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DEVICES

EE 207

EE-207
Electronic Devices & CKts

(Book:- Anderson & "fundamental of S C devices")

Some Devices ⟶ BJT, MOSFET, Diode, JFET, Relay, Thyristors, UJFET, HEMT, Memory Devices

↓

Eg. neuromorphic Computing, IOT Devices....

Digital CKts :- 2~3 Giga Hz.

4G Speed → 5 - 10 GHz

5G Speed → 5 - 20 GHz

Digital CKts → Purely based on mosfet

Midsem - 30%

Endsem - 70%

Quizzes - graded

SEMICONDUCTORS

Grp IV S.C → Si : Si {Equally Shared e^- b/w both atoms} → Proper Covalent Bond

↳ Isotype Semiconductor

Grp III-V S.C. → GaN ← An-isotype Semiconductor (distinct atoms) {e^- more drawn towards N}

↓

Covalent Bond / (Polar Bond)

↳ BRAVAIS LATTICE :- atoms arranged in a certain Config^n **

Eg → Simple Cubic, FCC (face Centered Cubic), BCC

Simple Cubic → every Corner

BCC → every Corner + 1 @ Centre of Cube

FCC → every Corner + 1 @ every face

Note → Silicon is FCC + FCC (Basis → 1 Si atom.)

fused diagonally ≡ Diamond Cubic Structure

GaN ≡ Hexagonally Closed Packed Structure (HCP)

Si → Crystal Structure → Lattice (Diamond Cubic) + Basis (Si atom)

↳ Driving force for formation of Crystal
↳ minimization of energy

Cost, Amorphous < Poly Cryst. < Crystal

Crystal → ordering in micron. → Costliest
Poly-Crystalline → like grains
Amorphous - in
↓
Cheapest

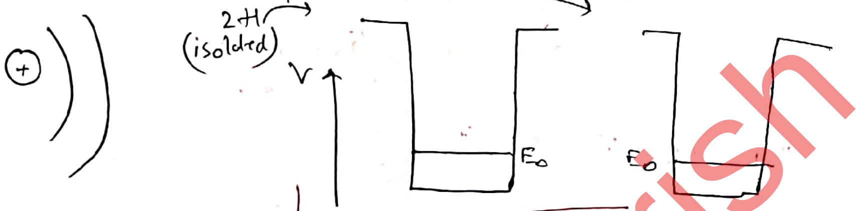
ENERGY BAND DIAGRAM

why is energy quantized?
↓
Duality Principle $\left(mvr = \frac{nh}{2\pi}\right)$

Waves ⟷ matter
|
Schrodinger Eq^n (hypothesis)

Current-Voltage
↓
flow of e^-
↓
e^- in a Crystal Structure

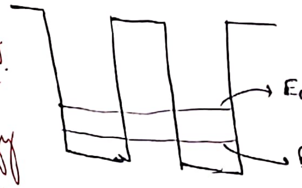
Potential wells



E_0 → ground level energy

when brought together

Splitting of Energy levels

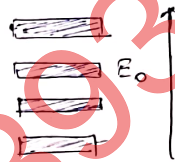


→ $E_0 + \Delta E$ (Antibonding State)

→ $E_0 - \Delta E$ (Bonding State)

In a Crystal Structure;
↓
order of $10^{23\sim24}$ atoms / cm^3

as we bring more & more atoms; a band starts to form due to splitting
↓

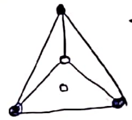


Energy Band Structure;

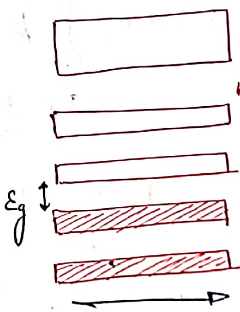
EXCLUSION
Pauli's Principle
filling electron
⇓
mostly lower level first

if we magnify a band; we start seeing distinct (Pauli's principle) energy levels; but separation is very small.

Si, 4 valence e^-



Tetrahedral Structure



e^- @ T=0K

Completely empty

Completely filled.

@ 0K; all e^- are held by Covalent Bond, no. electrons (e^-) available for Conduction

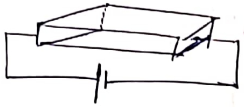
E_g → Bandgap.

Semiconductor → E_g is small

Insulator → E_g is large ($E_g > 4eV$)

Metal → ~~$E_g > 4eV$~~ half filled band at 0K
Partially

In metal @ 0 Kelvin :



almost empty = Conduction
most

Partially ~~filled~~ filled band @ 0 Kelvin

filled band
Topmost ~~Valence~~ = Valence Band

metal → e^-'s are free | when a e^- is moving in a metal ckt freely

$F_{int} + F_{ext}$

$m_e = 9.11 \times 10^{-31}\ kg$

Chng to m'

$p = \hbar K$

$K = \frac{2\pi}{\lambda}$

free e^- ;

$p = mv$ | $\varepsilon = \frac{p^2}{2m_e}$ — (1)

$\varepsilon = \frac{1}{2}mv^2$

$p = \hbar K$ → De broglie wavelength $\{ p = \frac{h}{\lambda} \}$

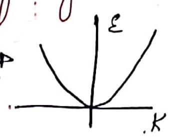
$K = \frac{2\pi}{\lambda}$ — (2)

$\Rightarrow p = \frac{hK}{2\pi}$

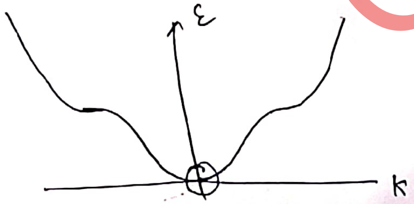
By (1) & (2);

$\varepsilon = \frac{\hbar^2 K^2}{2m_e}$ → E-k relation of a free elc.

a/k/a Dispersion Relation



E-k relation in a Semiconductor



Expanding ε about encircled pt;
& $\boxed{K_0 = 0}$

$\varepsilon = \varepsilon_0 + \cancel{\frac{\partial \varepsilon}{\partial K}}_{0} + \frac{1}{2}\frac{\partial^2 E}{\partial K^2}K^2 + \ldots [\ldots]$

Hence; for Semiconductor;

(for S.C.) $E = E_0 + \frac{1}{2}\frac{\partial^2 E}{\partial K^2}K^2$

P.E → KE

$V_g = \frac{1}{\hbar}\cdot\frac{dE}{dK}$ → vel. of free

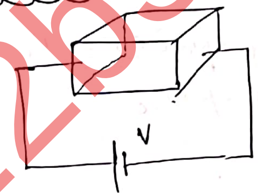
(~~for metal~~) ; (free e^-) ⇒ $E = \frac{\hbar^2 K^2}{2m_e} = \frac{\partial^2 \varepsilon}{\partial K^2}K^2$

E-K curve parabolic
$\therefore \frac{\partial^2 \varepsilon}{\partial K^2} = \text{Const.}$

$m_{eff} / m^* = \hbar^2 \cdot \left(\frac{\partial^2 E}{\partial K^2}\right)^{-1}$

eg: for Silicon
$m_* = 0.2m_0$

if m^* is less, inertia will be less



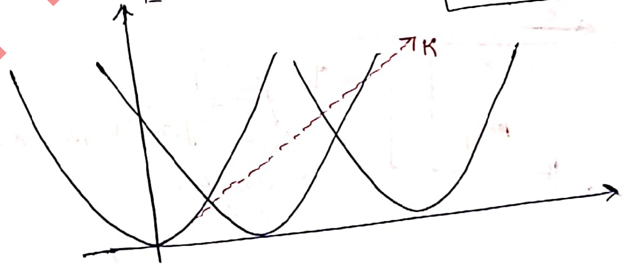
$|\varepsilon| = V/L$

$F = -q\varepsilon$

$\frac{\hbar^2 K^2}{2m_e} = \varepsilon$

$\boxed{= -q\frac{V}{L} = m^*\frac{dV_d}{dt}}$

force on e^- in SC



E_c (Conduction Band Edge) } Band gap v/s pos^n

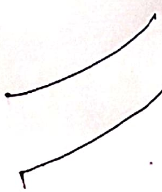
Band gap.

E_V (Valence Band Edge)

x.

E_c } without bias.

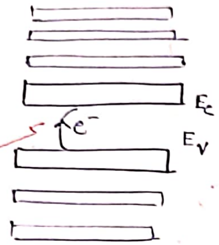
E_V



Free e^-
$\varepsilon = \varepsilon_0 + \frac{\hbar^2 K^2}{2m_0}$ (free e^-)
PE → KE

$\lambda = \frac{h}{K}$

Concept of holes



no. of e^- = 0%

@ 0 K

$n=0$ —— E_c

$p=0$ —— E_V

no. of empty states

@ T = 10 K

e^- e^- e^- E_c → $10^{11}/cm^3$

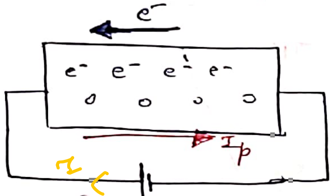
E_g

E_V → $10^{11}/cm^3$

$\approx 10^{22}/cm^3$

in principle every e^- below E_V also go upto & above E_c but Statistically; only e^- in E_V go upto E_c

In Semiconductor

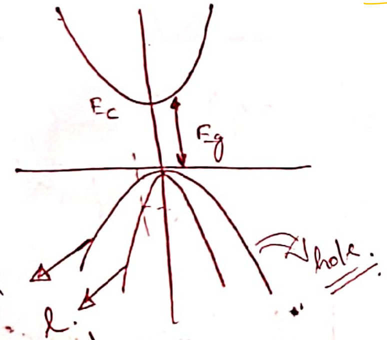


$I = I_e + I_p$

I_e: free e^- in Conduction Band

I_p: for e^- in Valence Band

#



$\frac{\partial^2 E}{\partial k^2}\Big|_h < \frac{\partial^2 E}{\partial k^2}\Big|_e$

heavy/h = Smaller Curvature

light/e = higher Curvature

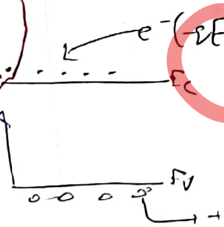
$-qE = m^* \frac{dv_d}{dt}$

$qE = (-m^*)\left(\frac{dv_d}{dt}\right)$

for holes → m_h^*

$m_e = m^*$

$m_h = -m^*$



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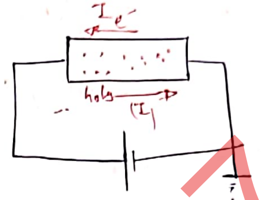


if u change Temp; E_c & E_V changes; Hence does the E_g

E_g changes in meV/°C

Energy

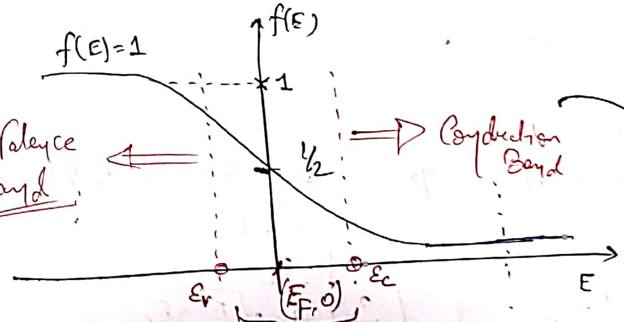
PE of System ↑ when e^- move from E_V to E_c & hence minimization of energy is not driving force.

e^- jum from E_c to E_V for randomization (↑ entropy)

Probability of occupation of an energy level of E for any e^- $= f(E) = \underbrace{\dfrac{1}{1 + e^{(E - E_F)/k_bT}}}_{\text{Fermi Dirac Statistics}}$

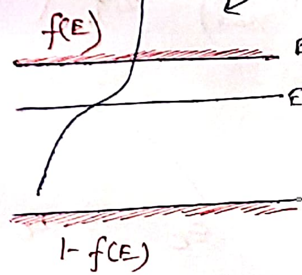
E_F, k_b } Const.

E_F = fermi energy



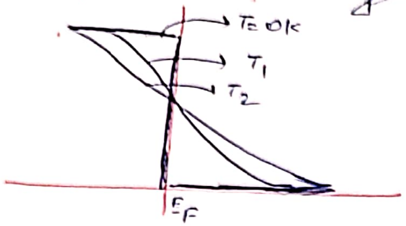
Prob. of occ. is high in vicinity of $E_F (\neq 0)$

f(E) also tells den... of Band... (f(E)...



Prob. of occup. of holes = $1 - f(E)$

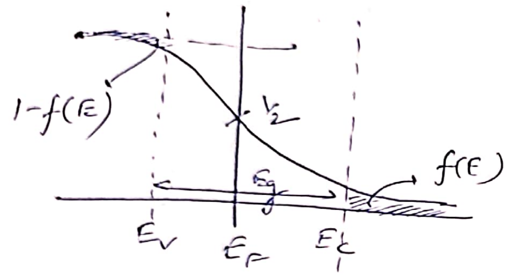
@ 0K,

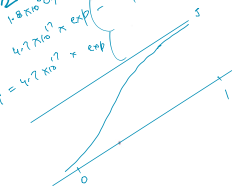


for fermions (e^-) { spin = $\pm\frac{1}{2}$ }

$T_2 > T_1 > 0K$

Note, E_F also Changes with Temp.



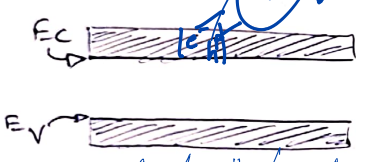


$\mu_n = 1200$
$\mu_p = 500$

$N_c = 4.7\times10^{17}$
$N_v = 7\times10^{18}\ cm^{-3}$
$E_g = 1.42$
$n_i = 1.8\times10^{6}\ cm^{-3}$
$n_0 = 4.7\times10^{17} \times \exp\left(-\frac{(E_c-E_F)}{kT}\right)$
$n_i = 4.7\times10^{17} \times \exp$

Density of States → unit = per unit energy / per unit volume

$F = qE = ma$

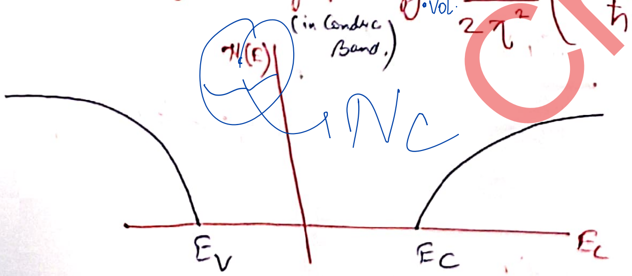


N = density / vol

$N_c = \frac{\text{density}}{\text{vol. energy}}$

$$N = \int_{E_c}^{E_c+\Delta E} N_c(E)\,dE = \text{no. of energy levels b/w } E_c \,\&\, E_c+\Delta E \,/\, \text{vol.}$$

N_c = Density / Energy. Vol. (in Conduc. Band) $= \frac{1}{2\pi^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\sqrt{E-E_c}$ (eff mass)



@ E_c ; density = 0

$$N_v = \frac{1}{2\pi^2}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2}\sqrt{E_v - E} \qquad (m_e^* \neq m_h^*)$$

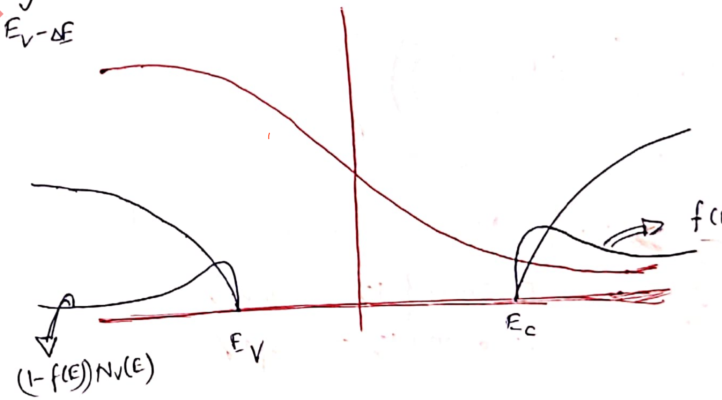
Note → Densities of States are independent of Temperature

$$\int_{E_c}^{E_c+\Delta E} \underbrace{f(E)\cdot \underbrace{N_c(E)\cdot dE}_{\text{no. of levels in the "dE"}}}_{\text{Prob. of occ. of that "dE" interval} \,\times\, \text{no. of levels}} = \int dn = n$$

" no. of e^-

$F = qE$

$$\int_{E_v-\Delta E}^{E_v} (1-f(E))\cdot N_v(E)\cdot dE = p.$$



$E - E_F = 2kT$

$E - E_F > 2kT$

if $E \gg E_F$; $f(E) = \frac{1}{1 + e^{(E-E_F)/k_BT}}$ when ...

Boltzmann approximation $\approx f(E) \approx e^{-(E-E_F)/k_BT}$

∵ f(E) of the e⁻s very ↓↓

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

$f(E)\uparrow \Rightarrow n\uparrow$

$n = N_c' \cdot e^{-(E_c-E_F)/k_BT}$

Prefactor = Effective Density of States

$N_c' = 2\left(\frac{m^* kT}{2\pi \hbar^2}\right)^{3/2} \Rightarrow N_c' \propto T^{3/2}$

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

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

if $(E-E_F) \gg 3K_BT$ → Thermal Voltage.

$T = 300K \mid K_BT = 26\ meV$

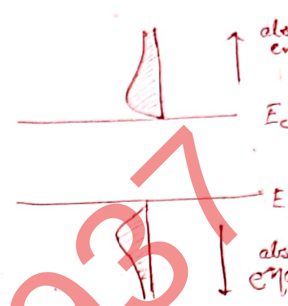
$T = 600K \mid K_BT \approx 52\ meV$

$f(E) = e^{-(E-E_F)/k_BT}$

$\frac{1}{1+20.08} \approx \frac{1}{20.08}$

Unit of $N_c(E)$ = $cm^{-3} eV^{-1}$

of allowed states per unit vol. per unit Energy



$\left(E = \frac{\hbar^2 k^2}{2m^*}\right)$

$\ln\left(\frac{n_i p_i}{N_c' N_v'}\right)^{-1}$ $\quad 2kT \ln\left(\frac{N_c' N_v'}{n_i^2}\right) = E_g$

for intrinsic S.C.

$n_i = p_i$

$n_i p_i = N_c' N_v' \exp\left[-\frac{E_c - E_V}{k_BT}\right]$

$p_i = n_i = \sqrt{N_c' N_v'} \exp\left[-\frac{E_g}{2k_BT}\right]$

$E_g \uparrow \Rightarrow n_i \downarrow$

if $n_i \neq p_i$ (Extrinsic Semiconductor)

$np = N_c' N_v' \exp\left[-\frac{E_c - E_V}{k_BT}\right]$

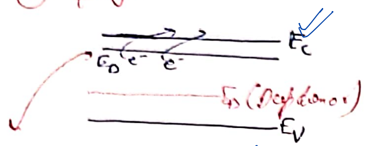
(Either n_i/p_i is dominant) $\boxed{np = n_i^2}$ → Law of mass action, always (whether $n = p$ or $n \neq p$)

In Intrinsic; $n_i = p_i$ {EHP} e⁻ hole pair

for Si; $n_i \simeq 1.1 \times 10^{10}$ cm

Extrinsic
- n-type {e^-} / Donor level
- p-type {h^+} / Acceptor level

① n-type

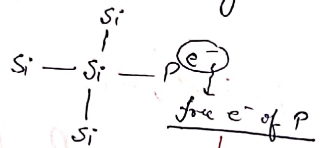


Shallow donor

Chem

Eg Si, Valency = 4
P " = 5

Substitutional Impurity



The free e^- rotates in the Crystal, for that e^-;

$E_C - E_D$ = Ionization energy.

Ionization energy
is the energy for movement of e^- to move from Donor level to the Conduction Band

if $E_C - E_D$ is ↓↓; e^- will find it very easy to jump to E_C & ext

K_BT = Reference

Such type of e^- are k/a Shallow Donors.

$E_C - E_D \simeq K_BT \rightarrow$ Shallow donor Eg → P, As

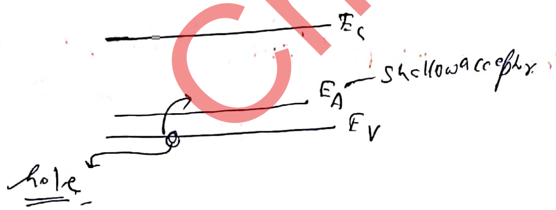
$E_C - E_D >>>> KT \rightarrow$ deep donor

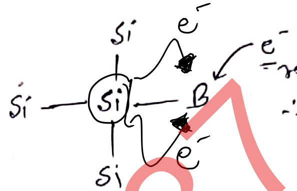
Eg Sulphur

Donor becomes +ve Charged in the process

Note, In b/w E_C & E_V; One can only have the Donor level having e^-. Rest no e^- can be b/w these 2 States

② p-type





e^- = req. from extra e^-
∴ hole in Si

Si — P

N_D = Donor density
N_A = Acceptor "

Charge neutrality

① $n + N_A = p + N_D$

② Law of mass action $np = n_i^2$

Q $n_i = 1.1 \times 10^{10}\ cm^{-3}$
$N_D = 10\ cm^{-3}$
$N_A = 10^{17}\ cm^{-3}$

$p = \frac{n_i^2}{n}$ & $e = \frac{n_i^2}{p}$

if $(N_A - N_D) >> n$

$p \simeq N_A + N_D$

Si

$n + N_A$

ne

H

Li Be B

C
Si
Ge

N
P
As
Sb

Ga → p

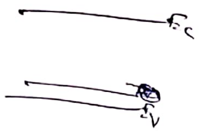
As → n

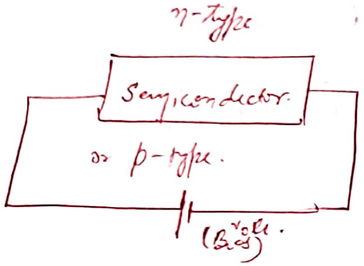
n-type

$n >> p$

$E_F - E_i$ is large

$E_V - E_F$ is small.





.The highest energy level that an electron can occupy at the absolute zero temperature is known as the Fermi Level. The Fermi level lies between the valence band and conduction band because at absolute zero temperature, the electrons are all in the lowest energy state

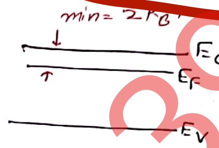
Extrinsic S.C.

why?? Why??

$$\boxed{n + N_A^- = p + N_D^+}$$

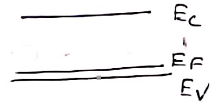
$$n \simeq N_D - N_A \quad , \quad N_D - N_A >> n_i$$

$$N_C = (\ )\sqrt{E - E_C} \quad , \quad E \geq E_C$$



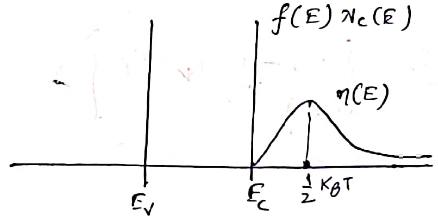
⇓ as E_F moves down ; Boltzman approximation becomes Valid

Similarly



⇑ as E_F moves up

$$\langle E \rangle = \left(\frac{\int E\, n(E)\, dE}{n} \right) = \text{avg energy of an } e^-$$



$$\text{avg energy of } e^- = \frac{3}{2} k_B T = \underbrace{\tfrac{1}{2} k_B T}_{\text{Energy / deg. of freedom}} \times \underbrace{3}_{\text{no. of deg. of freedom}}$$

Silicon

$E_g = 1.1\,eV$.

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

$N_V' = 2 \times 10^{22}\,cm^{-3}$

(hypothetical Values)

$$n_i' = \sqrt{N_c' N_V'} \cdot \exp\left(-\frac{E_g}{2 k_B T}\right)$$

$$= 10^{22}\sqrt{2}\ \exp\left(\frac{-1.1}{2 \times 0.026}\right)$$

$$= 9.192 \times 10^{22}\ cm^{-3}$$

Close to E_C

E_C, E_{Fi}, E_V, $1.1\,eV$

$$n = N_c' \exp\left(\frac{E_F - E_C}{k_B T}\right)$$

$$E_F - E_C = k_B T \ln\left(\frac{n}{N_c'}\right)$$

$$= 0.026 \ln\left(\frac{9.19 \times 10^{12}}{10^{22}}\right)$$

$$= -0.54\,eV$$

when $m_e^* = m_p^*$

$$E_F = \frac{E_C + E_V}{2}$$

if S.C. is intrinsic ; $E_F = E_{FI}$ — Intrinsic Fermi level.

Note: if $n_i = p_i$

$$E_F = \frac{E_C + E_V}{2} \quad \{ E_{Fi} - E_C = E_V - E_{Fi}$$

$E_g = 1.1\,eV$

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

$N_v' = 2 \times 10^{22}\,cm^{-3}$

$n_i = 9.19 \times 10^{12}\,cm^{-3}$

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

$N_A = 0$

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

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

$n \approx N_D - N_A = 10^{17} \gg n_i$

$$n = N_c \exp\left(\frac{E_F - E_C}{KT}\right)$$

$E_C - E_F \gg k_B T$

290 meV, 26 meV

$$E_F - E_C = k_B T \ln\left(\frac{n}{N_c'}\right) = 0.026 \ln\left(\frac{10^{17}}{10^{22}}\right) = -0.29$$

if $N_D = 10^{22}$;

$E_F - E_C$ can't be done using Boltzmann factor

if $N_D - N_A \approx N_c'$ then Boltzmann not valid

Effect of Temp on E_F

$N_c' = 10^{22}\,cm^{-3}$, $T = 300\,K \longrightarrow T = 400\,K$

$N_c \sim T^{3/2}$

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

C, F, V

E_C, E_F, E_V

$n\uparrow \Longleftarrow T\uparrow$

as $T\uparrow$; $E_F \longrightarrow \frac{E_C + E_V}{2}$

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

$$\boxed{n = N_c' \cdot \exp\left(\frac{E_F - E_C}{K_B T}\right)}$$

$n_i = 10^{12}$ (for large T)

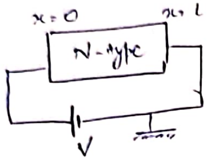
$n = 10^{17}$

$$p = \frac{n_i^2}{n} = \frac{10^{24}}{10^{12}} = 10^7\,cm^{-3}$$

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

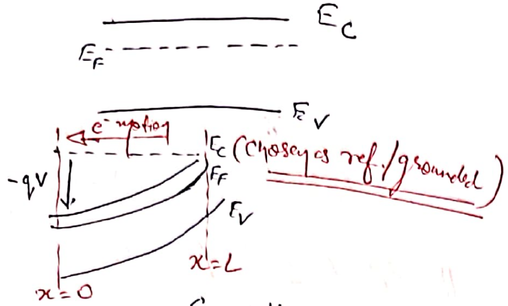
Transport

$J = \frac{I}{\text{Area}}$



$n(x) = N_c' \exp\left(\frac{E_F - E_C}{K_B T}\right)$

if $n(x)$ is constant & N_c' is material const then $E_F(x) - E_c(x)$ is also constant



$\mathcal{E} = -\nabla V = -\frac{\partial V}{\partial x} = \frac{V}{L}$

motion of e^- → random but net motion from $x=L$ to $x=0$ in a zig zag path.

now; $V = IR$

$R = \frac{\rho l}{A}$; $J = \frac{I}{A}$

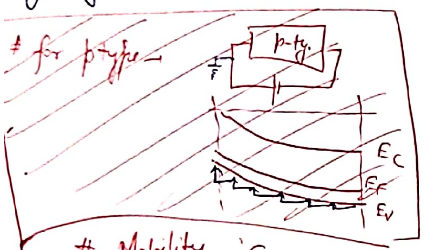
now; $V = J\cancel{A}\,\frac{\rho l}{\cancel{A}}$

$\Rightarrow \frac{V}{L} = \frac{J}{\sigma}$; $\sigma = \frac{1}{\rho}$ conductivity

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

another form of ohm's law.

$J = \sigma \mathcal{E}$

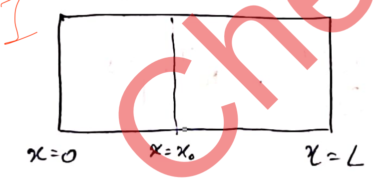


Mobility :-

unit ≡ cm^3

$J(x) =$ Constant. for const. current in same surface area obj

$J = \frac{I}{A} \Rightarrow J = I$ ($A \to 1$)



if J not const; then charge is accumulating in device

now ($A=1$) assume then $J = \frac{dq}{dt} = qnv$

Drift vel = v (avg speed of e^-)

$\left(\frac{\text{drift current}}{\text{area}}\right) = \boxed{q n v = J_{drift}}$ ⇒

e^- in vol. in dist trav. by e^- in 1 sec.

Order of n
metal n ~ $10^{22} cm^{-3}$
S.C n ~ $10^{17-19} cm^{-3}$

Mobility

$v = \mu \mathcal{E}$ | $\mu = \frac{v}{\mathcal{E}}$ (cm^2/Volt-sec.)

vel.
EF
mobility

mobility order

$\mu = 0.5 - 1\ cm^2/Vsec$ ⇒ metal

$\mu = 5000\ cm^2/sec$ ⇒ Graphene

$\mu =$

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

Now; $J = qnv \Rightarrow \boxed{J = qn\mu E}$

now; $F = m^* a = q\mathcal{E} = m^*\left(\frac{d\,v_{el}}{dt}\right) = m\frac{\langle v\rangle}{\tau}$

avg vel.

effective mass

$\langle v\rangle$ ≡ avg. velocity = V_{drift}

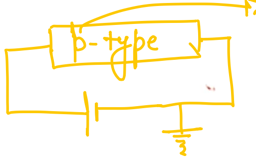
τ = scattering time (Time b/w 2 collisions)

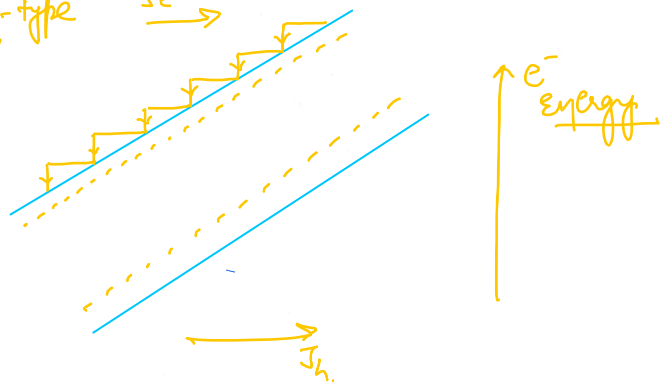
Hence; $\mu = \frac{q\tau}{m^*}$ ($\mu \propto \frac{1}{m^*}$)

$v\tau$ = dist b/w 2 collision

Ballistic Transport → all e^- travel without any scattering

TRANSISTER's (eg. 7nm) are semi-Ballistic transport type





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

$J_n = q\,n\,\mu_n\,\mathcal{E}$

$J = J_n + J_p$

$= q\,(p\mu_p + n\mu_n)\,\mathcal{E}$

$= \sigma \mathcal{E}$

DIFFUSION

Driving force $= \frac{\partial n}{\partial x}$ → Conc^n gradient

Carrier Transport < Drift (due to E.F) / Diffusion (due to Conc^n diff)

Drift

$V = \mu\mathcal{E}$; $\mu = \frac{e\tau}{m^*}$

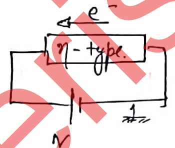
$J_n = q\,n\,\mu_n\,\mathcal{E}$

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

$J = J_n + J_p$

we want $\uparrow\mu \Rightarrow \uparrow$ Current → $\left[\frac{\tau\uparrow}{m^*\downarrow}\right]$

$q\mathcal{E} = m\frac{dv}{dt} = m\frac{\langle v\rangle}{\tau}$

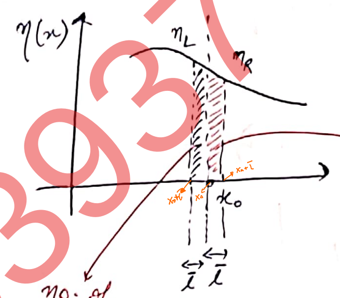


$\mathcal{E} = V/L$

Diffusion

Diffusion

Conc. Gradient → Driving force for diff Current



no. of e^- $= n_l\cdot\bar{l}$ → Half of each of this will go left & right due to equal probabilistic events.

no. of e^- $= n_R\bar{l}$

no of e^-/time.

Net flux from left to right $= \frac{n_l\cdot\bar{l} - n_r\cdot\bar{l}}{2\tau}$ → e^- flux density

Time taken to hop a distance of $\bar{l}$ $= \tau$

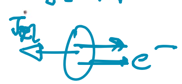
$\therefore\ \phi = \left(\frac{n_l - n_r}{2\tau}\right)\bar{l}$

$f(x+\Delta x) = f(x) + \Delta x\cdot f'(x) + \ldots$

$n_R \simeq n_l + \left(\frac{\partial n}{\partial x}\right)\bar{l}$ | $\frac{\partial n}{\partial x} = \left(\frac{n_R - n_l}{\bar{l}}\right)$

$\therefore\ \phi = \frac{-\bar{l}^2}{2\tau}\cdot\frac{dn}{dx} = -D\left(\frac{\partial n}{\partial x}\right)$

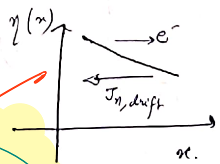
$J = -nF$



$\phi = -\frac{(\bar{l})^2}{2\bar{t}}\cdot\frac{dn(x)}{dx}$

$D = \frac{\bar{l}^2}{2\tau}$

ϕ/F = Current density OK.



Imp

$F = -D\frac{\partial n}{\partial x}$

$J_{n\,drift} = -qF = q\,D_n\left(\frac{\partial n}{\partial x}\right)$

Charge × flux

$J_{p\,drift} = +qF = -q\,D_p\left(\frac{\partial p}{\partial x}\right)$

So now; accompaling both diffusion & drift:-

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

$$J_p = q p \mu_p \mathcal{E} - q D_p \frac{\partial p}{\partial x}$$

$$\boxed{J_{Tot} = J_n + J_p}$$

Einstein's Relation

same for n/p

$$\frac{D}{\mu} = \frac{k_B T}{q}$$

only for material in which $E_V - E_F > 2k_BT$

$$\frac{D}{\mu} = \frac{K_B T}{q}$$

without any Bias in a S-C. ; $J_{Tot(x)} = 0$

assuming $J = 0 \; \forall \; x$

$$\left.\begin{aligned} J_n &= 0 \\ J_p &= 0 \end{aligned}\right\}$$

By applying Boltzmann's app. Relation (Book)

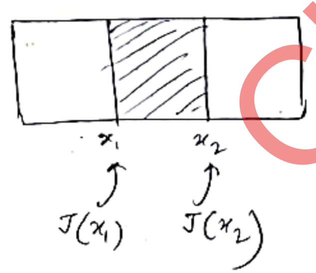
By Einstein's relation on J_n]

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

\# $E_c - E_F < 2\text{-}3 K_BT \longrightarrow$ Degenerate S-C. (Boltzman not valid)

\# $E_c - E_F > 2\text{-}3 K_BT \longrightarrow$ non-degenerate S-C

\#



Steady State

$$J(x_1) = J(x_2)$$

(eq^m)

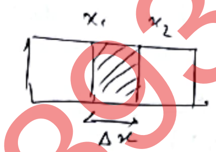
@ eq^m; $R = G$

∴ eq^m Conc^n of $e^- = p^+$

But S.C. devices don't operate in eq^m conditions.

\# non. eq^m : F → flux

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



now; ~~$J_n = q F_n$~~ $J = -qF$

$$\frac{J(x_2) - J(x_1)}{\Delta x} = q$$

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

$$J_p = q\mu_p \left(p\mathcal{E} - \frac{K_B T}{q} \frac{\partial p}{\partial x} \right)$$

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

$$J_p = q\mu_p \left[p\mathcal{E} - \frac{KT}{q} \frac{dp}{dx} \right]$$

$$J_{Tot} = J_n + J_p$$