Module - 2

P-N Junctions

Forward and Reverse biased Junctions :

Qualitative Description of current flow at a junction

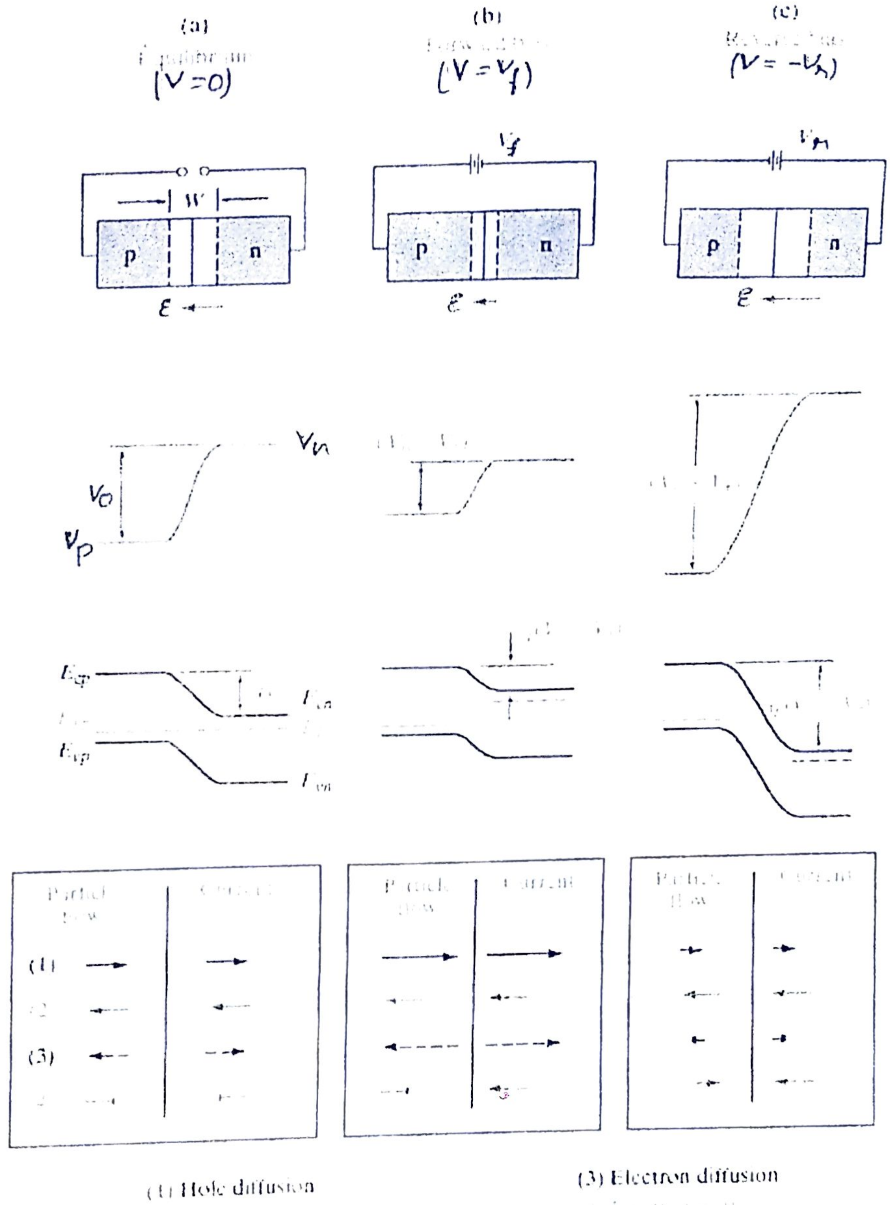
We assume that an applied voltage bias 'V' appears across the transition region of the junction rather than in the neutral n & p regions. In most p-n junction devices, the length of each region is small compared with its area, and the doping is usually moderate to heavy. thus the resistance is small in each neutral region & only a small voltage drop can be maintained in neutral region.

For all calculations, we assume that an applied voltage appears entirely across the transition region. And we take 'V' to be positive when the external bias is positive on the p side relative to the n side.

The electrostatic potential barrier at the junction is lowered by a forward bias V_f from the equilibrium contact potential V_0 to the smaller value $V_0 - V_f$. This lowering of the potential barrier occur because a forward bias (p positive with respect to n) raises the electrostatic potential on the p side relative to the n side

For a reverse bias ($V = -V_r$) the electrostatic potential of the p side lowered relatived to the n side. and the potential barrier at the junction becomes larger ($V_0 + V_r$).

Fig: effect of a bias at a p n junction; transition region width & electric field, electrostatic potential, energy band diagram & particle flow & current directions with IV for (a) equilibrium (b) Forward bias & (c) reverse bias



(1) Hole diffusion
(3) Electron diffusion

The electric field within ~~that~~ the transition region can be conclude from the potential barrier. As shown in fig. the field decreases with forward bias. since the applied electric field opposes the built in field. With reverse bias the field at the junction is increased by the applied field, which is in the same direction as the equilibrium field.

If there is change in electric field at the junction there is a change in the transition region width W. where it is necessary that proper number of positive & negative charges must be exposed for a given value of the $\mathcal{E}$ field. Thus the width W decrease under forward bias and W increase under reverse bias

$$W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$$= \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)\right]^{1/2}$$ - to calculate width W.

To Calculate the penetration of the transition region into the n and p materials:

$$x_{po} = \frac{W N_d}{N_a + N_d} = \frac{W}{1 + \frac{N_a}{N_d}}$$

$$x_{po} = \left\{\frac{2\epsilon(V_0 - V)}{q}\left[\frac{N_d}{N_a(N_a + N_d)}\right]\right\}^{1/2}$$

$$x_{no} = \frac{W N_a}{N_a + N_d} = \frac{W}{1 + N_d / N_a}$$

$$x_{no} = \left\{\frac{2\epsilon(V_0 - V)}{q}\left[\frac{N_a}{N_d(N_a + N_d)}\right]\right\}^{1/2}$$

The Separation of the energy bands is a direct function of the electron energy barrier & ~~Simply~~ at the junction.

The height of the electron barrier is simply the electronic charge q times the height of the ~~barrier~~ potential barrier

Under forward bias, the fermi level on the n side E_{Fn} is above E_{FP} by the energy qV_f

Under reverse bias, E_{FP} is higher than E_{Fn} by the energy qV_R.

The "diffusion current" is composed of majority carrier electrons on the n side overcoming the potential energy barrier to diffuse to the P side, and holes overcome their barrier from p to n.

With forward bias, the barrier is lowered and electrons in the n-side conduction band have sufficient energy to diffuse from n to p over the smaller barrier. Therefore, the electron diffusion current quite large with forward bias.

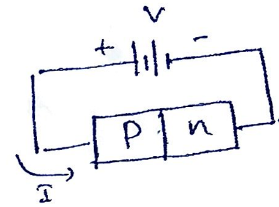
Similarly, more holes can diffuse from p to n under forward bias.

For reverse bias barrier becomes so large $(V_0 + V_R)$ that virtually no electrons in the n-side conduction band & holes in the p-side valence band have enough energy to overcome the barrier. Therefore, the diffusion current is usually negligible for reverse bias.

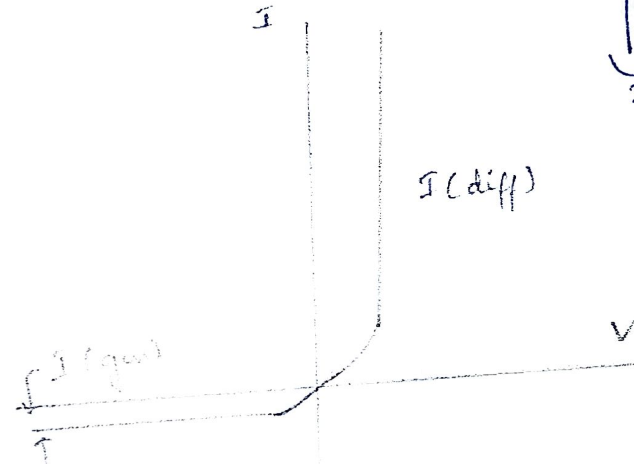
The drift current is relatively insensitive to the hight of the potential barrier. The drift current is limited not by how fast carriers are swept down the barrier, but rather how often.

The Total current crossing the junction is composed of the sum of the diffusion & drift components. As shown in fig (1), the electron & holes diffusion currents are both directed from p to n & the drift currents are from n to p.

The net current crossing the junction is zero at equilibrium. Under reverse bias, both diffusion components are negligible bcz of the large barrier at the junction, & the only current is the relatively small generation current from n to p. This generation current is shown in fig (2).



$I = [I(gen.)(e^{qV/kT} - 1)$



Fig(2) I-V characteristic of a p-n junction

In the fig 2) the positive direction for the current I is taken from p to n, & the applied voltage is positive. The current at V = 0 (equilibrium) is zero since the generation & diffusion currents cancel.

$I = I(diff.) - |I(gen.)| = 0$ for $V = 0$.

As the forward bias voltage $V = V_f$ increases there is probability that a carrier can diffuse across the junction by the factor $e^{(qV_f/kT)}$. Thus the diffusion current under forward bias is given by its equilibrium value multiplied by $e^{(qV_f/kT)}$

Similarly, for reverse bias the diffusion current is the equilibrium value reduced by the factor $e^{(qV/KT)}$ with $V = -V_r$.

Since the equilibrium diffusion current is equal ~~to~~ in magnitude to $|I(gen.)|$, the diffusion current with applied bias is simply $|I(gen.)| e^{(qV/KT)}$.

The total current I is then the diffusion current minus the absolute value of the generation current I_o.

$$I = I_0 (e^{qV/KT} - 1)$$

In the above equation applied voltage V can be positive or negative, $V = V_f$ or $V = -V_r$.

When V is positive & greater than a few KT/q ($KT/q = 0.0259$ V at room temperature), the exponential term is much greater than ~~to~~ unity. Thus the current increases exponentially with forward bias.

When V is negative, the exponential term approaches zero & the current is $-I_o$. This negative generation current is also called the reverse saturation current.

current flows relatively freely in the forward ~~bias~~ direction of the diode, but almost no current flows in the reverse direction.

Reverse Bias

Under reverse bias $V = -V_r$ (p negatively biased with respect to n) we can approximate the excess hole concentration Δp_n at the edge of the transition region x_{no} by the equation

$$\Delta p_n = P(x_{no}) - p_n = p_n (e^{q(-V_r)/KT} - 1)$$

$$\simeq -p_n \quad \text{for } V_r >> KT/q$$

and similarly $\Delta n_p \approx -n_p$.

Thus for a reverse bias of more than a few tenths of a volt, the minority carrier concentration at each edge of the transition region becomes zero as the excess concentration approaches the negative of the equilibrium concentration.

The excess minority carrier concentrations in the neutral regions are given by eqn.

excess carriers
$$\begin{cases} \delta n(x_p) = \Delta n_p e^{-x_p/L_n} = n_p (e^{qV/KT} - 1) e^{-x_p/L_n} \\ \delta p(x_n) = \Delta p_n e^{-x_n/L_p} = p_n (e^{qV/KT} - 1) e^{-x_n/L_p} \end{cases}$$

$L_p \rightarrow$ hole diffusion length

$L_n \rightarrow$ electron diffusion length

So, that depletion of carriers below the equilibrium values extends approximately a diffusion length beyond each side of the transition region. This reverse bias depletion of minority carriers can be thought of as minority carrier extraction.

Physically, extraction occurs bcz minority carriers at the edge of the depletion region are swept down the barrier at the junction to other side & are not replaced by an opposite diffusion of carriers.

For example, when holes at x_{no} are swept across the junction to the p side by the $\mathcal{E}$ field, a slope in the hole distribution in the n material exists, & holes in the n region diffuse towards the junction. The steady state hole distribution in the n region has inverted exponential shape of fig (a).

The rate of carrier drift across the junction depends on the rate at which holes arrive at x_{no} by diffusion from the neutral material. These minority carriers are supplied by thermal generation - equation $p_n = n_i^2 e^{(F_n - F_p)/KT} = n_i^2 e^{(qV/KT)}$ represents the rate at which carriers are generated thermally within a diffusion length of each side of the transilion region.

As shown in fig (b) the quasi-Fermi levels split in the opposite sense. ~~the~~ The F_n moves farther away from E_c (close to E_v) and F_p moves farther away from E_v, reflecting the fact that in reverse bias we have fewer carriers than in equilibrium.

In reverse bias, in the depletion region, we have $p_n = n_i^2 e^{(F_n - F_p)/KT} \simeq 0$

The quasi-Fermi levels in reverse bias can go inside the bands.

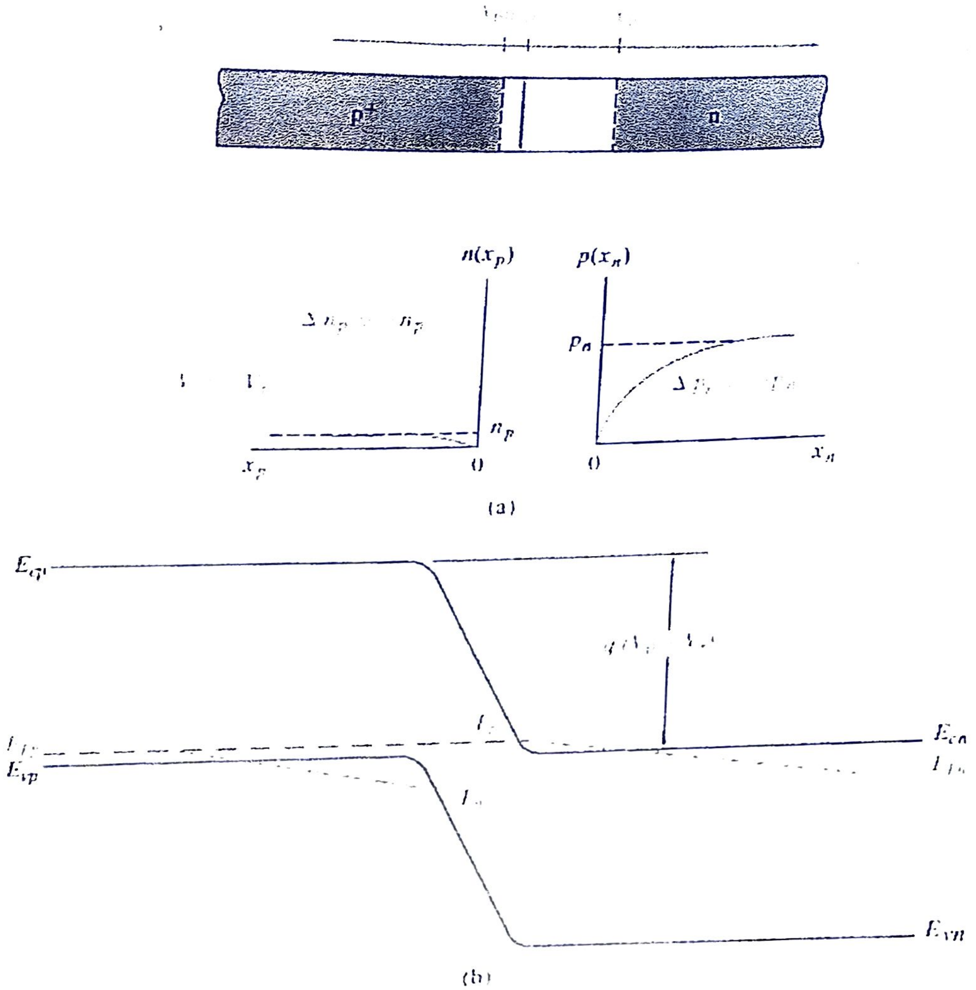


Fig : reverse biased p-n junction

(a) Minority carrier distributions near the reverse-biased junction

(b) Variation of the quasi-fermi levels.