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26/7/2016

• Ideal pn junction diode assumptions:-

1) Abrupt junction formed betn uniformly doped n & p region

2) Current flow across the pn Jn is 1-D.

3) All of the applied voltage appears across the space-charge region & the neutral regions are field-free.

4) There is no net generation or recombination of carriers in the junction's depletion region.
(ie e^- & hole currents remain constant throughout the depletion region)

5) Low-level injection prevails on both sides of the junction (ie only minority carrier concentratn is disturbed).
(This condition places a restriction on the current that can be drawn through the ideal diode and it is not valid at high currents)

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• Real diodes :-

The ideal diode eq^n $I = I_0(e^{\frac{V_a}{V_T}} - 1)$ is not quite accurate in describing the I-V characteristics of real diodes.

- Thus several deviations from ideal behavior are observed such as,
  a) The generation- and recombination of EHPs in the depletion region.
  b) Voltage drop associated with E-field in neutral n and p regions.
  c) Current arising from leakage across the surface of the junction.

- When a semi-conductor is in non-equilibrium, then excess carriers may be generated.
- The rate at which these excess carriers recombine is called "Recombination rate" (R)

$$\boxed{R = \frac{\delta}{\tau}}$$

; $\delta \rightarrow$ excess carriers
$\tau \rightarrow$ Lifetime of excess carrier

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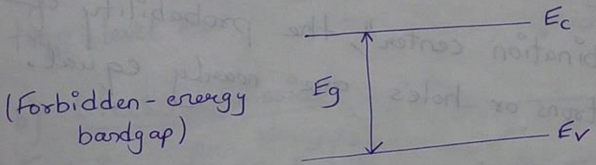
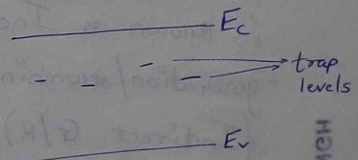
- Generation and Recombination of carriers:- 03

- In a pure semiconductor (as it is a perfect crystal), the electronic energy states do not exist within the forbidden-energy bandgap (E_g).



- In actual (real) semiconductor materials, however, defects or deep impurities are present within the semi-conductor crystal and these defects will create discrete electronic energy states within the forbidden energy gap known as "trap level" (E_t).



- This trap level depending on its location in the energy-gap may act as an e^- trap or hole trap or as an "Recombination centers" (As per Shockley-Read-Hall (SRH) theory of recombination)

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a) An electron trap has a high probability of capturing a electron, & setting it free after some time.

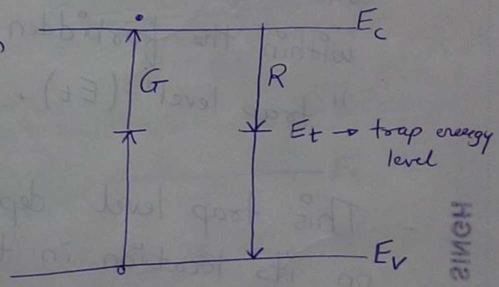
b) A hole trap has a high probability of capturing a hole

c) At a "recombination center", the probability of capturing electrons or holes are nearly equal.

SRH theory of recombination :-

- It assumes that a single "recombination centers" or "trap levels", exists at a energy E_t within the bandgap of semiconductor.

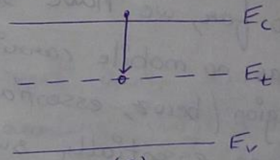
- This type of mechanism is known as Indirect generation/recombination (Indirect G/R) ie here recombination or generation occurs via an "trap level" within the energy gap.



- There are 4 basic processes, that may occur at single trap level.

a) <u>Electron capture:</u>

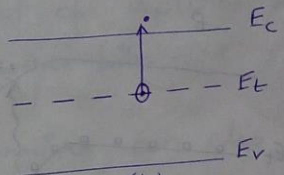
→ Capture of an e^- from conduction band by trap level E_t



(a)

b) <u>Electron emission:</u>

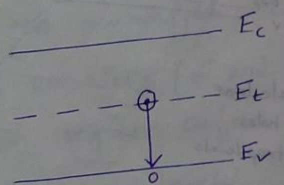
→ Emission of an e^- (ie initially occupying a trap level E_t) from E_t level back into conduction band.



(b)

c) <u>Hole capture:</u>

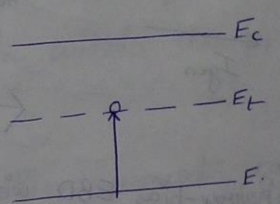
→ Capture of a hole from the valence band by trap level 'E_t'.



(c)

d) Hole emission:-

→ Trap level captures an e^- from valence band. OR (Emission of an holes into valence band from trap level)



(d)

- **Reverse-bias generation current :-** (assumed)

So far, we have seen that a reverse-bias pn junctn has no mobile carriers (e^-s or holes) within the depletn region (becoz, essentially all mobile carriers have been essentially swept out of depletion region due to Electric-field)

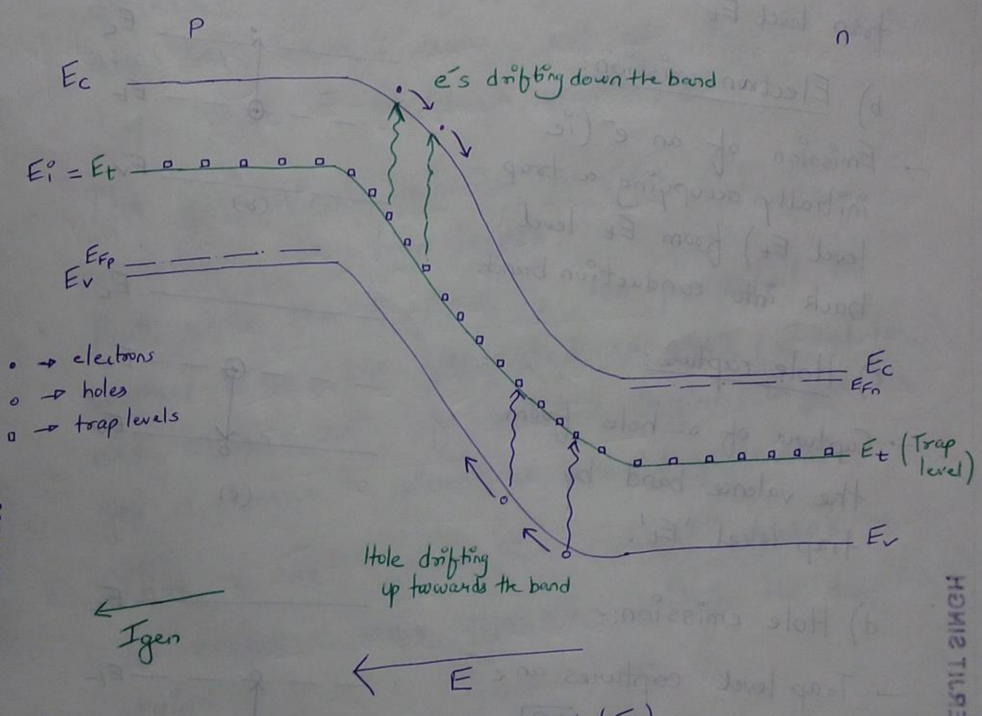


fig. • Reverse-bias EBD with trap level (E_t)
• Generation current (I_{gen}) in a Reverse-bias pn junction due to thermal generation of carriers via "trap level"

Assumption: let the trap level be at the intrinsic Fermi level

- But, according to SRH theory, there are trap levels around mid-gap within the energy band gap.
- Now, these trap levels can act as a source of generation of excess carriers within the depletion region, before these excess carriers are being swept away out of depletion region by large E-field in reverse-bias.
- The generated minority carriers can also recombine via 'trap levels'.
- But since the E-field is too powerful in reverse-bias, the generated carriers (e^- and holes) are swept out of depletion region before they get a chance to recombine via 'trap levels'.
- Thus, a net "generation current" flows, due to excess carrier generation within the depletion region
- This reverse-bias generation current caused by the generation of carriers (e^-s and holes) via trap-levels in depletion region is in addition to ideal reverse-bias saturation current.

ie Reverse current I_R becomes

$$\boxed{I_R = I_0 + I_{gen}}$$

ie Total reverse current flowing through Reverse-bias pn junction is the sum of reverse-bias generation current (I_{gen}) and reverse saturation current (I_0)

{ Note: I_{gen} is dominant current among the two in pn junction diode }

- Now, for a constant 'generation' rate across the depletion region, we have

$$\boxed{I_{gen} = \frac{qAn_iW}{2\tau_0}}$$

where $\tau_0 = \frac{\tau_{p0} + \tau_{n0}}{2}$ → average life time

; W - width of depletn region

ie $\boxed{I_R = I_0 + I_{gen}}$

where, I_0 → reverse saturation current

→ It is independent of V_R

I_{gen} → generation current in reverse-bias

→ It is a f^n of depl^n width W ie it is a f^n of V_R

∴ I_R is dependent on reverse-bias voltage V_R.

• Forward-bias Recombination current :-

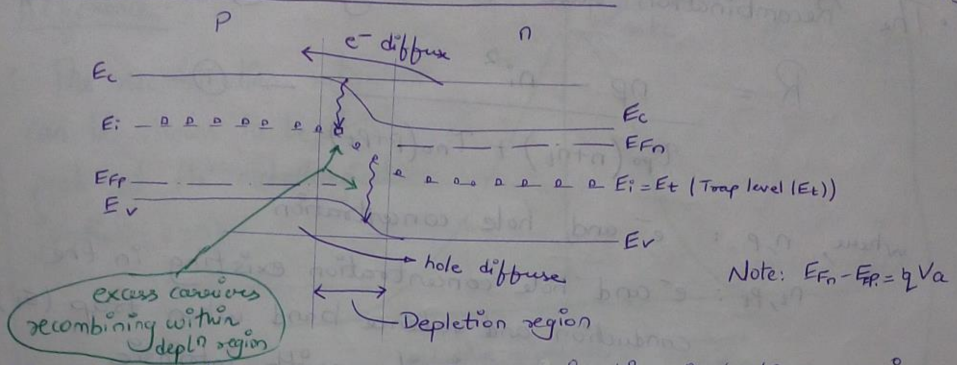


fig a) EBD of a forward-bias pn junction including quasi-fermi-level

- In a forward-bias pn junction, electrons and holes are injected across the depletion region (which further diffuse in these regions and contribute to minority carrier diffusion current) ie we have some excess carriers in depletion region for some time.

- Some of these excess carriers (electrons and holes) which are diffusing away, can recombine within the depletion region via "Recombination centers" or "trap levels" & not become a part of minority carrier diffusion; hence, we now have a recombination current flowing in forward bias pn junction in addition to diffusion current.

- The Recombination rate 'R' is given by

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

where, n, p : e^- and hole concentration

n_t, p_t : e^- and hole concentration existing in the conduction and valence band when trap (E_t) energy level coincides with intrinsic Fermi-level (E_i)

Now, e^- concentration in conduct band is given by,

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

Hole concentration in valence band is given by,

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

From fig (a), we may note that,

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

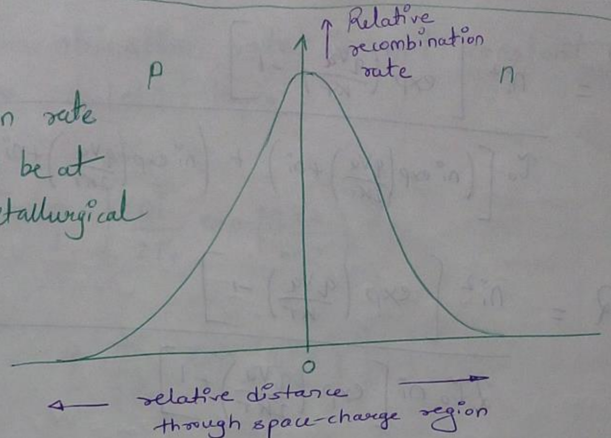
where, V_a is the applied forward-bias voltage.

Assume trap level is at intrinsic fermi-level,

then $\boxed{n_i = n_t = p_t}$

Reference:-

- The recombination rate can be shown to be at peak at the metallurgical junction (i.e. $x=0$)



At the center of the depletion region, we have (from fig a)

$$E_{Fn} - E_i = E_i - E_{Fp} = \frac{qV_a}{2} \quad \text{— (5)}$$

Using eq^n (5) in (2) and (3), we get

$$n = n_i \exp\left(\frac{qV_a}{2kT}\right) \quad \text{and} \quad p = n_i \exp\left(\frac{qV_a}{2kT}\right)$$

If we assume $n_t = p_t = n_i$ and $\tau_{no} = \tau_{po} = \tau_o$, then eq^n (1) becomes,

$$R = \frac{n_i^2 \exp\left(\frac{qV_a}{kT}\right) - n_i^2}{\tau_o\left[(n+n_i) + (p+p_i)\right]}$$

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$$R = \frac{n_i^2\left[\exp\left(\frac{qV_a}{KT}\right)-1\right]}{\tau_o\left[\left(n_i\exp\left(\frac{qV_a}{2KT}\right)+n_i\right)+\left(n_i\exp\left(\frac{qV_a}{2KT}\right)+n_i\right)\right]}$$

$$R = \frac{n_i^2\left[\exp\left(\frac{qV_a}{KT}\right)-1\right]}{2\tau_o n_i\left[\exp\left(\frac{qV_a}{2KT}\right)+1\right]}$$

$$\therefore R_{max} = \frac{n_i\left[\exp\left(\frac{qV_a}{KT}\right)-1\right]}{2\tau_o\left[\exp\left(\frac{qV_a}{2KT}\right)+1\right]} \quad \text{— (6)}$$

R_{max} is the maximum recombination rate for e's & holes that occur at the center of forward-bias pn's depletion region.

Eq^n (6) can be written as,

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

Now, recombination current density J_{rec} is

$$J_{rec} = \int_0^W q\, R_{max}\, dx$$

means Integral over entire depletion region

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

$$J_{rec} = q \int_0^W \frac{n_i}{2\tau_0} \exp\left(\frac{qV_a}{2kT}\right) dx$$

$$J_{rec} = q \frac{n_i}{2\tau_0} \exp\left(\frac{qV_a}{2kT}\right) [x]_0^W$$

ie
$$J_{rec} = \frac{qWn_i}{2\tau_0} \exp\left(\frac{qV_a}{2kT}\right)$$

$$\boxed{J_{rec} = J_{r0} \exp\left(\frac{qV_a}{2kT}\right)} \quad -(8)$$

Total Forward-Bias current:-

→ Total forward-bias current in pn junction is the sum of recombination and the ideal diffusion currents.

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

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

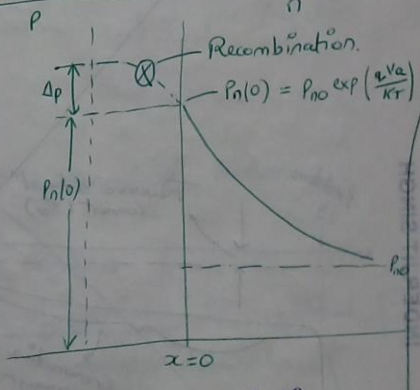


fig b) Becoz of recombination, additional holes from p-region are injected into the depl^n region to establish minority carrier hole concentration in the n-region.

$\therefore$ Total forward-bias current density is

$$\boxed{J_{F.B} = J_{rec} + J_{diff}}$$

where,

$$J_{rec} = J_{ro} \exp\left(\frac{qV_a}{2kT}\right)$$

$$J_{diff} = J_{o} \exp\left(\frac{qV_a}{kT}\right)$$

Note

J_{rec} dominates at low forward-bias voltages; whereas J_{diff} dominates at high-forward-bias voltages

• Practical I-V characteristics of pn junction diode 15

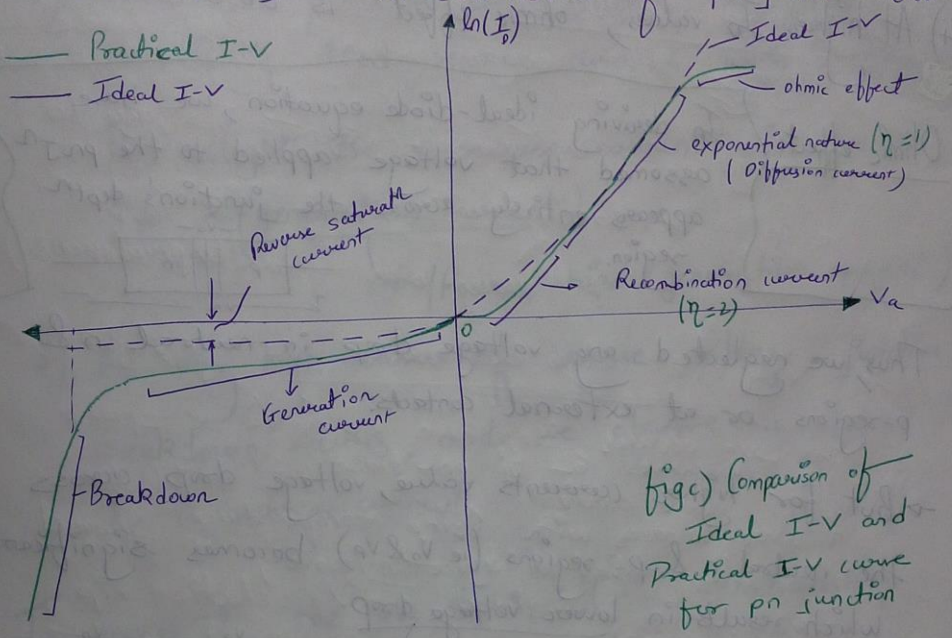


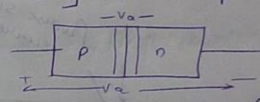
fig c) Comparison of Ideal I-V and Practical I-V curve for pn junction

Interpretations from fig c)

1) Ideal I-V curve follows exponential nature
2) For low forward voltages, I_D reduces from its exponential nature due to Recombination in practical I-V. (Recombinatn current's dominates at low Va)
3) After that diode current I_D ↑ses exponentially with voltage Va due to diffusion.

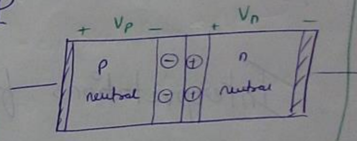
4) At higher I_0 values, "ohmic effect" is observed.

Ohmic effect: In deriving ideal-diode equation, we have assumed that voltage applied to the pn J^n appears entirely across the junction's depl^n region.



Thus, we neglected any voltage drop in neutral n & p-regions or at external contacts.

→ But for higher currents value, voltage drop across the neutral n & p regions (ie V_n & V_p) becomes significant which results in lower voltage drop across pn junction.



This is known as "ohmic" effect or "series resistance effect"

$$V_T = \frac{KT}{q}$$

Now,
$$I = I_0\left[\exp\left(\frac{V_a - IR_s}{V_T}\right) - 1\right]$$

R_s → series resistance accounting for neutral n & p resistance.

5) In ideal I-V curve, I_0 (reverse-saturation current) is a constant and it is independent of applied reverse-bias voltage.

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6) Whereas, in practical I-V curve, we get a slightly ↑sed reverse current with reverse vtg.

- This slight ↑se in reverse current is due to ↑se in (generation current) → (Reverse-bias generation current)

7) At very high values of reverse voltage, junction breakdown occurs, and we observe a sharp ↑se in reverse current.

In general, the pn diode I-V relationship may be written as,

$$\boxed{I = I_0 \left[e^{\left(\frac{qV_a}{\eta KT}\right)} - 1 \right]}$$

where the parameter η is called "ideality factor" (betn 1 & 2)

η → determines the departure of practical I-V from ideal I-V curve.

→ It depends on the material & temperature.

For low-forward bias voltages, $\eta = 2$ when recombination dominates & for large-forward bias vtg, $\eta = 1$ when diffusion dominates.

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Effect of Temperature on diode characteristics: 18

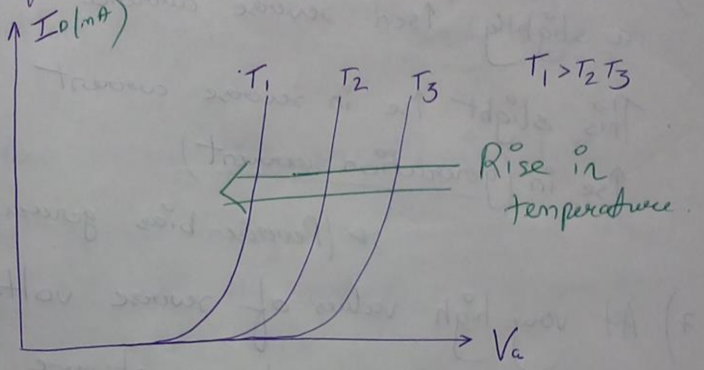

fig:- The I-V curves of Si pn-diode shifts to lower voltages with ↑sing temperature (at the rate −2.5mV per degree centigrade) in forward bias region

- The figure shows that at higher temperature it takes a smaller vtg for the diode to conduct a given current due to a large n_i.

$$I = I_0 \left(e^{\frac{qV_a}{KT}} - 1 \right)$$

n_i → strong dependence on temperature

intrinsic carrier concentratn.

where, $I_0 = A q n_i^2 \left(\frac{D_P}{L_P} \times \frac{1}{N_d} + \frac{D_n}{L_n N_a} \right)$

reverse-saturation current.

- In the reverse-bias region, the reverse-saturation current of Si and Ge diodes DOUBLES for every 10°C rise in temperature

—x—