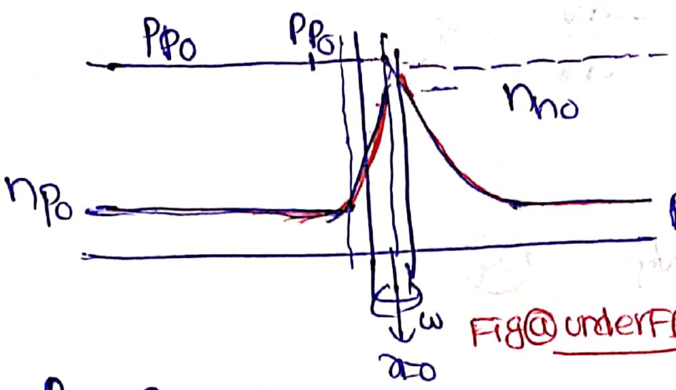
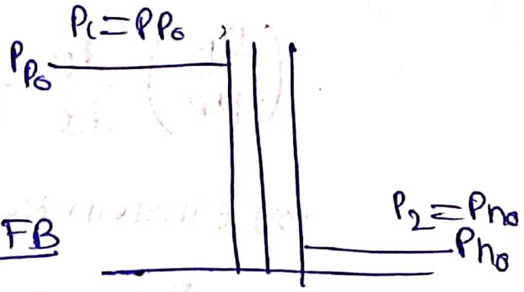
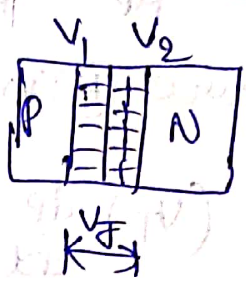


Fig ⓐ under FB



under FB

Fig ⓑ under open ckt



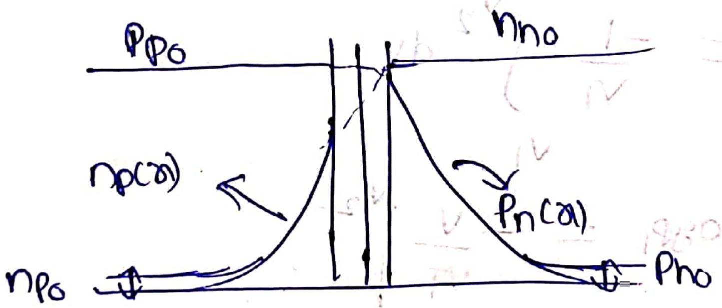
$P_1 = P_{Po} \quad P_2 = P_{no}$

$$\boxed{P_{Po} = P_{no}\, e^{V_{21}/V_T}}$$

$V_2 - V_1 = V_J = V_0$ In openckt condition

$$\boxed{P_{Po} = P_{no}\, e^{V_0/V_T}} \rightarrow Ⓐ$$

② under Forward Bias:



$P_1 = P_{Po}$

$P_2 = P_n(x)$

$$P_{Po} = P_n(x)\, e^{(V_2 - V_1)/V_T}$$

$$\boxed{P_{Po} = P_n(x)\, e^{(V_0 - V_f)/V_T}} \rightarrow Ⓑ$$

$$\frac{Ⓐ}{Ⓑ} \Rightarrow \frac{P_{Po}}{P_{Po}} = \frac{P_{no}}{P_n(x)} \frac{\left(e^{V_0/V_T}\right)}{\left(e^{(V_0 - V_f)/V_T}\right)}$$

$$I = \frac{P_{no}}{P_n(x)} \cdot e^{\left(V_0/V_T - \frac{V_0}{V_T} + \frac{V_f}{V_T}\right)}$$

$$\boxed{P_n(x) = P_{no}\, e^{V_f/V_T}}$$

This is called "Law of Junction"

Diode-current equation :-

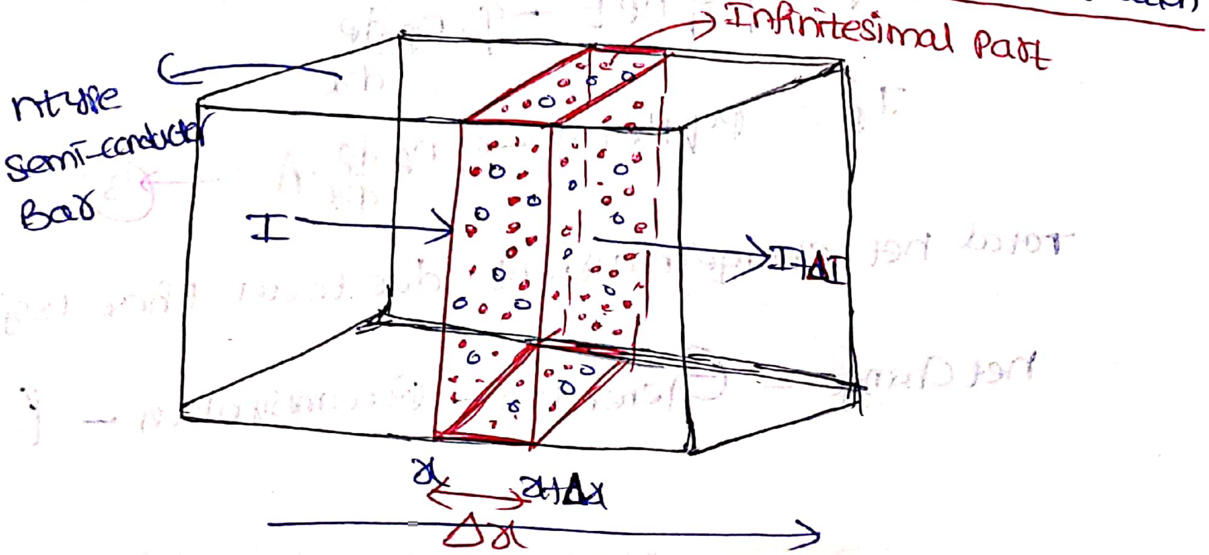
To derive the diode current equation we need to refer continuity equation

Continuity equation :

⇒ The continuity equation of a semi-conductor tells about the carrier concentration in a semi-conductor is a function of both time & distance.

⇒ If we disturb the equilibrium concentrations of carriers in a semi-conductor material, then the concentration of holes (or) electrons will vary with time.

The continuity equation is based on the fact that the charge can neither be created nor be destroyed. i.e "Law of conservation of Charge"

⇒ 

$\Rightarrow$ consider the Infinitesimal element(or) part of a n-type semi-conductor of volume & Area "A" and length "Δx" within which the average ($A \cdot \Delta x$)

hole concentration is "p"

$\Rightarrow$ If τ_p is the mean life time of the holes then $\frac{p}{\tau_p}$ equals the holes per second lost by recombination per unit volume.

The current decreases due to recombination is given by

$\Rightarrow$ I decrease within the volume $= q \cdot A \cdot \Delta x \cdot \frac{p}{\tau_p} \rightarrow (1)$

If "G" is the Thermal generation of e^--hole pairs per unit volume then $G = \frac{P_o}{\tau_p}$

$\Rightarrow$ The increase in hole current due to Generation is

$$= q \cdot A \cdot \Delta x \cdot \frac{P_o}{\tau_p} \rightarrow (2)$$

$\Rightarrow$ The Drift & diffusion depends on ~~dis~~ distance

$$J_p = p q \mu_p E - q \cdot D_p \frac{dp}{dx}$$

$$I_p = p q \mu_p E A - q D_p \frac{dp}{dx} \cdot A \rightarrow (3)$$

Total net change in current due to all these is given by

net change = Generation − Recombination − [Drift + Diffusion]

$$\boxed{\text{Net rate of Change in current} = G - R - \frac{d}{dx}\left(I_p(x)\right)} \rightarrow (A)$$

The rate of change in current within a volume $A \cdot \Delta x$ is $= q \cdot A \cdot \Delta x \cdot \frac{dp}{dt}$

$$I = \frac{Q}{t} \Rightarrow \frac{Nq}{t} = \frac{Nq}{t}$$ due to N e⁻s

$$I = \frac{Pq}{t}$$ due to 'p' holes

$$\therefore I = q \cdot \frac{dp}{dt}$$

I | within a volume $A \cdot \Delta x$ is

$$I = q \cdot A \cdot \Delta x \cdot \frac{dp}{dt}$$

$$q \cdot A \cdot \Delta x \cdot \frac{dp}{dt} = q \cdot A \cdot \Delta x \cdot G - q \cdot A \cdot \Delta x \cdot \frac{P}{\tau_p} - \frac{d}{dx}\left(I_p(x)\right)$$

$$= q \cdot A \cdot \Delta x \frac{P_0}{\tau_p} - q \cdot A \cdot \Delta x \cdot \frac{P}{\tau_p} - \frac{d}{dx}\left[Pq\mu_p E A - q A D_p \frac{dp}{dx}\right] \Delta x$$

$$q \cdot A \cdot \Delta x \cdot \frac{dp}{dt} \Rightarrow q A \cdot \Delta x \left[\frac{P_0}{\tau_p} - \frac{P}{\tau_p}\right] - q \mu_p A \cdot \Delta x \cdot \frac{d}{dx}(PE) + q \cdot A \cdot D_p \cdot \Delta x \frac{d^2 p}{dx^2}$$

$$q\cdot\cancel{A}\cdot\Delta x\cdot\frac{dp}{dt} = q\cdot\cancel{A}\cdot\Delta x\left(\frac{p_0}{\tau_p}-\frac{p}{\tau_p}-\mu_p\frac{d}{dx}(pE)+D_p\frac{d^2p}{dx^2}\right)$$

$$\boxed{\frac{dp}{dt} = \frac{-(p-p_0)}{\tau_p} - \mu_p\frac{d}{dx}(pE) + D_p\frac{d^2p}{dx^2}} \rightarrow (B)$$

This is called continuity equation.

To derive the diode current equations conditions are

1. concentration Independent of time with zero electric field

[Electric Field effect presents on holes is upto it reaches the N-Region, After entering into N-Region Diffusion dominates Drift so $\underline{E=0}$]

The concentration is Independent of time becoz the Generation & Recombination are fast process & the parameter distance dominates the time]

$$\frac{dp}{dt}=0,\quad E=0,\quad \underbrace{p_0 = p_{n0},\ p = p_n}_{\text{holes enter into n-Region}}$$

$$0 = -\frac{(p_n-p_{n0})}{\tau_p} + D_p\frac{d^2p_n}{dx^2} - \mu(0)$$

$$D_p\frac{d^2p_n}{dx^2} = \frac{p_n-p_{n0}}{\tau_p}$$

$$\frac{d^2p}{dx^2} = \frac{p_n - p_{n0}}{D_p \tau_p}$$

Let $L_p = \sqrt{D_p \cdot \tau_p} \Rightarrow$ Diffusion length

$$\frac{d^2p_n}{dx^2} = \frac{p_n - p_{n0}}{L_p^2}$$

$$\frac{d^2p_n}{dx^2} = \frac{p_n - p_{n0}}{L_p^2}$$

It is in the Form $D^2y - \frac{1}{a^2}y = 0$

ie $\left(D^2 - \frac{1}{a^2}\right)y = 0$

$$\frac{d^2(p_n - p_{n0})}{dx^2} = \frac{1}{L_p^2}(p_n - p_{n0})$$

$$\frac{d^2(p_n - p_{n0})}{dx^2} - \frac{1}{L_p^2}(p_n - p_{n0}) = 0$$

$\left(\because \frac{d^2p_{n0}}{dx^2} = 0 \right.$

$\frac{d^2p_n}{dx^2} = \frac{d^2p_n - 0}{dx^2}$

$\Rightarrow \frac{(d^2p_n - d^2p_{n0})}{dx^2}$

$$p_n - p_{n0} = \underbrace{K_1 e^{-x/L_p}}_{\text{Term-I}} + \underbrace{K_2 e^{+x/L_p}}_{\text{Term-II}} \rightarrow (4)$$

$K_1, K_2 \Rightarrow$ constants of Integration

From eq (4) AS $x \rightarrow \infty$, the concentration becomes Infinite, But practically the "p" or holes entered in n-region never becomes "∞" as $x \rightarrow \infty$ so neglect Term-II

$$P_n - P_{no} = K_1 e^{-x/L_p} + \cancel{K_2 e^{+x/L_p}}$$

$$P_n - P_{no} = K_1 e^{-x/L_p}$$

since P_n is a function of "x" so P_n becomes $P_n(x)$

$$P_n(x) - P_{no} = K_1 e^{-x/L_p}$$

$K_1 \big|_{x=0}$ is

$$P_n(0) - P_{no} = K_1$$

$$\underbrace{P_n(x) - P_{no}} = (P_n(0) - P_{no})\, e^{-x/L_p}$$

$$\boxed{P_n'(x) = P_n'(0)\, e^{-x/L_p}}$$

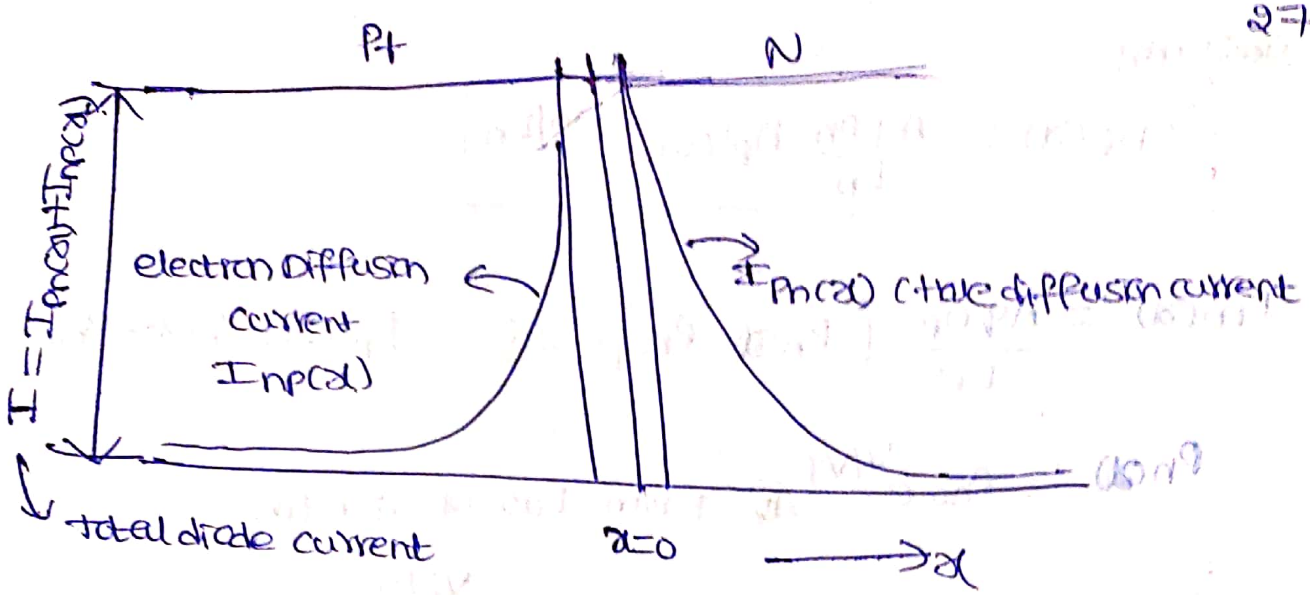
(or)

$$\boxed{P_n(x) = P_{no} + P_n'(0) e^{-x/L_p}}$$

As distance ↑ the conc of holes ↓ with the avg distance "L_p" called Diffusion Length

Diffusion length: The Avg distance travelled by the charged particle before Recombination is called Diffusion Length

$$\boxed{L_p = \sqrt{D_p \cdot \tau_p}} \qquad \boxed{L_n = \sqrt{D_n \cdot \tau_n}}$$



$$\underbrace{P_n'(x)}_{\text{Hole conc. in n-Region}} = P_n'(0)\, e^{-x/L_p}$$

Let The hole current in n-Region is

$$\cancel{I_{pn}(x) = q \frac{dp}{dx}} \cdot D_p$$

$$I_{pn}(x) = -q D_p \frac{dp}{dx} \cdot A$$

hole conc. in the n Region so $P = P_n'(x)$

$$I_{pn}(x) = -A q D_p \frac{d P_n'(x)}{dx}$$

$$\Rightarrow -A q D_p \frac{d}{dx}\left(P_n'(0)\, e^{-x/L_p}\right)$$

$$= -A q D_p \cdot P_n'(0)\, e^{-x/L_p} \times \frac{-1}{L_p}$$

$$\boxed{I_{pn}(x) = \frac{A q D_p}{L_p} P_n'(0)\, e^{-x/L_p}}$$

Similarly

$$\boxed{I_{np}(x) = \frac{Aq D_n}{L_n} n_p'(0) \cdot e^{-x/L_n}}$$

$$I_{pn}(x) = \frac{Aq D_p}{L_p} \left[P_n(x) - P_{no} \right] \rightarrow (a) \qquad P_n'(0) = P_n(x) - P_{no}$$

$$P_n(x) = P_{no} e^{V/V_T} \rightarrow (b) \quad \text{From Law of junction}$$

$$P_n(x) = P_{no} e^{V_f/V_T} \rightarrow \quad V = V_f \text{ in FB}$$

$$V = V_R \text{ in R.B}$$

$$I_{pn}(x) = \frac{Aq D_p}{L_p} \left[P_{no} e^{V/V_T} - P_{no} \right] \rightarrow (c)$$

consider the space charge width is very small then

$x = 0$ (negligible)

Sub $x = 0$ in eq (a)

$$I_{pn}(0) = \frac{Aq D_p}{L_p} \left[P_n(x) - P_{no} \right]$$

$$I_{pn}(0) = \frac{Aq D_p}{L_p} \left[P_n(0) - P_{no} \right] = \frac{Aq D_p}{L_p} \left[P_{no} e^{V/V_T} - P_{no} \right]$$

lly

$$I_{np}(0) = \frac{Aq D_n}{L_n} \left[n_{po} e^{V/V_T} - n_{po} \right]$$

Total current

$$I = I_{np}(0) + I_{pn}(0)$$

$$I = \frac{Aq D_p}{L_p} P_{no} \left[e^{V/V_T} - 1 \right] + \frac{Aq D_n}{L_n} n_{po} \left[e^{V/V_T} - 1 \right]$$

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$$I = \underbrace{\left[\frac{AqD_p}{L_p} p_{no} + \frac{AqD_n}{L_n} n_{po}\right]}_{I_o} \left[e^{V/V_T} - 1\right]$$

$$\boxed{I = I_o\left[e^{V/V_T} - 1\right]}$$

where $\boxed{I_o = \frac{AqD_p}{L_p} p_{no} + \frac{AqD_n}{L_n} n_{po}}$

But while deriving the Diode current equation we assumed $x = 0$ that means we assumed the Recombination current in space charge is neglected. But practically we need to take the Recombination current that is lost in space charge.

So to compensate that Recombination current we will add a factor against the Ideal condition is called Ideality factor "η" in the denominator of exponential term to reduce the current to compensate which is lost in space charge

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

$$\boxed{I = I_o\left(e^{V/\eta V_T} - 1\right)}$$ Diode current equation

η = Ideality factor. = 1 ⟹ For large current

2 ⟹ For small current

η : Ideality factor :

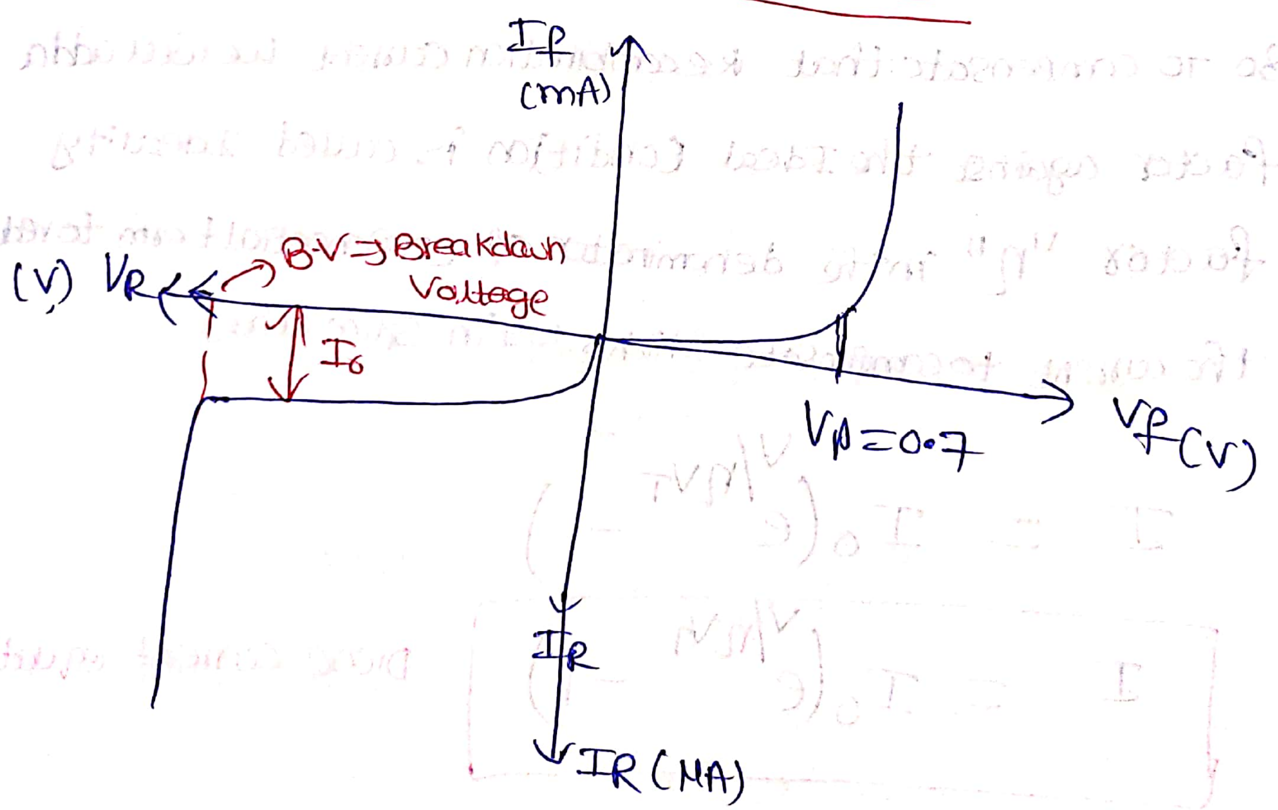
The factor which is added against the Ideality assumptions is called Ideality factor; i.e to consider the loss in space charge Region

For large currents the loss in Recombination current is negligible so we are adding "η" less i.e 1 & For small currents it is considered into account

$$\boxed{\begin{array}{l} \eta = 1 \Rightarrow \text{For large currents} \Rightarrow \text{Ge} \\ \eta = 2 \Rightarrow \text{For small currents} \Rightarrow \text{"Si"} \end{array}}$$

GATE

V-I Characteristics of Pn-Diode



V_γ = cut-in Voltage $= 0.7 \Rightarrow$ Si

$= 0.3 \Rightarrow$ Ge

★ ⇒ V_γ = cut-in voltage: The Forward voltage which is added ~~against the~~ to overcome the Barrier Potential is called cut-in Voltage

Is cut-in voltage & Barrier Potential are same?

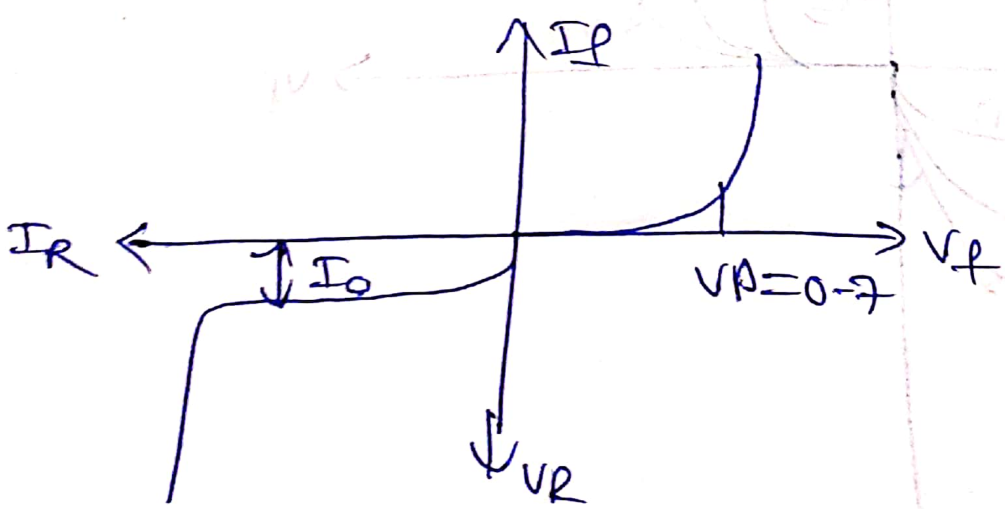
"No." The Barrier Potential is always a Fixed value ie either 0.7 (or) 0.3 But the Forward Voltage given by us will varies as 0.1, 0.2, 0.3 --- 0.7, 1, 2 --- In that the amount of voltage which is required to overcome the Barrier Potential is called cut-in voltage

Built-in Potential ⇒ Depends on manufacturer (Based on Doping conc)

cut-in Voltage ⇒ Fwd voltage given by us

Dependency of V-I c/s on Temperature

⇒



The Forward Biased Voltage which is to be given to the diode decreases by 2.5 mv /°c.

F·B - Voltage
(or) I/p voltage $\boxed{\frac{dV}{dT} = -2.5\, mV/°C}$

The Reverse saturation current "I_0" ⇑ when the Temp ⇑

ie For every 10°c raise in Temp the Reverse sat-current doubles

For every 10°c ⇑ in Temp ⟹ I_0 doubles

$$\boxed{I_0(T_2) = I_0(T_1) \cdot 2^{\frac{T_2 - T_1}{10}}}$$

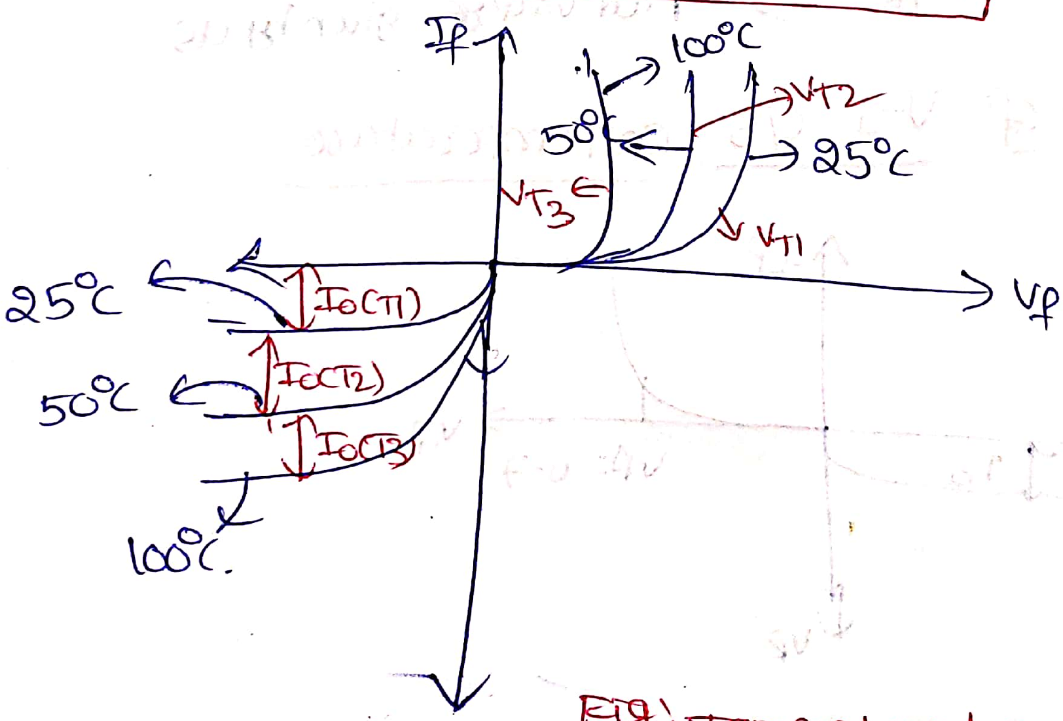


Fig: Temperature dependency of VI C/S of pn diode

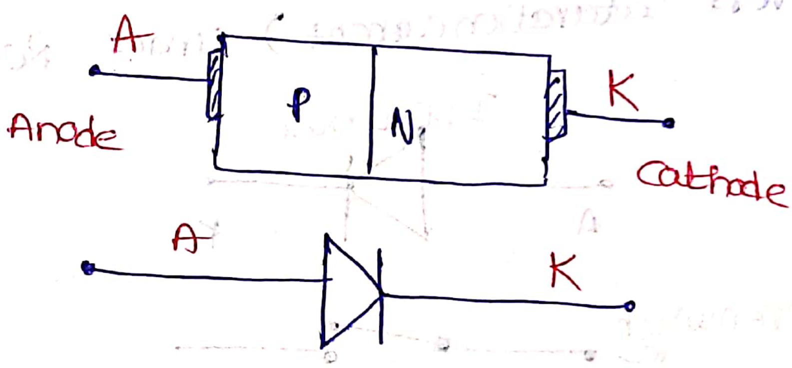
Diode-equivalent models:

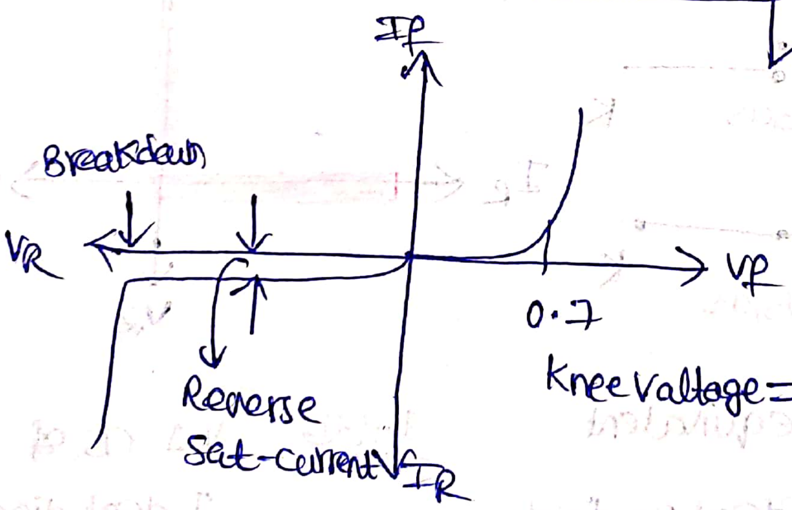
⇒ Resistor is a ~~non~~ Linear device because the graph of its current versus voltage is a straight line But diode is a Non-Linear device because the graph of its current versus voltage is not a Straight line.

⇒ when the Diode Voltage is less than the Barrier Potential, the diode current is small.

when the Diode Voltage exceeds the Barrier Potential, the diode current increases rapidly.

Diode symbol:





⇒ In F.B, the diode conducts after Knee voltage "0.7" in Si & In R.B the Reverse Sat current is Produced which is very low

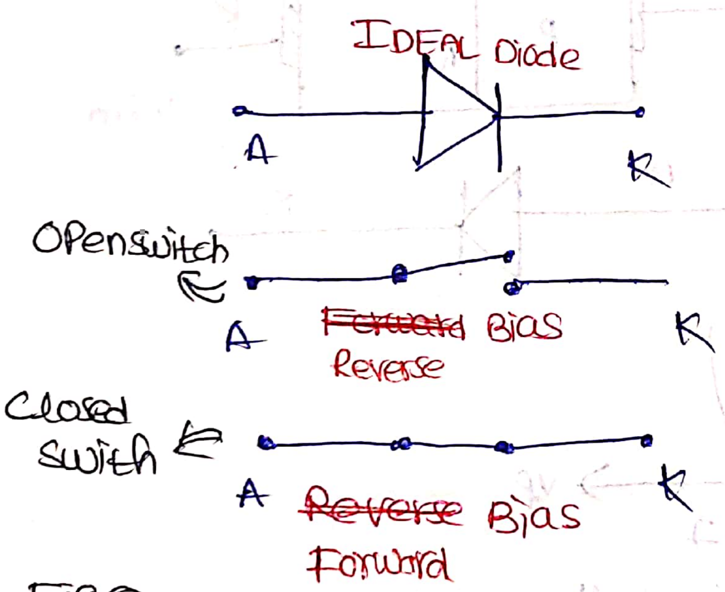
F.B ⇒ High current ⇒ So Acts as a closed switch after Barrier potential "0.7" practically

R.B ⇒ very very low current ⇒ Acts as an open switch.

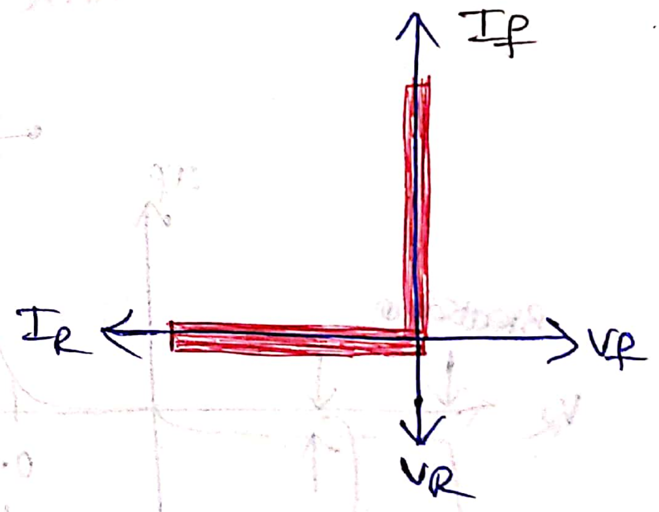
Diode eq. models

(I) The Ideal Diode model:

The Ideal diode conducts Even for a small Forward Biased Voltage ≃ 0V FB That means In Forward Bias the diode acts as a perfect conductor (Zero resistance ⇒ No Barrier Potential) and acts as a perfect insulator (Infinite Resistance ⇒ No Reverse Saturation current) under Reverse Bias condition



Fig(a) Switching on equivalent CKt of Ideal pn-diode



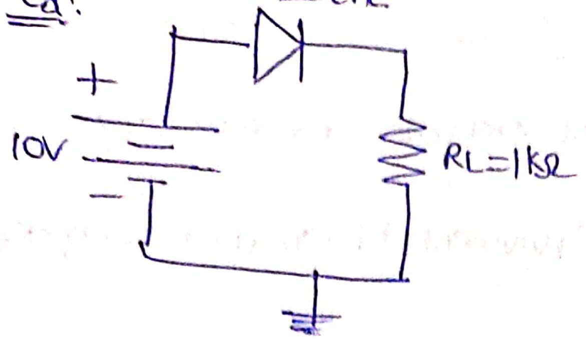
Fig(b): V-I C/S of Ideal diode

⇒ In F.B: Acts as "Closed switch" (conducts current)

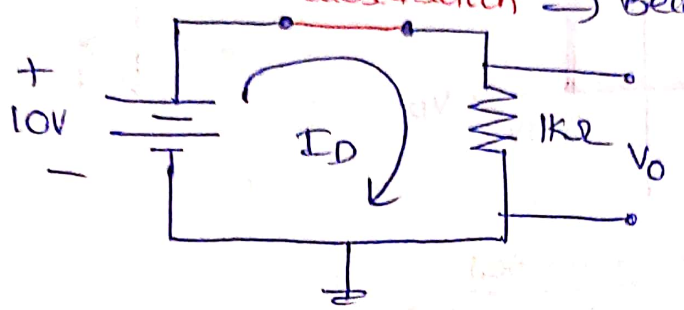
In R.B: Acts as "Open switch" (No current)

Scanned by CamScanner

⇒ ex:



Closed switch ⇒ Becoz the diode is F.B



$I_D = \frac{10}{1k\Omega} \Rightarrow 10mA$, $V_o = I_D \cdot R_L$

$V_o = 10mA \times 1k\Omega$

$\boxed{V_o = 10V}$ No loss due to Ideal diode

Characteristics of Ideal diode

⇒ No Builtin Potential $(V_{bi}) = 0$

⇒ No Reverse Saturation current $(I_0 = 0)$

⇒ No Internal Resistance

Use!

⇒ The Ideal approximation circuit is used always in "TROUBLE SHOOTING" & "For quick analysis" But to get more accurate value for load current & Load voltage we are going for Second approximation ckt

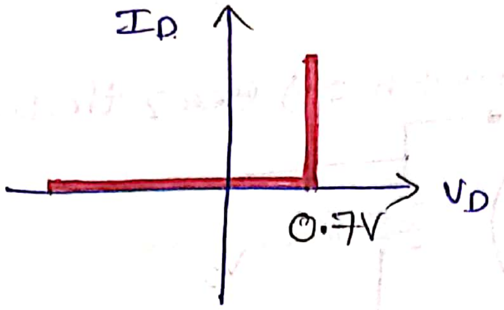
[TROUBLE SHOOTING: To Find Out the Problem in a ckt i.e. to know whether the diode is ON (or) not (or) else working (or) not, There is no need to measure the Builtin Potential and all]

II

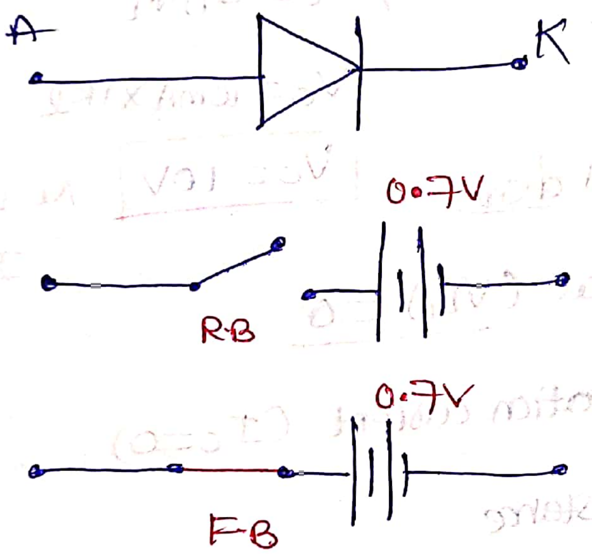
⇒ Practical equivalent circuits

⇒ The practical equivalent ckts are again two types

① Technical Analysis equivalent ckt (or) practical eq ckt



Fig@ V-I c/s of practical eq-ckt

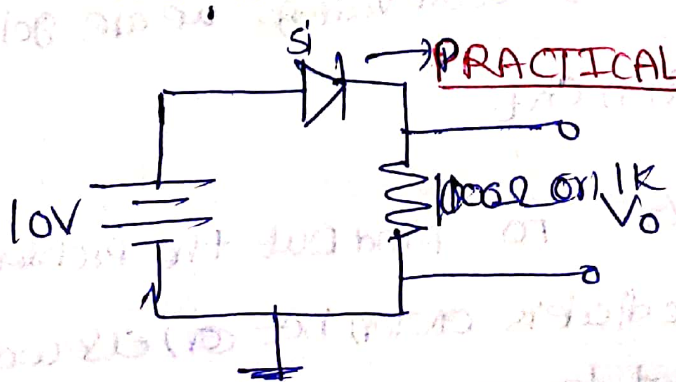


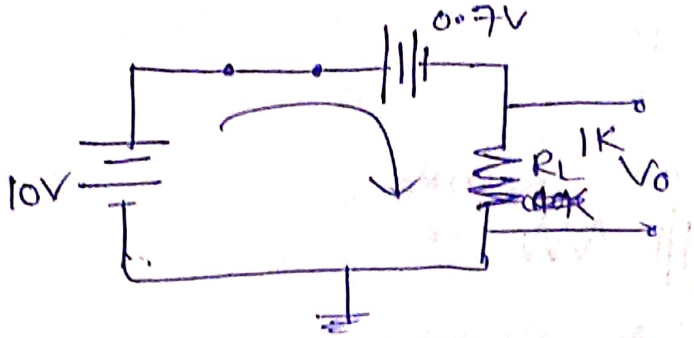
$\boxed{V_D = 0.7V}$

Uses: used for technical analysis in Technical level.

Here the Resistance due to crystal is neglected. i.e Bulk resistance (or) Diode Resistance is neglected.

eg:





$$-10 + 0.7 + I_L R_L = 0$$

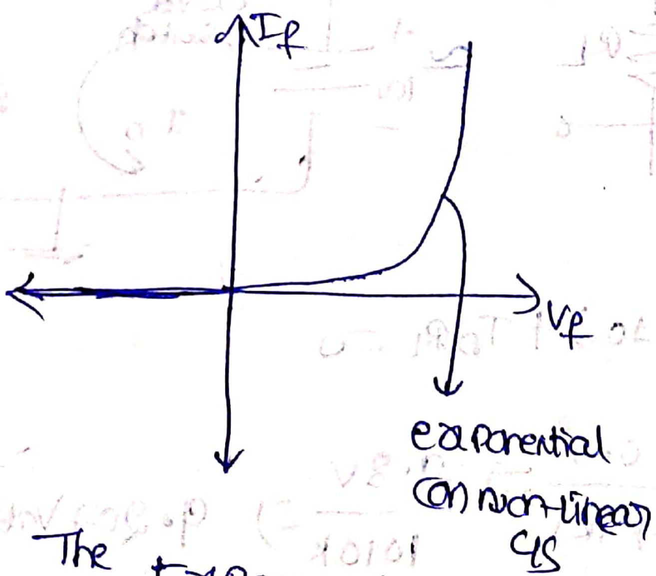
$$I_D = I_L = \frac{10 - 0.7}{R_L} \Rightarrow \frac{9.3}{1K} \Rightarrow 9.3mA$$

$$V_0 = I_L R_L \Rightarrow 9.3mA \times 1K \Rightarrow 9.3V$$

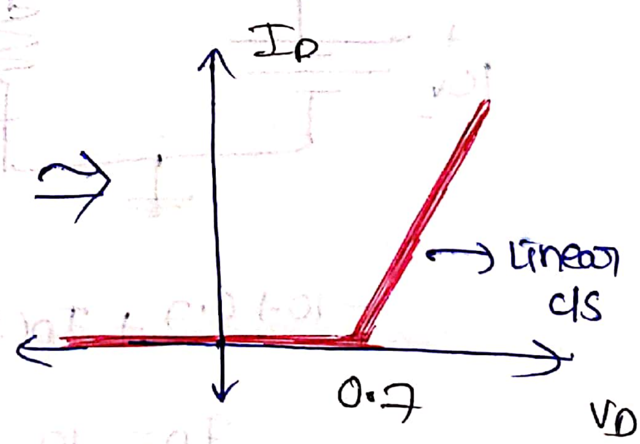
III Piecewise-Linear equivalent circuit

⇒ To get the exact & accurate values we are going for piece-wise linear eq. ckt

The non-linearity in VI c/s of the Diode is considered as a Linear VI c/s

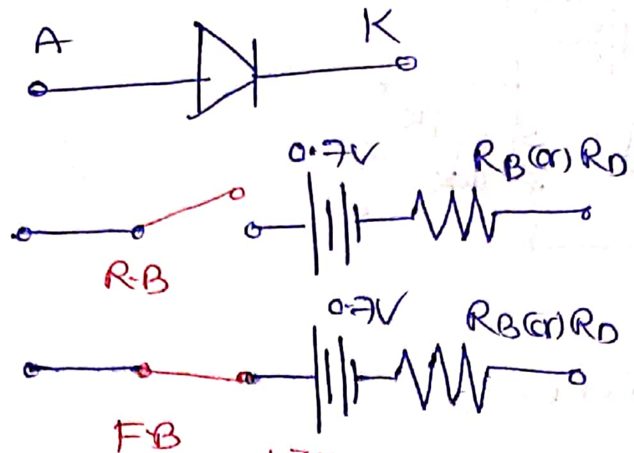


⇒



The Exponential is Non-Linear Function, For exact analysis we are going for Linear Analysis

⇒



$$\boxed{V_D = 0.7V + I_D R_D}$$

Eg: Piece-wise eq. ckts

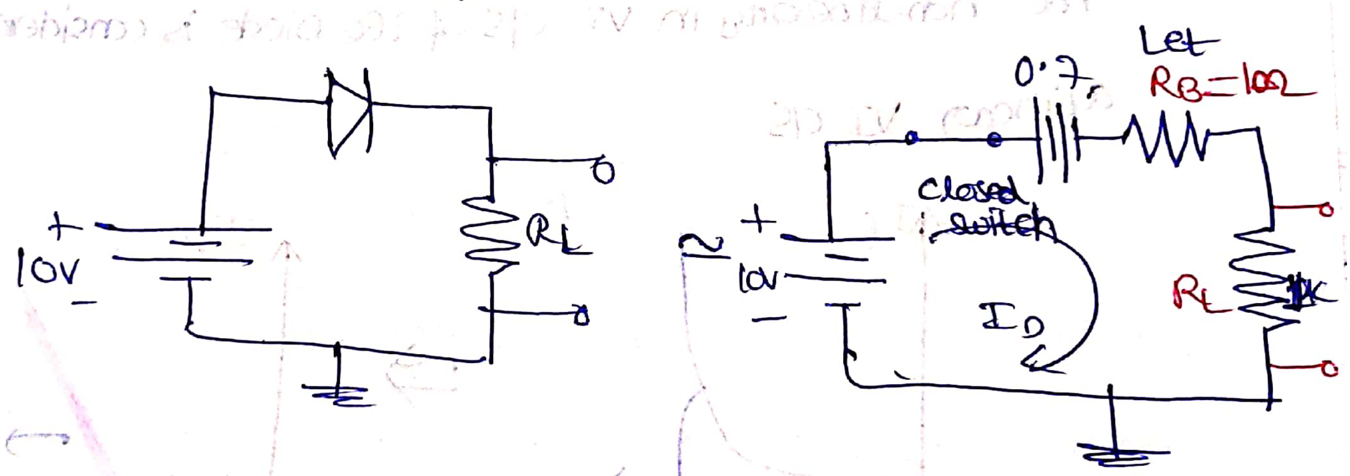
R_B (or) R_D ⇒ Diode Resistance (or) Bulk Resistance

Bulk Resistance (or) Diode Resistance

It is not specified by the manufacturer in the Data Sheet

So to calculate Bulk Resistance need to know the VI c/s

$$R_B = R_D = \frac{\Delta V}{\Delta I} = \text{Dynamic Resistance} = R_D$$



$$-10 + 0.7 + I_D(10) + I_D R_L = 0$$

$$I_D = \frac{10 - 0.7}{(10 + 1K)} \Rightarrow \frac{9.3V}{1010K} \Rightarrow 9.207 \text{ Volts}$$

Uses:

⇒ For High level (or) Engineering level analysis

⇒ to get the exact & Accurate Values

Exact & Accurate Value

Diode Resistance

① Static Resistance:

The Ratio of voltage to the current at any point on the volt-ampere characteristics of Diode (when DC i/p is given)

$$\boxed{R_{static} = \frac{V}{I}\Big|_{\text{at any point on V-I c/s}}}$$

② Dynamic Resistance:

The Reciprocal of the slope of the volt-ampere characteristics

$$r \equiv \frac{1}{(dI/dV)} = \frac{dV}{dI}$$

It is not constant, But depends on the operating voltage

$$r = \frac{1}{(dI/dV)} = \frac{1}{g} = \frac{dV}{dI}$$

$$\frac{dI}{dV} = \frac{d}{dV}\left(I_o\left(e^{V/\eta V_T} - 1\right)\right) = I_o e^{V/\eta V_T} \times \frac{1}{\eta V_T} \quad -①$$

$$\frac{dI}{dV} = \frac{I_o e^{V/\eta V_T}}{\eta V_T}$$

$$\frac{dI}{dV} = \frac{I + I_o}{\eta V_T}$$

$I >> I_o$ so neglect "I_o"

$$\frac{dI}{dV} = \frac{I}{\eta V_T}$$

$$r = \frac{1}{(dI/dV)} = \frac{1}{(I/\eta V_T)} = \frac{\eta V_T}{I}$$

$$\boxed{r = \frac{\eta V_T}{I}}$$ $\eta = 1$, For Ge

$\eta = 2$, For "Si"

Diffusion capacitance (C_D):

⇒ Diffusion capacitance is the capacitance offered by the pn junction in Forward Bias (It is formed due to the charge diffusion so called Diffusion capacitance)

⇒ The change in charge w.r.to change in voltage, such a capacitance exists when P-n junction diode is in Forward Bias, then it is called Diffusion capacitance.

(In Forward Bias, Diffusion capacitance dominates the Depletion capacitance)

$$C_D = \frac{dQ}{dV}$$

C_D ranges from nF to μF

$$I = \frac{Q}{t} \qquad dI = dQ/dt \qquad (dt = \tau)$$

$$dQ = \tau \cdot dI$$

$$C_D = \tau \cdot \frac{dI}{dV} \qquad \left(\because r = \frac{dV}{dI}\right)$$

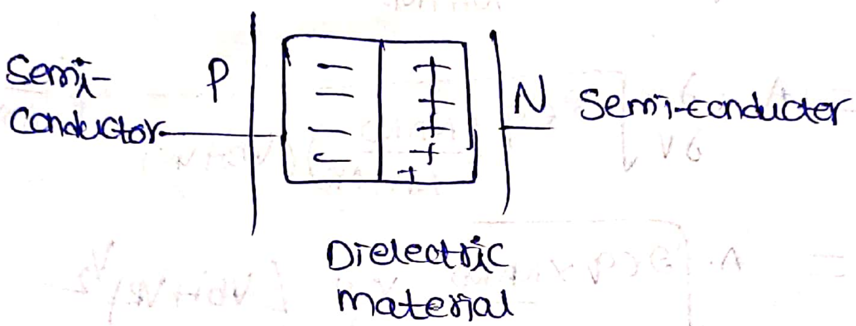
$$C_D = \tau \cdot \left(\frac{1}{r}\right)$$

$$\boxed{C_D = \frac{\tau}{\left(\frac{\eta V_T}{I}\right)} \Rightarrow \frac{\tau I}{\eta V_T}}$$

⇒ Transition capacitance:

change in charge w.r.to change in voltage, which exists in a P-n junction diode. when it is in Reverse Bias it is called Transition capacitance

Transition capacitance is the capacitance offered by the P-n junction diode when it is in Reverse Bias



$$C_T = \frac{dQ}{dV}$$

$$Q = q \cdot N_A \cdot x_p \cdot A \qquad x_p = \frac{N_D w}{N_A + N_D}$$

$$Q = q \cdot N_A \cdot A \left[\frac{N_D w}{N_A + N_D}\right]$$

$$= q \cdot N_A \cdot A \left(\frac{N_D}{N_A + N_D}\right) \sqrt{\frac{2\epsilon}{q}(V_{bi} + V_R)\left(\frac{1}{N_A} + \frac{1}{N_D}\right)}$$

$$\Rightarrow Aq \frac{N_A \cdot N_D}{N_A + N_D} \sqrt{\frac{2\epsilon}{q}(V_{bi} + V_R)\left(\frac{N_A + N_D}{N_A \cdot N_D}\right)}$$

$$\Rightarrow Aq \sqrt{\left(\frac{N_A \cdot N_D}{\cancel{N_A + N_D}}\right)^2 \times (V_{bi} + V_R)\left(\frac{\cancel{N_A + N_D}}{\cancel{N_A \cdot N_D}}\right) \times \frac{2\epsilon}{q}}$$

$$= Aq\sqrt{\left(\frac{N_A \cdot N_D}{N_A+N_D}\right)(V_{bi}+V_R)\times\frac{2\epsilon}{q}}$$

$$= A\sqrt{q^2\times\frac{N_A \cdot N_D}{N_A+N_D}(V_{bi}+V_R)\times\frac{2\epsilon}{\cancel{q}}}$$

$$= A\sqrt{2\epsilon q\left(\frac{N_A N_D}{N_A+N_D}\right)(V_{bi}+V_R)}$$

$$Q = A\sqrt{2\epsilon q\left(\frac{N_A N_D}{N_A+N_D}\right)(V_{bi}+V_R)}$$

$$C = \frac{dQ}{dV} = A\frac{\partial}{\partial V}\sqrt{2\epsilon q\left(\frac{N_A N_D}{N_A+N_D}\right)(V_{bi}+V_R)}$$ $\left(\frac{\partial}{\partial x}(\sqrt{x}) = \frac{1}{2\sqrt{x}} = \frac{1}{2}x^{-1/2}\right)$

$$C_T = A\cdot\sqrt{2\epsilon q\times\frac{N_A N_D}{N_A+N_D}}\times\frac{\partial}{\partial V}(V_{bi}+V_R)^{1/2}$$

$$C_T = A\sqrt{2\epsilon q\times\frac{N_A N_D}{N_A+N_D}}\times\frac{1}{2}(V_{bi}+V_R)\left(0+\frac{\partial V_R}{\partial V_R}\right)$$

V_R becoz the Transition capacitance is obtained in R.B

$$C_T = A\cdot\sqrt{2\epsilon q\times\frac{N_A N_D}{N_A+N_D}}\times\frac{1}{2}(V_{bi}+V_R)^{-1/2}$$

$$= A\sqrt{\frac{\cancel{2}\epsilon q}{4/2}\times\left(\frac{N_A N_D}{N_A+N_D}\right)} = A\sqrt{\frac{\epsilon q}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)} \rightarrow A$$

$$(\cancel{\tfrac{1}{2}}(V_{bi}+V_R))^{-1/2}$$

$$C_T = A\sqrt{\frac{\epsilon^2 \,(N_A N_D)}{\left(\frac{2\epsilon}{q}\right)(N_A + N_D)}}\left(\frac{1}{2}\frac{1}{\sqrt{V_{bi}+V_R}}\right)$$

$$\Rightarrow A\epsilon\sqrt{\frac{1}{\left(\frac{2\epsilon}{q}\right)\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}+V_R)}}$$

$$\Rightarrow \frac{A\epsilon}{\sqrt{\frac{2\epsilon}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)(V_{bi}+V_R)}}$$

$$\boxed{C_T \Rightarrow \frac{A\epsilon}{W}}$$

&

From eq (A)

$$C_T = A\sqrt{\frac{\epsilon q}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)}\;\frac{1}{2}(V_{bi}+V_R)^{-1/2}$$

$$C_T = A\sqrt{\frac{\epsilon q}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)}\;(V_{bi})^{-1/2}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

$$C_T = A\sqrt{\frac{\epsilon q}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)\times\frac{1}{V_{bi}}}\;\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

$$C_T = \underbrace{A\sqrt{\frac{\epsilon q}{2}\left(\frac{N_A N_D}{N_A+N_D}\right)\times\frac{1}{V_{bi}}}}_{C_{T0}}\;\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2}$$

GATE

$$\boxed{C_T = C_{T0}\left(1+\frac{V_R}{V_{bi}}\right)^{-1/2} \quad \text{(or)} \quad \frac{C_{T0}}{\left(1+\frac{V_R}{V_{bi}}\right)^{1/2}}}$$

$\Rightarrow$

$$\boxed{C_T = \frac{C_{T0}}{\left(1+\frac{V_{bi}}{V_R}\right)^{1/2}}}$$

$\Rightarrow$ For Step-graded Junction (or) abrupt junction

$$\boxed{C_T = \frac{C_{T0}}{\left(1+\frac{V_{bi}}{V_R}\right)^{1/3}}}$$

$\Rightarrow$ For Linearly graded junction

So

$$\boxed{C_T = \frac{C_{T0}}{\left(1+\frac{V_{bi}}{V_R}\right)^{n}}}$$

$n = 1/2 \Rightarrow$ Step graded junction

$n = 1/2 \Rightarrow$ Linearly graded junction

Zener-Diode: Zener diode is a heavily doped diode which is specially designed to operate in Reverse Bias condition (or) breakdown Region

⇒ Doping concentration in zener diode is 1 in 10^5 atoms/cm3

Doping concentration of P-N Diode is 1 in 10^8 atoms/cm3

By ⇑ Doping conc. the V_{bi} is ⇑ but In zener diode the cutin voltage when it is F.B is 0.7, which is same in P-N Diode

$$V_{bi} = \frac{KT}{q}\left(\ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)\right)$$

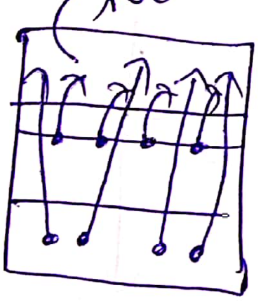
If N_A & N_D ⇑ in zener diode then

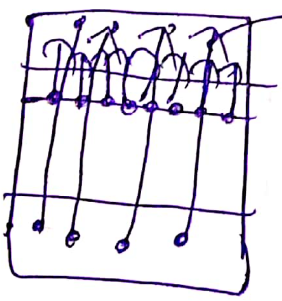
n_i^2 ⇑ ie $N_C \cdot N_V$ ⇑

$$n_i^2 = N_C N_V e^{-E_{g0}/KT}$$

when N_A & N_D are low or moderate

N_C





→ N_C ⇑, when doping concentration ⇑ similarly in P-type N_V ⇑, when we ⇑ N_A

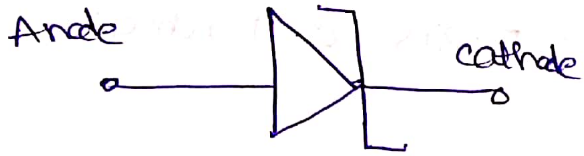
$$\boxed{V_{bi} = \frac{KT}{q}\ln\left(\frac{(N_A \cdot N_D)⇑}{⇑(N_C \cdot N_V)e^{-E_g/KT}}\right)}$$

Due to this the Result is increase of Both Parameters is Compensated.

⇒ So $V_{bi} = 0.7$ Volts for PN Diode

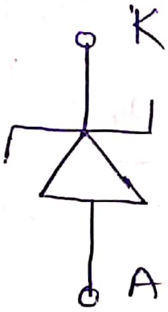
⇒ Zener diode always operates in Reverse Biased Breakdown Region

Schematic Symbol

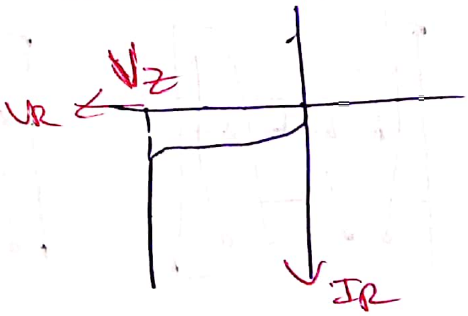


⇒ This symbol "Z" indicates scientist Zener who invented Zener diode [⇒ The VI c/s of Zener diode is a coincidence to the symbol]

⇒ Zener diode always operates in Reverse Biased breakdown Region.

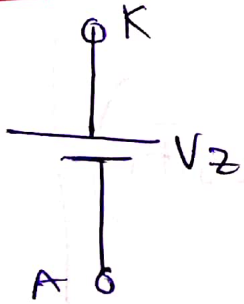


Ideal V-I C/s

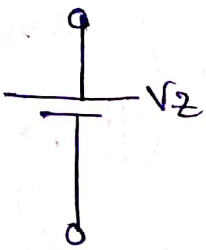


⇒ Zener diode equivalent ckt:

Ideal:



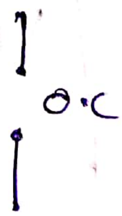
Zener diode ON



$V \geq V_Z$

⇒ ON

Zener Diode OFF



$V < V_Z$

⇒ OFF

Zener Diode - Zener diode is Heavily doped. Becoz of heavy doping ~~High~~ the width of depletion Region ⇑

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

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

As N_A & N_D ⇑ the width W ⇓

$$\Uparrow E = \frac{V}{W\Downarrow}$$

⇒ Due to high electric field the sufficient energy to disturb the bonds (or) direct rupture of Bonds becoz of existence of strong electric field at the junction even for low voltages

⇒ For a specified voltage, the high electric field will breaks the covalent bonds and a rapid increase in current takes place. The voltage at which Breaking of covalent Bonds and a sudden (or) rapid increase in current takes place is called "Breakdown Voltage" The Breakdown takes place becoz of the "Field Ionization" i.e due to high electric field.

⇒ The Breakdown Phenomena in zener diode is due to both Zener & Avalanche Breakdown. But in pn diode the Breakdown is due to Avalanche only.

Zener Breakdown – heavily doped zener diode

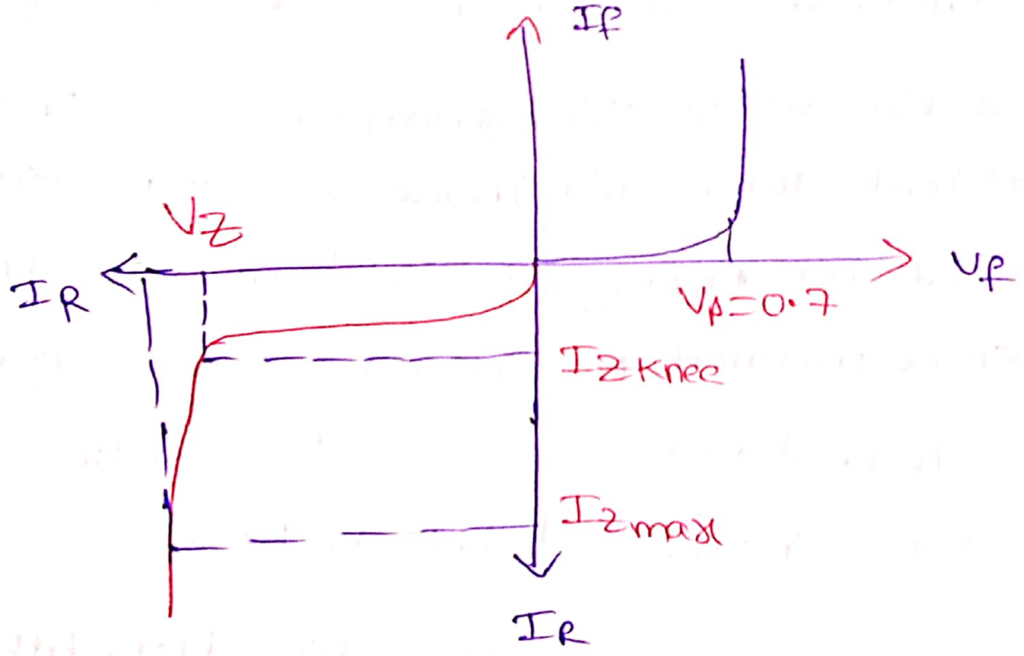
Avalanche Breakdown – lightly doped zener diode.

⇒ For heavily doped Zener diodes the Field is high (due to low width) so no need to apply large voltages so $V_Z < 6V$

⇒ For lightly doped Zener diodes, the Field is less becoz of high width so we need to apply large Voltages so $V_Z > 6V$ so Avalanche Breakdown occurs due to acquiring high Voltages & high K.E & breaks the covalent Bonds.

VI c/s of zener diode:

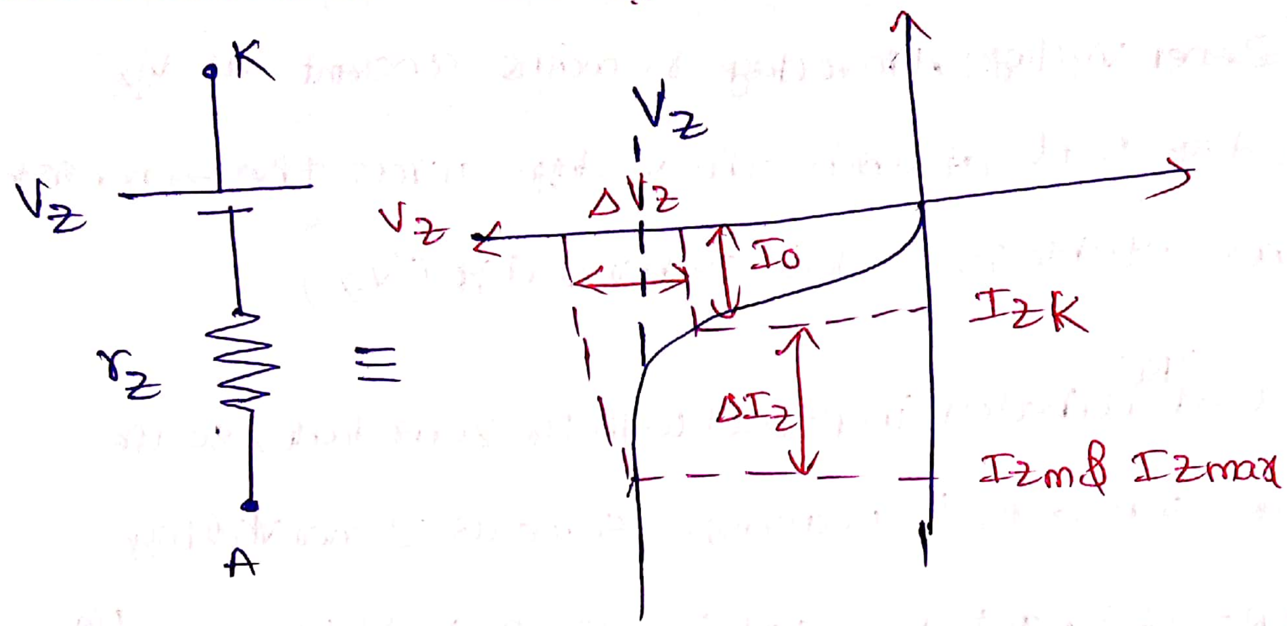
⇒



⇒ The Forward c/s are same as PN diode, But the Reverse c/s are different. The minimum current is $I_{Z\,knee}$ & the maximum current is $I_{Z\,max}$ which is indicated in the above diagram.

$$\boxed{P_{Z\,max} = V_Z \cdot I_{Z\,max}}$$

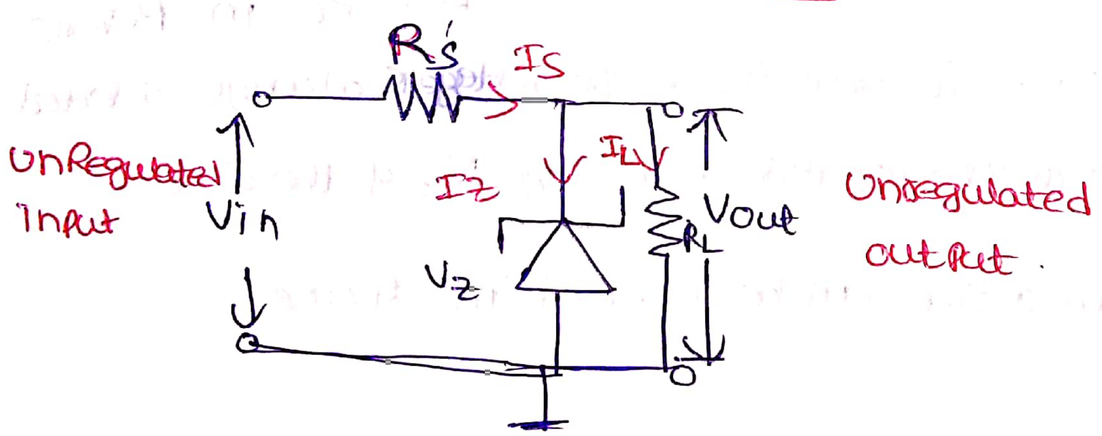
Practical zener diode eq. ckt:



$$I_{ZK} \le I_Z < I_{Zm}$$

$$r_Z = \frac{\Delta V_Z}{\Delta I_Z}$$: zener dynamic Resistance

Zener diode acts as a regulator:



⇒ A zener diode is always operated in its Reverse Biased condition

A voltage regulator circuit can be designed using a zener-diode to maintain a constant DC output voltage across the load inspite of variations in the input voltage (or) changes in the load current

⇒ when Reverse voltage applied across the zener diode exceeds the ~~that~~ Zener Voltage, the voltage remains constant at "V_Z"

The Voltage point at which the voltage across the zener diode becomes stable is called zener voltage (V_Z)

⇒ The load "R_L" connected in parallel with the zener diode, so the voltage across "R_L", is always same as Zener Voltage ($V_R = V_Z$). For a constant V_Z (or) output voltage the current changes from $(I_Z)_{knee}$ to $(I_Z)_{max}$. The voltage is constant so called Voltage Regulator.

⇒ The voltage Regulator consists of Resister R_S & I/P V_S with zener connected in parallel with the Load R_L in Reverse Biased condition. The stabilized o/p voltage is always selected to be same as the breakdown voltage V_Z of the diode.

The Regulation action can be observed in 4 cases

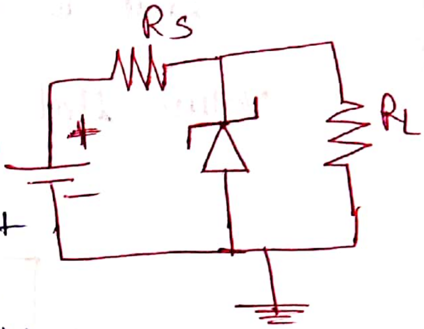
case(i) :

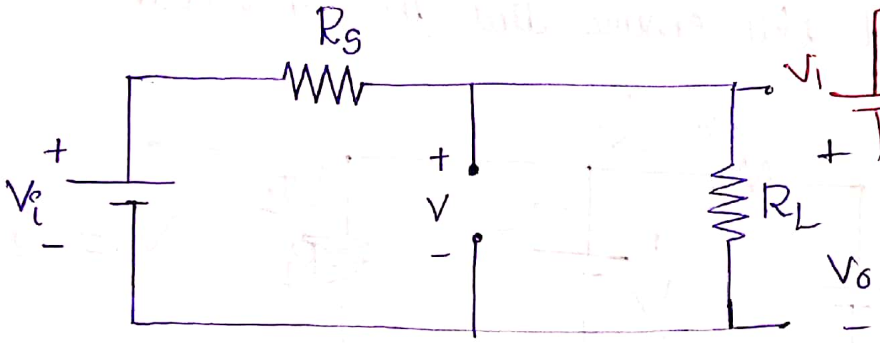
1. V_i (Input) & R_L (Load) & R_S Fixed (V_i, R_L)
2. V_i Fixed, R_L variable (V_i, R_L?)
3. R_L Fixed, variable V_i (V_i?, R_L)
4. Both V_i & R_L are variable (V_i?, R_L?)

Case (i): V_i and R_L and R_S fixed:

In this type the analysis can be divided into two steps

(a) Determine the state of Zener diode by removing it from the network and calculate the voltage across the resulting open circuit.





$$V = \frac{V_i \cdot R_L}{R_S + R_L}$$

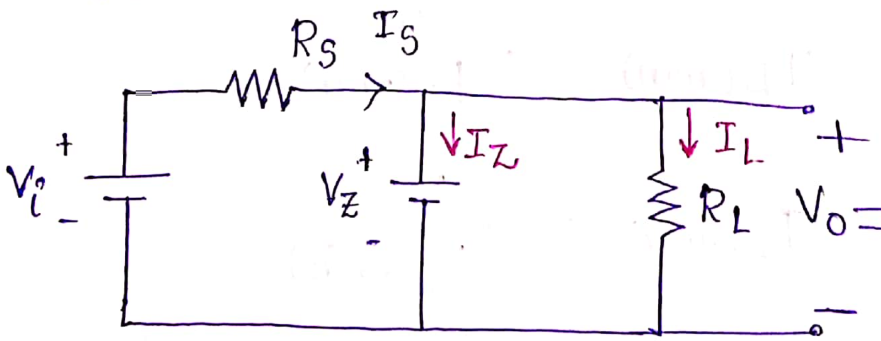
(To know the maximum voltage across the diode open ckt the diode)

If $V \geq V_Z$ Zener diode is ON Replaced with "V_Z"

If $V < V_Z$ Zener diode is OFF (Open circuit)

(b) Substitute the appropriate equivalent circuit.

Diode is ON:



$V_o = V_Z$ Regulated (or) Constant Voltage

$$I_S = I_Z + I_L$$

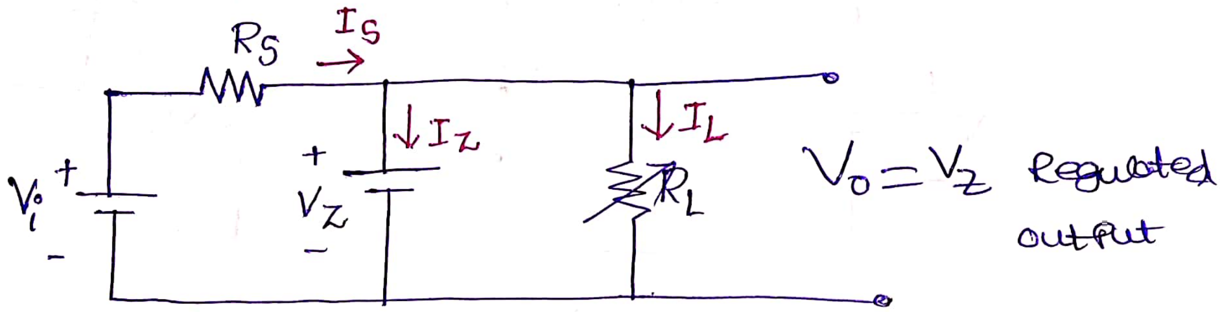
$$I_S = \frac{V_i - V_Z}{R_S}$$

The power dissipated by the Zener diode is

$$P_Z = V_Z \cdot I_{Z(max)}$$

Case (ii) Fixed V_i, R_S and Variable R_L

Due to offset voltage V_Z, there is a specific change of values that will ensure that the Zener diode is in ON state



$$I_S = I_Z + I_L$$

I_S is Fixed since "V_i" is fixed

$$I_S = I_{Z(min)} + I_{L(max)}$$

$$I_S = I_{Z(max)} + I_{L(min)}$$

Here $V_Z = V_L$ is fixed, V_i, R_S is fixed So I_S is also fixed

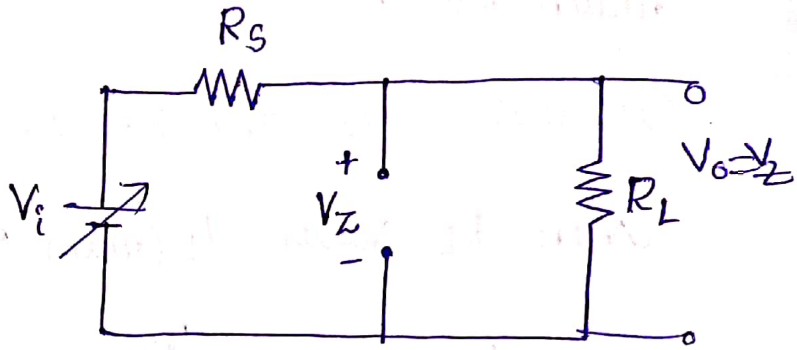
$$\therefore \quad I_{L(min)} = \frac{V_L}{R_{L(max)}}$$

$$I_{L(max)} = \frac{V_L}{R_{L(min)}}$$

$I_{Z(min)}$ and $I_{Z(max)}$ are given in the Manufacturer Datasheet.

Case (iii): Fixed R_L and R_S; Variable V_i

From the circuit



$$V_L = V_Z = \frac{V_i \cdot R_L}{R_L + R_S}$$

Here R_L and R_S are fixed,

∴ V_i will decide whether the diode is at break down (or) not.

So $$V_{i\,(min)} = \frac{R_S + R_L}{R_L} \cdot V_Z$$

If we does not provide this voltage then the diode is in OFF condition.

But V_i (max) depends on the Zener diode's power dissipation capabilities

$$I_{S\,(min)} = \frac{V_{i\,(min)} - V_Z}{R_S} = I_{Z\,(min)} + I_L$$

$$I_{S\,(max)} = \frac{V_{i\,(max)} - V_Z}{R_S} = I_{Z\,(max)} + I_L$$

If R_S is variable

$$(I_S)_{min} = \frac{V_{i(min)} - V_Z}{(R_S)_{max}}$$

$$(I_S)_{max} = \frac{V_{i(max)} - V_Z}{R_{S\,max}}$$

Here I_L is fixed, why because R_L is fixed

$$I_{S\,(max)} \geq I_{Z\,(max)} + I_L$$

If $I_{S\,(max)}$ value is not satisfy the above condition then the diode will damage, because it will not sustain that much current.

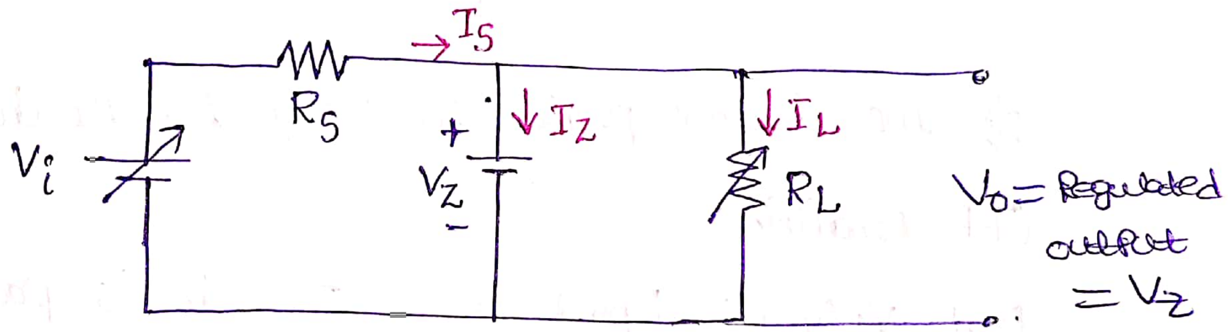
Case (iv) : V_i and R_L are Variable

When R_L varies $I_{L(max)}$ and $I_{L(min)}$ will occur

$$I_{L(max)} = \frac{V_Z}{R_{L(min)}}$$

$$I_{L(min)} = \frac{V_Z}{R_{L(max)}}$$

If V_i varies then I_S will vary



$$I_{S\,max} = \frac{V_{i\,(max)} - V_Z}{R_{S\,(min)}}$$

$$I_{S\,min} = \frac{V_{i\,(min)} - V_Z}{R_{S\,(max)}}$$

$$I_S \geq I_Z + I_L$$

$$\frac{V_i - V_Z}{R_S} \geq I_Z + I_L$$

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$$R_S \leq \frac{V_i - V_Z}{I_Z + I_L}$$

$$R_{S\,min} \leq \frac{V_{i\,max} - V_Z}{I_{S\,max}}$$

$$R_{S\,max} \leq \frac{V_{i\,min} - V_Z}{I_{S\,min}}$$

If $\underline{(R_L)_{max}}$ then $(I_L)_{min}$

when $(V_i)_{max} \Rightarrow (I_S)_{max} = I_{Z\,max} + I_{L\,min}$

when $(V_i)_{min} \Rightarrow (I_S)_{min} = (I_Z)_{min} + (I_L)_{min}$

If $\underline{(R_L)_{min}}$ then $(I_L)_{max}$

when $(V_i)_{max} \Rightarrow (I_S)_{max} = (I_Z)_{min} + I_{L(max)}$

when $(V_i)_{min} \Rightarrow (I_S)_{min} = (I_Z)_{min} + I_{L(max)}$

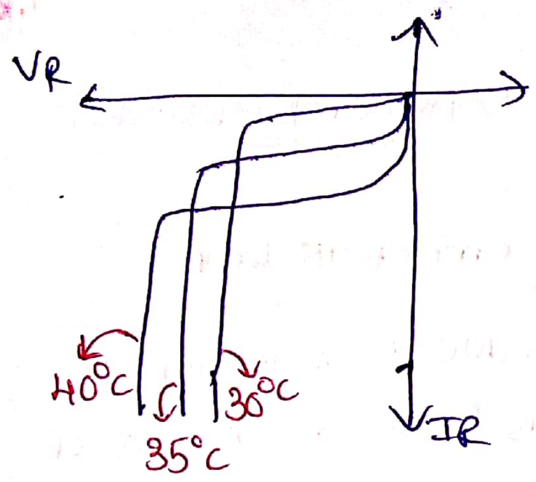
$\Rightarrow \quad (R_S)_{min} \leq \dfrac{V_{i\,max} - V_Z}{I_{Z\,max} + I_{L\,min}}$ when R_L is maximum

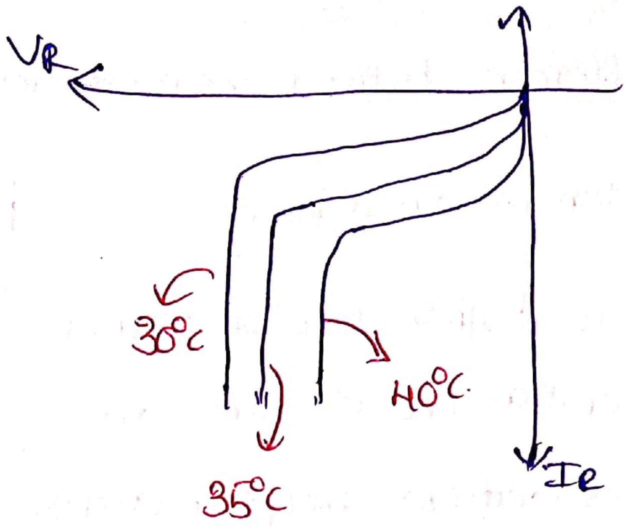
$\Rightarrow \quad (R_S)_{min} \leq \dfrac{V_{i\,max} - V_Z}{(I_Z)_{min} + (I_L)_{max}}$ R_L is minimum

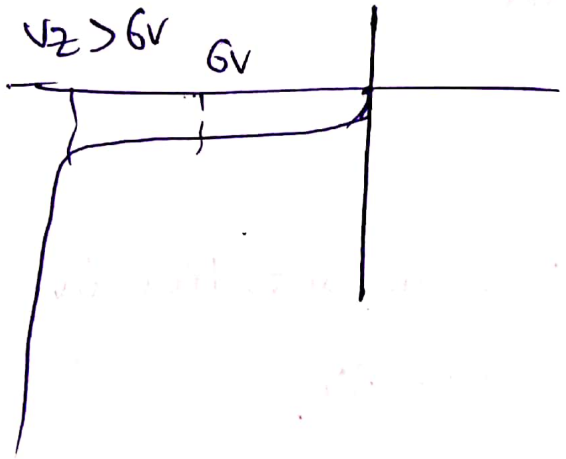
$\Rightarrow \quad (R_S)_{max} \leq \dfrac{V_{i\,min} - V_Z}{I_{Z\,min} + I_{L\,min}}$ when R_L is is maximum

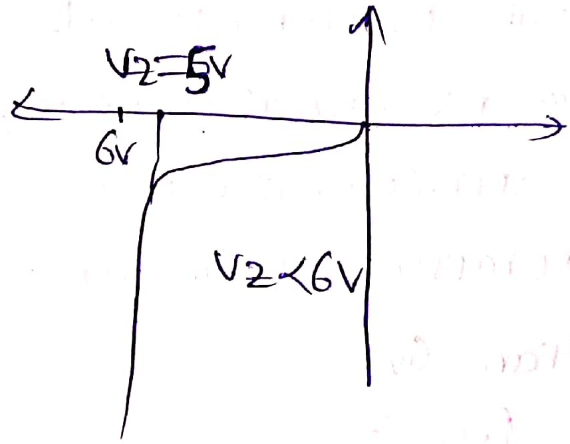
Difference between Zener Breakdown & Avalanch Breakdown

Avalanche Breakdown	Zener Breakdown
⇒ Due to high voltage (or) Thermal generation the electrons and holes acquires sufficient energy from the applied potential to produce new carriers by disturbing bonds. It is Cumulative Process	⇒ It is due to rupturing of Bonds becoz of existence of Strong electric Field. at the Junction.
⇒ It happens at greater than 6V $\boxed{V_Z > 6V}$	⇒ It occurs less than 6V $\boxed{V_Z < 6V}$
⇒ It is a cumulative process.	⇒ It is not a cumulative process
⇒ It happens due to collision of electrons with the Ions	⇒ It happens due to direct rupture of the bonds becoz of the existence of Strong electric Field at the Junction.
⇒ Low doping concentration.	⇒ High doping levels
⇒ It has +ve Temperature coefficient, i.e., As temp ↑↑ avalanche Breakdown voltage increases	⇒ Zener Breakdown voltage is having −ve temperature Coefficient. i.e., As temp ↑↑, Breakdown voltage decreases
⇒ It is formed due to "IMPACT IONIZation"	Zener Breakdown is due to "Field Ionization"









V-I c/s of Zener Diode