UNIT – I

Semiconductor Diode

PN junction diode, Current Equations, Energy band diagram, diffusion and drift Current densities, forward and reverse bias Characteristics, Transition and diffusion Capacitances, Switching Characteristics, Breakdown in PN junction diodes, Applications of PN diode.

PN Junction Diode

→ In a piece of semiconductor material, if one half is doped by P-type impurity and the other half is doped by N-type impurity, a PN junction is formed. Such a PN junction forms a very useful device and is called a Semiconductor diode, PN junction diode or simply a crystal diode.

→ Special fabrication techniques are used to prepare PN junctions.

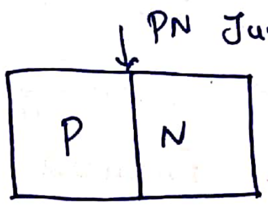
Formation of depletion layer in a PN junction :-

→ The P-region has majority holes and negatively charged impurity atoms called acceptor ions.

→ The N-region has majority free electrons and positively charged impurity atoms called donor ions.

→ When PN is formed, the holes from the P-region diffuse to the N-region where they combine with the free electrons.

→ The free electrons from the N-region diffuse to the P-region where they combine with the holes.



Theory of PN Junction diode

PN Junction diode in Equilibrium with no applied voltage:

→ The N-type material has high concentration of free electrons while P-type material has high concentration of holes. Therefore, at the junction there is a tendency for the free electrons to diffuse over to the P-side and holes to the N-side. This process is called diffusion.

→ As the free electrons move across the junction from N-type to P-type, the donor ions become positively charged. Hence a positive charge is built on the N-side of the junction. Similarly, a net negative charge is established on the P-side of the junction.

Potential barrier (or) Junction barrier (or) Diffusion potential (or) Contact Potential $\Big\} : V_0$

The negative charge on the P-side prevents further diffusion of electrons into the P-side. Similarly the net +ve charge on the N-side repels the hole crossing from P-side to N-side. Thus a barrier is set up near the junction which prevents further movement of charge carriers (i.e.) electrons & holes. As a consequence of the induced electric field across the depletion layer, an electrostatic potential difference is established between P and N-regions, which is called the potential barrier, junction barrier, diffusion potential (or) Contact potential V_0.

Note: The magnitude of the Contact potential V_0 varies with doping levels and temperature.

V_0 is 0.3V for germanium.

0.72V for silicon.

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BIASING:-

Applying external supply voltage to a PN junction diode is called biasing.

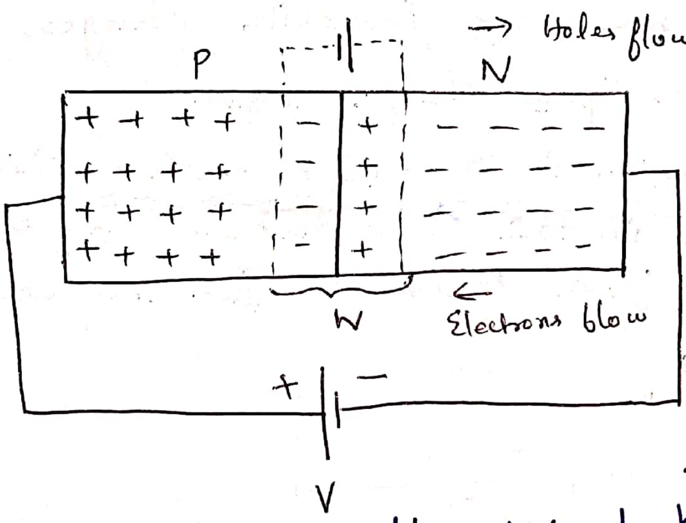
Biasing can be applied in 2 ways.

1) Forward biasing
2) Reverse biasing.

Forward biasing:-

→ When positive terminal of the battery is connected to the P-type and negative terminal to the N-type of the PN junction diode, the bias applied is known as Forward bias.

Operation:-



PN junction under FB.

W → Depletion width.

→ Under the FB Condition, the applied positive potential needs the holes in p-type region so that the holes move towards the junction and the applied negative potential repels the electrons in the N-type region and the electrons move towards the junction.

→ Eventually, when the applied potential is more than the internal barrier potential the depletion region and internal potential barrier disappear.

VI characteristics of a diode under FB:

→ Under FB condition, the V-I characteristics of a PN junction diode is shown below.

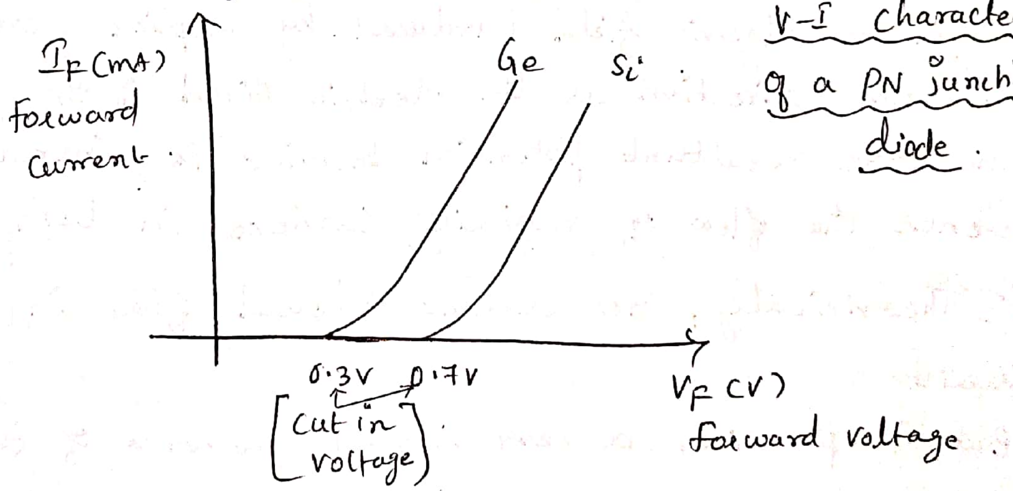
→ As ~~Vf is~~ the forward Voltage V_F is increased, for $V_F < V_0$ ($V_0 \Rightarrow$ Barrier potential), the forward Current I_F is almost zero. The potential barrier prevents the carriers to move across the depletion region.

→ For $V_F > V_0$, the ~~barrier~~ potential barrier Completely disappears and hence the holes and electrons cross the junction, resulting in relatively large current flow in the external circuit.

→ The external voltage after which Current starts to increase is called the cut-in voltage.

The cut-in voltage for Germanium = 0.3V.

The cut-in Voltage for Silicon = 0.7V.



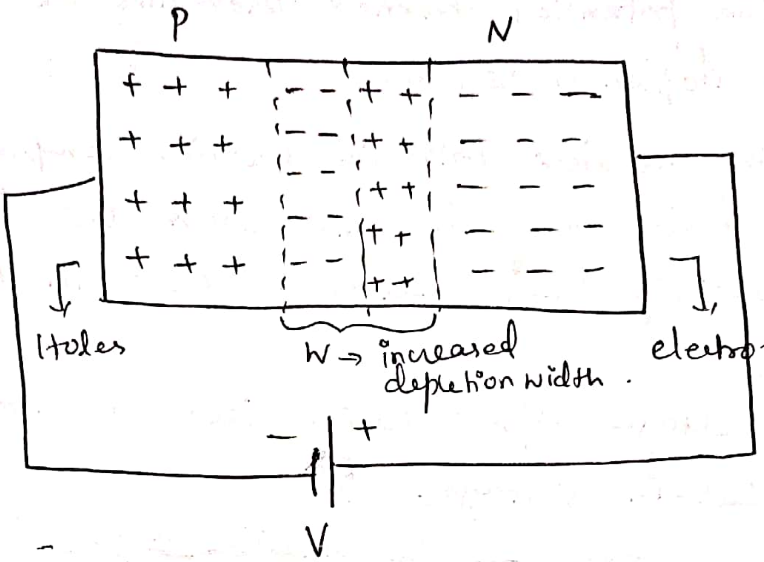
V-I characteristics of a PN junction diode.

Reverse Biasing:

→ When the negative terminal of the battery is connected to the P-type and positive terminal of the battery to the N-type of the PN junction, the bias applied is known as reverse bias.

Operation:-

→ Under applied reverse bias, holes in the P-side [majority carriers] move towards -ve terminal of the ~~barry~~ battery and electrons in the N-side [majority carriers] are attracted towards the positive terminal of the battery.



→ Hence, the width of the depletion region increases.

→ Thus, the electric field produced by applied reverse bias, is in the same direction as the electric field of the potential barrier. Hence, the resultant potential barrier is increased which prevents the flow of majority carriers in both b directions.

→ ∴ Theoritically, no current should flow in the external circuit.

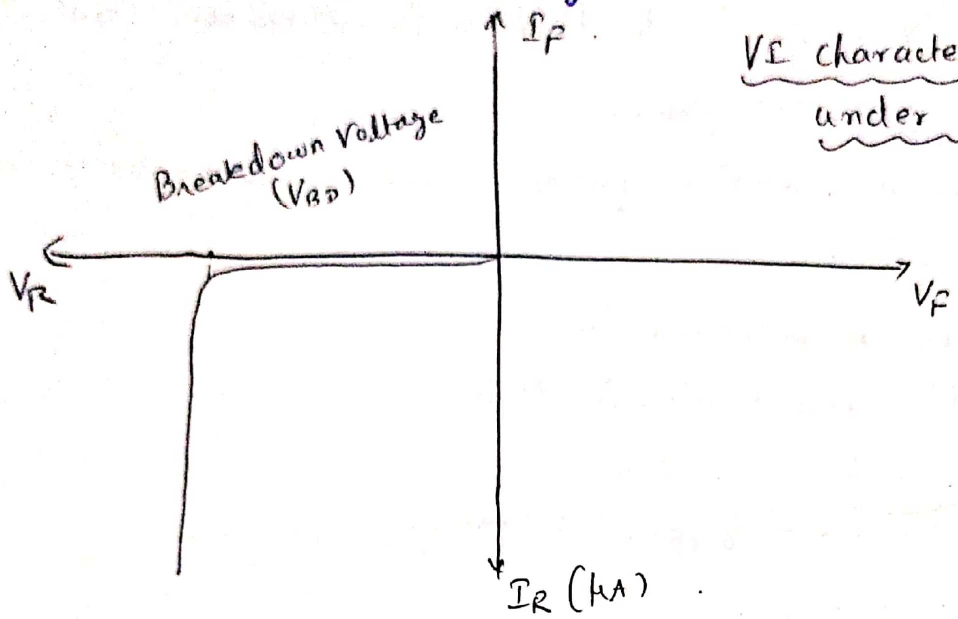
→ But in practice, a very small current of the order of a few microamperes flows due to minority carriers. (in the order of μA's)

VI Characteristics of a diode under RB:-

→ Under the reverse bias condition, the thermally generated holes in the P-region are attracted towards the negative terminal of the battery and the electrons in the N-region are attracted towards the positive terminal of the battery. Consequently, the minority carriers, electrons in the P-region and holes in the

N-region, wander over to the Junction and flow towards their Majority Carrier side giving rise to a small reverse Current. This current is known as Reverse Saturation Current I_o. The magnitude of reverse Saturation Current mainly depends upon Junction temperature because the major source of minority carriers is thermally broken Covalent bonds.

VI characteristics of PN diode under RB



→ For large applied reverse bias, the free electrons from the N-type moving towards the positive terminal of the battery acquire sufficient energy to move with high velocity to dislodge Valence electrons from semiconductor atoms in the Crystal.

→ These newly liberated electrons, in turn, acquire sufficient energy to dislodge other parent electrons.

→ Thus, a large number of free electrons are formed which is commonly called as an avalanche of free electrons.

→ This leads to the breakdown of the junction leading to very large reverse Current.

→ The reverse Voltage at which the junction breakdown occurs is known as Breakdown Voltage, V_{BD}.

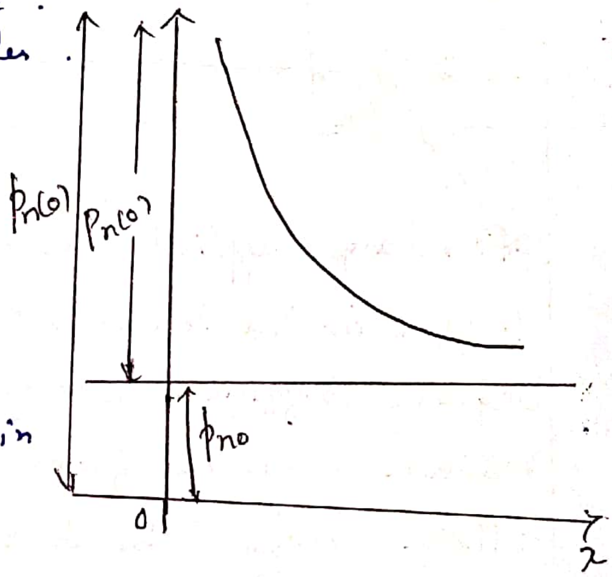
Quantitative theory of PN diode Currents: / Diode Current Equation

→ Let us now derive the expression for the total current as a function of applied Voltage assuming that the width of the depletion region is zero.

→ When forward bias is given, holes move from P to N. Therefore, the Concentration of holes in the N side is increased from its thermal equilibrium value p_{no}.

→ Injected hole Concentration $p_n(x)$ decreases exponentially with respect to x [distance].

→ Let p_p → hole Concentration in P-type.
p_n → hole Concentration in N-type.
p_{no} → Thermal Equilibrium value
(ie) Thermally generated holes.



Injected hole Concentration

in general,

$$\boxed{p_n(x) = P_n(0)\, e^{-x/L_p} + p_{no}} \quad \text{——} \ (1)$$

where x → distance.
L_p → diffusion length for holes in N-type.

At $x = 0$;

$$\boxed{p_n(0) = P_n(0) + p_{no}} \quad \text{——} \ (2)$$

$$\boxed{P_n(0) = p_n(0) - p_{no}} \quad \text{——} \ (3)$$

According to law of junction,

$$p_p = p_n\, e^{V_B/V_T}$$

where V_B → Barrier potential
V_T → Thermal Voltage.

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At $x=0$; (i) when $V=0$:

$$\boxed{p_{po} = p_{no}\, e^{V_o/V_T}} \quad \text{—— (4')} \qquad (\because V_B = V_o)$$

(ii) when forward voltage V is applied,

Effective barrier voltage $V_B = V_o - V$ ⇒ [∵ The applied voltage is opposite to the barrier potential developed, hence considering the effective voltage]

$$\boxed{p_{po} = p_n(0)\, e^{V_o - V/V_T}} \quad \text{—— (5)}$$

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Equating (4') & (5)

$$p_{no}\, e^{V_o/V_T} = p_n(0)\, e^{\frac{V_o - V}{V_T}}$$

$$p_n(0) = p_{no} \frac{e^{\frac{V_o}{V_T}}}{e^{\frac{V_o - V}{V_T}}} = p_{no}\, e^{\frac{\cancel{V_o} - \cancel{V_o} + V}{V_T}}$$

$$\boxed{p_n(0) = p_{no}\, e^{V/V_T}} \quad \text{—— (6)}$$

Sub (6) in (3)

$$P_n(0) = p_{no}\, e^{V/V_T} - p_{no}.$$

$$\boxed{P_n(0) = p_{no}\left(e^{V/V_T} - 1\right)} \quad \text{—— (7)}$$

The diffusion hole current crossing the junction from P-side to N-side

At $x=0$,

$$\boxed{I_{pn}(0) = \frac{A q D_p P_n(0)}{L_p}} \quad \text{—— (8)}$$

Sub (7) in (8)

$$\cancel{I_{pn}(0) = \frac{A q D_p p_{no}}{L_p} + \frac{A q D_n n_{po}}{L_n}}.$$

$$I_{pn}(0) = \frac{A q D_p}{L_p}\, p_{no}\left(e^{V/V_T} - 1\right)$$

Similarly, the electron current crossing the junction into p-side

$$\boxed{I_{np}(0) = \frac{Aq\, D_n\, n_{po}}{L_n}\left(e^{V/V_T} - 1\right)}$$

(replacing n as p & p as n)

The total diode current,

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

$$I = \left(\frac{Aq\, D_p\, p_{no}}{L_p} + \frac{Aq\, D_n\, n_{po}}{L_n}\right)\left(e^{V/V_T} - 1\right)$$

General equation of the diode current is approximately given by,

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

where η — constant ; 1 for Ge
2 for Si.

$I_o \rightarrow$ Reverse Saturation Current.

$$I_o = \left[\frac{Aq\, D_p\, p_{no}}{L_p} + \frac{Aq\, D_n\, n_{po}}{L_n}\right]$$

Note :

The diode current equation relating the voltage V and current I is given by

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

Where $I \rightarrow$ diode current.

$I_o \rightarrow$ diode reverse saturation current at room temperature.

$V \rightarrow$ External voltage applied to the diode.

$\eta \rightarrow$ a constant, 1 for germanium
2 for silicon.

$V_T = KT/q = T/11600$, Volt - equivalent of temperature (ie) Thermal Voltage.

where $k \rightarrow$ Boltzmann's Constant ($1.38 \times 10^{-23} J/k$)

$q \rightarrow$ Charge of the electron ($1.602 \times 10^{-19} C$).

$T \rightarrow$ Temperature of the diode junction (K)

$= (°C + 273°)$.

→ At room temperature, ($T = 300k$), $V_T = 26mV$.

Sub this value in the Current equation.

$$I = I_0 [e^{(40V/\eta)} - 1]$$

∴ for germanium diode, $I = I_0 [e^{40V} - 1]$

∵ $\eta = 1$ for Ge

for silicon diode, $I = I_0 [e^{20V} - 1]$

∵ $\eta = 2$ for Si.

→ If the value of applied voltage is greater than unity, then the equation of diode current for germanium,

$$I = I_0 (e^{40V})$$

for silicon, $I = I_0 (e^{20V})$.

→ When the diode is reverse biased, its current equation may be obtained by changing the sign of the applied voltage V. Thus, the diode current with reverse bias is

$$I = I_0 [e^{(-V/\eta V_T)} - 1].$$

→ If $V >> V_T$, then the term $e^{(-V/\eta V_T)} << 1$,

∴ $I \approx -I_0$, termed as reverse saturation current.

which is valid as long as the external voltage is below the breakdown value.

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Ideal Vs Practical - Resistance levels (Static & Dynamic).

→ An ideal diode should offer zero resistance in FB & ∞ resistance in the RB.

→ But in practice no diode can act as an ideal diode i.e) an actual diode does not behave as a perfect conductor when FB & as a perfect insulator when RB.

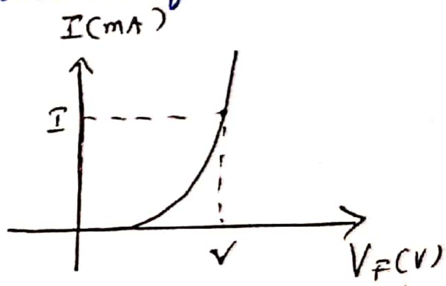
→ Consider 4 resistance of the diode.

1) DC or static resistance.
2) AC or dynamic resistance.
3) Average AC resistance.
4) Reverse resistance.

1) DC or static resistance (R_F):

It is defined as the ratio of the voltage to the current, V/I, in the forward bias characteristics of the PN junction diode.

$$\boxed{R_F = \frac{V}{I}}$$

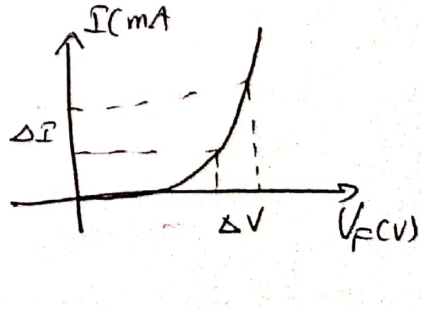


2) AC or dynamic resistance (r_f):

It is defined as the reciprocal of the slope of the volt-ampere characteristics.

$$r_f = \frac{\text{Change in Voltage}}{\text{resulting change in current}} = \frac{\Delta V}{\Delta I}.$$

$$\boxed{r_f = \frac{\Delta V}{\Delta I}}$$



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3) Average Ac resistance :-

It is the resistance associated with the device for the region if the input signal is sufficiently large to produce a wide range of the characteristics.

$$\therefore \; r_{av} = \left.\frac{\Delta V}{\Delta I}\right|_{\text{point to point}}$$

4) Reverse resistance :

It is the resistance offered by the PN junction diode under reverse bias condition. It is very large compared to the forward resistance, which is in the range of several MΩ.

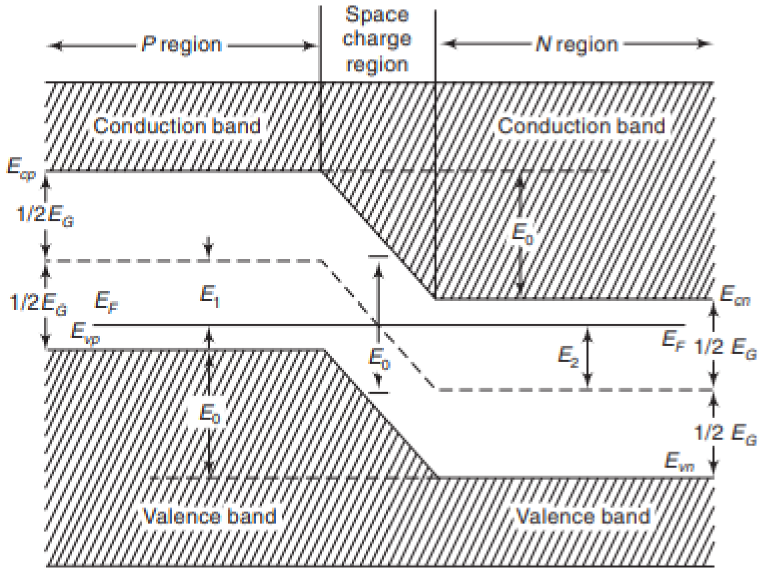
Energy band Structure of Open circuited PN Junction.

→ We know, the fermi level lies just below the Conduction band in n-type material; the fermi level lies just above the Valence band in P-type material.

→ When PN junction is formed, the diffusion starts.

→ The charges get adjusted to equalize the fermi level (ie) charges flow from P to N and N to P till the fermi level on the 2 sides gets lined up.

[This is similar to the adjustment of water levels in 2 tanks of unequal level, when connected to each other].



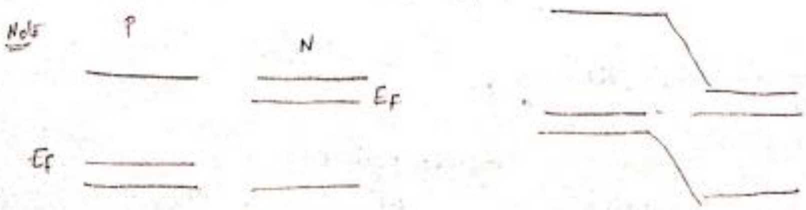
Energy-band structure

Note:

Fermi level → Shows max at energy level occupied by the electrons

→ depends on temperature & impurity Concentration.

→ No impurities – E_F lies in the middle of the energy gap indicating equal Concentration of holes & electrons.



→ E_F → closer to CB edge in N-type. (E_{cn})
closer to VB edge in P-type (E_{vp}).

→ It is clear that, E_{cp} is higher than E_{cn}.
(IIly; E_{vp} is higher than E_{vn}.

→ E_1 → Shift in the fermi level on P-side.
E_2 → Shift in the fermi level on N-side.

→ Total shift $E_0 = E_1 + E_2$; which is responsible to produce Contact difference of potential across the junction. This is called barrier potential (or) Junction potential (or) Contact potential.

$$\left.\begin{aligned} E_0 &= E_1 + E_2 \\ &= E_{cp} - E_{cn} \\ &= E_{vp} - E_{vn} \end{aligned}\right\} \quad \text{①}$$

To derive E_0:-

from the structure,

$$E_F - E_{vp} = \tfrac{1}{2} E_G - E_1 \Rightarrow \boxed{E_1 = \tfrac{1}{2} E_G - E_F + E_{vp}} \quad \text{②}$$

$$E_{cn} - E_F = \tfrac{1}{2} E_G - E_2 \Rightarrow \boxed{E_2 = \tfrac{1}{2} E_G - E_{cn} + E_F} \quad \text{③}$$

Combining ② & ③ we get,

$$E_0 = E_1 + E_2$$

$$= \tfrac{1}{2} E_G - E_F + E_{vp} + \tfrac{1}{2} E_G - E_{cn} + E_F.$$

$$\boxed{E_0 = E_G - (E_{cn} - E_F) - (E_F - E_{vp})} \quad \text{④}$$

We know that,

$$n = N_c e^{-(E_c - E_F)/kT}$$

$$p = N_v \cdot e^{-(E_F - E_v)/kT}$$

By mass action law, $np = n_i^2$.

$$N_c e^{-(E_c - E_F)/kT} \cdot N_v e^{-(E_F - E_v)/kT} = n_i^2.$$

$$N_c N_v \, e^{\frac{-E_c + \cancel{E_F} - \cancel{E_F} + E_v}{kT}} = n_i^2.$$

$$N_c N_v e^{-E_G/KT} = n_i^2 \qquad [\because E_c - E_v = E_G]$$

Taking $\ln$ on both sides,

$$\ln e^{-E_G/KT} = \ln \frac{n_i^2}{N_c N_v}$$

$$\frac{-E_G}{KT} = \ln \frac{n_i^2}{N_c N_V}$$

$$\boxed{E_G = KT \ln \frac{N_c N_v}{n_i^2}} \quad \text{——— (5)}$$

We know that,

for n-type, $E_f = E_c - KT \ln \frac{N_c}{N_D}$.

$$\therefore \boxed{E_{cn} - E_f = KT \ln \frac{N_c}{N_D}} \quad \text{——— (6)}$$

for p-type

$$E_f = E_v + KT \ln \frac{N_v}{N_A}.$$

$$\boxed{E_f - E_{vp} = KT \ln \frac{N_v}{N_A}} \quad \text{——— (7)}$$

Sub (5), (6) & (7) in (4)

$$E_o = KT \ln \left(\frac{N_c N_v}{n_i^2}\right) - KT \ln \left(\frac{N_c}{N_D}\right) - KT \ln \left(\frac{N_v}{N_A}\right)$$

$$= KT \ln \left[\frac{N_c N_v}{n_i^2} \div \frac{N_c}{N_D} \div \frac{N_v}{N_A}\right]$$

$$= KT \ln \left[\frac{N_c N_v}{n_i^2} \times \frac{N_D}{N_c} \times \frac{N_A}{N_v}\right]$$

$$E_o = KT \ln \left[\frac{N_D N_A}{n_i^2}\right] \qquad \text{But } E_o = q V_o.$$

$$\boxed{V_o = \frac{E_o}{q} = \frac{KT}{q} \ln \frac{N_D N_A}{n_i^2}.}$$

Mass action law:

Under thermal equilibrium for any Semiconductor, the product of the number of holes and the number of electrons is constant and is independant of the amount of donor and acceptor impurity doping. This relation is known as Mass action law.

$$\boxed{n \cdot p = n_i^2}$$ [∵ $n = p = n_i$ for intrinsic material]

where $n \rightarrow$ no. of free electrons per unit volume
$p \rightarrow$ no. of holes per unit volume.
$n_i \rightarrow$ Intrinsic Concentration.

~~Currents in PN Junction:~~

~~The net current that flows through a PN junction diode has 2 Components (i) Drift Current (ii) Diffusion Current.~~

~~Drift Current:~~

Charge densities in N-type & P-type SC

Note: ∵ The Semiconductor is electrically neutral, the magnitude of the +ve charge density = −ve concentration.

$$\boxed{N_D + p = N_A + n} \quad — ①$$

For N-type: $N_A \approx 0$; $n >> p$. $\Rightarrow n \approx N_D \Rightarrow n_n \approx N_D$ — ②

W.K.T by mass action law, $n_n \cdot p_n = n_i^2$

$$p_n = \frac{n_i^2}{n_n}.$$

$$\boxed{p_n = \frac{n_i^2}{N_D}} \quad \text{(from ②)}$$

|||ly W.K.T)

$$\sigma = q n \mu_n$$

$$\boxed{\sigma_N \approx q N_D \mu_n}$$

For P-type, from ① ⇒ $N_D = 0$; $p >> n$;

$$\Rightarrow p \approx N_A$$

$$p_p \approx N_A \quad \text{——— ③}$$

W.K.T by mass action law, $n_p p_p = n_i^2$

$$n_p = \frac{n_i^2}{p_p}$$

$$\boxed{n_p = \frac{n_i^2}{N_A}} \quad \text{from ③}$$

III^ly W.K.T,

$$\sigma = q p \mu_p$$

$$\boxed{\sigma_p = q N_A \mu_p}$$

Currents in PN junction:

The net current that flows through a PN junction diode has 2 components (i) Drift current and (ii) Diffusion current.

Drift current:

→ When an electric field is applied across the semiconductor material, the holes move towards the −ve terminal of the battery and electrons move towards the +ve terminal of the battery. This combined effect of the movement of holes and electrons constitute a current called drift current.

→ The equation for the drift current density, J_n due to free electrons is given by

Applied field

$$J_n = q n \mu_n E \quad A/cm^2 \quad \text{——— ①}$$

due to holes $$J_p = q p \mu_p E \quad A/cm^2 \quad \text{——— ②}$$

where $q \to$ charge of an electron $= 1.6 \times 10^{-19}$ coul.

$n \to$ no. of electrons per cubic cm.

$p \to$ no. of holes per cubic cm. ; unit = /cm^3 (or) cm^{-3}.

$\mu_n \rightarrow$ mobility of electrons in $cm^2/V\text{-}s$
$\mu_p \rightarrow$ mobility of holes in $cm^2/V\text{-}s$
$E \rightarrow$ Applied Electric field intensity in V/cm.

Diffusion current:-

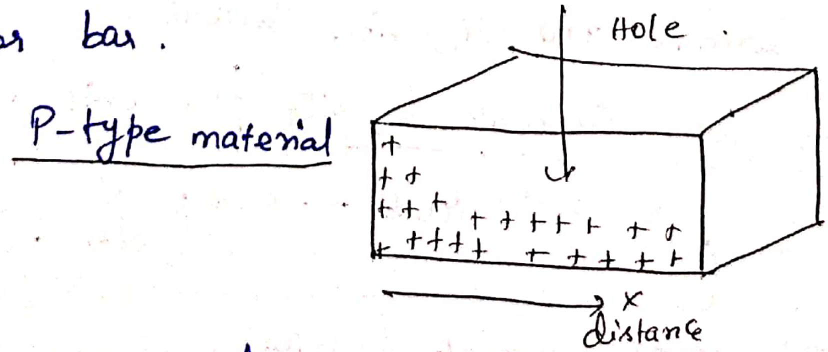
→ It is possible for an electric current to flow in a semiconductor even in the absence of an applied voltage provided a concentration gradients exists in the material.

→ A concentration gradient exists if the number of either electrons or holes is greater in one region of a semiconductor as compared to the rest of the region.

→ When concentration gradient exists, the carriers tend to move from higher concentration to lower concentration. This process is called diffusion and the current due to diffusion is called diffusion current.

→ The diffusion current depends on
- → the material of the semiconductor
- → type of charge carriers.
- → the concentration gradient.

→ Consider a non-uniformly doped p-type semiconductor bar.



Excess hole concentration varying along the axis in the p-type semiconductor bar.

→ Let $\frac{dp}{dx}$ → the hole concentration in a semiconductor bar varies from a high value to a low value along the x-axis.

→ The diffusion current density is proportional to the concentration gradient.

<u>due to holes,</u> $J_p \propto \frac{dp}{dx}$. → decrease

$$\boxed{J_p = -q\, D_p \frac{dp}{dx}} \quad A/cm^2 \quad \text{—— (3)}$$

→ change in conc. w.r.t. distance

where

D_p → Diffusion coefficients in cm^2/s for holes.

q → charge of an electron.

$\frac{dp}{dx}$ → Concentration gradient for holes.

<u>due to electrons,</u>

$$\boxed{J_n = q\, D_n \frac{dn}{dx}} \quad A/cm^2 \quad \text{—— (4)}$$

where D_n → Diffusion coefficient in cm^2/s for electrons.

$\frac{dn}{dx}$ → Concentration gradient for electrons.

<u>Total Currents:</u>

The total current in a semiconductor is the sum of drift current and diffusion current.

For p-type; Total current density per unit area

$$\boxed{J_p = q p \mu_p E - q D_p \frac{dp}{dx}} \quad \text{Adding (2) \& (3)}$$

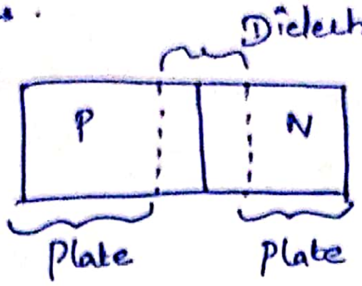
For N-type; Total current density.

$$\boxed{J_n = q n \mu_n E + q D_n \frac{dn}{dx}} \quad \text{Adding (1) \& (4)}$$

Transition (or) Space Charge Capacitance C_T (or) Depletion region capacitance.

→ It occurs under reverse bias.

→ When a diode is reverse biased, depletion region width increases.



→ Here, the parallel layers of oppositely charged immobile ions on the 2 sides of the junction form the transition capacitance C_T.

$$C_T = \frac{\varepsilon A}{W}$$

where ε → Permittivity of the material

A → cross-sectional Area.

W → Width of the depletion layer.

→ Under no bias, when $V=0$; W is the order of 0.5 microns.

The depletion region acts as a dielectric between 2 Conducting P & N regions.

∴ These regions act as a parallel plate capacitor whose transition capacitance $C_T \approx 20PF$ with no bias.

→ when $-V$ is applied, W → depletion width ↑ses.

C_T → ↓ses.

→ when $+V$ is applied, W → ↓ses.

C_T → ↑ses.

C_T ranges from 5 to 200PF.

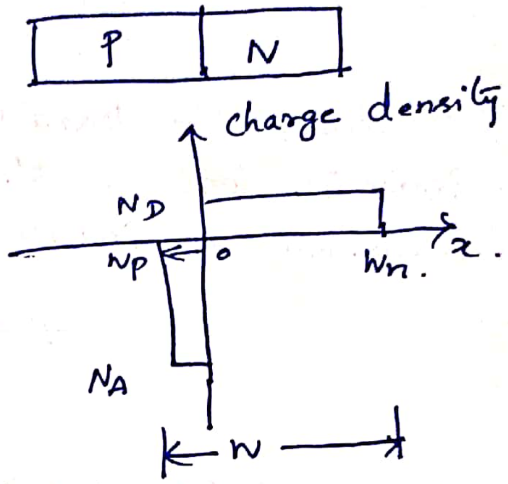
→ Used in Varactors (or) Vari-caps (or) Volta-caps diodes.

Derivation:

→ Consider a PN diode which is asymmetrically doped at the junction.

→ Assume that the doping level of p-side is greater than the doping level of n-side (ie) $N_A >> N_D$.

→ As we know, net charge = 0.



$$N_A W_p = N_D W_n.$$

$$\uparrow \frac{N_A}{N_D} = \frac{W_n \uparrow}{W_p}.$$

∴ when $N_A >> N_D$

$W_n >> W_p$.

→ By poisson's law,

$$\boxed{\frac{d^2V}{dx^2} = \frac{-qN_A}{\varepsilon}.}$$

Note: Doping ↑ . ↓
Conductivity ↑ . ↓
Depletion layer ↓ ↑

Integrating one time,

$$\frac{dV}{dx} = \frac{-qN_A}{\varepsilon}x.$$

Integrating again, $V = \frac{-qN_A}{\varepsilon}\frac{x^2}{2}$

At $x = W_n = W$.

$$\boxed{V = \frac{-qN_A W^2}{2\varepsilon}.}$$

$$\frac{dV}{dw} = \frac{-qN_A \cancel{2}w}{\cancel{2}\varepsilon}$$

$$\boxed{\frac{dw}{dV} = \frac{-\varepsilon}{qN_A W}} \quad \text{---} \ (1)$$

→ If A is the area of the junction, the charge in the depletion layer is

$$Q = qN_A WA.$$

$$\boxed{\frac{dQ}{dV} = qN_A A \frac{dW}{dV}.} \quad \text{---} \ (2).$$

Sub (1) in (2)

$$\frac{dQ}{dV} = \cancel{q}\cancel{N_A} A \cdot \left(\frac{-\varepsilon}{\cancel{q}\cancel{N_A} W}\right).$$

$$\Rightarrow \left|\frac{dQ}{dV}\right| = \frac{A\varepsilon}{W}.$$

$$\Rightarrow \boxed{C_T = \frac{A\varepsilon}{W}.}$$

Note:-

→ The derivation can also be made in the other type as assuming the doping level high.

→ If W_D is not neglected, the above results are slightly modified. W should be → total width. $\frac{1}{N_A}$ should be replaced by $\left[\frac{1}{N_A} + \frac{1}{N_D}\right]$.

Diffusion Capacitance (Storage Capacitance) [occurs under FB]

→ The capacitance that exists in a forward biased junction is called diffusion or storage capacitance. It is denoted by C_D.

→ The value of C_D is much larger than C_T ($C_D >> C_T$)

→ In forward biased condition, the width of depletion region decreases and the holes from P side get diffused in N side, while electrons from N side move into the P-side. As the applied voltage increases, the concentration of injected charged particles increases. This rate of change of injected particles with the applied voltage constitutes a capacitance called diffusion capacitance.

→ The expression for diffusion capacitance is,

$$C_D = \frac{dQ}{dV}$$; rate of change of injected charge with applied voltage
[e^{-ns} : n to p ; holes : p to n]

dQ → change in the number of minority carriers outside the depletion region.

dV → change in voltage.

→ $C_D \propto$ forward current I.

C_D → value ranges from 10 to 1000 pF.

C_D → Negligible for a RB PN junction.

$C_D \propto \frac{1}{f}$; C_D high at low freq.
C_D low at high freq.

According to Diode Current equation,

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

$$= I_0 \, e^{V/\eta V_T} - I_0 .$$

$\because I_0$ is very small, it can be neglected.

$$I \simeq I_0 \, e^{V/\eta V_T} \quad \text{———} \ (6)$$

Differentiating,

$$\frac{dI}{dV} = I_0 \, e^{V/\eta V_T} \left(\frac{1}{\eta V_T} \right) \quad \text{———} \ (7)$$

From (5), $\left| \frac{dQ}{dV} \right| = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV}$

Sub (7) here,

$$\left| \frac{dQ}{dV} \right| = \frac{L_p^2}{D_p} \cdot \underbrace{I_0 \, e^{V/\eta V_T}}_{(\text{from } (6))} \left(\frac{1}{\eta V_T} \right).$$

113, 116, 143, 144, 149, 197,

$$\boxed{C_D = \frac{\tau \cdot I}{\eta V_T}}$$

where $\tau \rightarrow$ mean lifetime for holes & electrons.

$I \rightarrow$ diode forward current.

η is a constant, (for Ge; $\eta = 1$; Si ; $\eta = 2$).

$V_T = \frac{KT}{q} = \frac{T}{11{,}6000}$, Volt equivalent of temp (ie) Thermal voltage.

K is the Boltzmann constant $= 1.38066 \times 10^{-23}$ J/k.

q is the charge of electron $= 1.602 \times 10^{-19}$ col

T is the temp of diode junction in K.

Derivation for C_D:

Formulas:

1) Excess minority charge (holes) Q exist on N side

$$Q = Aq\, L_p\, P_n(0) \quad \text{—— (1)}$$

2) Hole current : $$I = \frac{Aq\, D_p\, P_n(0)}{L_p} \quad \text{—— (2)}$$

Differentiating (1) w.r.t V

$$\frac{dQ}{dV} = Aq\, L_p \frac{dP_n(0)}{dV} \quad \text{—— (3)}$$

From (2), $P_n(0) = \frac{L_p I}{Aq\, D_p}$.

Differentiating w.r.t V,

$$\frac{dP_n(0)}{dV} = \frac{L_p}{Aq\, D_p} \cdot \frac{dI}{dV} \quad \text{—— (4)}$$

Sub Eqn (4) in (3),

$$\frac{dQ}{dV} = Aq\, L_p \cdot \frac{L_p}{qA\, D_p} \cdot \frac{dI}{dV}.$$

$$\frac{dQ}{dV} = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV}. \quad \text{—— (5)}$$

$$C_D = \frac{L_p^2}{D_p} \cdot g \Rightarrow \boxed{C_D = \tau \cdot g}$$

where $\tau = \frac{L_p^2}{D_p}$; Mean life time.

Junction diode Switching Characteristics:

→ Diodes are often used in a switching mode.

→ When the applied bias voltage to the PN diode is suddenly reversed in the opposite direction, the diode response reaches a steady state after an interval of time called the recovery time.

2 recovery times < forward t_{fr}, reverse t_{rr}

Defn → The forward recovery time t_{fr} is defined as the time required for forward voltage or current to reach a specified value ~~(time interval between the~~ after switching diode from its reverse-to forward-biased state.

→ Fortunately, the forward recovery time possess no serious problem. ∴ only the reverse recovery time, t_{rr} has to be considered in practical applications.

→ When the PN junction diode is forward biased, the minority electron concentration in the P-region is approximately linear.

→ If the junction is suddenly reverse biased at t_1, then because of this stored electronic charge, the reverse current (I_R) is initially of the same magnitude as the forward current (I_F).

→ During the time interval from t_1 to t_2, the injected minority carriers have remained stored and hence this time interval is called the storage time (t_s).

Note → Defn Storage time: t_s It is the time required to remove the excess minority charge carriers.
The time period for which the diode remains in conduction state even in reverse direction.

→ After the instant $t = t_2$, the diode gradually recovers and ultimately reaches the steady state.

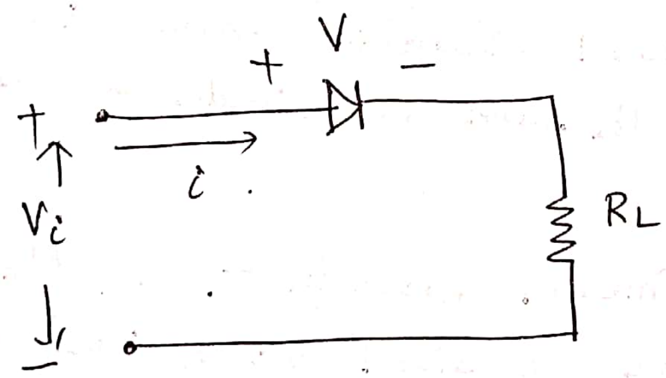
→ The time interval between t_2 and t_3, when the diode has recovered nominally is called "the transition time" (t_t). It is the time elapsed back to state of non-conduction.

Defn

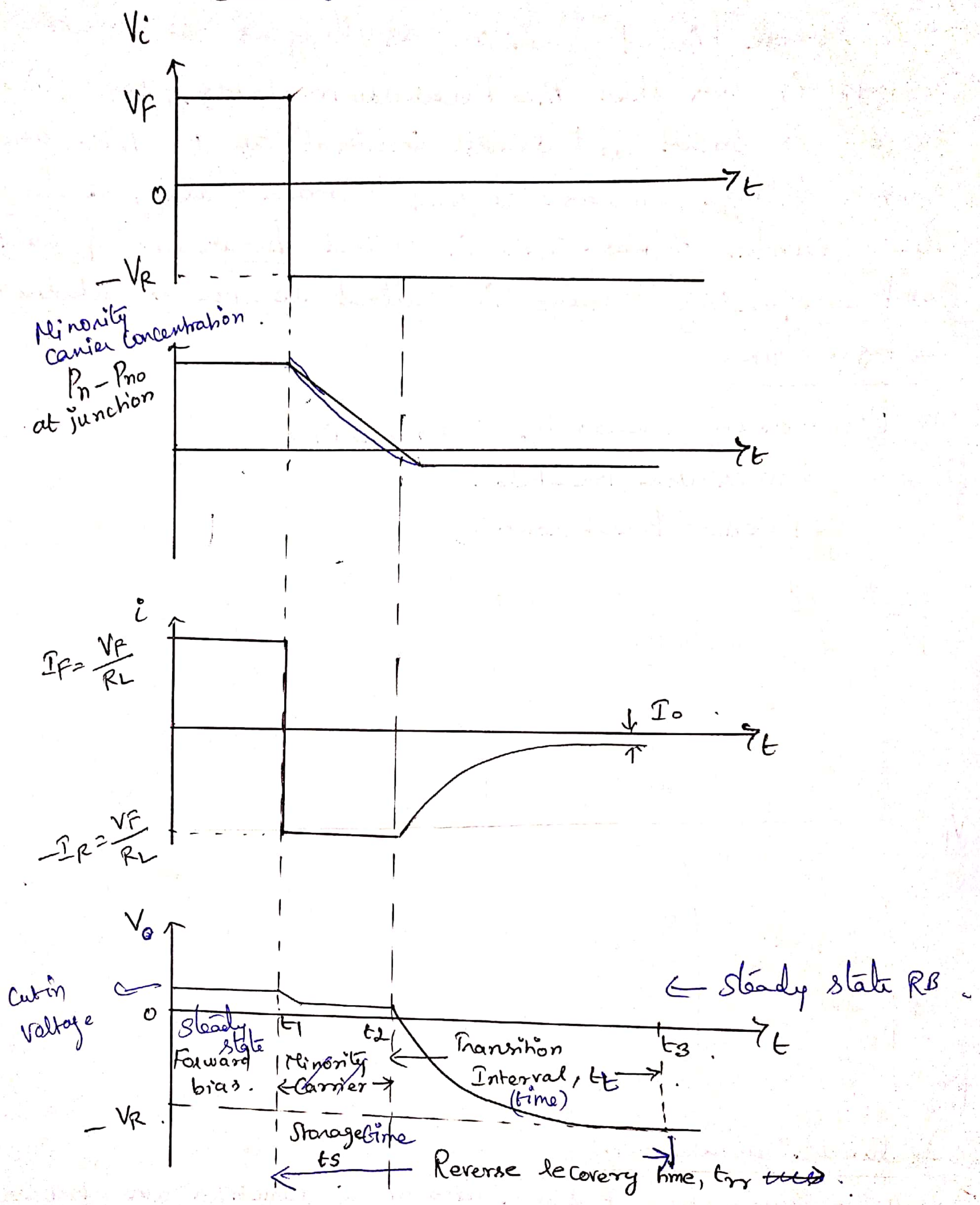
Transition time t_t: The time for the current to decrease to a reverse leakage current value after it remains at a constant level is called as transition time.
It is determined by the geometry of the PN junction and concentration of doping levels of the P-type and N-type materials.

Defn Reverse recovery time t_{rr}

The sum of the storage time and transition time is termed as reverse recovery. ; $\boxed{t_{rr} = t_s + t_t}$
It is the time taken for the PN junction diode to change from forward bias to reverse bias is Reverse recovery time.



Switching characteristics of PN junction diode



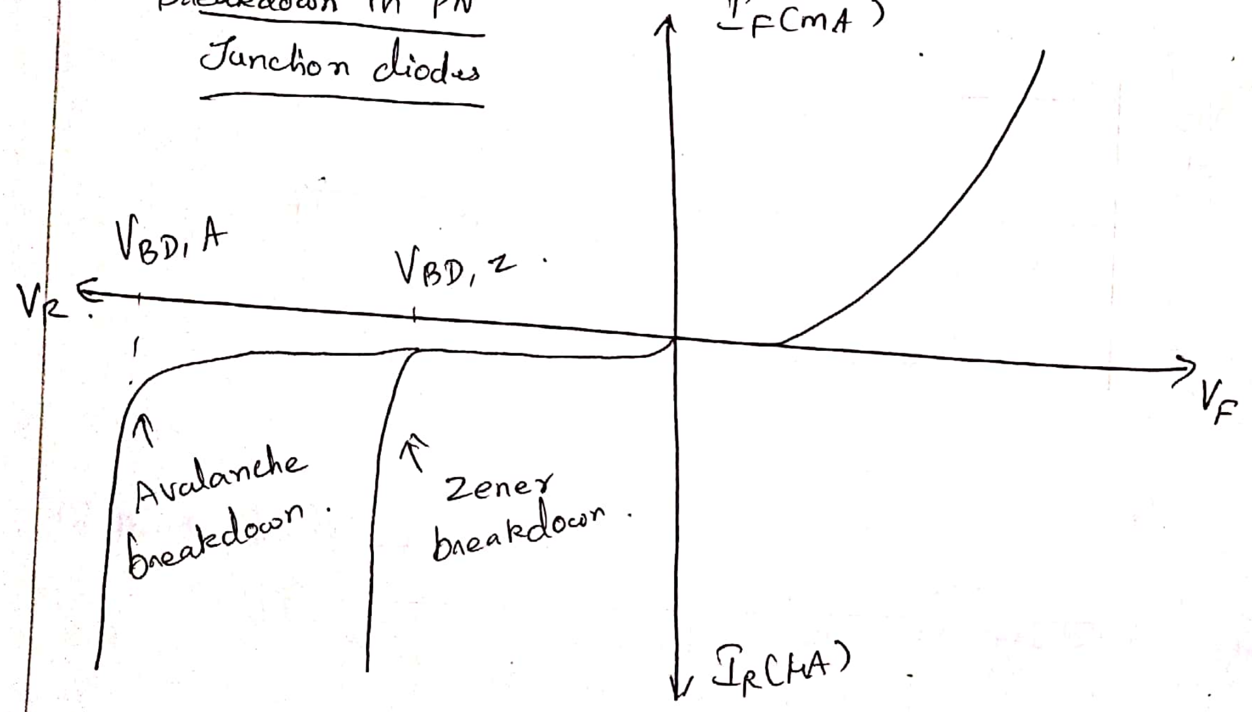
$$t_{rr} = t_s + t_t$$

Breakdown in PN junction diodes:

→ In reverse biased condition as long as the reverse voltage is less than the breakdown voltage, the diode current is small and almost constant at I_o. But when reverse voltage increases beyond certain value, a large diode current flows. This is called breakdown of diode and corresponding voltage is called reverse breakdown voltage V_{BR}.

→ Breakdown occurs by 2 mechanism
1) Avalanche Breakdown
2) Zener Breakdown.

Breakdown in PN Junction diodes



Avalanche breakdown:

→ It occurs when P & N sides of a junction are moderately doped & depletion layer is thick.

→ We know, under reverse biased condition, the reverse current flows due to minority charge carriers. when

Zener breakdown:

It occurs when Semiconductors are heavily doped and depletion layers are very thin.
Even if the initially available carriers do not gain enough energy to disrupt bonds, it is also possible to initiate breakdown through a direct rupture of the bonds because of the existence of strong electric field. Under these circumstances, the breakdown is referred to as zener breakdown.

The breakdown occurs in junctions which are heavily doped. The heavily doped junctions have a narrow depletion layer. When the reverse voltage is increased, the electric field at the junction also $\uparrow \xi \propto \frac{1}{d_t}$ increases. This field is enough to pull the electrons out of the valence bands. So this is not due to the collision of carriers with atoms. Such a creation of free electrons is called zener effect. These carriers constitute very large current & mechanism is called zener breakdown.

The effect is dominant for heavily doped diodes. For which, the depletion width is small. The field intensity for voltages less than 5-6V becomes intense and hence causes more carriers.

Note:

Zener $\Rightarrow$ -ve temp Coeff.
V_{BR} $\downarrow$ses with $\uparrow$se temp.

Avalanche $\Rightarrow$ +ve temp Coeff.
V_{BR} $\uparrow$ses with $\uparrow$se temp.

the applied reverse bias increases, the minority charge carriers increasingly accelerate. (ie) the velocity. Hence the the kinetic energy of electron increases. If such an electron dashes against an electron involved in covalent bond, then the collision break its covalent bond. And produces new carriers by removing valence electrons from their bonds. These new carriers will inturn collide with other atoms and will increase the number of electrons & holes available for conduction. Now, the current increases rapidly. This phenomenon is known as carrier multiplication. This cummulative process of carrier-generation (multiplication) is know as a Avalanche breakdown (or) Avalanche Multiplication.

→ This multiplication effect of free carriers is represented by

$$M = \frac{1}{1-\left(\frac{V}{V_{BD}}\right)^n}.$$

where $M \rightarrow$ Carrier Multiplication factor.

$V \rightarrow$ Applied reverse voltage.

$V_{BD} \rightarrow$ Reverse breakdown voltage.

$n \rightarrow$ Constant (depends on the material).

Note:

Avalanche breakdown occurs for lightly doped diodes. It occurs at very high reverse voltage.

105, 113, 115, 119, 122 (03), 136(02), + —

PN diode Applications:

1) Rectifiers in dc power supplies.

2) Switch in digital logic circuits used in Computers.

3) Clamping network used as dc restorer in TV receivers and voltage multipliers.

4) Clipping circuits used as wave shaping circuits used in Computers, RADAR's, Radio and TV receivers.

5) Demodulation (Detector) circuits.

Effect of temperature on PN Junction diodes:

→ The rise in temperatures increases the generation of electron - hole pairs in Semiconductors and increases their conductivity.

→ Current through the PN junction diode increases with temperature

$$\boxed{I = I_0 \left[e^{V/\eta V_T} - 1 \right]}.$$

→ Reverse saturation current I_0 increases approximately ~~doubles~~ 7% for every per degree rise in temperature for both Ge & Si

→ Reverse saturation current also doubles for every 10°C rise in temperature. Hence if the temp ~~is fixed at fixed voltage~~, the current I increases. To bring I to its original value, the voltage has to be reduced.

→ At room temperature, ~~the $V_B = 0.3V$ for Ge~~
0.7V for Si

$$\boxed{\frac{dv}{dt} \simeq -2.5\, mV/^\circ C}$$ ~~for~~

for either Ge or Si in order to maintain the current at its constant value.

→ The variation of saturation current with temperature is given by

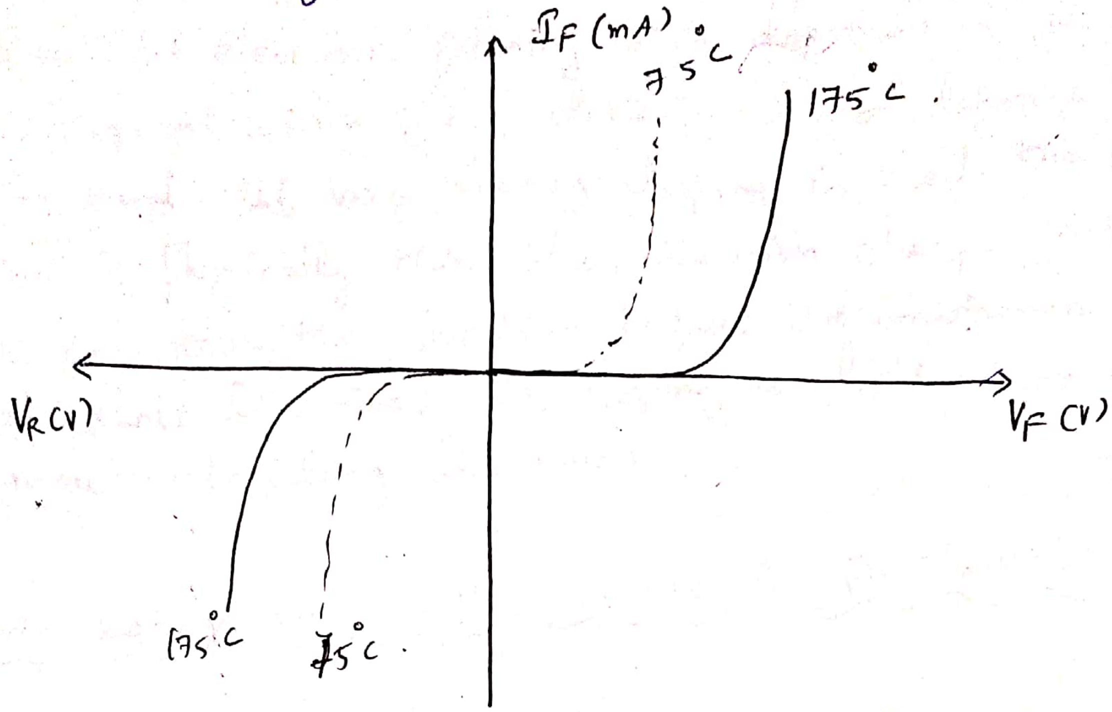
$$\boxed{I_{o2} = I_{o1} \times 2^{(T_2 - T_1)/10}}$$

where I_{o1} → Saturation current at temp T_1.
I_{o2} → Saturation current at temp T_2.

→ The barrier voltage or the cut-in voltage is about 0.3V for Ge and 0.7V for Si. This cut-in voltage is also temperature dependent. It decreases by 2mV/°C for both Ge & Si.

→ Hence as the temperature increases, the cut-in voltage decreases.

→ The effect of temperature on the V-I Characteristics of PN diode is given below,



Note:- Ge can be used upto a max of 75°C & Si to a max of 175°C.

Note:

$$\uparrow E \propto \frac{1}{d \downarrow \text{width}}.$$

if P heavily doped, the high concentration of holes combine with electrons forming thin depletion region.

→ The physical width of the depletion region depends on the doping level. If very heavy doping is used, the depletion region is physically thin b'coz diffusion charge need not travel far across the junction before recombination takes place (short life time). If doping is light, then depletion is more wide (long life time).

Diode ratings (or) Limiting values of PN Junction Diode:

1) Maximum forward Current:

It is the highest instantaneous current under forward bias condition that can flow through the junction.

2) Peak Inverse voltage (PIV):

It is the maximum reverse voltage that can be applied to the PN junction. If the voltage across the junction exceeds PIV, under reverse bias condition, the junction gets damaged.

3) Maximum Power rating:

It is the maximum power that can be dissipated at the junction without damaging the junction.

4) Power dissipation is the product of voltage across the junction and current through the junction.

$$\boxed{P = V \cdot I}$$

Note

Important Parameters:

1) Current density, J :

Electric current per unit area of cross section.

$$\boxed{J = \frac{I}{A}}\ ; \quad \underline{\text{unit}}: A/cm^2 \quad (Amp/cm^2)$$

2) Mobility, μ :

→ describes how quickly an electron can move through a metal/semiconductor when pulled by an electric field. When E is applied, electrons respond by moving with an average velocity called the drift velocity.

$$\boxed{\mu = \frac{V_d}{E}}\ ; \quad \underline{\text{unit}}: cm^2/V\text{-}s \quad \left[\frac{\frac{cm}{s}}{\frac{V}{cm}}\right.$$

V ↑ Volt, s ↑ sec.

V_d → drift velocity

E → Electric field.

3) Conductivity, σ :

→ Measure of its ability to conduct electricity

$$\boxed{\sigma = \frac{J}{E}}\ ; \quad \underline{\text{unit}}: mho/cm \ \text{(or) Siemen}/cm$$

$$\left(\text{Siemen}, S = \frac{1}{R} \ \text{(or)}\ \Omega^{-1}\right)$$

$$\frac{J}{E} = \frac{I}{A \cdot E} = \frac{amp}{cm^2 \cdot \frac{V}{cm}} = \frac{1}{cm \cdot R}.$$

4) Resistivity : $\boxed{\rho = \frac{1}{\sigma}}$

$\underline{\text{unit}}$: ohm^{-1}.

Total Current density :-

$J = J_n + J_p$; $J_n \rightarrow e^{-n}$ drift current density
$J_p \rightarrow$ hole drift current density

$J = qn\mu_n E + qp\mu_p E$.

$$\boxed{J = (n\mu_n + p\mu_p)qE}$$

$$\sigma = \frac{J}{E} = (n\mu_n + p\mu_p)q.$$

where $q \rightarrow$ charge of an e^{-n} or hole : 1.602×10^{-19} col.

n = no. of e^{-ns} per cubic cm $[cm^{-3}]$.

p = " " holes " " "

μ_n = Mobility of e^{-ns}] $cm^2/V\text{-}s$.

μ_p = " " holes

For intrinsic Semiconductor,

$n = p = n_i$.

$\therefore J = n_i(\mu_n + \mu_p)qE$.

$\sigma_i = n_i(\mu_n + \mu_p)q$.

for extrinsic Semiconductor,

N-type ; $n >> p$.

General formula. $\sigma = (n\mu_n + p\mu_p)q$.

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

P-type ; $p >> n$.

$$\boxed{\sigma = p\mu_p q}$$

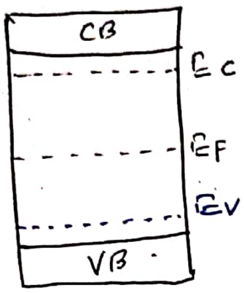
Fermi Level:

→ Shows maximum energy level occupied by the electrons

→ depends on temp and impurity concentration.

→ No impurities: E_F lies in the middle of the energy gap indicating equal concentration of holes and electrons in Intrinsic S.C.

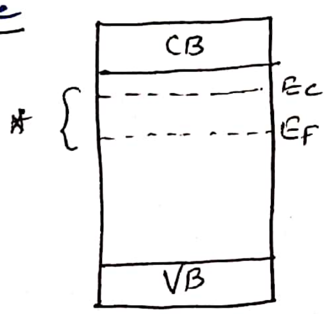
Intrinsic



$$\boxed{E_F = \frac{E_c + E_v}{2}} \quad \text{——— (1)}$$

Extrinsic.

N-type



$$\boxed{E_F = E_c - kT \ln\left(\frac{N_c}{N_D}\right)} \quad \text{——— (2)}$$

N_D → Concentration of Donor atoms.

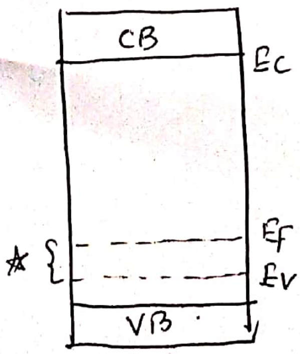
$$N_D = N_c \, e^{-(E_c - E_F)/kT}$$

$$N_c = 2\left(\frac{2\pi m_n kT}{h^2}\right)^{\frac{3}{2}} (1.602 \times 10^{-19})^{3/2}$$

h – Planck's Cons; m_n → effective mass of an e^-.

K – Boltzmann Constant.

P-type



$$\boxed{E_F = E_v + KT \ln \frac{N_v}{N_A}} \quad \text{——— (3)}$$

N_A – Concentration of Acceptor atoms.

$$N_v = 2\left(\frac{2\pi m_p kT}{h^2}\right)^{3/2} (1.602 \times 10^{-19})^{3/2}.$$

$$N_A = N_v \, e^{-(E_F - E_v)/kT};$$

m_p → effective mass of a hole.