EE 207: Electronic Devices

→ Web resources : ECE 606 by Prof. Alam
@ Nanohub : "Semiconductor Devices"

Nanohub.org

→ Crystal viewer tool.

→ Official text:

* Advanced semiconductor device fundamen.
* Semiconductor device fundamentals.

Both by Robert Pierret, Purdue univ.

Instructor : Prof. Pradeep. R. Nair

Grading Policy

Endsem	40 - 50 %
Midsem	25 %
Quizzes	20 %

L-I

EE 207

PAGE No. DATE / /

Lecture: Crystal properties and growth of semiconductors

Classification of Solids

Poly crystalline | Amorphous oxides | Crystalline

→ MOSFET Involves all three.

Solid State

→ Unit cells

	Atoms / unit cell
→ S.C	1
→ B.c.c	2
→ F.c.c	4

→ Tetrahedral Diamond Structure is in fact F.C.C, with some voids occupied

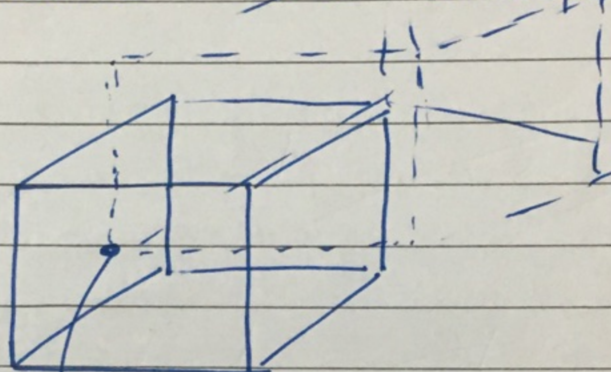
• ~~Visso~~ Visually.

Crystal Structure

→ Crystal ⇒ Lattice + Basis

→ Our Interest → Si

Si Structure → 2 Interpenetrating FCC



$\left(\frac{a}{4}, \frac{a}{4}, \frac{a}{4}\right)$

Corner of Shifted Cube

→ Alternatively it is like void occupying JEE cases.

→ Atoms per unit cell for Si special unit cells = 8

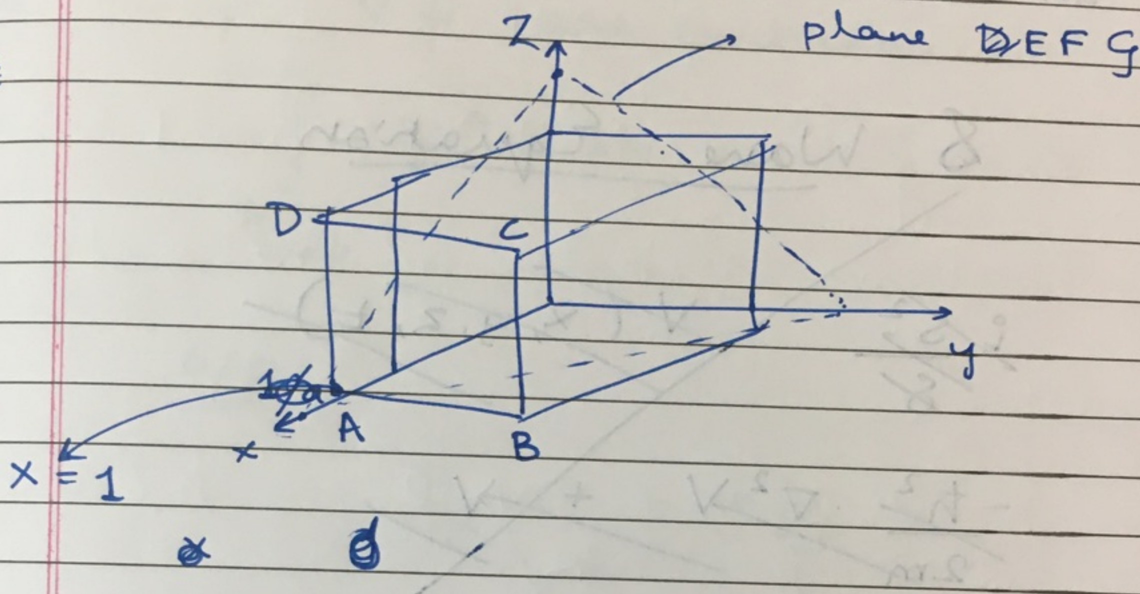
$$4\left(\frac{1}{8} \times 8 + 6 \times \frac{1}{2}\right) + 4 \text{ atoms}$$

Completely Inside the orignal box but from the shifted FCC

Miller Indices

→ For planes

ex



For planes ~~ABCD~~

	ABCD	EFG
x	1	3
y	∞	2
z	∞	1

Inverse (Coefficients of the correspon. planes)

	ABCD	EFG	
x	1	$1/3$	→ 2
y	0	$1/2$	→ 3
z	0	1	→ 6

Family of planes

$$ax + by + cz = d$$

(1 0 0) → ~~For~~ Single plane

{1 0 0} → Family of // planes

Similarly (2, 3, 6) and {2, 3, 6}

DATE / /

→ The atom Surface Density depend on how we cut it.

δ Wave Equation

$$\cancel{\frac{i\delta^2}{\delta} \quad V(x, y, z, t)}$$

$$\cancel{-\frac{\hbar^2}{2m}\nabla^2 V + V}$$

$$\cancel{\psi(x, y, z)}$$

→ Wave Equation Recall

$$\psi(x, y, z, t) \qquad V(x, y, z)$$

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = \hbar i \frac{\delta}{\delta t}\psi$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V\right) = \hat{H}, \quad \hbar i \frac{\delta}{\delta t} = \hat{E}$$

$$\hat{H}\psi = \hat{E}\psi$$

Properties

→ $\psi, \nabla\psi$ are continous

→ $\int_{\text{All space}} \psi^* \psi \, dv = 1$

→ O/P

$$P_x = \frac{\hbar}{i} \frac{\delta}{\delta x}$$

$$E = i\hbar \frac{\delta}{\delta t}$$

$$\langle \alpha \rangle = \int_{-\infty}^{\infty} \psi^* \alpha \psi \, dx$$

→ Solution to ψ for Crystals.

$$i\hbar \frac{\delta}{\delta t} \psi = \hat{E} \psi \qquad \psi \propto e^{\frac{-iEt}{\hbar}}$$

Let, $\psi = \psi(x)\,\phi(t)$

$$\langle E \rangle = E = \int \psi^* \left(\frac{-\hbar}{i} \frac{\delta \psi}{\delta x} \right) dV$$

Lecture - 4

Outline

a) Examples of SWE

b) Kronig Penny Model (Band Struct

c) Electrons + holes, in the model.

SWE

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = \hbar i \frac{\delta\psi}{\delta t}$$

Time Independent

constant.

$$\langle E\rangle = E = \int \psi^* \hbar i \frac{\delta\psi}{\delta t}\, dV$$

$$\hbar i \frac{\delta\psi}{\delta t} = E\psi$$

$$\Rightarrow \quad \psi = \psi(x,y,z)\, e^{-\frac{iEt}{\hbar}}$$

$\phi(t)$

~~ħiδ~~ iz

→ Take $V = 0$

$$\frac{\hbar^2}{2m} \nabla^2 \psi(x) + E\psi = 0$$

or

$$\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + E\psi = 0$$

$$\frac{d^2\psi}{dx^2} + k^2\psi = 0$$

↓

Solution

where $k^2 = \frac{2mE}{\hbar^2}$

$$\Rightarrow \psi_{(x)} = \left(Ae^{ikx} + Be^{-ikx}\right)$$

$$\phi(t) = e^{\frac{-iEt}{\hbar}}$$

$$\psi(x, t) = \left(Ae^{ikx} + Be^{-ikx}\right) e^{\frac{-iEt}{\hbar}}$$

→ Boundry Conditions

$\psi, \frac{d\psi}{dx}$ are continuous.

$$\int \psi^* \psi \, dv = 1$$

Momentum

$$\hat{p} = -\hbar i \frac{d}{dx}$$

$$\Rightarrow \cancel{p = \psi}$$

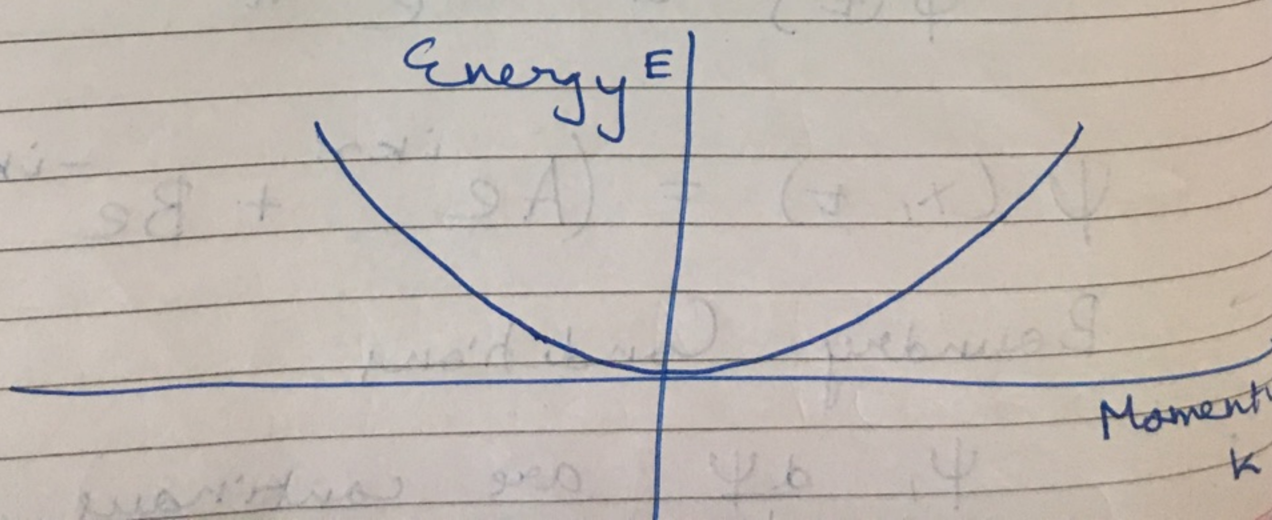
$$p_\psi = \hbar k$$

↓

De-Broglie Idea.

$$p = \hbar k$$

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



→ ~~Cases:~~ P

→ Particle in an ~~finite~~ Infinite Potential well.

i.e $V \to \infty$ x

$V = 0$

$0 < x < a$

$V \to \infty$

otherwise

Spatial part

$\psi(0) = 0$ $\psi(a) = 0$

Boundry Condition

$$\frac{\hbar^2}{2m}\frac{d^2\psi}{dx^2} + \cancel{k}E\psi = 0$$

$0 < x < a$

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

$$\psi(x) = A\sin(kx) + B\cos(kx)$$

$0 < x < a$

$x = 0, \psi = 0 \Rightarrow B = 0$

$x = a, \psi = 0 \Rightarrow A\sin(ka) = 0$

$ka = n\pi$

$ka = n\pi \qquad n \in I / \{0\}$

$\qquad\qquad \text{or } n \in N$ Depen

$\Rightarrow \quad k = \dfrac{n\pi}{a}$

$$\psi(x) = A \sin\left(\frac{n\pi x}{a}\right)$$

Normalisation

$$A^2 \int_0^a \sin^2\left(\frac{n\pi x}{a}\right) dx$$

$$\frac{A^2}{2} \int_0^a \left(1 - \cos\left(\frac{2n\pi x}{a}\right)\right) dx = 1$$

$$\Rightarrow \quad \frac{A^2 a}{2} = 1$$

$$\cancel{A^2 =} \quad A = \sqrt{\frac{2}{a}}$$

PAGE No.
DATE / /

→ Here $+n$ and $-n$ are mirror images of each other.

$$\hat{p} = -i\hbar \frac{d}{dx}$$

$$\hat{p}\psi = p\psi$$

$$= -i\hbar \cancel{\times \sqrt{\frac{2}{a}} \cos\left(\frac{n\pi x}{a}\right) \times \frac{n\pi}{a} k x}$$

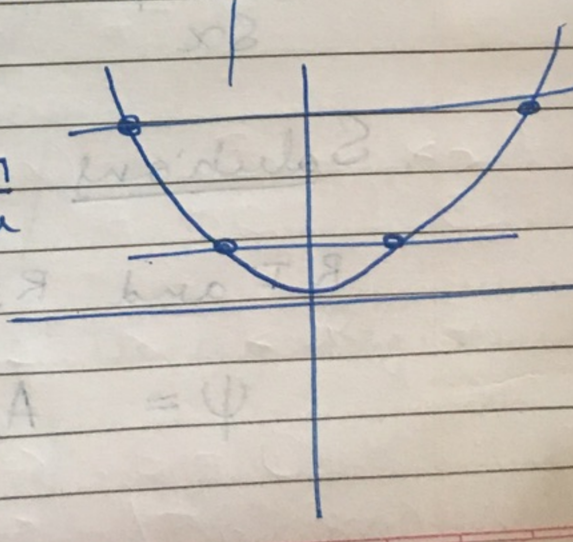
$$\langle p \rangle = \frac{2}{a}\int_0^a \sin\left(\frac{n\pi x}{a}\right) \times -i\hbar \cos\left(\frac{n\pi x}{a}\right) \times k$$

$$\Rightarrow \langle p \rangle = 0$$

Quantisation, certain values.

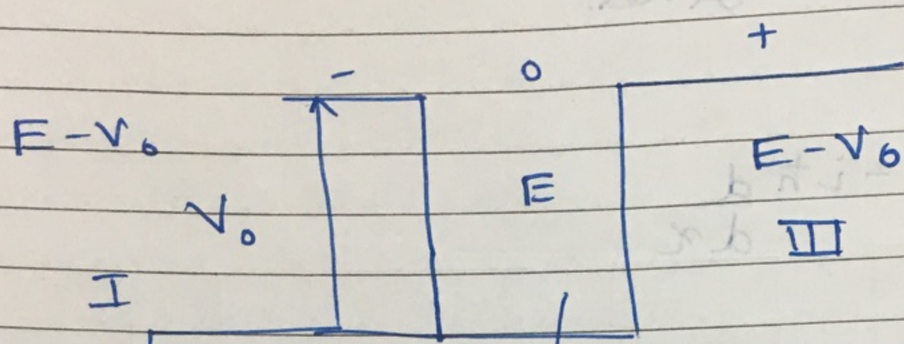
$$E = \frac{\hbar^2 \cancel{k^2} a^2 n^2 \pi^2}{2ma^2}$$

$$k = \frac{n\pi}{a}$$



$$n^2 \frac{\hbar^2 \pi^2}{2ma^2}$$

→ Finite Potential Well.



$k = \sqrt{\dfrac{2m(E-V_0)}{\hbar}}$ in I and III

$k = \sqrt{\dfrac{2mE}{\hbar}}$

→ Boundary conditions

$$\psi(0^-) = \psi(0^+)$$

$$\frac{\delta}{\delta x}\psi(0^-) = \frac{\delta}{\delta x}\psi(0^+)$$

$$\psi(a^-) = \psi(a^+)$$

$$\frac{\delta}{\delta x}\psi(a^-) = \frac{\delta}{\delta x}\psi(a^+)$$

Solutions

R I and R III

$$\psi = A_0 \sin kx + B_0 \cos kx$$

$x \in (0, a)$

$$\psi = Ae^{-\alpha x} + Be^{\alpha x}$$

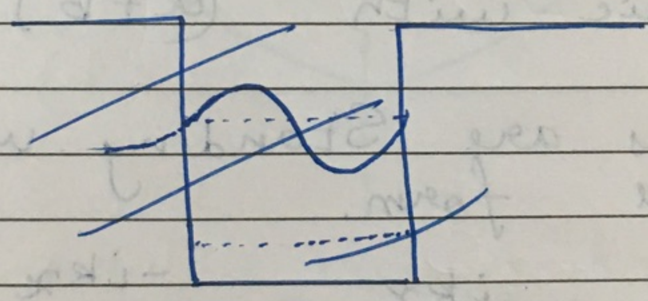
<u>Rewriting</u>

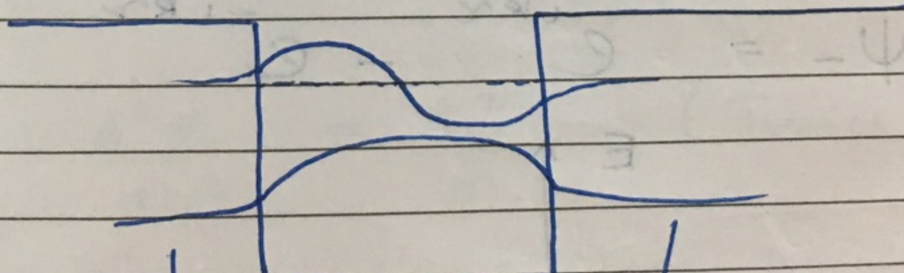
$$\psi_- = A_- e^{-\alpha x} + B_- e^{\alpha x}$$

$$\psi_0 = A_0 \sin kx + B_0 \cos kx$$

$$\psi_+ = A_+ e^{-\alpha x} + A_+ e^{\alpha x}$$

i.e the wavefunction "leaks" into the classically forbidden region

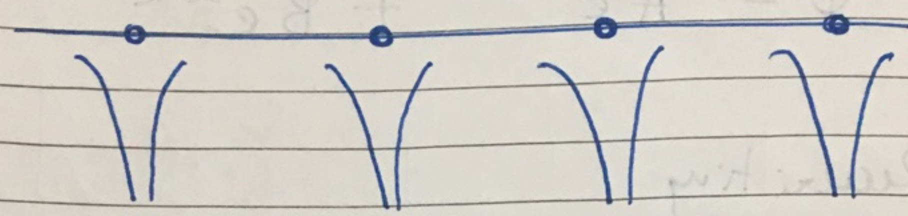


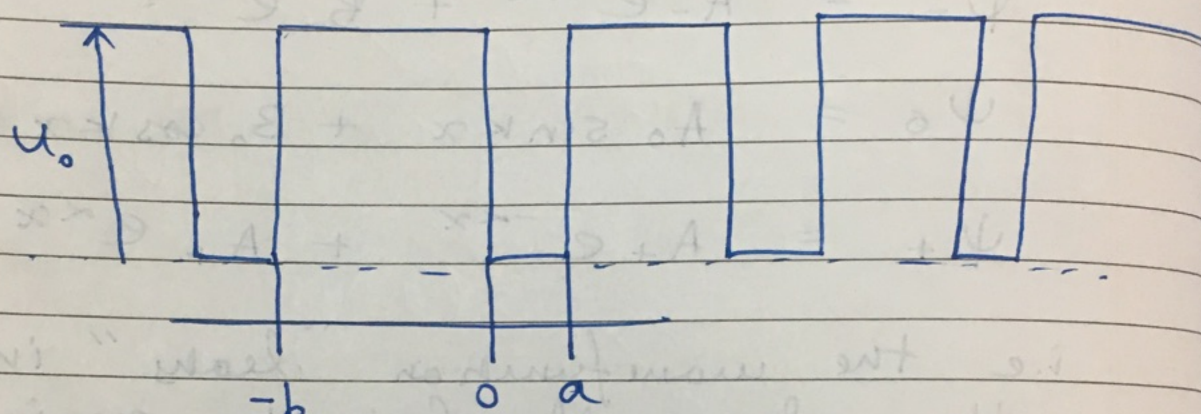


Exponential Decay Region

QM Tunneling

QM Model for Crystals



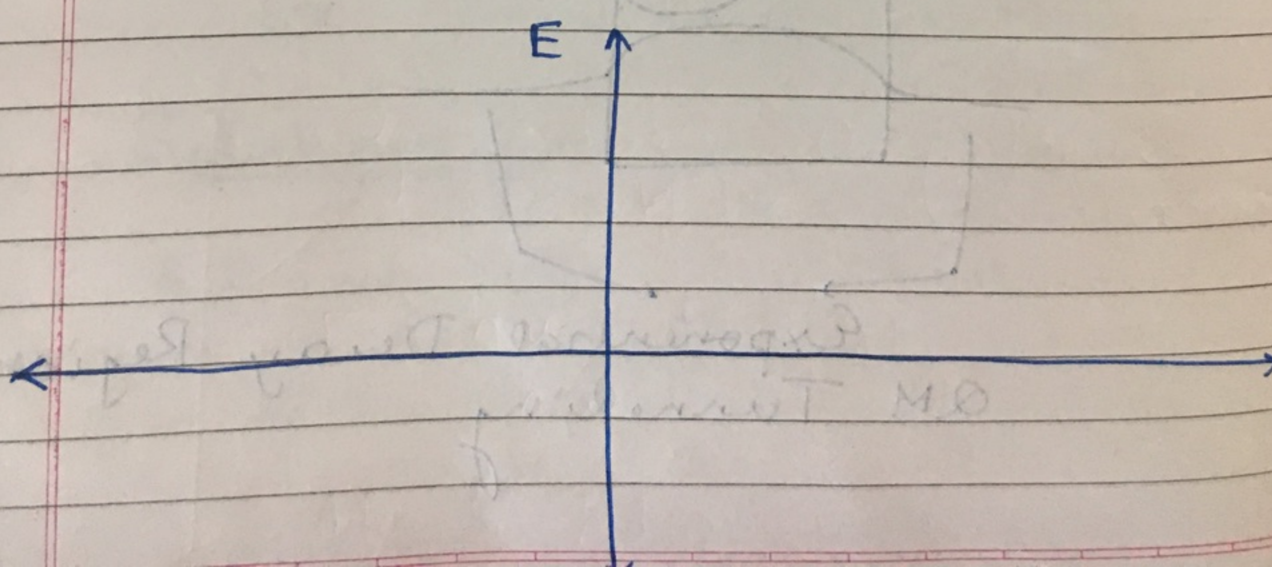


→ Periodic with $(a+b)$

Solutions are Standing waves of the form.

$$\psi_+ = e^{ikx} + e^{-ikx}$$

$$\psi_- = e^{ikx} - e^{-ikx}$$

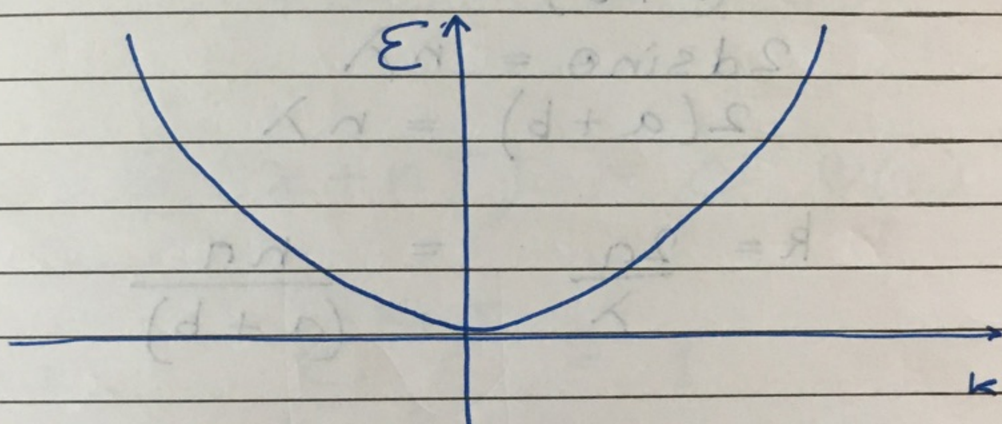


→ Important points

• Travelling waves reflect and superimpose to form Standing waves.

Parameters in Crystals

→ Free particle.

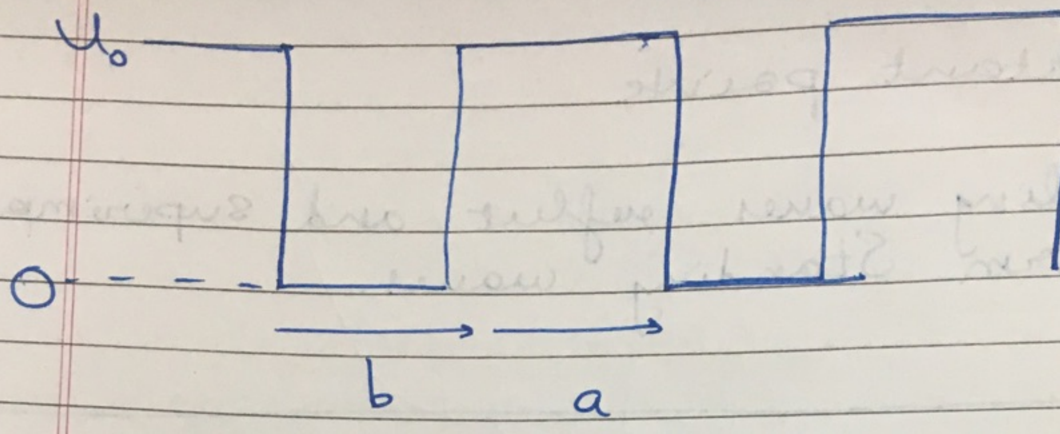


$$\cancel{m} \quad \varepsilon = \frac{\hbar^2 k^2}{2m}$$

$$\frac{d^2 \varepsilon}{dk^2} = \frac{\hbar^2}{m} \quad \text{(Twice Differential)}$$

• Ingriedients for $\psi_{crystal}$

1) Free particle $\varepsilon - k$
2) Particle in a box
3) Bragg Reflection.



Bragg Reflection

$$(a+b)$$
$$2d\sin\theta = n\lambda$$
$$2(a+b) = n\lambda$$

$$k = \frac{2\pi}{\lambda} = \frac{n\pi}{(a+b)}$$

→ Only Standing wave solutions are allowed.

$$v_p = \frac{\omega}{k}$$

$$v_g = \frac{d\omega}{dk} = 0 \quad \left(\text{for Standing waves}\right)$$

$$E = h\nu$$
$$= \hbar\omega$$

$$\frac{dE}{dk} = \hbar\frac{d\omega}{dk}$$

Periodic Boundary conditions

$$T = (a+b)$$

$$\psi(x+T) = e^{ikT}\psi(x)$$

~~Also~~

$$\cancel{\psi(x+n}$$

Let

$$\psi(x+T) = c\,\psi(x)$$

$$\psi(x+nT) = c^n\,\psi(x)$$

i.e $$e^{iknT} = 1$$

$$\Rightarrow \quad knT = 2\pi$$

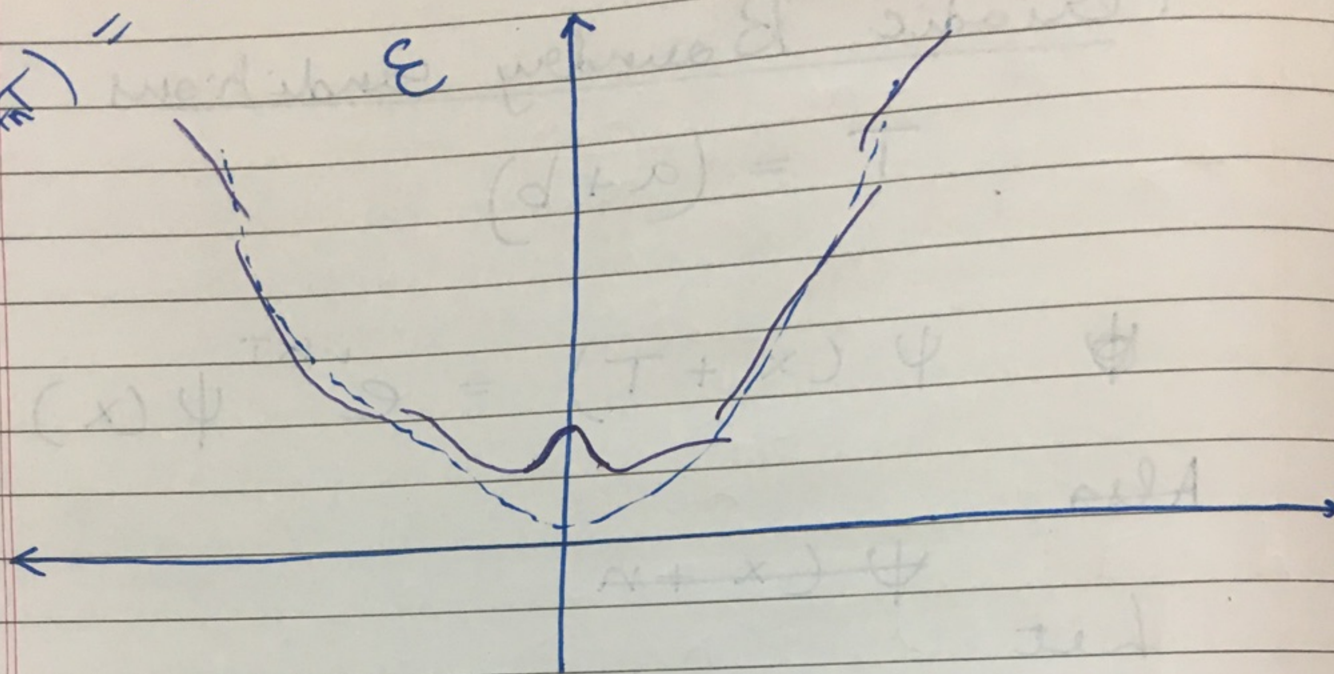
$$\frac{2\pi}{n} \qquad \cancel{e^{i\frac{2\pi}{n}}} \qquad e^{ik\frac{2\pi}{kn}}$$

$$c = e^{i\frac{2\pi kn}{N}}$$

$$\cancel{k = 0}$$

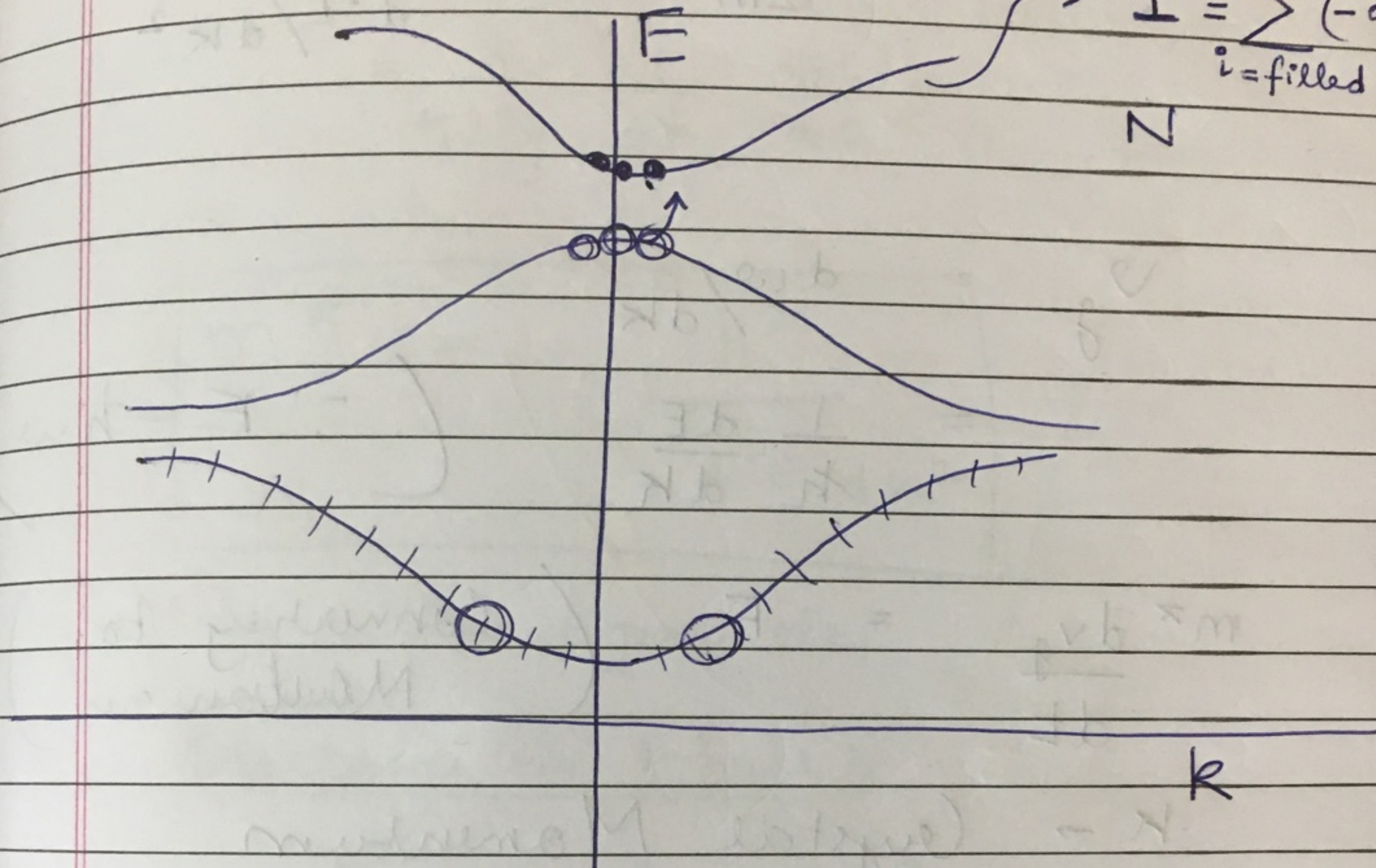
$C^N = e^{2\pi n} = 1$

$\psi(x + nT) = C_n \psi(x)$



Expression for Current

$$I = \sum_{i=\text{filled}}^{N} (-q) v_i$$



$$I = -q \sum_{i=1}^{N} v_i = 0 \longrightarrow (1)$$

from (1)

$$I = q \sum_{i=1}^{N} v_i + (-q) \sum_{i \text{ filled}} v_i$$

$$= \boxed{q \sum_{i \text{ vacant}} v_i}$$

Effective Mass

$$\mathcal{E} = \frac{\hbar^2 k^2}{2m} \qquad m = \frac{\hbar^2}{d^2E/dk^2}$$

$$v_g = d\omega/dk$$

$$= \frac{1}{\hbar}\frac{dE}{dk} \qquad \left(\because E = \hbar\omega\right)$$

$$m^* \frac{dv_g}{dt} = F \qquad \left(\text{Connecting to Newtonian}\right)$$

$k \rightarrow$ Crystal Momentum

$$\frac{dv_g}{dt} = \frac{1}{\hbar}\frac{d^2E}{dk^2}\frac{dk}{dt}$$

$$\frac{dv_g}{dt} = \underbrace{\frac{1}{\hbar^2}\frac{d^2E}{dk^2}}\ \underbrace{\frac{d(\hbar k)}{dt}}_{\text{Dim. of force}}$$

$$dE = F dx$$

$$= F \cdot v_g\, dt$$

PAGE No.
DATE / /

$$F = \frac{1}{v_g}\frac{dE}{dt}$$

$$= \frac{1}{\hbar v_g}\frac{dE}{dk}\frac{d(\hbar k)}{dt}$$

$$\boxed{m^* = \frac{\hbar^2}{d^2E/dk^2}}$$

→ Holes : Quasi particles

• Electrons & Holes

$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)} \qquad v_g = \frac{d\omega}{dk}$$

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

here
k → Crystal P

$$m^* \frac{dv_g}{dt} = F$$

$E = \hbar\omega$

$\cancel{\frac{dv_g}{dt}} =$ $\quad v_g = \frac{d\omega}{dk} = \frac{1}{\hbar}\frac{dE}{dk}$

$$\frac{dv_g}{dt} = \frac{1}{\hbar^2}\frac{d^2E}{dk^2}\frac{d(\hbar k)}{dt} \rightarrow F$$

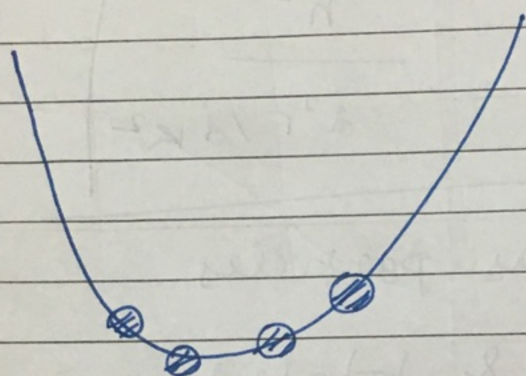
Lecture - 8

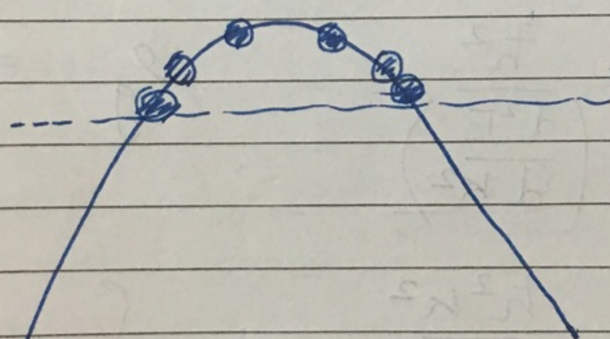
Electrons & Holes

★ Effective mass

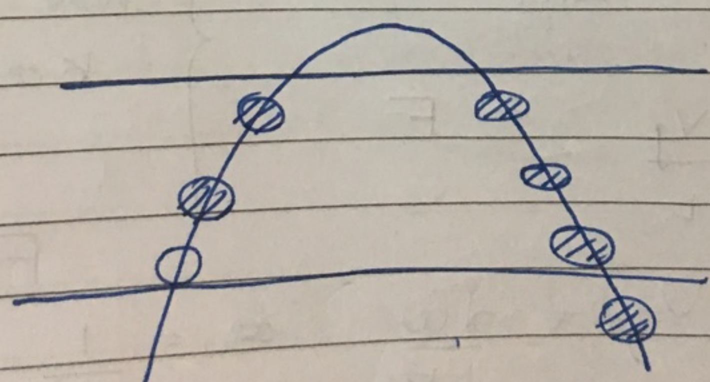
$$m^* = \frac{\hbar^2}{\frac{d^2E}{dK^2}}$$

★





Absence of field



Presence of field

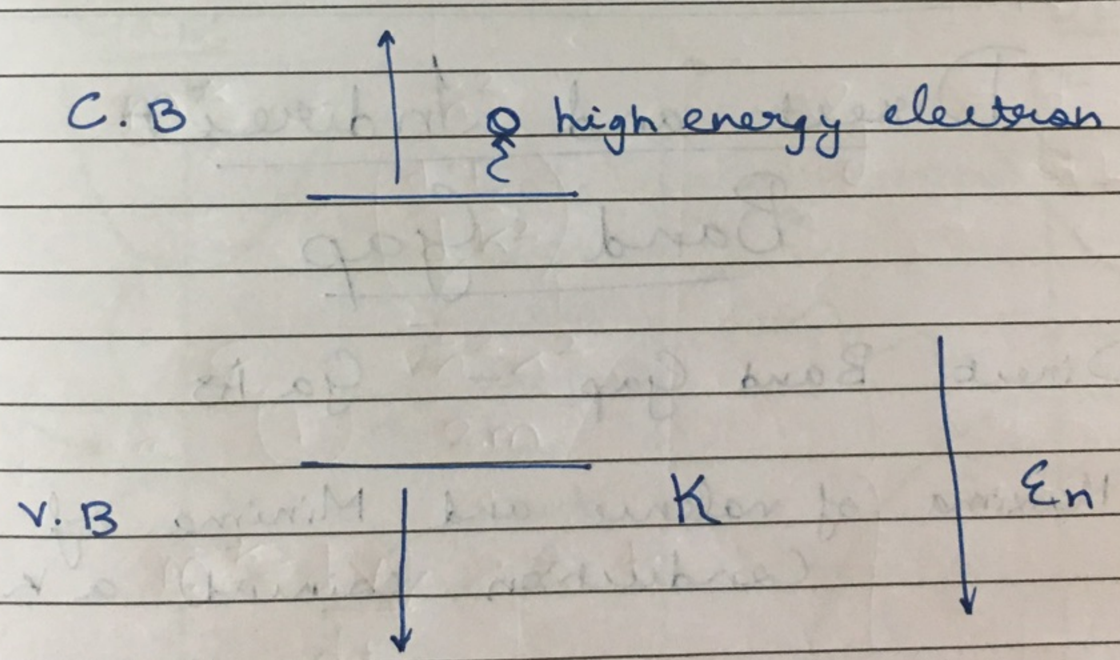
* Fully filled band – zero current
  Partially filled band – non zero current

Hole - Ideas

→ Absence of an electron.

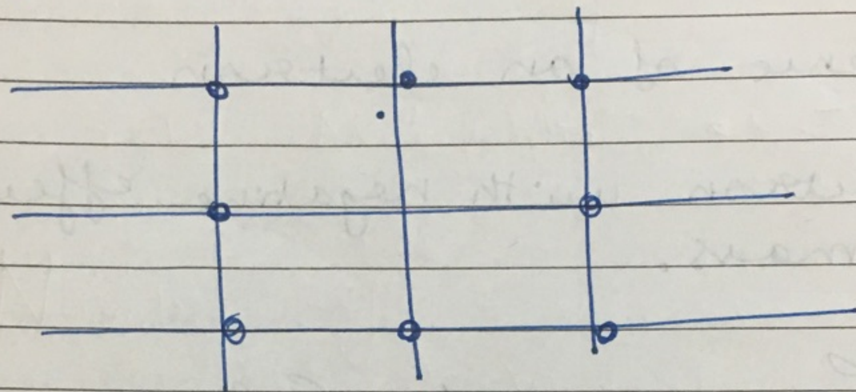
→ Electron with negative effective mass.

Energy of Electrons



→ Brillounzone : In b/w part of crystal.

→ Wigner - Satz



Direct and Indirect Band Gap

→ Direct Band Gap - Ga As

Maxima of valence and Minima of Conduction coincide a $k=0$

→ Indirect band Gap - Si, Ge

Don't coincide at all. Valence band maxima is always at $k=0$

** Quiz - Aug - 3rd week **

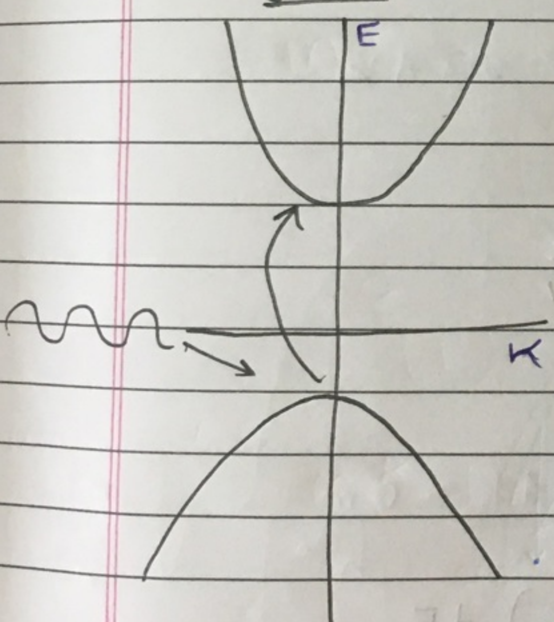
Lecture - ~~10~~ (9 actually)

→ We need · Switch
and · Amplifier

→ For Amplification, we need Dependant Sources.

Recap

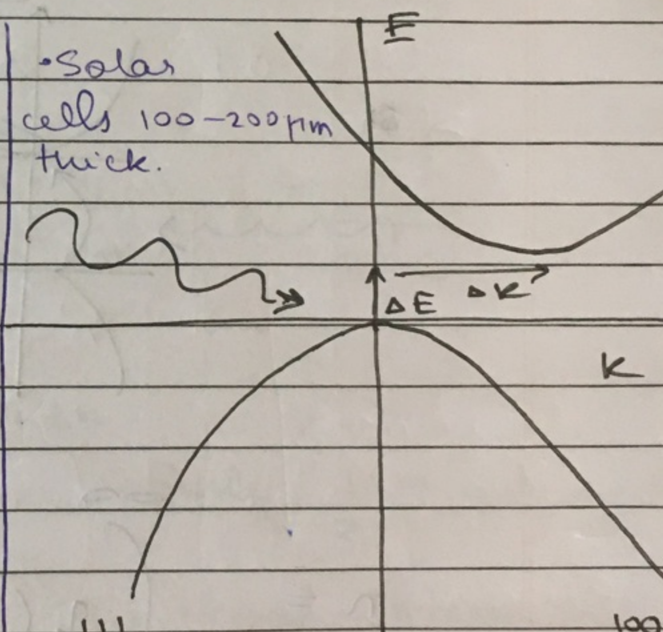
GaAs



· GaAs solar cells are just 1μm thick.

Si

· Solar cells 100–200μm thick.



Direct Band Gap.
ex → GaAs
~~Germanium,~~ ~~very~~ responsive to excitation.
→ Only Energy change no K change.

Indirect Band Gap. (Si/Ge)
→ Less responsive to excitation.
→ ΔE → Photon
ΔK → Momentum [from phonon] transfer
→ Hence excitation is a 3 body (↓ Prob.) collision.

→ Direct band Gap, Equienergy Surface are spherical

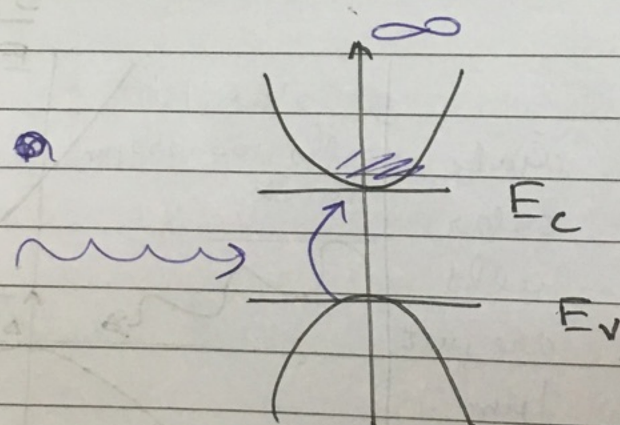
$$E = A(k_1^2 + k_2^2 + k_3^2)$$

→ Indirect, same thing

$$E = Ak_1^2 + B(k_2^2 + k_3^2)$$

→ Number of Electrons / Charge carriers in Conduction band

$I \propto nv$

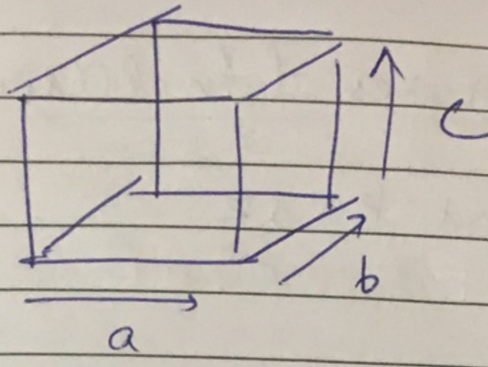


$$n = \int_{E_c}^{\infty} g(E)\, f(E)\, dE$$

$g(E)$ → Available Density of States

$f(E)$ → Probability of State being occupied

DATE / /



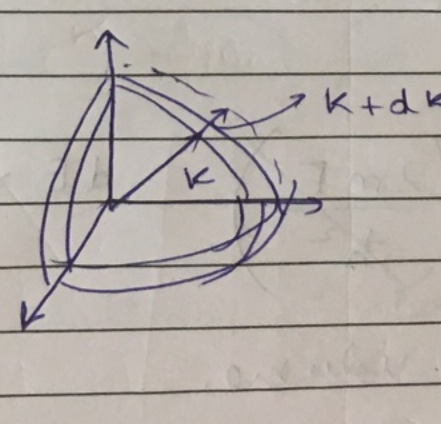
$$\psi(x) = A\sin(k_x x)\sin(k_y y)\sin(k_z z)$$

$$n\pi k_x = a$$

$$k_x = \frac{n_1\pi}{a} \quad k_y = \frac{n_2\pi}{b} \quad k_z = \frac{n_3\pi}{c}$$

⇒ Unit volume

$$\left(\frac{\pi}{a}\right)\left(\frac{\pi}{b}\right)\left(\frac{\pi}{c}\right) = \frac{\pi^3}{abc}$$



Only $\frac{1}{8}$th volume is of Interest

→ Solutions per unit volume in k-space

$$= \frac{abc}{\pi^3}$$

DATE / /

allowed states (Including spin)

b/w

k and $k+dk$

$$= (\cancel{4}\cancel{\pi} k^2 dk) \times \frac{1}{\cancel{8}\cancel{\pi}} \times \frac{abc}{\pi^{\cancel{3}}} \times \cancel{2}$$

$$= \frac{abc}{\pi^2} k^2 dk$$

→ Converting to E space.

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

$$dE = \frac{\hbar^2}{\cancel{2}m} (\cancel{2}k)\, dk$$

$$\sqrt{\frac{2mE}{\hbar^2}} = k$$

$$\frac{abc}{\pi^2} \times \cancel{\left(\frac{2mE}{\hbar^2}\right)} \quad dE \times \frac{m}{\hbar^2} \times \sqrt{\frac{2mE}{\hbar^2}}$$

Dividing by volume.

# of Allowed states b/w E & E+dE per unit volume.

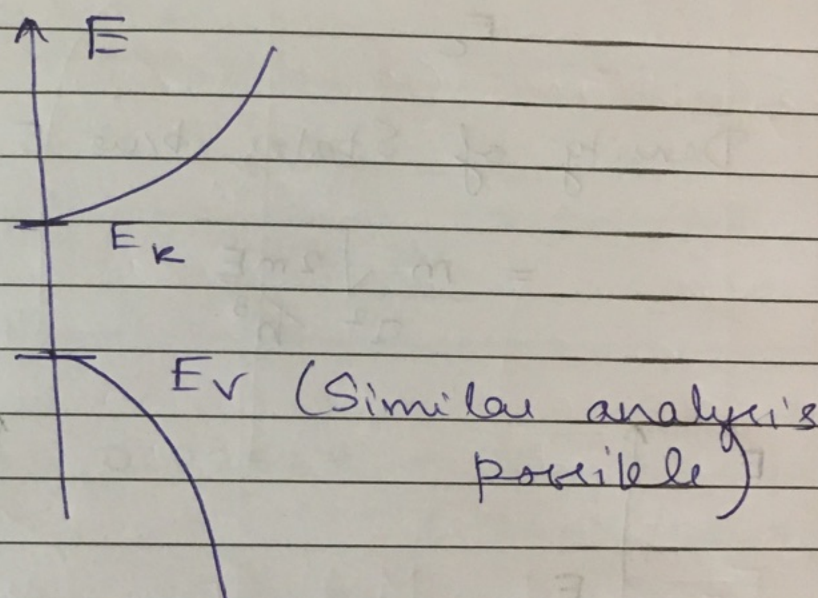
(Divide by abc)

for spherical, will be a diff. map for ellipsoid

$$= \frac{m\sqrt{2mE}}{\pi^2 \hbar^3} dE$$

$$= g(E)\, dE$$

m is not the same as effective mass of e^-/hole.



Assignment

1) $\sum N_i$ = const.
$\sum E_i N_i$ = total energy = const.

→ find $f(E)$ for fermion

2) Distribution of coin toss game.

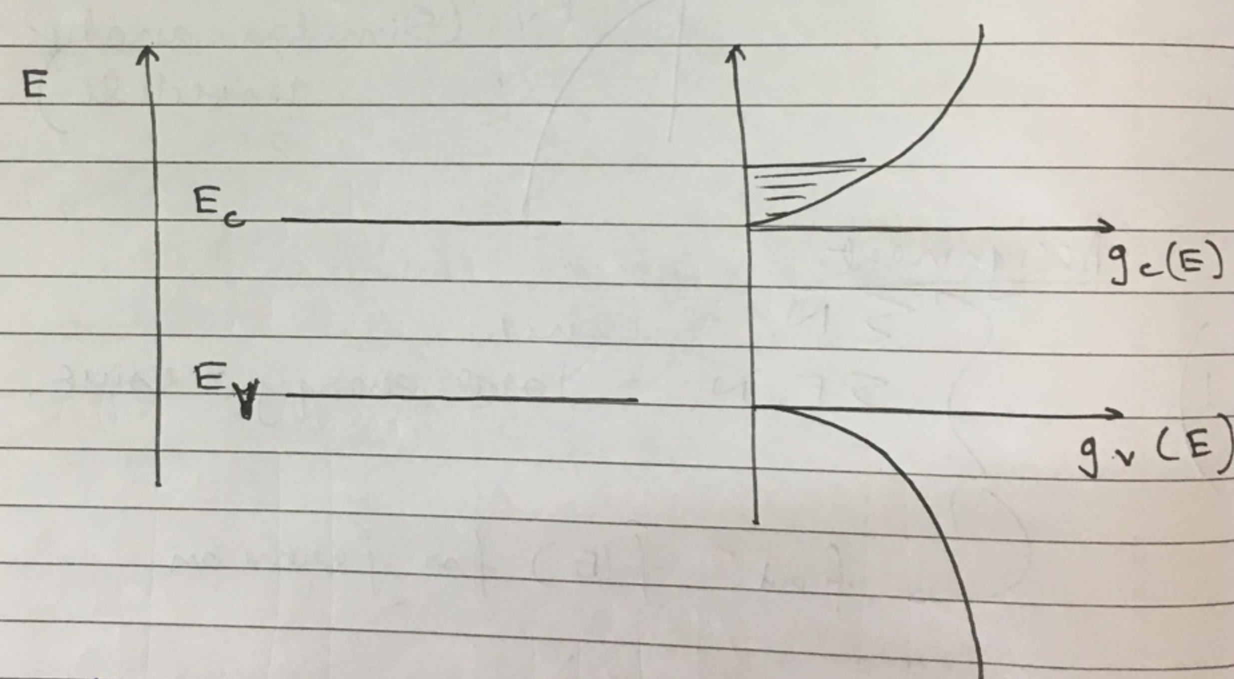
Lec. 10

Number of Charge car. in Cond. band

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

Density of States b/w E & E + dE

$$= \frac{m\sqrt{2mE}}{\pi^2 \hbar^3}$$



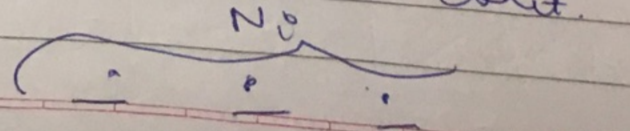
→ $\underline{\underline{f(E)}}$

Constraints

$$\sum N_i = \text{constant}$$

$$\sum E_i N_i = \text{Const.}$$

N_i



Si crystal

and.

$$f(E) = \frac{N_i}{N_{total}}$$ in a state of E

Derivation in Book

fD distribution

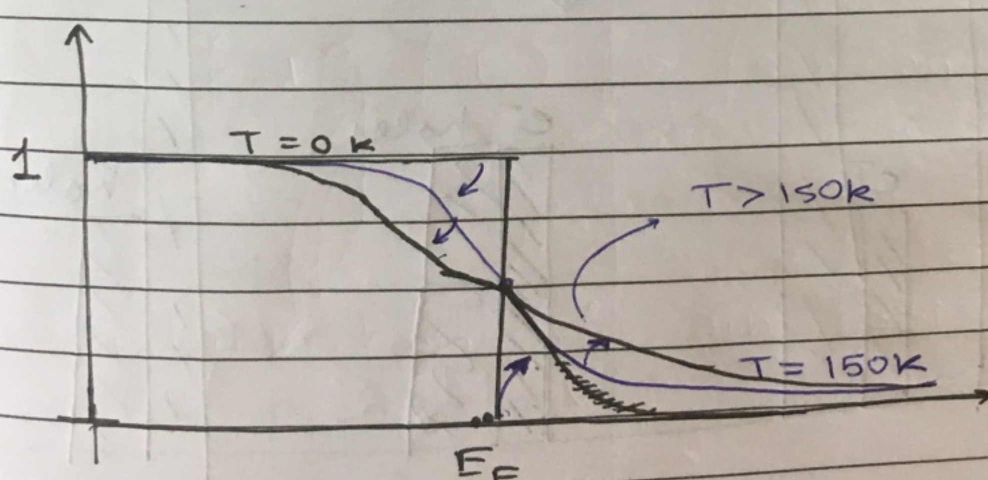
$$\boxed{f(E) = \frac{1}{1 + e^{(E-E_F)/KT}}}$$

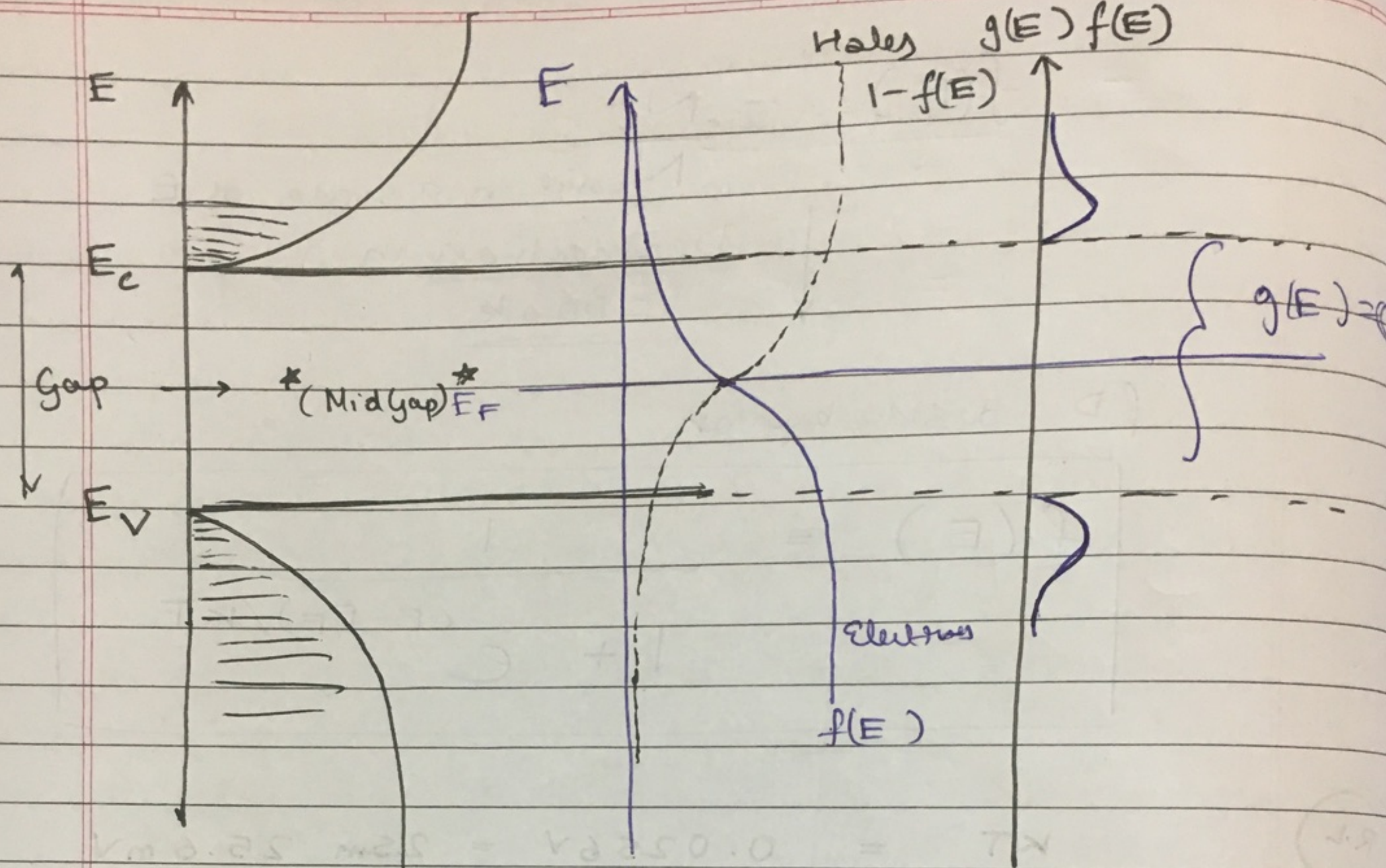
R.L

$$\frac{KT}{q} = 0.0256V = \cancel{25m}\ 25.6\,mV$$
(26mV / 25mV)

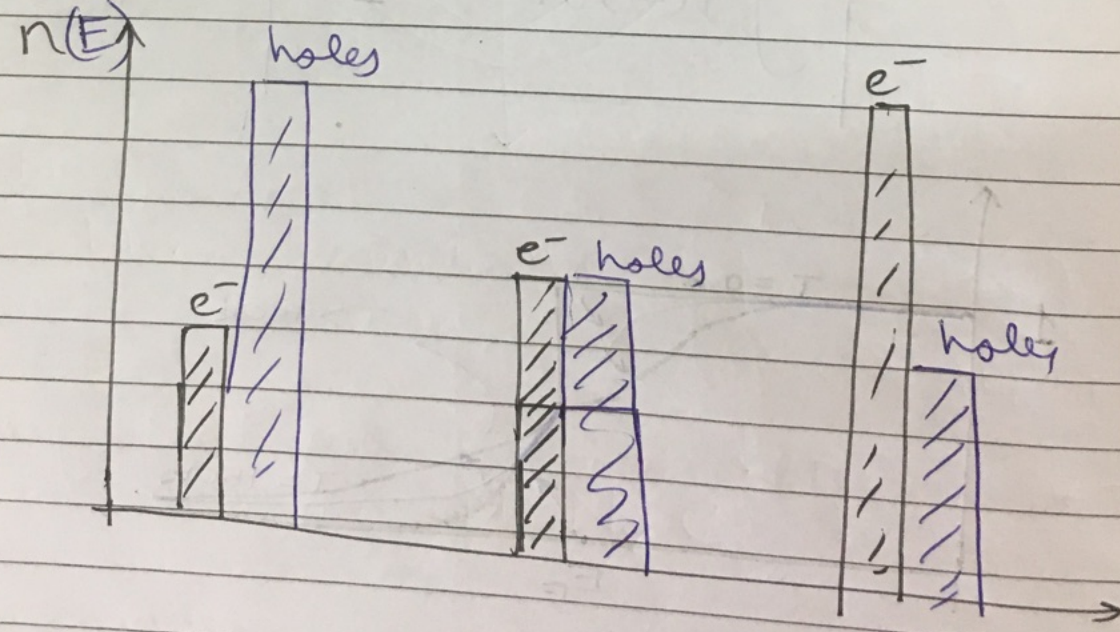
N.T

$$\boxed{\int f(E)\,dE \neq 1}$$ (Not Normalised)





→ E_F is at Mid Gap for pure crystals.
- Thermal effects always keep it at mid point.



Note: Same $\frac{3kT}{q}$ Approximation for E_F

Calculation of n(E)

$$n = \int_{E_c}^{\infty} \frac{m\sqrt{2m(E-E_c)}}{\pi^2 \hbar^3} e^{-(E-E_F)/kT} dE$$

$$= \frac{m\sqrt{2m}}{\pi^2\hbar^3} \int_{E_c}^{\infty} \sqrt{(E-E_c)}\, e^{-(E-E_F)/kT} dE$$

$$(\ )\int_{E_c}^{\infty} \sqrt{(E-E_c)}\, e^{\frac{-(E-E_c)}{kT}} e^{\frac{-(E_c-E_F)}{kT}} dE$$

$$= \frac{m\sqrt{2m}}{\pi^2\hbar^3} e^{\frac{-(E_c-E_F)}{kT}} \int_{E_c}^{\infty} \sqrt{(E-E_c)}\, e^{-(E-E_c)} dE$$

↓ final

$$n = \frac{m\sqrt{2m}}{\pi^2\hbar^3} e^{-(E_c-E_F)kT} \cdot (kT)^{3/2} \frac{\sqrt{\pi}}{2}$$

$$n = N_c e^{-(E_c-E_F)/kT}$$

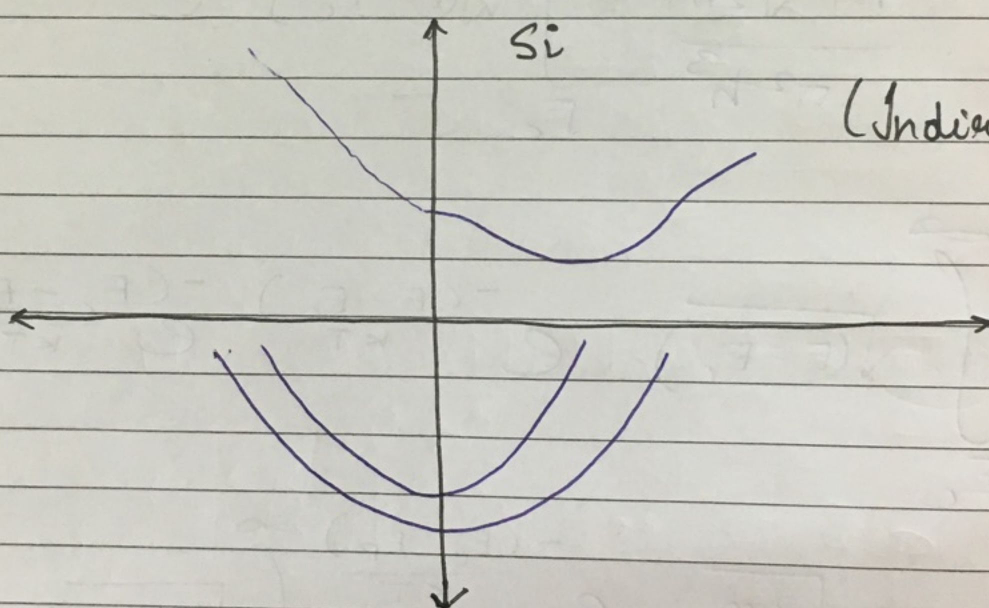
Lec - 11

Recap

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

Not the simple effective mass in General (only in GaAs)

$$= \frac{m\sqrt{2m(E-E_c)}}{\pi^2 \hbar^3} \times \frac{1}{\left(1 + e^{(E-E_F)/kT}\right)}$$



(Indirect B.G)

Non Degenerate Assumption (As long as $|E_F - E_c| > 3$ & $|E_F - E_v| > \frac{3kT}{q}$)

$\downarrow \frac{3kT}{q}$

$$\boxed{|E_F - E_g| > 3kT}$$

$$n = N_c e^{-(E_c - E_F)/kT}$$

Here, in (207)

$$\boxed{n < N_c}$$

$N_c \rightarrow$ Effective no. of Available ~~B~~ States at E

e^- $$n = N_c e^{-(E_c - E_F)/kT}$$

$$\updownarrow$$

holes $$p = N_v e^{(E_v - E_F)/kT}$$

E_c

$\frac{E_c + E_v}{2}$

$> \frac{3kT}{q}$, $E_i = E_F = \frac{E_c + E_v}{2}$

E_v

If we equate

$n_i = p_i \Rightarrow$

$$\ln N_c - \frac{(E_c - E_i)}{kT} = \ln N_v + \frac{(E_v - E_i)}{kT}$$

$$\frac{E_c + E_V - 2E_i}{kT} = \ln \frac{N_c}{N_V}$$

Say $N_c = 3.2 \times 10^{19}\ cm^{-3}$
$N_V = 1.8 \times 10^{19}\ cm^{-3}$ } Well known for Si

$$E_i = \frac{E_c + E_V}{2} + \boxed{\frac{1}{2} kT \ln \left(\frac{N_V}{N_c} \right)}$$

correction term because

$$N = \frac{m \sqrt{2m}}{\pi^2 \hbar^3} (kT)^{3/2} \times \frac{\sqrt{\pi}}{2}$$

Different for e^- & p

Now

$E_c - E_V = E_g$ (Gap).

Equilibrium

$$n_i p_i = N_c N_V e^{-(E_c - E_V)/kT}$$

$$n_i = p_i$$

DATE / /

$$n_i^2 = N_c N_v \, e^{-E_g/kT}$$

$$n_i = \sqrt{N_c N_v} \, e^{-E_g/2kT}$$

→ Gives $n_i \approx 10^{10} \text{cm}^{-3}$, Much lower than Atomic cm^{-3} density.

Rewriting Earlier Equations

$$n = N_c e^{-(E_c - E_F)/kT} = n_i e^{(E_F - E_i)/kT}$$

$$p = N_v e^{(E_v - E_F)/kT} = n_i e^{(E_i - E_F)/kT}$$

* $\boxed{(np) = n_i^2}$ * → Valid for Doped too.

→ Constant at a Given temp.

→ This Equilibrium is valid, if our Non degenerate Assumption holds.

→ This is a Dynamic Equilibrium, Analogous to Chemical Equi.

Doping

+'ve $\Rightarrow$ p, N_D^+

-'ve $\Rightarrow$ n, N_A^-

$$\nabla \cdot (\varepsilon E) = \rho$$

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

$$\boxed{p - n + N_D - N_A = 0}, \quad np = n_i^2$$

+'ve $\Rightarrow$ p, N_D^+

-'ve $\Rightarrow$ N, N_A^-

Quiz

Aug 26 (Sat.)

Syllabus till Aug 23

Lec - 12

Lec - 11 Formula Recap

- $n = n_i e^{(E_F - E_i)/KT}$

$p = n_i e^{(E_i - E_F)/KT}$

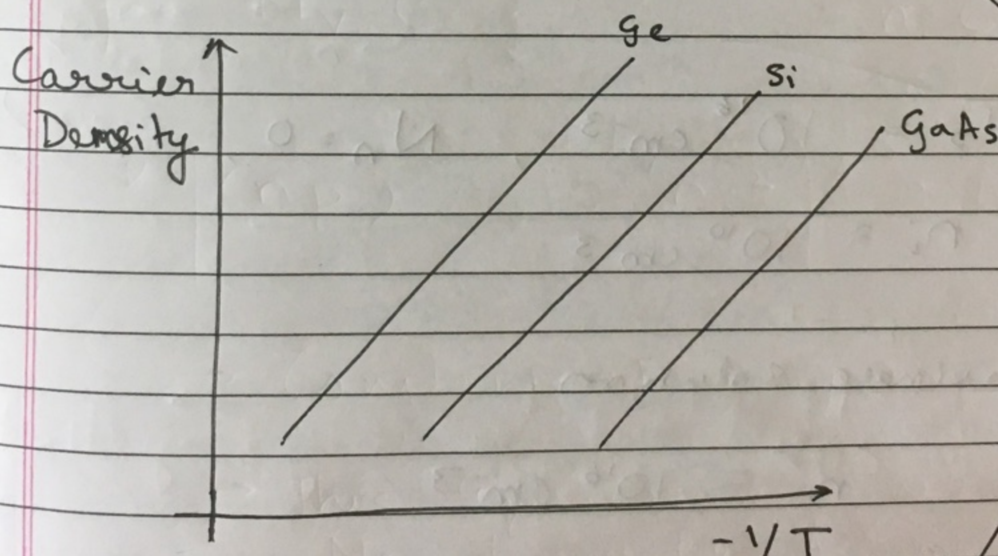
** $\boxed{np = n_i^2}$ ** Equilibrium

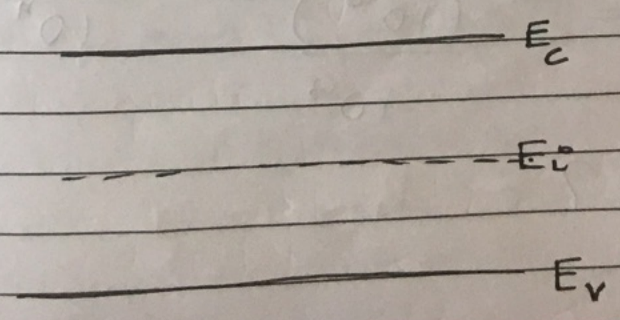
Band Gaps

Ge → 0.7

Si → 1.12

GaAs → 1.5





Fermi Level (E_F) for a doped Material

$$\nabla \cdot (\varepsilon E) = \underbrace{p - n}_{\text{Intrinsic}} + \underbrace{N_D^+ - N_A^-}_{\text{Dopants.}}$$

$$p - n + N_D^+ - N_A^- = 0 \quad - (2)$$

Neutrality

$$np = n_i^2$$

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

Cases

(1) $N_D = N_A = 0 \Rightarrow E_F = E_i$

(2) $N_D = 10^{16}\ cm^{-3}$, $N_A = 0$, $E_F = ?$

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

Approximate solution

$$n \approx 10^{16}\ cm^{-3}$$

$$p = \frac{(10^{10})^2}{10^{16}} = 10^4\ cm^{-3}$$

$E_F = ?$

PAGE No. DATE / /

$$\frac{(E_F - E_i)}{kT} = x$$

$$10^4 = 10^{10} e^{-x}$$

- (1)

$$e^{-x} = 10^{-6}$$

$$\cancel{-}x = 2.3 \times \cancel{-}6$$

$$x = 2.3 \times 6$$

$$(E_F - E_i) = 2.3 \times 6 \times 25 \times 10^{-3}$$

$$= \boxed{0.345 \text{ eV}}$$

(3) $N_D = 10^{19} \text{ cm}^{-3}$ $N_A = 0$ $E_F = ?$

$$n \approx 10^{19}$$

$$p \approx 10^1 / \text{cm}^3$$

$$10 = 10^{10} e^{-x}$$

$$e^{-x} = 10^{-9}$$

$$0.345 \times \frac{3}{2} = \boxed{0.52 \text{ eV}}$$

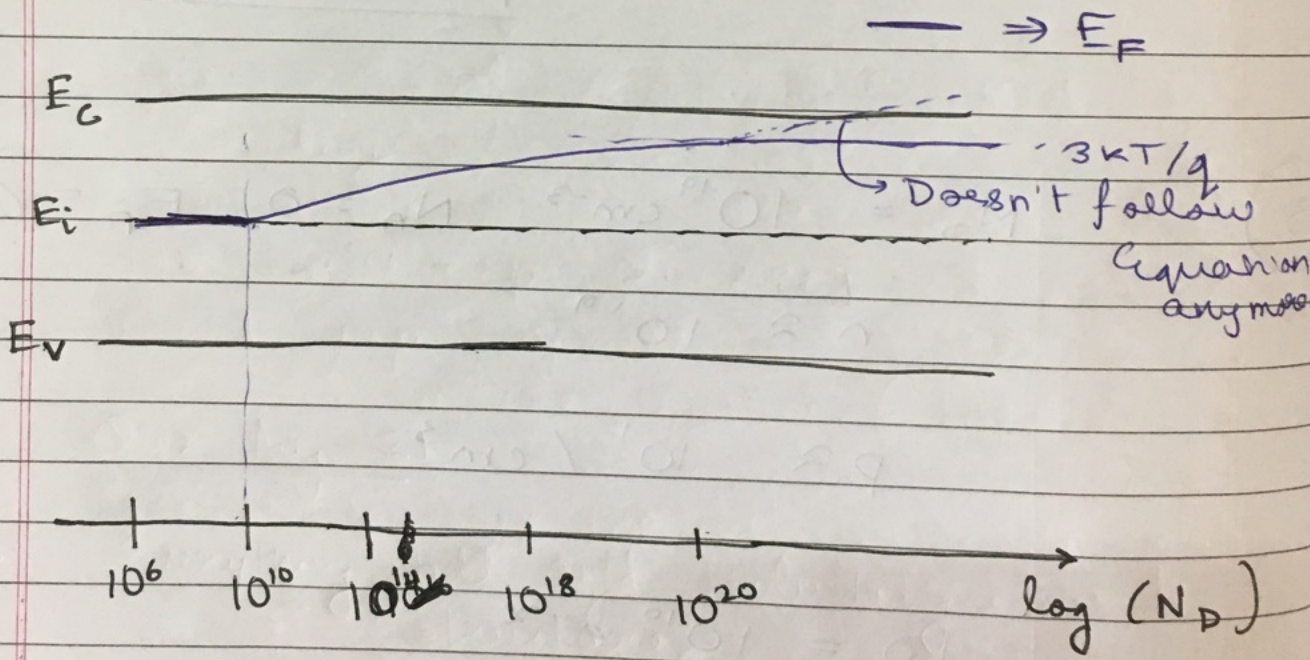
PAGE No.
DATE / /

→ In case (3) the Ans. is not correct, since the Doping is so high that our approximation is not valid.

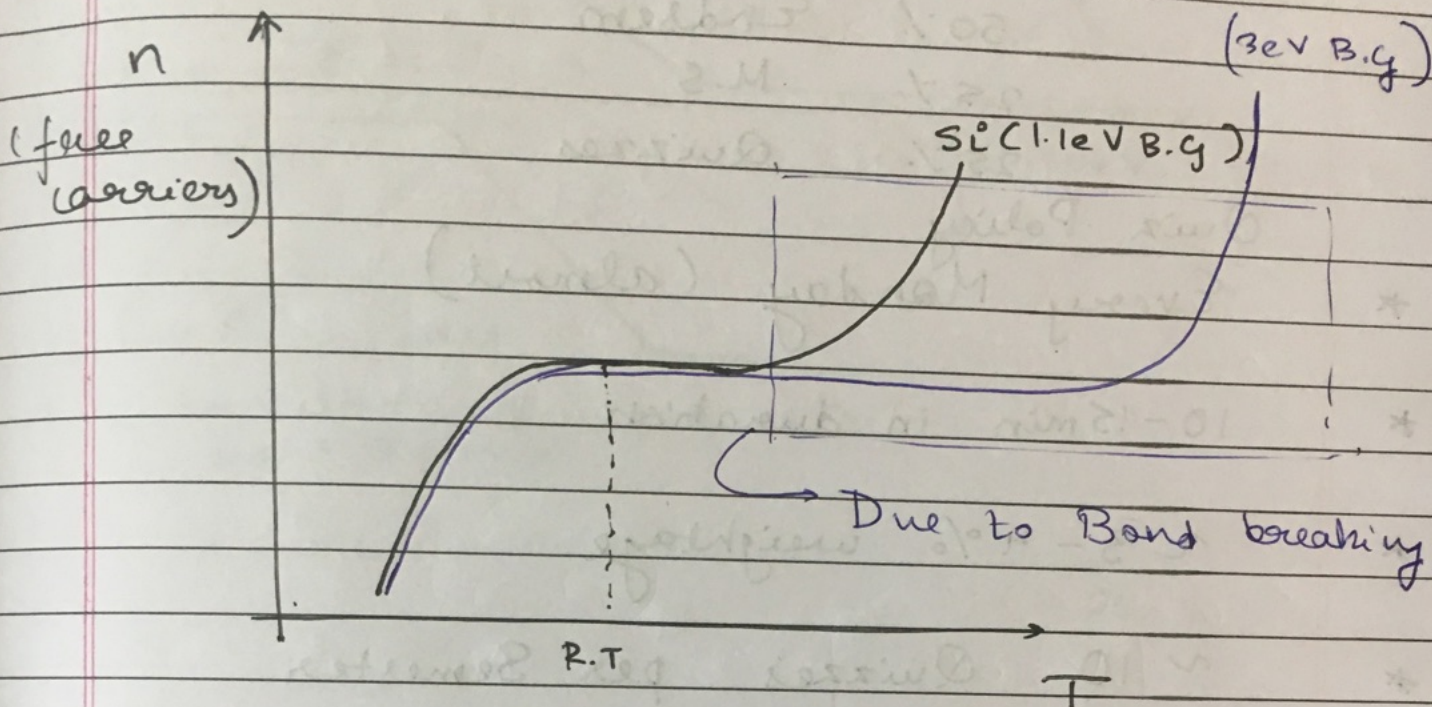
(4) $N_D = 10^8/cm^3$, $N_A = 10^7/cm^3$

We'll have to solve Quadratic, but here ~~low~~ much less than n_i, hence
$E_i \approx E_F$

Plot



n Vs T trends



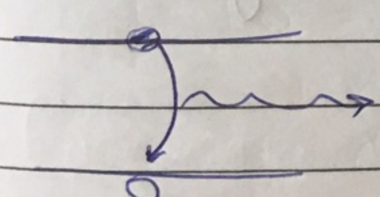
→ 3eV B.G material is used for ↑T applications

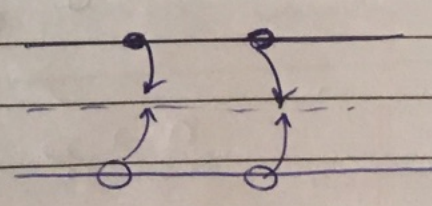
Equilibrium in Doping

→ e^- hole recombination

radiative process

non-radiative process





$n + p \longrightarrow (\ )$

n, p equilibrium

$$\boxed{\frac{dn}{dt} = B(np - n_i^2)}$$

Lec -13

New Grading Policy

50% Endsem
25% M.S
25% Quizzes

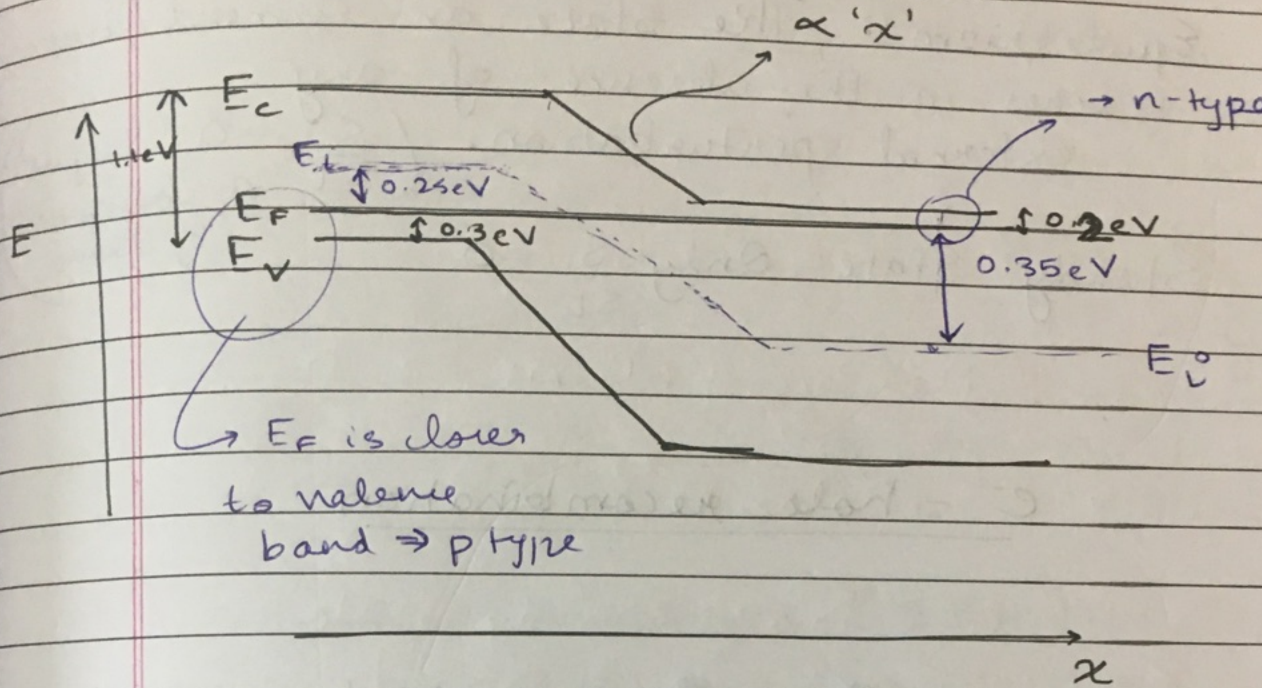
Quiz Policy

* Every Monday (almost)
* 10-15 min in duration
* ~ 3-4% weightage
* ~ 10 Quizzes per Semester
* Best 8 or so to be counted for Grading
* No make up Quizzes

Quiz Aug-21

→ Everything till and including band structure.

Lec - 13

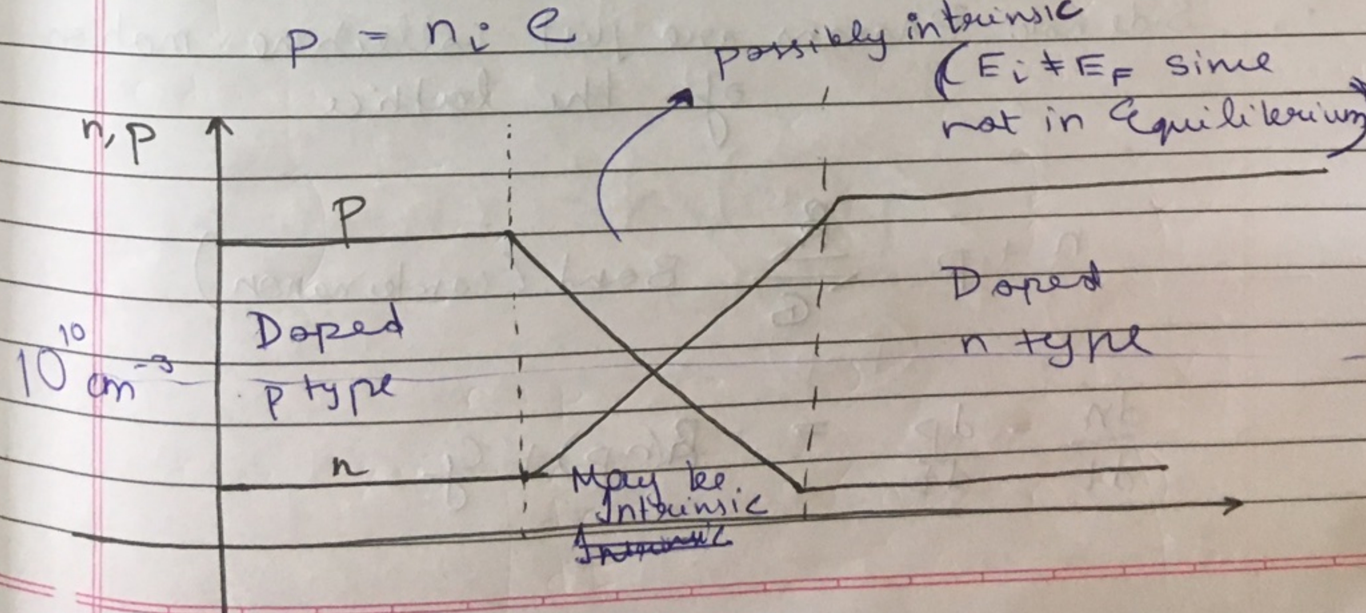


Q-1) Plot E_i Vs x (Just take M.D)

Q-2) Plot n, p Vs x (Plotted below)

$$n = n_i e^{(E_F - E_i)/KT} \quad \left(n_i = 10^{10}\,cm^{-3}\right)$$

$$p = n_i e^{(E_i - E_F)/KT}$$

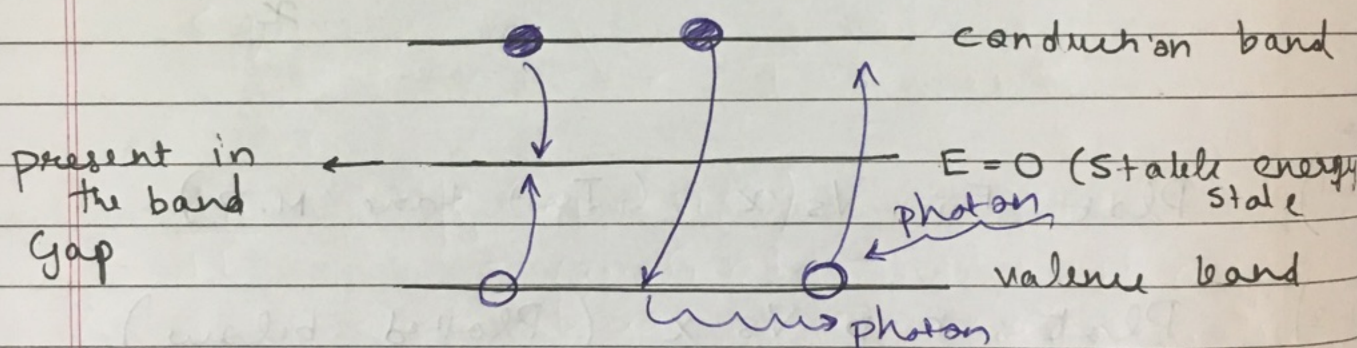


Equilibrium Vs Steady State

→ Equilibrium : The state an element/device reaches in the absence of any external perturbation. ($\frac{\delta}{\delta t} = 0$ is just a consequence of absence)

→ Steady State: Only $\frac{\delta}{\delta t} = 0$

e^- - hole recombination



• Band Gap may have some states in an impure crystal. (Trap Levels/Defects)

• Side note: Phonons are just collective motion of the lattice

$$n + p \underset{G}{\overset{R}{\rightleftharpoons}} \text{Bond (combination)}$$

$$\frac{dn}{dt} = \frac{dp}{dt} = -R(np) + G$$

Edit: Replaced B by R
(or Maybe it was B ??)

$np = n_i^2$ – Equilibrium not Steady state

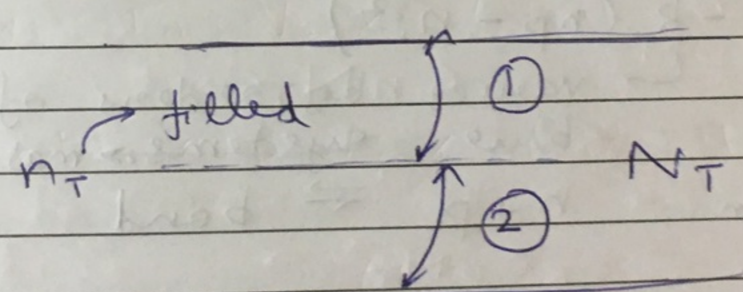
$-\cancel{B}$

$$-Rnp + G = 0 = -\overset{R}{B} n_i^2 + G$$

$$\frac{\delta n}{\delta t} = \frac{\delta p}{\delta t} = -R(np - n_i^2)$$

→ Called Shockley (SRH)

Band-Band



$$\frac{dn}{dt} = -k_1 (N_1 - n_1) n$$

$$\frac{dp}{dt} = -k_2(n_T) p$$

Quiz 2

Lec - 14

Quiz-2

Equilibrium Carrier conc.

from Density of States → Doping

Lec - 14

Equilibrium → Steady State / → Transient

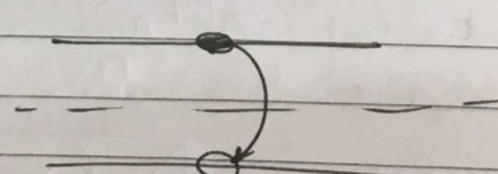
$$\frac{dn}{dt} = -k\,(np - n_i^2)$$

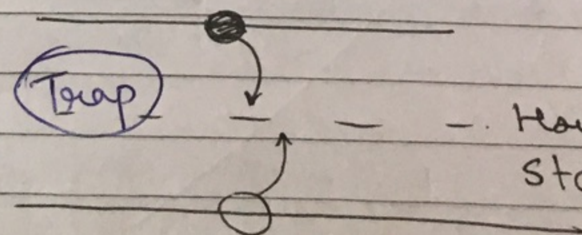
↳ varies by orders of magnitude b/w ~~systems~~ materials.

from $n + p \rightleftharpoons$ bond

Rate eq^n

Mechanisms

1) 

2) 

However e⁻ should stay in the trap for long enough for a hole to reach there

→ Traps exist because crystals are not pure.

Insights

→ $\frac{\delta n}{\delta t} = \frac{\delta p}{\delta t} = 0$

→ Probability increases as traps are closer to mid gap.

Rate eqn for 2

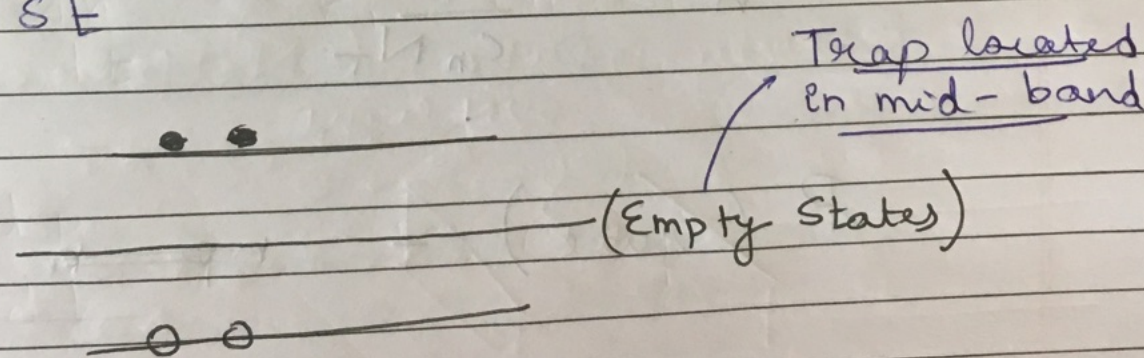
$N_T \rightarrow$ Total states

$n_T \rightarrow$ total filled states

$$\cancel{\frac{\delta n}{\delta t} \approx c_e (n_T) n}$$

$$\frac{\delta n}{\delta t} \approx -c_e (N_T - n_T) n$$

$$\frac{\delta p}{\delta t} = -c_p (n_T) p$$



$$c_e (N_T - n_T) n = c_p (n_T) p$$

→ In writing we neglect certain processes to simplify calc.

$$\frac{\delta p}{\delta t} = \frac{\delta n}{\delta t} = n_T p$$

$$\downarrow$$

Get

$$\cancel{\ } = \frac{C_e N_T n}{C_e n + e_p P}$$

Dividing N^r & D^r

$$= \frac{np}{\frac{n}{C_p N_T} + \frac{P}{C_n N_T}}$$

$$I_p = \frac{1}{C_p N_T}$$

$$I_n = \frac{1}{C_n N_T}$$

$$R \text{ (rate)} = \cancel{np} \frac{np}{n I_p + p I_n}$$

PAGE No. | DATE / /

→ This was approx sol, correct sol. is

$$\left(\frac{np - n_i^2}{n\tau_p + p\tau_n}\right)$$

Modify since it doesn't have Near to mid gap prob. info

$$R_{SRH} = \frac{(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

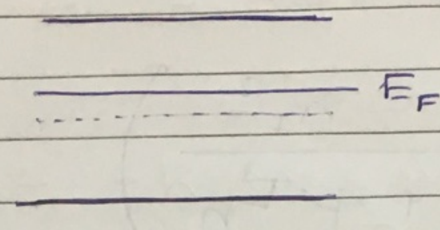
SRH rate eq^n

$$\left.\begin{aligned} n_1 &= n_i e^{(\ )} \\ p_1 &= p_i e^{(\ )} \end{aligned}\right\} \text{in book}$$

Around Mid band, ~~$n_1 \approx p_1$~~
$n_1 \approx p_1 \approx n_i$

Lec - 15

Re- Cap

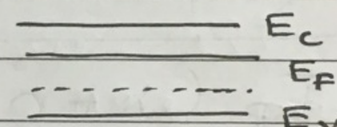


Equilibr. $\begin{cases} n_0 = n_i e^{(E_F - E_i)/KT} \\ p_0 = n_i e^{(E_i - E_F)/KT} \end{cases}$

$$n_0 p_0 = n_i^2$$

$$n_i = 10^{10} \quad (\text{for Si})$$

Doped Case

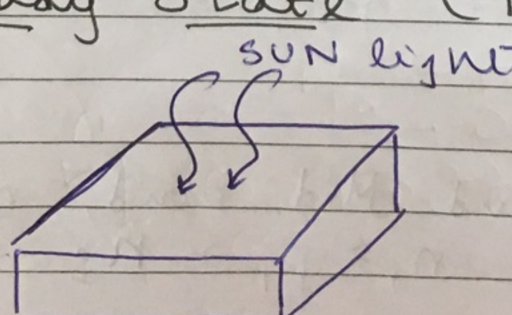


(Still Equilibrium, but $n \neq p$)

$N_D \leftarrow n \sim 10^{17} \rightarrow$ Called Majority ca[rriers]

$p \sim 10^{3} \rightarrow$ Called Minority carriers

→ **Steady State** (Not Equilibrium)

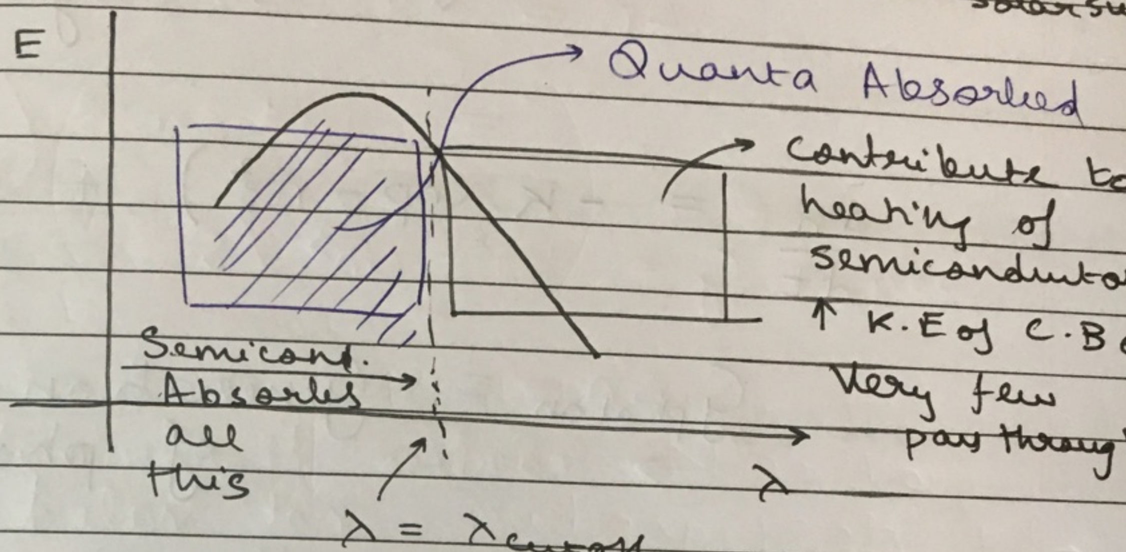


- After transition period

$$n \rightarrow n(t)$$

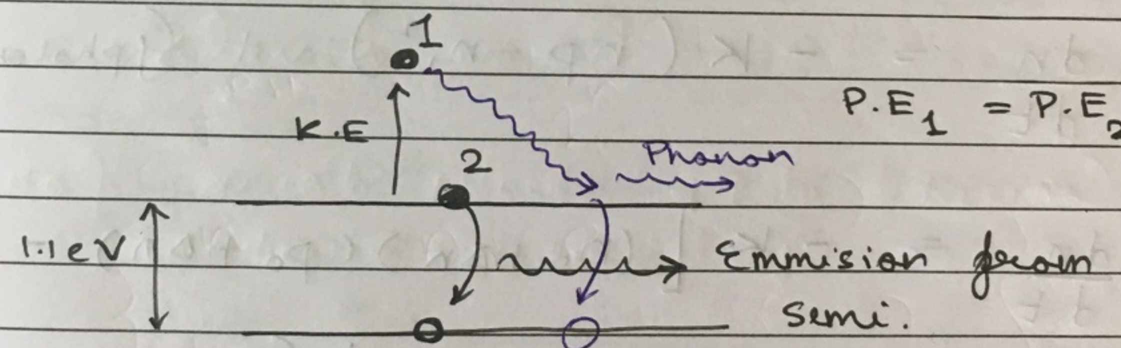
$$p \rightarrow p(t)$$

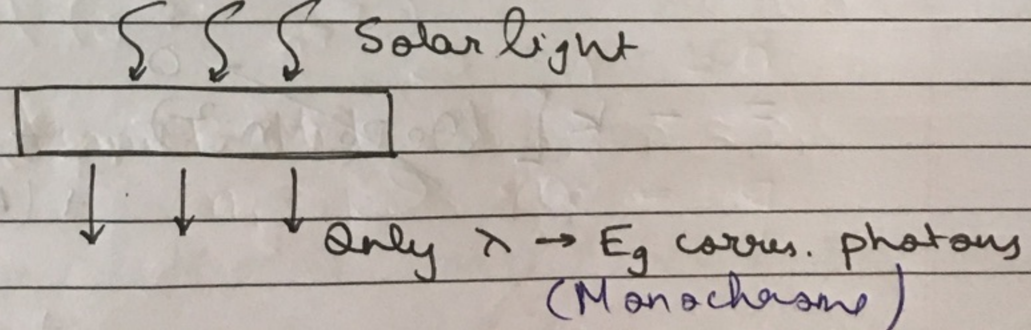
Solar Spectrum (BBR at $T = T_{solar\ surface}$)



$$E_g(eV) = \frac{1240}{\lambda(nm)}$$

Recombination & Generation





→ Number of Quanta coming out is equal to no. of Quanta Abs.

→ $R = G$ at Steady state (By Def.)

$$\frac{dn}{dt} = -k(np - n_i^2) + G_{photon}$$

G_{photon} = Generation rate of photons

$n = n_o + \Delta n$

$p = p_o + \Delta p$

$\Delta n = \Delta p$ since all processes are pair wise

$$\frac{dn}{dt} = -k(np - n_i^2) + G_{photon}$$

$$\frac{dn}{dt} = -k\left[(n_o + \Delta n)(p_o + \Delta n) - n_i^2\right] + G_{photon}$$

$$= -k\left[\cancel{(n_o p_o - n_i^2)}^{\,0} + \Delta n(n_o + p_o) + (\Delta n)^2\right] + G_{photon}$$

$$\frac{\delta n}{\delta t} = -k\left[\Delta n(n_o + p_o) + \Delta n \cdot \Delta n\right) + G_{photon}$$

Ignoring 2^{nd} order terms.....

[Low level irradiation]

$$\frac{\delta n}{\delta t} = -k(n_o + p_o)\Delta n + G_{photon}$$

- $$\frac{\delta(\Delta n)}{\delta t} = -k(n_o + p_o)\Delta n + G_{photon}$$

$$\frac{\delta(\Delta n)}{\delta t} = -\frac{\Delta n}{\tau_{eff}} + G_{photon}$$

$$\tau_{eff} = \frac{1}{k(n_o + p_o)}$$

Typical k values

$$GaAs \rightarrow 10^{-10} \text{ (unit)}$$
$$Si \rightarrow 10^{-15} \text{ (unit)}$$

Say,

$$G = 10^{16} \text{ photons } cm^{-3}/s$$

$$\tau_{eff} = \frac{1}{10^{-15}(\underbrace{10^{17} + 10^{3}}_{\sim 10^{17}})}$$ for N_D Doped case

$$\tau_{eff} = 10^{-2}\,s = 10\,mS$$

Average life time post excitation
= 10 mS

$$\frac{\delta(\Delta n)}{\delta t} = 0 \Rightarrow (\Delta n = G_{photon} \times \tau_{eff})$$

$$\boxed{\Delta n = G\tau_{eff}}$$

Here,
$$\Delta n = 10^{16}\ cm^{-3}/s \times 10^{-2}\ s$$
$$= 10^{14}\ cm^{-3} \quad \left(<< \text{ than } 10^{17}\ (N_D) \right.$$

Say, $G = 10^{22}\ cm^{-3}/s$

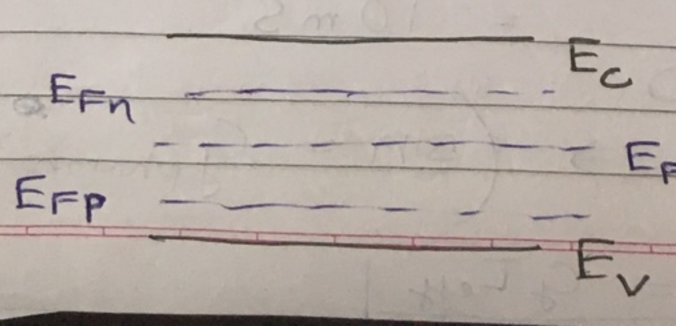
$$\Delta n = 10^{20}\ cm^{-3}$$
→ Earlier Approximation not valid.

End Result for $G = 10^{16}$
$$\Delta n = 10^{14}$$
$$n \approx 10^{17} + 10^{14} \sim 10^{17}$$
$$p = 10^{3} + 10^{14} \sim 10^{14}$$

Quasi - Fermi Levels

- → Concept of E_F breaks down for non equilibrium situations
- → We use Quasi fermi levels

$$n = n_i\, e^{(E_{Fn} - E_i)/KT}$$
$$p = n_i\, e^{(E_i - E_{Fp})/KT}$$

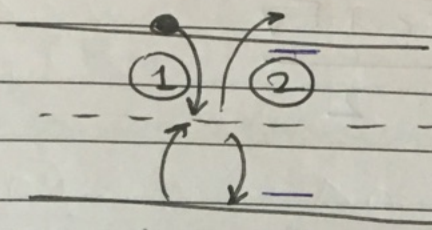


SRH

PAGE No.
DATE / /

→ The e^- & hole trap concept

$$e^- + \text{empty} \rightleftharpoons \text{filled}$$



E_T (Trap level)

N_T → Total traps (depends on impurities)

n_T → traps filled with e^-

$N_T - n_T$ → empty traps

$$\frac{\delta n}{\delta t} = -c_n n (N_T - n_T) + e_n n_T$$

$$\frac{\delta p}{\delta t} = -c_p p n_T + e_p (N_T - n_T)$$

→ Contribution of 2 is lesser (Ignore.

Get,

$$R = \frac{-(np - n_i^2)}{\tau_p (n + n_1) + \tau_n (p + p_1)}$$

To account for $R \to 0$ as Trap level is near E_c or E_V

DATE / /

$$n_1 = n_i e^{(E_T - E_i)/kT}$$

$$p_1 = n_i e^{(E_i - E_T)/kT}$$

$$E_i \sim \frac{E_c + E_V}{2}$$

$$E_T \rightarrow E_i + \frac{E_c + E_V}{2}$$

$$\rightarrow \quad \frac{\delta(\Delta n)}{\delta t} = -\frac{\Delta n}{\tau_{eff}} + G$$

is valid for both $G \neq 0$ (Irradiation / Charging)

and $G = 0$ (Return to equ / Discharge)

Lec 16

PAGE No.
DATE / /

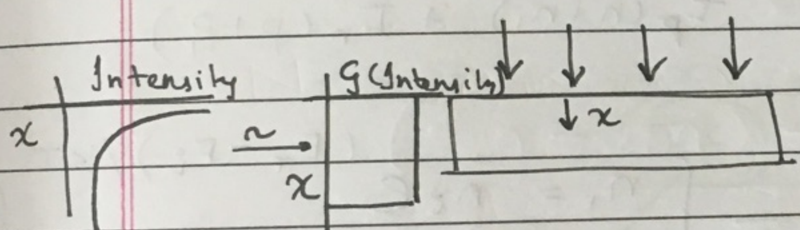
Upcoming Quizzes/tests

M.S 16/9/17, Sat, 8:30 - 10:30am

Quiz
(Mon)

Equilibrium carrier conc.

(DOS
↓
Doping)



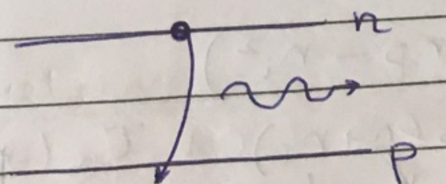
$G \rightarrow$ Uniform Generation in cm^{-3}/s

→ Equilibrium

→ $np = n_i^2$

$np \neq n_i^2$
(Non. equ.)

→



$$\frac{dn}{dt} = -k\,(np - n_i^2) + G$$

Assumed constant with no spatial variation.

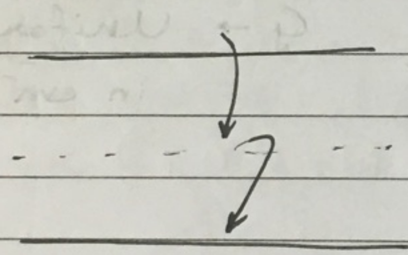
$$\Delta n, \Delta p << \begin{pmatrix} n_0 \\ p_0 \end{pmatrix}$$

Majority carrier conc.

~~Indirect Band Gap Materials~~

→ Above analysis lead to.

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$



$$E_T \begin{cases} n_1 = n_i e^{(E_T - E_i)/KT} \\ p_1 = n_i e^{(E_i - E_T)/KT} \end{cases}$$

<u>Analysis</u>

$$\left.\begin{array}{l} n \to n_0 + \Delta n \\ p \to p_0 + \cancel{\Delta p}\, \Delta n \end{array}\right\} \because \Delta n = \Delta p$$

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p(\underset{\sim 10^{17}}{n} + \underset{\sim 10^{10}}{n_1}) + \tau_n(\underset{\substack{\sim 10^{14} \\ (10^3 + 10^{14})}}{p} + \underset{\sim 10^{10}}{p_1})}$$

$$\tau_p \sim \tau_n$$

Approximating

$$\frac{-\Delta n(n_0+p_0)+\cancel{\Delta n^2}^{\,0}}{\tau_p n_0 + \cancel{(\ )}^{\,0}}$$

$\tau_p n_0 \rightarrow$ eq. value
equilibrium value

$$\approx \frac{-\Delta n}{\tau_p}$$

$$R = \frac{-\Delta n}{\tau_p} \quad \text{for N-type semiconductors}$$

$\tau_p \rightarrow$ Minority carrier lifetime $\leftarrow \tau_n$

$$= \frac{-\Delta n}{\tau_n} \quad \text{for P-type semiconductors}$$

→ Conclusion

→ B - B (Band to Band) Model for Direct Band Gap materials

$$\tau_{eff} = \frac{1}{K(n_0+p_0)}$$

DATE / /

→ SRH → Model for Indirect B.G mat.

$$\left\{\begin{array}{l} \tau_{eff} = \tau_p \\ \tau_{eff} = \tau_n \end{array}\right\} \begin{array}{l} \to N \text{ type} \\ \to P \text{ type} \end{array}$$

→ Minority carrier lifetime.

→ Irridation of Intrinsic semiconductor by SRH Model (Indirect B.G)

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_i) + \tau_n(p+p_i)}$$

Intrinsic Semiconductor

$$= (n_o + \Delta n)(p_o + \Delta n) - n_i^2$$
$$= \Delta n(n_o + p_o) + \Delta n^2$$

This time

$\Delta n, \Delta p \gg (n_o, p_o = n_i)$
→ for typical G values.

$\Rightarrow$ $(\Delta n)^2$ is Dominant term

$$= \cancel{\frac{-(\Delta n)^2}{\tau_n \Delta n + \tau_p \Delta p}}$$

$$= \frac{-(\Delta n)^2}{\tau_n \Delta n + \tau_p \Delta n}$$

$$= \frac{-(\Delta n)}{(\tau_n + \tau_p)}$$

$$\frac{d(\Delta n)}{dt} = -\frac{\Delta n}{\tau_{eff}} + g$$

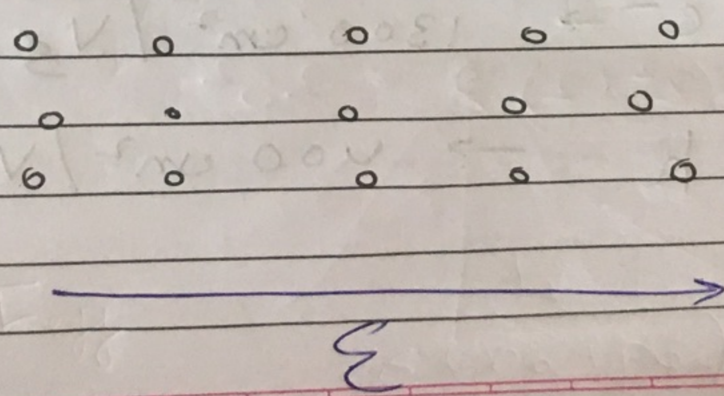
→ here $\tau_{eff} = (\tau_n + \tau_p)$

Transport

→ In presence of electric field

$$F = -qE$$

→ But in presence of regular lattice collissions.

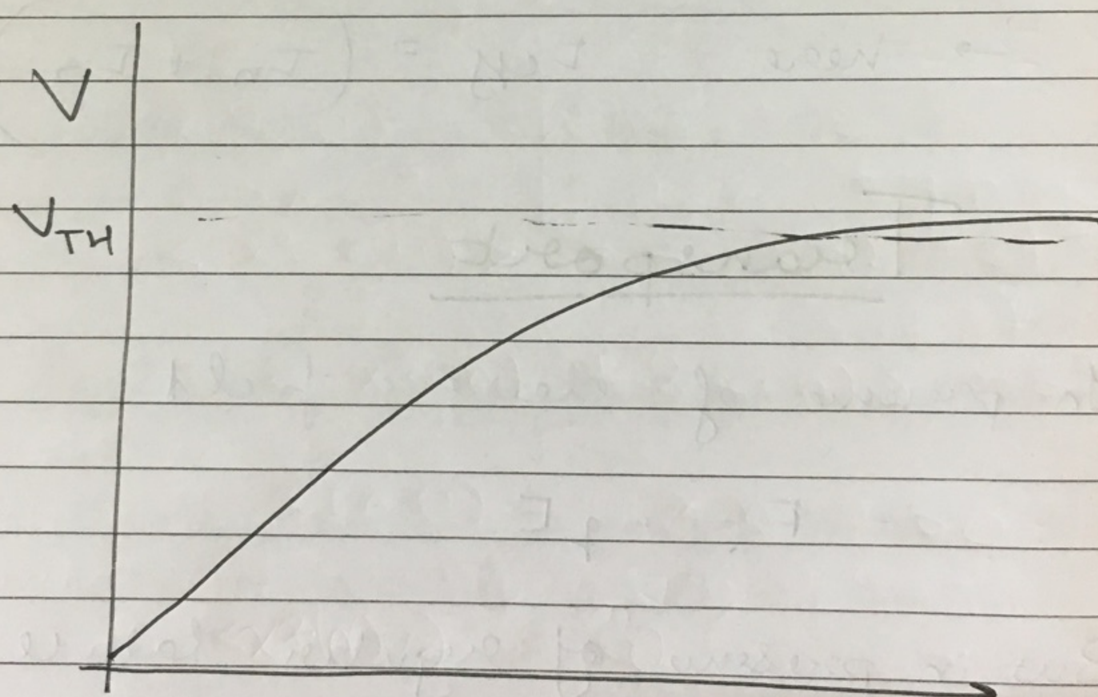


$$V = \mu \mathcal{E}$$

$$\Delta V = \frac{q E t}{m}$$ → mobility measure.

$$J_{n\,drift} = -q n \mu_n \mathcal{E}$$

$$J_{p\,drift} = q p \mu_p \mathcal{E}$$



Si values.
- $e^- \rightarrow 1300\ cm^2/Vs$
- $h \rightarrow 400\ cm^2/Vs$

Lec - 18

Next Monday

Quiz - 3

Syllabus → Gen. - Recom.

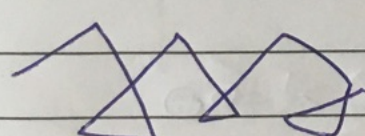
- Generation - Recombination

Email
- → Radius(??)
- → SRH
- → Optical gen.
- → Quasi - Fermi

Transport

→ Phenomenon of ~~ds~~ drift

$\vec{\mathcal{E}}$



$\xrightarrow{\mathcal{E}}$

→ ~~Cot~~ Mean collision time τ_c

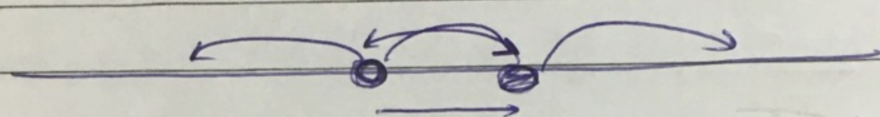
$$m^* \frac{dv}{dt} = -qE$$

$$v = \underbrace{\frac{-q\,\tau_c}{m^*}}_{\mu\ (\text{Mobility})} E$$

$\mu_n = 1200\ cm^2/Vs$??

$\mu_p = 400\,cm^2/Vs$

Transport via Diffusion
(Random walk)



δ (Stride length)

$$x(n+1) = x(n) \pm \delta$$

$$\langle x^2(n+1)\rangle = \langle (x(n) \pm \delta)^2 \rangle$$

$$= \langle x^2(n) \pm 2x(n)\delta + \delta^2 \rangle$$

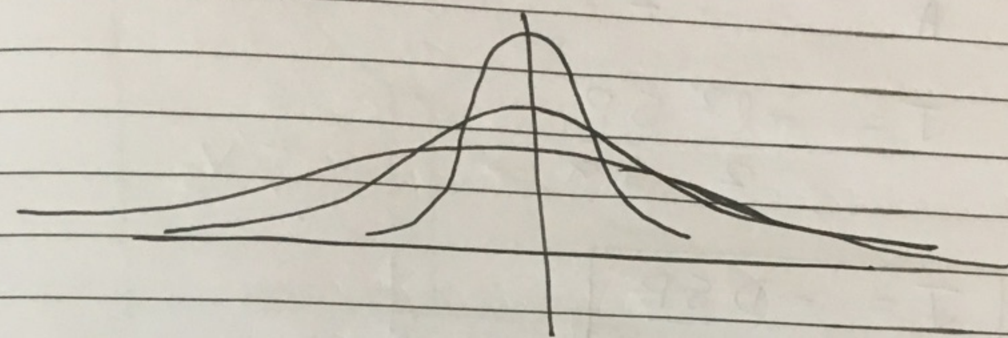
$$\langle\,\rangle = 0$$

$$x^2(0) = 0$$

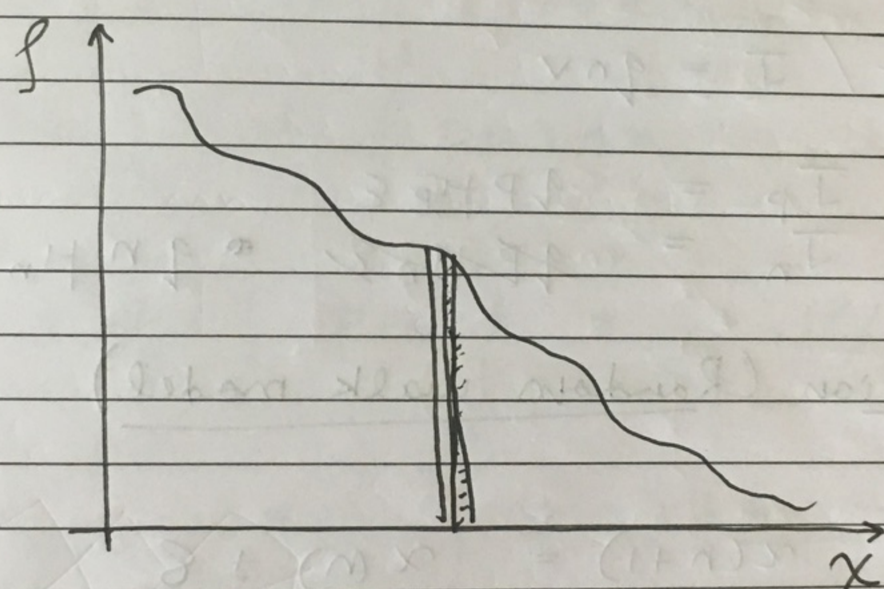
$$\langle x^2(1)\rangle = \delta^2$$

$$\langle x^2(2)\rangle = 2\delta^2$$

$$\langle x^2(n) \rangle = n\delta^2$$



→ Diffusion can lead to net current if there is a concentration gradient.



$$p(x) = p(0) + \frac{\delta p}{\delta x}\bigg|_{x=0} \cdot x$$

$$I_{left} = A \times \frac{1}{2}\int_0^l p(x) = \frac{A}{2}\left[p(0)\,l + \frac{\delta p}{\delta x}\bigg|_{x=0} \cdot \frac{l^2}{2}\right]$$

$$I_{right} = A \times \frac{1}{2}\int_{-l}^{0} p(x) = \frac{A}{2}\left[p(0)(+l) - \frac{\delta p}{\delta x}\bigg|_{x=0} \frac{l^2}{2}\right]$$

$$\frac{I}{A} = \frac{-l^2}{2}\frac{\delta P}{\delta x}$$

$$J = \frac{-l^2}{2}\frac{\delta P}{\delta x}$$

$$\boxed{J = -D\frac{\delta P}{\delta x}}$$

Carrier Transport

- Drift / $J = qnv$

$$J_p = qP\mu_p \varepsilon$$
$$J_n = \cancel{qP\mu_n\varepsilon} \; qn\mu_n\varepsilon$$

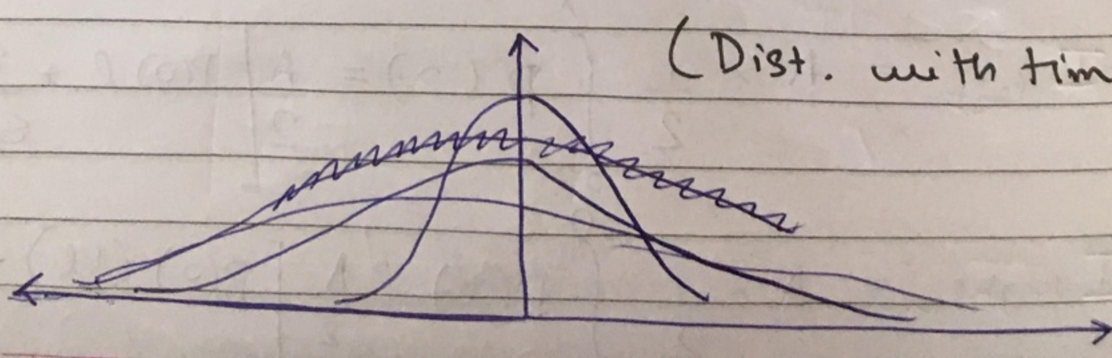
Diffusion (Random walk model)

$$x(n+1) = x(n) \pm \delta$$

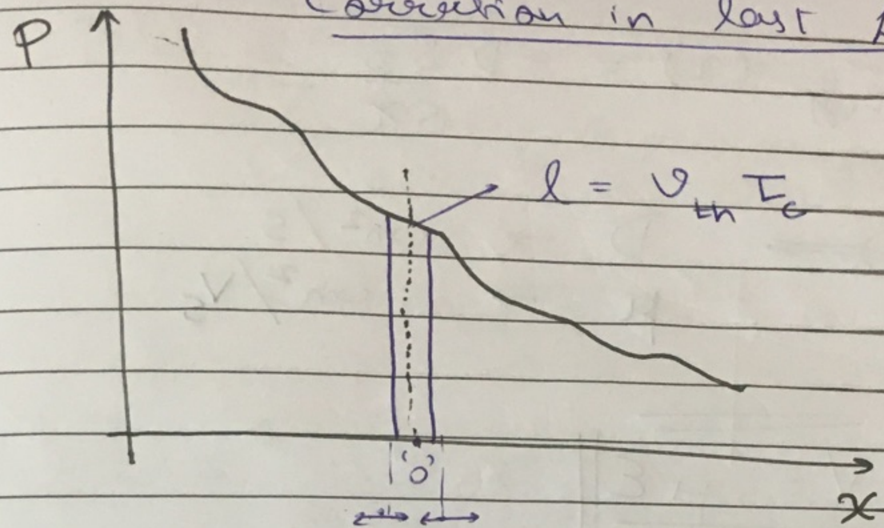
$$\langle x(n) \rangle = 0$$

$$\langle x^2(n) \rangle = n\delta^2$$

(Dist. with time)



Correction in last Lecture



$$p(x) = p(0) - \left.\frac{\delta p}{\delta x}\right|_{x=0} \cdot x$$

$$N_{left} = \frac{A}{2} \int_0^l p(x)\, dx$$

$$= \frac{A}{2} \left[p(0)\, l + \frac{\delta p}{\delta x}\, l^2/2 \right]$$

$$N_{Right} = \frac{A}{2} \int_{-l}^{0} p(x)\, dx$$

$$= \frac{A}{2} \left[p(0)\, l - \frac{\delta p}{\delta x}\, l^2/2 \right]$$

$$\Delta N_{right} = -\frac{A}{2} \frac{\delta p}{\delta x} l^2 = J \times \tau_c \times A$$

$$J(x) = \underbrace{\frac{-l^2}{2\tau_c}}_{\text{called } D} \frac{\delta p}{\delta x}$$

PAGE No.
DATE / /

$$J_{Diff}(x) = -D\frac{\delta p}{\delta x}$$

$$D \rightarrow cm^2/s$$
$$\mu \rightarrow cm^2/Vs$$

$$\boxed{V = \mu \mathcal{E}}$$

$$F = -qE$$

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

$$V = \underbrace{\left(\frac{q\mathcal{E}}{m}\right)}_{\mu} E$$

Diffusion

$$J_{p,diffusion} = -q D_p \frac{\delta p}{\delta x}$$

$$J_{n,diffusion} = q D_n \frac{\delta n}{\delta x}$$

Einstein Relation

PAGE No.
DATE / /

$$D = \frac{l^2}{2\tau_c} \qquad \mu = \frac{q\tau_c}{m^*}$$

$$l = v_{th}\tau_c$$

$$D = \frac{v_m^2 \tau_c^2}{2\tau_c} = \frac{v_{th}^2 m^* \mu}{2q}$$

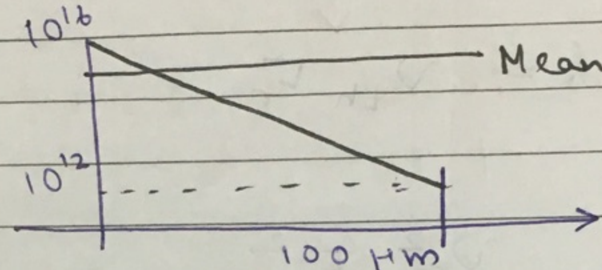
get, $$\frac{D}{\mu} = \left(\frac{1}{2} m^* v_{th}^2\right) \times \frac{1}{q}$$

$$\boxed{\frac{D}{\mu} = \frac{kT}{q}}$$

Relation b/w Mobility & Drift coefficient.

Non-uniformly Doped Semiconductor

Semiconductor → $N_D(x)$



Mean value $= \frac{10^{16} + 10^{12}}{2} \simeq 5 \times 10^{15}$

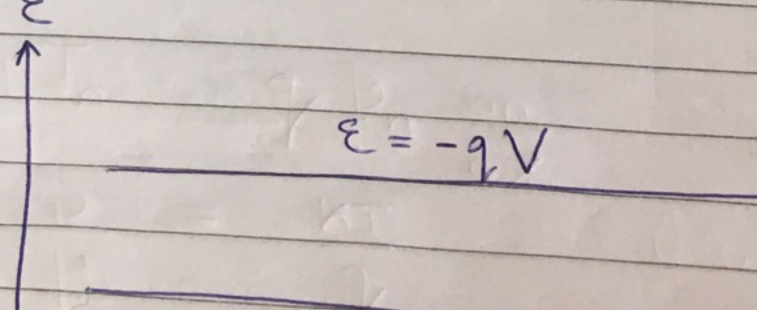
→ If diffusion distributes ~~chan~~ dopants uniformly, there will be a charge sep. which will lead to a drift current

$$\boxed{\begin{array}{c}\text{Equilibrium} \\ J = 0\end{array}}$$

→ Solving for $J = 0$

Using,

$$n = n_i e^{(E_F - E_i)/KT}$$



$$E = -\frac{dV}{dx} = \frac{1}{q}\left[\frac{dE_c}{dx}, \frac{dE_v}{dx}, \frac{dE_i}{dx}\right] \quad (1)$$

Equilibrium

$$J_{drift} + J_{diffusion} = 0$$

$$\frac{\delta n}{\delta x} = \frac{n_i}{kT} e^{(E_F - E_i)/kT} \times \left[\frac{\delta E_F}{\delta x} - \frac{\delta E_i}{\delta x}\right]$$

$$\to n$$

$$q D_n \frac{\delta n}{\delta x} = \frac{q D_n}{kT} n_0 \left[\frac{\delta E_F}{\delta x} - \frac{\delta E_i}{\delta x}\right]$$

$$\mu$$

$$= \mu n_0 \left(\frac{\delta E_F}{\delta x} - qE\right) \quad \text{from } (1)$$

$$\to J_{drift} = (q n \mu_n \mathcal{E})$$

$$\underbrace{q n \mu_n \mathcal{E}}_{J_{drift}} + \underbrace{\mu_n n_0 \left[\frac{\delta E_F}{\delta x} - qE\right]}_{J_{diff}} = 0$$

$$\Rightarrow \boxed{\frac{\delta E_F}{\delta x} = 0}$$

Hence

$J = 0$ + Einstein Relation

$\downarrow$

E_F is a constant

(Constant Fermi Level)

Re - Cap

Mon Quiz → R-G

M.S Exam → Everything

→ Drift and Diffusion

Drift

$$J_p = (qp\,\mu_p E)$$

$$J_n = (qn\,\mu_n E)$$

Diffusion

$$J_p = -qD_p \frac{\delta p}{\delta x}$$

$$J_n = qD_n \frac{\delta n}{\delta x}$$

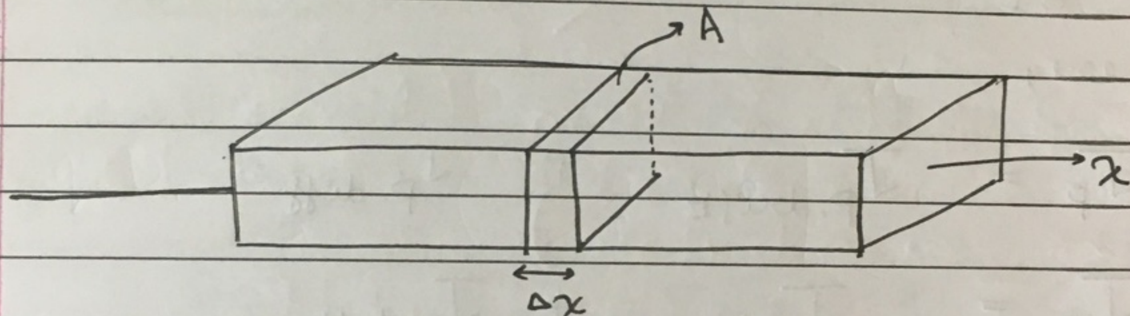
$$\frac{D}{\mu} = \frac{KT}{q}$$ (Einstein rel.)

Equilibrium Cond.

$$\nabla E_F = 0 \qquad \left(\frac{d}{dx} E_F = 0 \right)$$

$$\nabla(\varepsilon E) = \left(p - n + N_D^{+} - N_A^{-}\right)$$

Continuity Eqn



$N_{left} \longrightarrow \quad \longrightarrow N_{right}$

$$\underset{(\Delta t)}{\Delta N} = \Delta p \, A \, \Delta x = \left(Flow_{left} - Flow_{right}\right) \Delta t A$$

Taking into account R-g and writing Flow in terms of J_p

$$\Delta N = \left\{ \Delta p \cancel{A} \Delta x = \frac{1}{q}\left(J_{p\,left} - J_{p\,right}\right) \Delta t \cancel{A} - R(\cancel{A}\Delta x)\Delta t + G(\cancel{A}\Delta x)\Delta t \right.$$

Dividing both sides by $\Delta x \Delta t$ (In the lim

$$\frac{\delta p}{\delta t} = \frac{1}{q}\left(\frac{(J_p)_{left} - (J_p)_{right}}{\Delta x}\right) - R + G$$

$$\frac{\delta p}{\delta t} = -\frac{1}{q}\frac{\delta J_p}{\delta x} - R + G$$

Similarly

$$\frac{\delta n}{\delta t} = \frac{1}{q}\frac{\delta J_n}{\delta x} - R + G$$

Where,

$$J_p = J_{p,drift} + J_{p,diff}$$

$$J_n = J_{n,drift} + J_{n,diff}$$

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

$$p = p_i e^{(E_i - E_{Fp})/kT}$$

Examples

Band Diagram & Equilibrium

for

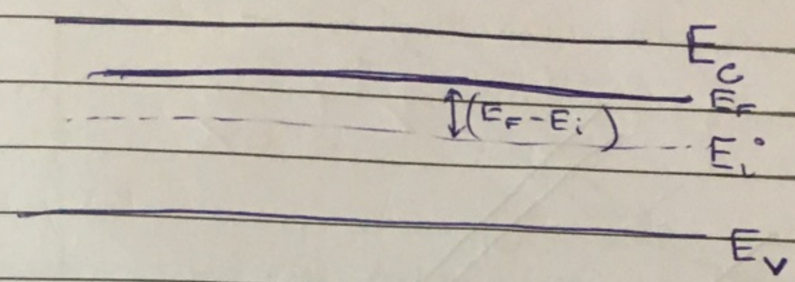
Semi. Resistor

$N_d = 10^{17} cm^{-3}$

(a) Equilibrium

(b) Steady State ($E = 10^3$ V/cm)

Band Diagram



~~Equo~~ **Lec 20**

Equations

$$\frac{\delta n}{\delta t} = \frac{1}{q} \nabla J_n - R + G$$

$$\frac{\delta p}{\delta t} = -\frac{1}{q} \nabla J_p - R + G$$

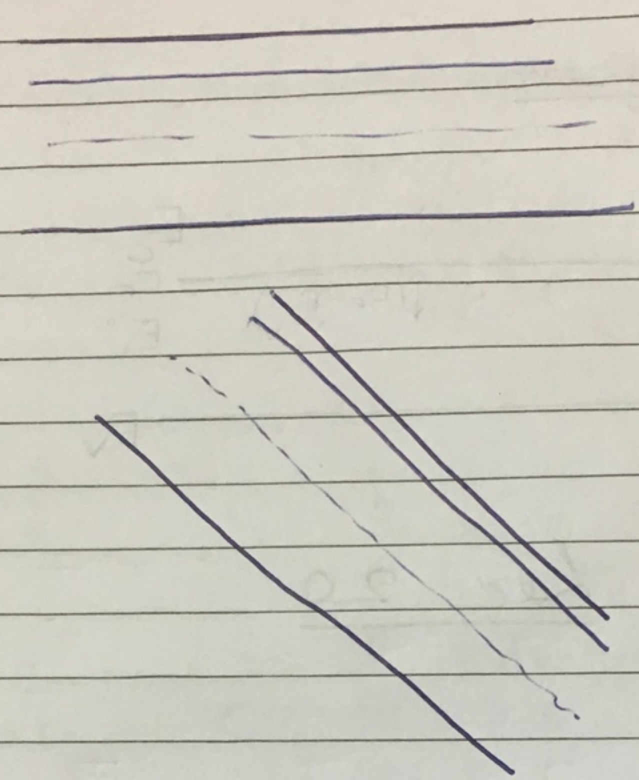
$$\nabla (\varepsilon \underline{E}) = \left(\overset{\delta}{p} - \overset{\delta}{n} + N_D^+ - N_A^- \right)$$

$$J_p = \cancel{q\ldots}\; q \mu_p p E - q D_p \frac{\delta p}{\delta x}$$

$$J_n = q \mu_n n E + q D_n \frac{\delta n}{\delta x}$$

→ Constant and Uniform electric field

(E)



→ Drop Diffusion term (Assume correctly that p & n are uniform throughout the semiconductor)

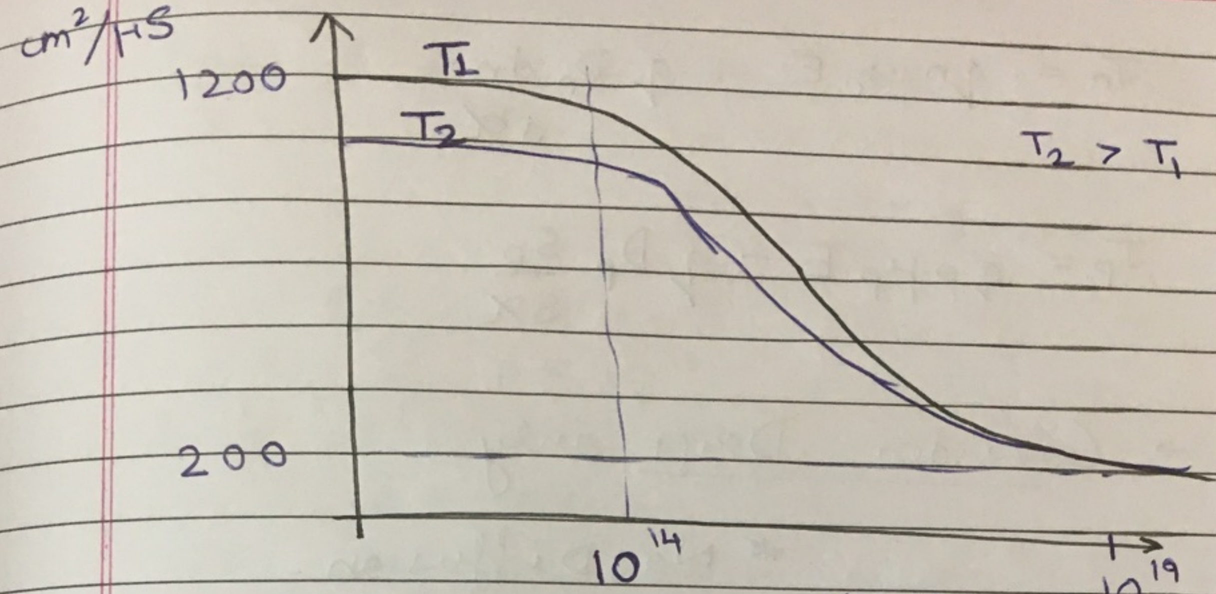
<u>Current</u>

$$J = J_p + J_n$$

$$= q\mu_n n E + q\mu_p p E$$

$$J = \underbrace{q(\mu_n n + \mu_p P)}_{\sigma} E$$

(from $J = \sigma E$)



$N_A + N_D$ ~~N_D / N_A~~

→ conc of ions

carrier

for ↑ speed carriers spends less time near deflector.

With ~~fa~~

1) Lattice atoms ($\mu \downarrow$)

2) Ionic impurities ($\mu \uparrow$)

Lec - 21

Recap

$$\frac{\delta n}{\delta t} = \frac{1}{q} \nabla \cdot J_n - R + G$$

$$\frac{\delta p}{\delta t} = \frac{-1}{q} \nabla \cdot J_p - R + G$$

$$\nabla \cdot (\varepsilon E) = p - n + N_d^+ - N_A^-$$

DATE / /

$$J_n = qn\mu_n E + qD_n \frac{dn}{dx}$$

$$J_p = qp\mu_p E - qD_p \frac{\delta p}{\delta x}$$

→ Consider Drift only

* No Diffusion
* constant E

$$J_n = q\mu_n n E$$

$$J_p = q\mu_p p E$$

$$J = q(\mu_n n + \mu_p p)E$$

Now,

$$J = \sigma E$$

$$\sigma = q(\mu_n n + \mu_p p)$$

Take,

$$\frac{kT}{q} = 25\,mV$$

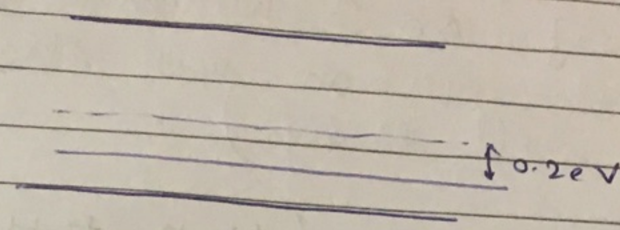
$$n_i = 10^{10}\,cm^{-3}$$

$$\mu_n = \cancel{1000}\ 1200\,cm^2/Vs$$

$$\mu_p = 400\,cm^2/Vs$$

DATE / /

Band



$p \approx 10^{13}$ $\quad n \approx 10^{7}$

$J = \sigma E$

$\sigma = q(\mu_n n + \mu_p p)$ $\rightarrow$ $\div 3$ if $p \approx 10^{13}$

$\sigma \approx 1.8 \times 10^{-3}\ \Omega^{-1}\,cm^{-1}$

$\hookrightarrow$ Hence σ varies with Doping

→ Under Illumination

$G = 10^{17}\ cm^{-3}\,s^{-1}$

$\tau_n = \tau_p = 1\,\mu s$

$\Delta n = G\,\tau_n$

$\Delta n = 10^{17}\ cm^{-3}\,s^{-1} \times 1\,\cancel{\mu s}\ 10^{-6}$

$= 10^{11}\ cm^{-3} = \Delta p$

→ Here low level Injection is valid

$\Rightarrow \quad \sigma = q(1200 \times 10^{11} + 400 \overset{\times 3}{\times} 10^{13})$

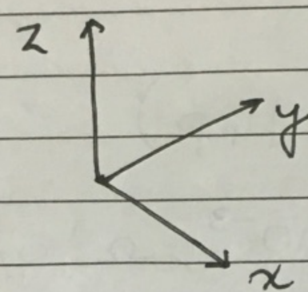
$\sigma \approx 1.8 \times 10^{-3}$ (Still unaffected)

$\div 3$ if $p \approx 10^{13}$

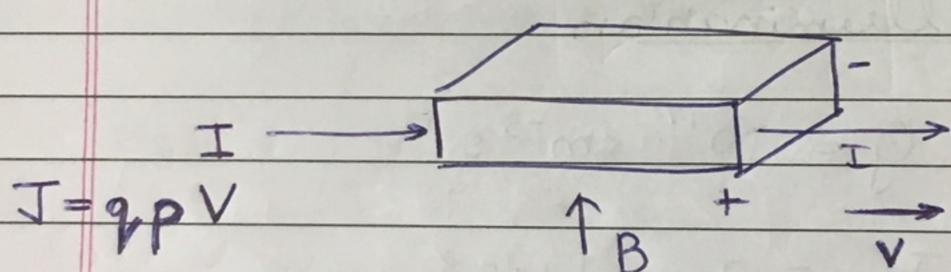
→ Say if $\Delta n \sim 10^{12}\ cm^{-3}$ (Still low level injection but change in σ will be sig.)

→ $\sigma = q(\mu_n n + \mu_p p)$

splitting by hall effect



→ Use hall effect (for Drift only ⇒ Majority carrier)



$$-qBv + qE_y = 0$$

$$-q\frac{BJ}{qp} + qE_y = 0$$

$$\boxed{\frac{E_y}{BJ} = \frac{1}{qp}}$$

→ Get p (Majority) carrier from here.

Diffusion

→ Take $E = 0$, No drift, only diffusion.

$$J_n = q D_n \frac{\delta n}{\delta x}$$

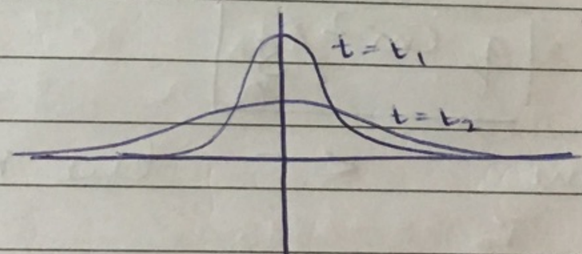
$$J_p = -q D_p \frac{\delta p}{\delta x}$$

Ficks 1st Law of Diffusion

$R = G = 0$ (Equilibrium)

$$\frac{\delta n}{\delta t} = \frac{1}{q}(\nabla \cdot J_n)$$

$$\frac{\delta n}{\delta t} = D_n \frac{\delta^2 n}{\delta x^2}$$



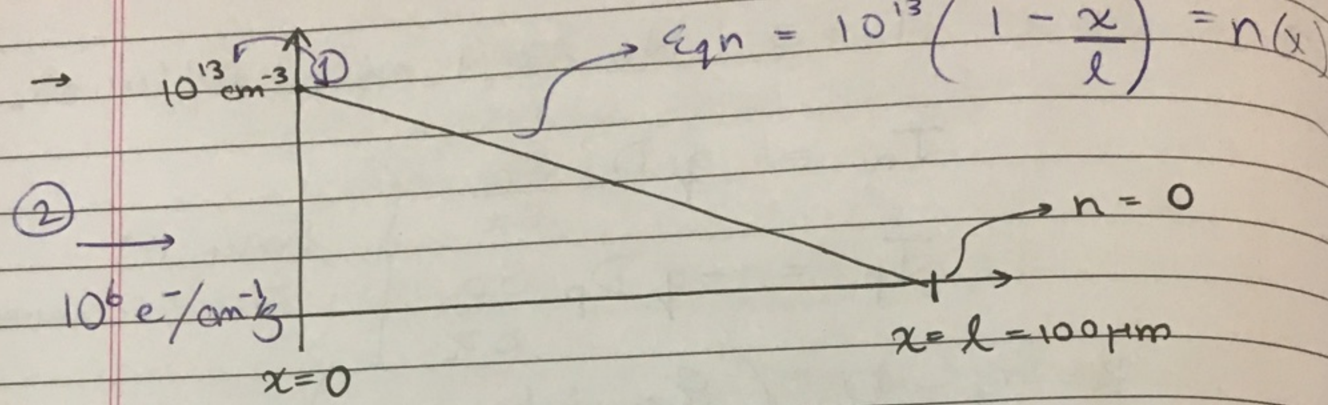
$t_2 > t_1$

In steady state : $\frac{\delta n}{\delta t} = 0$

$\Rightarrow D_n \frac{\delta^2 n}{\delta x^2} = 0$

→ Just like Laplace Equation → V

→ Here in → n



~~n(x)~~ ⇒

$$J_n = (-q)(-D_n)\frac{\delta n}{\delta x}$$

$$J = -q \times (0.025 \times 1200) \times \frac{10^{13}}{100\,\mu m}$$

Unit: $(-q)\; cm^2/s \times \frac{cm^{-3}}{cm}$

$$= \boxed{q\; cm^{-2}/s}$$

→ Here current ← but n →

Case 2

→ Steady state but constant current is being pushed through.

Now find new $n(x)$ soln.

$$n(x) = Ax + B$$

$$n(l) = 0$$

$$D\frac{\delta n}{\delta x}\Big|_{x=0} = 10^{6}\; cm^{-2}/s$$

$$n(x) = \frac{10^6}{D} x + B = 0$$

$\boxed{n(x=l) \; \cancel{10} \; \rightarrow \text{Get } B.}$

Lec - 23

Mid-sem exam

* ASDF
* SDF - Chapter 3
  Carrier Action

Diffusion continued

$$E = 0, \quad R = G = 0 \quad \frac{\delta n}{\delta t} = \frac{\delta p}{\delta t} = 0$$

In 1-D

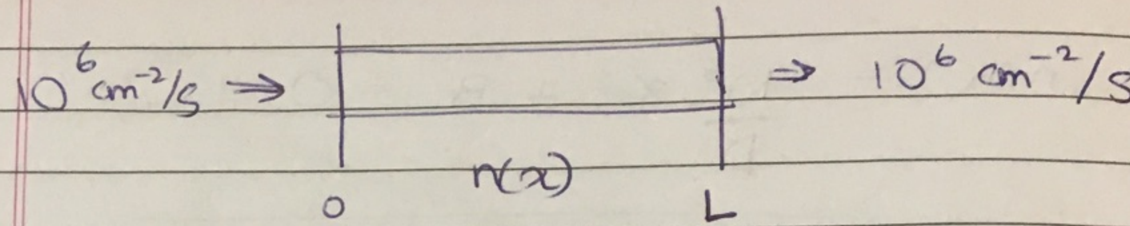
$$0 = D \frac{\delta^2 n}{\delta x^2}$$

case 1: End point conc. specified (Like attaching a battery)

$$n(0) = n_0 \qquad n(L) = 0$$

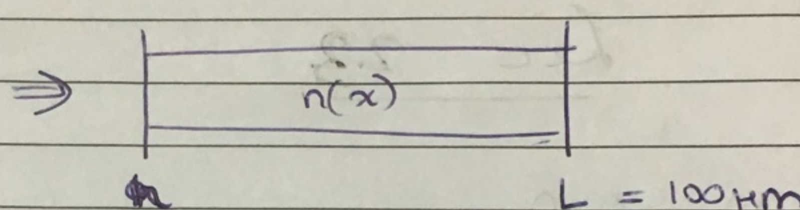
case 2: J through semicond. (Like a constant current source)

$$n(L) = 0 \qquad J_n = -D_n \left. \frac{\delta n}{\delta x} \right|_{x=0}$$



(Last Lecture)

<u>Case 3</u>



$$E = 0, \qquad G = 0 \quad (R \neq 0)$$

but $\frac{\delta n}{\delta t} = \frac{\delta p}{\delta t} = 0$

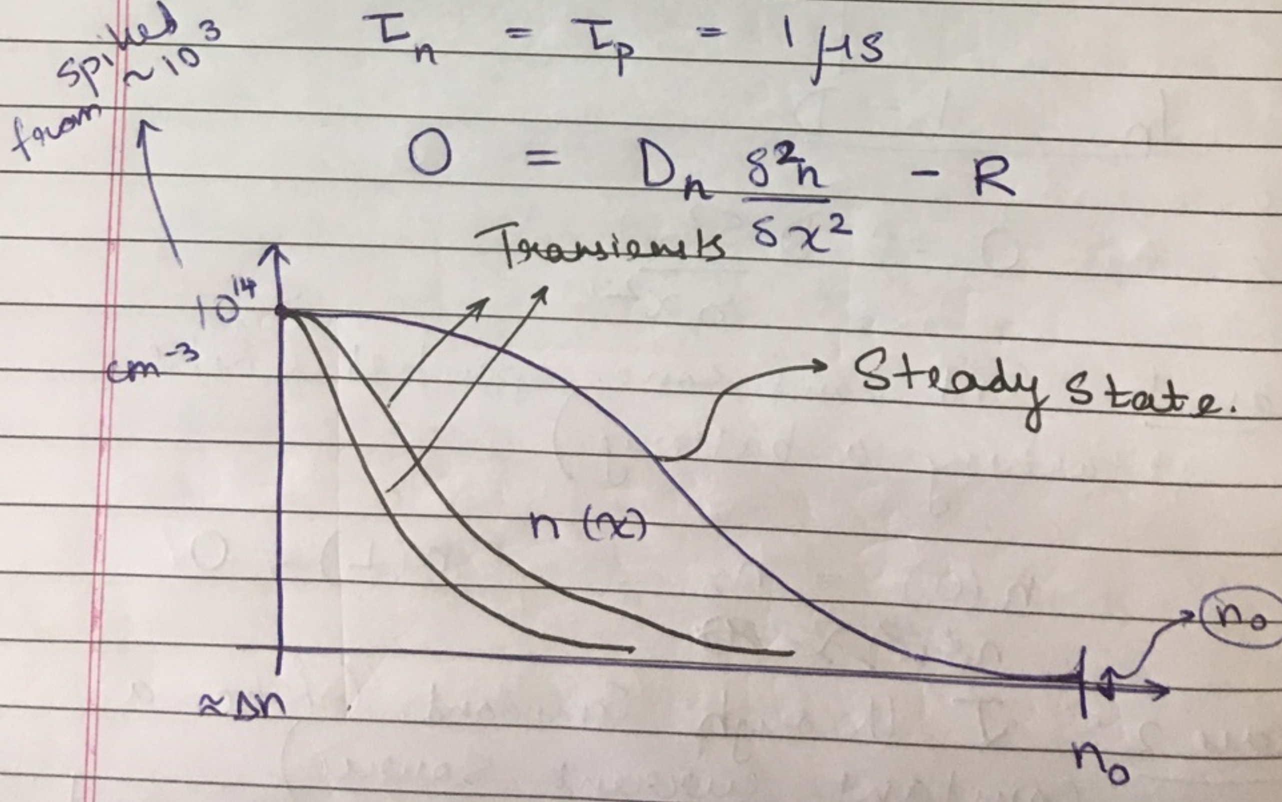
<u>P-Type semi.</u>

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

$n \sim 10^3\ cm^{-3}$

$\tau_n = \tau_p = 1\,\mu s$

$$0 = D_n \frac{\delta^2 n}{\delta x^2} - R$$



→ We have spiked the carrier density at left end, this is not illumination.

Now we shift are Analysis from $n \rightarrow \Delta n$

$$0 = D_n \frac{\delta^2 \Delta n}{\delta x^2} - \frac{\Delta n}{\tau_n}$$

$$\Delta n = A e^{-x/l} + B e^{x/l}$$

→ Let the semiconductor be semi ∞

$$\Delta n(0) \simeq 10^{14}\ cm^{-3} = N$$
$$\Delta n(\infty) = 0$$

$$\Delta n(\infty) = 0 \Rightarrow B = 0$$

$$\Delta n(0) = N = A$$

$$\Delta n = N e^{-x/l}$$

$$l = \sqrt{D_n \tau_n} =$$

→ L finite case also covered

Case : 4

$E = 0$, $g = G_0$ $\frac{\delta n}{\delta t} = \frac{\delta p}{\delta t} = 0$

P - type,

$N_A = p_0 = 10^{17} cm^{-3}$

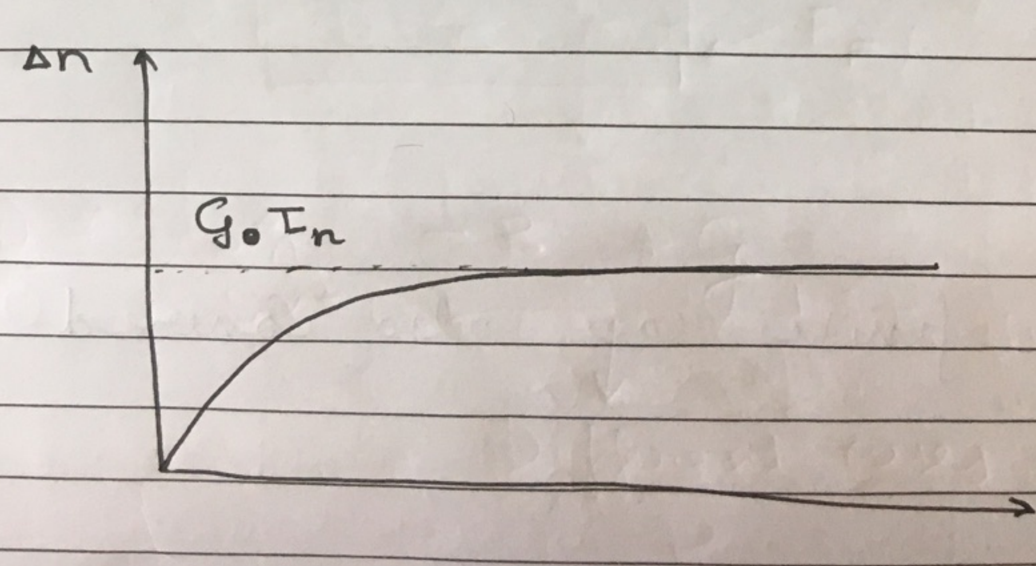
$n_0 \sim 10^3 cm^{-3}$

$\tau_n = \tau_p = 1 \mu s$

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

$$0 = D_n \frac{\delta^2 \Delta n}{\delta x^2} - \frac{\Delta n}{\tau_n} + G_0$$

$$\Delta n = A e^{x/l} + B e^{-x/l} + C$$



→ Friday 15/9/17

TA help session GG 001/102
2:30 - 4:30 pm
6 - 8:30 pm

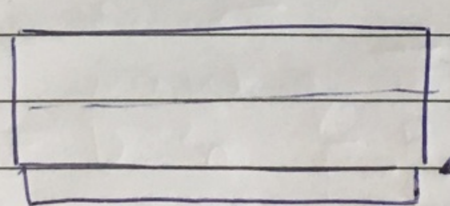
Lec 24

→ Our (Diffusion) Eq^n

$$\frac{\delta n}{\delta t} = \frac{1}{q} \nabla \cdot J - R + G$$

$$J = \underbrace{\cancel{q \mu_n n E}}_{\text{Drift}} \rightarrow 0 \quad + \underbrace{q D_n \frac{dn}{dx}}_{\text{Diffusion}}$$

Steady State → $\frac{dn}{dt} = 0$



E_F

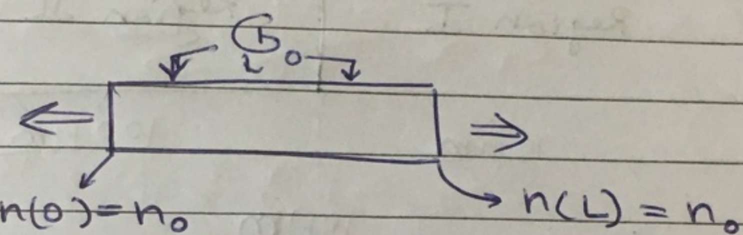
$$0 = D \frac{\delta^2 n}{\delta x^2} \underbrace{- R + G}$$

↓

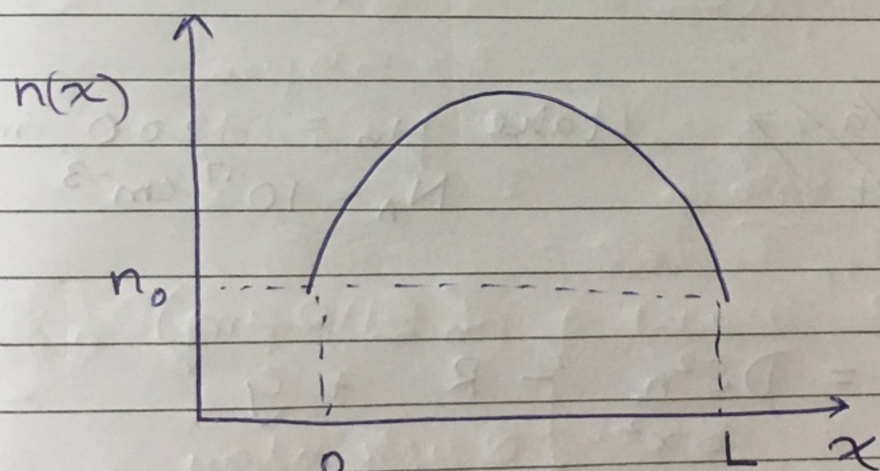
Different cases

$$n(x) = \begin{cases} Ax + B & R = G = 0 \\ \frac{G x^2}{2} + Ax + B & R = 0,\ G \neq 0 \\ Ae^{-x/l} + Be^{x/l} & R \neq 0,\ G = 0 \\ & R \neq 0,\ G \neq 0 \end{cases}$$

→ Uniform Illumination $(G = G_0)$



↓ n(x) profile

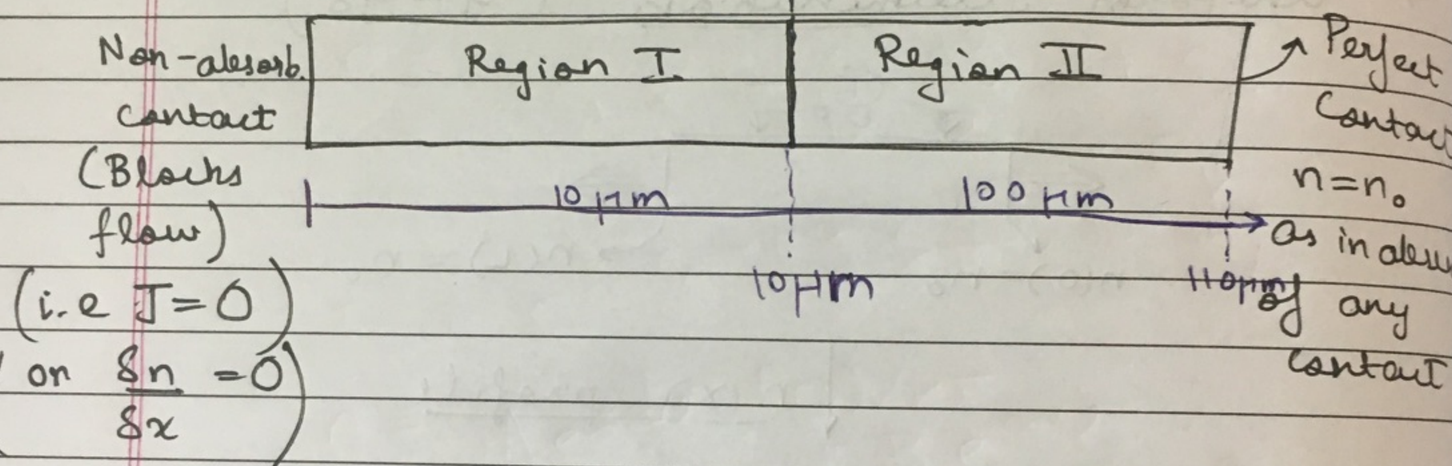


Note that

$$\left| -D\frac{\delta n}{\delta x}\bigg|_{x=0} \right| + \left| -D\frac{\delta n}{\delta x}\bigg|_{x=L} \right| = (G_0 L)$$

→ Complicated case $\left(\frac{\delta n}{\delta t} = 0 \ \because \text{Steady State} \right)$

I	II
$G_0 = 10^{17}\ cm^{-3}/s$	$G_0 = 0$
$\tau_n = \tau_p = \infty$ $\Rightarrow R \to 0$	$\tau_n = \tau_p = 1\ \mu s$



$\cancel{\frac{\delta n}{\delta t}}$ take $\mu_n = 1200\ cm^{-2}/s$

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

$$0 = D\frac{\delta^2 n}{\delta x^2} - R + G$$

Region-1

$$0 = D\frac{\delta^2 n}{\delta x^2} + G_0$$

$$\frac{\delta^2 n}{\delta x^2} = \frac{-G_0}{D}$$

PAGE No.

DATE / /

$$n = -\frac{g_0}{D}\frac{x^2}{2} + c_1 x + c_2$$

Region 2

$$0 = \frac{D\delta^2 n}{\delta x^2} - \frac{\Delta n}{\tau_n}$$

$$\Delta n = (D\tau_n)\frac{\delta^2(\Delta n)}{\delta x^2}$$

$$\left(\frac{1}{k}\right)^2 y = \frac{\delta^2 y}{\delta x^2}$$

$$y = Ae^{-x/l} + Be^{x/l}$$

$$l = \sqrt{D\tau_n} = \sqrt{25\times10^{-3}\times12\times10^{2}\times10^{-6}}$$

$$= \sqrt{25\times12\times\sqrt{10^{-7}}}$$

$$\approx \sqrt{25\times10^{-4}} \to 55\,\mu m$$

$$n(x) = Ae^{-x/l} + Be^{x/l} + \cancel{n_0}^{\,0}$$

background (negligible)

$$n(x) = Ae^{-x/l} + Be^{x/l}$$

$$\underline{\underline{l = 55\,\mu m}}$$

$$J(0) = 0$$

$$\left.\frac{\delta n}{\delta x}\right|_{x=0} = 0 \quad — ①$$

$$n(110\,\mu m) = n_0 \text{ (perfect)} \quad — ②$$

10^3

$$n = c_1 x - \frac{G_0}{D}\frac{x^2}{2} + c_2$$

$$x \in [0, 10\,\mu m]$$

$$n = Ae^{-x/l} + Be^{x/l} \qquad x \in [10\,\mu m, 110\,\mu m]$$

$$l = 55\,\mu m$$

→ <u>Quick soln.</u>

We want $J(110\,\mu m)$ (flux at Right side)

↓ Quick way without finding all coefficients.

$$n(x)\ Ce^{-x/l} + De^{x/l}$$

PAGE No. | DATE / /

variable transform

$10\mu m \rightarrow 0\mu m$

$110\mu m \rightarrow 100\mu m$

$$J\Big|_{x=\cancel{l}\ 10\mu m} = D\frac{\delta n}{\delta x}\Big|_{x=10\mu m} = g_0 \times 10\mu m \quad -(1)$$

Uniform Generation

2^{nd} eqn

$$n = \cancel{n_0}^{\,10^3} \text{ at } x = 100\mu m$$

$$\Delta n = 0 \text{ at } x = 100\mu m$$

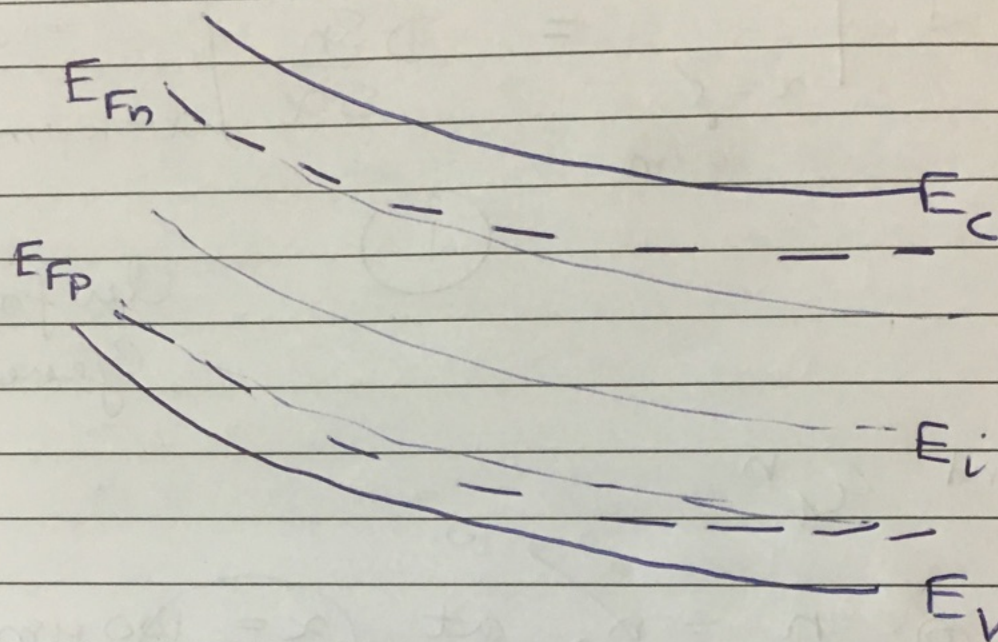
Shifted x

Get C & D

μm

DATE / /

→ Band Diagram Question



$$n = n_i e^{(E_{F_n} - E_i)/kT}$$

$$p = n_i e^{(E_i - E_{F_p})/kT}$$

$$J_n = nq\mu_n E + qD_n \frac{\delta n}{\delta x}$$

$$\overset{n}{\cancel{n_i e^{(E_{F_n} - E_i)/kT}}} \quad q\mu_n E + qD_n \frac{\cancel{n}}{kT}(E_{F_n}' - E$$

$$n\left(q\mu_n E + \frac{qD_n}{kT}\left(\frac{E_{F_n}'}{dx} - \frac{E_i'}{dx}\right)\right)$$

DATE / / /

$$\boxed{\frac{D}{\mu_n} = \frac{kT}{q}}$$

$$n\left(q\mu_n E + \mu_n\left(\frac{dE_{Fn}}{dx} - \frac{dE_i}{dx}\right)\right)$$

$$E = \frac{dV}{dx}$$

$$\Rightarrow \quad E_e = -q\,V(x)$$

$$E(x) = \frac{1}{q}\left(\frac{dE_c}{dx}, \frac{dE_v}{dx}, \frac{dE_i}{dx}\right)$$

$- E_i'$) $\times n$

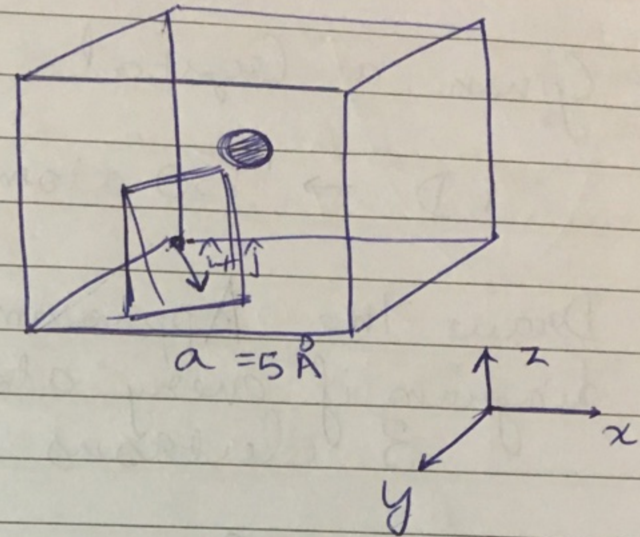
$$n\left(\mu_n \frac{dE_i}{dx} + \mu_n\left(\frac{dE_{Fn}}{dx} - \frac{dE_i}{dx}\right)\right)$$

$$J = \boxed{n\mu_n \frac{dE_{Fn}}{dx}}$$

Last concept in Midsem

Tut - 1

Q-1)

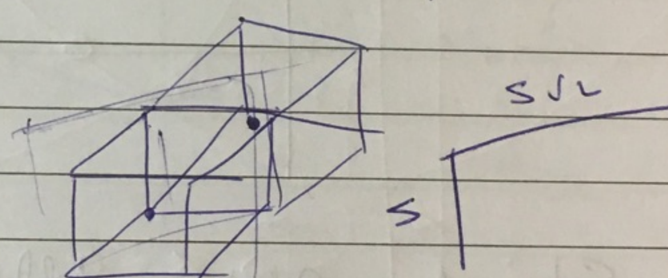


(110) plane density of atoms

$\rightarrow$ Miller Indices, Inverse of Intercepts

$\hat{n} = \hat{i} + \hat{j}$

1 atom per 5 Å × 5√2 Å



1 atom for

$$\frac{1}{25\sqrt{2}} \times 10^{30} \,/m^2$$

$\cancel{5.66 \times 10^{27} /m^2}$

$2.82 \times 10^{28} / m^2$

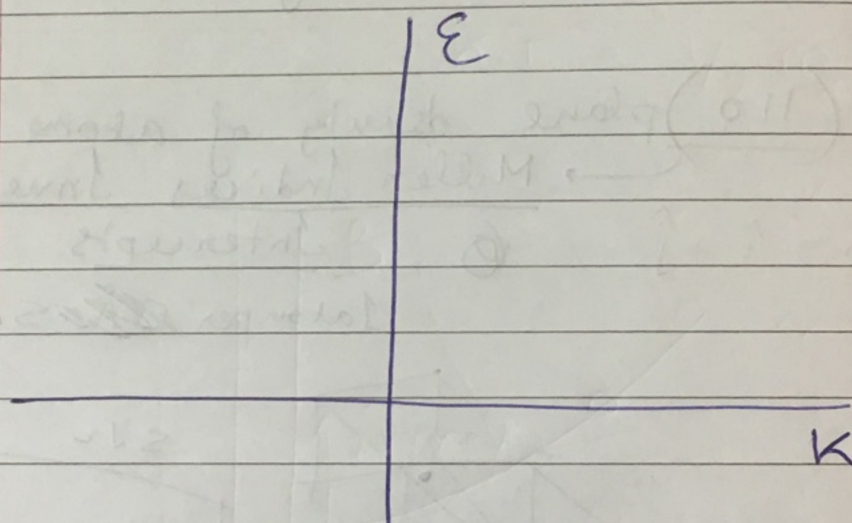
$\cancel{5.66 \times 10^{23} /cm^2}$

$2.82 \times 10^{24} / cm^2$

Q-2) Given a Crystal

1D → 150 atoms

Draw the Approximate $\mathcal{E}$-k diagram if every atom has 3 electrons



Step 1: Obtain Allowed values of K

$$e^{ik(x)} = e^{ik[(Na)+x]}$$

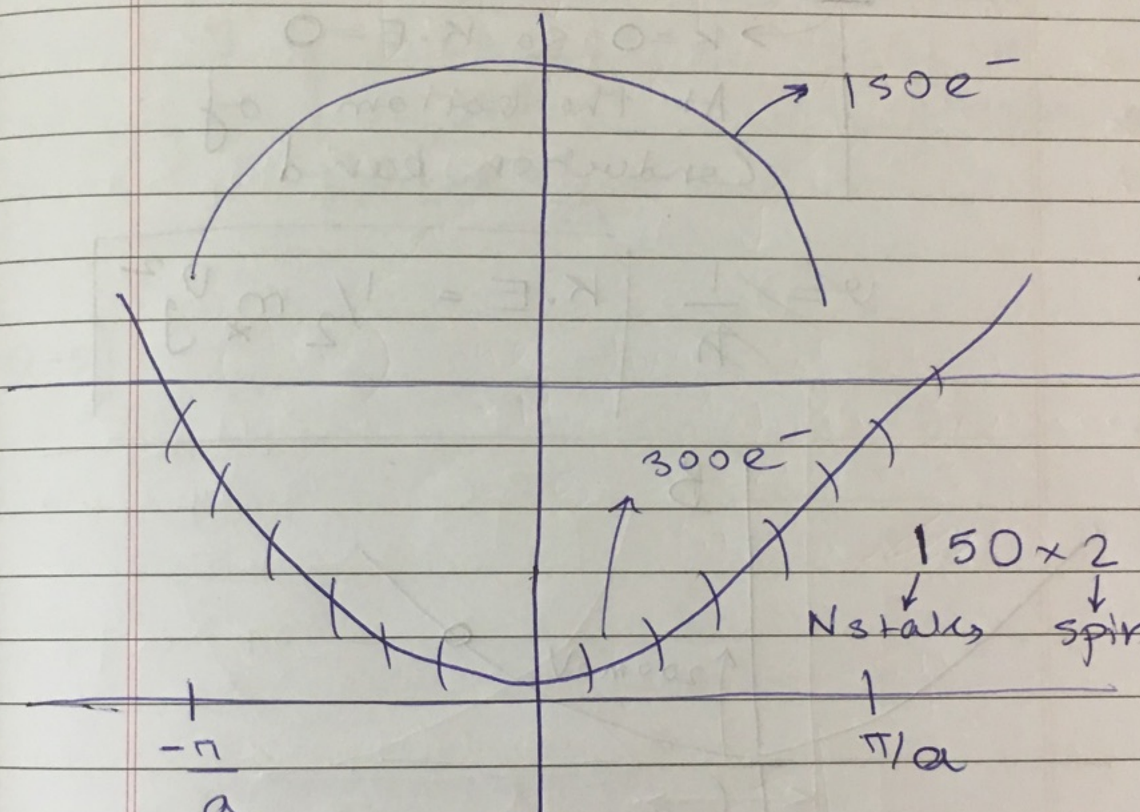
$$e^{ikNa} = e^{i2\pi n}$$

$$KNa = 2\pi n$$

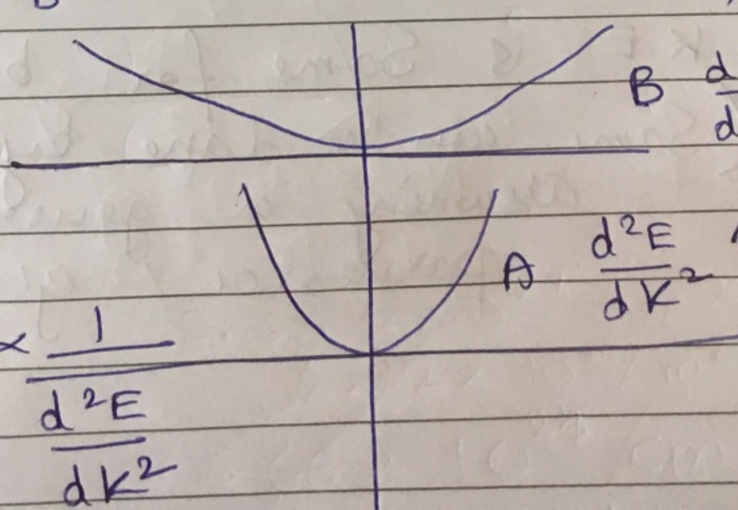
$$K = \frac{p^2}{2m}$$

$$k = \frac{2\pi n}{K N a}$$

N = 150
total number of atoms

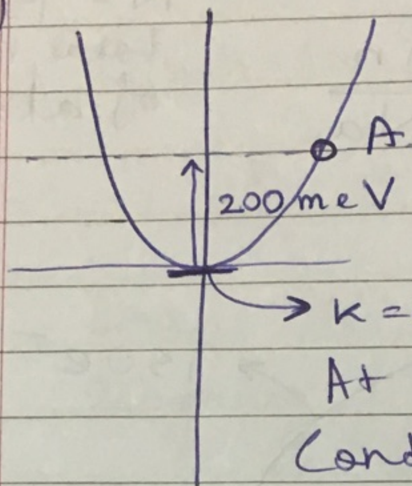


Q-3) $\frac{m^*_A}{m^*_B} < 1$ if Diagram looks like



Since $m^* \propto \frac{1}{\frac{d^2E}{dK^2}}$

A

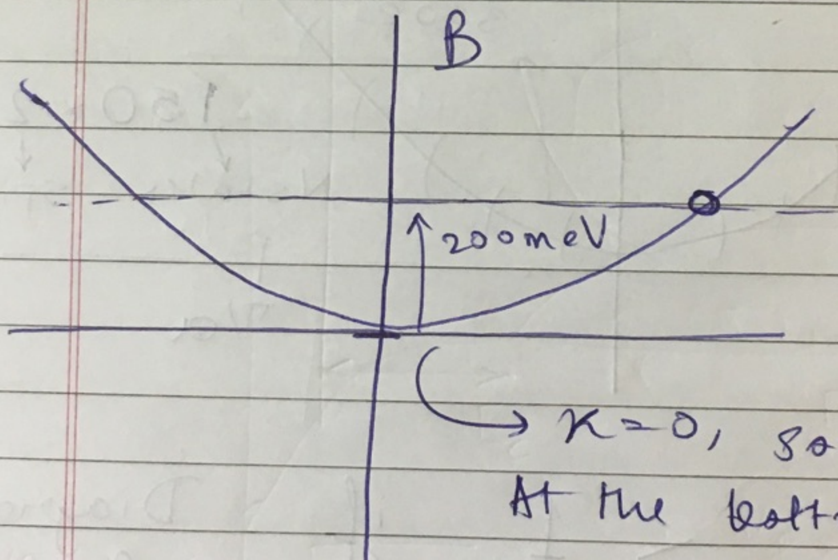


$$v = \frac{1}{\hbar}\frac{dE}{dk}$$

$k = 0$ so $K.E = 0$

At the bottom of conduction band

$$\cancel{v = \frac{1}{\hbar}} \quad \boxed{K.E = \frac{1}{2} m_* v_g^2}$$



$k = 0$, so $K.E = 0$

At the bottom,

So $K.E = 0$

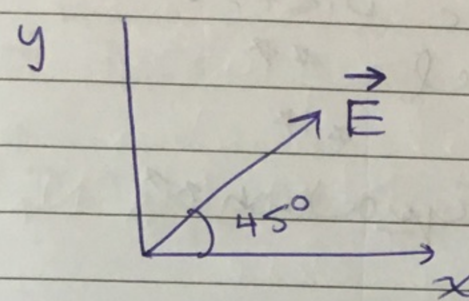
$\Rightarrow$ K.E is Same for both

(Same can be done by assuming a general parabola $y = ak^2$)

$\frac{dE}{dk}$

Q-4) $$\boxed{\mathcal{E}(k) = \frac{\hbar^2 k_x^2}{2m_1} + \frac{\hbar^2 k_y^2}{2m_2}}$$

$\mathcal{E} - k$ Dispersion



Q-5)

2)

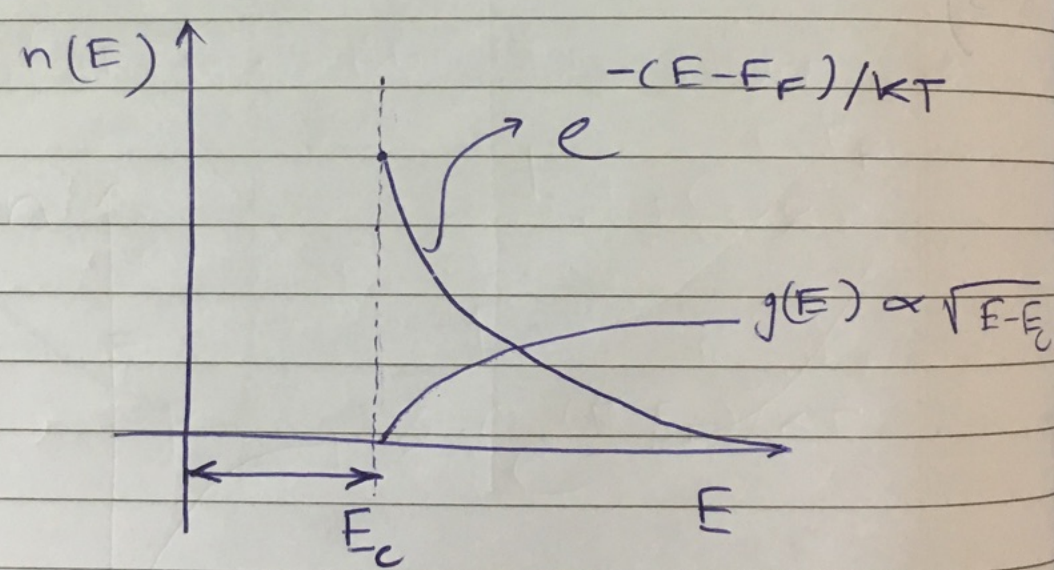
Equilibrium Carrier Conc.

Agenda

- ★ DoS ✓
- ★ Fermi Dirac Dist. ✓
- ★ Fermi Level ★★
- ★ Doping ★★
- ★ Poissons Equation ★★

DoS

→

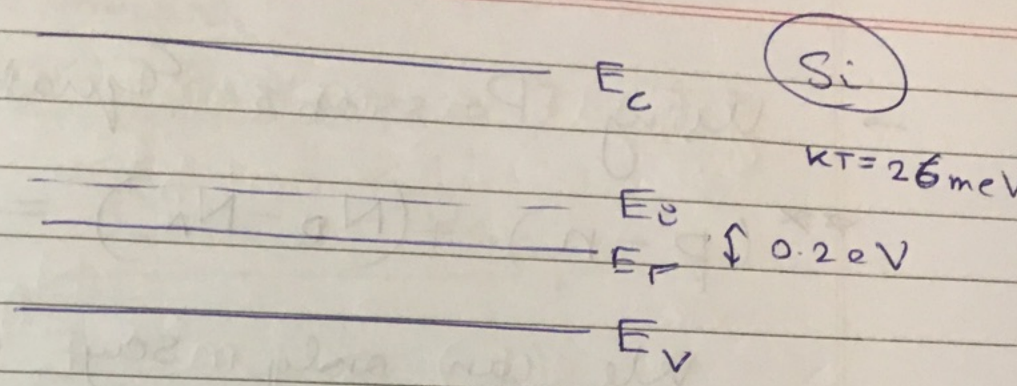


$$n(E) \propto \sqrt{E-E_c}\, e^{-(E-E_F)/kT}$$

↓

Approximating to Boltzman.

Q →



⇒ P Doped

$$P = 10^{10}\, e^{\overset{200\,meV}{(E_F - E_V)}/26\,meV}$$

$$P = P_i\, e^{(E_i - E_F)/26\,meV}$$

$$e^{\frac{200}{26}}$$

$$\Rightarrow \boxed{2.19 \times 10^{13}\ cm^{-3}}$$

$\Rightarrow N_D \sim 2.19 \times 10^{3}\ cm^{-3}$

→ But it is also possible that :

$$\begin{cases} N_A = 3.19 \times 10^{13} \\ N_D = 1.00 \times 10^{13} \end{cases}$$

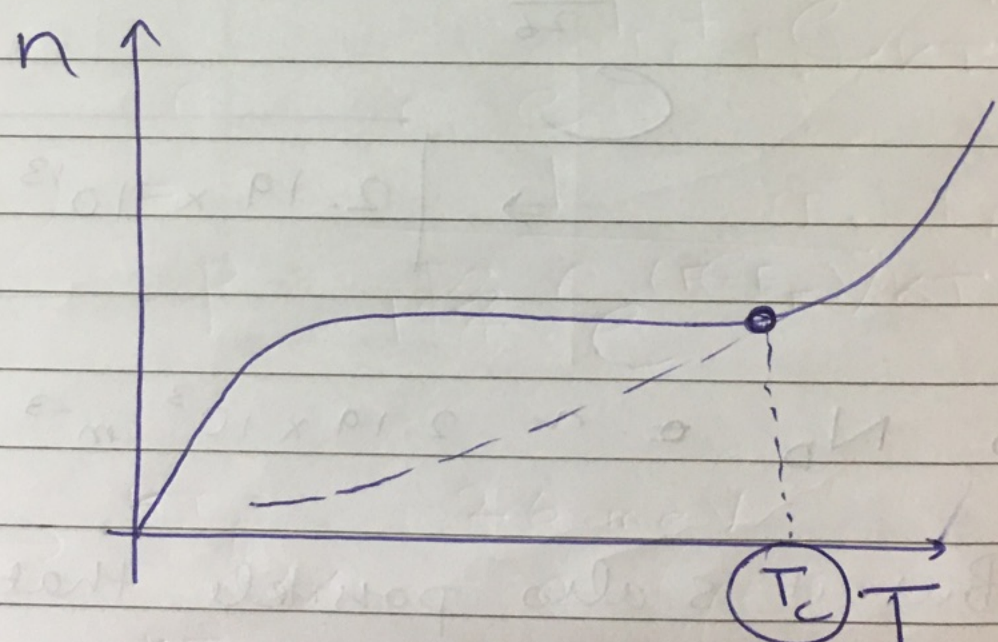
→ Net Result is same

→ Using Poisson's Equation

$$(p-n)+(N_D-N_A)=0$$

We can only say the total number of holes is $p=N_A-N_D$ nothing else

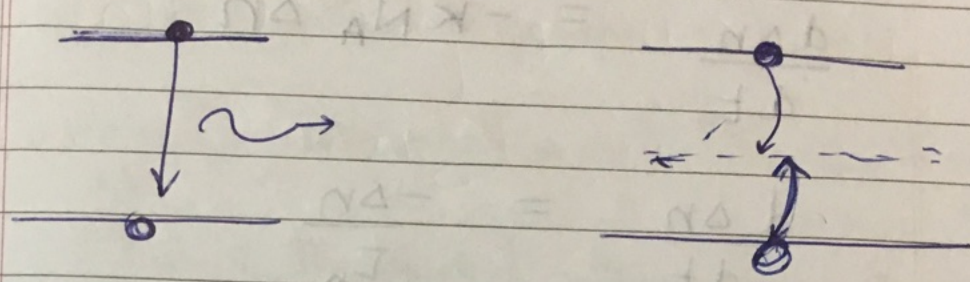
Q → Estimate the temperature at T



$$n_i \propto e^{-E_g/2kT}$$

Tut - 3

Recom - Gen



Equations

$$\frac{dn}{dt} = -K\,(np - n_i^2)$$

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p\,(n + n_1) + \tau_n\,(p + p_1)}$$

Equilibrium

Ex Say,

$$\tau_n = \tau_p = 100\,\mu s$$

with,

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

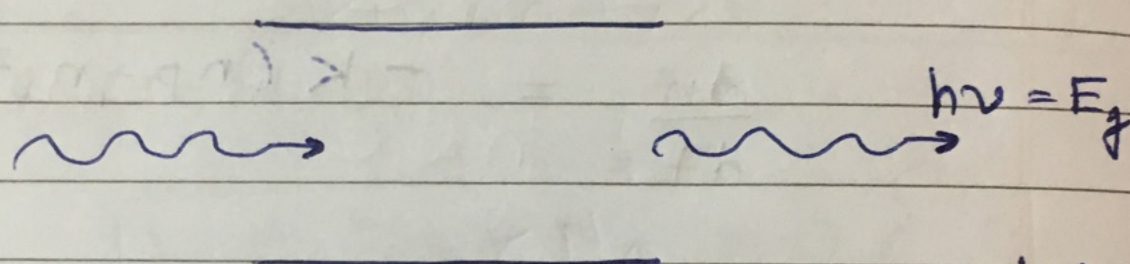
→ Rate of Recomb. = ?

→ Rate of thermal gen = ?

$$\frac{d\Delta n}{dt} = -K N_A \Delta n$$

$$\frac{d\Delta n}{dt} = \frac{-\Delta n}{\tau_n}$$

Q →



$$\text{Efficiency} = \frac{N(E_g)}{N_{input}}$$

All above E_g

→ $\dfrac{\text{No. of } E_g \text{ photons out}}{\text{Total input photons}}$

→ Radiative Recom.

$$\frac{d\Delta n}{dt} = -K(np - n_i^2) \xrightarrow{App:} \frac{d\Delta n}{dt} = -KN_A\Delta n$$

→ SRS (Thermal) $\xrightarrow{App.}$ $\frac{d\Delta n}{dt} = \frac{-\Delta n}{\tau_n}$

$$\frac{d\Delta n}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

App.

Combined Rate

$$\frac{d\Delta n}{dt} = -KN_A\Delta n - \frac{\Delta n}{\tau_n}$$

Irradiation

$$= -KN_A\Delta n - \frac{\Delta n}{\tau_n} + G = 0$$

spits out photons

No photons

In unit time

$$\text{Efficiency} = \left(\frac{KN_A}{KN_A + \frac{1}{\tau_n}}\right)$$

Derivation

$$\eta = \frac{K N_A \Delta n}{G}$$

$$= \frac{K N_A \Delta n}{K N_A \Delta n + \frac{\Delta n}{\tau_n}}$$

$$\boxed{= \frac{K N_A}{K N_A + \frac{1}{\tau_n}}}$$

Direct B.G Mat.

Given
$$\left\{ \begin{aligned} K &= 10^{-10}\ cm^{-3}/s \\ \tau_n &= 100\ \mu s \\ N_A &= 10^{17}\ cm^{-3} \end{aligned} \right.$$

$$= \frac{10^{-10} \times 10^{17}}{10^{-10} \times 10^{17} + 10^{4}} \approx 1$$

$$\approx 1$$

Case - II

$k = 10^{-15}\ cm^{-3}/s$

→ Indirect BG Mat.

$$\approx \frac{10^2}{10^4} \approx 0 \text{ (Low)}$$

Case III

Q→ Given a semi. cond. All holes and e^- combine such that no e^-/hole left, how much time to return to equilibrium (Intrinsic Semicond., at $t=0$ all carriers are depleted)

n_i

n_i

$$\frac{d\Delta n}{dt} = -\cancel{k N_A \Delta n^2}$$
$$-k(np - n_i^2)$$

Case 1: Creation using only B2B

$$\frac{d\Delta n}{dt} = -k(n^2 - n_i^2)$$

$n << n_i$ for most time

$$\frac{d\Delta n}{dt} = k n_i^2$$

$$\cancel{t} = n_i$$

$(k n_i^2 \Delta t) \approx n_i$ ✓✓

Lowers Δt

→ Using Trap levels near mid-band

$-(np - n_i^2)$

$$\overline{I_p(n+n_1) + I_n(p+p_1)}$$

$n_i e^{-(\,)}$ $\quad$ $n_i e^{-(\,)}$

$n = p \approx 0$

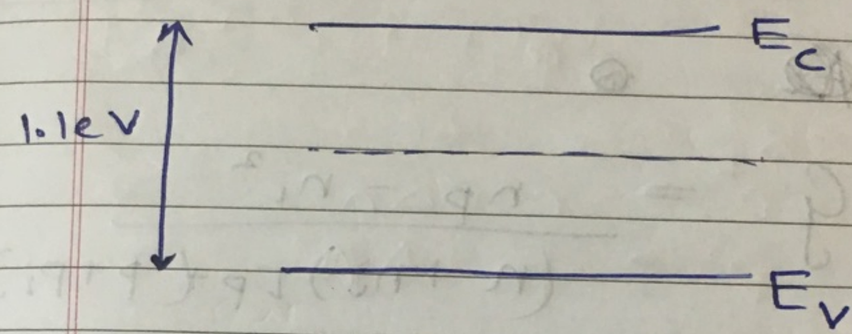
$$= \frac{n_i^2}{I_p n_1 + I_n p_1}$$

~~Around mid band~~

$n_1 \approx p_1 \approx n_i$

$$\frac{d(\Delta n)}{dt} = \left(\frac{n_i}{\tau_p + \tau_n} \right)$$ Lower bound on Δt

Q → $G = 10^{18}\ cm^{-3}/s$



$\tau_n = \tau_p = 10^{-6}s$

~~Efn~~ $E_{F_n} - E_{F_p} = ?$

For, (Consider only SRH)

(a) Intrinsic

(b) Doped with $N_d = 10^{17} cm^{-3}/s$

(a) $\frac{d\Delta n}{dt}$

$$n = n_i e^{(E_{Fn} - E_i)/KT}$$

$$p = n_i e^{(E_i - E_{Fp})/KT}$$

Only SRH

$$\Rightarrow \boxed{G = \frac{np - n_i^2}{(n+n_1)\tau_p + (p+p_1)\tau_n}}$$

$$G = \frac{np - n_i^2}{(n+n_i)\tau_p + (p+p_i)\tau_n}$$

$n_1 = p_1 \approx n_i$ (Trap at mid gap)

$n = p$ (Intrinsic)

$$G = \frac{n^2 - n_i^2}{(n+n_i)(\tau_p + \tau_n)}$$

$$G = \frac{n - n_i}{\tau_p + \tau_n}$$

Date
Page

$n = p \Rightarrow \quad E_{Fn} - E_i = E_i - E_{Fp}$

$E_{Fn} + E_{Fp} = 2E_i$

$\underbrace{G}_{10^{18}} (I_p + \underbrace{I_n}_{10^{-6}}) + \underline{\underline{n_i}}^{\,10^{-10}}$

$\approx G (I_p + I_n)$

$= 10^{18} \times 2 \times 10^{-6}$

$= 2 \times 10^{12}$

$= n_i e^{(E_{Fn} - E_i)/kT}$

$\ln\left(\dfrac{2 \times 10^{12}}{10^{10}}\right) = \dfrac{E_{Fn} - E_i}{kT}$

$\boxed{\ln(2 \times 10^2) \times kT}$

$= E_{Fn} - E_i$

$2 \times \ln(2 \times 10^2) \times kT$

(b) **Doped** ($10^{17} = N_d$)

$$g = \frac{np - n_i^2}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$$n \rightarrow n + \Delta n$$
$$p \rightarrow p + \Delta p$$

$$g = \frac{(n+\Delta n)(p+\Delta p) - n_i^2}{\tau_p(n + \Delta n + n_1) + \tau_n(p}$$

$\downarrow$ Mid level traps

$$\cancel{np} + \frac{\Delta n(n+p) - \cancel{n_i^2}}{\tau_p(n)}$$

$$\approx \frac{\Delta n}{\tau_p} = g$$

$$\Delta n = 10^{18} \times 10^{-6}$$
$$\approx 10^{12}\ \text{cm}^{-3}$$

→ <u>End Results to Remember with Irradiation</u>

$$\frac{dn}{dt} = -K(np - n_i^2)$$

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$$\left\{\begin{array}{l} n_0 = n_i e^{(E_F - E_i)/KT} \\ p_0 = n_i e^{(E_i - E_F)/KT} \end{array}\right.$$

→ <u>Equilibrium Equations</u>

→ <u>Irradiation</u>

G → Rate of Absorption / Generation of photons.

$$n = n_0 + \Delta n$$
$$p = p_0 + \Delta p$$

$\Delta n = \Delta p$ (Pairwise)

$$\frac{dn}{dt} = -k(np - n_i^2) + G_{photon}$$

$$\frac{dn}{dt} = -k\left[(n_o + \Delta n)(p_o + \Delta n) - n_i^2\right] + G_{photon}$$

$$= -k\left[\cancel{n_o p_o} + \Delta n(n_o + p_o) + \cancel{(\Delta n)^2}^{\,0} - \cancel{n_i^2}\right] + G_{photon}$$

$$\frac{\delta n}{\delta t} = -k(n_o + p_o)\Delta n$$

(2^{nd} order term Δn Ignored)

called low level ionidation

$$\frac{\delta(\Delta n)}{\delta t} = -k(n_o + p_o)\Delta n + G_{photon}$$

Rewrite

$$\frac{\delta(\Delta n)}{\delta t} = \frac{-\Delta n}{\tau_{eff}} + G_{photon}$$

where $\tau_{eff} = \dfrac{1}{k(n_o + p_o)}$

Typical k values

GaAs → 10^{-10}
Si → 10^{-15} (Indirect BG)

Say,
$G = 10^{16}$ photons cm^{-3}/s

then,
$$\tau_{eff} = \frac{1}{10^{-15}(10^{17}+10^{3})}$$

Doped N_D ~ 10^{17}

τ_{eff} = 10 mS

→ ** Avg. lifetime post excitation = 10mS **

Steady state, $\frac{\delta(\Delta n)}{\delta t} = 0$

$$\boxed{\Delta n = G_{photon} \times \tau_{eff}}$$

$\Delta n = G\,\tau_{eff}$
Here $= 10^{16} \times 10^{-2} = 10^{14}$
Ans → 10^{14} cm^{-3}

Date
Page

High Level Irradiation

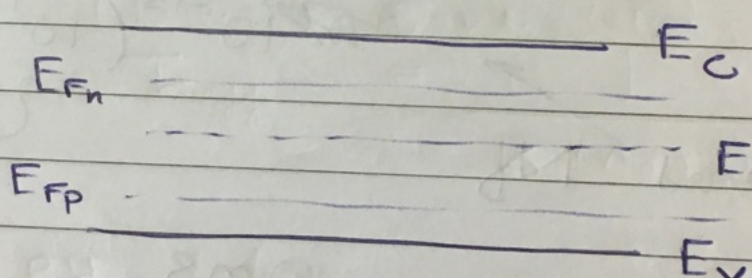
$$G = 10^{22}\ cm^{-3}/s$$

$\hookrightarrow$ Get $\Delta n = 10^{20}\ cm^{-3}$

Quasi - Fermi Levels

$$n = n_i\, e^{(E_{F_n} - E_i)/kT}$$

$$p = n_i\, e^{(E_i - E_{F_p})/kT}$$



→ SRH recombination with Irradiation G

Get,

$$R = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$$\rightarrow \quad \frac{\delta(\Delta n)}{\delta t} = \frac{-\Delta n}{\tau_{eff}} + G$$

$$\tau_{eff} = \frac{1}{K(n_0 + p_0)}$$

<u>Irradiation with SRH</u>

$$n \rightarrow n_0 + \Delta n$$
$$p \rightarrow p_0 + \Delta n$$

$$\frac{dn}{dt} = \frac{-(np - n_i^2)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$\tau_p \sim \tau_n$ (Same order)

<u>Say N_D doped</u>

$$\frac{dn}{dt} = \frac{-\left(\cancel{n_0^2 - n_i^2} + \Delta n(n_0+p_0) + (\Delta n)^2\right)}{\tau_p(n+n_1) + \tau_n(p+p_1)}$$

$$= \frac{-\Delta n(n_0+p_0)}{\tau_p(n+n_1) + \cancel{\tau_n \overset{\approx 0}{(p+p_1)}}}$$

$$= \frac{-\Delta n \overset{\approx n_0}{(n_0+p_0)}}{\tau_p \underset{\approx n_0}{(n+\cancel{n_1})}}$$

↓ End Result

$$R = \frac{-\Delta n}{\tau_p}$$

for N - type

Minority carrier lifetime.

R.L formulas

B2B (Direct Band Gap)

$$\tau_{eff} = \frac{1}{K(n_0 + p_0)}$$

SRH (Indirect Band Gap)

Doped $\begin{cases} \tau_{eff} = \tau_p \rightarrow \text{N type} \\ \quad\;\; = \tau_n \rightarrow \text{P type.} \end{cases}$

SRH for Intrinsic Semiconductor

$$\frac{-(\Delta n)^2}{(\tau_p + \tau_n)\Delta n}$$

$$= \frac{-(\Delta n)}{(\tau_p + \tau_n)}$$

$$\frac{\delta(\Delta n)}{\delta t} = \frac{-\Delta n}{\tau_{eff}} + g$$

$$\tau_{eff} = (\tau_n + \tau_p)$$