1. Forward-bias Recombination current:-

- In forward bias of a pn junction, e⁻s and holes are injected across the depletion region (which further diffuse in these region and contribute to minority current ie we have some excess carriers in depletion region).

- Some of these excess carriers (e⁻s & holes) can recombine within depletion region and not become part of minority carrier distribution & hence the current.

The Recombination rate is given by,

CB - conductn band

VB - valence band

$$R = \frac{np - n_i^2}{\tau_{po}(n+n_t) + \tau_{no}(p+p_t)} \quad \text{—} \ (1)$$

where, n, p : e⁻, hole concentration

n_t, p_t : e⁻, hole concentration existing in the CB(VB) when trap energy level E_t coincides with E_{Fi} (Fermi level).

Va - applied F.B voltage.

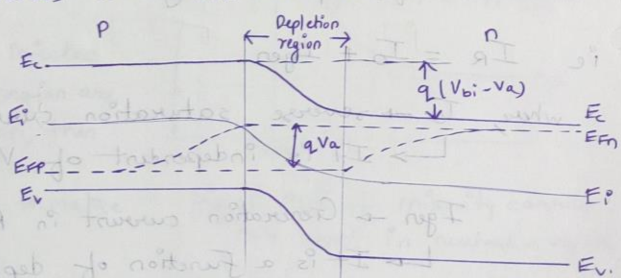


fig (b): EBD of a F.B pn junction showing quasi-Fermi-levels for e⁻ (E_{fn}) and holes (E_{fp})

Now, e^- concentration in CB is

$$n = n_i \exp\left(\frac{E_{fn} - E_i}{KT}\right) \quad \text{--- (2)}$$

Hole concentration in VB is

$$p = n_i \exp\left(\frac{E_i - E_{Fp}}{KT}\right) \quad \text{--- (3)}$$

} From fig(b)

From fig (b), we have

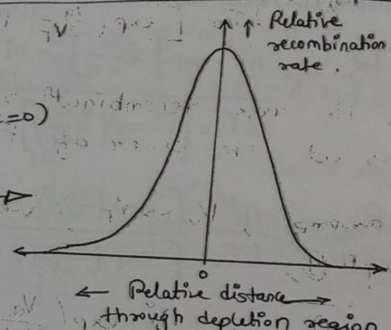
$$(E_{Fn} - E_i) + (E_i - E_{Fp}) = qV_a \quad \text{--- (4)}$$

We will assume that the trap level to be at the intrinsic fermi level such that

$$\boxed{n_t = p_t = n_i} \quad \text{--- (5)}$$

Reference

The recombination rate can be shown to peak at the metallurgical junction (ie, $x=0$)



At the center of depletion region, we have (From fig(b))

$$E_{Fn} - E_i = E_i - E_{Fp} = \frac{qV_a}{2} \quad \text{--- (6)}$$

Using equation (6) in ② and ③, we get

$$n = n_i \exp\left(\frac{qV_a}{2KT}\right) \quad \text{— (7)}$$

and

$$p = n_i \exp\left(\frac{qV_a}{2KT}\right) \quad \text{— (8)}$$

If we assume that $n_t = p_t = n_i$ and $\tau_{no} = \tau_{po} = \tau_0$, then equation ① becomes.

$$R = \frac{n_i^2 \exp\left[\frac{qV_a}{KT}\right] - n_i^2}{2\tau_0\left[n_i \exp\left(\frac{qV_a}{2KT}\right)\right] + 2\tau_0\left[n_i \exp\left(\frac{qV_a}{2KT}\right)\right]}$$

$$R_{max} = \frac{n_i}{2\tau_0} \frac{\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]}{\left[\exp\left(\frac{V_a}{2V_T} - 1\right)\right]} \quad \text{— (9)} \qquad \boxed{V_T = \frac{KT}{q}}$$

R_{max} is the max recombinatn rate for e & holes that occurs at the center of F.B pn junction.

If we assume, $V_a >> V_T$; we can neglect (-1) & (+1) from eqn ⑨,

$$\boxed{R_{max} \simeq \frac{n_i}{2\tau_0} \exp\left(\frac{V_a}{2V_T}\right)} \quad \text{— (10)}$$

Now, Recombination current density (J_{rec}): is

$$J_{rec} = \int_0^W q R \, dx \quad \text{— (11)}$$

↑ Integral is over the entire Depletion region.

In this case recombination rate is not constant throughout the depletion region,

$$J_{rec} = q x_m \frac{n_i}{2\tau_0}\left[\frac{V_a}{2V_T}\right] \quad — (12)$$

where, x_m is the width of depletion region where recombination rate is effective.

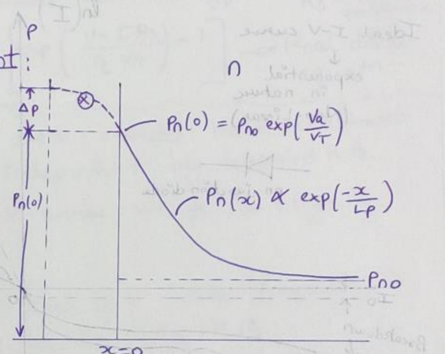
$$\therefore \quad J_{rec} = \left\{\frac{qWn_i}{2\tau_0}\right\} \exp\left(\frac{V_a}{2V_T}\right) \quad — (13)$$

ie $J_{rec} = J_{ro} \exp\left(\frac{V_a}{2V_T}\right)$

⊢ Total Forward-bias current:

The distribution shown in fig(c), is established as a result of holes being injected across the depletion region.

If, now, some of the injected holes in the depletion region are lost due to recombination, then additional holes must be injected from p region to make up for this loss.



fig(c): Plot of minority carrier hole concn in neutral n region.

The flow of these additional injected carriers, results in the recombination current.

∴ Total F.B current density is

$$J = J_{rec} + J_D$$

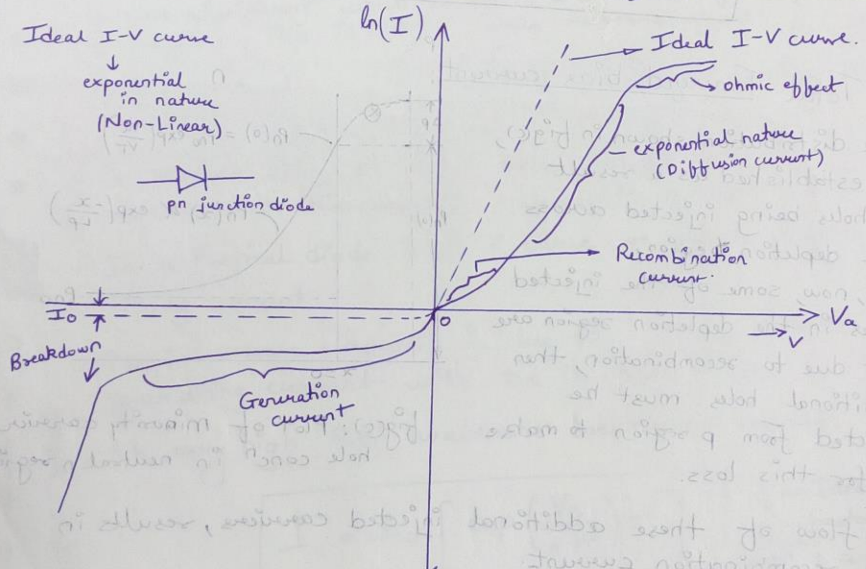
— J_D: ideal diffusion current density; J_{rec}: recombinatn current density

Note: J_{rec} dominates at low-bias voltage, whereas J_D dominates at high bias vtg

ie $J_{rec} = J_{ro} \exp\left(\frac{V_a}{2V_T}\right)$ — (from (13))

and $J_D = J_s \exp\left(\frac{V_a}{V_T}\right)$; — where J_s or J_o → Ideal reverse saturatn current density.

⊢ Practical I-V characteristics of pn junction diode:-



fig(d): Practical I-V characteristics of pn junction diode in forward as well as in reverse bias

Interpretation from fig(d),

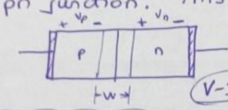
∴ Ideal I-V follows exponential nature.

- For low F.B, I_D (diode current) reduces from its exponential value due to recombination in a practical I-V curve
- After that I_D ↑ses exponentially with voltage due to (diffusion current).
- At higher I_D, "ohmic effect" comes into picture.

Ohmic effect { In deriving ideal diode eq^n, we assumed that voltage applied to the device appears entirely across the junction }

Thus, we neglected any voltage drop in neutral regions or at external contacts

- But for higher current, voltage drop across neutral n & p regions (ie V_p & V_n) becomes significant which results in a lower voltage drop across pn junction. This is called 'Series-resistance effect' R_S - Series resistance



$$I = I_o\left[\exp\left(\frac{V - IR_S}{\eta V_T}\right) - 1\right]$$ → Real diode equatn.

$V - IR_S$ → lower vtg drop

- In reverse bias, an ideal diode should have constant reverse saturation current independent of applied R.B.
- In a Pratical diode ie in I-V curve we get a slightly ↑sing current.
- ↑se in reverse current is due to the increase in generating current with ↑se in ↑sing R.B.
- At very high R.B avalanche breakdown occurs.

$$\boxed{I = I_o\left[\exp\left(\frac{V_a}{\eta V_T}\right) - 1\right]}$$

η → Ideality factor
↳ Value (Betn 1 and 2)

η → determines the departure from ideal diode characteristics.
↳ It depends on the material and temperature

—x—