UNIT- 2

* Semiconductor diode characteristics

→ Qualitative Theory of the pn junction

→ p-n junction as a diode

→ Band structure of an open circuited pn junction

→ current components in a pn diode

→ Quantitative Theory of pn diode currents

→ VI characteristics

→ Temperature dependence of VI characteristics

→ Diode Resistance

→ Ideal Vs Practical diode

→ Diode equivalent circuits

→ space charge or transition capacitance (C_T)

→ Diffusion capacitance (C_D)

→ Breakdown mechanism in diode

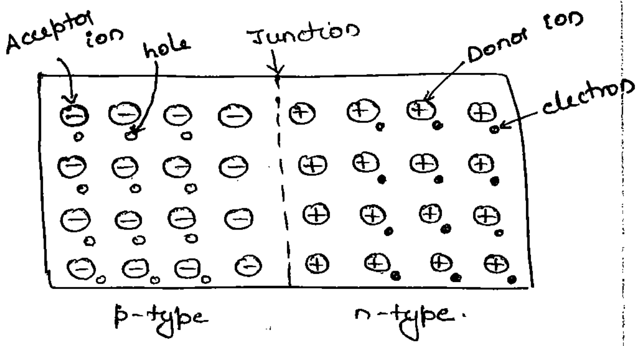
→ zener diode

→ VI characteristics of zener diode

Semiconductor Diode characteristics

* Qualitative Theory of pn Junction

If donor impurities are introduced into one side and acceptors into the other-side of a single crystal of a semiconductor, a pn junction is formed. Such a system is shown below.



The donor atom (ion) is indicated symbolically by a plus sign because, after this impurity atom "donates" an electron, it becomes a positive ion.

The acceptor ion is indicated by a minus sign because, after this atom "accepts" an electron, it becomes a negative ion.

Initially there are nominally only p-type carriers to the left of the junction and only n-type carriers to the right. Because there is a density gradient across the junction, holes will diffuse to the right across the junction, and electrons to the left.

~~The holes recombine with the donor atoms. As donor atoms accepts accept an~~

The holes which neutralized the acceptor ions near the junction in p-type have disappeared as a result of recombination with electrons which have diffused from n-type. Illy, the neutralizing electrons in the n-type germanium have combined with holes which have crossed the junction from p-material.

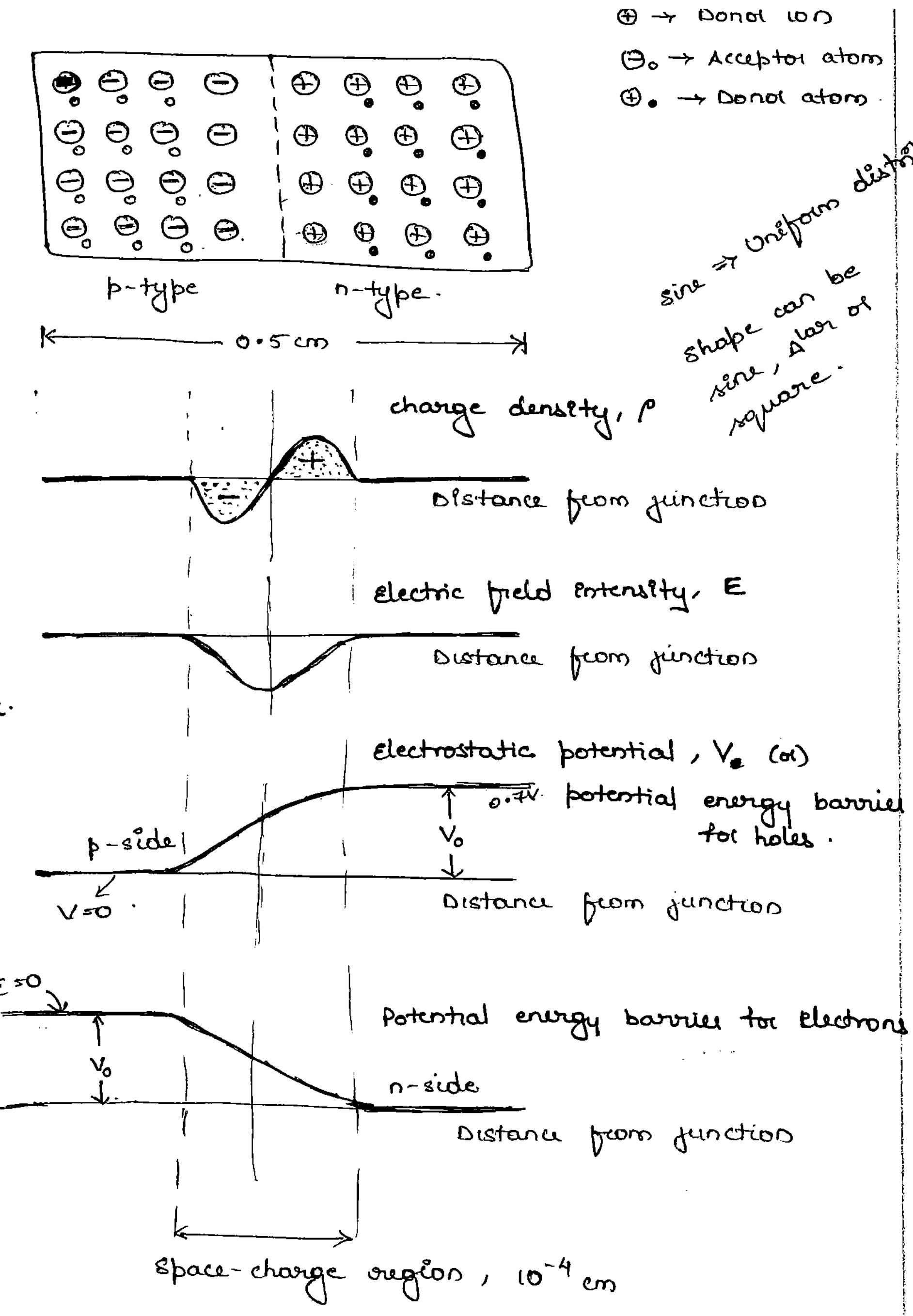
⇒ The unneutralized ions in the neighborhood of junction are referred to as uncovered charges. Since, the region of the junction is depleted of mobile charges, it is called the depletion region (or) the space-charge region (or) the transition region.

The thickness of this region is

$$10^{-4}\ cm = 10^{-6}\ m = 1\ micron.$$

The electric charges are confined to the neighborhood of the junction & consist of immobile ions. The general shape of the charge distribution is shown in fig (b).

a)



Poisson's Equation

b) $\dfrac{d^2V}{dx^2} = \dfrac{-\rho}{\epsilon}$

ϵ = permittivity.

c) $E = \dfrac{-dV}{dx}$

$= \int \dfrac{\rho}{\epsilon} \cdot dx.$

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

e)

Near the junction, on one side there are many +ve charges and on the other side there are many -ve charges. According to coulomb's law, There exists a force between The opposite charges. And This force produces an electric field between The charges. This electric field is responsible to produce potential difference across The junction, which is called barrier potential.

The electric field intensity in the neighborhood of The junction is shown in figure (c). And The curve is The integral of the density function in figure (b).

The electrostatic potential variation in the depletion region for holes is shown in fig (d). and this is the negative integral of the function E in fig (c). This variation constitutes a potential energy barrier against the further diffusion of holes across the barrier.

The potential energy barrier against the flow of electrons from the n-side across the junction is shown in figure (e). It is similar to that shown in fig (d) except that it is inverted since the charge on electron is negative.

Barrier Potential.

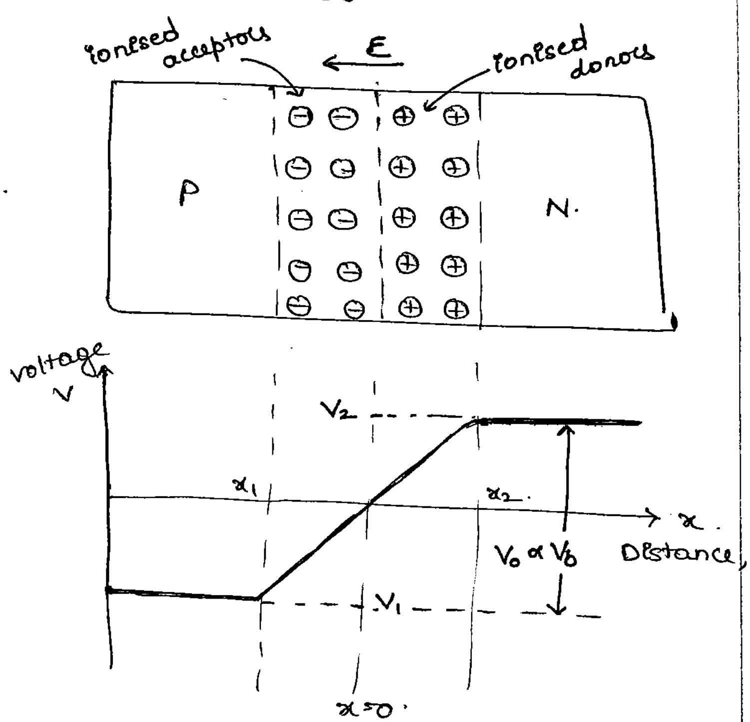
Barrier potential indicates the amount of voltage to be applied across the pn junction to restart the flow of electrons and holes across the junction. The barrier potential is also called as junction potential or built in potential barrier or contact potential or diffusion potential.

The barrier potential is expressed in volts. Its value is called height of barrier. It is denoted by V_0 or V_b.

Barrier potential for Si = 0.7 V at 25°C. Ge = 0.3 V. at 25°C } ⟶ (2.1)

The magnitude of barrier potential varies with doping levels & temperature.

The barrier potential can be increased or decreased by applying an external voltage.



The barrier potential of a pn junction mainly depends on the following factors:

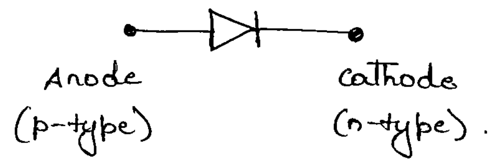
1) Type of semiconductor used.
2) Concentration of acceptor impurity on p-side
3) Concentration of donor impurity on n-side
4) Intrinsic concentration of basic semiconductor
5) Temperature.

* The pn junction as a diode

The essential characteristic of a pn junction is that it constitutes a diode which permits flow of current in one direction but restrains the flow in opposite direction.

In order to consider working of a diode we shall consider the effect of forward bias and reverse bias across PN junction.

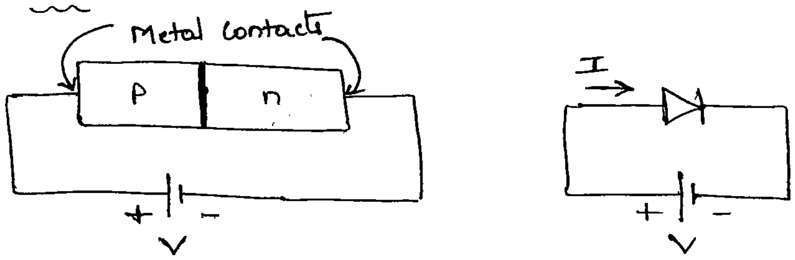
The symbol of diode is shown below.



when diode is forward biased, the arrow head shows the conventional direction of current flow, i.e the direction in which the hole flow takes place.

a) Forward bias

when positive terminal of battery is connected to p-type and negative terminal is connected to n-type, then it is called forward bias.



when the pn junction is forward biased, as long as applied voltage is less than the barrier potential, there cannot be any conduction.

when the applied voltage becomes more than the barrier potential, the negative terminal of the battery pushes the free electrons against the barrier potential from n to p region. Illy, positive terminal pushes the holes from p to n region. Thus, holes get repelled by +ve terminal and across the junction against the barrier potential, electrons get repelled from -ve terminal and across the junction against barrier potential.

⇒ applied voltage overcomes the barrier potential → reduces the width of the depletion region.

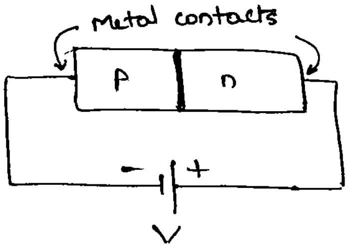
barrier voltage. when the external voltage is slowly increased, the size of depletion region slowly decreases. Once the external voltage is greater than the internal barrier potential then depletion region is almost reduced. ⇒ current increases very rapidly.

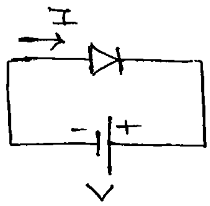
The voltage at which the current increases sharply and suddenly is known as cut-in-voltage. It is represented by V_γ.

$$\left.\begin{aligned} V_\gamma &= 0.2V / 0.3V \text{ for Ge.} \\ &= 0.6V / 0.7V \text{ for Si.} \end{aligned}\right\} \rightarrow (2.2)$$

b) Reverse bias

when a negative terminal of the battery is connected to the p-type semiconductor and +ve terminal is connected to n-type semiconductor, then it is called Reverse biased.





when the pn junction is reverse biased, the negative terminal attracts the holes in the p-region, away from the junction. The positive terminal attracts the free electrons in the n-region away from the junction. No charge carriers is available to cross the junction. As electrons & holes both move away from the junction, the depletion width increases.

As depletion region widens, barrier potential across the junction also increases. The polarities of barrier potential are same as that of applied voltage.

Due to increased barrier potential, the positive side of barrier potential drags electrons from p-region towards +ve terminal of battery. (minority carriers e^- in p-type move towards +ve terminal of the battery). Illy, negative side of barrier potential drags holes from n region towards negative terminal of battery (i.e minority carriers holes from n-type move [illegible] of p-type.

These holes from n-type and electrons from p-type constitute current in reverse biased condition, called as reverse current or reverse saturation current (I_0) of diode.

Minority carriers are very small in number. ⇒ reverse saturation current is very small. It is few microamperes. (μA).

For a constant temperature, the reverse current is almost constant through reverse voltage is increased upto a certain limit ⇒ The name reverse saturation current.

The generation of minority charge carriers depends on the temperature and not on the applied reverse bias voltage. ⇒ reverse current depends on the temperature i.e thermal generation and not on the reverse voltage applied.

Short-circuited & Open-circuited pn junction

Energy band structure of an open circuited pn junction

A pn junction is formed by placing n-type and p-type materials in intimate contact on an atomic scale. Under these conditions the fermi level must be constant throughout the specimen at equilibrium.

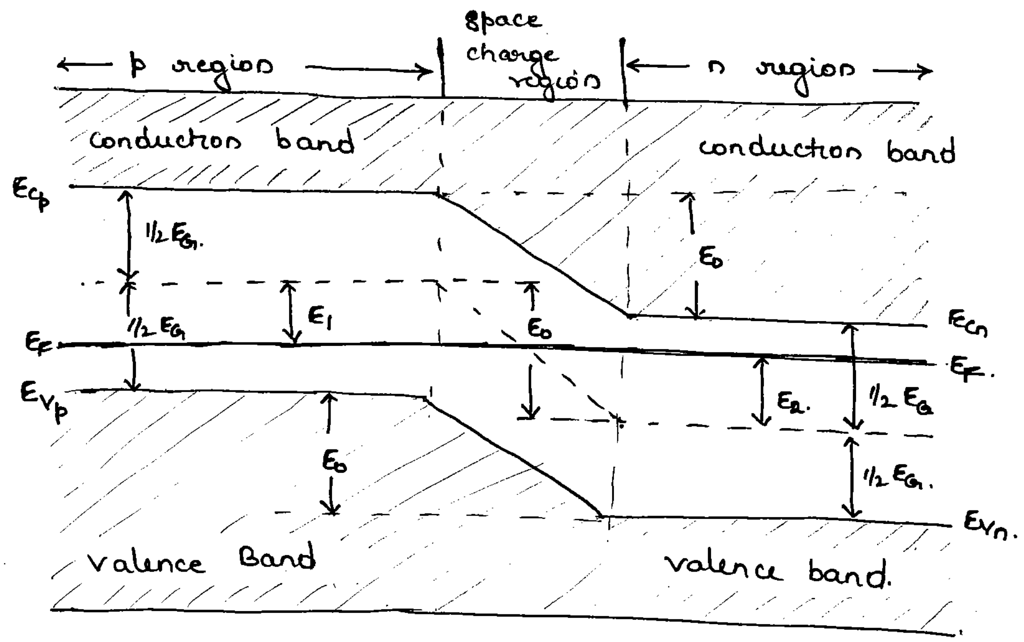
If there were not so, electrons on one side of the junction would have an average energy level higher than those on the other side, and there would be a transfer of e^- and energy until fermi levels on both sides line up.

But we know that the fermi level is close to conduction band edge E_{Cn} in the n-type material and closer to valence band edge E_{Vp} in the p-type material.

⇒ clearly E_{Cn} and E_{Cp} cannot be at the same level

Illy E_{Vn} and E_{Vp} cannot be at the same level.

Hence, the energy band diagram for a pn junction appears as shown below.



Let E_1, E_2 indicates a shift in the fermi level, from the intrinsic conductions in p-type and n-type semiconductor. The shift in the energy level.

$$\boxed{\begin{aligned} E_0 = E_1 + E_2 &= E_{Cp} - E_{Cn} \\ &= E_{Vp} - E_{Vn} \end{aligned}} \longrightarrow (2.3)$$

Derivation for Contact Potential.

From mass action law,

$$np = n_i^2$$

where $n = N_C \cdot e^{-(E_C - E_F)/KT}$

$$p = N_V \cdot e^{-(E_F - E_V)/KT}$$

$$\Rightarrow np = N_C \cdot N_V \cdot e^{-(E_C - \cancel{E_F} + \cancel{E_F} - E_V)/KT}$$

$$= N_C \cdot N_V \cdot e^{-(E_C - E_V)/KT}$$

$$np = N_C \cdot N_V \cdot e^{-(E_G)/KT} \longrightarrow (2.4)$$

$$\Rightarrow \boxed{n_i^2 = N_C \cdot N_V \cdot e^{-E_G/KT}} \longrightarrow (2.5)$$

$$\Rightarrow \boxed{E_G = KT \ln\left(\frac{N_C \cdot N_V}{n_i^2}\right)} \longrightarrow (2.6)$$

For n-type,

$$n \simeq N_D = N_C \cdot e^{-(E_{C_n} - E_F)/KT}.$$

$$\Rightarrow E_{C_n} - E_F = KT \ln\left(\frac{N_C}{N_D}\right). \longrightarrow (2.7)$$

For p-type,

$$p \simeq N_A = N_V \cdot e^{-(E_F - E_{V_p})/KT}$$

$$\Rightarrow E_F - E_{V_p} = KT \ln\left(\frac{N_V}{N_A}\right) \longrightarrow (2.8)$$

But from ~~the~~ energy band structure,

$$E_{C_n} - E_F = \frac{1}{2} E_G - E_2 \longrightarrow (2.9)$$

and $E_F - E_{V_p} = \frac{1}{2} E_G - E_1. \longrightarrow (2.10)$

$$\Rightarrow \frac{1}{2} E_G - E_2 + \frac{1}{2} E_G - E_1 = (E_{C_n} - E_F) + (E_F - E_{V_p})$$

$$\Rightarrow E_1 + E_2 = E_G - (E_{C_n} - E_F) - (E_F - E_{V_p}) = E_0. \longrightarrow (2.11)$$

$$\Rightarrow E_0 = KT \ln\left(\frac{N_C \cdot N_V}{n_i^2}\right) - \left(KT \ln\left(\frac{N_C}{N_D}\right) + KT \ln\left(\frac{N_V}{N_A}\right)\right)$$

$$= KT \ln\left(\frac{\cancel{N_C} \cdot \cancel{N_V}}{n_i^2} \cdot \frac{N_D \cdot N_A}{\cancel{N_C} \cdot \cancel{N_V}}\right)$$

(eq (2.6), (2.7), (2.8) in (2.11))

$$\Rightarrow \boxed{E_0 = KT \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right)} \longrightarrow (2.12)$$

E_0 is the potential energy of open-circuit PN junction.

But $E_0 = qV_0$.

$\Rightarrow$ Contact potential, $\boxed{V_0 = \frac{1}{q} KT \ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)} \rightarrow$ (2.13)

<u>Note</u> :- $E_0 = KT \ln\left[\frac{N_A \cdot N_D}{n_i^2}\right]$.

But $n_n \simeq N_D$ (e^- concentration in n-type).

$p_n = \frac{n_i^2}{N_D}$ (hole concentration in n-type).

$p_p \simeq N_A$ (hole concentration in p-type)

$n_p = \frac{n_i^2}{N_A}$ (e^- concentration in p-type)

$\Rightarrow E_0 = KT \ln\left(\frac{p_p}{p_n}\right)$ since $E_0 = qV_0$ and $V_T = \frac{KT}{q}$.

$\Rightarrow \boxed{p_p = p_n \cdot e^{E_0/KT} = p_n e^{V_0/V_T}} \rightarrow$ (2.14)

* Current Components in a pn diode

In a forward bias condition, holes get diffused into n-side from p-side while electrons get diffused into p-side from n-side $\Rightarrow$ on p-side, The current carried by electrons is minority carrier current which is due to diffusion.

Since, diffusion current of minority carriers is proportional to the concentration gradient $\Rightarrow$ This current exponentially decreases with distance from junction because injected minority carriers fall off exponentially with distance from junction.

The minority current due to electrons on p-side is denoted by I_{np} and the minority current due to holes on n-side is denoted by I_{pn}.

If x denotes distance, Then

$I_{np}(x)$ = current due to e^- on p side as function of x.

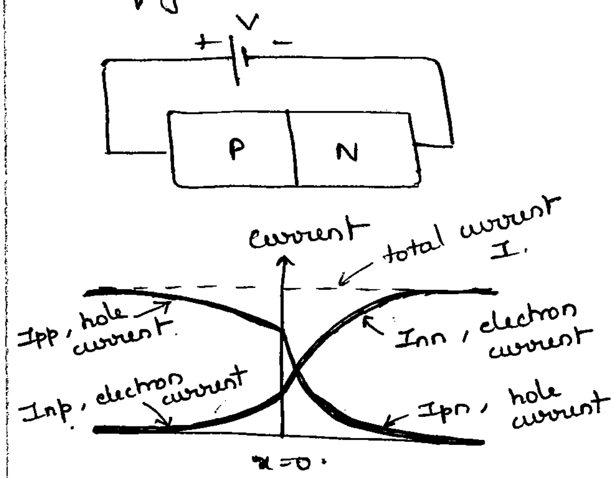
$I_{pn}(x)$ = current due to holes on n-side as function of x.

At junction i.e at $x=0$, electrons crossing from right to left $I_{np}(0)$ constitute a current in the same as holes crossing from left to right $I_{pn}(0)$.

$\Rightarrow$ total current at the junction,

$$\boxed{I = I_{np}(0) + I_{pn}(0).} \longrightarrow (2.15)$$

Since, the current is the same throughout a series circuit, I is independent of x and is indicated as a straight line in the figure shown below



Consequently, in the p side, there must a second component of current I_{pp} which, when added to I_{np} gives the total current I

$\Rightarrow$ The hole current (majority current) in p side is given by.

$$I_{pp}(x) = I - I_{np}(x) \rightarrow (2.16)$$

I_{pp}, I_{nn} = drift current

I_{np}, I_{pn} = diffusion current.

$$\text{Illy}, \; I_{nn}(x) = I - I_{pn}(x). \longrightarrow (2.17)$$

The current I_{pp} of holes is due to the electric field in the semiconductor (drift current). As the holes approach the junction, some of them recombine with the electrons, which are injected into p-side from n-side.

$\Rightarrow$ part of the current I_{pp} becomes a negative current just equal to I_{np} (diffusion current) $\Rightarrow$ I_{pp} decreases towards the junction at just the proper rate to maintain total current constant independent of distance.

The remaining current of I_{pp} enters into n-side & becomes the hole diffusion current I_{pn}

Illy I_{nn} decreases toward the junction

$\Rightarrow$ In forward bias, current enters p-side as hole current & leaves the n-side as electron current of the same magnitude.

** The total current is constant throughout the device, but the

Quantitative theory of pn diode currents

↳ Derive the expression for the total current as a function of the applied voltage (VI characteristics).

① Assumption: we neglect the depletion-layer thickness and hence assume the barrier width is 0.

② From continuity eq of holes in n-type,

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

when concentration is independent of t and $E = 0$

$$\Rightarrow \frac{dp}{dt} = 0 \quad \text{and} \quad \mu_p \cdot \frac{d(pE)}{dx} = 0.$$

$$\Rightarrow 0 = -\frac{(p-p_0)}{\tau_p} + D_p \cdot \frac{d^2p}{dx^2} - 0.$$

$$\Rightarrow \frac{d^2p}{dx^2} = \frac{p-p_0}{\tau_p D_p} = \frac{p-p_0}{L_p^2} \qquad \left(\because L_p = \sqrt{\tau_p \cdot D_p} = \text{diffusion length}\right)$$

$$\frac{d^2p}{p-p_0} = \frac{dx^2}{L_p^2}$$

solution to this eq is

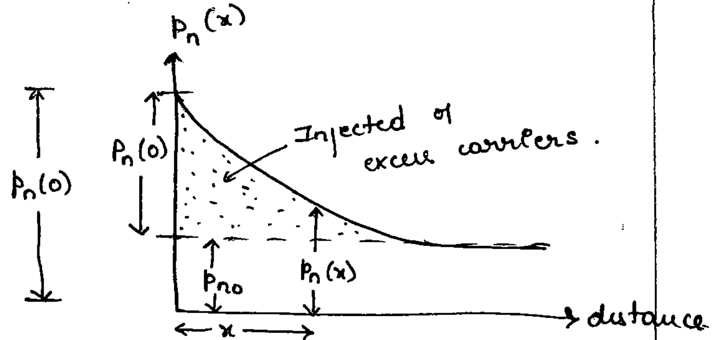
$$p_n - p_{n_0} = K_1 e^{-x/L_p} + K_2 \cdot e^{x/L_p} \qquad \left[\because \int \frac{1}{p} \cdot dp = \log p\right]$$

As $x \to \infty$, $e^{x/L_p} \to \infty \Rightarrow$ concentration tend to ∞

But concentration doesnot tend to ∞ as $x \to \infty$.

$$\Rightarrow K_2 = 0.$$

$$\Rightarrow p_n - p_{n_0} = K_1 e^{-x/L_p}$$



Let $p_n - p_{n_0} = P_n(x)$

= Excess or Injected carrier concentration

Now, at $x = 0$,

$$p_n(0) - p_{n_0} = P_n(0).$$

To satisfy this boundary condition, $K_1 = P_n(0)$

$$\boxed{p_n(x) - p_{no} = P_n(0) \cdot e^{-x/L_p}} \longrightarrow (2.18)$$

and injected or excess concentration at $x=0$ is

$$\boxed{P_n(0) = p_n(0) - p_{no}} \longrightarrow (2.19)$$

The diffusion hole current in n-side is given by

$$I_{p_n} = -A\,e\,D_p \cdot \frac{dp_n}{dx}.$$

but $p_n(x) = p_{no} + P_n(0) \cdot e^{-x/L_p}$

$$\Rightarrow \frac{dp_n}{dx} = 0 - \frac{P_n(0)}{L_p} \cdot e^{-x/L_p}.$$

$$\frac{dp_n}{dx} = -\frac{P_n(0)}{L_p} \cdot e^{-x/L_p}.$$

$$\Rightarrow \boxed{I_{p_n}(x) = \frac{A\,e\,D_p\,P_n(0)}{L_p} \cdot e^{-x/L_p}} \longrightarrow (2.20)$$

$\Rightarrow$ hole current decreases exponentially wrt distance

The dependence of I_{p_n} upon applied voltage is contained implicitly in the factor $P_n(0)$ because the injected concentration is a function of voltage.

We will now find the dependence of $P_n(0)$ on V.

(3) If the hole concentrations at the edges of space-charge regions are p_p and p_n in p and n type respectively and if the barrier potential across the depletion region is V_B, then

from eq (2.14), $\boxed{p_p = p_n \cdot e^{V_B/V_T}} \longrightarrow (2.21)$

This eq is called Boltzmann's relationship of kinetic gas theory

In an open circuit pn junction, $p_p = p_{po}$, $p_n = p_{no}$, $V_B = V_o$.

$$\Rightarrow \boxed{p_{po} = p_{no} \cdot e^{V_o/V_T}.} \longrightarrow (2.22)$$

Under forward bias with an applied voltage of V, $V_B = V_o - V. \rightarrow (2.23)$

+ hole concentration is constant throughout p region $\Rightarrow p_p = p_{po}$.

At edge of depletion region, $x=0$, $p_n = p_n(0)$.

$$\Rightarrow \boxed{p_{po} = p_n(0) \cdot e^{(V_o - V)/V_T}} \longrightarrow (2.24) \qquad \text{IIIly } \boxed{n_p(0) = n_{po} \cdot e^{V/V_T}} \rightarrow (2.26)$$

eq (2.22) - (2.24) $\Rightarrow p_n(0) \cdot e^{(V_o-V)/V_T} = p_{no} \cdot e^{V_o/V_T} \Rightarrow \boxed{p_n(0) = p_{no} \cdot e^{V/V_T}} \rightarrow (2.25)$

From law of junction, we have.

$$p_n(0) = p_{no} \cdot e^{V/V_T}.$$

where p_{no} = hole concentration at the edge of the space charge region in n-type material under open circuited condition

$p_n(0)$ = hole concentration at the edge of the depletion region in n-type material under forward biased condition.

The hole concentration $P_n(0)$ injected into the n side at the junction is obtained by substituting (2.25) in (2.19)

$$P_n(0) = p_n(0) - p_{no}.$$

$$= p_{no} \cdot e^{V/V_T} - p_{no}$$

$$\Rightarrow P_n(0) = p_{no}\left[e^{V/V_T} - 1\right]. \longrightarrow (2.27)$$

a) <u>Forward current</u>

The hole current $I_{pn}(0)$ crossing the junction into the n-side is given by eq (2.20), with $x = 0$ ($\Rightarrow$ exponent $e^{-0/L_p} = 1$).

$$I_{pn}(0) = \frac{A e D_p}{L_p} \cdot P_n(0). \longrightarrow (2.28)$$

Substituting eq (2.27) in (2.28)

$$I_{pn}(0) = \frac{A e D_p p_{no}}{L_p}\left[e^{V/V_T} - 1\right]. \rightarrow (2.29)$$

finally, from eq (2.15), the total diode current I is

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

we have $I_{pn}(0) = \dfrac{A e D_p \cdot p_{no}}{L_p}\left[e^{V/V_T} - 1\right]$

Illy $I_{np}(0) = \dfrac{A e D_n n_{po}}{L_n}\left[e^{V/V_T} - 1\right] \rightarrow (2.29)$

$$\Rightarrow I = I_o\left[e^{V/V_T} - 1\right] \longrightarrow (2.30)$$

where $I_o = \dfrac{A e D_p \cdot p_{no}}{L_p} + \dfrac{A e D_n n_{po}}{L_n}. \longrightarrow (2.31)$

The diode equation assumes that $W_p \gg L_p$ and $W_n \gg L_n$.
If at some times this condition is not true, the expression for I_o remains valid provided that L_p and L_n are replaced by W_p and W_n.

b) Reverse saturation current

If V is +ve in the current eq $\Rightarrow$ forward bias
If V is −ve in the current eq $\Rightarrow$ reverse bias.

For a reverse bias whose magnitude is large compared with V_T ($\sim$ 26 mV at room temperature)

$$I \rightarrow -I_o \quad (I \text{ approaches } -I_o). \longrightarrow (2.32)$$

Hence, I_o is called Reverse saturation current.

from eq (1.72) and (1.74) and (2.31)

$$I_o = Ae\left(\frac{D_p}{L_p \cdot N_D} + \frac{D_n}{L_n \cdot N_A}\right) n_i^2 . \longrightarrow (2.33)$$

$$\left.\begin{aligned} \text{where } n_i^2 &= A_o T^3 \cdot e^{-E_{GO}/KT} \\ &= A_o T^3 \cdot e^{-V_{GO}/V_T} \end{aligned}\right\} \longrightarrow (2.34)$$

where V_{GO} = voltage which is numerically equal to the forbidden-gap energy E_{GO} in eV

V_T = volt-equivalent of temperature.

For germanium, D_p + D_n vary approximately inversely proportional to T.

$\Rightarrow$ temperature dependence of I_o is

$$I_o = K_1 T^2 e^{-V_{GO}/V_T} . \longrightarrow (2.35)$$

where K_1 = constant independent of temperature.

If we consider the carrier generation + recombination in the space-charge region, the general eq of diode is

$$\boxed{I = I_o\left[e^{V/\eta V_T} - 1\right].} \longrightarrow (2.36)$$

where $\eta = 2$ for small currents +
$\eta = 1$ for large currents.

$$+ \quad \boxed{I_o = K_2 T^{1.5} \cdot e^{-V_{GO}/2V_T}.} \longrightarrow (2.37)$$

for silicon, we have to consider recombination also. $\Rightarrow \eta = 1$ for Ge
$\eta = 2$ for Si

For a pn junction, The current I is related to the voltage V by the equation

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

A positive value of $I \Rightarrow$ current flows from p to n side. The diode is forward biased if V is positive, indicating that The p side of the junction is positive wrt n side.

$$\left.\begin{aligned} \eta &= 1 \text{ for Ge} \\ &= 2 \text{ for Si.} \end{aligned}\right\} \longrightarrow (2.38)$$

and $V_T = \dfrac{T}{11,600}$ = volt equivalent of temperature.

At room temperature, $V_T = 26\,mV$ (at $300°K$).

a) **Forward bias characteristics of pn junction diode**

when a voltage V is applied to pn junction diode, below the cut-in voltage V_γ, the diode will not conduct and the current flowing is 0.

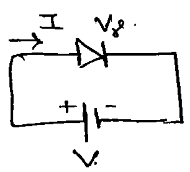
The diodes will have a cutin voltage, offset voltage, or breakpoint or Threshold voltage V_γ, below which the current is very small (say, less Than 1% of maximum rated value). Beyond V_γ, The current raises very rapidly.

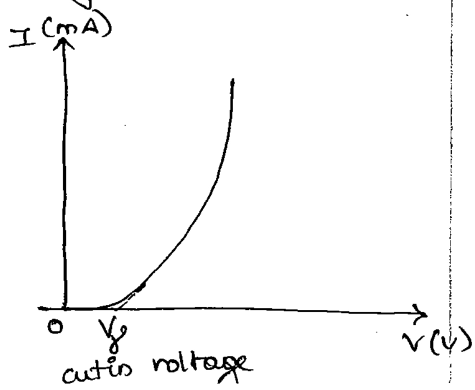
$$\left.\begin{aligned} V_\gamma &= 0.2V \text{ for Ge} \\ &= 0.6V \text{ for Si.} \end{aligned}\right\} \longrightarrow (2.39)$$

when the voltage V is greater Than V_γ, The potential barrier across The junction is completely eliminated & current rises very rapidly i.e when V is several times greater than V_T, The unity in The parenthesis of diode eq. is neglected

$$\Rightarrow \boxed{I = I_0\, e^{V/\eta V_T}} \longrightarrow (2.40)$$

$\Rightarrow$ current increases exponentially with applied voltage V

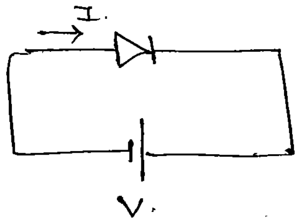




b) Reverse characteristics of pn junction diode

when diode is reverse biased with $|V| \gg V_T$,
The exponent term becomes very small because V is -ve
⇒ Exponent term is neglected & $\boxed{I \simeq -I_0}$ → (2.41)

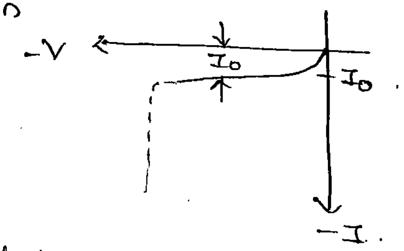
⇒ Reverse current is constant independent of the applied reverse bias ⇒ called as reverse saturation current.



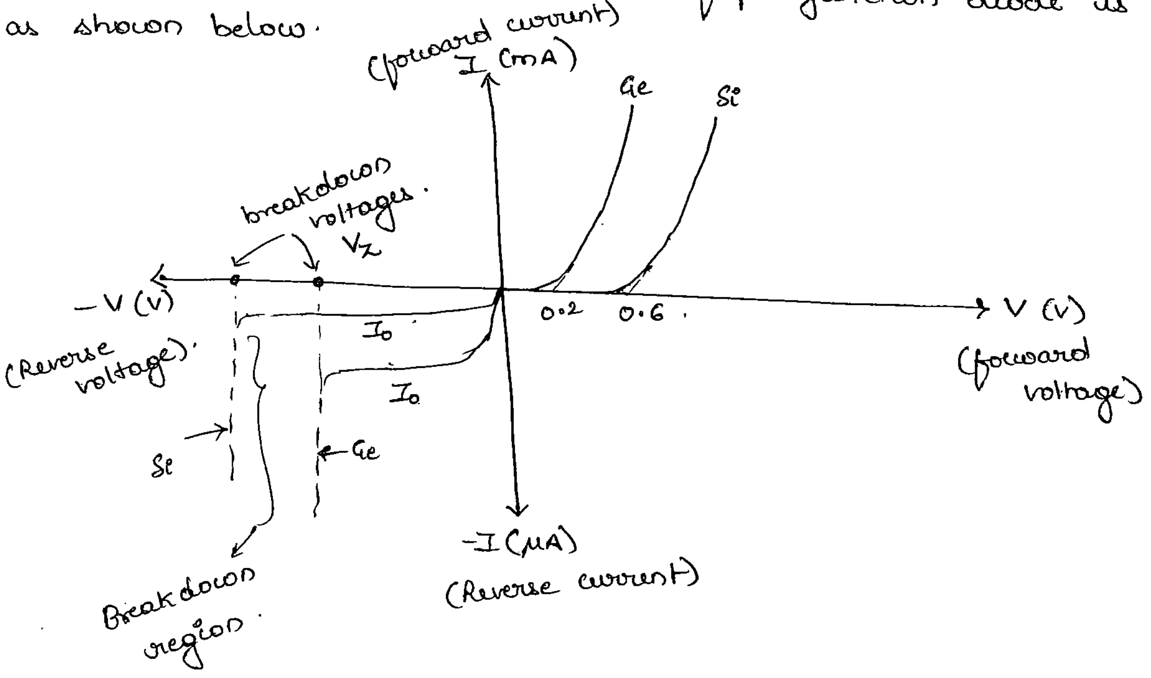
when pn junction is reverse biased, The negative terminal of The battery attracts holes in p-region away from the junction. The positive terminal attracts electrons in n-region away from The junction.

⇒ As holes and electrons move away from the junction, depletion region widens ⇒ barrier potential across the junction increases Thus polarities of barrier potential is same as applied voltage.

However, a small current (μA) flows across The junction due to movement of minority charge carriers. The generation of minority charge carriers depend on temperature but not on applied voltage ⇒ Io is constant. as shown



The complete VI characteristics of pn junction diode is as shown below.



Calculate the forward bias voltage at room temperature of 27°c and 1% of the rated current is flowing through forward biased diode. The diode forward rated current is 1 A.

Sol: Given That, $I_0 = 3\mu A$.

$T = 27°C = 27 + 273 = 300° K.$

$\eta = 1$ for Ge.

Now, $I_{rated} = 1A$ for diode

4 $I = 1\%$ of I_{rated} at 27°C

$= \frac{1}{100} \times 1 = \underline{\underline{0.01}} A$

$V_T = KT = 8.62 \times 10^{-5} \times 300 = 0.026 V.$

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

According to diode equation,

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

$$0.01 = 3 \times 10^{-6} (e^{V/1 \times 0.026} - 1).$$

$$e^{V/0.026} = 3334.3333$$

$$\frac{V}{0.026} = \ln(3334.3333) = 8.112.$$

$$V = \underline{\underline{0.2109 V}}$$

(Pb) A diode operating at 300° K at a forward voltage of 0.4V carries a current of 10mA. When voltage is changed to 0.42V, The current becomes twice. Calculate The value of reverse saturation current + η for the diode.

Sol: Given That, $V_1 = 0.4 V$, $I_1 = 10 mA$

Then at $V_2 = 0.42V$, $I_2 = 2I_1 = 20 mA$.

Now, $I = I_0 (e^{V/\eta V_T} - 1)$

$$10 \times 10^{-3} = I_0 (e^{0.4/\eta \times 0.026} - 1)$$

$$20 \times 10^{-3} = I_0 (e^{0.42/\eta \times 0.026} - 1)$$

$\Rightarrow$ neglecting 1

$$10 \times 10^{-3} = I_0 \cdot e^{15.384/\eta}$$

$$20 \times 10^{-3} = I_0 \cdot e^{16.153/\eta}$$

dividing these two eq.

$$\frac{1}{2} = \frac{e^{15.384/\eta}}{e^{16.153/\eta}}$$

$$2e^{15.384/\eta} = e^{16.153/\eta}$$

Taking natural logarithms on both sides

$$\frac{16.153}{\eta} = \ln 2 + \frac{15.384}{\eta}$$

$$\frac{1}{\eta}(16.153 + 15.384) = \ln 2 = 0.6931$$

$$\Rightarrow \eta = \underline{\underline{1.109}}$$

and $I_0 = \underline{\underline{9.45\,mA}}$ $\left(I_0 = \frac{I}{[e^{V/\eta V_T} - 1]} \right)$.

(Pb) The voltage across the diode (Si) at room temperature of 300°K is 0.71V when 2.5mA current flows through it. If the voltage increases to 0.8V, calculate the new diode current.

Sol: $I = I_0 (e^{V/\eta V_T} - 1)$

At 300°K, $V_T = 26\,mV = 26 \times 10^{-3}\,V$

$V = 0.71V$ for $I = 2.5mA$

for Si diode $\eta = 2$

$$\Rightarrow 2.5 \times 10^{-3} = I_0 \left(e^{0.71/2 \times 26 \times 10^{-3}} - 1\right)$$

$$I_0 = \underline{\underline{2.93 \times 10^{-9}\,A}}$$

Now, $V = 0.8V$

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

$$= 2.93 \times 10^{-9} \left(e^{0.8/2 \times 26 \times 10^{-3}} - 1\right)$$

$$= 0.0141\,A = \underline{14.11\,mA}$$

when 2mA current flows through it. If the voltage increases to 0.75V, calculate the diode current assuming $V_T = 26$ mV.

Sol: Given $V = 0.75V$, $\eta = 2$ for Si, $V_T = 26$ mV at $300°K$, $I = 2mA$

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

$$2 \times 10^{-3} = I_0 (e^{0.7/2 \times 26 \times 10^{-3}} - 1)$$

$$I_0 = 2.8494 \times 10^{-9} A$$

New voltage, $V' = 0.75V$

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

$$= 2.8494 \times 10^{-9} (e^{0.75/2 \times 26 \times 10^{-3}} - 1)$$

$$= \underline{5.2313 \text{ mA}}$$

(Pb) Determine the values of forward current in the case of a pn junction diode, with $I_0 = 10$ mA. $V_f = 0.8V$ at $T = 300°K$. Assume Si diode

Sol: Given, $V_f = 0.8V$, $T = 300°K \Rightarrow V_T = 26mV$.

$I_0 = 10mA$, $\eta = 2$ for Si

$$I = I_0 (e^{V/\eta V_T} - 1) = 10 \times 10^{-3} (e^{0.8/2 \times 26 \times 10^{-3}} - 1).$$

$$= \underline{52.1945 \text{ A}}$$

(Pb) A Si diode has a reverse saturation current of 7.12 nA at room temperature of 27°C. Calculate its forward current if it is forward biased with a voltage of 0.7V.

Sol: Given $I_0 = 7.12nA$, $V = 0.7V$

$\eta = 2$ for Si, $T = 273 + 27 = 300°K$. $\Rightarrow V_T = 26mV$

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

$$= 7.12 \times 10^{-9} (e^{0.7/2 \times 0.026} - 1)$$

$$= 4.99 \times 10^{-3} A$$

$$\Rightarrow \underline{I \simeq 5mA}$$

and 20mA when The applied voltage is 500 mV. Determine η. Assume $\frac{KT}{q} = 25 mV$.

Sol: $I = I_0 (e^{V/\eta V_T} - 1)$

$0.6 \times 10^{-3} = I_0 (e^{400/25\eta})$ ($\Rightarrow$ neglecting 1)

Illy $20 \times 10^{-3} = I_0 (e^{500/25\eta})$.

$\Rightarrow \frac{20 \times 10^{-3}}{0.6 \times 10^{-3}} = \frac{e^{500/25\eta}}{e^{400/25\eta}}$.

$\Rightarrow \frac{100}{3} = e^{4/\eta}$

$\Rightarrow \ln\left(\frac{100}{3}\right) = \frac{4}{\eta} \Rightarrow \eta = \frac{4}{3.507} = \underline{\underline{1.14}}$

a) Effect of temperature on reverse saturation current (I_0)

we know that,

$$I_{pn}(0) = \frac{Ae D_p P_{no}}{L_p}\left(e^{V/V_T} - 1\right). \quad \text{(from eq 2.29)}$$

$$I_{np}(0) = \frac{Ae D_n n_{po}}{L_n}\left(e^{V/V_T} - 1\right). \quad \text{(from eq 2.29)}$$

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

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

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

$$\Rightarrow I_0 = \frac{Ae D_p P_{no}}{L_p} + \frac{Ae D_n n_{po}}{L_n}.$$

According to Mass-Action Law,

$$P_n = \frac{n_i^2}{N_D} \quad \text{and} \quad n_p = \frac{n_i^2}{N_A}.$$

$$\Rightarrow I_0 = \left(\frac{Ae D_p}{L_p N_D} + \frac{Ae D_n}{L_n N_A}\right) n_i^2.$$

But $n_i^2 = A_0 T^3 e^{-E_{G0}/KT}$.

$$\Rightarrow I_0 = Ae\left(\frac{D_p}{L_p N_D} + \frac{D_n}{L_n \cdot N_A}\right) A_0 T^3 e^{-E_{G0}/KT}.$$

$$\Rightarrow \boxed{I_0 = K_1 \cdot T^m \cdot e^{-E_{G0}/\eta KT}}$$

(or) $\longrightarrow$ 2.42

$$\boxed{I_0 = K_1 \cdot T^m \cdot e^{-V_{G0}/\eta V_T}}$$

for Ge, $\eta = 1$, $m = 2$, $V_{G0} = 0.785$ V.

for Si, $\eta = 2$, $m = 1.5$, $V_{G0} = 1.21$ V.

$$I_0 = K_1 T^{m} e^{-V_{G0}/\eta V_T}$$

$$\Rightarrow \ln(I_0) = \ln\left(K_1 T^m e^{-V_{G0}/\eta V_T}\right)$$

$$\Rightarrow \ln(I_0) = \ln(K_1) + \ln(T^m) + \ln\left(e^{-V_{G0}/\eta V_T}\right)$$

$$\Rightarrow \ln(I_0) = \ln(K_1) + m\ln(T) - \frac{V_{G0}}{\eta V_T}.$$

$$\Rightarrow \frac{d\ln(I_0)}{dT} = 0 + \frac{m}{T} - \frac{V_{G0}}{\eta\, K/q}\left(-\frac{1}{T^2}\right) \qquad \left(\because V_T = \frac{KT}{q}\right)$$

$$\Rightarrow \boxed{\frac{1}{I_0}\cdot\frac{dI_0}{dT} = \frac{m}{T} + \frac{V_{G0}}{\eta T V_T}} \longrightarrow (2.43)$$

where $\frac{dI_0}{dT}$ = fractional change in I_0 per degree rise in temperature

$$\boxed{\frac{d(\ln I_0)}{dT} = \frac{m}{T} + \frac{V_{G0}}{\eta V_T \cdot T}} \longrightarrow (2.44)$$

Case (a) :- For Germanium

Substituting the values of various terms at room temperature we get,

$$\frac{d(\ln I_0)}{dT} = \frac{2}{300} + \frac{0.785}{1 \times 300 \times 26 \times 10^{-3}} = 0.11 \text{ per } ^\circ C.$$

This indicates that I_0 increases by **11% per degree** rise in temperature.

Case (b) :- For silicon

$$\frac{d(\ln I_0)}{dT} = \frac{1.5}{300} + \frac{1.21}{2 \times 300 \times 26 \times 10^{-3}} = 0.08 \text{ per } ^\circ C.$$

This indicates that I_0 increases by **8% per degree** rise in temperature.

** But experimententally it was found that I_0 increases by 7% per °C change in temperature for both Si & Ge.

If at T°C, I_0 is $1\,\mu A$, Then at $(T+1)^\circ C$, I_0 is $1.07\,\mu A$

From This it can be concluded That I_0 approximately doubles i.e 1.07^{10} for every 10°C rise in temperature.

Mathematically, it is interpreted

$$I_{o2} = 2^{\frac{T_2 - T_1}{10}} \cdot I_{o1}.$$

$$\boxed{I_{o2} = 2^{\frac{\Delta T}{10}} \cdot I_{o1}.} \longrightarrow (2.45)$$

where I_{o2} = reverse saturation current at T_2

I_{o1} = reverse saturation current at T_1.

b) **Effect of temperature on forward voltage**

The dependence of I_o on temperature T is given by

$$I_o = K_1 T^m e^{-V_{GO}/\eta V_T}.$$

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

for a forward current, $I = I_o \left(e^{V/\eta V_T}\right)$

— neglecting 1.

$$\Rightarrow I = K_1 T^m e^{-V_{GO}/\eta V_T} \cdot e^{V/\eta V_T}$$

$$\Rightarrow \boxed{I = K_1 T^m e^{(V - V_{GO})/\eta V_T}} \longrightarrow (2.46)$$

or

$$\boxed{I = K_1 T^m e^{(V - V_{GO})/\eta KT}} \longrightarrow (2.47)$$

Now, for constant current diode current, $\frac{dI}{dT} = 0$.

hence differentiating eq (2.47) wrt T.

$$\frac{dI}{dT} = K_1 \left[m T^{m-1} \cdot e^{(V - V_{GO})/\eta KT} + T^m \cdot e^{(V - V_{GO})/\eta KT} \cdot \frac{d}{dT}\left(\frac{V - V_{GO}}{\eta KT}\right)\right]$$

$$\Rightarrow \frac{dI}{dT} = K_1 \left[m T^{m-1} + \frac{T^m}{\eta K}\left(\frac{T\frac{dV}{dT} - (V - V_{GO}) \times 1}{T^2}\right)\right] e^{(V - V_{GO})/\eta KT}.$$

$$= K_1 e^{(V - V_{GO})/\eta KT} \left[\frac{m T^m}{T} + \frac{T^m}{\eta K T^2}\left(T\frac{dV}{dT} - (V - V_{GO})\right)\right]$$

$$\frac{dI}{dT} = K_1 \cdot e^{(V - V_{GO})/KT\eta} \times T^m \left[\frac{m\eta KT + \left[T\frac{dV}{dT} - (V - V_{GO})\right]}{\eta K T^2}\right]$$

$$\frac{dI}{dT} = K_1 \cdot e^{(V - V_{GO})/KT\eta} \times \frac{T^m}{\eta K T^2}\left[m\eta KT + T\frac{dV}{dT} - (V - V_{GO})\right].$$

$$\Rightarrow \frac{dI}{dT} = K_1 \cdot e^{\cdots} \times \frac{(\cdots)}{\eta V_T}\left[m\eta V_T + T\frac{dV}{dT} - (V - V_{G0})\right] \rightarrow (2.48)$$

But $\frac{dI}{dT} = 0$.

$$\Rightarrow m\eta V_T + T\frac{dV}{dT} - (V - V_{G0}) = 0.$$

$$\Rightarrow T\frac{dV}{dT} = V - V_{G0} - m\eta V_T.$$

$$\boxed{\frac{dV}{dT} = \frac{V - (V_{G0} + m\eta V_T)}{T}} \rightarrow (2.49)$$

This is the required change in voltage necessary to keep diode current constant.

Hence, for Ge, at cutin voltage, $V = V_\gamma = 0.2V$ and with $m = 2$, $\eta = 1$, $T = 300^\circ K$ and $V_{G0} = 0.785 V$ in eq (2.49) we get

$$\frac{dV}{dT} = \frac{0.2 - (0.785 + 2 \times 1 \times 26 \times 10^{-3})}{300^\circ K}$$

$$\boxed{\frac{dV}{dT} = -2.12\ mV/^\circ C \text{ for Ge.}} \rightarrow (2.50)$$

The negative sign indicates that the voltage must be reduced at a rate of $2.12 mV/^\circ C$ change in temperature to keep diode current constant.

Illy, for Si, we get

$$\boxed{\frac{dV}{dT} = -2.3\ mV/^\circ C \text{ for Si.}} \rightarrow (2.51)$$

Practically, the value of $\frac{dV}{dT}$ is assumed to be $-2.5 mV/^\circ C$ for either Ge or Si at room temperature.

will get multiplied when The temperature is increased from 27°c to 82°c.

Sol: $(I_o)_2 = 2^{\Delta T/10} \times (I_o)_1$ $\quad \Delta T = 82-27 = 55$

$= 2^{55/10} \times (I_o)_1$

$\Rightarrow (I_o)_2 = 2^{5.5} \times (I_o)_1$

$(I_o)_2 = 45.25 (I_o)_1$

The I_o gets multiplied by 42.54 when temperature changes from 27°c to 82°c.

(Pb) A Si diode has a saturation current of 1nA at 20°c. Find its current when it is forward biased by 0.4V. Find The current in The same diode when temperature rises to 110°c.

Sol: Given That $I_o = 1nA$

$T = 273 + 20 = 293°K. \Rightarrow V_T = \frac{293}{11,600} = 0.025\,V$

$V = 0.4V$

for Si diode $\eta = 2$.

$I = I_o(e^{V/\eta V_T} - 1) = 1\times10^{-9}(e^{0.4/2\times0.025} - 1)$

$I = 2.97\,\mu A$

change in I_o.

$(I_o)_2 = 2^{\Delta T/10} \times (I_o)_1$

$= 2^{90/10} \times (I_o)_1$.

$= 2^9 \times 1\times10^{-9} = 512\,nA$

Now, $I_2 = (I_o)_2 \cdot (e^{V/\eta V_T} - 1)$

here $V_T = \frac{T_2}{11,600} = \frac{383}{11,600} = 0.033\,V$

$I_2 = 512\times10^{-9}(e^{0.4/2\times0.033} - 1)$

$I_2 = 0.2\,mA$

of $10\mu A$ at the room temperature of $27°C$. It is observed to be $30\mu A$, when the room temperature is increased. calculate the new room temperature.

Sol: $(I_o)_1$ at temperature T_1

$(I_o)_2$ at temperature T_2

Given $(I_o)_1 = 10\mu A$, $(I_o)_2 = 30\mu A$.

Now, $(I_o)_2 = 2^{\Delta T/10} \times (I_o)_1$

$$30 \times 10^{-6} = 2^{\Delta T/10} \times 10 \times 10^{-6}$$

$$\Rightarrow 2^{\Delta T/10} = 3.$$

$$\frac{\Delta T}{10} \ln 2 = \ln 3.$$

$$\Delta T = 15.8496.$$

$$\Rightarrow T_2 - T_1 = 15.8496.$$

$$T_2 = T_1 + 15.8496. = 27 + 15.849$$

$$T_2 = 42.849°C$$

(Pb) The reverse saturation current of a germanium diode is $100\mu A$ at room temperature of $27°C$. Calculate the current in forward bias condition, if forward bias voltage is $0.2V$ at room temperature. If temperature is increased by $20°C$, calculate the reverse saturation current and the forward current, for same forward voltage, at new temperature.

Sol: $(I_o)_1 = 100\mu A$, $T_1 = 273 + 27°C = 300°K$., $V = 0.2V$.

$(I_o)_2 = ?$, $T_2 = 273 + 27°C + 20°C = 320°K$.

$$(I_o)_2 = 2^{\Delta T/10} \times (I_o)_1$$

$$= 2^{20/10} \times 100 \times 10^{-6} = \underline{400\mu A}$$

New current at T_2

$I = I_o (e^{V/\eta V_T} - 1)$ here $\eta = 1$ for Ge., $V = 0.2V$

$= 653.168\ mA$ $\qquad V_T = \frac{T}{\ } = \frac{320}{\ }$

Diode Resistance

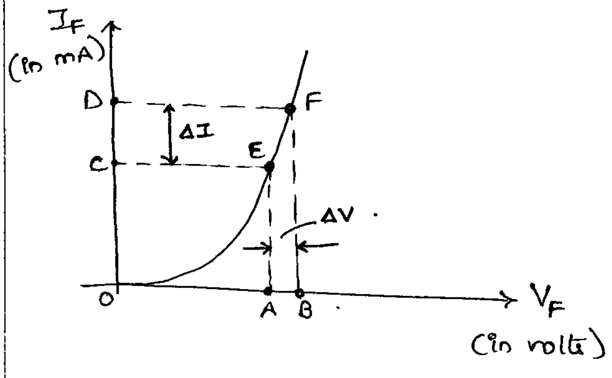
a) Forward Resistance of a diode

The resistance offered by the diode in forward bias condition is called forward resistance.

The forward resistance is defined in 2 ways

a) Static or DC forward resistance (R_F)

b) Dynamic or AC forward resistance. (r_f)



$$R_F = \frac{OA}{OC}.$$

$$r_f = \frac{\Delta V}{\Delta I} \doteq \frac{AB}{CD}.$$

The static forward resistance R_F is defined as the dc voltage applied across the pn junction to dc current flowing through the pn junction.

$$\boxed{R_F = \frac{\text{dc forward voltage}}{\text{dc forward current}}} = \frac{OA}{OC} \longrightarrow (2.52)$$

The resistance ~~for~~ offered by the pn junction under AC conditions is dynamic ~~resta~~ resistance r_f. It is defined as the reciprocal of slope of VI characteristics

$$\boxed{r_f = \frac{dV}{dI}} \longrightarrow (2.53)$$

dynamic resistance is not constant but depends on operating voltage.

from diode equation, we have. $I = I_0 \left(e^{V/\eta V_T} - 1\right)$

differentiating above eq wrt V.

$$\frac{dI}{dV} = I_0\left(e^{V/\eta V_T} \cdot \frac{1}{\eta V_T} - 0\right)$$

$$\Rightarrow \frac{dI}{dV} = \frac{I_0 \cdot e^{V/\eta V_T}}{\eta V_T} = \frac{I + I_0}{\eta V_T}.$$

for forward bias, $I >> I_0$

$$\Rightarrow r_f = 1 \Big/ \frac{dI}{dV} = \frac{\eta V_T}{I}$$

$$\Rightarrow \boxed{r_f = \frac{\eta V_T}{I}} \longrightarrow (2.54)$$

$\Rightarrow$ dynamic resistance varies inversely wrt I.

At room temperature & $\eta = 1$, $r_f = \frac{26}{I}$ where $I = mA$

for a forward current of 26 mA,

$$r_f = 1\Omega.$$

from the figure, $r_f = \frac{\Delta V}{\Delta I} = \frac{1}{\Delta I/\Delta V} = \frac{1}{\text{slope of forward characteristics}}$.

Generally, r_f = few ohms.

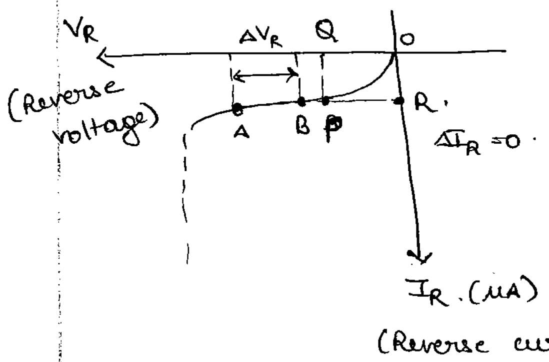
b) Reverse resistance of diode

The resistance offered by diode in reverse biase condition is called reverse resistance.

The reverse resistance is defined in 2 ways:

a) static or dc reverse resistance (R_R)

b) Dynamic or ac reverse resistance (r_r)



$$R_R = \frac{OQ}{OR}$$

$$r_r = \frac{\Delta V_R}{\Delta I_R}$$

The static reverse current R_R is defined as the ratio of applied reverse dc voltage to reverse saturation current I_0 flowing through pn junction.

$$\boxed{R_R = \frac{\text{applied reverse dc voltage}}{\text{Reverse saturation current}}} \longrightarrow (2.55)$$

$$= \frac{OQ}{OR} \text{ at point } P$$

a) Ideal Diode

1) The cutin voltage is 0.

Since for an ideal diode there is no barrier potential, Thus any small FB voltage causes conduction through the device.

2) The forward resistance (dynamic resistance) is 0.

3) The reverse resistance is infinity (∞).

4) The diode readily conducts when forward biased and it blocks conduction when reverse biased.

5) The reverse saturation current I_0 is 0.

6) Ideal diode acts as a fast-acting electronic switch.

b) Practical diode

1) There is a potential barrier across the junction and this must be overcome before the diode can conduct.

The cutin voltage or Threshold voltage or offset voltage or break-point voltage V_γ = 0.2 V for Ge
= 0.6 V for Si.

2) The forward resistance is in few tens of ohms.

3) The reverse resistance is in the range of megaohms.

4) The diode conducts when forward biased and the bias voltage is more than that of cutin voltage.

5) The diode doesnot conduct when reverse biased. However, a small reverse saturation current flows across the junction in the range of ~~microseconds~~ nanoamperes for Si diode & microamps for Ge.

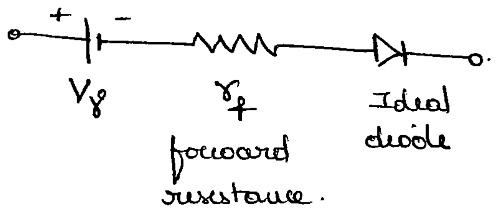
6) Diode also acts as fast acting switch.

* Diode equivalent circuit

The circuit model of any device is represented by its equivalent circuit.

An equivalent circuit is a combination of elements properly chosen to best represent the actual terminal characteristics of a device, system in a particular operating region.

A diode is replaced by a model with a battery equal to cutin voltage of a diode, the forward resistance of a diode in series with an ideal diode.

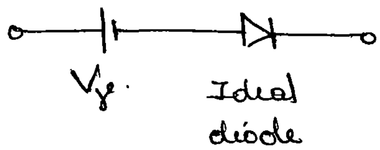


This is the circuit model of a diode.

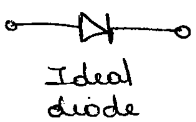
This is also called as "piece-wise linear equivalent circuit."

Assuming $r_f = 0$, since for most applications, it is too small ~~to be~~ compared to resistance of other elements of the network.

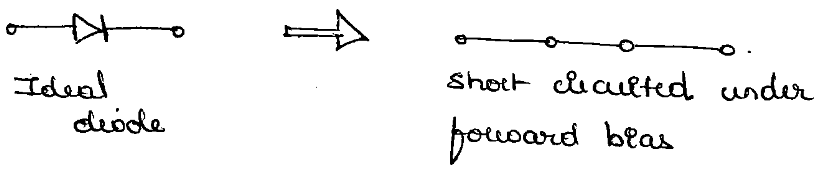
⇒ The simplified equivalent circuit is as shown below.



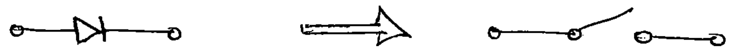
Assuming $V_\gamma = 0$ and $r_f = 0$, the equivalent circuit becomes the circuit model for an ideal diode.



In forward bias condition, the ideal diode acts as short circuit.

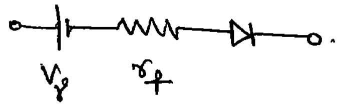
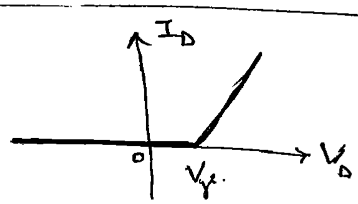
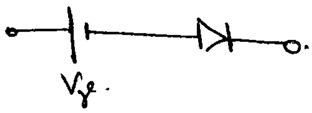
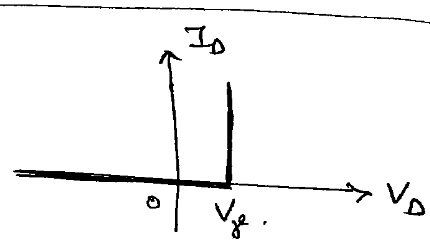
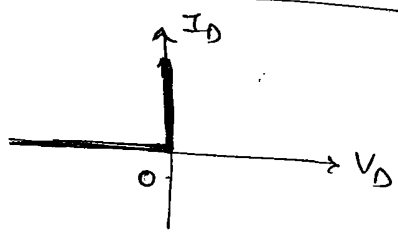


In reverse biased condition, the ideal diode acts as open circuit.



Ideal diode — open circuited under reverse biased.

Diode equivalent models & VI characteristics

Type	Model	VI characteristics
1) Piece-wise linear model.	 here $V_\gamma \neq 0$, $r_f \neq 0$, $r_r = \infty$.	
2) Simplified model.	 here $V_\gamma \neq 0$, $r_f = 0$, $r_r = \infty$.	
3) Ideal model.	 here $V_\gamma = 0$, $r_f = 0$, $r_r = \infty$.	

pn junction can be constructed by using different methods. The different construction types of pn junction are

1) Alloy or step-graded junction
2) Grown or linearly-graded junction
3) Diffused junction

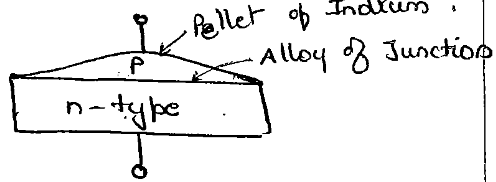
a) Alloy or step-graded junction

The step-graded junction is a junction in which there is an abrupt change from acceptor ions on one side to the donor ions on the other side.

Such a junction is formed by placing Indium (trivalent) pallet against n-type germanium wafer and heating this assembly to a high temperature for a short time.

As a result of this heating, some of the indium dissolves into the germanium to change the germanium from n-type to p-type at the junction.

Such a junction is called alloy junction or fused junction or step-graded junction.



b) Grown or linearly-graded junction

If donor impurities are introduced into one side and acceptor impurities into the other side of a single crystal growing from a melt of Si (or) Ge, then grown-junction or linearly-graded junction is formed.

c) Diffused Junction

In diffusion process, a wafer of semiconductor material (say p-type) is exposed to a gas of impurity (say n-type) material, then the atoms of the impurity material diffused into the semiconductor material to form a diffused pn junction.

* Diode capacitances or junction capacitances.

In a semiconductor pn-junction, there are 2 types of capacitances.

1) Transition capacitance

2) Diffusion capacitance

1) Transition capacitance:

The transition capacitance come into play when the junction is under reverse biased condition.

The reverse bias in a pn diode results in majority carriers moving away from the junction leaving only uncovered immobile ions. Thus thickness of the space-charge region at the junction increases with the increase of reverse bias magnitude.

This depletion region along with concentration of uncovered immobile charges may be considered to constitute a ~~capacitance~~ capacitor whose incremental capacitance C_T is given by.

$$\boxed{C_T = \left|\frac{dQ}{dV}\right|} \longrightarrow (2.57)$$

where dQ = increase in charge

dV = increase in voltage.

Hence, a voltage change dV in time dt will result in a current "i" given by

$$i = \frac{dQ}{dt}$$

$$\Rightarrow \boxed{i = C_T \cdot \frac{dV}{dt}} \longrightarrow (2.58)$$

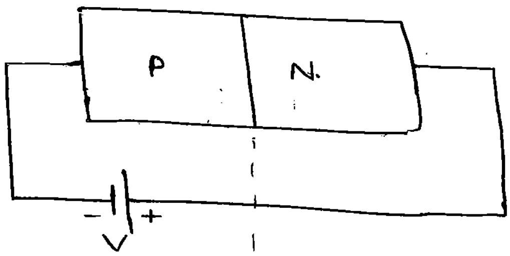
This capacitance C_T is referred to the space-charge capacitance, transition capacitance, barrier capacitance or depletion capacitance.

The expression for C_T can be derived for

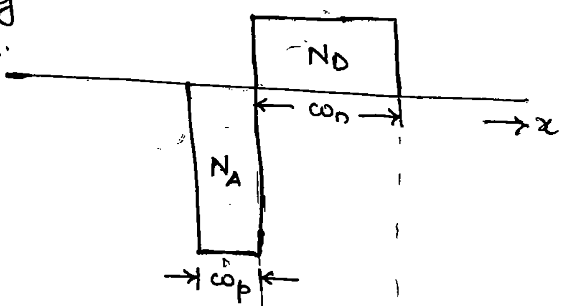
a) step-graded &

b) linearly-graded junctions

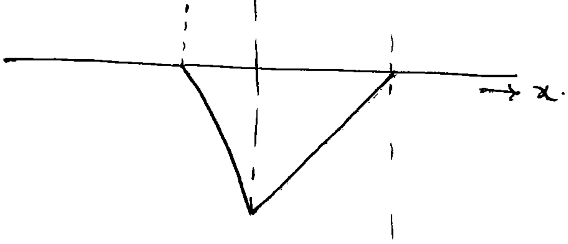
i) Reverse-biased step graded junction



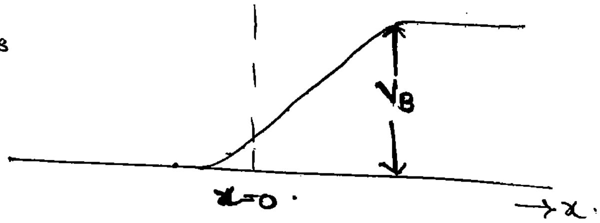
(ii) charge density Vs distance.



(iii) Electric field Vs distance.



(iv) Potential Vs distance



The figure shows the charge density as a function of distance from an alloy junction in which The acceptor impurity density is assumed to be much greater Than The donor concentration. Since, The net charge must be zero, Then

$$q N_A' \omega_p = q N_D \omega_n.$$

If $N_A \gg N_D$, Then $\omega_p \ll \omega_n$.

For simplicity, we neglect ω_p and assume that the entire barrier potential V_B appears across The uncovered donor ions.

The relationship between potential & charge density is given by poisson's equation

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

$$\Rightarrow \frac{d^2V}{dx^2} = -\frac{qN_D}{\epsilon} \longrightarrow (2.59)$$

where ϵ = permittivity of semiconductor.

Integrating eq (2.59) we get.

$$\frac{dV}{dx} = -\frac{qN_D}{\epsilon}.x + C_1. \longrightarrow (2.60)$$

The electric flux lines originates on the positive donor ions and terminates on the negative acceptor ions.

Applying, boundary conditions i.e

at $x = w_n \approx w$, $E = \frac{-dV}{dx} = 0$.

$$\Rightarrow C_1 = \frac{qN_D}{\epsilon}.w.$$

Substituting C_1 in eq (2.60)

$$\frac{dV}{dx} = -\frac{qN_D}{\epsilon}x + \frac{qN_D}{\epsilon}w.$$

$$\frac{dV}{dx} = -\frac{qN_D}{\epsilon}(x - w). \longrightarrow (2.61)$$

on integrating eq (2.61) wrt x, we get

$$V = -\frac{qN_D}{\epsilon}\left(\frac{x^2}{2} - wx\right) + C_2.$$

Applying boundary conditions. i.e,

at $V = 0$ & at $x = 0$,

$$\Rightarrow C_2 = 0.$$

$$\Rightarrow \boxed{V = -\frac{qN_D}{\epsilon}\left(\frac{x^2}{2} - wx\right).} \longrightarrow (2.62)$$

At $x = w_n \approx w$, $V = V_B$, The barrier height

$$\therefore V_B = -\frac{qN_D}{\epsilon}\left[\frac{w^2}{2} - w^2\right]$$

$$\Rightarrow \boxed{V_B = \frac{q.N_D}{\epsilon}.\frac{w^2}{2}.} \longrightarrow (2.63)$$

Let A be the area of the junction, thus the total charge on one side of the depletion layer is

$$Q_t = \frac{1}{2} A \cdot \frac{W}{2} \cdot q \cdot K \cdot \frac{W}{2}$$

$$Q_t = \frac{AqKW^2}{8} \longrightarrow (2.73)$$

Hence, the transition capacitance is given by

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

$$C_T = \frac{AqK}{8} \cdot 2W \cdot \frac{dW}{dV} = \frac{AqKW}{4} \cdot \frac{dW}{dV} \longrightarrow (2.74)$$

from eq (2.72), $V = \dfrac{qKW^3}{12\epsilon}$

Differentiating wrt V we get

$$1 = \frac{qK}{12\epsilon} \cdot 3W^3 \cdot \frac{dW}{dV}$$

$$\Rightarrow \frac{dW}{dV} = \frac{4\epsilon}{qKW^2} \longrightarrow (2.75)$$

substituting this equation in (2.

$$C_T = \frac{AqKW}{4} \times \frac{4\epsilon}{qKW^2}$$

$$\Rightarrow \boxed{C_T = \frac{\epsilon A}{W}} \longrightarrow (2.76)$$

Thus, we get the same expression for C_T in case of both grown and alloy junction diodes.

*) Diffusion capacitance (C_D):

The diffusion capacitance C_D exists across the junction when it is forward biased.

The rate of change of injected charge with applied voltage is called as "diffusion capacitance" (or) "storage capacitance"

Expression for diffusion capacitance C_D

For simplicity we assume that one side of the diode, say the p-material is so heavily doped in comparison with the n-side and the current across the junction entirely by holes moving from p-side to the n-side

i.e $I = I_{pn}(0)$.

The charge $Q = A e L_p P_n(0) \rightarrow (2.77)$

By differentiating equation (2.77) we get.

$$\frac{dQ}{dV} = A e L_p \frac{dP_n(0)}{dV} \rightarrow (2.78)$$

$$I = I_{pn}(0) = \frac{A e D_p P_n(0)}{L_p} \rightarrow (2.79)$$

By differentiating w.r.t V.

$$\frac{dI}{dV} = \frac{Ae D_p}{L_p} \cdot \frac{dP_n(0)}{dV}$$

$$\Rightarrow \frac{dP_n(0)}{dV} = \frac{L_p}{Ae D_p} \cdot \frac{dI}{dV} \rightarrow (2.80)$$

Substituting eq (2.80) in (2.78) we get

$$\frac{dQ}{dV} = A e L_p \cdot \frac{L_p}{Ae D_p} \cdot \frac{dI}{dV}$$

$$\Rightarrow \frac{dQ}{dV} = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV}$$

we know that $\frac{dQ}{dV} = C_D$

$$\therefore C_D = \frac{L_p^2}{D_p} \cdot \frac{dI}{dV} \rightarrow (2.81)$$

where $\frac{dI}{dV} = g$ is the diode conductance

Let A be the area of the junction. Then the total amount charge in the distance "ω" of the depletion layer is

$$Q_t = q\, N_D \cdot \omega \cdot A . \longrightarrow (2.64)$$

Hence, the capacitance C_T is given by

$$C_T = \frac{dQ_t}{dV_B} = q\, N_D \cdot A \cdot \frac{d\omega}{dV_B} . \longrightarrow (2.65)$$

differentiating eq (2.63) w.r.t V_B we get

$$1 = \frac{q N_D}{2\epsilon} \cdot 2\omega \cdot \frac{d\omega}{dV_B}$$

$$\Rightarrow \frac{d\omega}{dV_B} = \frac{\epsilon}{q\, N_D \cdot \omega} .$$

Substituting this value in eq (2.65) we get

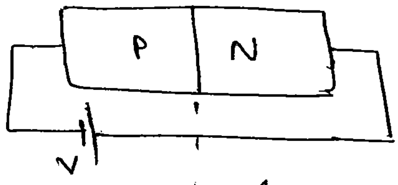
$$C_T = \cancel{q}\, \cancel{N_D} \cdot A \cdot \frac{\epsilon}{\cancel{q}\, \cancel{N_D} \cdot \omega} .$$

$$\Rightarrow \boxed{C_T = \frac{\epsilon A}{\omega} .} \longrightarrow (2.66)$$

The transition capacitance C_T given by eq (2.66) is exactly the same as the equation giving the capacitance of a parallel plate capacitor having plate area A, plate seperation ω, containing material of permittivity ϵ.

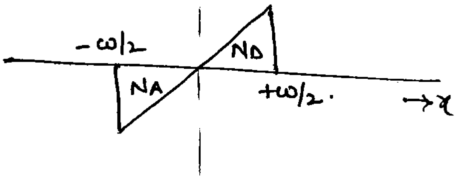
b) Expression for C_T in linearly graded junction

(i)



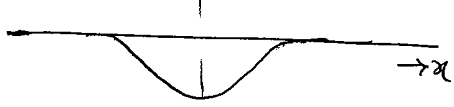
Reverse biased linearly-graded junction

(ii)



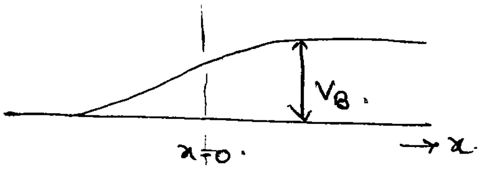
charge density Vs distance curve

(iii)



Electric field Vs distance curve.

(iv)



Potential Vs distance curve.

For the grown junction, the net charge density in the depletion region varies linearly wrt distance and becomes to 0 abruptly at the edges of distance $+\omega/2$ and $-\omega/2$ as shown

The net charge density $\rho = qKx$. $\rightarrow$ (2.67)

where K = proportionality constant

q = charge.

x = distance, $-\frac{\omega}{2} < x < \frac{\omega}{2}$.

The relationship between potential & charge density is given by poisson's equation.

$$\frac{d^2V}{dx^2} = \frac{-qKx}{\epsilon}. \longrightarrow (2.68)$$

on integrating eq (2.68) we get.

$$\frac{dV}{dx} = \frac{-qKx^2}{2\epsilon} + C_1$$

At $x = \pm\frac{\omega}{2}$, $E = -\frac{dV}{dx} = 0$.

Substituting boundary conditions in the above equation we get

$$C_1 = \frac{qK}{\epsilon} \cdot \frac{\omega^2}{8}.$$

$$\Rightarrow \frac{dV}{dx} = \frac{-qK}{\epsilon}\left[\frac{x^2}{2} - \frac{\omega^2}{8}\right] \longrightarrow (2.69)$$

on integrating eq (2.69) we get

$$V = \frac{-qK}{\epsilon}\left[\frac{x^3}{6} - \frac{\omega^2}{8}x\right] + C_2. \longrightarrow (2.70)$$

Using boundary conditions at $x = 0$, $V = 0$ we get $C_2 = 0$.

$$\Rightarrow V = \frac{-qK}{\epsilon}\left[\frac{x^3}{6} - \frac{\omega^2}{8}x\right] \longrightarrow (2.71)$$

The total potential across the junction from $\frac{-\omega}{2}$ to $\frac{+\omega}{2}$ is given by.

$$V_B = V_{(x = +\frac{\omega}{2})} - V_{(x = -\frac{\omega}{2})}$$

$$V_B = \frac{-qK}{\epsilon}\left[\frac{\omega^3}{48} - \frac{\omega^3}{16}\right] + \frac{qK}{\epsilon}\left[\frac{-\omega^3}{48} + \frac{\omega^3}{16}\right]$$

$$C_D = \frac{1}{D_p} \cdot g$$

But $\tau = \tau_p = \frac{L_p^2}{D_p}$

$\therefore$ Diffusion capacitance $C_D = \tau \cdot g \rightarrow (2.82)$

we know that the transconductance

$$g = \frac{dI}{dV} = \frac{I}{\eta V_T} \rightarrow (2.83)$$

$$\therefore \boxed{C_D = \frac{\tau I}{\eta V_T}} \rightarrow (2.84)$$

* Limiting values or specification parameters of a PN junction

Data on specific semiconductor devices are normally provided by the manufacturer. The diode specification sheet includes.

1) Forward voltage V_F :

It is the maximum forward voltage that can be applied across the junction.

2) Maximum forward current, I_F :

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

3) Reverse saturation current, I_0 :

This is the small diode current in the reverse direction when reverse bias is applied. It is independent of the magnitude of the reverse bias.

I_0 is of the order of $1\,\mu A$ ($1\,nA$) for Ge (Si) diode

4) Peak Inverse Voltage (PIV):

It is 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.

5) Maximum power dissipation

It is the max ~~current~~ power that can be dissipated at the junction without damaging the junction.

6) Reverse recovery time (t_{rr})

It is defined as the time interval from the instant of current reversal from the ~~ras~~ forward to reverse condition until the diode has recovered to a specified extent either in terms of the diode current (typically 1 mA) or in terms of diode resistance (typically 400 KΩ).

t_{rr} lies in 1ns to 1μs range.

7) Capacitance levels.

The capacitance offered by the junction under forward bias and reverse bias conditions.

8) Operating temperature range

It is the range of temperature for which the pn junction diode operates safely without getting damaged. Its typical value is ranging from $-65°C$ to $+160°C$.

* Breakdown mechanisms in a diode

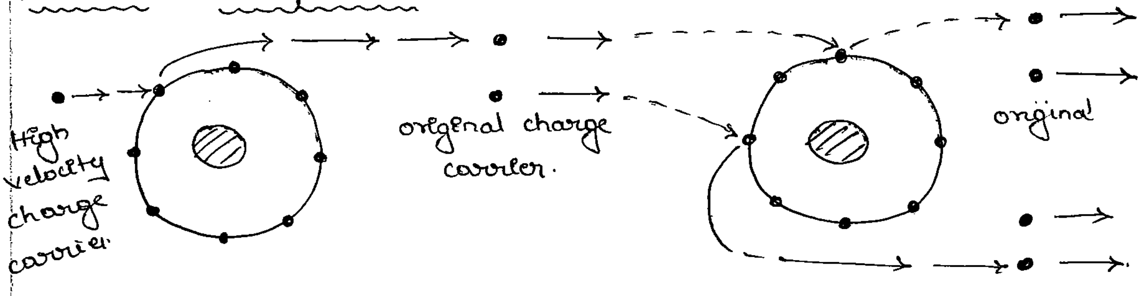
When diode is reverse biased, for a small reverse voltage, then the diode current is small and almost constant at I_0. But when reverse voltage increases beyond certain value, large diode current flows. This is called breakdown of a diode; and corresponding voltage is called reverse breakdown voltage of a diode.

There are 2 distinct mechanisms due to which the break down may occur in a diode. They are

1) Avalanche Breakdown
2) Zener Breakdown.

a) Avalanche Breakdown

In this mechanism, the thermally generated electrons & holes acquire sufficient with the applied reverse voltage and gets accelerated ⇒ the kinetic energy of electrons, $K.E = \frac{1}{2}mv^2$ increases. If such charge carriers collide against an electron involved in covalent bond, it breaks and new charge carriers are produced. These new carriers, in turn, produce additional carriers again through the process of disturbing bonds. This cumulative process is called Avalanche multiplication.



$1 \times 2 \Rightarrow 2 \times 4 \Rightarrow$.

The avalanche multiplication factor is given by

$$\boxed{M = \frac{1}{1 - \left(\frac{V}{V_{BD}}\right)^n}} \rightarrow (2.85)$$

where M = carrier multiplication factor

n = empirical constant $= 4$ for Si n-type.

$= 2$ for Si p-type

V = applied reverse voltage.

V_{BD} = reverse breakdown voltage.

The avalanche multiplication results in the flow of large reverse currents, and the diode finds itself in the region of avalanche breakdown.

** The diodes having reverse breakdown voltage greater than 6V, show the avalanche mechanism of breakdown.

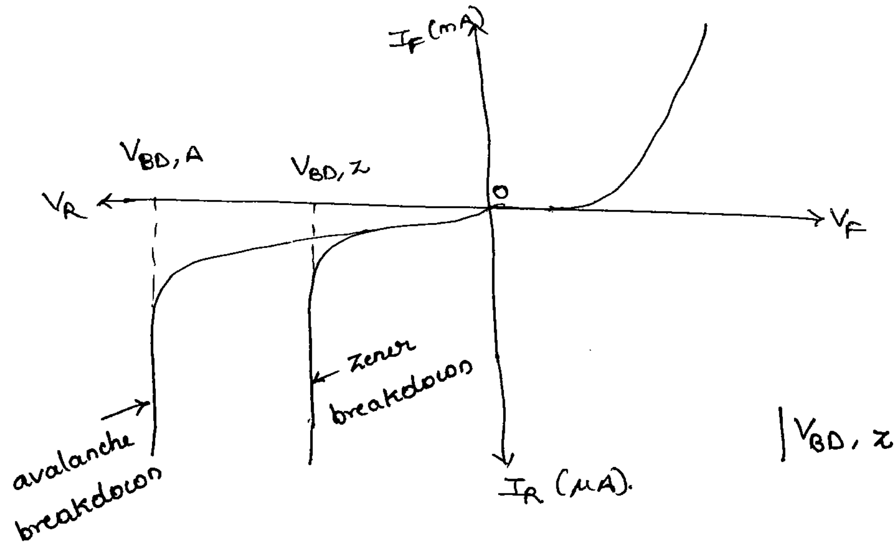
The avalanche breakdown occurs for lightly doped diodes.

b) Zener breakdown

Even if the initially available carriers do not acquire sufficient energy to disrupt bonds, it is possible to initiate breakdown through a direct rupture of bonds because of the existence of strong electric field. Under these circumstances, the breakdown is referred to as Zener breakdown.

Zener breakdown occurs in heavily doped diodes. For such heavily doped diodes, the depletion region width is small. Under reverse bias conditions, the electric field across the junction (narrow depletion region) is very intense and such an intense electric field is enough to pull the electrons out of the valence bonds of stable atoms. This mechanism of generating carriers in heavily doped diodes is called zener effect

** The diodes having reverse breakdown voltage less than 5V shows zener mechanism of breakdown.



$|V_{BD,Z}| < |V_{BD,A}|$.

temperature dependence of breakdown voltage.

A junction with a broad depletion layer and therefore a low field intensity will breakdown by the avalanche mechanism. In this case, we rely on intrinsic carriers to collide with valence electrons and create avalanche multiplication. As temperature increases, the vibrational displacement of atoms in the crystal grows. This vibration increases the probability of collisions with the lattice atoms of the intrinsic particles as they cross the depletion width. The intrinsic holes and electrons thus have less opportunity to gain sufficient energy between collisions to start the avalanche process.

⇒ value of avalanche voltage must increase with increase in temperature.

$$\text{As } T \uparrow, \quad V_{BD,A} \uparrow.$$

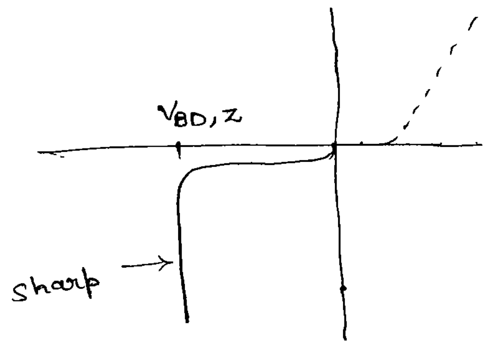
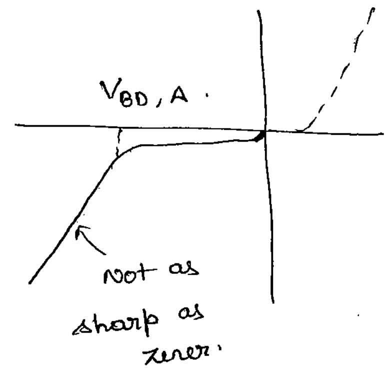
⇒ It has positive temperature coefficient

A junction having narrow depletion layer width and hence high field intensity ($\sim 10^6$ V/cm even at low voltages) will break down by the zener mechanism. An increase in temperature, increases the energies of valence electrons, and hence makes it easier for these electrons to escape from the covalent bonds. Less applied voltage is therefore required to pull these electrons from their positions in the crystal lattice and convert them into conduction electrons.

⇒ Zener breakdown voltage decreases with temperature.

$$\text{As } T \uparrow, \quad V_{BD,Z} \downarrow.$$

⇒ It has negative temperature coefficient

Zener Breakdown	Avalanche Breakdown
1. Breaking of covalent bonds is due to intense electric field across the narrow depletion region. This generates a large number of free electrons to cause breakdown.	1. Breaking of covalent bonds is due to collision of accelerated charge carriers having large velocities and kinetic energy with adjacent atoms. The process is called carrier multiplication.
2. This occurs for zener diodes with V_{BR} less than 6V.	2. This occurs for zener diodes with V_{BR} greater than 6V.
3. The temperature coefficient is negative.	3. The temperature coefficient is positive.
4. The breakdown voltage decreases as junction temperature increases.	4. The breakdown voltage increases as junction temperature increases.
5. VI characteristic is very sharp	5. VI characteristic is not as sharp as zener breakdown.
6. occurs in heavily doped diodes	6. Occurs in lightly doped diodes
7. 	7.  $\lvert V_{BD,A} \rvert > \lvert V_{BD,Z} \rvert$.

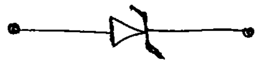
Diodes which are designed with adequate power dissipation capabilities to operate in the breakdown region may be employed as voltage-reference or constant-voltage devices.

Such diodes are called Zener diodes. Zener diode is a heavily doped diode.

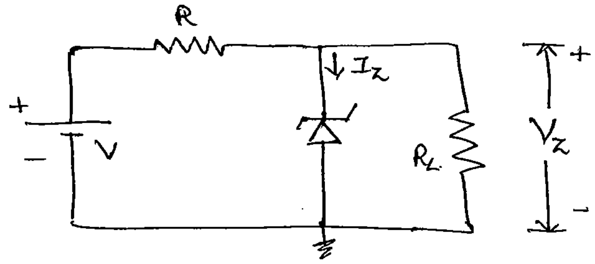
The operation of zener diode is same as that of ordinary PN diode in forward biased condition.

In reverse biased condition, the diode carries reverse saturation current till reverse voltage applied is less than the reverse breakdown voltage. When reverse voltage exceeds the reverse breakdown voltage, the current through it changes drastically but the voltage across it remains almost constant.

The symbol for zener diode is



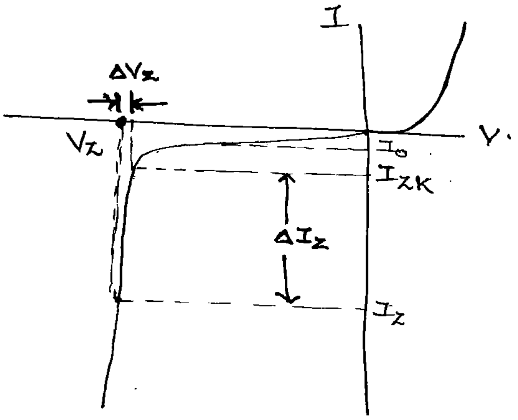
The breakdown region is the normal operating region for diode ⇒ always used in reverse biased condition as shown below.



V_Z = Zener diode voltage

I_Z = Zener diode current.

The VI characteristics of zener diode is shown below.



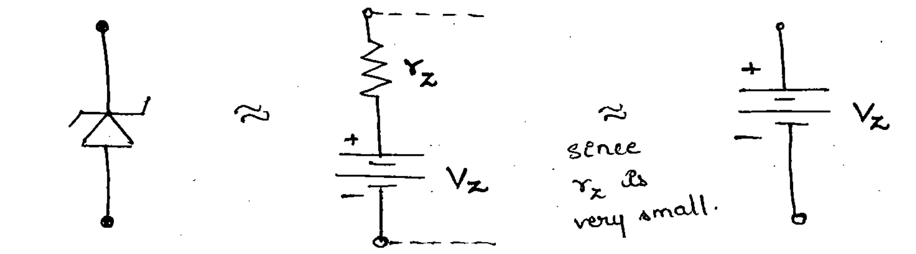
I_{ZK} = knee voltage.

Dynamic resistance of zener diode is the reciprocal of slope of the reverse characteristics in zener region

$$\boxed{r_Z = \frac{\Delta V_Z}{\Delta I_Z}} \rightarrow (2.86)$$

$$= \frac{1}{\text{slope of characteristics in zener region}}$$

Dynamic resistance is very small (few tens of ohms).

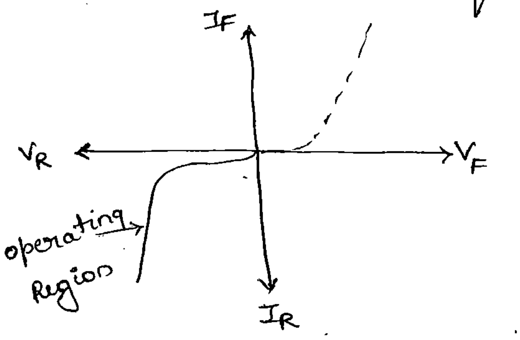
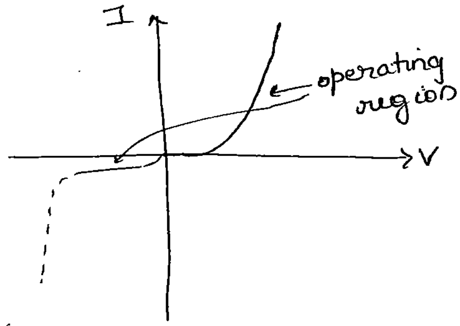
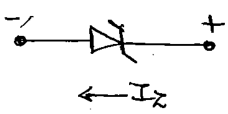
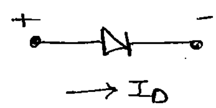


Zener diode — Practical Equivalent Circuit — Ideal Equivalent Circuit.

when breakdown occurs, even if current I_z increases, voltage across zener diode remains constant at V_z
⇒ zenerdiode is replaced by a series connection of dynamic resistance r_z and zener voltage V_z.

As r_z is very small, ideally zener diode is replaced by zener voltage, V_z.

Comparison of zener diode Vs pn junction diode

Zener diode	PN junction diode
1. Operated in reverse breakdown condition.	1. operated in forward biased condition + never operated in reverse breakdown condition.
2. characteristics lies in 3rd quadrant 	2. characteristics lies in 1st quadrant 
3. Dynamic resistance of zener diode is very small.	3. Dynamic resistance of ~~zener~~ pn junction diode is very high
4. Zener diode symbol is 	4. Pn junction diode symbol is 
5. Applications: 1) voltage regulator. 2) protection circuits.	5. Applications: 1) Rectifiers 2) voltage multipliers