Formula sheet

(1) $J_{drift} = \sigma \mathcal{E}$; $J = I/A$

(2) $J_{drift} = J_{n,drift} + J_{p,drift} = (\sigma_n + \sigma_p)\mathcal{E}$

(3) $dQ = qpAv_{dp}\,dt \implies I_p = qpAv_{dp} \Rightarrow J_p = qpv_{dp} = \sigma_p \mathcal{E} \implies \sigma_p = qp\frac{v_{dp}}{\mathcal{E}} = qp\mu_p$

(4) $\mu = v_d/\mathcal{E}$ {mobility = drift vel. per unit field}

(5) $\mu_p = v_{dp}/\mathcal{E}$ | $\mu_n = -v_{dn}/\mathcal{E}$ | $\sigma_n = qn\mu_n$ | $\sigma_p = qp\mu_p$

(6)

	n type	p type
maj. Carrier	e^-	p^+/h^+
mob. maj.	$\approx 1330\ cm^2/Vs$	$495\ cm^2/Vs$
min Carri.	p^+/h^+	e^-
mob min	$495\ cm^2/Vs$	$\approx 1330\ cm^2/Vs$

$J_{drift} = q(\mu_n n + \mu_p p)\mathcal{E} = \sigma\mathcal{E} \implies \sigma = qn\mu_n + qp\mu_p$

(7) e^- & hole mob. reduce Monotonically with ↑ impurities

(8) $\mu = q\tau/m^*$

(9) $v_d = q\mathcal{E}\tau/m^*$

* Electric field (+) → (−)

$$\boxed{\mu = \frac{v_{drift}}{\text{Elec field}}}$$

(10) $\dfrac{1}{\mu_{eff}} = \dfrac{1}{\mu_I} + \dfrac{1}{\mu_p}$

(11) $\dfrac{1}{\tau_{eff}} = \dfrac{1}{\tau_I} + \dfrac{1}{\tau_p}$

(12) $\mu_p \propto \dfrac{1}{T^{3/2}}$

(13) $\mu_I \propto T^{3/2}$

(14) $\mu = \dfrac{\mu_0}{1 + \mathcal{E}/\mathcal{E}_c}$ → low field mobility (μ_0)

(15) **For minority carriers the drift current can be neglected compared with diffusion current in the quasi-neutral regions.**

Hence →

$$J_{n(p)} = qD_n\frac{dn_p}{dx}$$

$$J_{p(n)} = -qD_p\frac{dp_n}{dx}$$

where D_n and D_p are the minority carrier diffusion coefficients.

The electron diffusion *current* density is equal to the flux density multiplied by the charge of the electron:

$$J_{n(\text{diff})} = -qF_n = qD_n\frac{dn(x)}{dx} \qquad (3.40)$$

Similarly for holes,

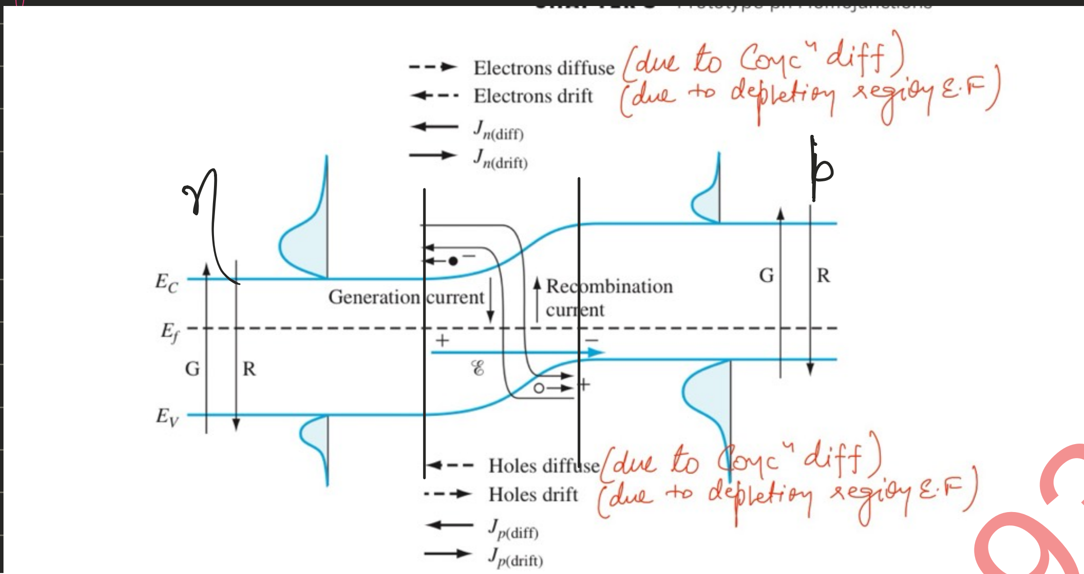
$$J_{p(\text{diff})} = +qF_p = -qD_p\frac{dp(x)}{dx} \qquad (3.41)$$

(16)

EXTRA

① with ↑ doping; impurity Band from bottom of Conduction Band to Normally forbidden Bad ↑ with inc. in doping

2



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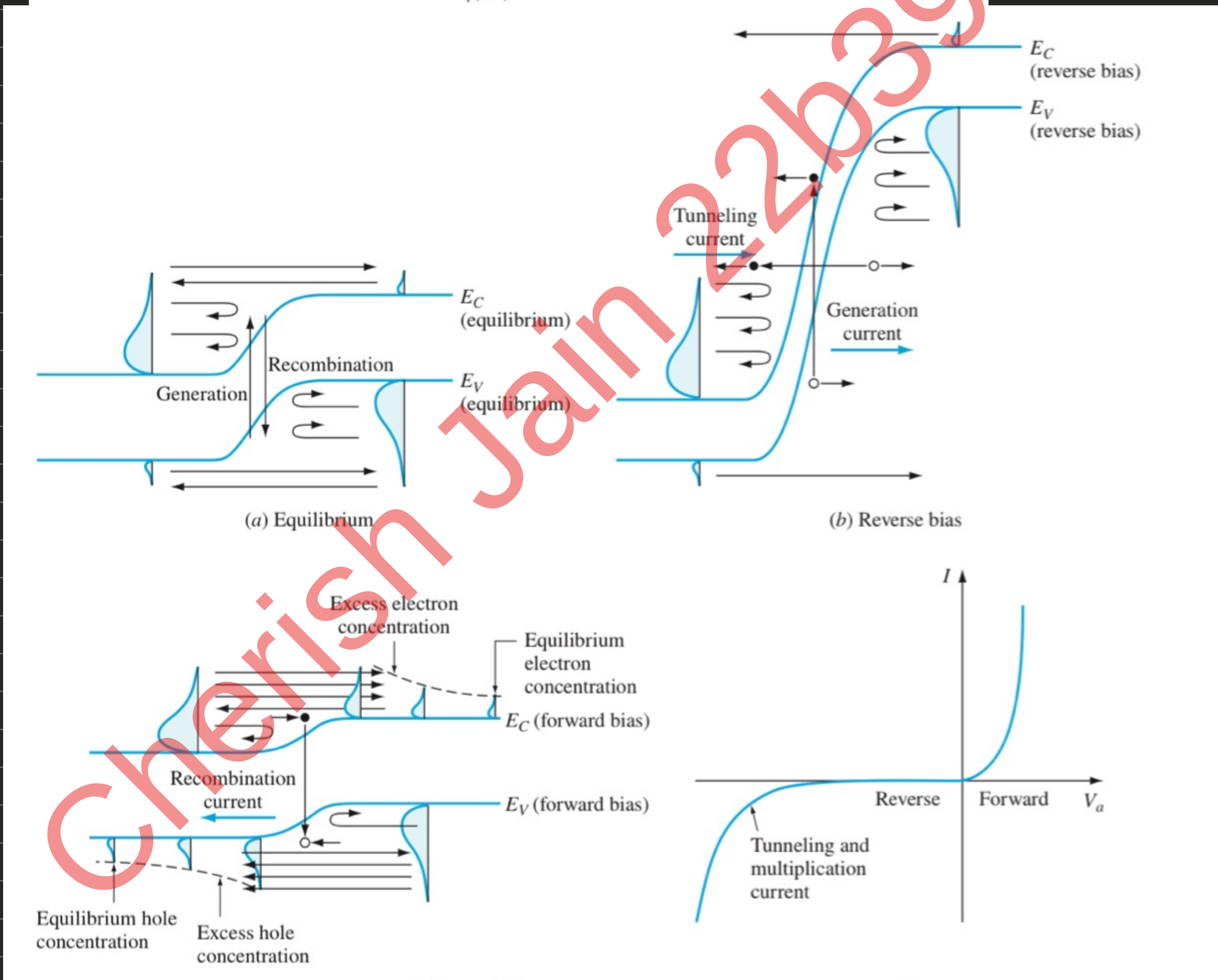


(a) Equilibrium

(b) Reverse bias

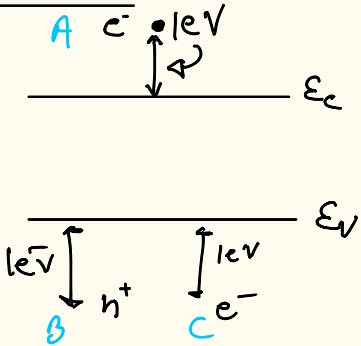
(c) Forward bias

(d)

4

Quiz - 1

Q



find PE & KE of A, B, C

Sol^n :

	KE	PE
A	1	E_c
B	1	E_V
C	−1	E_V

Very Imp

⇒ Non-Eq^m (Bias Applied)

$$F(x_2) - F(x_1) = -\partial\left(\frac{n\,\Delta x}{\partial t}\right) \quad \Big|\; J = -qF$$

F → flux

$$\frac{J(x_2) - J(x_1)}{\Delta x} = q\left\{\frac{\partial n}{\partial t}\right\}$$

$$\therefore \frac{\partial J}{\partial x} = q\frac{\partial n}{\partial t} = -\frac{\partial}{\partial t}(-nq)$$

$$\Rightarrow \frac{\partial J}{\partial x} = -\frac{\partial}{\partial t}(\rho)$$

ρ = rho

$$\nabla \cdot J = -\frac{\partial \rho}{\partial t}$$

⇓ Divergence of J

Now $J_n = qn\mu_n\mathcal{E} + qD_n\frac{\partial n}{\partial x}$

also; $\frac{\partial J}{\partial x} = q\frac{\partial n}{\partial t}$ ∴

$$\text{So; } \mu_n q\left[n\frac{\partial\mathcal{E}}{\partial x} + \mathcal{E}\frac{\partial n}{\partial x}\right] + qD_n\frac{\partial^2 n}{\partial x^2} = q\frac{\partial n}{\partial t}$$

→ This is for e^-; for hole, refer book

$$\text{Hence} \rightarrow \mu_n\left(n\frac{\partial\mathcal{E}}{\partial x} + \mathcal{E}\frac{\partial n}{\partial x}\right) + D_n\frac{\partial^2 n}{\partial x^2} = \frac{\partial n}{\partial t}$$

If $E = 0$,

$$D_n \cdot \frac{\partial^2 n}{\partial x^2} = \frac{\partial n}{\partial t} \quad \{\text{Flick's } 2^{nd} \text{ law}\}$$

↓ Drift neglected

@ eq^m $n(x) = $ Const. $= n_0$

@ excitation $n(x) = n_0 + \underbrace{\Delta n(x)}_{\text{may be non uniform}}$

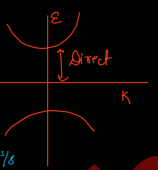
giving $h\nu$ to S.C

may be Const. if S.C. is illuminated uniformly

$n_0 = f(T)$

But $n(x) = \underbrace{n_0}_{\text{indep of } x} + \Delta n(x)$

Excess Carrier Dynamics: $D_n \cdot \frac{\partial^2(\Delta n(x))}{\partial x^2} = \frac{\partial \Delta n}{\partial t}$



if min & max @ same K ⇒ Direct Band Gap b/w indirect " "

Direct Band Gap S.C. ⇒ used for making LED

E_g → ______

{ { { { (Optical generation) → G_{op} (gen. optical) unit:- cm^{-3}/s

$\boxed{\text{p-type [EHP]}}$

@ $t = 0$; light turned on

what is $\frac{\partial \Delta n}{\partial t} = ?$

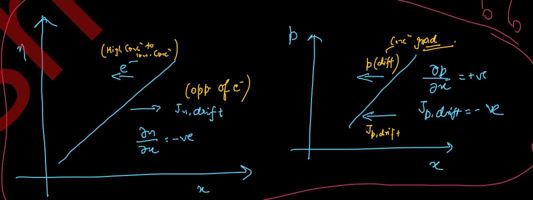
$\Delta n(t=0) = 0$

$$D_n\frac{\partial^2\Delta n}{\partial x^2} = \frac{\partial\Delta n}{\partial t} = G$$

G_n = generation rate $[G_n] = cm^{-3}s^{-1}$

✓ Now $\frac{\partial \Delta n}{\partial x} = 0$ {'cause light incident on every x}

$\Rightarrow \frac{\partial \Delta n}{\partial t} = 0 \;\Big|\; \Delta n = $ Const.

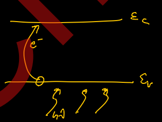


??

drift / Diff

So; J_n & J_p are in Same direc^n

For Intrinsic S.C.



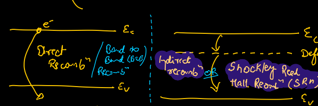
if $\mathcal{E} > E_g$; EHP generation {optical generation}

* Also there is Thermal Generation

✓ These generations are reversible

✓ Reverse of that is k/a Recombination

RECOMBINATION



Recomb^n via Defect State is easy as Compared to Direct^n Recomb^n

Generation (G) ↳ $n\uparrow$ | Recomb^n (R) ↳ $n\downarrow$

$$\text{So; } \frac{\partial\Delta n}{\partial t} = D_n\frac{\partial^2\Delta n}{\partial x^2} + G - R$$

Thermal Generation

↳ helps in Creating intrinsic Charge Carrier

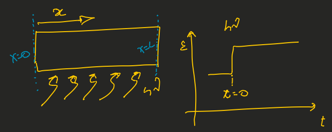
Recomb^n

$$R = \frac{\Delta n}{\tau_n} \rightarrow \text{Recomb}^n \text{ lifetime}$$

Recomb^n time:- Time spent before recomb^n

$$\frac{\partial(\Delta n)}{\partial t} = D_n\frac{\partial^2\Delta n}{\partial x^2} + G_{op} - \frac{\Delta n}{\tau_n}$$

Let's say $\frac{\partial^2(\Delta n)}{\partial x^2} = 0$ {can be achieved by uniform illumination}



$\therefore \frac{\partial(\Delta n)}{\partial t} = G_{op} - \frac{\Delta n}{\tau_n}$

By solving this :-

$\Delta n(t) = G_{op}\,\tau_n\left(1 - e^{-t/\tau_n}\right)$

$\therefore \Delta n(t=0) = 0$

$\Delta n(t=\infty) = G_{op}\,\tau_n$

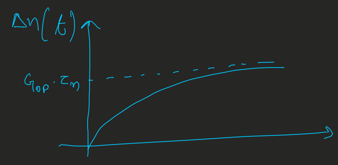
find $\Delta n(t)$

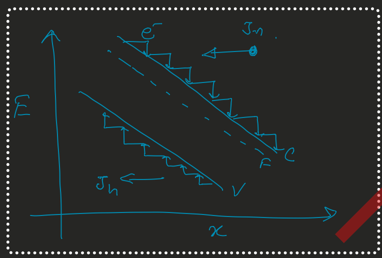
$\boxed{\text{In most Gen Sense; } \Delta n(t,x)}$

we created cond^n in which $\Delta n(x) = $ Const

@ Steady State

$\frac{\partial(\Delta n)}{\partial t} = 0$ OR {Gen^n Rate = Recomb^n rate}





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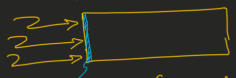


← Non Uniform Illum^n

$\Delta n(x=0) = \Delta n_0$

Max Carrier density @ $x=0$

Find xs e⁻ density profile $\{\Delta n(x)\}$ (Steady State) $= \Delta n(x,\infty)$

$D\frac{\partial^2(\Delta n)}{\partial x^2} + \cancel{G_{op}} = \frac{\Delta n}{\tau_n}$ ⟹ $\Delta n(x) = A\,e^{\frac{-x}{\sqrt{D_n\tau_n}}} + \cancel{B\,e^{\frac{x}{\sqrt{D_n\tau_n}}}}$

$0\ \forall x > 0$

0 {as conc^n grad ↓ as x ↑}

$A = B$

$L_n = \sqrt{D_n\cdot\tau_n}$

⇓

Diffusion length

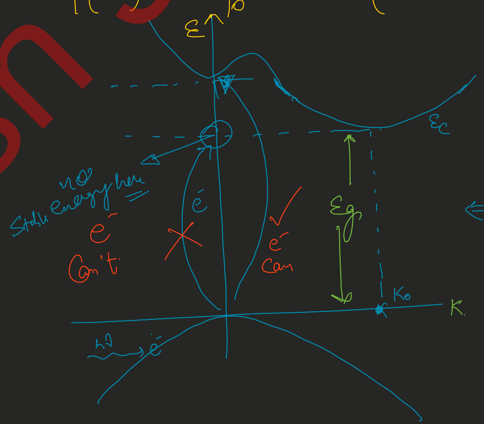
$\therefore$ $\Delta n(x) = A\,e^{\frac{-x}{\sqrt{D_n\tau_n}}}$ ⟹ Profile

$\Delta n(x) = A\,e^{-x/L_n}$

$\Delta n(x) = \Delta n_0\,e^{-x/L_n}$ (from initial cond^n)

Diffusion in P

net going from left to right $= \frac{p_2 l}{2} - \frac{p_1 l}{2}$



Photon momentum is small ; Energy large

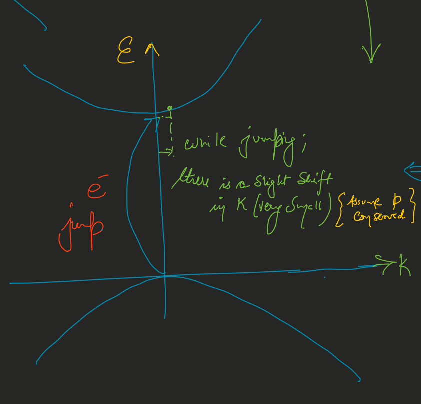
Phonon momentum is large; Energy small

} Quantum Reasons

⇐ Indirect Bandgap SC

* p, E conserved while jumping

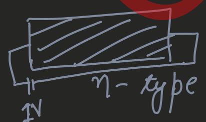
$p = \hbar k$



while jumping; there is a slight shift in K (very small) {assume p conserved}

⇐ direct Bandgap SC

Q



$l = 1\mu m$

$N_D = 10^{17}\,cm^{-3}$

$\mu_n = 100\,cm^2/V\cdot s$

$K_BT = 26\,meV \Rightarrow \frac{K_BT}{q} = 26\,mV$

$N_V'(T=300) = 10^{21}\,cm^{-3}$

$N_C' = 10^{22}\,cm^{-3}$

$D = \mu\cdot\frac{K_BT}{q} = 100\cdot 0.026 = 26\,cm^2/s$

Sol $J = nq\mu_n E$

SCATTERING

(1) Ionized Impurity Scattering: $\mu_I = \dfrac{q\,\tau_p}{m^*}$ → mobility due to imp. scat. due

amnt of deflection depends on speed of charge

→ depends on $N_D + N_A$ as both donor & acceptor scatter equally

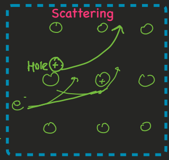
more doping ⇒ high prob of collision ⇒ smaller mean time of collision (τ)

$\mu = \dfrac{q\tau}{m^*}$

(2) Phonon Scattering / Lattice Scattering: $\mu_p = \dfrac{q\,\tau_p^{*}}{m^*}$

Phonons ⇒ Thermal waves

Both are present if one is "



Matthiessen's Rule

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_I} + \frac{1}{\mu_p} + \frac{1}{\dots} + \frac{1}{\dots} + \dots$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_I} + \frac{1}{\tau_p^*}$$

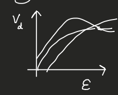
Total scatt./sec. ; no of scattering/sec.

$$\boxed{\mu = \frac{q\,\tau}{m^*} \quad V_d = \frac{q\,\mathcal{E}}{m^*}\,\tau}$$

for hole; $q = +q$ (+e)
e^- $q = -q$ (−e)

⇓ Valid only @ low Electric field (assuming Const τ)

@ high EF; $\tau \propto \dfrac{1}{\mathcal{E}}$



Temperature Dependency

$T\uparrow$ → Scatt rate ↑ ⇒ $\mu_p \propto \dfrac{1}{T^{3/2}}$ (Quantum)

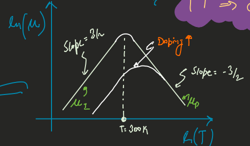
e^- speed ↓

$\mu_I \propto T^{3/2}$

$T\uparrow$ ⇒ more vib ⇒ more Scat. ⇒ more phonon Scatt → result in hindered motion
⇓ less mobility

$T\uparrow$ ⇒ e^- intrinsic motion fast ⇒ interaction time with fixed Charge is less ⇒ less Scattering ⇒ more mobility

Aim → make μ large.

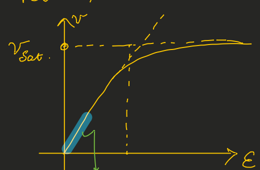


@ low Temp; μ_p → negligible, μ_i → dominates

@ high Temp; μ_p → dominates, μ_i → negligible

At low temp , impurity scattering dominates

$v_{el} = \mu \cdot \mathcal{E}$



$\dfrac{\partial v}{\partial \mathcal{E}} = \mu_0$: low field mobility = slope @ low E

$$\mu = \frac{\mu_0}{1 + \mathcal{E}/\mathcal{E}_c}$$

low field Mobility

Empirical relation

@ $\mathcal{E} = \mathcal{E}_c$;

$V = \dfrac{\mu_0 \cdot \mathcal{E}_c}{2}$

ideal vel. ⇒ $V = \mu_0 \cdot \mathcal{E}_c$

Q p-type

$\Delta n(x) = ?$

light (gen. rate = G_l)

$t = 0$ $t = T$

Sol.
$$\Delta n(t) = G_l\,\tau_n\left(1 - e^{-t/\tau_n}\right) \quad \{\text{for } t \in [0, T]\}$$

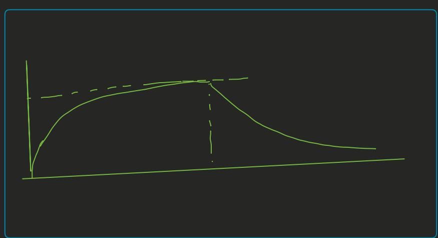
$$\frac{\partial(\Delta n(t))}{\partial t} = D_n \frac{\partial^2}{\partial x^2}(\Delta n) + G_l - \frac{\Delta n}{\tau_n}$$

for $t > T$; $G_l = 0$

$$\therefore \frac{\partial(\Delta n(t))}{\partial t} = -\frac{\Delta n}{\tau_n}$$

$$\Delta n(t) = \Delta n(t = T) \cdot e^{-t/\tau_n} \Rightarrow \text{for } t \geq T \quad \left\{\Delta n(t = T) = G_l\,\tau_n\left(1 - e^{-T/\tau_n}\right)\right\}$$

$\tau_n \downarrow$ ⇒ faster decay



$\mathcal{E} = -\dfrac{dV}{dx}$

$= -\left\{\dfrac{V(x=L) - V(x=0)}{L}\right\}$

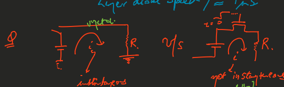
$= -\dfrac{V}{L}$

$= \dfrac{d(E_c/q)}{dx}$

$$\boxed{\mathcal{E} = \frac{1}{q}\frac{dE_c}{dx}}$$

We want faster diode whose freq = 50Hz

Zener diode speed; = 1nS



Smaller the τ_n; higher the speed ↑

τ is high ; Smaller the τ; low time to charge

⇒ DIFFUSION Eqⁿ → for minority carrier only

$\dfrac{\partial \Delta n}{\partial t} = D_n \dfrac{\partial^2 \Delta n}{\partial x^2} + G - R$

$= D \dfrac{\partial^2 \Delta n}{\partial x^2} + G_{op} - \dfrac{\Delta n}{\tau_n}$

$R = \beta n p = \dfrac{1}{\tau}$

p-type ($\tau_n \propto \dfrac{1}{p}$)

if S.C. is p-type;

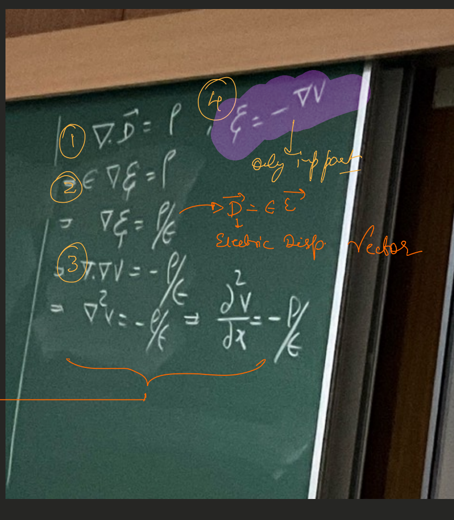
Δn → then Diff ; Δp → Maj. Drift

p type N_A

$p = p_0 + \Delta p$ ← Majority
$n = n_0 + \Delta n$ ← Minority

$\tau_n = \dfrac{1}{\beta N_A}$

if majority charge carrier; then even small Electric field gives gives large Drift



Vector

Poisson's Eqⁿ

for minority ; $\Delta n(x) = \Delta n_0 e^{-(\ )}$

" majority ; $\tau_p \sim \frac{1}{\beta n}$ $\quad n \uparrow \tau_p \uparrow$ {lifetime of holes ↑ ; they will remain in majority}

$$\frac{\partial \Delta p}{\partial t} = D_p \frac{\partial^2 \Delta p}{\partial x^2} + G_{op} - \frac{\Delta p}{\tau_p}$$

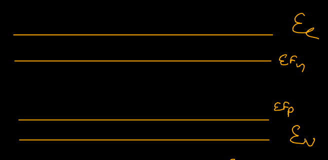
Drift α hole density ; Diff α grad. ∴ if p type then drift will dominate

Fermi's Golden Rule

$R \propto n$; p = Const.
$R \propto p$; n = Const. → p ~ app. Const.
$R = \beta n p$ $\quad \tau_n = \frac{1}{\beta N_A}$ → p-type.

Quasi Fermi level.

Exp occurs. light shined. n-type

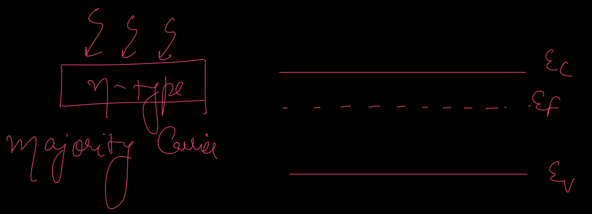


$n \to n + \Delta n$
$p \to p + \Delta p$

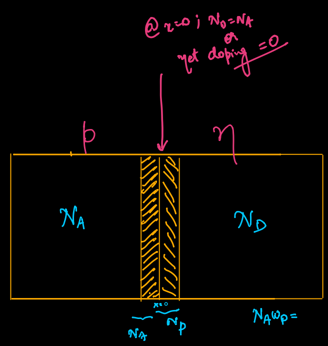
$$n = N_c' \exp\left(\frac{\varepsilon_{fn} - \varepsilon_c}{k_B T}\right)$$

$$p = N_A' \exp\left(\frac{\varepsilon_v - \varepsilon_{fp}}{k_B T}\right)$$

#



DIODE



$N_A w_p = $

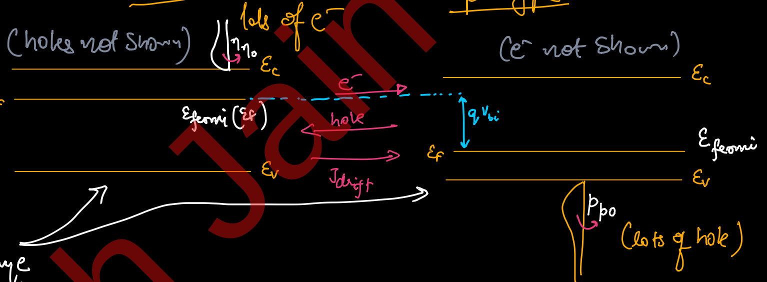
Not Compensated

w_p = width of p side over which holes have left p side & gone to n side.

$\boxed{N_D^+ w_n = N_A^- w_p}$ → charge balance

we have assumed Complete ionization.
$p = N_A^-$ | $N_A \rightleftharpoons N_A^- e_j^+$
$n = N_D^+$ | $N_D \rightleftharpoons N_D^+ e_j^-$

n-type ; p-type ; put together



assume initially isolated

(after all impurities are ionized)

* eqm e⁻ Conc on "n" Side : $n_{no} = N_D'$
* eqm p^+_{hole} Conc on "p" Side $= P_{po} = N_A'$

@ eqm ; $J_n = J_p = 0$ (no net current)

* Built in Pot. Energy Barrier $= qV_{bi}$

$\boxed{qV_{bi} = \Phi_p - \Phi_n}$

* for unequal doping ; most of the space charge is in the region with lighter doping

@ eqm.

$V = 0$; $J = 0 = J_n + J_p$

app. voltage.

∴ $J_n = 0$
$J_p = 0$

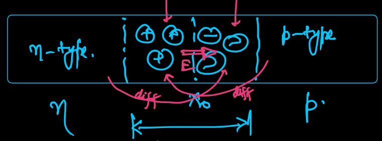
after diffusion ;
$N_D w_n = N_A w_p$
$W = w_n + w_p$

in eqm

ε_F = Const. @ eqm.

Quasi free electrons: very small interaction with the electrons. But not entirely free

non neutralized holes ; non neutralized e⁻ → means there are no compensating free e⁻/holes



Junction width (w)

* Total charge same on both sides but of diff sign

Also k/a Transition Region / Space Charge Region
This region is depleted of free charges (free = without any force)
Hence also k/a depletion Region

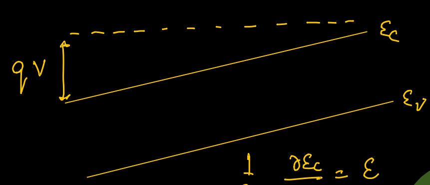
$$J_n = q\left(n \mu_n \mathcal{E} + D \frac{\partial n}{\partial x}\right) \qquad \frac{D}{\mu} = \frac{k_B T}{q}$$

$$\boxed{J_n = q\mu_n\left[n\mathcal{E} + \frac{kT}{q}\frac{dn}{dx}\right]}$$

both are pos^n dependent.

also ; $n = N_c' \exp\left(\frac{E_F - E_c}{K_B T}\right)$

$$\Rightarrow \frac{\partial n}{\partial x} = \frac{N_c'}{K_B T} \cdot \exp\left(\frac{E_F - E_c}{K_B T}\right) \cdot \left[\frac{\partial E_F}{\partial x} - \frac{\partial E_c}{\partial x}\right]$$



$$= \frac{n}{K_B T}\left[\frac{\partial E_F}{\partial x} - q\mathcal{E}\right]$$

$$\frac{1}{q}\frac{\partial \varepsilon_c}{\partial x} = \mathcal{E}$$

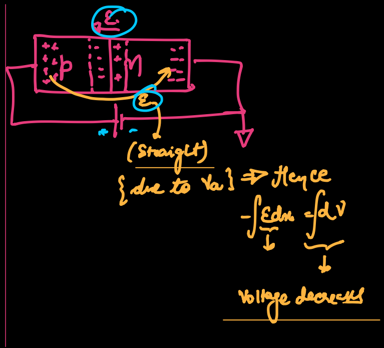
Hence ; $J_n = q \mu_n n \left(\frac{\partial E_F}{\partial x}\right)$

$\left(\frac{\partial n}{\partial x}\right) \neq 0$

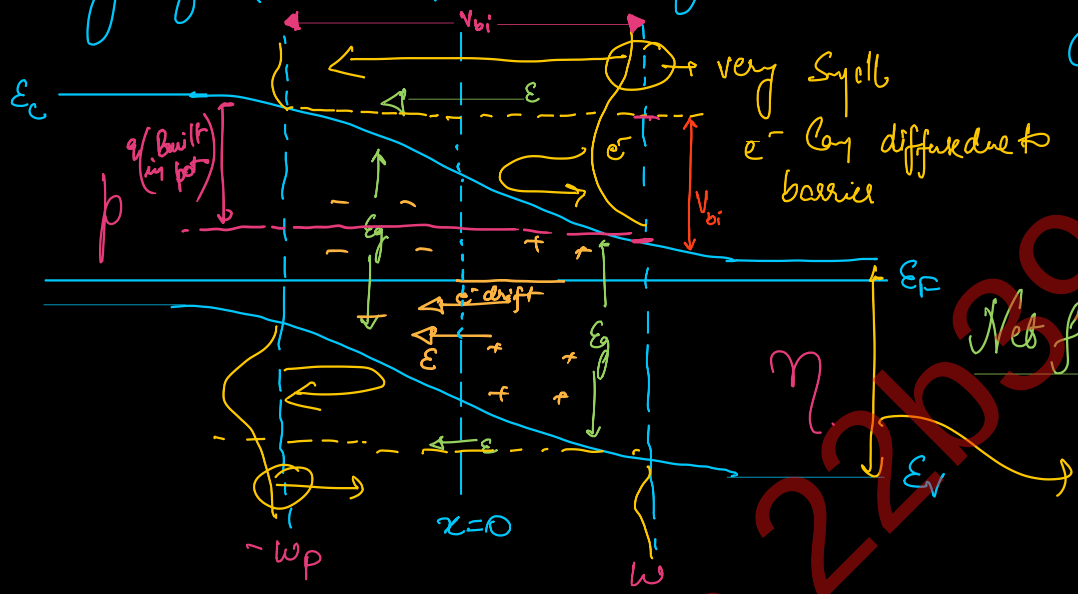
if $\mathcal{E}_{eff} = \frac{1}{q}\frac{\partial E_F}{\partial x} \Longrightarrow J_n = \underbrace{\mu_n \cdot n \cdot q \cdot \mathcal{E}_{eff}}_{\text{drift current of } e^-}$

$\therefore$ @ eqm

$\frac{\partial E_F}{\partial x} = 0$



Far away from the interface; Nothing has changed



@ every posn; $E_C - E_V = E_g$ = Const.

$J_n = -J_p = V_{app} = 0$

drift exactly cancels diffusion @ eqm

Net flow = 0

Built in Pot.

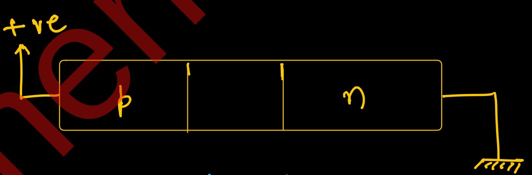
Intrinsic Potential Barrier / Built in pot^n / Cut-in voltage

(V_{bi})

⟹ Forward Bias Applied

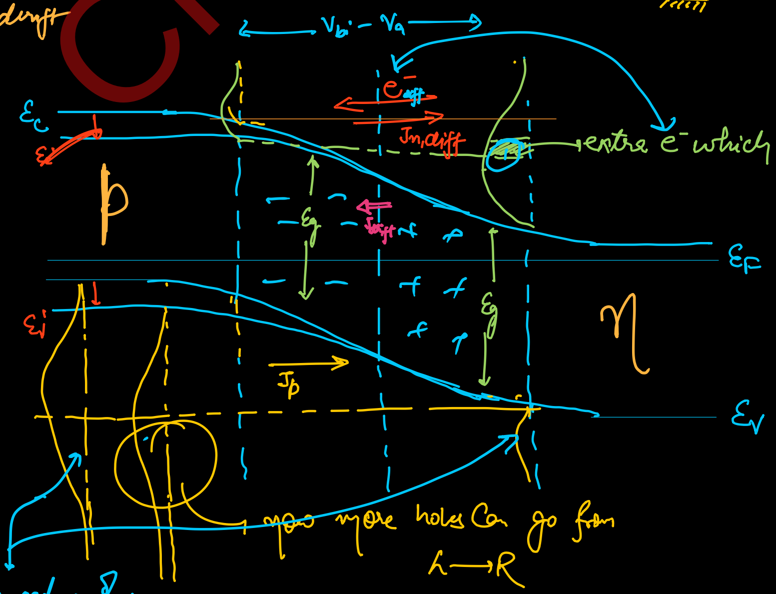
diff > drift

* In forward bias; no of e^- increases as well as Built in pot ↓; Hence diff >>> drift



new barr. $= q(V_{bi} - V)$

$|w_n| + |w_p| =$ Depletion Width



extra e^- which can also go. (V_{bi} is ↓); so some e^- can diffuse from $n \to p$

more holes can go from $L \to R$

Balanced no of holes

note

resistivity $\propto \frac{1}{\text{Conc}^n \text{ of free Carriers}}$

Recall:- Depletion region has no free Carriers

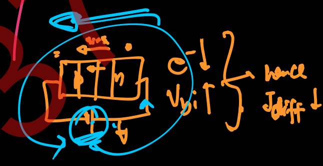
⟹ Reverse Bias Applied

very small. $\left\{ \underbrace{J_{minority}}_{\text{already very small.}} > J_{major.} \right)$

New barr = $q(V_{bi} + V)$

$J = J_{n,diff} + J_{p,diff}$

J is Small.



xs e^-

minor n
major p
$n << p$.

xs holes
(from $p \to n$)
xs inj holes

$x=0$

major n
minor p
$p << n$

$N_D^+ W_n = N_A W_p$

① Quasi neutral region

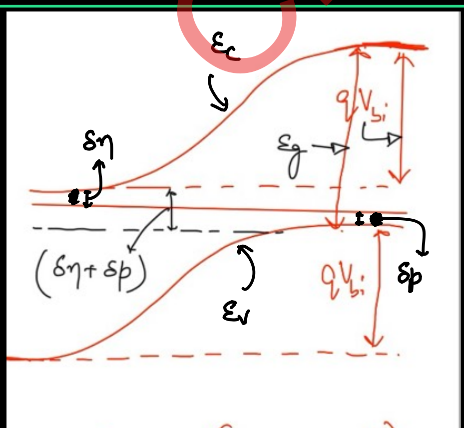
region far way from interface have $\mathcal{E} \approx 0$ ✓

② Abrupt + Junction:-

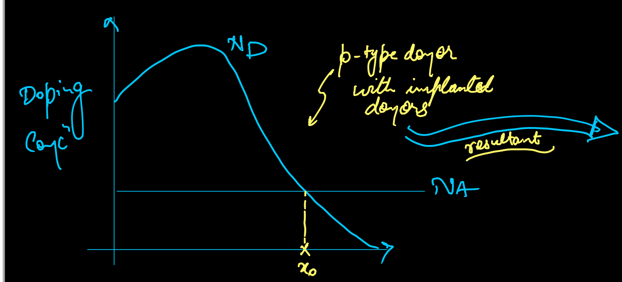
just outside Junction n & p Starts abruptly

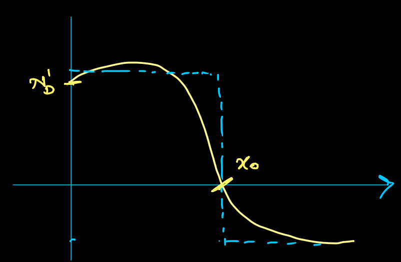
③ Boltzman App. Valid.

④ Low Level injection



$qV_{bi} = \mathcal{E}_g - (\delta n + \delta p)$





* on n-side; $N_D' = N_D - N_A$ = Constant ⟶ $n_{n_0} = N_D'$ ⟶ eq^m e^- Conc^n in n side

* on p-side; $N_A' = N_A - N_D$ = Const ⟶ $p_{p_0} = N_A'$ ⟶ eq^n hole Conc^n in p side

$$\delta n = E_c - E_F = KT\ln\left(\frac{N_c'}{n}\right) = KT\ln\left(\frac{N_c}{N_D'}\right)$$?? → why not N_c'

→ non-degenerate

$\eta = N_c' \exp\left(-\left(\frac{E_c - E_F}{KT}\right)\right)$

$p = N_v' \exp\left(-\left(\frac{E_F - E_v}{KT}\right)\right)$

$\delta n = 0$; → n side, degenerate

Similarly $\delta p = KT\ln\left(\frac{N_v}{N_A'}\right)$ p side, nondegen

$= 0$; p side ; degen.

Degenerate semiconductors contain high level of doping, with significant interaction between dopant atoms. The interaction results in the formation of donor/acceptor bands rather than discrete energy levels. These impurity bands can overlap with the corresponding band edges of conduction or valence bands.
The convention is that for degenerate semiconductors that Fermi level is present close to the conduction and valence band edges, typically in the range of 3kT from the band edges.

→ $\delta n | \delta p << 2\text{-}3 K_B T$

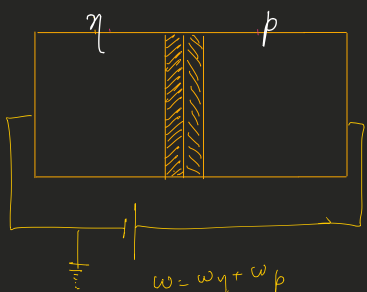
* if material is degenerately doped; we take fermi level to be at the band edge

Hence; $qV_{bi} = E_g - KT\ln\left(\frac{N_c}{N_D'}\right) - KT\ln\left(\frac{N_v}{N_A'}\right)$

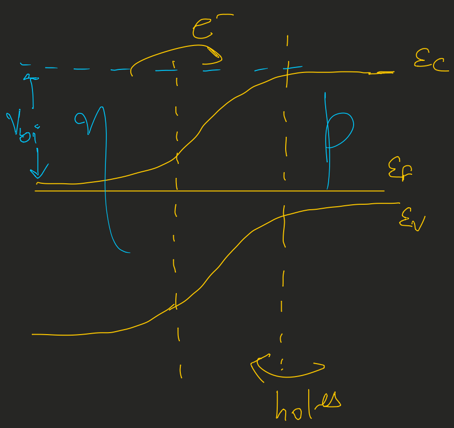
Fermi level

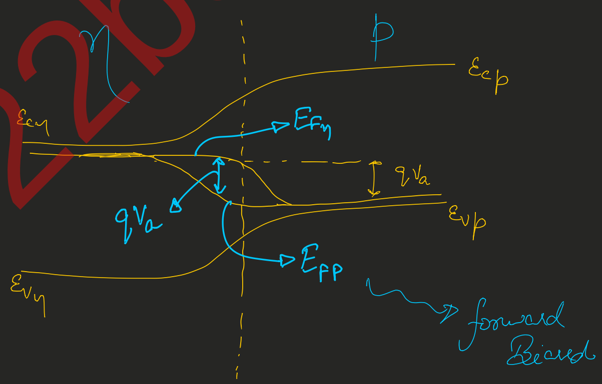
① when forward biased ; $w = (w_n + w_p)\downarrow$

② For away ; n is n & p is p

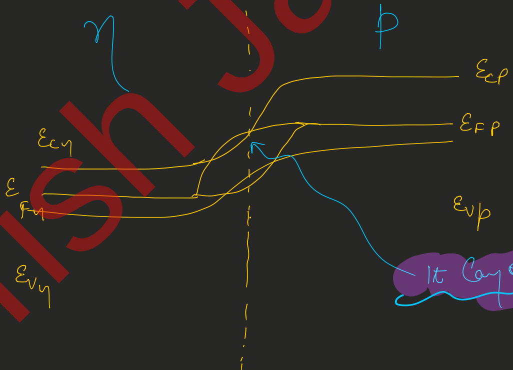


* Due to quasi neutral region; beyond depletion region; "n" remains n & "p" remains "p"





→ forward Biased



→ Reverse Biased

* $T\uparrow \Rightarrow V_{bi}\downarrow$

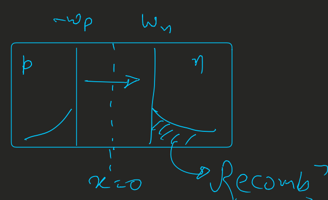
* $T\uparrow \Rightarrow n_i\uparrow$

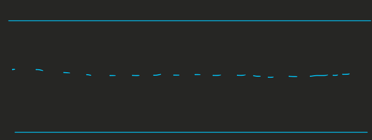
⇓

$N_D << n_i \Rightarrow n_i >> N_D$

$N_A << n_i$; $p_i >> N_A$

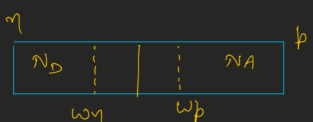
↳ almost intrinsic





if $V_{bi} = 0$ | diode acts as a resistor

√ Diode @ Eqm ($V_a = 0$)

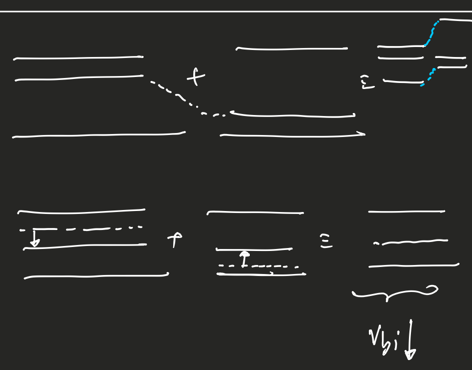


$N_D w_n = N_A w_p$

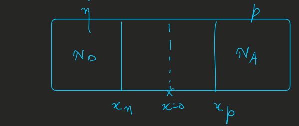
Q why $V_{bi}\downarrow$ as Temp↑

Sol: @ RT → $n + p =$

@ High T ⇒ $n + p$ =

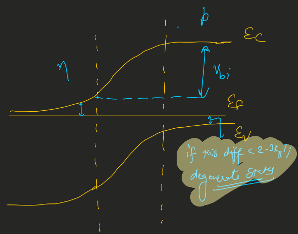


p-n Junction



$N_D(x_0 - x_A) = N_A(x_p - x_0)$

$N_D w_n = N_A w_p$



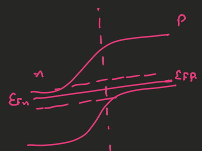
@ eqm ; $V_a = 0$

$n = N_c \exp\left(\frac{E_{Fn} - E_{cn}}{k_BT}\right)$

$E_{cn} - E_{Fn} = k_BT \ln\left(\frac{N_c}{N_D}\right)$

$p = N_v \exp\left(\frac{E_{vp} - E_{Fp}}{k_BT}\right)$ } assuming quasi neutral reg.

$E_{Fp} - E_{vp} = k_BT \ln\left(\frac{N_v}{N_A}\right)$



$V_{bi} = E_g - (\quad)$

$n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2k_BT}\right)$

$V_{bi} = \frac{k_BT}{V} \ln\left(\frac{N_A N_D}{n_i^2}\right)$

* $qV_{bi} = E_g - (\delta_n + \delta_p)$

$qV_{bi} = E_g - k_BT\left[\ln\frac{N_c}{N_D} + \ln\frac{N_v}{N_A}\right]$

$= E_g - k_BT \ln\left(\frac{N_c N_v}{N_A N_D}\right)$

$= E_g - k_BT \ln\left(\frac{n_i^2}{N_A N_D}\right) + E_g$

$V_{bi} = \frac{k_BT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$

* max obtainable Built-in-pot = E_g

Often; 1 Side is degeneratively doped, So nomenclature is that n^+p junction has n Side degenerate & p Side non degenerate. { p^+n → opposite)

Pn junct^n:- $qV_{bi} = E_g - KT\left(\ln\frac{N_c'}{N_D'} - \ln\frac{N_v'}{N_A'}\right)$

n^+p junction:- $qV_{bi} = E_g - KT \ln\frac{N_v'}{N_A'}$

p^+n junct^n:- $qV_{bi} = E_g - KT \ln\frac{N_c'}{N_D'}$

for a non degn. S.C. $n_i^2 = N_c N_v e^{-E_g/KT}$

$E_g = KT \ln\left(\frac{N_c N_v}{n_i^2}\right)$

THUS

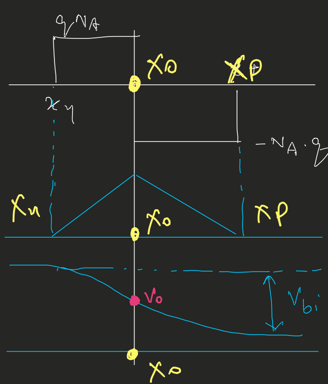
$$V_{bi} = \frac{kT}{q} \ln \frac{N_D' N_A'}{n_i^2} \qquad \text{pn junction}$$

$$V_{bi} = \frac{kT}{q} \ln \frac{N_V N_D'}{n_i^2} \qquad \text{p}^+\text{n junction}$$

$$V_{bi} = \frac{kT}{q} \ln \frac{N_C N_A'}{n_i^2} \qquad \text{n}^+\text{p junction}$$

To find the electric field $\mathscr{E}(x)$, we solve Poisson's equation:

{ $Q_V(x)$ = Charge density per unit Volume }
$$\frac{d\mathscr{E}}{dx} = \frac{Q_V(x)}{\varepsilon}$$
$x \in x_n, x_0$; $Q_V = qN_D'$
$x \in x_0, x_p$; $Q_V = -qN_A'$



$\frac{w_n}{w_p} = \sqrt{\ }$

$\frac{\partial E}{\partial x} = \frac{\rho(x)}{\epsilon}$, $x_n < x \le x_0$

$E = \frac{qN_D}{\epsilon}(x - x_n)$

$V(x) = \frac{qN_D}{2\epsilon}(x - x_n)^2$

$W = w_n + w_p = \left[\frac{2\epsilon V_{bi}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2} = |x_0 - x_n| + |x_0 - x_p|$

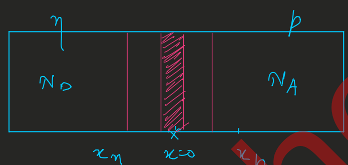
$|x_0 - x_n| + |x_0 - x_p|$

On the n side the result is

$$\mathscr{E}(x) = q\frac{N_D'}{\varepsilon}(x - x_n) \quad x_n \le x \le x_0$$

and on the p side

$$\mathscr{E}(x) = q\frac{N_A'}{\varepsilon}(x_p - x) \quad x_0 \le x \le x_p$$



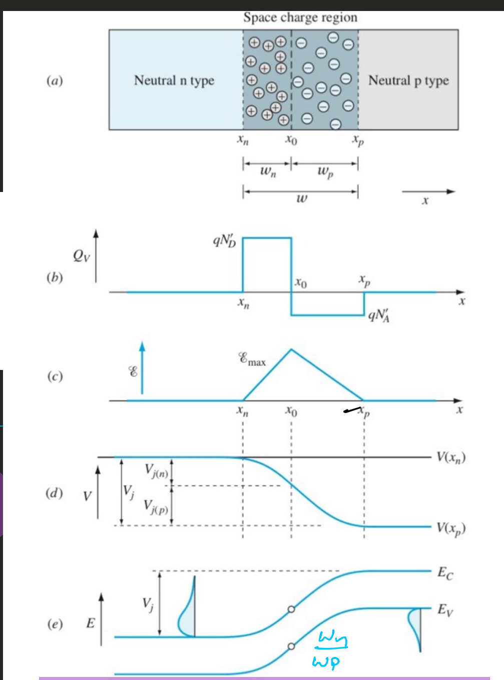


Figure 5.14 A prototype homojunction: (a) the physical diagram; (b) the distribution of charge; (c) the electric field, obtained by integrating the charge; (d) the voltage, obtained by integrating the field; (e) the energy band diagram, with the same shape as the voltage but inverted. The energy band diagram of (e) is for the device reverse-biased.

$N_D >> N_A$

$w_n << w_p$

both at n side

n_{no} ← eqm e⁻ density $= N_c \exp\left(\frac{E_{Fn} - E_{cn}}{k_BT}\right)$ ①

p_{no} ← hole eqm density $= \frac{n_i^2}{n_{no}}$

$n_{po} = N_c \exp\left(\frac{E_{Fp} - E_{cp}}{k_BT}\right)$ ②

$p_{no} = p_{po} \exp\left(-\frac{q|V_{bi}|}{k_BT}\right)$

@ eq^m ; $E_{Fp} = E_{Fn}$

By ①, ② {assuming eqm case} → $E_{Fp} = E_{Fn}$

$n_{po} = n_{no} \exp\left[-\frac{q|V_{bi}|}{k_BT}\right]$

$n_{no} >> n_{po}$

If $N_D >> N_A \Rightarrow w_n << w_p$

$$V(x) - V(x_n) = -\frac{qN_D'}{2\varepsilon}(x - x_n)^2 \quad x_n \le x \le x_0$$

$$V(x_p) - V(x) = -\frac{qN_A'}{2\varepsilon}(x_p - x)^2 \quad x_0 \le x \le x_p$$

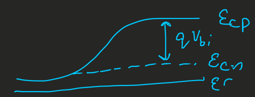
$$\frac{V(x_n) - V(x_0)}{V(x_0) - V(x_p)} = \frac{V_j^n}{V_j^p} = \frac{N_D' w_n{}^2}{N_A' w_p{}^2}$$

note $\to q V_{bi,\,max} \sim E_g$ $\quad$ * @ eq^m; $E_{FP} = E_{Fn}$

Density of States (N_c, N_v) depends upon material property. Since n & p type have same material; they are same on both sides. $N_{cn} \simeq N_{cp} \,/\, N_{vn} = N_{vp}$

in forward bias; $qV_{bi} \longrightarrow q(V_{bi} - V_a)$

$$|E_{cp} - E_{cn}| = |qV_{bi}|$$



$$p_n = p_{po}\exp\left\{\frac{-q|V_{bi}-V_a|}{KT}\right\}$$

$$n_p = n_{no}\exp\left\{\frac{-q|V_{bi}-V_a|}{KT}\right\}$$

in f.b.

$$\Delta n_p(x=x_p) = n_p - n_{po} = n_{no}\exp\left\{\frac{-q|V_{bi}-V_a|}{KT}\right\} - n_{no}\exp\left\{\frac{-q|V_{bi}|}{KT}\right\}$$

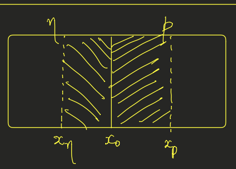
$$\boxed{\Delta n_p\,(x=x_p) = n_{no}\exp\left(-\frac{qV_{bi}}{KT}\right)\left\{\exp\left(\frac{qV_a}{KT}\right) - 1\right\}}$$

$$n_{no} = N_c \exp\left(\frac{E_{Fn} - E_{cn}}{K_BT}\right)$$

$$n_{po} = N_c \exp\left(\frac{E_{FP} - E_{cP}}{K_BT}\right) = n_{no}\exp\left(\frac{-q|V_{bi}|}{K_BT}\right)$$

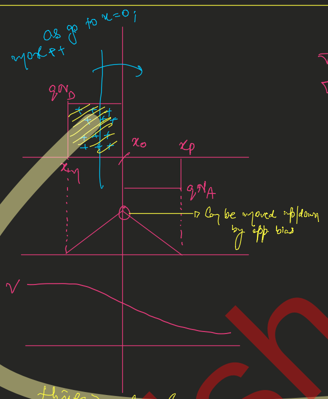
Similarly; $p_{po} = N_v \exp\left(\frac{E_{vP} - E_{FP}}{K_BT}\right)$

$$p_{no} = N_v \exp\left(\frac{E_{vn} - E_{Fn}}{K_BT}\right) = p_{po}\exp\left(\frac{-q|V_{bi}|}{K_BT}\right)$$



$N_D \longrightarrow N_D^+ + e^-$

$N_A + e^- \longrightarrow N_A^-$



$\nabla \cdot D = \rho$

$\nabla \cdot \mathcal{E} = \frac{\rho}{\epsilon}\,x$ $\quad$ $x\,\rho \to$ charge density

$$\frac{\partial \mathcal{E}}{\partial x} = \frac{\rho}{\epsilon} = \frac{qN_D}{\epsilon}$$

$$\boxed{\mathcal{E} = \frac{qN_D}{\epsilon}x + c}$$

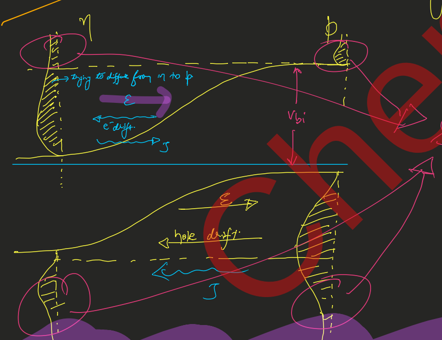
$\mathcal{E}(x = x_n) = 0$

$$\boxed{\mathcal{E}(x) = \frac{qN_D}{\epsilon}(x - x_n)}$$

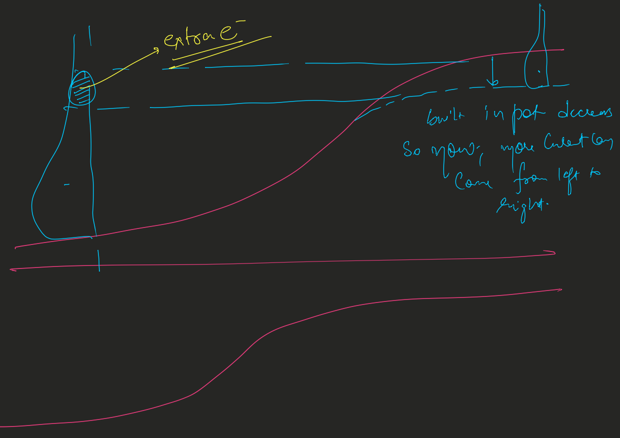
Only for $x \in (x_n, x_o)$

Note $\to$ Electrostatic is Instantaneous

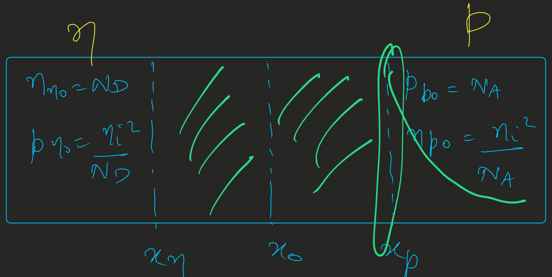
Eq^m!



Same Conc ; $\therefore$ no Current



Width of the depletion layer is affected by built in potential .If built in potential dec, width decreases. It happens in forward bias



$$\boxed{\Delta n_p = n_{no}\left[e^{\frac{qV_a}{KT}} - 1\right] \cdot e^{\frac{-qV_{bi}}{K_BT}}}$$

$$\Delta n_p(x=x_p) = n_{n0}\left(e^{qV_a/KT}-1\right)e^{-qV_{bi}/KT}$$

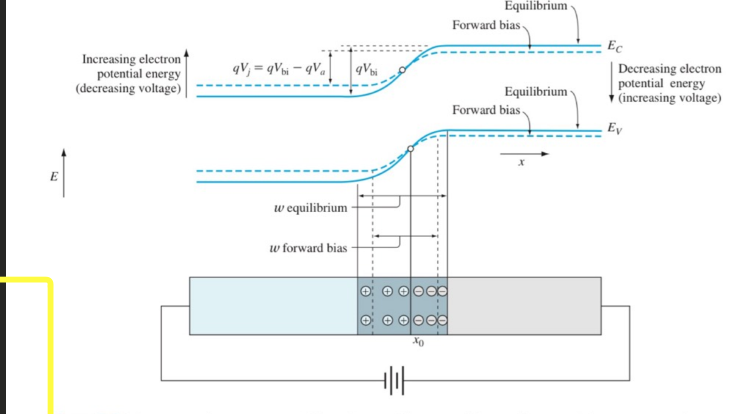
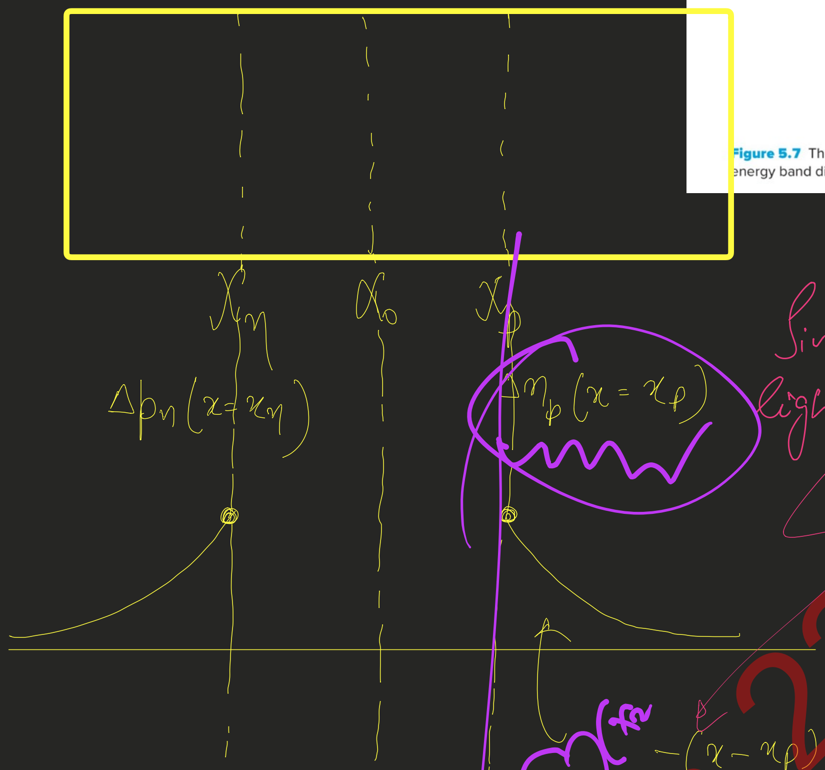


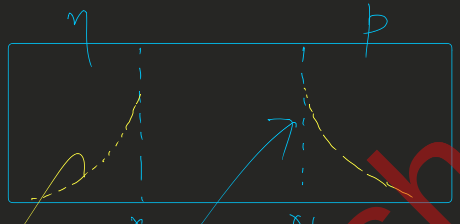
Figure 5.7 The space charge region width under equilibrium and forward bias, and the corresponding energy band diagrams.

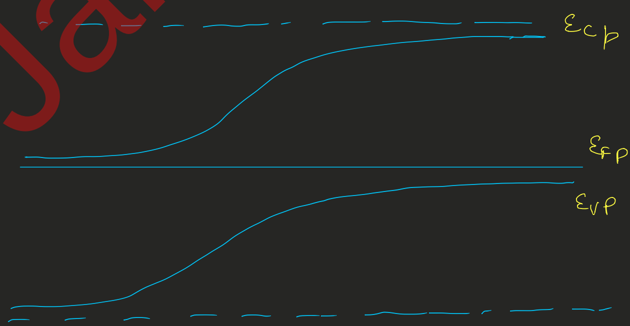
$e^- \rightarrow$



Similar to light on

$$\Delta n_p\, e^{-(x-x_p)/L_n}$$





Diffusing & recombining of xs e^-/h^+

n_{n0}

p_{n0}

p_{p0}

n_{p0}

@ eqm; $n_{N0} = N_D$

$p_{N0} = \dfrac{n_i^2}{N_D}$

$p_{p0} = N_A$

$n_{p0} = \dfrac{n_i^2}{N_A}$

$$n_{p0} = N_C \cdot \exp\left(-\frac{\mathcal{E}_{cp} - \mathcal{E}_{fp}}{K_BT}\right)$$

$$n_{N0} = N_C \cdot \exp\left[-\frac{\mathcal{E}_{cn} - \mathcal{E}_{fn}}{K_BT}\right]$$

$$n_{n0} = N_C \cdot \exp\left[-\frac{(\mathcal{E}_{cn} + qV_{bi}) - \mathcal{E}_{fn}}{K_BT}\right]$$

$$n_{n0} = n_{N0} \cdot \exp\left(\frac{-qV_{bi}}{KT}\right) = n_{p0}$$

$$n_{p0} = n_{n0} \cdot e^{-qV_{bi}/KT}$$

xs e^- density when FB applied: @ exactly x_p: $\Delta n_p = n_{p0}\left(e^{qV_a/KT}-1\right)$

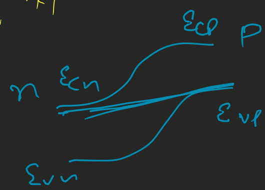
$$n_{n0} = N_c \exp\left(\frac{E_{fn} - E_{cn}}{K_BT}\right)$$

$$n_{p0} = N_c \exp\left(\frac{E_{fp} - E_{cp}}{K_BT}\right) = n_{n0} \exp\left(\frac{-q|V_{bi}|}{K_BT}\right)$$

Similarly; $p_{p0} = N_v \exp\left(\dfrac{\mathcal{E}_{vp} - E_{fp}}{K_BT}\right)$

$$p_{n0} = N_v \exp\left(\frac{E_{vn} - E_{fn}}{K_BT}\right) = p_{p0} \exp\left(\frac{-q|V_{bi}|}{K_BT}\right)$$

* Subscript tells side whether p or n



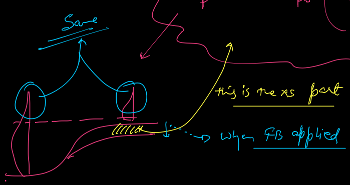
@ Forward Bias ;

$n_p = n_{n_0} \cdot e^{\frac{-q(V_{bi} - V_a)}{KT}}$

$\Delta n_p = n_p - n_{p_0}$

$= n_{n_0} \cdot e^{\frac{-qV_{bi}}{KT}} \left(e^{\frac{qV_a}{KT}} - 1 \right)$

$\Delta n_p = n_{p_0} \left(e^{\frac{qV_a}{KT}} - 1 \right)$



$$\frac{\partial(\Delta n_p)}{\partial t} = D \frac{\partial^2(\Delta n_p)}{\partial x^2} - \frac{\Delta n_p}{\tau_n}$$

@ Stdy State ; $\frac{\partial}{\partial t}(\Delta n_p) = 0$

Hence ; @ x_p ;

$\Delta n_p = \Delta n_p (x = x_p)\, e^{\frac{-(x - x_p)}{L_n}}$; $L_n = \sqrt{D_n \tau_n}$

At $x = x_p$;

$J_{n,diff} = ?$

$J_{n,diff} = D_n \cdot q \cdot \frac{\partial}{\partial x}(\Delta n_p) \Big|_{x = x_p}$

$= \frac{q D_n}{L_n} \Delta n_p (x = x_p)$

$= \frac{q D_n}{L_n} \cdot n_{p_0} \left(e^{\frac{qV_a}{KT}} - 1 \right)$

$J_{p,diff} = \frac{q D_p p_{n_0}}{L_p} \cdot \left(e^{\frac{qV_a}{KT}} - 1 \right)$

Total $J_{diff} = J_{n,diff} + J_{p,diff} = \left[q \left(e^{\frac{qV_a}{KT}} - 1 \right) \right] \left[\frac{D_n \cdot n_{p_0}}{L_n} + \frac{D_p \cdot p_{n_0}}{L_p} \right]$

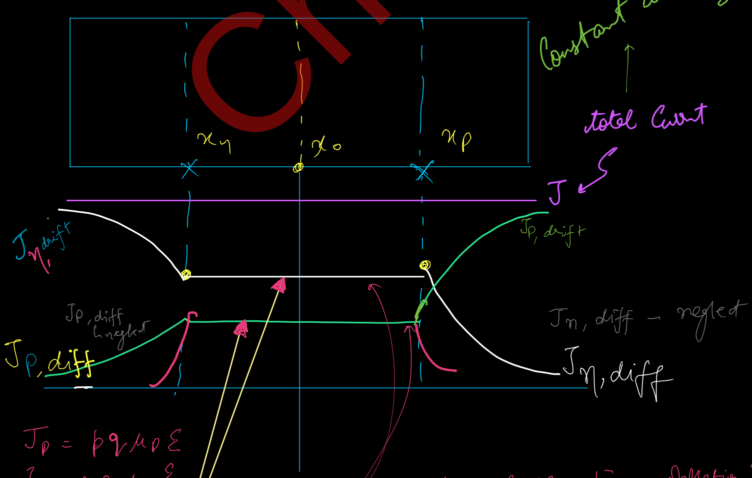
$$\boxed{J = J_0 \left(e^{\frac{qV_a}{KT}} - 1 \right)}$$

we have only Considered diffusion current because in graph we chose depletion area in which i = Const & then summed up

$J_{p,diff} \Big|_{x = x_n} = J_{p,drift} \Big|_{x = x_p}$

AND

$J_{n,diff} \Big|_{x = x_p} = J_{p,drift} \Big|_{x = x_n}$



$J_p = p q \mu_p \mathcal{E}$

$J_n = n q \mu \mathcal{E}$

no generation & recomb in depletion layer

rate of flow of holes @ x_n = " " " holes " x_p

rate of flow of h^+ @ x_n = " " " " " @ x_p

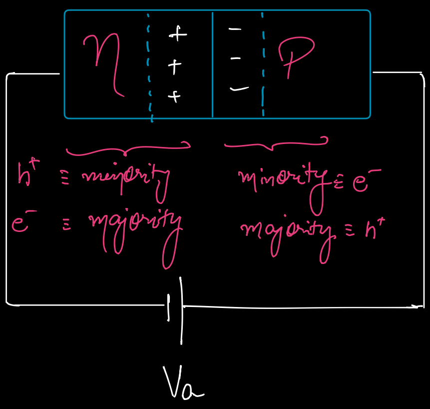
While deriving we Calculated Sum of these 2 Currents

$\Delta n_p = n_{p_0} \left(e^{\frac{qV_a}{KT}} - 1 \right)$

$\Delta n_p \sim e^{-x \left[e^{-\frac{(x - x_p)}{L_n}} \right]}$

$\frac{\partial(\Delta n_p)}{\partial x} \sim 0$ as $x \longrightarrow \infty$

Diode Current Eq^n



Assumptions:-

① On either side of p-n junction; minority ≪ maj

∴

	P side	n side
e^-		$\approx n_{n_0} \approx N_D'$
h^+	$\approx N_A' \approx p_{p_0}$	

② for minority Carriers we are Considering Only diffusion Current in Quasi-neutral region

Current due to e^- on p side ≡ $J_{n(p)} = q D_n \dfrac{\partial n_p}{\partial x}$

Current due to h^+ on n side ≡ $J_{p(n)} = -q D_p \dfrac{\partial p_n}{\partial x}$

$$n_0 = N_C' \cdot \exp\left(\frac{\mathcal{E}_F - \mathcal{E}_C}{KT}\right)$$

$$p_0 = N_V' \exp\left(\frac{\mathcal{E}_V - \mathcal{E}_f}{KT}\right)$$

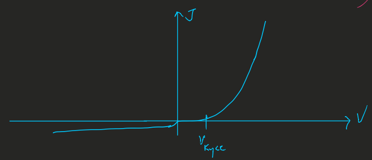
③ Boltzmann Valid ⟺ Non-degenerate

④ I = +ve for $V_a > 0$ | I_a = -ve for $V_a < 0$

⑤ $J_n \approx J_n(\text{diff})$
$J_p \approx J_p(\text{diff})$ {Ignore drift}

Final Diode Eq^n → $J = J_0\left(e^{\frac{qV_a}{kT}} - 1\right)$

{J-V characteristics of the Diode}



Why diode built in potential can't be measured via voltmeter?

sol; whenever we try to make contact; there is

Q $N_D = 10^{17}\ cm^{-3}$ $N_A = 10^{18}\ cm^{-3}$

given:

$E_g = 1.12\ eV$

$N_c = 2.86 \times 10^{19}\ cm^{-3}$

$N_v = 3.01 \times 10^{19}\ cm^{-3}$

$n_i = \sqrt{N_c N_v}\exp\left(\frac{-E_g}{2k_BT}\right)$

$\simeq 1.1 \times 10^{10}\ cm^{-3}$

$T \simeq 300K$

$KT = 0.026\ eV$

$\mu_n = 300\ cm^2/V\cdot s$

$\mu_p = 100\ cm^2/V\cdot s$

$\epsilon_{si} = 11.0$

$\epsilon_0 = 8.85 \times 10^{-12}\ F/cm$

$L_n = 200\ \mu m$

$L_p = 100\ \mu m$

sol

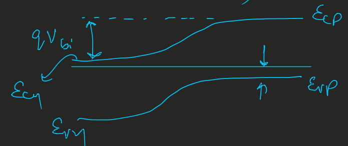
$n_{no} = 10^{17}\ cm^{-3}$

$p_{no} = \frac{n_i^2}{n_{no}} = 1.21 \times 10^{3}\ cm^{-3}$

$p_{po} = N_A = 10^{18}\ cm^{-3}$

$n_{po} = \frac{n_i^2}{p_{po}} = 1.21 \times 10^{2}\ cm^{-3}$

$qV_{bi} = K_BT\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.3\ eV$



$E_{cn} - E_F = K_BT\ln\left(\frac{N_C}{n_{no}}\right) = 0.146\ eV$

$E_F - E_{vp} = K_BT\ln\left(\frac{N_V}{p_{po}}\right) = 0.088\ eV$

both > 2-3 K_BT hence Boltzmann valid

Width of Depletion Region

$$W = \left[\frac{2\epsilon V_{bi}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right]^{1/2}$$

$W = 0.2 \times 10^{-4}\ cm = 0.2\ \mu m$

$N_D W_n = N_A W_p$

$\frac{W_n}{W_p} = \frac{N_A}{N_D} \Rightarrow W_n = \frac{N_A}{N_A + N_D} W = 0.18\ \mu m$

$E_{max} = \frac{2V_{bi}}{W} = \frac{2 \times 0.3}{0.2 \times 10^{-4}}\ V/cm = 3 \times 10^4\ V/cm$

$D_n = \frac{K_BT}{q}\mu_n = 7.8\ cm^2/s$

$D_p = 2.6\ cm^2/s$

$L_n = \sqrt{D_n \tau_n} \Rightarrow \tau_n = \frac{L_n^2}{D_n} = \frac{(200 \times 10^{-4})^2}{7.8} = 5.1\ \mu s$

$\tau_p = 3.8\ \mu s$

$J_0 = q\left(\frac{D_n \cdot n_{po}}{L_n} + \frac{D_p \cdot p_{no}}{L_p}\right)$

$= 6.54\ pA/cm^2$

Low Level injection:

the state where the number of minority carriers generated is small compared to the majority carriers of the material.

High level injection

At high injection levels occurring in power thyristors, the injected carrier concentration may exceed several times the impurity concentration for the lightly doped regions

Now; we applied $V_a = 0.8\ V$ | $A = 10^{-6}\ cm^2$ {$10\mu m \times 10\mu m$}

$J = J_0\left(e^{V/V_T} - 1\right) = 6.54\left(e^{\frac{0.8}{0.026}} - 1\right)\ pA/cm^2$

$= 6.54\left(2.3 \times 10^{13} - 1\right)$

$= 150\ A/cm^2$

$I = JA$

$= 150 \times 10^{-6}\ A$

Sanity check

$\Delta n_p = n_{po}\left(e^{V/V_T} - 1\right)$

$= 1.21 \times 10^{2} \times 2.3 \times 10^{13}\ cm^{-3}$

$= 2.8 \times 10^{15}\ cm^{-3}$

$\Delta p_n = p_{no}\left(e^{V/V_T} - 1\right)$

$= 1.21 \times 10^{3} \times 2.3 \times 10^{13}\ cm^{-3}$

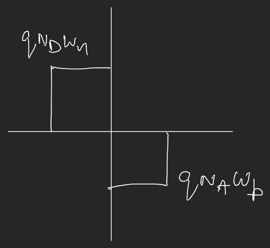
$= 2.8 \times 10^{16}\ cm^{-3}$

low level injection

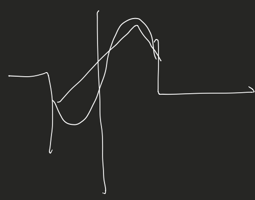
$\Delta n_p \ll p_{po}$ | $\Delta p_n \ll n_{no}$

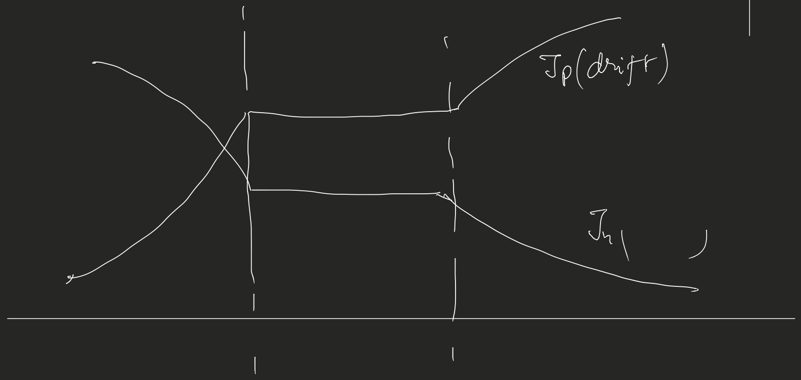
Assumptions made in last question

1. Low level injection
2. Abrupt junction
3. Depletion Approximation (4. Quasineutral beyond boundary)



Other profiles





$$\therefore J = 150\ A/cm^2$$
$$= q\, n_{n_0}\, \mu_n\, \mathcal{E}_n$$

$$\mathcal{E} = \frac{150}{1.6\times10^{-19}\times10^{17}\times300} = \underbrace{31.25\ V/cm \lll \mathcal{E}_{max} = (3\times10^4\ V/cm)}_{\text{Validation of quasineutral region}}$$

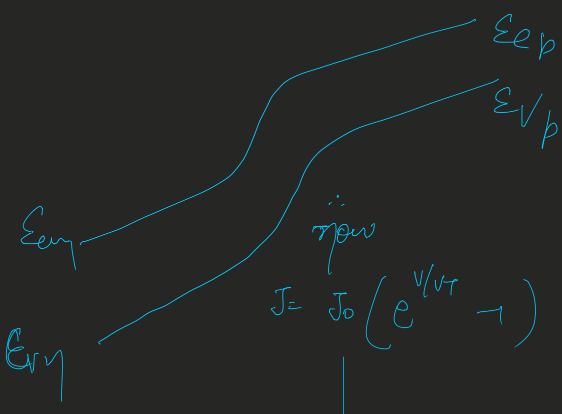
if $V_a = 0.8\ V$;

$$J = J_0\left(e^{V/V_T} - 1\right)$$
$$= 6.54\left(e^{\frac{1}{0.026}} - 1\right)\ pA/cm^2$$
$$= 3.3\times10^5\ A/cm^2$$

$$\Delta p_n = p_{n_0}\left(e^{V/V_T} - 1\right)$$
$$= 1.21\times10^3\times5\times10^{16}$$
$$= 6\times10^{19}\ cm^{-3} \longrightarrow \text{High level injection (minority > majority after biasing of } V_a = 1V)$$

$\mathcal{E}_p = 6.8\times10^4\ V/cm \longrightarrow$ now larger than $\mathcal{E}_{max}$

$\therefore$ Effective voltage across depletion region < 1



$\therefore$ now $J = J_0\left(e^{V/V_T} - 1\right)$

No longer quasi neutral as we have considerable EF in earlier quasineutral region