**Semester-IV**

**Unit - CC10**

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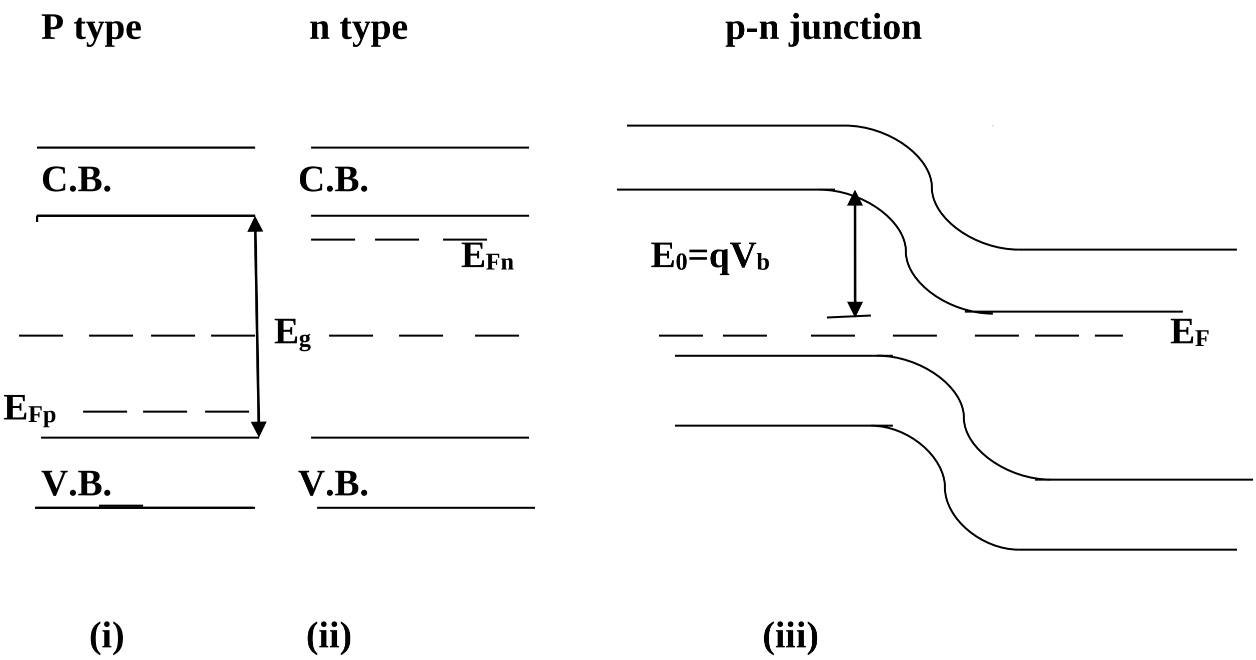
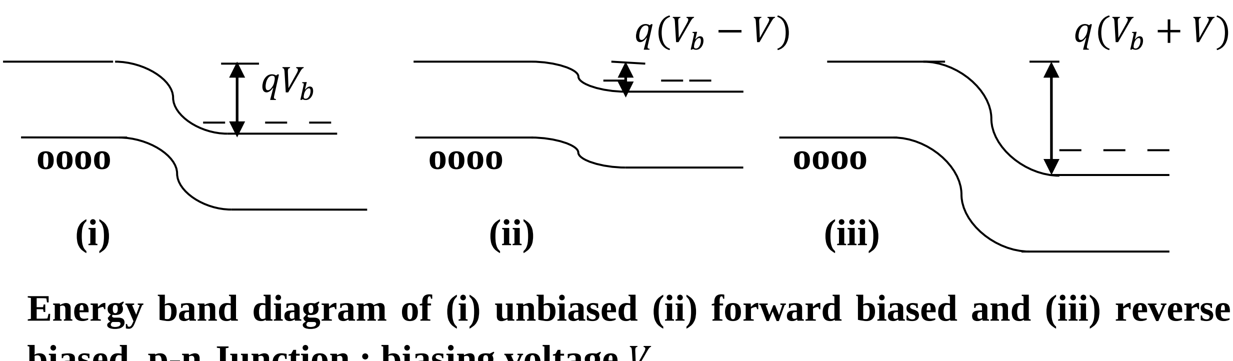
**Online--2**




**Energy band diagram of (i) p-type semiconductor, (ii) n type semiconductor and (iii) p-n junction**

**<u>Equation of diode current:</u>**




**Energy band diagram of (i) unbiased (ii) forward biased and (iii) reverse biased p-n Junction : biasing voltage** $V$

If a p-n junction is forward biased by a voltage $V$, then the contact or barrier potential at the junction is reduced to $(V_b - V)$. This change in potential barrier height results in lowering of the electrostatic field in the depletion region and a decrease in the width of the depletion region ($\because$ $width\ W = \sqrt{\frac{2\in V_b(N_a+N_d)}{qN_aN_d}}$.

Since potential barrier is reduced under forward bias of the p-n junction, diffusion of holes from p-region to n-region and that of electrons from n-region to p-region begins. So there is a current due to diffusion of carriers and it is sum of hole diffusion current and the electron diffusion current.

The holes after crossing the junction, becomes minority carrier in the region and similarly, electros after crossing the junction become minority carrier in the p-region. The majority carrier density in both sides of the junction remains almost unaffected but there is a significant change in minority carrier density in both sides.

To determine the change in minority carrier hole density let us consider the equation of continuity of holes for x-directional flow of carriers:

$$\frac{\partial J_{p_n}}{\partial x} + q\frac{\partial p_n}{\partial t} + q\frac{p_n - p_{no}}{\tau_p} = 0 \qquad (1)$$

Similarly for electrons: $\frac{\partial J_{n_p}}{\partial x} + q\frac{\partial n_p}{\partial t} + q\frac{n_p - n_{po}}{\tau_n} = 0$

Here $p_n$ and $n_p$ are minority hole concentration in the n-side and minority electron concentration in the p-side respectively. $p_{no}$ and $n_{po}$ are equilibrium values of minority carriers hole and electrons respectively. $\tau_p$ and $\tau_n$ are life time of holes and electrons respectively.

Here we see that the rate of change of minority holes per unit volume depends on the rate of generation per unit volume $\frac{p_{no}}{\tau_p}$, rate of recombination per unit volume $\frac{p_n}{\tau_p}$ and the hole current due to flow of holes.

Again hole current and electron current density are given respectively by:

$$J_{p_n} = qp_n\mu_p E - qD_p\frac{\partial p_n}{\partial x} \qquad (2)$$

$J_{n_p} = qn_p\mu_n E + qD_n \frac{\partial n_p}{\partial x}$

Under forward bias the built in electric field ($E$) decreases. So, we can neglect the drift current and hole current becomes

$J_{p_n} = -qD_p \frac{\partial p_n}{\partial x}$ .

So the continuity equation (1) becomes

$\frac{\partial p_n}{\partial t} + \frac{p_n - p_{no}}{\tau_p} - D_p \frac{\partial^2 p_n}{\partial x^2} = 0$

In the steady state, concentration of holes is independent of time. So $\frac{\partial p_n}{\partial t} = 0$ and equation (3) becomes

$$D_p \frac{\partial^2 p_n}{\partial x^2} = \frac{p_n - p_{no}}{\tau_p} = \frac{\Delta p_n}{\tau_p} = \frac{p_n'}{\tau_p}$$

[ $p_n' = p_n - p_{no}$ is the excess minority hole concentration]

$$\frac{\partial^2 \Delta p_n}{\partial x^2} = \frac{\Delta p_n}{D_p \tau_p} = \frac{\Delta p_n}{L_p^2}$$

[$L_p = \sqrt{D_p \tau_p}$ is diffusion length of holes]

Solution of the equation is : $\Delta p_n(x) = Ae^{x/L_p} + Be^{-x/L_p}$

Since excess minority carrier concentration can't be infinite at $x = \infty$, $A = 0$

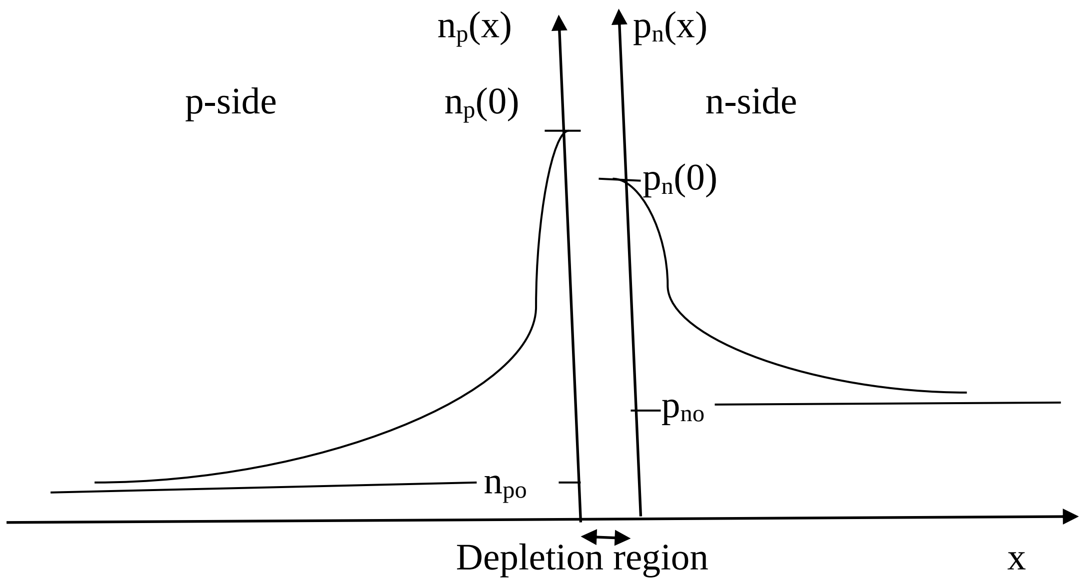
$$\therefore \Delta p_n(x) = Be^{-x/L_p}$$

If we assume that at the junction i.e. at $x = 0$, injected concentration is $p_n'(0) = \Delta p_n(0)$ then,

$$\Delta p_n(x) = \Delta p_n(0) e^{-x/L_p} = p_{n(x)} - p_{no} \qquad (3)$$

$$\therefore p_{n(x)} = p_{no} + \Delta p_n(0) e^{-x/L_p}$$

Thus the hole concentration decreases exponentially with distance. We see that the diffusion length $L_p$ represents the distance into the semiconductor at which injected concentration falls to $1/e$ of its value at x=0. $L_p$ also represents the average distance that an injected hole travels before recombining with an electron.




As we have seen that $\quad p_n = p_p\, e^{-qV_b/kT}$

So at equilibrium, $p_{no} = p_{po}\, e^{-qV_b/kT}$ (4)

With forward biasing voltage V, the junction potential is reduced to $(V_b - V)$.

So, $p_n(x) = p_p\, e^{-q(V_b-V)/kT} = p_{po}\, e^{-q(V_b-V)/kT}$ (5)

[Majority carrier concentration is not changed due to biasing voltage or diffusion. So, $p_p = p_{po}$ ]

So, at the junction, $p_n(0) = p_{po}\, e^{-q(V_b-V)/kT}$ (6)

And from equation (4) & (6) we get : $\frac{p_n(0)}{p_{no}} = e^{qV/kT}$

Or, $p_n(0) = p_{no}e^{qV/kT}$ (6)

This boundary condition is known as the law of the junction. It indicates that for a forward biased (V>0) and with V>>kT/q (26mV at room temperature), the hole concentration at the junction in the n-side is greatly increased over the thermal equilibrium value $p_{no}$.

[And in reverse biased condition with |V|>>$V_{T,}$, $p_n(0) \approx 0$]

$$\therefore p'_{no} = p_{n(0)} - p_{no} = \Delta p_n(0) = p_{no}(e^{qV/kT} - 1) \quad (7)$$

Now from equation (3) $p'_n(x) = \Delta p_n(x) = \Delta p_n(0)e^{-x/L_p}$

Using the equation (7), $p'_n(x) = \Delta p_n(x) = p_{no}(e^{qV/kT} - 1)e^{-x/L_p}$

**So the hole diffusion current density is given by:**

$$J_{p_n}(x) = -qD_p\frac{\partial p_n}{\partial x} = -qD_p\frac{\partial(p'_n(x)+p_{no})}{\partial x}$$

$$\therefore J_{p_n}(x) = \frac{qD_p}{L_p}p_{no}(e^{qV/kT} - 1)e^{-x/L_p}$$

So at x=0,

$$J_{p_n}(0) = \frac{qD_p}{L_p}p_{no}(e^{qV/kT} - 1)$$

Similarly electron diffusion current density is:

$$J_{n_p}(0) = \frac{qD_n}{L_n}n_{po}(e^{qV/kT} - 1)$$

It causes the current in the same direction as that due to holes crossing the junction.

Because of low level injection, minority drift current may be neglected. Therefore the total forward current density at the junction is

$J(0) = J_{p_n}(0) + J_{n_p}(0) = q(\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po})(e^{qV/kT} - 1)$

If A be the cross-sectional area of the junction, then the total diode current at the junction is

$I = I_{p_n}(0) + I_{n_p}(0) = Aq(\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po})(e^{qV/kT} - 1)$

$\therefore I = I_0(e^{qV/kT} - 1)$

Where $I_{0=}Aq(\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po})$

Since the current is same through a series circuit, I is independent of x and the expression fo diode current is

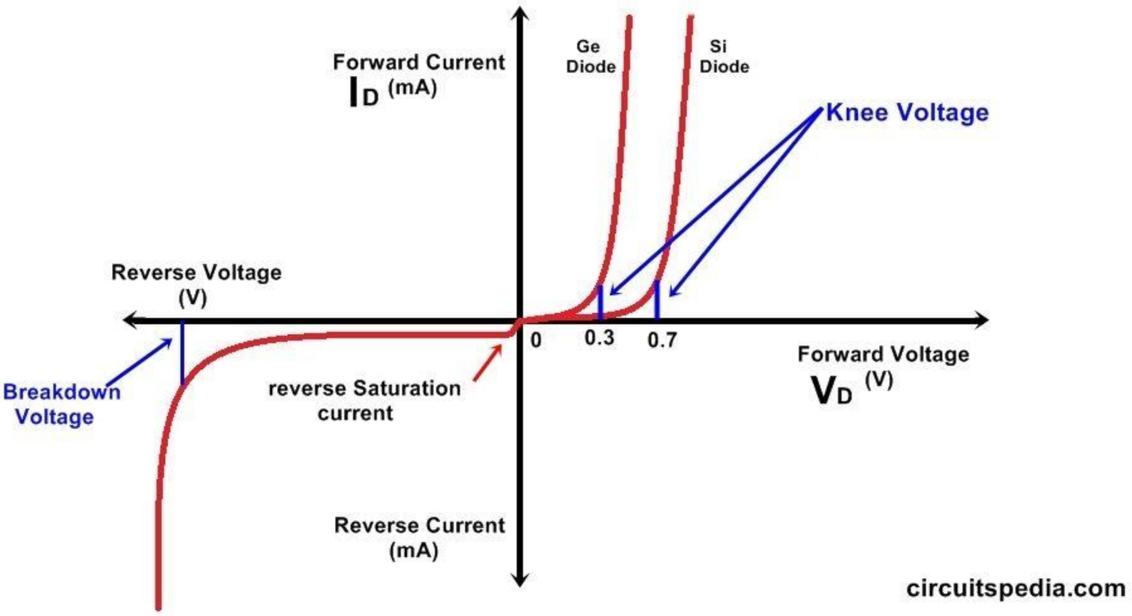
$$I = I_0(e^{qV/kT} - 1) = I_0(e^{V/V_T} - 1)$$

$(V_T \approx 26mV$ at room temperature.

If the forward voltage is large compared to $V_T$ the the diode current may be approximated as

$I = I_0 e^{qV/kT} = I_0 e^{V/V_T}$

This shows that the forward current increases exponentially with the bias voltage.




**P-N Junction Diode V-I Characteristics**

**Reverse biased p-n junction:**

For a reverse biased p-n junction, V is negative. If the magnitude of reverse bias is large compared with $V_T = kT/q$ then from the equation of diode $I = I_0\left(e^{qV/kT} - 1\right) = I_0\left(e^{V/V_T} - 1\right)$ we get $I \approx -I_0$

$I_0$ is called reverse saturation current. It is independent of reverse voltage upto the breakdown voltage but increases with the increase of temperature.

In the above derivation of diode current we have neglected the carrier generation and recombination in the space charge region. Taking this effect into consideration, small rated current flowing through a p-n junction can be approximated by the relation,

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

where $\eta \approx 1$ for Ge and $\eta \approx 2$ for Si.

**Practical Current-Voltage characteristics**

In practical Si and Ge diodes it is found that the forward current does not get significant value below certain threshold voltage $V_{\gamma}$., called cut in voltage.

Typically $V_{\gamma} \approx 0.2 - 0.3\ V$ for Ge diode

and $V_{\gamma} \approx 0.6 - 0.7\ V$ for Si diode