

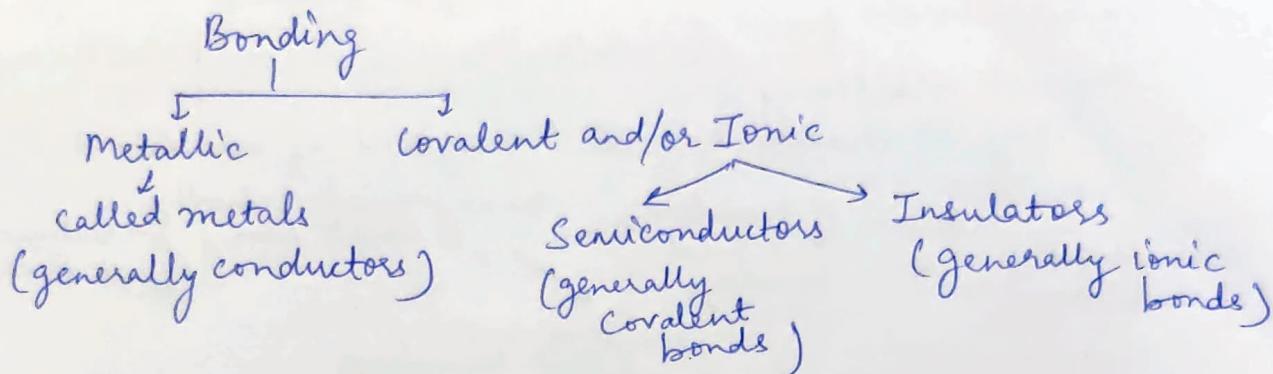
RACHIT DHAR

ELECTRONIC, OPTICAL AND MAGNETIC [MLL253]
PROPERTIES OF MATERIALS

Prof. Nirat Ray

LECTURE-1

1] Electrical Properties



Q ~ Give an example of a metal that is a bad conductor.

2] Conductivity, $\sigma = \frac{1}{\rho}$ ($\rho \rightarrow$ resistivity, $R \rightarrow$ resistance)

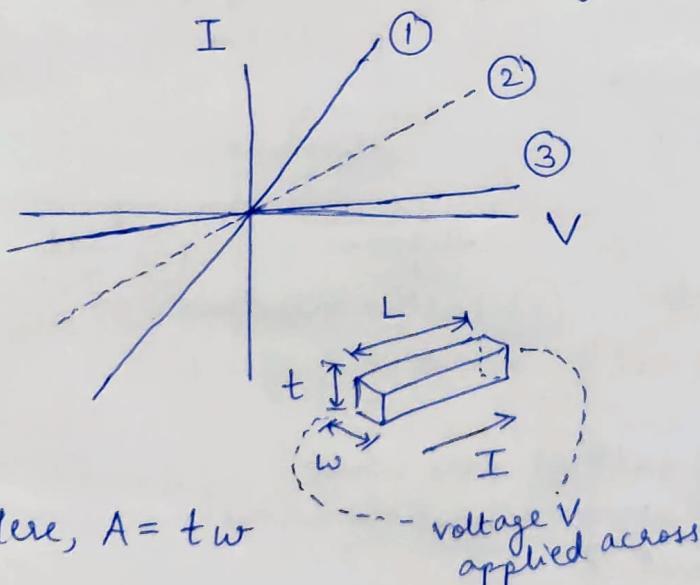
↓
this is
intrinsic to
the material (and NOT
Resistance (R))

Also, we will assume

$$V \propto I \quad (\text{Ohm's Law})$$

[Only in few v. rare/special cases is
this violated]

3]



Here, $A = t w$

- ① Al/Cu (R_1)
- ② Silicon (R_2)
- ③ Wood (R_3)

NOTE :

This is NOT same as diode

∴ diode has a junction, and also two diff. dopings

$$\therefore R_3 > R_2 > R_1$$

But only for equal dimensions

∴ The general statement

for 3 such materials is:

$$\rho_3 > \rho_2 > \rho_1$$

NOTE:

$$R = \frac{\rho L}{A}$$

4] Range of values of σ :

$$\sigma \sim 10^{-20} \text{ to } 10^{20} \text{ S/cm}$$

↳ (Siemens)

The boundaries for Insulators | Semiconductors | Conductors are not arbitrary.

They are chosen bcz at the regions of boundaries

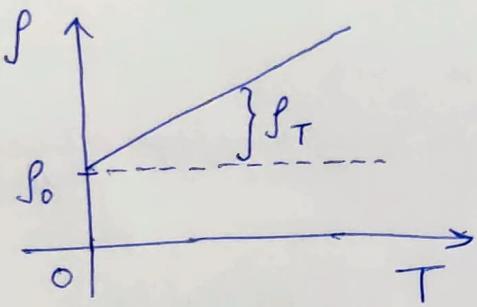
In case of Semi-cond. & Insul. boundary

slightly blurred due to some materials present there

no materials usually exist having σ values equal to that

Semi-cond. & Cond. boundary is more clear relatively (for now) but may not be so in the future with more materials being found in this region

5] Resistivity of Metals



$$\boxed{\rho = \rho_0 + \rho_T}$$

Matheissen's Rule

Material
Assumptions:

- e^- s exist that are free to move
- e^- collisions occur
 - ↓ (technically called scattering)

causes of collision

- 1
- ① Collision with Lattice Vibrations
 - ② with Intrinsic Defects
 - ③ Impurities alloying

Q ~ Why can we talk of Lattices even when lattice vibrations (atomic vibrations in the lattice atoms) exist?

NOTE: Matheissen's Rule is not just limited to that equation (i.e. $\rho_0 + \rho_T$). If there are multiple sources of resistivity, we can write:

$$\boxed{\rho = \rho_0 + \rho_1 + \rho_2 + \dots}$$

$$\text{In general, } \rho = \rho_0 + \alpha T$$

↓ where α is called TCR

LECTURE-2

(Temperature Coefficient
of Resistance)

6] Classical Theory of Conductivity

We know: $V = IR$ (Ohm's law)

$$R = \frac{\rho l}{A}$$

$\rho \rightarrow$ based on this we can classify as conductor, semi-cond or insul.

What factors does this depend on?

Using the two equations:

$$V = I \cdot \frac{\rho l}{A}$$

$$\Rightarrow \frac{V}{l} = \frac{\rho I}{A}$$

$$\Rightarrow E = \rho J$$

$$\text{or } J = \sigma E$$

(in vector form: $\vec{J} = \sigma \vec{E}$)

① →

↓ scalar form

We can call this

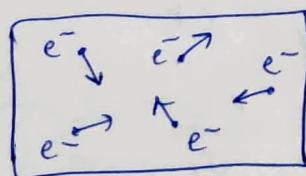
Ohm's Law as well

Here σ is actually a tensor

The Assumption we took:

1. e^- s are free to move [Sea of electrons]

At temp. T



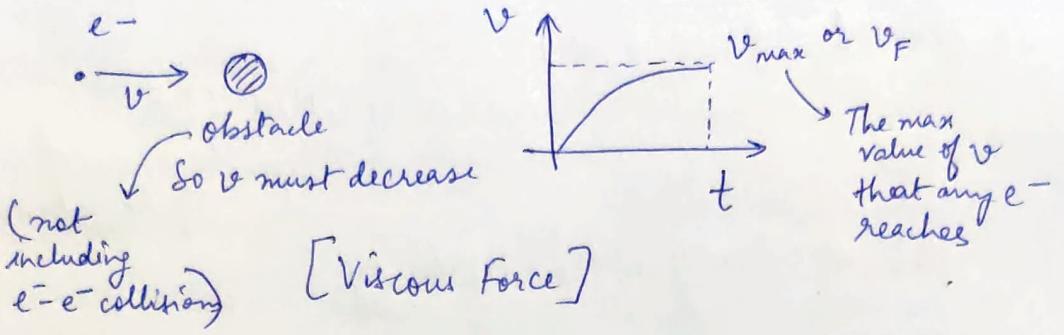
Net velocity = 0

(sum of all velocities)

When we apply electric field E , we get a net velocity, $v \neq 0$

By Newton's 2nd Law: $m \frac{dv}{dt} = eE$

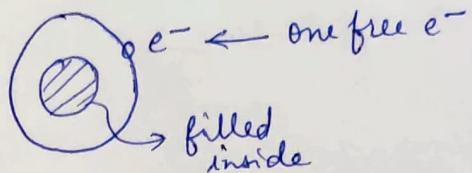
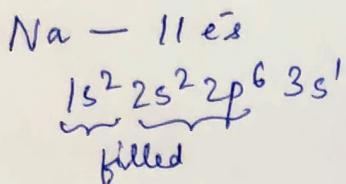
→ But here we haven't taken into account any drag force



Taking into account some source of scattering:

$$\boxed{m \frac{dv}{dt} + \gamma v = eE}$$

In most theories like this, we take the case of Na atom.



∴ Now we can write :

No. of free e⁻s, per unit volume $N_f = \frac{1 \cdot dN_A}{M}$

density Aragadro's no.

$\sim 10^{22} - 10^{23}/\text{cm}^3$

Our eq.ⁿ above has a steady state solution :

$$\left. \frac{dv}{dt} \right|_{v=v_f} = 0$$

$$\Rightarrow \gamma v_f = eE$$

$$\Rightarrow \gamma = \frac{eE}{v_f}$$

Thus, $m \frac{dv}{dt} + \frac{eE}{v_f} v = eE$

$$\Rightarrow m \frac{dv}{dt} = eE \left(1 - \frac{v}{v_f} \right)$$

$$\int_0^v \frac{dv}{1 - \frac{v}{v_f}} = \int_0^t \frac{eE}{m} dt$$

(Talking about an avg. e^-)

$$-v_f \ln \left| 1 - \frac{v}{v_f} \right| \Big|_0^v = \frac{eEt}{m}$$

$$\ln \left| 1 - \frac{v}{v_f} \right| = -\frac{eEt}{mv_f}$$

$$1 - \frac{v}{v_f} = \exp \left(-\frac{eEt}{mv_f} \right)$$

$$v = v_f \left[1 - \exp \left(-\frac{eEt}{mv_f} \right) \right]$$

So here we define :

Relaxation time,

$$\tau = \frac{mv_f}{eE}$$

(tells the avg. time b/w two collisions)

Our goal is to calculate σ from $J = \sigma E$

By writing expression for J by putting values for current I , we get :

$$J = N_f v_F e$$

$$\begin{aligned} \therefore J &= \sigma E \quad \text{and} \quad J = N_f v_F e \\ &= N_f \left(\frac{eE\tau}{m} \right) e \\ &= \frac{N_f e^2 \tau}{m} E \end{aligned}$$

$$\Rightarrow \boxed{\sigma = \frac{N_f e^2 \tau}{m}}$$

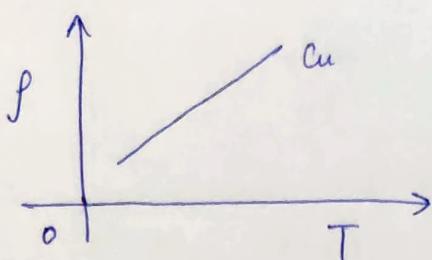
- One Drawback, case of Si \rightarrow has 4 times free e^- s (N_f) but σ_{Si} is not at all 4 times of σ_{Na}
- 2nd Drawback, can't really explain the effect of impurity addition

* \rightarrow So basically, classical theory can't explain existence of Semiconductors
But otherwise the theory is quite useful.

NOTE: The classical theory is v. good at explaining conductivity of metals (and also the temp. dependence of σ for metals)

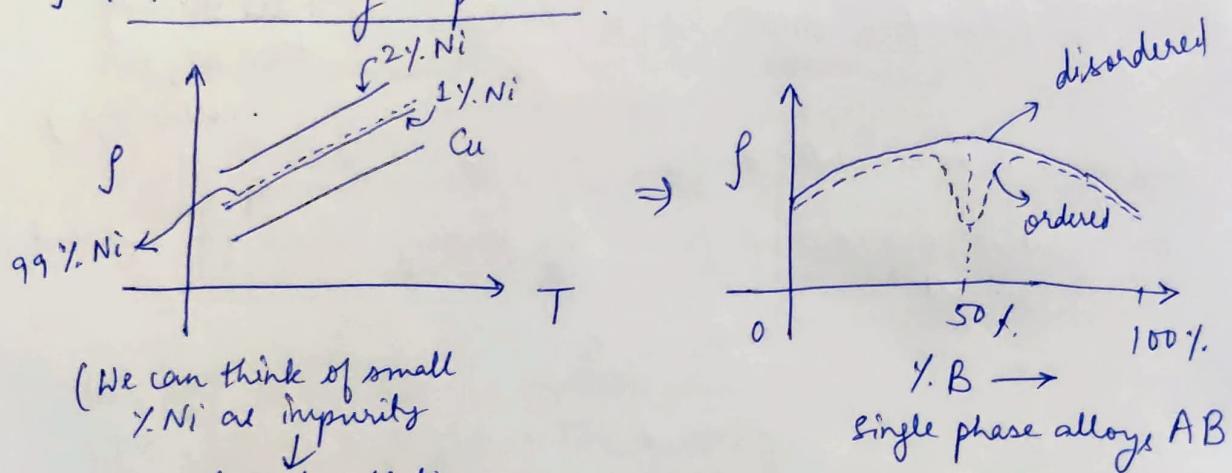
7] With increase in T ($T \uparrow$)

$\tau \downarrow$ (decreases), and thus $\sigma \downarrow \Rightarrow \rho \uparrow$

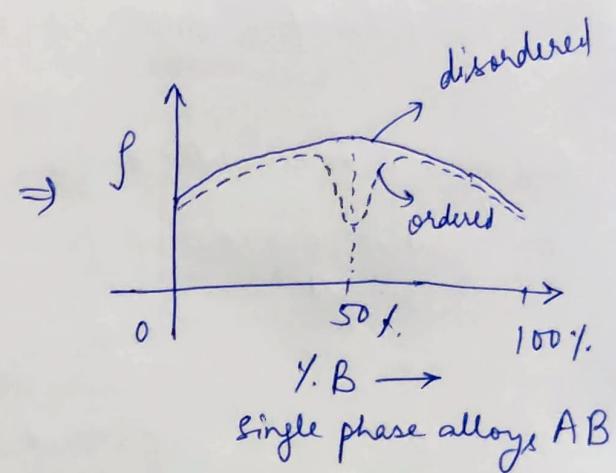


* However, doesn't explain for v. low temperatures
(Another drawback)

8] With increasing impurities:



(We can think of small γ Ni as impurity
obstacles, that will decrease τ
 $\therefore \sigma \downarrow$ and $\rho \uparrow$)



* NOTE: Any kind of ordering will reduce ρ

(For eg: The vertical lines we see in phase diagrams.)

But for v. high Ni
 \downarrow
situation just
reverses (we can think of Cu as
behaving as impurity)

Ordering means that, previously AB was just an alloy, but now it has

actually formed a new crystal structure itself)

LECTURE-3

9] Limitations of Classical Theory

$$\sigma = \frac{ne^2\tau}{m}$$

Limitations

- Semiconductors (doesn't explain)
 - impurities
 - conductivity values
 - temp. behaviour
- Low temp. behaviour of conductivity of metals ↓

intrinsic conductivity

Thus, we need a new theory
that explains behaviour better
↓
Quantum Theory

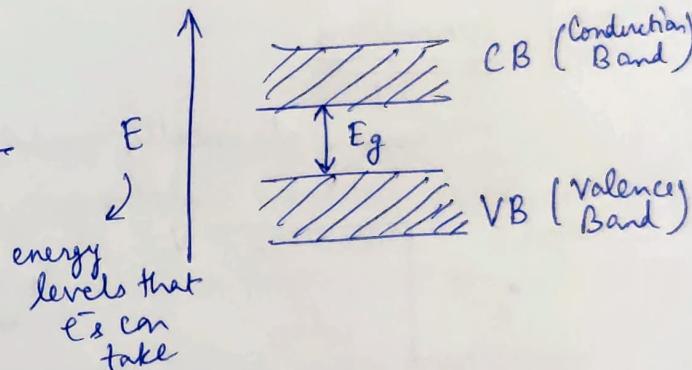
10] Quantum Theory

We have read about Band gaps

Classical theory
CANNOT explain bands.

The concept of
band

↓
is completely a
quantum mechanical
concept



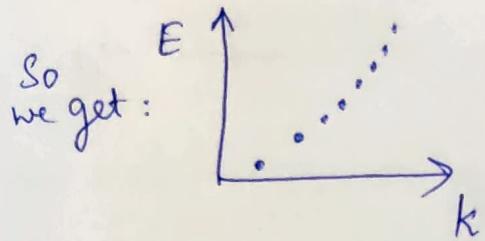
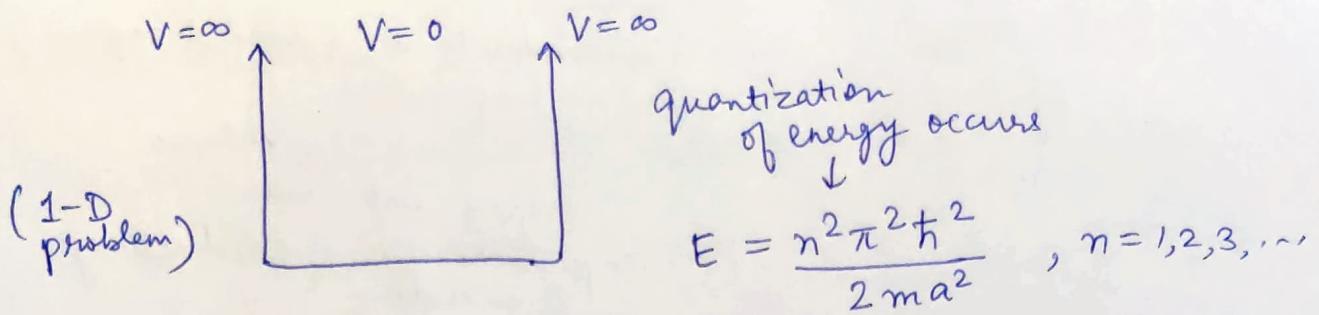
11] For Free Electron



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

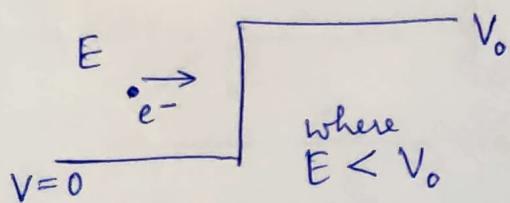
$$\left\{ p = \hbar k, k = \frac{2\pi}{\lambda} \right\}$$

12] e^- in a box



13] Tunnelling

↓
Crossing classically forbidden regions



In classical mechanics
this e^- cannot cross this barrier when $E < V_0$.

But in Q.M., it can cross even in case when $E < V_0$.

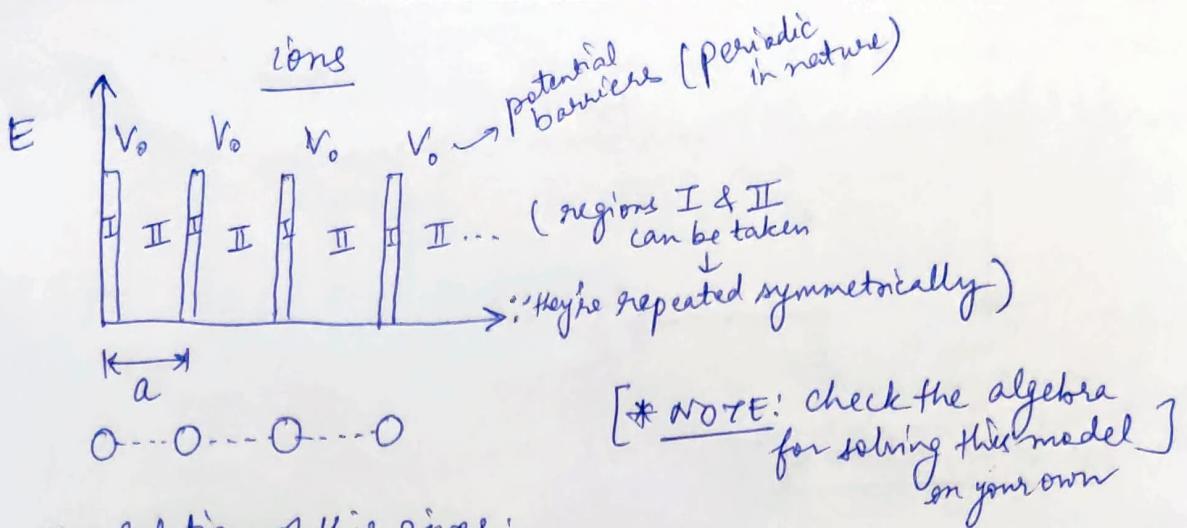
14] Electrons inside a Solid (crystal)

↓ i.e. [Periodicity assumed]

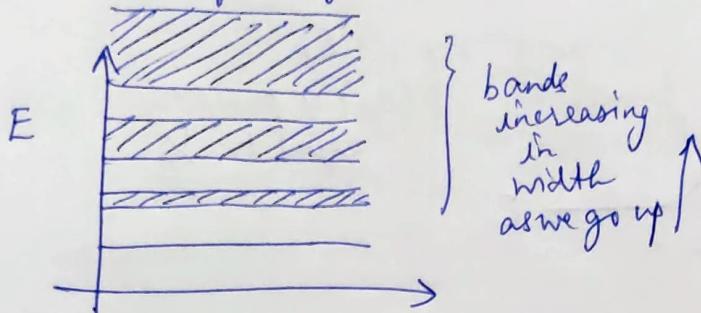
this model
is called

Kronig-Penny Model

[details → self reading]



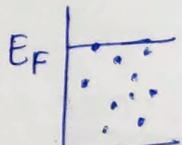
The solution of this gives :



15] Thus we observe :

Free electrons $\xrightarrow{\text{confined}}$ Quantization $\xrightarrow{\text{periodic}}$ Allowed Bands
(allowed)

16] 1. Fermi energy : Energy of highest energy electron
 ↓
 we are assuming Pauli's Exclusion principle to be valid here (i.e. interacting e^-s)
 (but this definition needs to be further generalized)

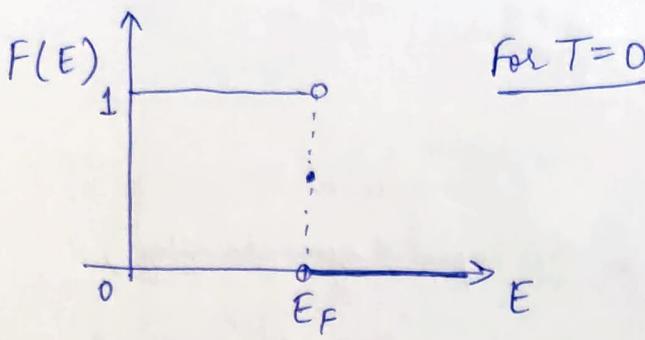


2. Probability \rightarrow that any given level is full or empty

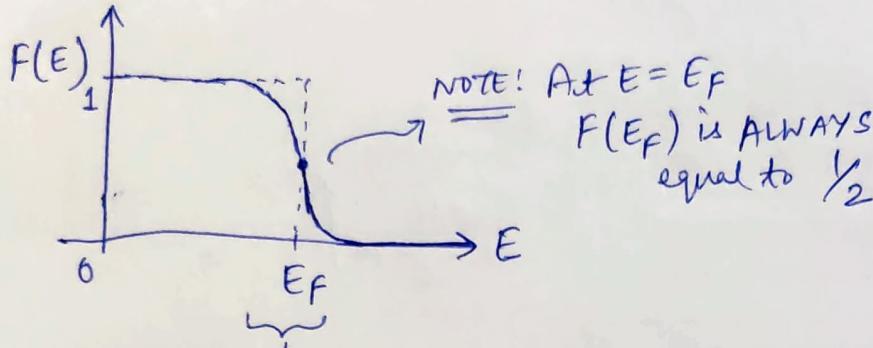
Given by
Fermi-Dirac function :

$$F(E) = \frac{1}{\exp\left(\frac{E-E_F}{k_B T}\right) + 1}$$

\uparrow
 this gives more accurate definition for Fermi Energy (E_F)



For other values of T:



thus, this means that
we are only concerned
with electrons in the
energy band around E_F .

∴ When we discuss
conductivity:
We need to replace n with $n(E_F)$

$$\Rightarrow \sigma = \frac{n(E_F) e^2 T}{m}$$

LECTURE-4

17] Quantum Theory for σ

Quantization \rightarrow Tunneling

KP model \rightarrow 'bands'

We discussed:

1. Fermi energy: E_F

2. Probability Distribution

probability that energy level E
is filled

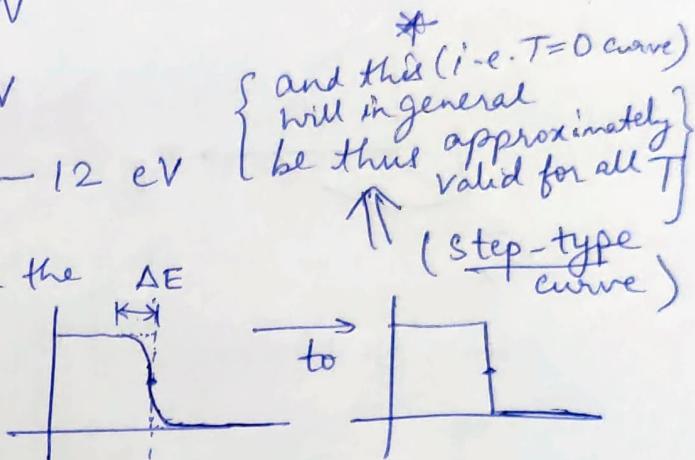
$$F(E) = \frac{1}{\exp\left(\frac{E-E_F}{k_B T}\right) + 1}$$

*NOTE: (To remember) $k_B \approx 8.6 \times 10^{-5} \text{ eV/K}$ ← memorize this value
 Thus to convert for given temp. to energy of that system
 we can do: $E = k_B T$

eg: $T = 300 \text{ K} \rightarrow 0.026 \text{ eV}$
 or
 (Room Temperature) 26 meV

And we know that $E_F \rightarrow 2-12 \text{ eV}$

So this tells us
 that we can approximate the curve!



18] The next point in Quantum Theory

↓
 3. Density of states: The no. of states between energy E and $E + dE$ per unit volume per unit energy

↓ (represented by $D(E)$)

If we want to find total electrons in system:

$$N = F(E) \times D(E) \times 2$$

↓ energy of band ↓ Density of states

i.e. if dn is the no. of states (as above) per unit volume, then:

$$D(E) = \frac{dn}{dE}$$

due to 2 electrons possible by pauli exclusion

For 1-D electron in box: $E_n = \frac{n^2 \pi^2 \hbar^2}{2ma^2}$ ($a \rightarrow$ size of box)

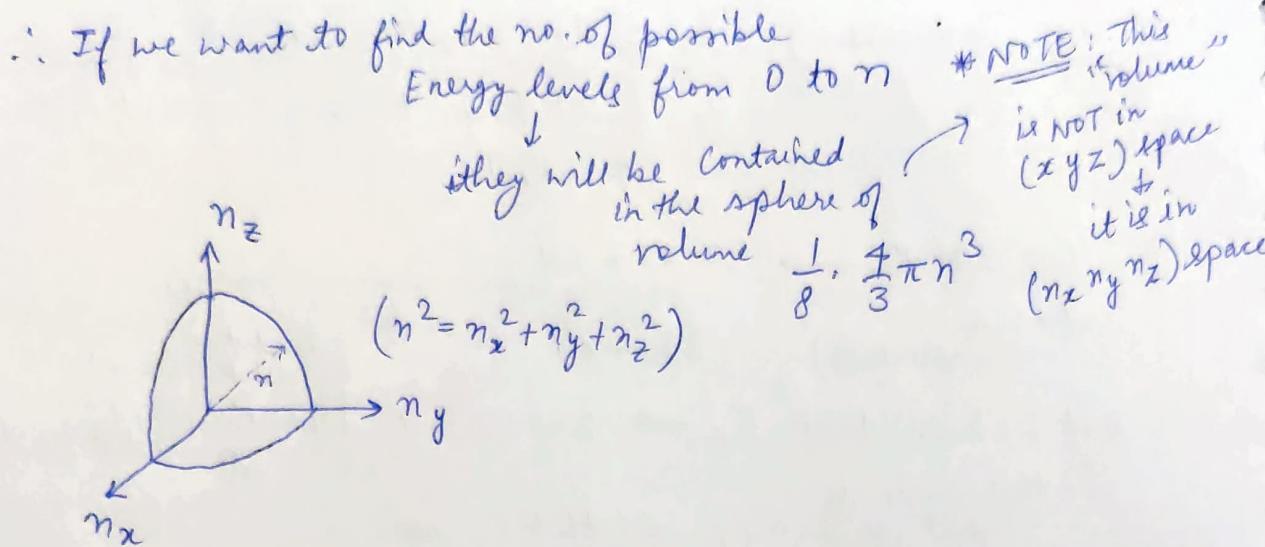
↓ 3-D analog

Particle in 3-D box:

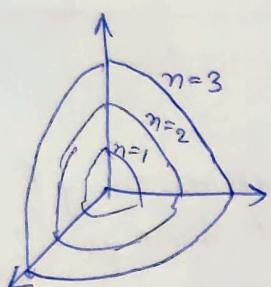
$$E_{n_x, n_y, n_z} = \frac{(n_x^2 + n_y^2 + n_z^2) \pi^2 \hbar^2}{2ma^2}$$

(← *important)

We can write, $n^2 = n_x^2 + n_y^2 + n_z^2$, $n_x, n_y, n_z > 0$
 some n defined as: $(n_x, n_y, n_z \in \mathbb{N})$



Now, we observe:



Ground state
⇒ $n^2 = 1$:

n_x	n_y	n_z
1	0	0
0	1	0
0	0	1

* degenerate means states of equal energy

3 states
(degeneracy = 3)

$n^2 = 2$:

1	1	0
0	1	1
1	0	1

3 states

$n^2 = 3$:

1	1	1
---	---	---

← degeneracy of 1

$n^2 = 4$:

2	0	0
0	2	0
0	0	2

So as we increase the n upto which we want to count our possible energy levels

it can be approximated by a Continuum approximation

∴ we can take:

$$N = \frac{1}{8} \cdot \frac{4}{3} \pi n^3$$

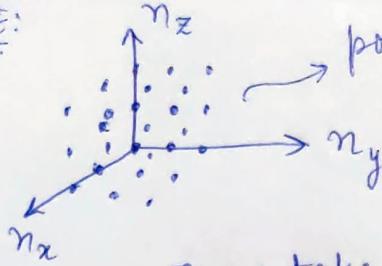
[Justification for the concept

of approximating no. of points

by the volume of the containing region, is given by me on the next page]

* Explanation behind the idea of using volume to count no. of points

NOTE:

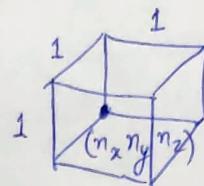
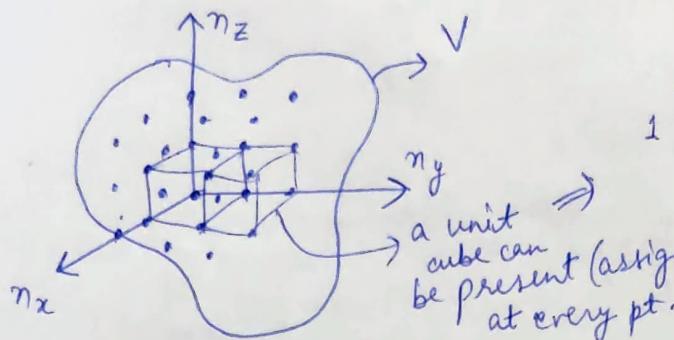


points in 3D n -space

of the form (n_x, n_y, n_z)

[where $n_x, n_y, n_z > 0$
 $\& n_x, n_y, n_z \in \mathbb{N}$]

If we take any region of volume V in this n -space:



Thus we can say:

$$\text{Total volume of region, } V \approx \sum_{\text{all cubes}} \text{Vol}^m \text{ of 1 cube at integer point } (n_x, n_y, n_z)$$

And since
 the vol^m of a unit cube = 1

$$\Rightarrow V \approx \sum_{\text{all cubes}} 1 = \frac{\text{no. of cubes present inside volume } V}{\text{no. of points inside volume } V} = \text{no. of points inside volume } V$$

$$\therefore \boxed{V \approx \text{No. of integer points inside volume } V}$$

LECTURE - 5

19] We were discussing :

Density of States \rightarrow How the energy states are distributed within a band

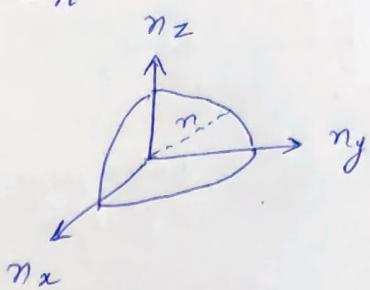
Then, we discuss : Particle in a box

here, the box is the crystal dimensions

($1e^- \rightarrow$ moving freely inside can't leave the crystal/box)

20] We were discussing
how to find
no. of states with energy $\leq E_n$
+ if we call
this n :

$$\text{We get: } n = \frac{1}{8} \cdot \frac{4}{3} \pi n^3$$



$$\Rightarrow n = \frac{1}{8} \cdot \frac{4}{3} \pi \left(\frac{2m a^2 E}{\pi^2 \hbar^2} \right)^{3/2}$$

$$= \frac{\pi}{6} \left(\frac{2m a^2}{\pi^2 \hbar^2} \right)^{3/2} E^{3/2}$$

Hence we
now have n
as a function of E

Thus, we can write:

$$\boxed{Z(E) = \frac{dn}{dE}}$$

(defining $Z(E)$)
i.e. density
of states

but actually it's
DOS times volume

$$\Rightarrow Z(E) = \frac{\pi}{6} \left(\frac{2m}{\pi^2 \hbar^2} \right)^{3/2} a^3 \frac{d}{dE} (E^{3/2})$$

$$= \frac{\pi}{6} \left(\frac{2m}{\pi^2 \hbar^2} \right)^{3/2} \underbrace{\frac{3}{2} E^{1/2}}_{\text{this actually was
supposed to
be absorbed in the
definition of DOS}}$$

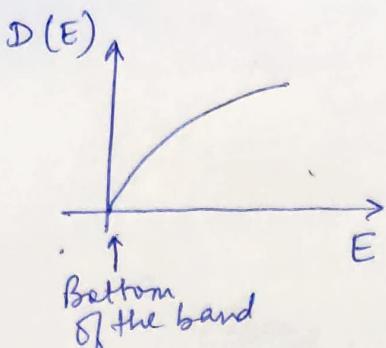
(i.e. the dn should become
no. per unit volume)

$$\Rightarrow D(E) = \frac{Z(E)}{V} = \frac{\pi}{4} \left(\frac{2m}{\pi^2 \hbar^2} \right)^{3/2} E^{1/2} \quad \leftarrow \text{So we define } D(E) \text{ as:}$$

$$\Rightarrow \boxed{D(E) \propto E^{1/2}}$$

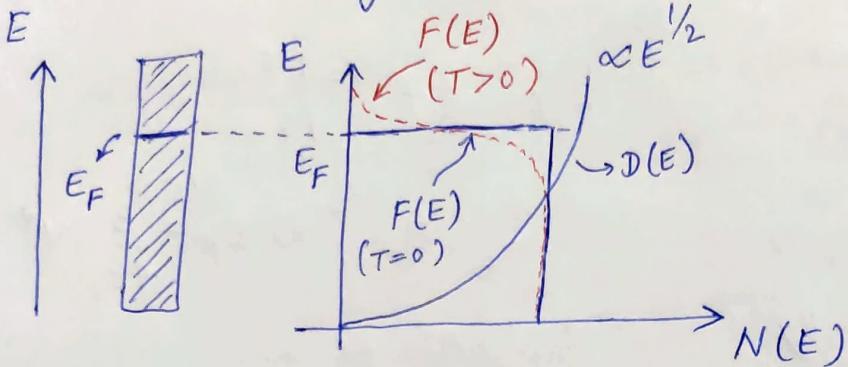
actual: Density of states

E^x E^y E^z $\begin{cases} 2D \rightarrow \text{Graphene, 2D materials} \\ 2D \rightarrow \text{2DEG (interface)} \\ 1D \rightarrow \text{Nanowires, nanorods, CNTs} \\ 0D \rightarrow \text{Quantum dots} \end{cases}$



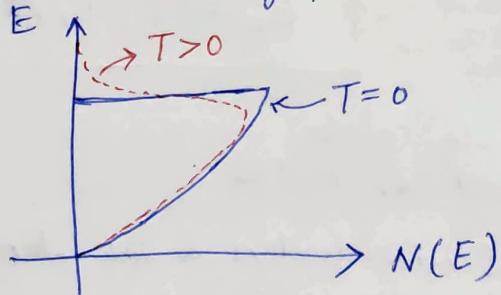
21] Now, we can write:

Population density : $N(E) = 2 \cdot D(E) \cdot F(E)$



NOTE:
Generally we draw this graph with E on the x-axis

↓ from both graphs we obtain



Thus, total no. of electrons
given by area
under the curve \rightarrow [i.e., upto E_F \rightarrow]

At $T=0$, $E_F \rightarrow N^*$ (i.e. let N^* be the area under the curve for the $T=0$ case, for limits $E=0$ to E_F)
We will now derive an expression for E_F :

$$N(E) = 2 \cdot F(E) \cdot D(E)$$

$$\text{At } T=0 \Rightarrow E < E_F \Rightarrow F(E)=1$$

$$\Rightarrow N(E) = 2 \cdot D(E)$$

$$\begin{aligned}
 \text{Thus, } N^* &= \int N(E) dE \\
 &= 2 \int D(E) dE \\
 &= 2 \int_0^{E_F} D(E) dE \\
 &= 2 c_1 \int_0^{E_F} E^{1/2} dE \\
 &= 2 c_1 \cdot \frac{2}{3} E^{3/2} \Big|_0^{E_F} \\
 &= \frac{4c_1}{3} E_F^{3/2} \Rightarrow E_F = \frac{3}{4c_1} N^*
 \end{aligned}$$

the constant
 present in
 $D(E)$

(i.e. $D(E) \propto E^{1/2}$
 $\Rightarrow D(E) = c_1 E^{1/2}$)

NOTE: We actually showed this exactly what it is

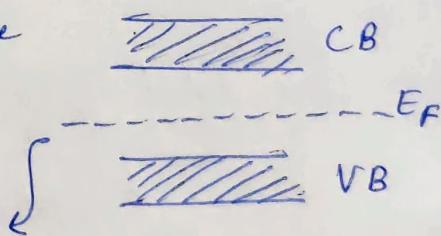
Taking this as a new const. c_2 :

$$E_F = c_2 (N^*)^{2/3}$$

NOTE: This formula can be used for Metals

However, for Semiconductors & Insulators

We cannot measure Fermi energy using this formula



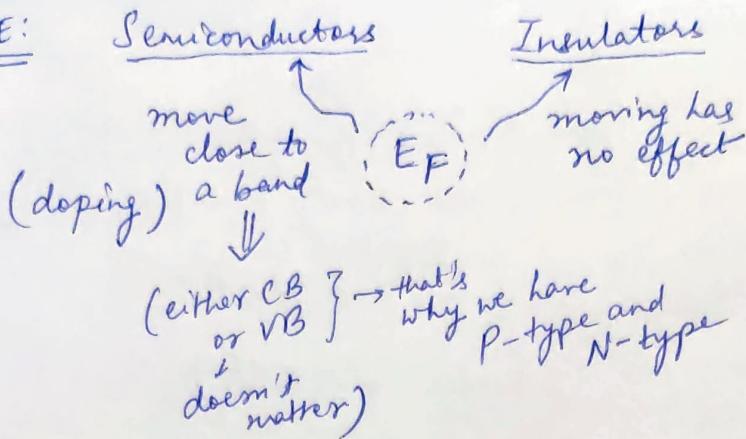
E_F lies in between
 Here there are NO
 such energy levels (which is
 why it is a "gap")

* If E_F lies in a gap
 No states at $E_F \rightarrow$ semiconductor / insulator

If E_F lies in a band
 states exist at $E_F \rightarrow$ metal

↓
 i.e. no valid
 energy states
 are existing
 there

* NOTE:



LECTURE-6

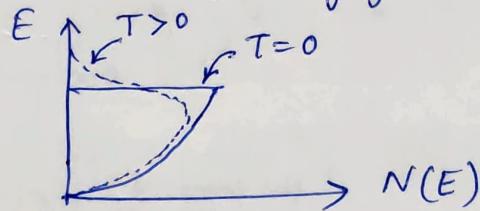
22] From our previous discussions, we know:

$$D(E) \propto E^{1/2}$$

$$\text{and also, } F(E) = \frac{1}{\exp\left(\frac{E-E_F}{k_B T}\right) + 1}$$

Since we also know that: $N(E) = 2 \times D(E) \times F(E)$
thus we also have an expression for $N(E)$

And we obtained the following graph:



23] Velocity Space

[this is actually a 3D sphere, but we can also draw the version for the 2D case]

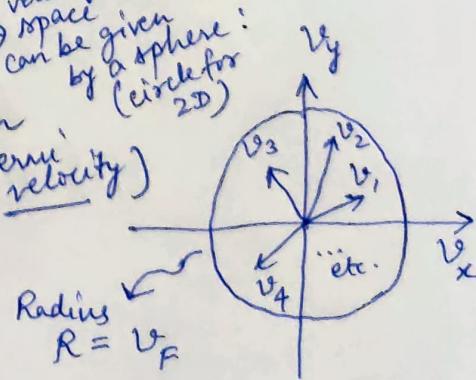
Assume we have a solid with a lot of e^- s

e^- s will have random velocities

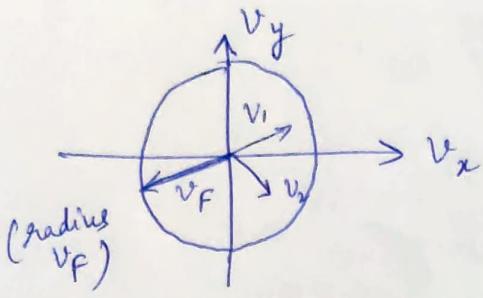
* But the velocities cannot be higher than v_F (Fermi velocity)
thus the velocity space can be given by a sphere (circle for 2D)

Thus, if external electric field is absent ($i.e. \vec{E} = \vec{0}$)

$$\text{then: } \sum \vec{v} = \vec{0}$$



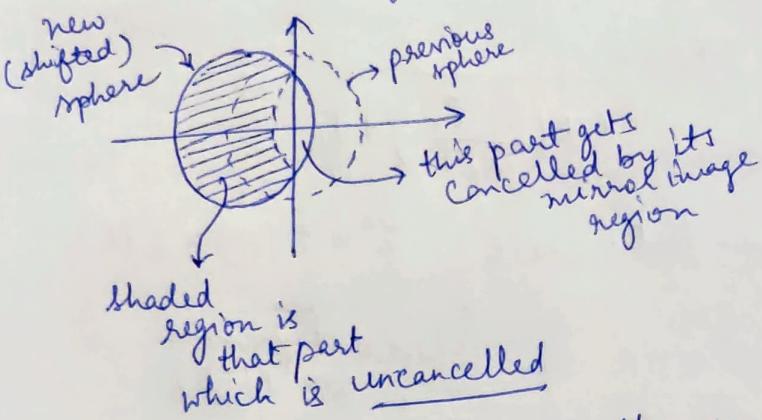
24] Velocity Space [continued]



At $E_F \rightarrow v_F$ will be the velocity of e's (avg.)
 Net velocity = 0 \rightarrow (i.e. $\sum \vec{v} = \vec{0}$)
 Electric field, $\vec{E} = \vec{0}$
 (NOTE: $J = \sigma E$)

If we apply Electric field in x-dir? :

The circle (actually a sphere) will shift towards the left (\because it is the speeds of e's) so dir. of acceleration will be opposite to that of applied electric field E



* NOTE: The actual shift is generally very small.

(thus the avg. velocity can be taken to be v_F)

Going back to Ohm's law:

$$J = \sigma E$$

$$\Rightarrow J = N' e v_F$$

We can write this as:

$$N' = N(E_F) \Delta E \quad (\text{here, } N(E) = 2 \times D(E) \times F(E))$$

Thus, we get:

$$J = N(E_F) e v_F \Delta E$$

$$\text{Let's take: } \Delta E = \frac{dE}{dp} \cdot \Delta p$$

$$\left\{ \begin{array}{l} \text{we know,} \\ E = \frac{p^2}{2m} \end{array} \right.$$

$$\Rightarrow \frac{dE}{dp} = \frac{p}{m} = \frac{mv_F}{m} = v_F$$

Hence, we get:

$$J = N(E_F) e v_F^2 \Delta p$$

We can use Newton's 2nd law: $F = \frac{dp}{dt} = eE$

$$\Rightarrow \Delta p = e E \Delta t \downarrow \tau$$

Putting this in:

$$J = N(E_F) e^2 v_F^2 \tau E$$

↓ But in reality

(if we derive it using the accurate way) → a factor of $\frac{1}{3}$ is present

We get: $J = \frac{1}{3} N(E_F) e^2 v_F^2 \tau E$

Which gives us that:

$$\sigma = \frac{1}{3} N(E_F) e^2 v_F^2 \tau$$

Conductivity
in Quantum Mechanical
model

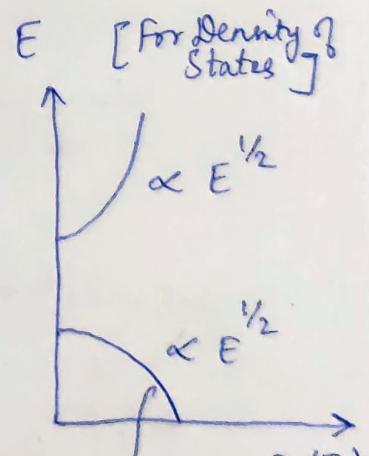
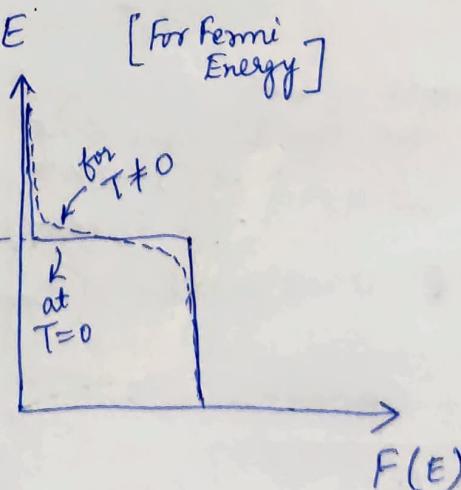
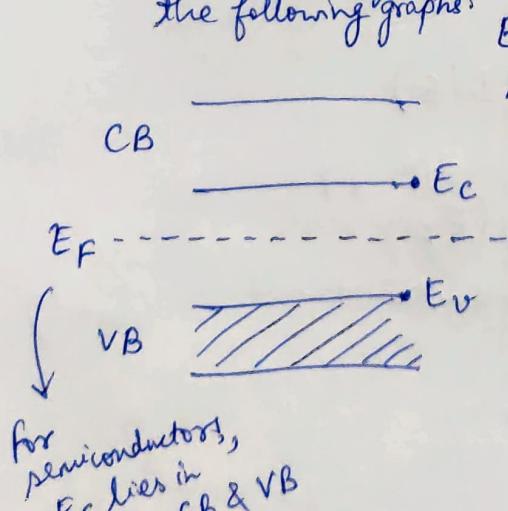
(NOTE: It is $\frac{1}{3}$ for
the 3D (spherical) case,
and $\frac{1}{2}$ for 2D case)

{ Classical model was:
 $\sigma = \frac{n e^2 \tau}{m}$ }

From this we can
clearly see some similarities
to classical picture
(eg: proportionality to τ)

25]

We thus will get
the following graphs:



for
semiconductors,
EF lies in
b/w CB & VB

(we will
explain
later why this
bottom part exists
here)

LECTURE-7

26] We have seen that:

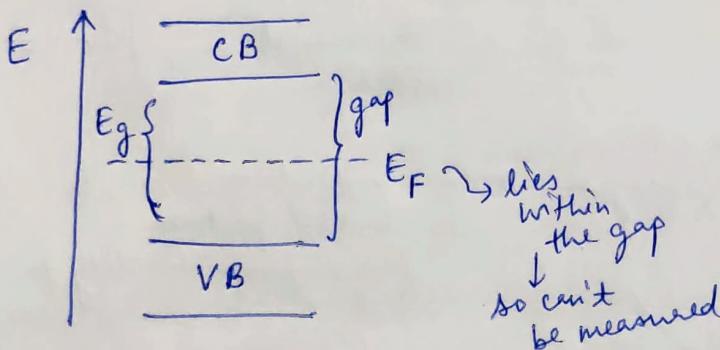
$$\sigma \propto \underbrace{N(E_F)}_{\text{depends on } D(E)} T$$

We will now look at:

- Semiconductors
 - Superconductors
 - Polymers \rightarrow Conducting
 - Glasses + Amorphous materials
- ↓ and then
Dielectrics

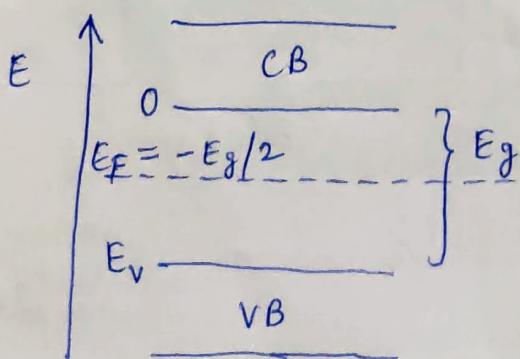
27] Semiconductors

↑
we use the assumption
that the semicond.
will have a
Valence Band & Conduction
Band



Using concepts of both $F(E)$ and $D(E)$
we can observe that
there exists such a gap
of energy (E_g)

We will take $E=0$ at bottom of Conduction Band (this is our choice)



We can take

$$E_F = -\frac{E_g}{2}$$

by symmetry
 (Should separate the
filled and unfilled
states)

Also, we know, $E_F \propto n^{2/3}$
 Thus by measuring E_g , E_V , and looking at n
 we observe (we can verify) that E_F lies in the
 middle of the gap.

For conductivity of semiconductor:

$$\sigma \propto n_e (\dots) + n_h (\dots)$$

↓
 there
 will be
 e's in region
 below E_F

↑
 and holes
 above
 region of E_F

thus again, by
 symmetry, it should
 be right to place
 E_F in the middle
 of gap.

NOTE! The fact that E_F is in the
 middle ↓

is only true (i.e. the "natural"
 place for E_F is the middle
 of the gap)
 for $T=0$

↓
 and we can move it up or down
 by changing Temperature T .

28] Taking $N^* \rightarrow$ No. of e⁻ in the
 conduction band

↓
 We want to
 capture the

Temp. dependence of N^*

(and also any other
 factors on which it
 depends)

Let's take: $dN^* = N(E) dE$

(We also know, $N(E) = 2 \cdot D(E) \cdot F(E)$)

$$\Rightarrow N^* = \int_0^\infty N(E) dE \quad \left(\because \text{we kept } E=0 \text{ at bottom of C.B.} \right)$$

Recalling, $D(E) \propto E^{1/2} \Rightarrow D(E) = A E^{1/2}$

$$\text{and } F(E) = \frac{1}{\exp\left(\frac{E-E_F}{k_B T}\right)+1}$$

We will make an assumption to get $F(E)$

{ This assumption
typically made for
Semiconductors }

i.e. $\Rightarrow \underbrace{E - E_F}_{\sim 0.5 \text{ eV}} \gg k_B T$
 \downarrow
 26 meV
(0.026 eV
 \Downarrow
 300 K)

Thus, we can say: $F(E) \approx \exp\left(\frac{E_F - E}{k_B T}\right)$

Hence: $N^* = \int_0^\infty N(E) dE$
 $= 2A \int_0^\infty E^{1/2} \exp\left(\frac{E_F - E}{k_B T}\right) dE$

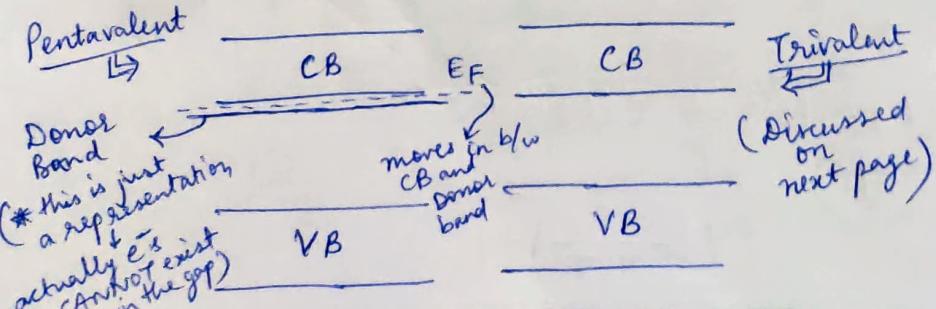
$$= 2A \exp\left(\frac{E_F}{k_B T}\right) \int_0^\infty E^{1/2} \exp\left(-\frac{E}{k_B T}\right) dE$$

\downarrow taking $E_F = -\frac{Eg}{2}$ this is some function $I_1(T)$
 \downarrow taking $f(T) = 2A I_1(T)$

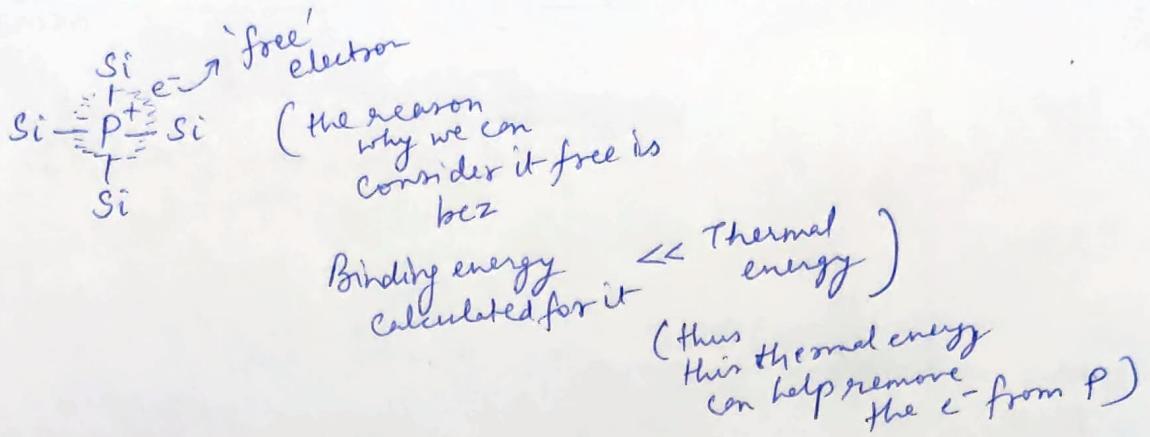
Thus $\Rightarrow \boxed{N^* \propto f(T) \exp\left(-\frac{Eg}{2k_B T}\right)}$

From the integral for $f(T) \Rightarrow$ We see that for higher $T \rightarrow N^*$ will increase

29] Doping \rightarrow Moving the Fermi Level



\rightarrow "small" amount of trivalent (e.g.: B) or pentavalent (e.g.: P) species into Si



* NOTE: By increasing doping

We DON'T change the donor band

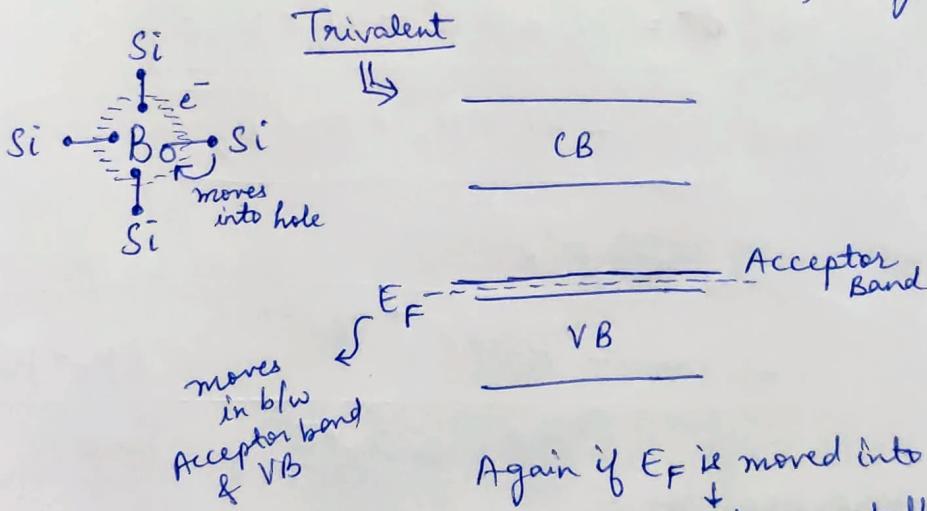
we only increase the EF

* If this crosses into CB

becomes a metal (called degenerate doping)

* NOTE: Non-doped semiconductor is called Intrinsic semiconductor.

* NOTE: Eg does NOT change by doping. (Band gap remains same, only EF is changed)



Again if EF is moved into VB
it will show metallic behaviour

(will be called degenerate semiconductor)

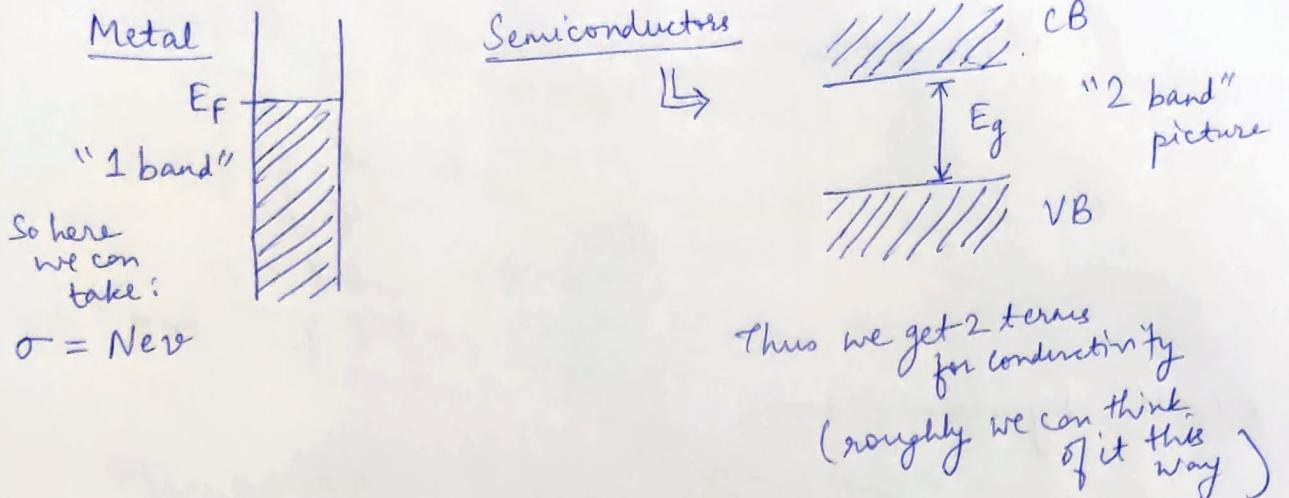
LECTURE - 8.

30] We know now that for semi-cond.

$$N_e \propto f(T) \exp\left(-\frac{E_g}{2k_B T}\right)$$

Generally we use this to find σ

but here we need to consider both 'e's and 'holes'



Thus we get 2 terms for conductivity
(roughly we can think of it this way)

$$so \Rightarrow J = N_e e v_e + N_h e v_h$$

Here, we define a term: "Mobility" (μ)

$$\text{defined by, } \mu = \frac{v}{E} \rightarrow \text{electric field}$$

$$\Rightarrow J = N_e e \mu_e E + N_h e \mu_h E$$

$$\text{and, } \sigma = N_e e \mu_e + N_h e \mu_h$$

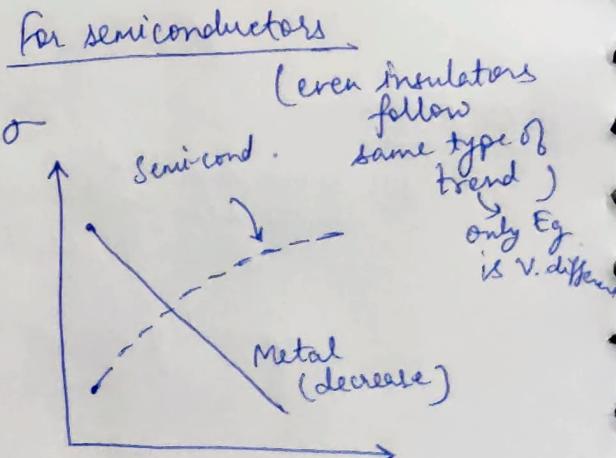
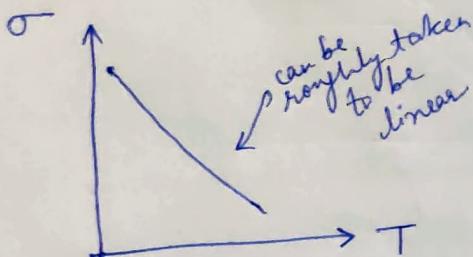
Since no. of carriers $\propto e^{-E_g/2k_B T}$

$$\Rightarrow \sigma = A(T) e^{-E_g/2k_B T} \cdot e^{-(\mu_e + \mu_h)}$$

constant e (2.77828...) charge of electron

31] Temperature Dependence

For Metals:



{ This is the case for Intrinsic semiconductors }