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Lec 10: Minority carriers distribution and Ideal I-V characteristics of pn junction.

Reference (R):

- $\boxed{\dfrac{D}{\mu} = V_T}$ → Einstein Relation (It holds under quasi-equilibrium)

where, 'D' → Constant associated with "diffusion" transport. (Diffusivity)
'μ' → constant associated with "drift" transport. (Mobility)

$\boxed{V_T = \dfrac{KT}{q}}$ → Thermal voltage ; At $T = 300K$ or $27°C$, $V_T = 0.0259$ Volts

Also, $\boxed{\dfrac{D_n}{\mu_n} = V_T = \dfrac{D_p}{\mu_p}}$

- $J_{p\,drift} = -q\,p\,\mu_p \dfrac{d\psi}{dx}$

$\boxed{E = -\dfrac{d\psi}{dx}}$

It shows, that E-field is caused by gradient of potential.

- $J_{p\,diffus^n} = -q\,D_p \dfrac{dp}{dx}$

Transport eq^n for holes :- $J_p = \underbrace{q\,p\,\mu_p E}_{drift} - \underbrace{q\,D_p \dfrac{\partial p}{\partial x}}_{diffusion}$

Transport eq^n for electrons :- $J_n = \underbrace{q\,n\,\mu_n E}_{drift} + \underbrace{q\,D_n \dfrac{\partial n}{\partial x}}_{diffusion}$

drift → potential gradient
diffusion → concentration gradient

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· Diffusion approximations: (ie Diffusion current dominating over drift)

eg Consider holes as charge carriers.

$$\boxed{J_{P_{diff}} \simeq -q D_p \frac{\partial p}{\partial x}} \quad \text{ie } |\text{diffusion}| >> |\text{drift}| \quad \text{—(a)}$$

Let us take a example of a situation; where eqn(a) is Valid.

Example: When low-level → injection prevails in a region of a device, we find excess carrier concentration given by equation eqn (a).

Eqn(a) will hold for minority carriers (holes) eg [for holes in a ntype Si] → becoz of ① & ② points

① Drift current depends on concentration of carriers and electric field.

② Diffusion current depends only on gradient of concentration of carriers.

∴ Diffusion approximatn holds for minority carriers.

· $\boxed{L_p^2 = D_p \tau_{po}}$ or $\boxed{L_n^2 = D_n \tau_{n_0}}$ (for e⁻s)

where L_p → Minority carrier (hole) diffusion length

D_p → hole diffusion co-efficient.

τ_{p_0} → Excess minority carriers lifetime (holes).

· Physical Interpretation of L_p: (Diffusion length) → [Length over which hole travels by diffusion before it recombines]

For a n-region,

$n_{n0} \approx N_d$ (Assuming complete ionization)

$p_{n0} \approx \frac{n_i^2}{N_d}$ (From Law of mass action Law) —(i)

For a p-region

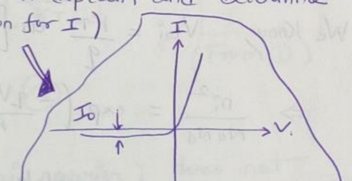
$p_{p0} \approx N_a$ (Assuming complete ionization)

$n_{p0} \approx \frac{n_i^2}{N_a}$ —(ii)

Equation (i) and (ii) represent total minority carrier concentration in p and n region.

- pn Junction Analysis → (Goal is to explain and determine expression for I)

- The potential barrier of a pn junction is lowered when a forward bias is applied, allowing electrons and holes to flow across the space-charge region.



$$\boxed{I = I_0 \exp\left(\frac{qV}{KT} - 1\right)}$$

- When holes flow from p-region into n-region, they become excess minority carrier (holes) and are subject to the excess minority carrier diffusion, drift and recombination processes.

- Likewise, when electrons from n-region flow into p region, they become excess carriers (electrons).

• Minority Carrier Distribution: (pn Junction)

I] Thermal equilibrium case:

• The n-region contains many e^-s in CB than p-regions; V_{bi} prevents this large density of e^-s from flowing into p region.

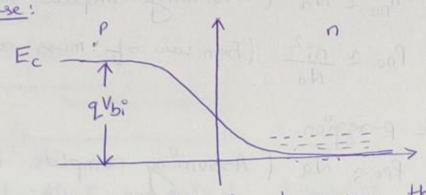


fig: Conduction band energy through a pn junction in thermal equilibrium

• Build-in potential barrier (V_{bi}) maintains equilibrium between carrier distributions on either side of the junction.

We know, $V_{bi} = \frac{KT}{q} \ln\left[\frac{N_a N_d}{n_i^2}\right] = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right]$ $\left\{ V_T = \frac{KT}{q} \right\}$

$$\Rightarrow \frac{n_i^2}{N_a N_d} = \exp\left(-\frac{qV_{bi}}{KT}\right)$$

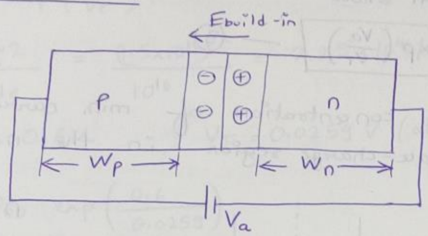
If we assume complete ionization ie $\boxed{n_{no} \approx N_d}$

and $\therefore$ $\boxed{n_{po} \approx \frac{n_i^2}{N_A}}$

$$\therefore \boxed{n_{po} = n_{no} \exp\left(-\frac{qV_{bi}}{KT}\right)} \quad \text{—— (1)}$$

Eq^n (1) relates minority carrier concentration on p-side of the junction to the majority carrier concentration on nside of the junction in a thermal equilibrium.

II Forward bias case:



Va - Applied bias

· In forward bias, E-field that prevented majority carriers from crossing the space-charge region is reduced.

$$n_p = n_{no} \exp\left[\frac{-q(V_{bi} - V_F)}{KT}\right]$$

$$= n_{no} \exp\left[\frac{-qV_{bi}}{KT}\right] \exp\left[\frac{qV_a}{KT}\right] \qquad \boxed{\frac{KT}{q} = V_T}$$

(From ①)

$$\boxed{n_p = n_{po} \exp\left[\frac{V_a}{V_T}\right]} \text{ — ②}$$

Assuming low injection level, n_{no} (maj. carrier) does not change significantly.

$n_p \rightarrow$ deviates from thermal-equilibrium value n_{po} as seen in eq^n ②.

Equation ② is the expression for minority carrier (e^-s) concentration at the edge of space-charge region in p-side.

→ Va lowers potential barrier, so that maj. carrier e^-s from n side are injected across the junction into p-side, thereby increasing minority carrier concentration.

∴ There is excess minority carriers (e^-s) in p-region.

Similarly, we can show

$$\boxed{p_n = p_{no} \exp\left(\frac{V_a}{V_T}\right)} \quad \text{--- (3)}$$

Eq^n (3) represents concentration of min. carriers (holes) at the edge of space-charge region in the n-side.

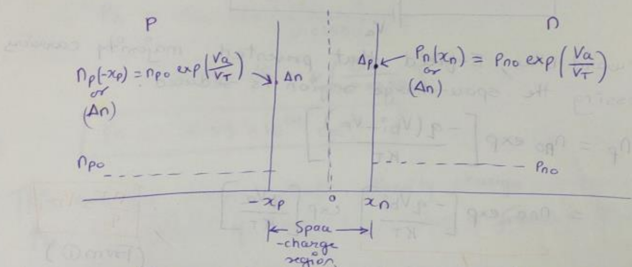


fig a): Excess minority carrier concentration at space charge edge generated by applied bias Va.

∴ By applying a voltage $\boxed{V_a = V_F}$ (forward-bias), we create excess minority carriers in each region of pn junction.

$$\boxed{\Delta n = n_p = n_{po} \exp\left(\frac{V_a}{V_T}\right) \quad \& \quad \Delta p = p_n = p_{no} \exp\left(\frac{V_a}{V_T}\right)}$$

↳ Minimum carrier concentrat^n at depletion layer edges derived assuming $(V_a > 0)$ is applied across pn junction.

→ $\boxed{\Delta n \;\&\; \Delta p}$ → symbol is used to indicate value at the depletion layer edge.

III Reverse Bias Case:

- Va → -ve (Reverse bias)

→ $\boxed{n_p \text{ and } p_n \rightarrow \text{reduces to zero at space-charge edges.}}$

This page is just for explaining how we got the Ambipolar transport circuit

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$\delta n_p = n_p - n_{po}$ → Excess minority carrier e^- (holes) concentration in p (n) region.

$\delta p_n = p_n - p_{no}$ — (a)

· Continuity equation → (Describe's the distribution of e^-s and holes, when there is excess carrier generation, recombination and carrier movement)

Continuity eq^n for holes ⇒

$$\boxed{\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G' - \frac{\delta p}{\tau_p}} \quad \text{— (1.1)}$$

→ Excess generat^n rate.

Now, $\frac{\partial \delta p_n}{\partial t} = \frac{\partial p_n}{\partial t} - \frac{\partial p_{no}}{\partial t}$ → constant, → 0

From (a) →

Since p_{no} is const with x; uniform doping in semiconductor → (b).

$$\boxed{\frac{\partial \delta p_n}{\partial t} = \frac{\partial p_n}{\partial t}} \quad \text{— (1.2)}$$

τ_p → life time of minority carriers.

Eq^n (1.1) becomes,

$$\boxed{\frac{\partial \delta p_n}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} + G' - \frac{\delta p_n}{\tau_p}} \quad \text{— (1.3)}$$

$\frac{\partial^2 p}{\partial x^2} = \frac{\partial^2(\delta p)}{\partial x^2}$ Since p_o is constant (from b).

Now, $J_p = q\mu_p p E - q D_p \frac{\partial p}{\partial x}$ — (1.4).

$$\Rightarrow \frac{\partial \delta p_n}{\partial t} = -\frac{1}{q}\frac{\partial}{\partial x}\left[-q D_p \frac{\partial p}{\partial x} + q\mu_p p E\right] + G' - \frac{\delta p_n}{\tau_p}$$

$$\boxed{\frac{\partial \delta p_n}{\partial t} = D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p . E \frac{\partial p}{\partial x} + G' - \frac{\delta p_n}{\tau_p}}$$

$\frac{\partial \delta p_n}{\partial x}$

Ambipolar Transport eq^n for excess minority carriers (holes) in n region → (1.4)

· Minority Carrier Distribution (in p and n regions)

→ Ambipolar transport eq^n for excess minority carriers (holes) in n-region is

$$\frac{\partial(\delta p_n)}{\partial t} = D_p \frac{\partial^2(\delta p_n)}{\partial x^2} - \mu_p . E \frac{\partial(\delta p_n)}{\partial x} + G' - \frac{\delta p_n}{\tau_{p}} \quad -①$$

where, $\delta p_n = p_n - p_{no}$ is the excess minority carrier holes concentration.

In equilibrium, when no voltage is applied $(E=0)$ in n-region for $x >> x_n$, the net change of hole concentratn $\left(\frac{\partial(\delta p_n)}{\partial t}\right) = 0$

∴ Equation ① reduces to,

$$\frac{d^2(\delta p_n)}{dx^2} - \frac{\delta p_n}{L_p^2} = 0 \quad --- \quad (x >> x_n) \quad -②$$

where, $\boxed{L_p^2 = D_p \tau_p}$

Similarily, for p-region,

$$\frac{d^2(\delta n_p)}{dx^2} - \frac{\delta n_p}{L_n^2} = 0 \quad -- \quad (x << x_p) \quad -③$$

where, $\boxed{L_n^2 = D_n \tau_n}$

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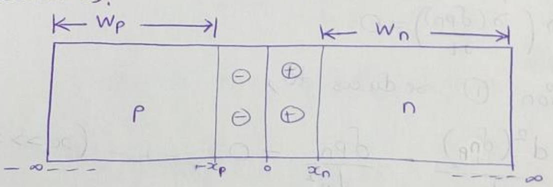
Boundary conditions for total minority carrier concentratⁿˢ are (Refer fig a)

$$4a \begin{cases} P_n(x_n) = P_{no} \exp\left(\frac{V_a}{V_T}\right) \\ n_p(-x_p) = n_{po} \exp\left(\frac{V_a}{V_T}\right) \end{cases}$$

$$4b \begin{cases} P_n(x \to +\infty) = P_{no} \\ n_p(x \to -\infty) = n_{po} \end{cases} \quad \text{— (4) a \& b}$$

- As minority carriers diffuse from the space charge edge into neutral n & p regions, they will recombine with majority carriers.



fig(b). : Long pn junction

We assume lengths W_n and W_p are very long i.e

$\boxed{W_n >> L_p \text{ and } W_p >> L_n}$

→ The excess minority carrier concentrations must approach zero at distance's far from the space-charge region. The structure is called "long pn junct".

. The general solution to eqⁿ (2) and (3) is

$$\delta p_n(x) = P_n(x) - P_{no} = A e^{x/L_p} + B e^{-x/L_p} \quad (x \geq x_n) \text{ — (5)}$$

$$\delta n_p(x) = n_p(x) - n_{po} = C e^{x/L_n} + D e^{-x/L_n} \quad (x \leq x_p) \text{ — (6)}$$

Applying Boundary conditions from eq^n (4b),

$$p_n(x\to\infty) - p_{no} = 0 = A e^{\infty/L_p} + B e^{-\infty/L_p}$$

$$\underline{A = 0}$$

$$\left\{ \begin{array}{l} e^{-\infty} = 0 \\ e^{+\infty} = \text{v high value} \end{array} \right\}$$

$$\therefore \; p_n(x) - p_{no} = B e^{-x/L_p} \quad -(7)$$

At $x = x_n$; $p_n(x_n) = p_{no} \exp\left(\frac{V_a}{V_T}\right) \Rightarrow$

$$p_{no} \exp\left(\frac{V_a}{V_T}\right) - p_{no} = B e^{-x_n/L_p} \quad \text{(From 7)}$$

$$B = \frac{p_{no}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]}{e^{-x_n/L_p}}$$

$$B = p_{no}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] e^{x_n/L_p} \quad -(8).$$

Put (8) in (7), we get

$$p_n(x) - p_{no} = p_{no}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] e^{\left(\frac{x_n - x}{L_p}\right)}$$

(neglect 1)

$$\delta p_n(x) = p_n(x) - p_{no} = p_{no}\left[\exp\left(\frac{V_a}{V_T}\right)\right] \exp\left(\frac{x_n - x}{L_p}\right)$$

$$\boxed{\delta p_n(x) = p_n \exp\left(\frac{x_n - x}{L_p}\right)} \quad -(9)$$

--- for $(x \geq x_n)$

where, $\boxed{p_n = p_{no} \exp\left(\frac{V_a}{V_T}\right)}$

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Similarly, For $(x \le x_p)$,

$$\delta n_p(x) = n_p(x) - n_{po} = n_{po}\left[\exp\left(\frac{V_a}{V_T} - 1\right)\right] \exp\left(\frac{x_p + x}{L_n}\right)$$

$$= n_{po} \exp\left(\frac{V_a}{V_T}\right) \exp\left(\frac{x_p + x}{L_n}\right)$$

$$\boxed{\delta n_p(x) = n_p \exp\left(\frac{x_p + x}{L_n}\right)} \quad \text{--- (10)}$$

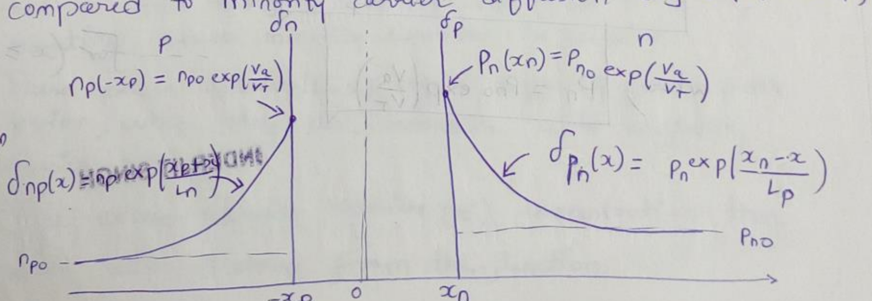
where, $\boxed{n_p = n_{po} \exp\left(\frac{V_a}{V_T}\right)}$ --- for $(x \le x_p)$

From eq^n (9) and (10), we interpretate

4. The minority carrier concentration decay exponentially with distance away from the junction to their thermal-equilibrium values !!

(Assuming $W_n >> L_p$ and $W_p >> L_n$)

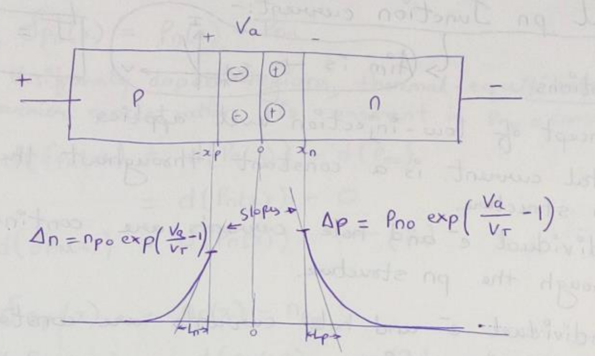
ie Both n region and p-region lengths are long compared to minority carrier diffusion lengths (L_p and L_p)



fig(c) Distribution of excess carriers

Summary:

fig(5)



(a) Concentratn of excess carriers.

From fig(a), we see exponential decay of excess carriers in n and p regions.

$$\boxed{\Delta p \approx p_{no}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]}$$

excess hole on n-side

$$\boxed{\Delta n = n_{po}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]}$$

excess e⁻s on p-side.

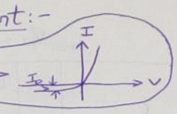
L_n & L_p → Diffusion length of e⁻ and holes.

(→ length over which holes/e⁻s travels by diffusion before it recombines)

1. $V_a = V_F$ (F.B) lowers built-in potential barrier, so that e⁻ from n-region are injected into p-region, creating excess minority carriers in p-region.
2. These excess carriers (e⁻s) begin diffusing into bulk p-region, where they can recombine with majority carrier holes.
3. The excess minority carrier (e⁻) concentration then ↓ses with distance from the junction.

· Ideal pn Junction current:-

↳ Aim is →



Current density

$$\boxed{J = \frac{I}{A}} \quad A/cm^2$$

Assumptions:

1) Concept of low-injection level applies.
2) Total current is a constant throughout the entire pn structure.
3) Individual e^- and hole currents are continuous function through the pn structure.
4) Individual e^- and hole currents are constant throughout the depletion region.

Total pn junction current = minority carrier hole diffusion current at $x = x_n$ + minority carrier electron diffusion current at $x = -x_p$

$$J_{total} = J_p(x_n) + J_n(-x_p) \quad \text{— (1)}$$

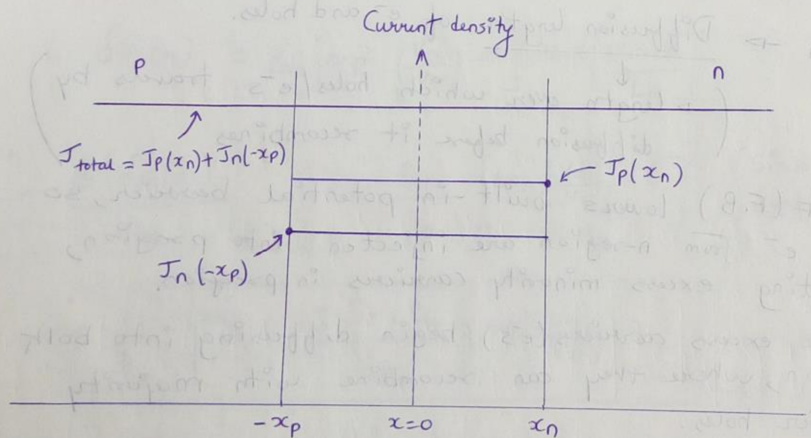


fig 3 : Electron and hole current densities through the space charge region of a pn junction.

We Know,

$\therefore \delta p_n(x) = p_n(x) - p_{no}$

(Assumption: Uniformly doped regions, thermal-equilibrium carrier concentration is constant ie $p_{no} = \text{constant}$)

$$\text{ie} \quad d(\delta p_n(x)) = d(p_n(x)) - d(p_{no})$$
$$= d(p_n(x)) - 0$$
$$d(\delta p_n(x)) = d(p_n(x)) \quad \text{--- (2)}$$

$$\therefore \delta n_p(x) = n_p(x) - n_{po}$$
$$\text{ie} \quad d(\delta n_p(x)) = d(n_p(x)) \quad \text{--- (3)}$$

Now, $$J_p(x_n) = -q D_p \left.\frac{d p_n(x)}{dx}\right|_{x=x_n}$$

$$\text{ie} \quad J_p(x_n) = -q D_p \left.\frac{d(\delta p_n(x))}{dx}\right|_{x=x_n} \quad \text{(From 2)}$$

$$\therefore \delta p_n(x) = p_{no}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \exp\left[\frac{x_n - x}{L_p}\right]$$

$$\therefore \left.\frac{d(\delta p_n(x))}{dx}\right|_{x=x_n} = -\frac{p_{no}}{L_p}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right] \quad \left(\begin{array}{l}\text{Since, At } x = x_n \\ \exp(0) = 1;\end{array}\right)$$

$$\therefore \boxed{J_p(x_n) = \frac{q D_p \cdot p_{no}}{L_p}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right]} \quad \text{--- (4)}$$

(hole current density)

$$\text{ie} \quad I_p(x_n) = \frac{q A D_p p_{no}}{L_p}\left[\exp\left(\frac{V_a}{V_T}\right) - 1\right].$$

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Similarily, at $x=-x_p$, e^- diffusion current density

$$J_n(-x_p) = q D_n \left.\frac{d\, n_p(x)}{dx}\right|_{x=-x_p}$$

$$\text{ie } J_n(-x_p) = q D_n \left.\frac{d(\delta n_p(x))}{dx}\right|_{x=-x_p} \quad \text{(From 3)}$$

Now, $\delta n_p(x) = n_{po}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left(\frac{x_p+x}{L_n}\right)$

$$\left.\frac{d\,\delta n_p(x)}{dx}\right|_{x=-x_p} = \frac{n_{po}}{L_n}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right] \quad \left(\because \exp(0)=1\right)$$

$$\therefore \boxed{J_n(-x_p) = \frac{q D_n n_{po}}{L_n}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]} \quad -(5)$$

→ Electron current density

Now, from eq^n ①,

$$J_{Total} = J_p(x_n) + J_n(-x_n)$$

$$J = \underbrace{\left[\frac{q D_p \cdot p_{no}}{L_p} + \frac{q D_n \cdot n_{po}}{L_n}\right]}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]$$

$$J = J_S\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]$$; where J_S – Reverse saturat^n current density.

$$\text{ie } I = \left[\frac{q A D_p \cdot p_{no}}{L_p} + \frac{q A D_n \cdot n_{po}}{L_n}\right]\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]$$

$$\boxed{I = I_o\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]}$$ → Ideal – diode equation → (Eq^n A)

where, $I_0 = \left[\dfrac{qAD_p\, p_{no}}{L_p} + \dfrac{qAD_n\, n_{po}}{L_n} \right]$

$I_0 \rightarrow$ Reverse saturation current

ie $\boxed{I = I_0 \left[\exp\left(\dfrac{V_a}{V_T} \right) - 1 \right]}$ — (A) → (Derived assuming $[V_a > 0]$) ie Forward-bias voltage.

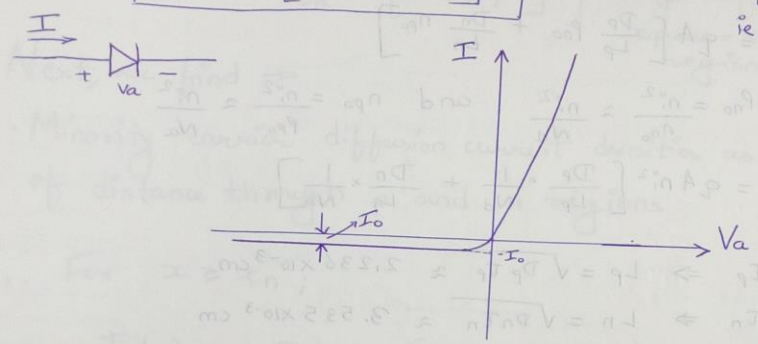

fig 6: Ideal I-V characteristic of a pn junction diod

- If the voltage V_a becomes negative (reverse-bias),

ie If $\boxed{V_a = -V_R}$

then $\boxed{I \approx -I_0}$ $\left\{ \exp\left(\begin{smallmatrix} \text{large} \\ -ve \\ \text{value} \end{smallmatrix} \right) \approx 0 \right\}$

ie Current saturates to I_0 in the negative direction and it is independent of voltage (applied reverse bias)

∴ I_0 is referred to as "reverse saturation current."

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1. Find reverse saturation current in a Si pn junction at T=300K. with following parameters:

$N_a, N_d = 10^{16}/cm^3$, $D_n = 25\,cm^2/s$, $D_p = 10\,cm^2/s$,

$\tau_p = \tau_n = 5\times10^{-7}s$, $A = 10^{-4}\,cm^2$, $n_i = 1.5\times10^{10}/cm^3$.

Also, find current for forward bias of 0.65V and a reverse bias of 10V.

A → cross-sectional area

Sol^n: $I_o = qA\left[\frac{D_p}{L_p}p_{no} + \frac{D_n}{L_n}n_{po}\right]$

we know, $p_{no} = \frac{n_i^2}{n_{no}} \approx \frac{n_i^2}{N_d}$ and $n_{po} = \frac{n_i^2}{p_{po}} \approx \frac{n_i^2}{N_a}$

$\therefore I_o = qAn_i^2\left[\frac{D_p}{L_p}\times\frac{1}{N_d} + \frac{D_n}{L_n}\times\frac{1}{N_a}\right]$

$L_p^2 = D_p\tau_p \Rightarrow L_p = \sqrt{D_p\tau_p} \approx 2.236\times10^{-3}\,cm$

$L_n^2 = D_n\tau_n \Rightarrow L_n = \sqrt{D_n\tau_n} \approx 3.535\times10^{-3}\,cm$

$\therefore I_o = 1.6\times10^{-19}\times10^{-4}\times(1.5\times10^{10})^2\left[\frac{10}{2.236\times10^{-3}}\times\frac{1}{10^{16}} + \frac{25}{3.535\times10^{-3}}\times\frac{1}{10^{16}}\right]$

$= 3.6\times10^{-16}\,[11.544]$

$\boxed{I_o = 4.156\times10^{-15}A}$

If $V_a = V_F = 0.65V$

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

$= 4.156\times10^{-15}\left[\exp\left(\frac{0.65}{0.0259}\right)-1\right]$

$\boxed{I = 0.329\,mA}$

for $V_F = V_a = 0.65V$

If $V_a = -V_R = -10V$

$\therefore I \approx -I_o$

$\boxed{I = -4.156\times10^{-15}A}$

for $V_a = -10V$

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∴ So far, we derived

$$J_p(x_n) = \frac{q D_p p_{no}}{L_p}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]$$

$$J_n(-x_p) = \frac{q D_n \cdot n_{po}}{L_n}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]$$

→ Minority carrier diffusion current densities at the edge of the space-charge region.

Next, we find →

- Minority carrier diffusion current densities as a function of distance through p and n regions

∴ For $x \geq x_n$;

$$J_p(x) = \frac{q D_p \cdot p_{no}}{L_p}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left[\frac{x_n - x}{L_p}\right] \quad \text{---(1.a)}$$

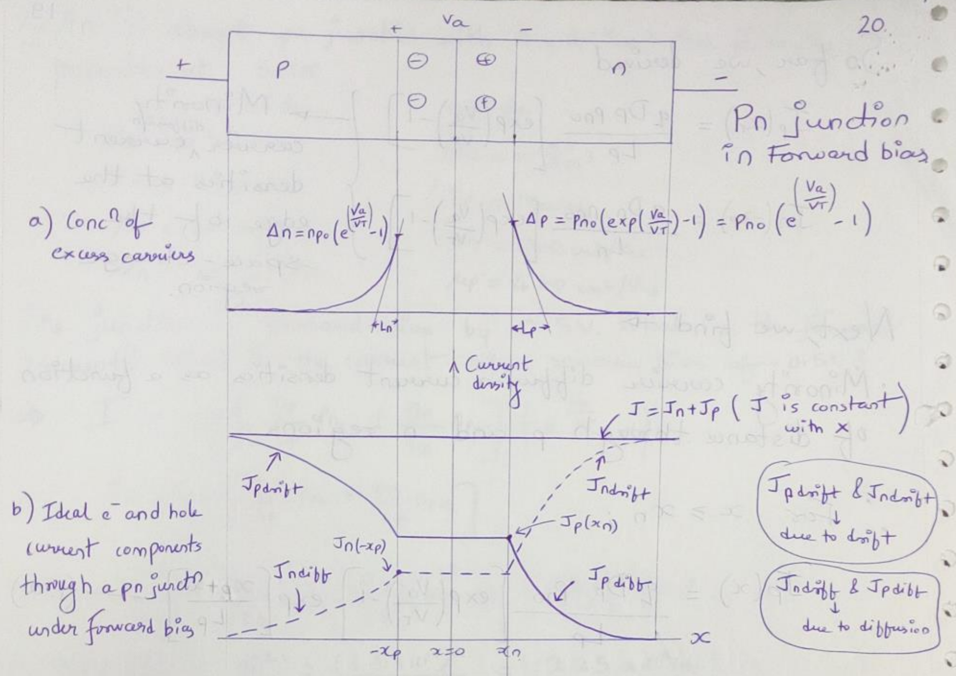
and for $x \leq -x_p$;

$$J_n(x) = \frac{q D_n \cdot n_{po}}{L_n}\left[\exp\left(\frac{V_a}{V_T}\right)-1\right]\exp\left[\frac{x_p + x}{L_n}\right] \quad \text{---(1.b)}$$

From (1.a) and (1.b), we interpretate that

" The minority carrier diffusion current densities decay exponentially in each p and n region".

However, the total current through the pn junction is constant.



Points to Remember: (from (a) and (b) diagram) ie [pn Junct^n in Forward bias]

1. Excess minority carrier decay exponentially in n and p regions (from (a)).
2. Total current in a pn junction is constant (from (b)).
3. Majority carrier current flow is becoz of → ($J_{p\,drift}$, $J_{n\,drift}$).
4. Minority carrier current flow is becoz of → ($J_{n\,diff}$, $J_{p\,diff}$).

1. An Si abrupt pn junction with $A = 10^{-4} cm^2$ has following properties at 300K.

p side	n side
$N_a = 10^{17}/cm^3$	$N_d = 10^{15}/cm^3$
$\tau_n = 0.1 \mu sec$	$\tau_p = 10 \mu sec$
$\mu_p = 200 \, cm^2/V\text{-}s$	$\mu_n = 1300 \, cm^2/V\text{-}s$
$\mu_n = 700 \, cm^2/V\text{-}s$	$\mu_p = 450 \, cm^2/V\text{-}s$

The junction is forward-bias by 0.5V. What is the forward current? What is the current at a reverse bias of −0.5V?

$$\Rightarrow \quad I = qA\left[\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po}\right]\left(e^{\frac{V_a}{V_T}} - 1\right)$$

$$I_o = qA\left[\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po}\right]$$

$$\cdot \; p_{no} = \frac{n_i^2}{n_{no}} \approx \frac{n_i^2}{N_d} \approx \frac{(1.5\times10^{10})^2}{10^{15}} = 2.25\times10^5/cm^3$$

$$\cdot \; n_{po} = \frac{n_i^2}{p_{po}} \approx \frac{n_i^2}{N_a} \approx \frac{(1.5\times10^{10})^2}{10^{17}} = 2.25\times10^3/cm^3$$

For minority carriers, (From Einstein relation)

$$D_p = V_T \cdot \mu_p = 0.0259 \times 450 = 11.66 \, cm^2/s \text{ on nside}$$

$$D_n = V_T \cdot \mu_n = 0.0259 \times 700 = 18.13 \, cm^2/s \text{ on pside}$$

$$L_p^2 = D_p \tau_p \Rightarrow L_p = \sqrt{D_p \tau_p} = 1.08\times10^{-2} cm$$

$$L_n^2 = D_n \tau_n \Rightarrow L_n = \sqrt{D_n \tau_n} = 1.35\times10^{-3} cm$$

$$\therefore \quad I_o = qA\left[\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po}\right] = qA n_i^2\left[\frac{D_p}{L_p}\frac{1}{N_d} + \frac{D_n}{L_n}\times\frac{1}{N_a}\right]$$

$$I_o = 4.37\times10^{-15} A$$

$$I = I_o\left(\exp\left(\frac{0.5}{0.0259}\right) - 1\right) = 1.058\times10^{-6} A \quad \text{in F.B } (V_f = 0.5V)$$

$$I = -I_o = -4.37\times10^{-15} A \quad \text{in R.B } (V_R = -0.5V)$$