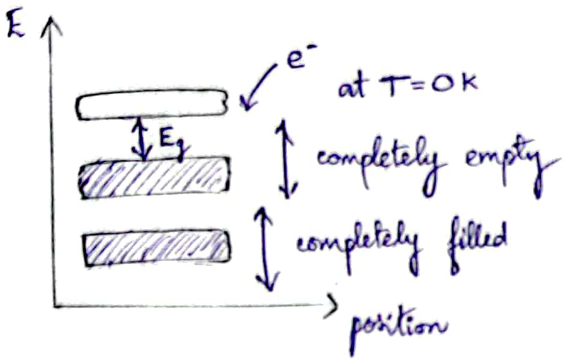
Diamond cubic structure (DC):-

Obtained by two FCC lattices interpenetrating body-diagonally.

Eg: Silicon (same FCC), GaAs (Different FCC), GaN $\rightarrow$ HCP

Basis :- Unit of a lattice

09/01/2023



$E_g \rightarrow$ bandgap

Semiconductor $\rightarrow$ E_g is small

Insulator $\rightarrow$ E_g is large $\rightarrow$ $E_g > 4eV$

Metal $\rightarrow$ Partially filled band at 0K

Free e^-

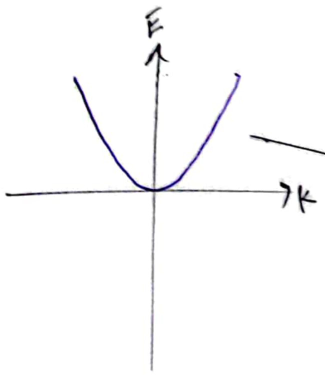
$p = mv$

$E = \frac{1}{2}mv^2 = \frac{p^2}{2m}$

$= \frac{\hbar^2 k^2}{2m}$

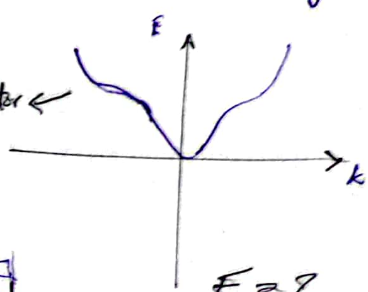
$p = \hbar k$ ($\hbar \rightarrow h/2\pi$)

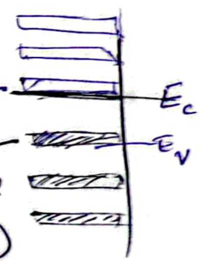
$k = \frac{2\pi}{\lambda}$ ($\lambda \rightarrow$ De-Broglie wavelength)



$\rightarrow$ E-k relation of a free e^- (Dispersion relation)

for semiconductor





lowest empty band (Conduction band)

highest filled band (Valence band)

$E_c \rightarrow$ conduction band edge

$E = ?$

$E = f(k)$ (∵ min) 0

$$E = E_0 + \cancel{\frac{\partial E}{\partial k} k} + \frac{1}{2}\frac{\partial^2 E}{\partial k^2} \cdot k^2 = E_0 + \frac{1}{2}\cdot\frac{\partial^2 E}{\partial k^2} \cdot k^2$$

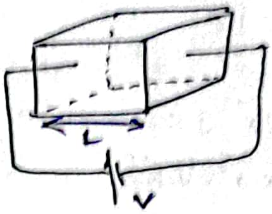
(that forms the plot for semiconductor e^-)

E_0 → reference energy

$$\Rightarrow \frac{\hbar^2 k^2}{2m} = E_0 + \frac{k^2}{2} \cdot \frac{\partial^2 E}{\partial k^2} \rightarrow \frac{\hbar^2 k^2}{2m^*}$$

I.v.imp!

$$\Rightarrow \boxed{m^* = \hbar^2 \left(\frac{\partial^2 E}{\partial k^2}\right)^{-1}}$$



$$|\mathcal{E}| = V/L$$

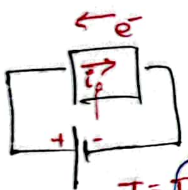
$$\Rightarrow F = -q\mathcal{E}$$

$$= -q\left(\frac{V}{L}\right) = m^* \frac{dv}{dt} \rightarrow \text{velocity}$$

15/01/2023

Concept of Holes

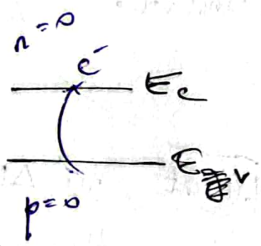
T = 0K



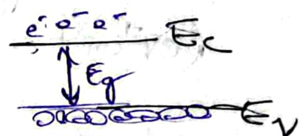
$$I = I_n + I_p$$

I_n → e^-s moving in conduction band (E_c)

I_p → "holes" moving in valence band (E_v)



T = 10K



No. of e^-s? $\sim 10^{22}\ cm^{-3}$.

---

e^- in a semiconductor: E-k relation:

$$-qE = m_e^* \frac{dv}{dt}$$

($E_0 = 0$ as e^- is in free band)

Now,

I'll be creating a virtual particle called "hole":

$$qE = (-m_e^*)\frac{dv}{dt}$$

$$\boxed{qE = m_h^* \frac{dv}{dt}}$$

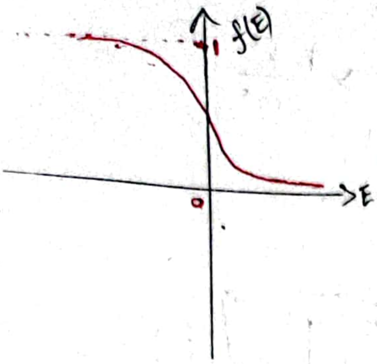
Entropy

Fermi-Dirac Eqn: $\boxed{f(E) = \dfrac{1}{1+e^{(E-E_F)/K_BT}}}$

K_B → Boltzmann CONST

E_F → Fermi-energy (CONST ref)

$f(E)$ → Probability of occupation of an energy level (E) for an e^-



* Tends to 1 as $E \to -\infty$.
* Tends to 0 as $E \to \infty$

Tells us the density of e^-s in any particular energy level.

$K_B = 1.38 \times 10^{-23}\ J\,K^{-1}$
$= 8.6 \times 10^{-5}\ eV\,K^{-1}$

16/01/2024

NOTE: Probability of occurrence of a hole = $\boxed{1-f(E)}$

Density of States (DOS)

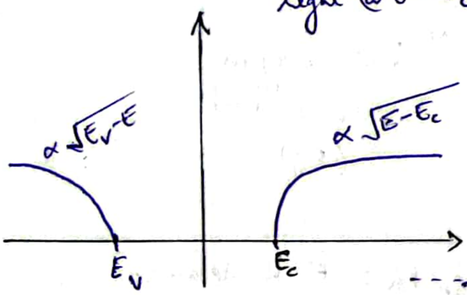
$N_c(E)$ → Unit: per unit energy per unit vol. ($eV^{-1}cm^{3}$)

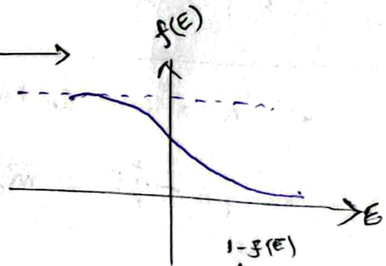
Number of states $N = \int_{E_c}^{E_c+\Delta E} N_c(E)\,dE$ for $\Delta E > 0$

Also, note that right @ $E = E_c$, $N = 0$.

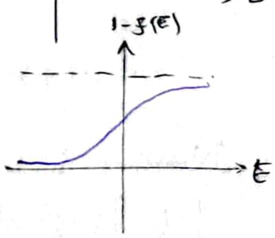
$$\boxed{N_c = \left[\frac{1}{2\pi^2}\left(\frac{2m_e^* e}{\hbar^2}\right)^{3/2}\right]\sqrt{E-E_c}}$$

$$\boxed{N_v = \left[\frac{1}{2\pi^2}\left(\frac{2m_h^* e}{\hbar^2}\right)^{3/2}\right]\sqrt{E_v-E}}$$





All these together explain why PMOS is slower than NMOS!



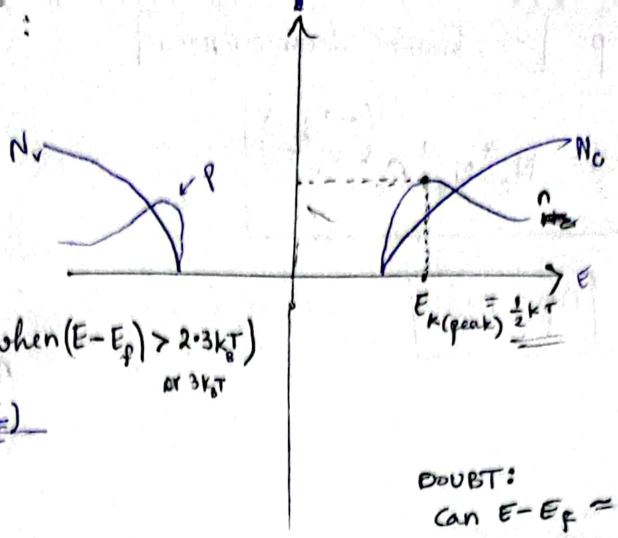
So...

no. of e^-s in conduction band per unit volume 'n' $= \int_{E_c}^{E_c+\Delta E} f(E)\cdot N_c(E)\,dE$

no. of holes in valence band per unit volume 'p' $= \int_{E_v-\Delta E}^{E_v} [1-f(E)]\cdot N_v(E)\,dE$

$\therefore$ n v/s E and p v/s E :

$\langle E_k \rangle = \frac{3}{2} kT$



NOTE:

If $E \gg E_F$,

Boltzmann Approximation: $(\text{when } (E-E_F) > 2.3k_BT)$ or $3k_BT$

$$f(E) = \frac{1}{1+e^{(E-E_F)/k_BT}} \simeq e^{-\frac{(E-E_F)}{k_BT}}$$

DOUBT:
Can $E - E_F \approx E$?

Another approximation :

$$n = \int_{E_c}^{E_c+\infty} f(E) N_c(E)\, dE$$

NOTE: @ room temp, $k_BT \approx 0.026eV$

Approximatn is valid as f(E) decays quite fast and has already decayed a lot. $\therefore$ negligible errors.

NOTE :
Requirement:
$E_c - E_F \geq 2k_BT$

$$\therefore n = \int_{E_c}^{\infty} f(E) N_c(E)\, dE = \boxed{N_c^* e^{-\left(\frac{E_c-E_F}{k_BT}\right)}}$$

"analytically integrable"

$N_c^* \rightarrow$ Effective DOS (just a prefactor of exponential)

$$= 2\left(\frac{m^* k_BT}{2\pi\hbar^2}\right)^{3/2}$$

[$\because e^-$ has 2 spins]

$$\therefore \boxed{\begin{aligned} n &= N_c^* e^{-\frac{(E_c-E_F)}{k_BT}} \\ p &= N_v^* e^{-\frac{(E_F-E_V)}{k_BT}} \end{aligned}}$$

18/01/2023

@ T = 300K, k_BT = 26meV
@ T = 600K, k_BT = 52meV

Ideal semiconductor $\longrightarrow$ $n_i = p_i$
(intrinsic semiconductor) ~~N_c~~ $n_i \cdot p_i$ = ?

$$n_i^2 = N_c^* N_v^* e^{-\left(\frac{E_c-E_v}{k_BT}\right)}$$

$\Rightarrow$ ~~$n_i p_i$~~

$$\boxed{n_i = \sqrt{N_c^* N_v^*}\, e^{\left(\frac{-E_g}{2k_BT}\right)}}$$

What if $n_i \neq p_i$?

The most driving force for semiconductor

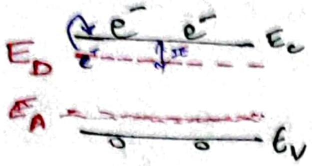
If $n \neq p$ [-Extrinsic Semiconductor] (created by doping)

Then $\boxed{np = N_c^* N_v^* e^{\left(\frac{-E_g}{K_B T}\right)}}$

$\boxed{np = n_i^2}$

It says that whether semiconductor intrinsic or extrinsic,
$n \cdot p =$ ~~CONSTANT~~ Same value

23/01/2024



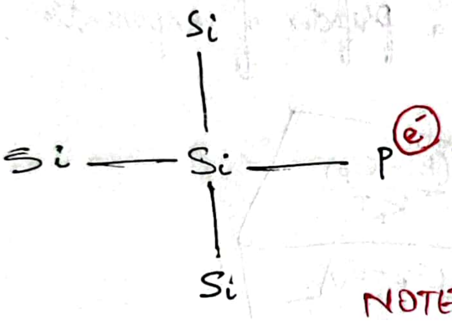
Si → $N_i \simeq 11 \times 10^{10}\ cm^{-3}$, $E_g = 1.1 eV$

Extrinsic → n-type (e^-) (donor level) (N_D = donor density)

Extrinsic → p-type ~~(p)~~ (h) (acceptor level) (N_A = acceptor density)

I've introduced something (doping) that gave rise to new energy level (E_D)

Si → val = 4 Phosphorus → val = 5



→ donated to the crystal, roams around the lattice

NOTE: $E_c - E_D$ = ionisation energy

Requirements for doping:

* Val (new atom) > Val (old atom)
* Donor must be shallow donor ($E_c - E_D$ must be less than $K_B T$)

Donor conc ~ $10^{19}\ cm^{-3}$, whereas ~~but~~ host atoms ~ $10^{24}\ cm^{-3}$.

∴ 1 donor atom among 10^5 host atoms, ∴ they do not bond.

⟹ ∴ they can't form a band, just a discrete line ~~of~~ defect of energy level E_D.

Charge Neutrality

Intrinsic $\longrightarrow n_i = p_i$

Extrinsic $\longrightarrow n + N_A = p + N_D$

In addition,

$\because$ law of mass action holds, $np = n_i^2$

$n_i = 10^{10}\ cm^{-3}$

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

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

Note: If $(N_D - N_A) >> n_i \iff$ predominantly doped by donors (n-type)

$n \simeq (N_D - N_A)$ ✓

[Similarly, if $(N_A - N_D) >> n_i$

$\Rightarrow p \simeq (N_A - N_D)$]

$p = \dfrac{n_i^2}{n}$

$n \simeq (N_D - N_A)$

$= 9 \times 10^{17}\ cm^{-3}$

$\therefore p = \dfrac{10^{20}}{9 \times 10^{17}} = \dfrac{1}{9} \times 10^{3}\ cm^{-3}$

Here, $n = N_c' \, e^{-\frac{(E_c - E_F)}{k_B T}}$

$p = N_v' \, e^{-\left(\frac{E_F - E_v}{k_B T}\right)}$

$n >> p$

$\hookrightarrow E_F - E_c$ is large

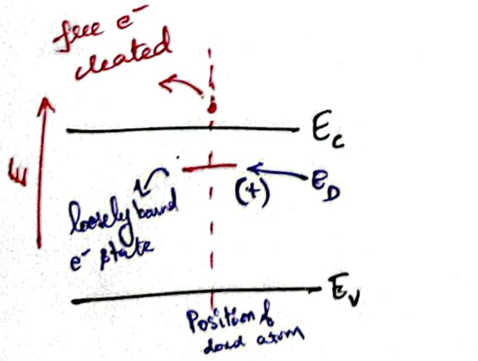
$E_v - E_F$ is small

(very very -ve)

Conclusion

Fermi-level being closer to $\longrightarrow E_c \iff$ n-type

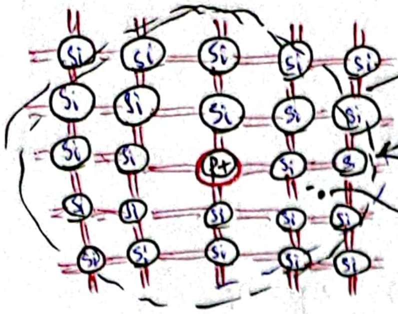
$\longrightarrow E_V \iff$ p-type



Phosphorus donating e⁻ to Si crystal

* The lowest energy (ground) state of an e⁻ associated with the donor atom exists only near that donor atom, so the donor state of energy (E_D) does not exist throughout the crystal.

* Donor state is close to conduction band edge.



covalent bond e-s

Orbital radius of loosely bonded e-

Free e-

* The loosely bound e- CANNOT contribute to current ∵ it is (loosely) bound to the fixed donor ion.

("chained down" to the crystal by 4 valence bonds)

25/01/2024

Summary

$$n = N_c' e^{-\left(\frac{E_c - E_F}{k_B T}\right)}$$

$$p = N_v' e^{-\left(\frac{E_F - E_V}{k_B T}\right)}$$

$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_B T}}$$

$$\simeq e^{-\frac{(E-E_F)}{k_B T}}$$

$$n = \int_{E_c}^{\infty} f(E) N_c(E) dE$$

$$= N_c' e^{-\left(\frac{E_c - E_F}{k_B T}\right)}$$

Intrinsic: $n_i = p_i = \sqrt{N_c' N_v'}\, e^{-\left(\frac{E_g}{k_B T}\right)}$

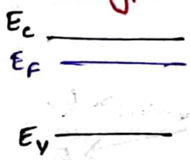
Extrinsic: $np = n_i^2$

AND $n + N_A^- = p + N_D^+$

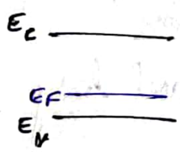
If $N_D - N_A \gg n_i \Rightarrow n \simeq (N_D - N_A)$

$N_c = [\ ]\sqrt{E - E_c}$ if $E \geqslant E_c$

n-type



p-type



Avg. energy of e^-: $\langle E\rangle = \dfrac{\int E\, n(E)\, dE}{n}$ ← total no. of e^-

$= \boxed{\dfrac{3}{2} K_B T}$

→ In a quantum well :- $\frac{2}{2} K_B T$

→ In nanoelectronics :- $\frac{1}{2} K_B T$

→ If a quantum dot :- Vanish!

Si

$E_g = 1.1 eV$

$N_c' = 10^{22} cm^{-3}$

$N_v' = 2\times10^{22} cm^{-3}$

$\Rightarrow n_i = \sqrt{N_c' N_v'}\; e^{-\frac{E_g}{2K_BT}}$

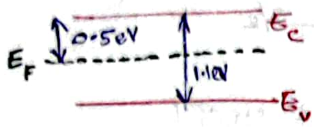
$= 10^{22}\cdot\sqrt{2}\; e^{-\frac{1.1}{2\times0.026}}$

$= 9.19425\times10^{12} cm^{-3}$

Q. Where is the position of Fermi level?

Sol.

$\because n = N_c' e^{\left(\frac{E_F-E_c}{K_BT}\right)}$ $\quad\therefore\; E_F - E_c = K_BT \ln\left(\frac{n}{N_c'}\right) = 0.026 \ln\left(\frac{9.19\times10^{12}}{10^{22}}\right)$



$= -0.5 eV$

NOTE: If the density e^-s and holes were equal $(N_c' = N_v')$ then don't you expect Fermi level to be right in the middle?

So, intrinsic $\Rightarrow n_i = p_i \Rightarrow e^{-\left(\frac{E_c-E_F}{K_BT}\right)} = e^{-\left(\frac{E_F-E_v}{K_BT}\right)} \Rightarrow E_c - E_{F_{ermi}} = E_{F_{ermi}} - E_V$

$\Rightarrow E_F = \dfrac{E_c + E_V}{2}$

Proved :)

Qn.

$E_g = 1.1eV$ $\quad N_c' = 10^{22} cm^{-3}$ $\quad N_v' = 2\times10^{22} cm^{-3}$ $\quad\therefore n_i = 9.19\times10^{12} cm^{-3}$

Doping : $N_D = 10^{17}$ $\qquad N_A = 0$ $\qquad$ then, $E_F = ??$

Sol. $n = N_D - N_A = 10^{17}$. $\quad (\because \gg n_i)$

Now, $n = N_c' e^{-\left(\frac{E_c-E_F}{K_BT}\right)}$

$\Rightarrow E_F - E_c = K_BT \ln\left(\frac{n}{N_c'}\right)$

$= 0.026 \ln\left(10^{17}/10^{22}\right)$

$= -0.29$

Conclusion: As you see, doping the SC with more e^- (by N_D) results in moving of E_{Fermi} closer to E_c

Q. In previous Qn, what if $N_D = 10^{22}\ cm^{-3}$? OO
(Shivani's eyes XD)

Sol.

$$E_F - E_C = K_BT \ln\left(\frac{n}{N_c'}\right)$$

$$= 0.026 \ln\left(\frac{10^{22}}{10^{22}}\right) = 0 \Rightarrow E_F = E_C .$$

Is it? ✗ What went wrong?

Boltzmann!

$|E_c - E_F| \gg K_BT$

$\downarrow$ 0 failed! ; $K_BT \rightarrow$ 26meV

* If my e^- density is much smaller that the effective density of states . . . then Boltzmann applox holds.

* If Auditorium is filling close complete . . . dont use Boltzmann instead use integratn approach .

V.imp !! * ~~Effective density of states is a fn of temp~~ , DOS is NOT! ($N_c' \sim T^{3/2}$)

(In the classroom, if Pizza is distributed, strength of class goes above normal, the no. of chairs don't)

Explanatn using physics ~~and not mere eqns~~: If $T\uparrow \Rightarrow E_F \downarrow$ (comes down) (to the middle) $\Rightarrow (E_c - E_F)\uparrow$

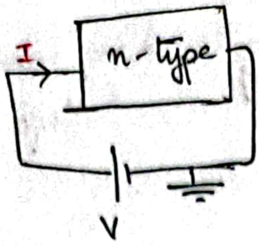
* No. of carriers ↑ when T ↑

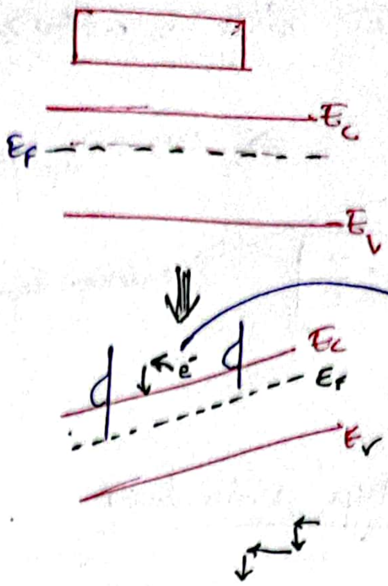
which may overpower the doping levels . . .

$\therefore$ $E_F \downarrow\uparrow$ and at extreme temp, E_F converges to E_{Fi} ($\because$ both e^- and holes are ↑↑)

and hence $n_i \approx p_i$ (for very large T) and E_F comes down to mid-point.

NOTE : E_F moves and moves but never crosses midline .





e^- moves down a little and falls down into C-band
"Scattering"

29/01/2024

Transport

$$\varepsilon = -\nabla V$$
$$= -\frac{\partial V}{\partial x} = -\frac{[V(x=L) - V(x=0)]}{L} = +\frac{V}{L}$$

$$V = IR = I\rho\frac{l}{A} = \vec{J}\rho l = \frac{Jl}{\sigma} \Rightarrow J = \frac{\sigma V}{l}$$

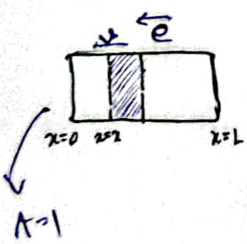
$$\Rightarrow \boxed{\vec{J} = \sigma\vec{E}} \longrightarrow \text{Ohm's law!}$$

Mobility unit : $\frac{cm^2}{Vs}$ $\left(= \frac{V}{E}\right)$

NOTE: Kirchoff's law → based on charge conservation!

Whatever comes in, goes out ✓

* No "accumulation" of charge carriers
$\Updownarrow$
$\vec{J} = \sigma\vec{E} = \text{Const}$ ✓



$J = \left(\frac{dQ}{dt}\right)$ per unit area

$= nqv$ → drift velocity $\propto E$

$\Rightarrow v = \mu E$ → mobility

$= nq\mu E$

$$\boxed{J = \sigma E}$$

holds for metals as well as semiconductors

NOTE:
Metal has very low mobility!
$\sim 0.052 \frac{cm^2}{Vs} \Rightarrow \therefore$ NOT used in high-speed devices
Semiconductors $\sim 500 \frac{cm^2}{Vs}$
Graphene $\sim 10^4 \frac{cm^2}{Vs}$

$$\text{Force} = qE = m^*\left(\frac{dv}{dt}\right) = m^*\frac{\langle v \rangle}{\tau}$$

$\tau \rightarrow$ Scattering time

$\langle v \rangle \rightarrow$ avg velocity $= v_{drift}$

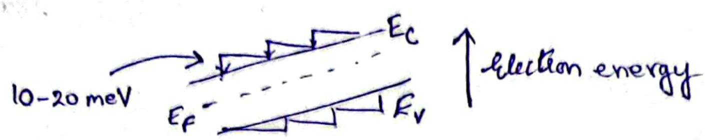
$$\Rightarrow \langle v \rangle = v_{drift} = \left(\frac{q\tau}{m^*}\right)E = \mu E$$

$$\Rightarrow \boxed{\mu = \frac{q\tau}{m^*} = \frac{v}{E}}$$

$\rightarrow$ microscopic definition of μ

31/01/2024

p-type Semiconductor

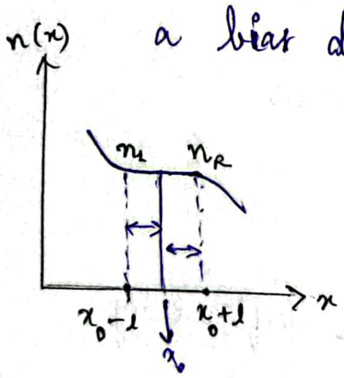


Holes act like balloons in the diagram for e^- energy.

$$\therefore J_p = qp\mu_p E \quad ; \quad J_n = qn\mu_n E$$

$$\therefore J = J_p + J_n = qE(p\mu_p + n\mu_n) = \sigma E.$$

Diffusion: Movement of carriers without application of a bias due to concentration gradient.



e^- collides $\rightarrow$ (in Brownian motion)

$\therefore$ Probability of carriers to be on the right $\rightarrow n_R l/2$

left $\rightarrow n_L l/2$

$\therefore$ flux of carriers across x_0 from left to right

$$= \frac{n_L l - n_R l}{2\tau}$$

$\tau \rightarrow$ "time taken for carrier to travel a length l, not the mean scattering time!"

$$\therefore F = \frac{(n_1 - n_2)l}{2\tau} = -\frac{l^2}{2\tau}\frac{\partial n}{\partial x} = -D\frac{\partial n}{\partial x}$$

D = Diffusion constant

$J_{n,diff}$ = Diffusion Curr for electrons

$$\therefore J_{n,diff} = -qF = qD_n\frac{\partial n}{\partial x} \quad //$$

Similarly, $J_{p,diff} = qF = -qD_p\frac{\partial n}{\partial x} \quad //$

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

$$J_p = qp\mu_p E - qD_p\frac{\partial n}{\partial x}$$

$\Rightarrow$ Total current density

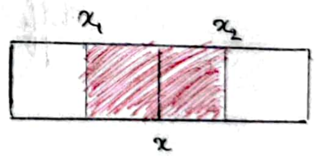
$J = J_n + J_p$

Einstein's relation : $\boxed{\dfrac{D}{\mu} = \dfrac{K_B T}{q}}$ (only valid with Boltzmann approx)

* $E_c - E_F > 2K_BT \rightarrow$ Non-degenerate Semi-conductor. Boltzmann ✓

$\Rightarrow$ Non-equilibrium condition

"Steady state has NOT been reached yet"



$$\therefore F(x_2) - F(x_1) = -\frac{\partial}{\partial t}(n\Delta x)$$

n = e^- density in Δx region

$$\therefore J_n = -qF$$

$$\Rightarrow J(x_2) - J(x_1) = q\frac{dn}{dt}\cdot\Delta x$$

$$\therefore \frac{\partial J}{\partial x} = q\frac{\partial n}{\partial t} \quad //$$

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

$$\therefore \frac{\partial J_n}{\partial x} = q\mu_n\left(n\frac{\partial E}{\partial x} + E\frac{\partial n}{\partial x}\right) + qD_n\frac{\partial^2 n}{\partial x^2} = q\frac{\partial n}{\partial t}$$

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

What if no bias is applied?

$$E = 0 \Rightarrow D_n\frac{\partial^2 n}{\partial x^2} = \frac{\partial n}{\partial t}$$

Fick's 2nd law of diffusion

$n = n_0 + \Delta n$ → eq. condition

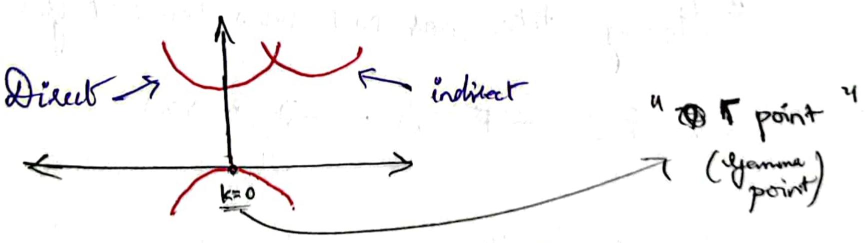
$$\therefore D_n\frac{\partial^2(\Delta n)}{\partial x^2} = \frac{\partial(\Delta n)}{\partial t}$$

* Direct Bandgap Semiconductor:

Valence band maxima and conduction band minima occur at same k. (GaN, GaAs)

* Indirect Bandgap Semiconductor:

Valence band maxima and conduction band minima are different k. (Si, Ge)



A semiconductor is illuminated uniformly by light

⇓

e^- - hole pair is produced.

$\because$ uniformly distributed,

$$\therefore \frac{\partial n}{\partial x} = 0$$

$\boxed{\text{p-type (EHP)}}$

$$\Rightarrow \frac{\partial^2 n}{\partial x^2} = 0 \quad \Rightarrow \frac{\partial n}{\partial t} = 0$$

$$\Rightarrow \Delta n = \text{const} .$$

Optical generation

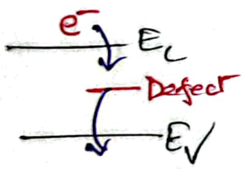
$E = h\nu$

If $h\nu > E_g$, e^- moves to the conduction band, creating an EHP.

Thermal generation: EHP generated due to thermal energy supplied.

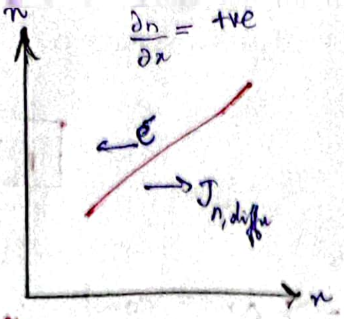
Direct recombination: e^- in conduction band directly jumps down to the valence band.

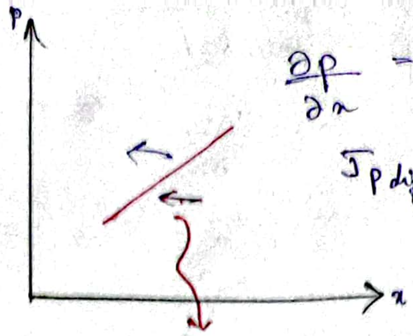
Indirect recombination: There may be defects in the lattice structure which can provide additional energy levels for e^- to ~~come~~ come into.



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

01/01/2024





$\frac{\partial p}{\partial x}$ = +ve

$J_{p\,diffu}$ = -ve

(Current is now in the -ve edge dirn)

$n(x)$ = const.

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

$$\frac{\partial n}{\partial x} = \frac{\partial \Delta n(x)}{\partial x}$$

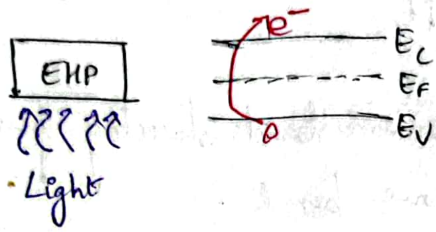
Excess carrier dynamics:

$$\frac{\partial \Delta n}{\partial t} = \frac{D\,\partial^2(\Delta n)}{\partial x^2}$$

Optical generation — measured as → GOP in cm^{-3}/s

↓

(generation optical)



* Thermal generation - G_{th} in cm^{-3}/s [n_i (intrinsic generated)]

Recombinations

Direct recombination [Band-to-band (B2B) recombination]

Defect-assisted recombination [Shockley Read Hall] (SRH)

$P(t) = (1 - e^{-t/\tau_n})$ [Poisson distributn]

Prob. of recombination

* Recombination $R = \Delta n / \tau_n$ ← average

τ_n = Recombination lifetime

So in this case, our continuity eqn becomes —

$$\boxed{\frac{\partial \Delta n}{\partial t} = \frac{D\,\partial^2(\Delta n)}{\partial x^2} + G_{OP} - \frac{\Delta n}{\tau_n}}$$

* NOTE: Again, if uniformly illuminated, Δn is same everywhere. Thus concn gradient $\frac{\partial(\Delta n)}{\partial x} = 0 \rightarrow \frac{\partial^2}{\partial x^2}(\Delta n) = 0$

So, $\frac{\partial \Delta n}{\partial t} = G_{OP} - \frac{\Delta n}{\tau_n}$

$\Rightarrow \Delta n(t) = G_{OP}\cdot\tau_n\left(1 - e^{-t/\tau_n}\right)$

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

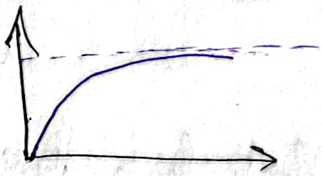
$\Delta n(t=\infty) = G_{OP}\,\tau_n$

(like charging of a —||—)!

at $t = \infty$, $\frac{\partial \Delta n}{\partial t} = 0$

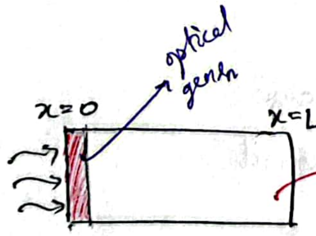
* whatever has to happen, has happened. That's how we find steady state right?

$\therefore \Delta n(t=\infty) = G_{OP}\cdot\tau_n$



$\boxed{\text{generation} = \text{recombination}}$

\#



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

→ G_{OP} zero here as I'm shining light only from left.

→ excess e⁻ density per unit time (G_{OP}) @ $x = 0$

$\Delta n(x,t) \longrightarrow \Delta n(x,\infty) \equiv \Delta n(x) = ?$

(mela interest)

excess e⁻ density profile at steady state $\longrightarrow \frac{\partial \Delta n}{\partial t} = 0$

$\rightarrow D_n \frac{\partial^2 \Delta n}{\partial x^2} + G_{OP} = \frac{\Delta n}{\tau_n}$

$\Rightarrow \Delta n(x) = A e^{\frac{-x}{\sqrt{D_n\tau_n}}} + B e^{\frac{x}{\sqrt{D_n\tau_n}}}$

$$\Delta n(x) = Ae^{\frac{-x}{\sqrt{D_n \tau_n}}} + \cancel{Be^{\frac{x}{\sqrt{D_n \tau_n}}}} \to 0$$

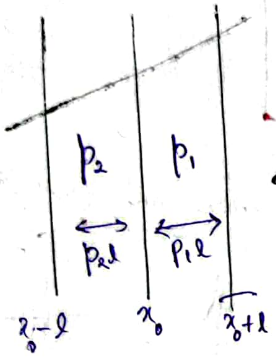
?

Excess carriers cannot grow as you go deeper ($\uparrow x$) in the semi-conductor

$$= Ae^{\frac{-x}{\sqrt{D_n \tau_n}}} = Ae^{-x/L_n}$$

$\sqrt{D_n \tau_n} = L_n =$ diffusion length

02/02/2024



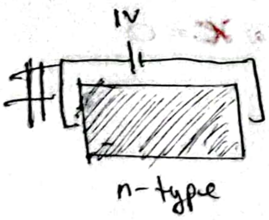
$p_1 = p_2 + \frac{\partial p}{\partial x}$ [Taylor expansion]

Total e^- moving towards right $= \dfrac{\frac{p_2 l}{2} - \frac{p_1 l}{2}}{t}$

Monte Carlo Algorithm: Studying the microscopic level

NOTE: * Photon momentum is small, energy is large

* Phonon momentum is large, energy is small



$L = 1\mu m$

$N_c' = 10^{22} cm^{-3}$

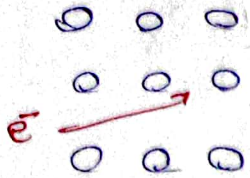
$N_v' (T = 300K) = 10^{21} cm^{-3}$

$N_D = 10^{17} cm^{-3}$ $\quad \mu_n = 100\ cm^2/Vs$

$n_i \sim 10^{12} cm^{-3}$ $\quad \frac{K_B T}{q} = 26mV$

Solution: ~~E~~ $J = nq\mu_n E$ $\quad$ [T = 300K]

Scattering → Impurity Scattering
→ Phonon Scattering → (atomic vibrations)



$\mu_I = \frac{q\tau_I^*}{m^*}$ $\mu_p = \frac{q\tau_p^*}{m^*}$

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_I} + \frac{1}{\mu_p}$$ [Mattissen's rule]

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

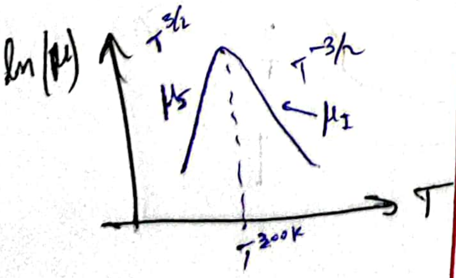
Temperature dependency of μ

$\mu_p \sim T^{-3/2}$
$\mu_I \sim T^{3/2}$

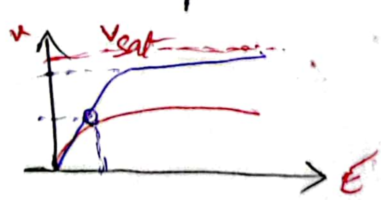
At low T, $\mu_p \to \mu_p$ negligible
$\mu_I \to \mu_I$ dominates

At high T, $\mu_p \to \mu_p$ dominates
$\mu_I \to \mu_I$ negligible

$T\uparrow \Rightarrow e^-$ intrinsic motion fast
↓
Interaction time with fixed charge is less → less scattering → more mobility



vel = $\mu \times E$



$$\mu = \frac{\mu_0}{1 + \left(\frac{E}{E_0}\right)}$$ μ_0 → low-field mobility

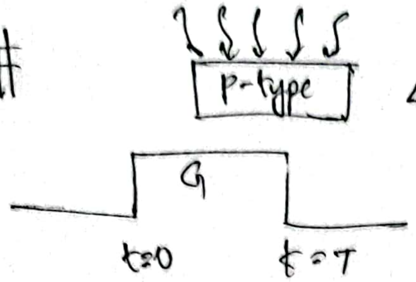
E_c is that electric field for which velocity is exactly half of what it ideally should have been.

$$\text{at } E = E_c, \quad v = \frac{\mu_0}{1 + \frac{E_c}{E_c}} \cdot E_c = \underline{\underline{\frac{\mu_0}{2} E_c}}$$

whereas

ideal : $\underline{\underline{v = \mu_0 E_c}}$

#



$\Delta n(t) = ?$

NOTE:

Recombination rate $R = \beta n p$
$\quad \llcorner_{\tau = 1/R}$

$\therefore \tau_n \propto \frac{1}{\beta N_A}$ (for a p-type)

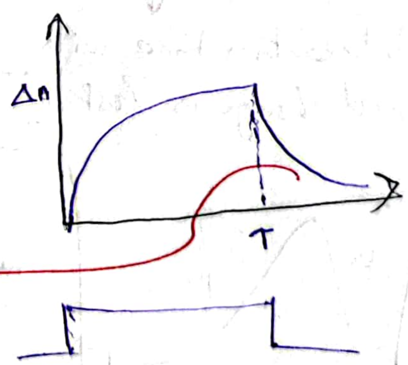
$$\Delta n(t) = G\tau_n\left(1 - e^{-t/\tau_n}\right)$$

$$\frac{\partial \Delta n}{\partial t} = \cancel{D_n \frac{\partial^2 \Delta n}{\partial x^2}}^{\,0} + \cancel{G}^{\,0} - \frac{\Delta n}{\tau_n} \qquad t > T$$

$$= -\Delta n / \tau_n$$

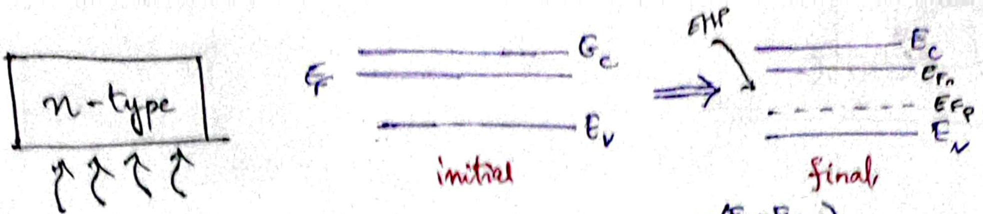
$$\Rightarrow \Delta n = \Delta n(t = T)\, e^{-t/\tau_n} \longrightarrow \text{Poisson distribution!}$$

&, $\Delta n(t = T) = G\tau_n\left(1 - e^{-T/\tau_n}\right)$



we want this to decay faster,
$\therefore$ reduce $\underline{\tau_n}$

05/02/2024



$n \rightarrow n + \Delta n$

$p \rightarrow p + \Delta p$

$$n = N_c' \, e^{-\left(\frac{E_c - E_{F_n}}{K_B T}\right)}$$

$$p = N_v' \, e^{-\left(\frac{E_{F_p} - E_v}{K_B T}\right)}$$

I can keep using these Quasi-Fermi levels for non-eqm conditions.

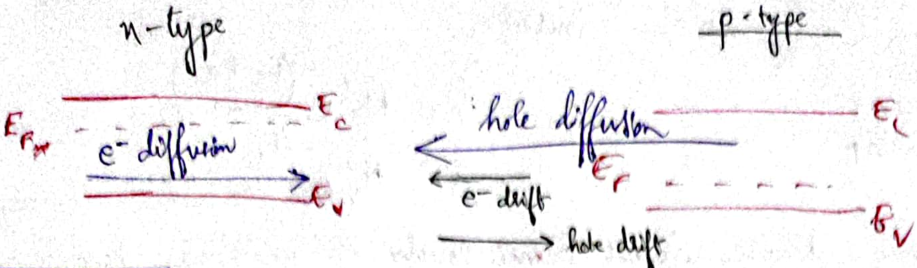
[NOTE: This is assumed purely for our ease of analysis]

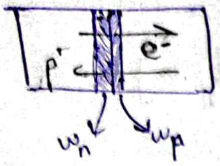
* Dielectric relaxation time ~ ps.

$N(E)dE$:- Number of electronic states per unit volume with an energy between E and E+dE in the conduction band.

$$E - E_c = \text{electron Kinetic energy} = \frac{p_x^2}{2m_x} + \frac{p_y^2}{2m_y} + \frac{p_z^2}{2m_z}.$$

Diode





N_D^+ ↔ Not compensated

Steps:

Gradient of charge carriers

⇓

e⁻/hole diffuse

⇓

create internal $\vec{E}$ field

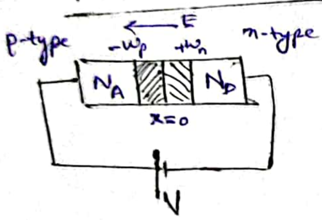
⇓

e⁻/hole now ~~diff~~ drifts.

$$N_D^+ \cdot w_n = N_A^- \cdot w_p$$

$$\frac{dE_F}{dx} = 0$$

06/02/2024 PN Junction diode



At eqm, V = 0, $J = J_p + J_n$

$J_p = 0 \quad J_n = 0$

Also, E_F = CONSTANT at eqm $\left(\frac{dE_F}{dx} = 0\right)$

$$N_A^- W_p = N_D^+ w_n$$

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

$$= q\mu_n \left(n\mathcal{E} + \frac{k_B T}{q} \frac{\partial n}{\partial x} \right) \qquad n = N_c' e^{-\left(\frac{E_c - E_F}{k_B T}\right)}$$

$$\frac{\partial n}{\partial x} = \frac{N_c'}{k_B T} e^{-\left(\frac{E_c' - E_F}{k_B T}\right)} \left[\frac{\partial E_F}{\partial x} - \frac{\partial E_c}{\partial x} \right]$$

$q\mathcal{E}$ (how?)

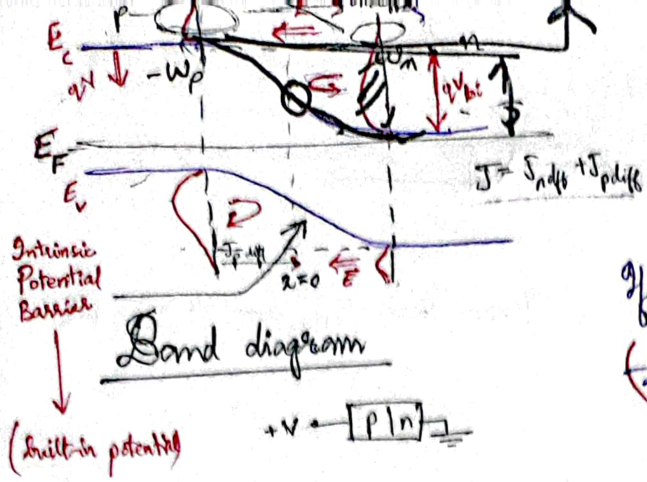
$$\Rightarrow \frac{\partial n}{\partial x} = \frac{n}{k_B T} \left(\frac{\partial E_F}{\partial x} - q\mathcal{E} \right)$$

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

Effective electric field

$$\mathcal{E} = \frac{1}{q} \left(\frac{\partial E_f}{\partial x} \right)$$

∴ At eqm $\frac{\partial E_f}{\partial x} = 0$, Fermi level lines up at the eqm



Band diagram

Forward bias

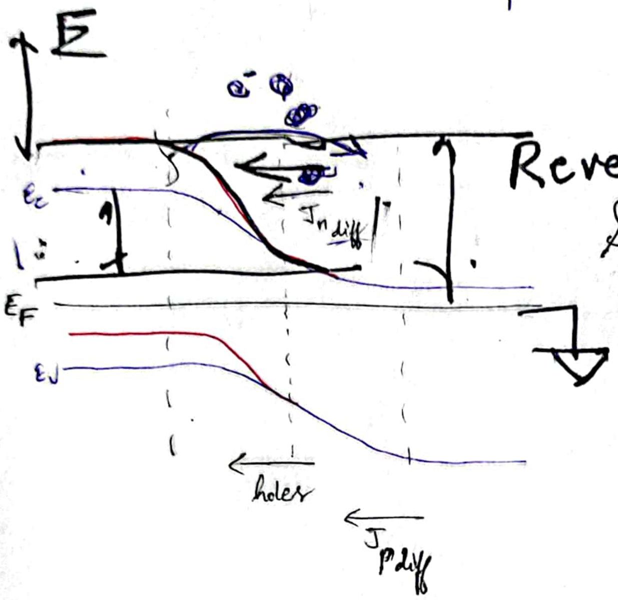
$|W_n| + |W_p| =$ depletion width

If I apply a bias of V, then energy ~~(built-in potential)~~ reduces to $q(V_{bi} - V)$.

What if I apply -ve bias at p-side? [Reverse bias]

-V [p|n]

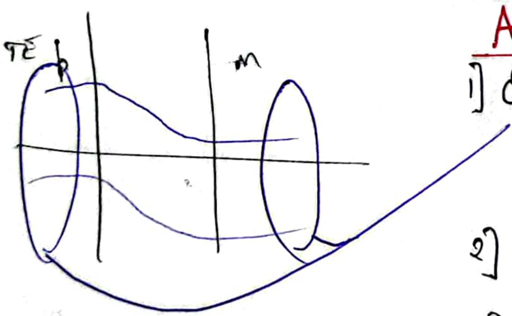
Now the levels are pulled up! → Barrier has increased for the n-side, but it has helped e^-s in p-side.



Reverse Bias

Still, $J = J_{n\,diff} + J_{p\,diff}$ (-ve)

NOTE



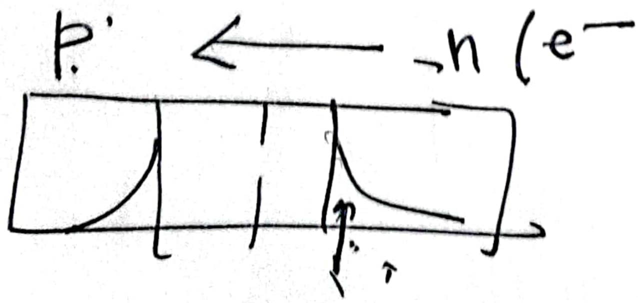
ASSUMPTIONS

1] Quasi-neutral region (far away from interface)
Here $\vec{E} \simeq 0$.

2] Abrupt junction

3] Boltzmann approximation is valid

4] Low-level injection



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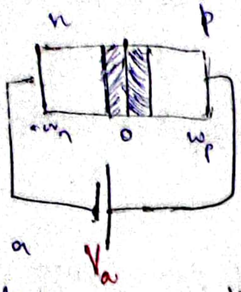
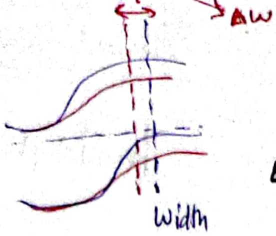
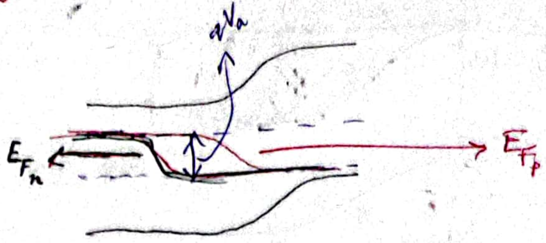


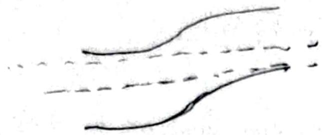




I apply a forward bias...

$W = W_n + W_p \downarrow$

Forward bias: E_{F_p} comes down by qV_a



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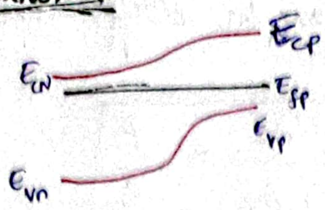
P-N Junction



At eqm, $V_a = 0$

$$n = N_c' e^{-\left(\frac{E_{cn}-E_{fn}}{k_B T}\right)} \qquad p = N_v' e^{-\left(\frac{E_{fp}-E_{vp}}{k_B T}\right)}$$

$$= N_D$$

$$E_{cn} - E_{fn} = K_B T \ln\left(\frac{N_c'}{N_D}\right) \qquad E_{fp} - E_{vp} = K_B T \ln\left(\frac{N_v'}{N_A}\right)$$

~~(How?)~~ $$V_{bi} \simeq \frac{K_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right) \qquad V_{bi} = E_g - \left(E_{cn} \cdot E_{fn} + E_{fp} - E_{vp}\right)$$

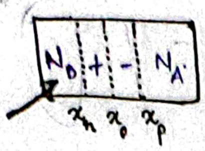
$$qV_{bi} = E_g - K_B T\left(\ln\left(\frac{N_c'}{N_D}\right) + \ln\left(\frac{N_v'}{N_A}\right)\right) = E_g - K_B T \ln\left(\frac{N_c' N_v'}{N_D N_A}\right)$$

using $n_i = \sqrt{\underline{\underline{N_c' N_v'}}}\, e^{\frac{-E_g}{2k_B T}}$

$$= E_g - K_B T \ln\left(\frac{n_i^2}{N_A N_D} e^{\frac{E_g}{K_B T}}\right)$$

$$= E_g - K_B T \ln\left(\frac{n_i^2}{N_A N_D}\right) - \cancel{K_B T} \cdot \frac{E_g}{\cancel{K_B T}}$$

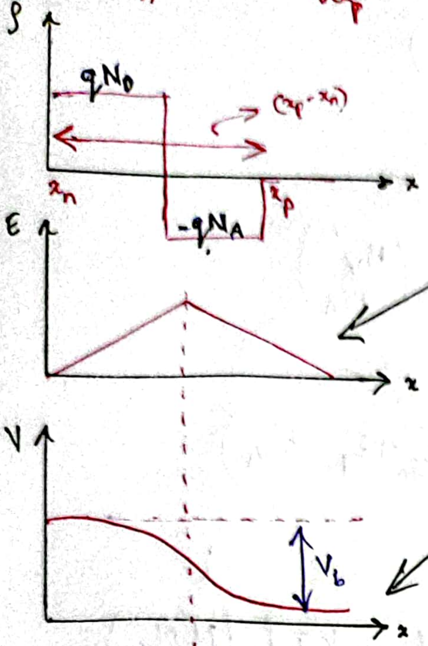
$$\Rightarrow \boxed{V_{bi} = \frac{K_B T}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}$$



Gauss' law in Differential form:

$$\boxed{\frac{\partial E}{\partial x} = \frac{\rho}{\epsilon_0}}$$

$$N_D \underbrace{(x_0 - x_n)}_{w_n} = N_A \underbrace{(x_p - x_0)}_{w_p}$$



$$E = \frac{qN_D}{\epsilon_0}(x - x_n)$$

$$\therefore\ V(x) = \frac{-qN_D}{\epsilon_0}(x - x_n)^2$$

$$W \propto V_{bi}$$

$$\underset{(x_p - x_n)}{W = W_n + W_p} = \left(\frac{2\epsilon V_{bi}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)\right)^{1/2}$$

Okay, consider a doping case like ...

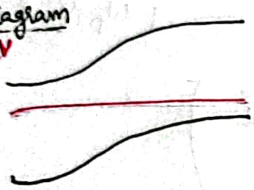
$N_D^+ \gg N_A^-$ * Holes moving from p to n (p → heavily doped)

$\Downarrow$

$w_n \ll w_p$ * Depletion region always penetrates into the lower doped region

Band diagram

$= -qV$



$$n_{no} = N_c' e^{-\left(\frac{E_{cn} - E_{Fn}}{k_B T}\right)}$$

$$n_{po} = N_c e^{-\left(\frac{E_{cp} - E_{Fp}}{k_B T}\right)}$$

$$= [\quad] \times$$

$$\times e^{E_{cn}/k_BT} \times e^{-E_{cn}/k_BT}$$

$$\therefore\ n_{po} = N_c \cdot e^{-\left(\frac{E_{cn} - E_{Fp}}{k_B T}\right)} e^{\left(\frac{\overbrace{-E_{cp} + E_{cn}}^{qV_{bi}}}{k_B T}\right)}$$

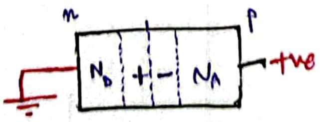
at eq^m, $E_{Fp} = E_{Fn}$

$$\Rightarrow \boxed{n_{po} = \overset{N_D^+}{n_{no}}\, e^{-\left(\frac{|qV_{bi}|}{k_B T}\right)}}$$

$q\mathcal{E}$

n_{po} ↓ minority carrier on p-side

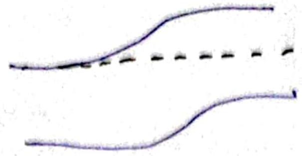
n_{no} ↓ majority carrier on n-side



* We found out the minority carrier concentration because we want to look into diffusion.

Now, what happens if we apply a forward bias?

If $V_a > 0$, $\Rightarrow$



$V_{bi} \to V_{bi} - V_a$

[Splitting in Fermi-level = V_a]

$$p_n = p_{p0}\, e^{\left(\frac{-|q(V_{bi}-V_a)|}{k_B T}\right)}$$

$$n_p = n_{n0}\, e^{\left(\frac{-|q(V_{bi}-V_a)|}{k_B T}\right)}$$

$$\Delta n_p (x = x_p) = n_p - n_{p0} = n_{n0}\, e^{\left(\frac{-q(V_{bi}-V_a)}{k_B T}\right)} - n_{n0}\, e^{\left(\frac{-qV_{bi}}{k_B T}\right)}$$

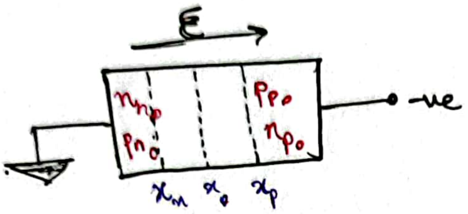
$$= n_{n0}\, e^{\frac{-qV_{bi}}{k_B T}} \left(e^{\frac{qV_a}{k_B T}} - 1\right)$$

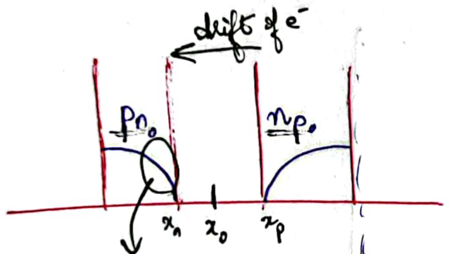
Δn_p: excess carriers that have come due to bias

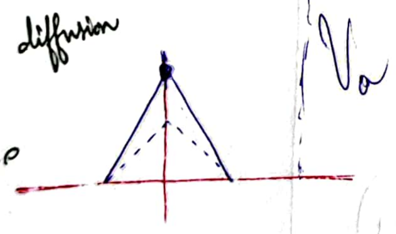
n_p: at bias

n_{p0}: at eqm

15/02/2024

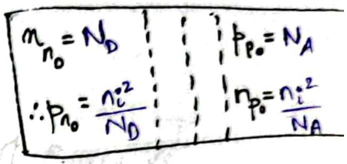






$\nabla \cdot J = -\cancel{\frac{\partial \rho}{\partial t}} \to 0$

$\therefore J \to$ continuous

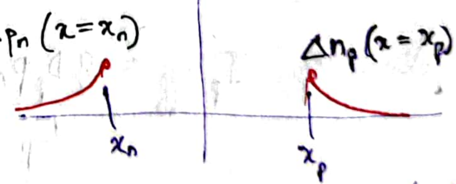


When I apply forward bias,

e- diffuse from n to p

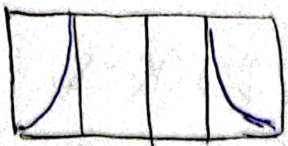
$n \xrightarrow{e^-} p$

Under FB



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

17/02/2024



$-x_n \quad x_0 \quad x_p$

$$\frac{\partial^2 \Delta n}{\partial x^2} = \frac{\Delta n_p}{L_n^2}$$

$$\Rightarrow \Delta n = Ae^{-x/L_n} + \cancel{Be^{x/L_n}}^{\,0}$$

decaying as $x=0$ to $x=L$

$$\therefore \; = Ae^{-x/L_n} = \Delta n_p(x=0)\, e^{-x/L_n}$$

$$\Delta n_p(x > x_p) = \Delta n_p\big|_{x=x_p} e^{-\cancel{x/L_n}\,(x-x_p)/L_n}$$

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

"excess carriers"

At steady state, $\frac{\partial}{\partial t}(\Delta n_p) = 0$

$$\therefore \; \underbrace{\Delta n_p}_{\text{in quasi-neutral region}} = \Delta n_p(x = x_p)\, e^{-(x-x_p)/L_n} \quad ; \; L_n = \sqrt{D_n \tau_n}$$

At $x = x_p$, $\quad J_{n,\,diff} = ?$

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

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

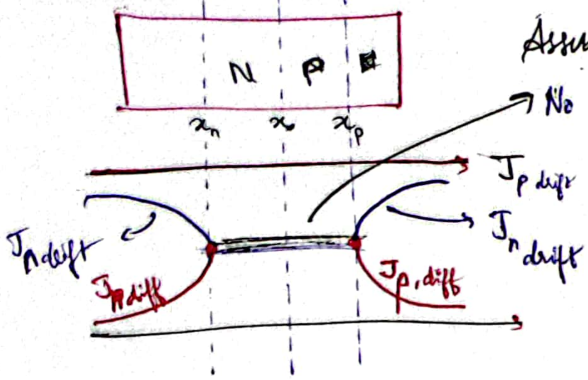
$$= \frac{qD_n}{L_n} n_{p_0} \left(e^{\frac{qV_a}{KT}} - 1\right)$$

Similarly, $J_{p\,diff} = \frac{qD_p p_{n_0}}{L_p}\left(e^{\frac{qV_a}{KT}} - 1\right)$.

$$\therefore \; J = q\left(\frac{D_n n_{p_0}}{L_n} + \frac{D_p p_{n_0}}{L_p}\right)\left(e^{\frac{qV_a}{KT}} - 1\right)$$

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

↪ Shockley diode eqn.



Assumptn:

No generatn / recombn here! $\because$ rate (flow of e^- at x_n)

= rate (flow of e^- at x_p)

$\because$ current is equal

(constant line)

(plot is so bcoz

J is const

& J_{diff} is decaying)

$J_{p\,diff}$ need not be symmetric to

$J_{n\,diff}$; depends on parameters