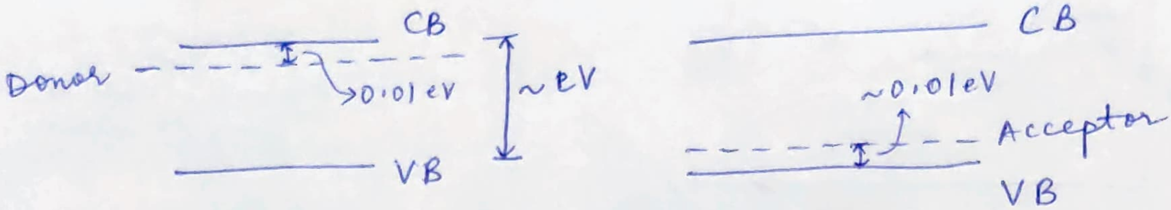
32] Semiconductors (Extrinsic)



n-type p-type

We know that:

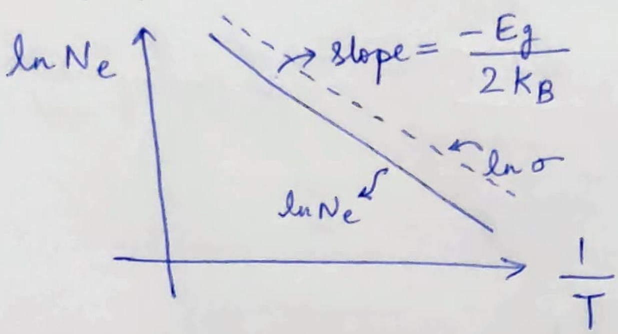
$$N_e \propto \exp\left(-\frac{E_g}{2k_BT}\right)$$

LECTURE-9

$$\ln N_e \propto -\frac{E_g}{2k_BT} + \underbrace{C(T)}_{\text{some term}}$$

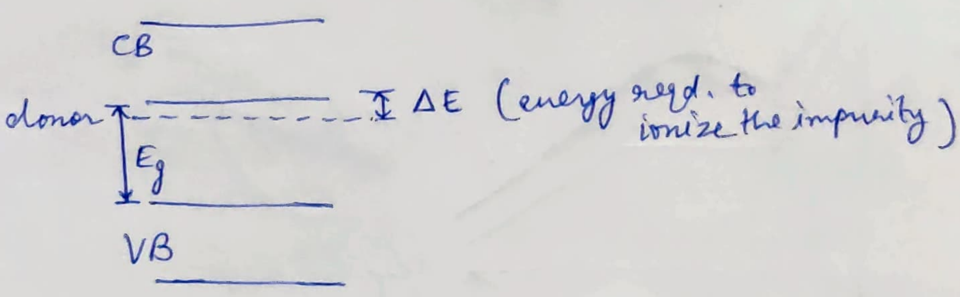
($\because$ if $N_e \propto A$ (let's say)
$\Rightarrow N_e = kA$
$\Rightarrow \ln N_e = \ln A + \ln k$)

So the graph will be like:



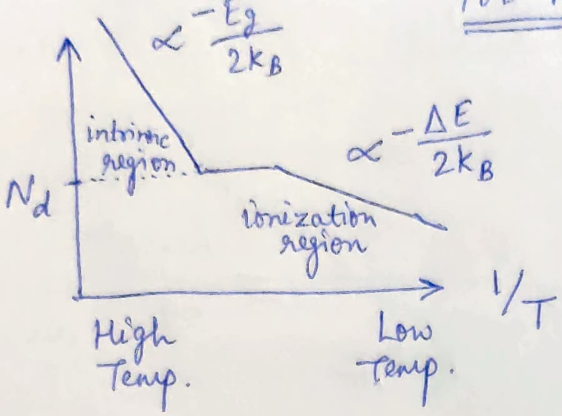
We can say that, $\sigma \propto N_e$
Thus, σ should follow a v. similar trend to N_e

33] Extrinsic Semiconductors



Here if we try to plot the trend with temperature: { On next page }

For n-type



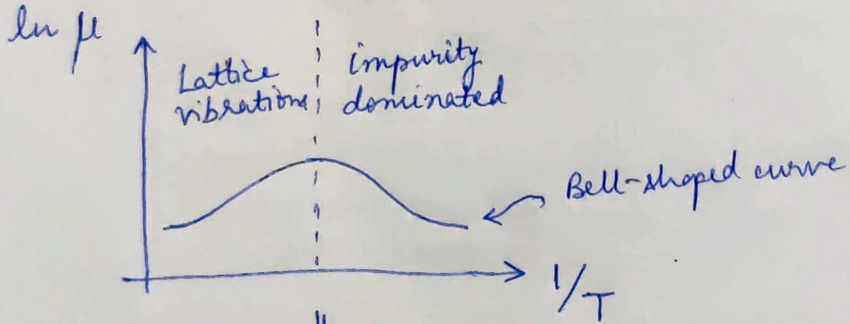
Just like for extrinsic
↓
on increasing T
↓
e^-s will be able to jump to higher energies
↓
and get into CB

Gives ⇒ Intrinsic region

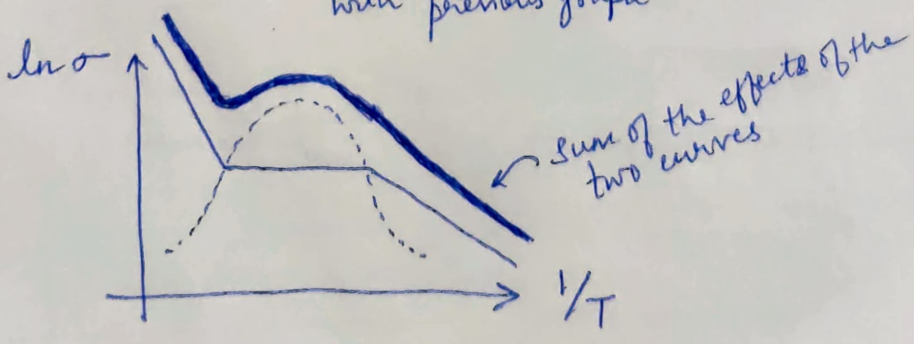
Ionization region: due to extracting the donor e^-s (which can be done at low T also)
↓
max^m N_d e^-s are present

We can now look at relation b/w μ_e and T ⟶ we will do this by intuition and won't derive it

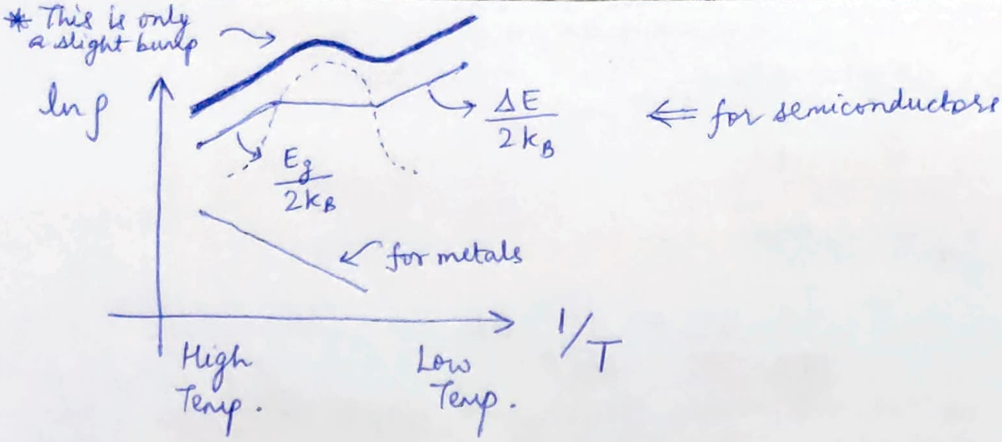
where this gives an idea of "scattering"



⇓ overlapping with previous graph



Now, we can next look at the relation b/w ρ and T :



34] Hall Effect

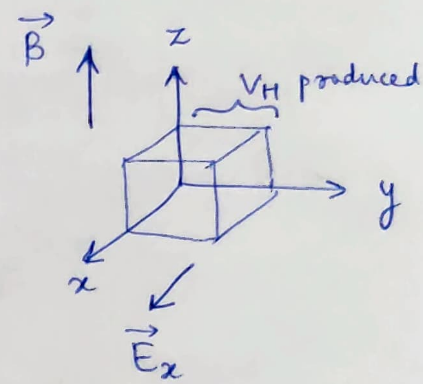
can be measured even for metals
↓
But is more useful for semiconductors
↓
data collected, helps tell no. of carriers in semiconductor < n-type / p-type

Make use of $\vec{E}$ and $\vec{B}$ fields

$e\vec{E}$ $\quad$ $e(\vec{v} \times \vec{B})$

We will apply

$\vec{B}$ along $+z$-dir^n $\quad$ $\vec{E}_x$ along $+x$-dir^n



By Ohm's law:

$$\overbrace{J_x = \sigma E_x}$$

⇓

Causes e^-s to move in $-x$ dir^n

⇓

& since $\vec{B}$ acts
↓
will cause voltage drop along y-dir^n ⇒ called V_H

(as e^-s are trying to push along y-dir^n)

⇓

But they can't escape the bounds of the solid

Equilibrium steady state:

$$\Rightarrow \quad eE_y = ev_x B$$

$$\Rightarrow \quad e\frac{V_H}{L} = ev_x B$$

$$\Rightarrow \quad V_H = v_x B L$$

↓

Hall Voltage

Using $j_x = \sigma E_x = N e v_x$

$\Downarrow$ we get:

$$V_H = v_x B L$$

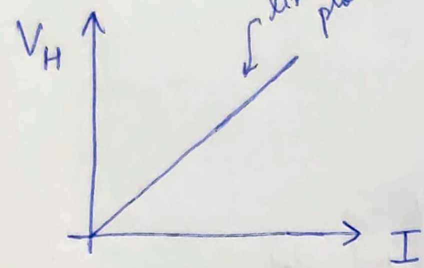
$$= \frac{j_x}{Ne} BL = \frac{I}{NeA} BL$$

$\hookrightarrow$ slope $\propto \frac{1}{Ne}$ $\rightsquigarrow$ defined as Hall coefficient

LECTURE-10

$$\Rightarrow \boxed{R_H = \frac{1}{Ne}}$$

Thus the plot will be:



35] • <u>Anomalous Hall effect</u>

$\downarrow$

seen in magnetic materials

• <u>Quantum Hall effect</u>

$\downarrow$

involved the quantization of σ_y

{ Assumption: Material is Anisotropic

$\downarrow$

so that σ will depend on dir.^{n} of voltage so $\sigma_x, \sigma_y, \sigma_z$ won't necessarily be equal }

We see that:

$$\sigma_y = n \frac{e^2}{\hbar}$$

(integral multiples of $e^2/\hbar$)

• <u>Fractional Hall Effect</u>: Similar to above case, but with $n = 1/3, 2/3, 5/2, \ldots$

36] <u>Semiconductor devices</u>

$\downarrow$

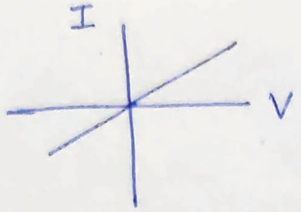
Contact

Ohmic (obey Ohm's law)

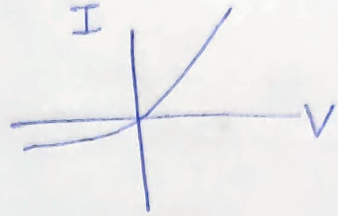
Rectifying / Blocking contacts

} Determining which of these classifications is present + done based on * <u>Fermi Level</u>

Ohmic contacts

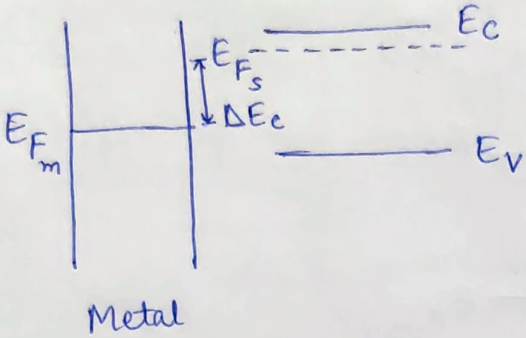


Rectifying / Blocking contacts



37] Metal – n-type semiconductor (for metal-semiconductor contacts)

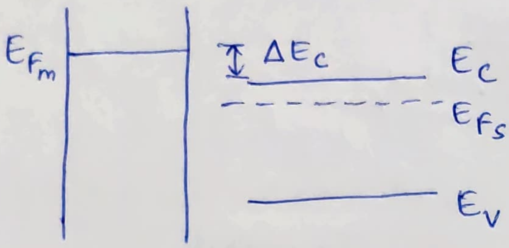
Case ①



$\Rightarrow E_{F_{metal}} < E_{F_{semicond.}}$

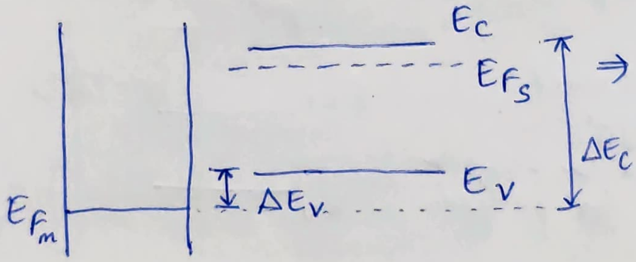
But E_{F_m} still lies within the gap

Case ②



$\Rightarrow E_{F_{metal}} >> E_{F_{semicond.}}$

Case ③



$\Rightarrow E_{F_{semicond.}} >> E_{F_{metal}}$

(or $E_{F_{metal}} << E_{F_{semicond.}}$)

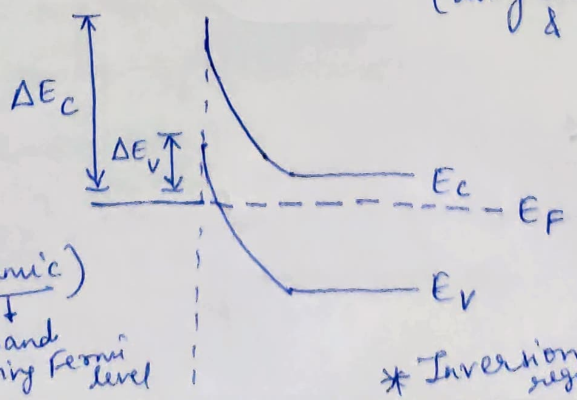
In order to achieve Uniform Fermi level $\Rightarrow$ i.e. both metal & semicond. having same E_F

↓

We perform $\Rightarrow$ * Band Bending

(using solid line for metal & dashed line for semicond.)

For case ③ $\Rightarrow$



$\Rightarrow$ Since E_V has crossed E_F

↓

that means carriers are actually holes

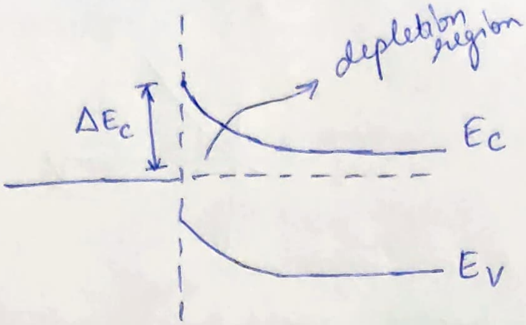
(Ohmic)

↓

Since band is crossing Fermi level

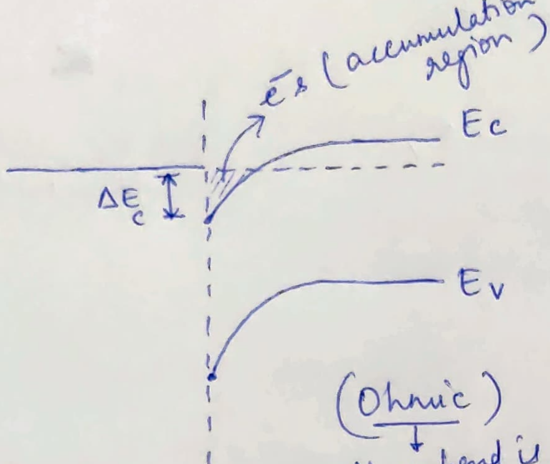
* Inversion region $\Leftarrow$

For Case ① ⇒



(Blocking / Rectifying) → since no band is crossing Fermi level

For Case ② ⇒

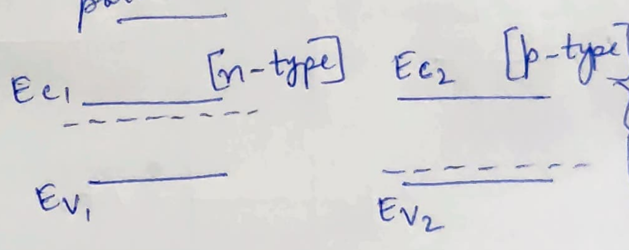


(Ohmic)
↓
since band is crossing Fermi level

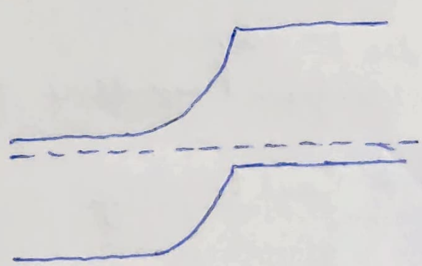
NOTE:

* Here, we are going to take E_F as ⇒ $E_F \to \infty$, i.e. Ionization potentials

NOTE: Till now we showed for n-type. Similarly, we can perform for p-type

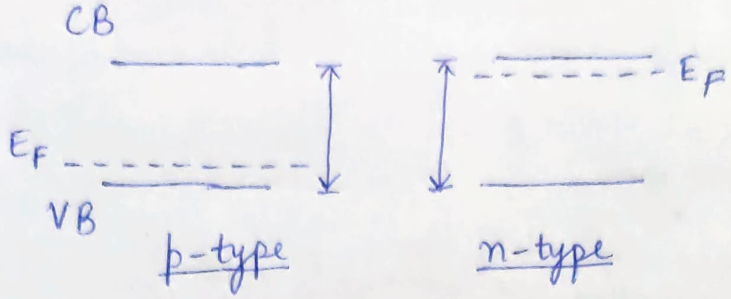


eg: For p-type we will do something like this:

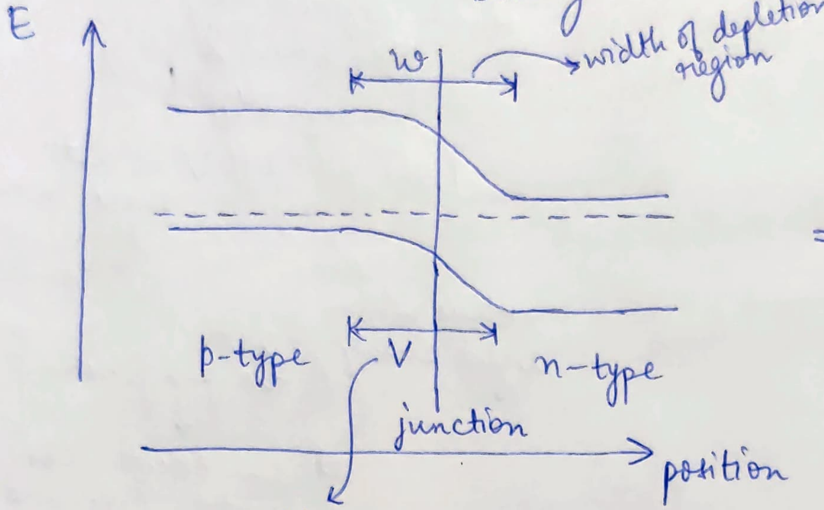


LECTURE-11

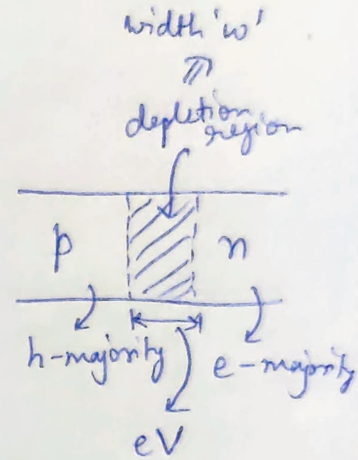
38] p-n junctions
↓
Same semiconducting material (so same individual band gaps)



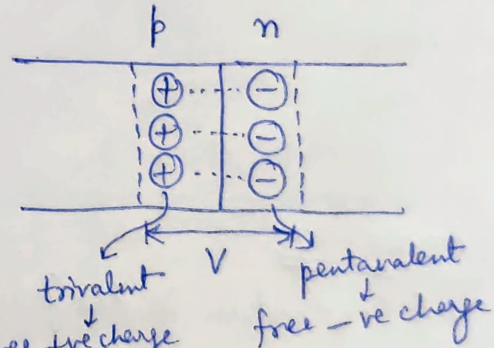
⇓ Band bending



⇒

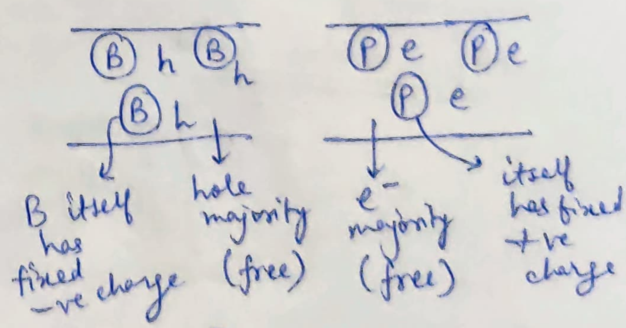


⇓ Atomic picture

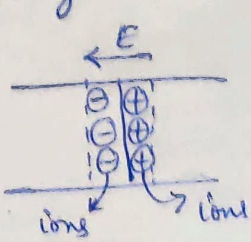


⇙ leads to an electric field
↓
which causes the potⁿ diff.

⇓ looks like



Near depletion region
↓
e^-s flow from n to p side
↓
gradually only ions left in that region which creates an electric field opposing further e^- flow ⇒



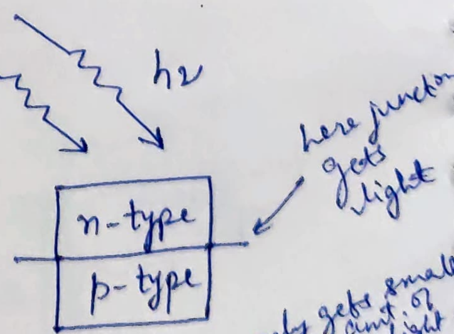
39] * In case of Solar cells
↓
its NOT same as ordinary p-n junction
↓
bcz here the ends of the p-n junction are connected with **Metal contacts**
↓
which significantly changes the band bending diagram
↓
(the potⁿ diff V is not there in the same way anymore)
↓
thus when light energy acts on the p-n junction
↓
it can excite electrons into C.B. and generate electricity
↓
But the same cannot be done for simple p-n junction
(i.e. a direct p-n junction with light cannot be used as a battery)

LECTURE-12

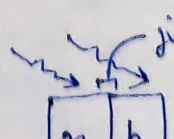
* { Covered in Slides }

LECTURE-13

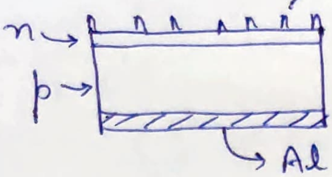
40] **Solar cells**
↓
p-n junctions
↓
typically n-type is at the top



{ NOT placed like: }



⇒ bcz 1) Surface area at top should be more
and mainly, 2) Junction needs to recieve more light

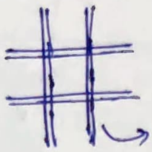


we don't cover entire surface with metal → (otherwise reflection of light will occur)

↓

instead we use a meshgrid

⇓ from Top, looks like: (i.e. the meshgrid)

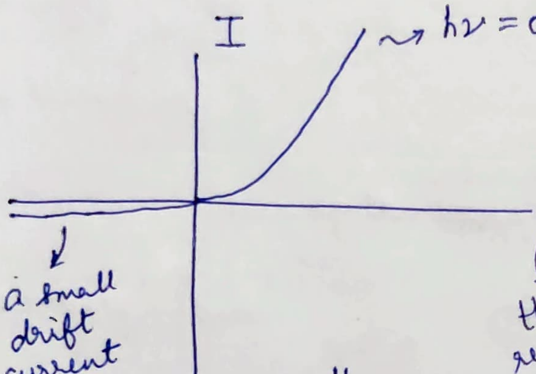


→ conducting oxides

*

(most common: ITO {Indium Tin Oxide})

41]

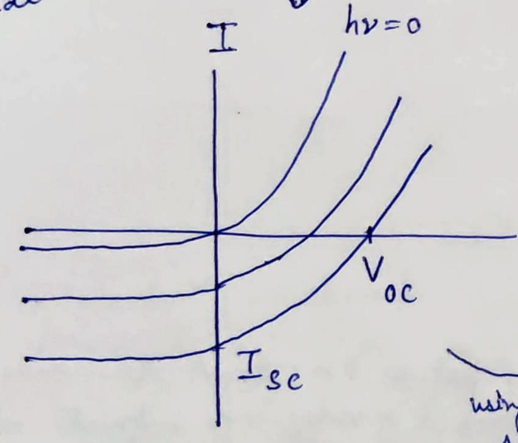


→ $h\nu = 0$ case [* NOT technically perfect, but says that this is the case for not applying light]

→ a small drift current on −ve side

→ this V here represents applied voltage

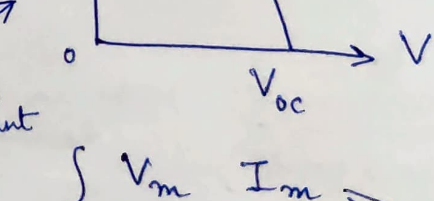
⇓



Increasing intensity

(the more light that falls → the more carriers are created)

using only this 4th quadrant



* Here, $VI < 0$ → −ve value for Power → implies that we are generating it

{ $\underbrace{V_m \quad I_m}$ → Power is maximum

⇓ NOTE: These are NOT max values of V and I. These are values of V and I for which Power is max^m. }

* We define, Fill Factor $\boxed{F.F. = \dfrac{V_m I_m}{V_{oc} I_{sc}}}$

It can also be written as :

$$F.F. = \frac{V_o I_o}{V_m I_m}$$

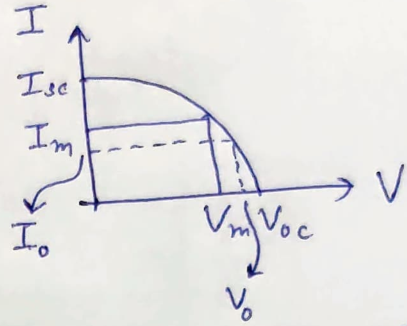
(V_o and I_o are called operating voltage and operating current)

thus, by definition it will always be < 1

⇓

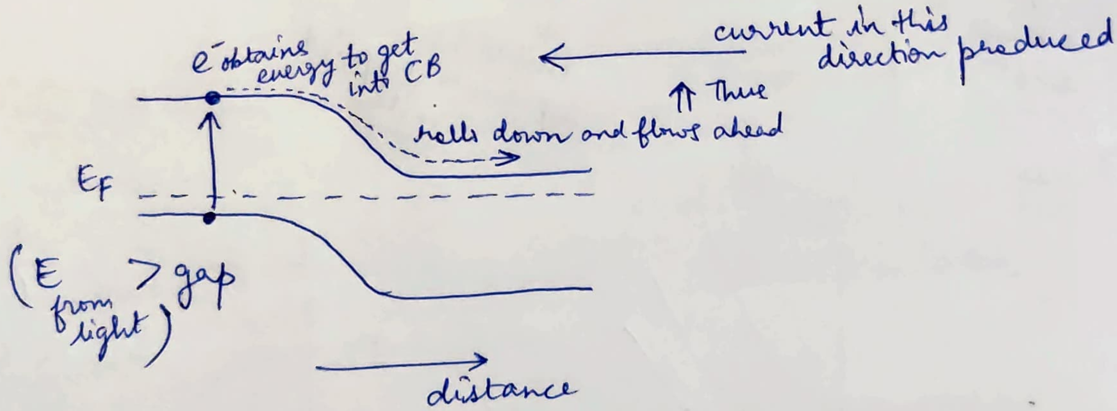
(usually value is ~0.7)

NOTE: n-part is thinner than p-part
↓
to allow more sunlight to reach the junction.



NOTE: V_{oc} → open circuit voltage ⇒ tells us the voltage we need to apply (of majority carriers) to cancel out the existing voltage (of minority carriers)
↓
so current becomes zero

I_{sc} → short circuit current
⇓
the current flow that exists even when no applied voltage



* **Bonus Assignment:** (1–5 points)

Make an elevator pitch on some semiconductor device. { Record a video and submit by whatsapp }
↓
Max time : 3 mins
Min time : 1 mins

Deadline: Before the Minor

{ Just need to propose some idea, not necessarily a new idea }

LECTURE-14

42] Superconductors

(we'll use the abbreviation "SC")

→ Marker of a SC → Zero Resistance

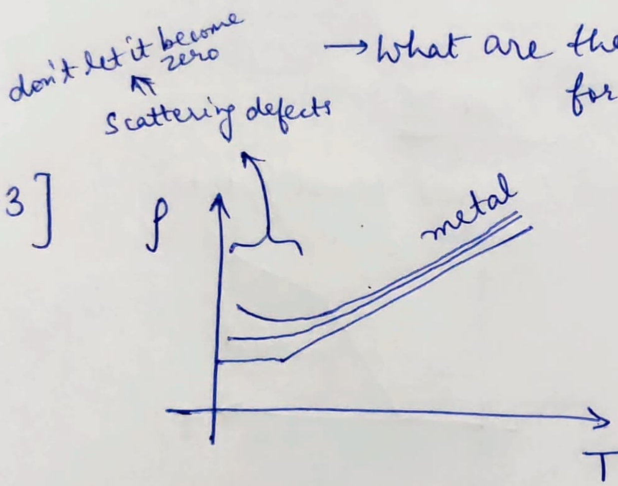
(although this v. hard to explain theoretically)

→ How zero is the resistance?

(how do we know whether it is exactly zero, or just some v. small no. that can't be picked up properly by our instruments?)

→ What are the conditions for observing SC behaviour

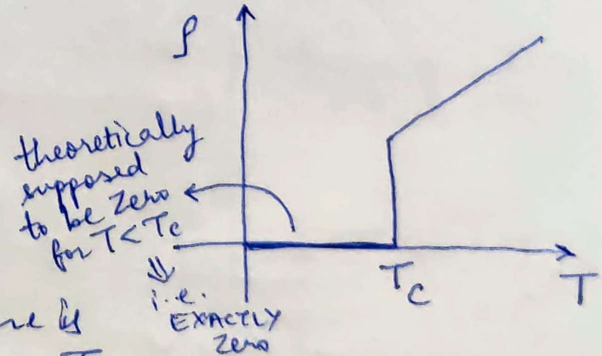
43]



* Some common metals that can show SC behaviour

↓

Pb, Hg, Al, etc.



For Superconducting behaviour, there is a critical temp. T_c

↓

below which the phase transition occurs in the metal

↓

giving it SC behaviour

For instance,
in the case of Pb:

$$\rho(300K) \approx 10^{-5}\ \Omega\ \text{cm}$$

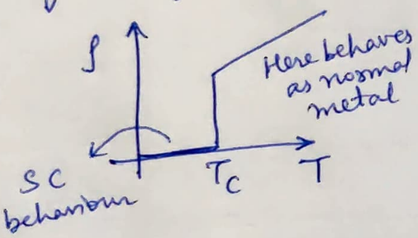
$$\rho(< T_c) \approx 10^{-25}\ \Omega\ \text{cm} \quad \text{(experimentally measured value)}$$

Generally T_c ranges from 4 – 10 K

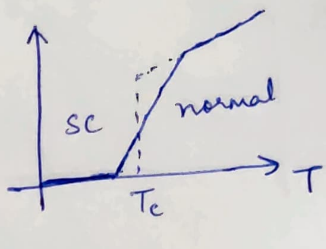
44] The most commonly used SC
↓
YBCO
(Yttrium Barium Copper Oxide)
↓
Has quite high T_c
(around liquid Nitrogen temp.)

45] Supercondutors

Type I
↓
generally pure metals

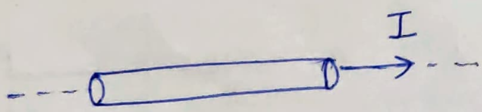


Type II
↓
mixed phase/state



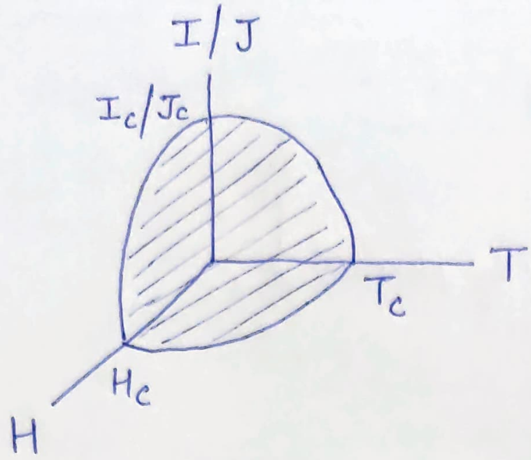
NOTE: Magnetic fields can destroy superconductivity → (i.e. can make $\rho > 0$)

46]



$$B = \frac{\mu_0 I}{2\pi a}, \text{ where } H = \frac{I}{2\pi a}$$

Thus, there is a critical current I_c
↓
above which the magnetic field
↓
destroys SC of a material in that region



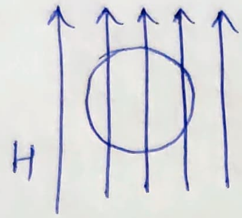
We know, $B = \mu_0(H+M)$

Inside the SC
↓
magnetic field B is exactly zero
↓
$\therefore \boxed{H = -M}$

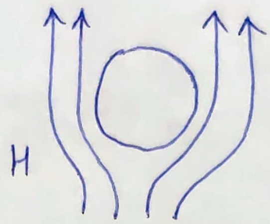
and $\boxed{\chi = \frac{M}{H} = -1}$

i.e. perfect diamagnet

NOTE:



Magnetic field through metal sphere



Field bends around SC sphere
↓
and the energy expended to bend these lines
↓
can be used to generate a force to counter, say gravity
↓
eg: for Magnetic Levitation

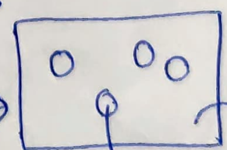
47] **Type I**
↓
Has a single H_c (critical H)

Type II
↓
Have two values
H_{c_1} H_{c_2}
have a gap of about 100 T

* **NOTE:** Check the plots for H_c for both type I and type II

under microscope

Mixed phase between H_{c_1} and H_{c_2} ⇒



rest shows normal behaviour

vortices
↓
these regions show SC behaviour

48] Currently the theory that explains SC most accurately (though not completely)
↓
* **BCS Theory**
↳ involves a concept called Cooper* Pairs

Cooper Pairs : Some kind of "bound" pair of e⁻s

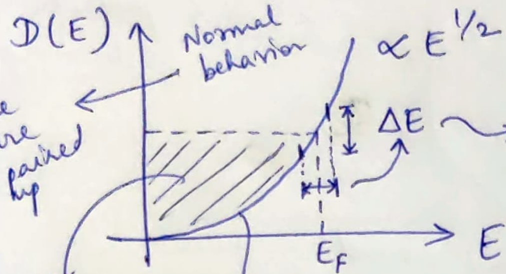
bound by phonons

Current explanation
↓
based on Density of states

Normal behavior

Here e⁻s are not paired up

$\propto E^{1/2}$



BCS theory explains that a gap is created due to cooper pairs → just above the fermi level

(called quasielectron gap)

in states below Fermi level
↓
e⁻s are paired up

original curve for normal metal

This explains destruction of SC behavior by Magnetic field quite well
↓
However still doesn't directly explain Zero resistance
[This is much more complicated to explain]

LECTURE-15

49] Conducting Polymers

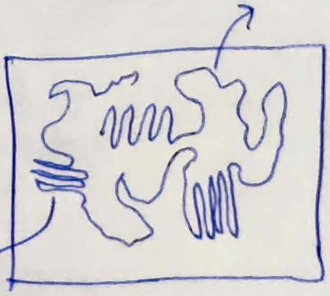
(Organic metals) (?) → semiconductors

↓
Used in Solar cells

Some examples (most commonly used)
- PANI
- Polyacetylene
- PEDOT-PSS

eg: PEDOT-PSS (used most commonly among conducting polymers)

Polymers : (structure)
↓
mixture of ordered & disordered



disordered region

crystalline region

Nature of Bonding

1) Predominantly covalent (although there could sometimes be small ionic interactions)

2) van-der-waal's interaction (especially between the molecules in a crystalline region)

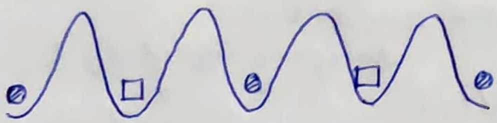
* **NOTE:** The Temperature dependence of Conducting polymers → closer to Semiconductor-like

But magnitude of conductivity → more resembles metals

50] **Ionic Conduction**

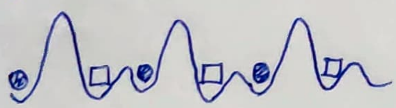
A^+B^- :

⊘ = A^+
□ = B^-

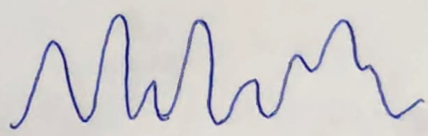


← representing the potential of the ions at their lattice sites

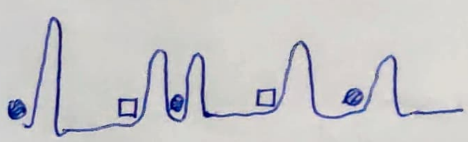
I. **Height disorder**



or



II. **Position disorder** (Amorphous)
↓
occurs due to some distortion in the lattice



51] Starting with the initial picture:

A^+B^- :

Deriving using concepts of diffusion:

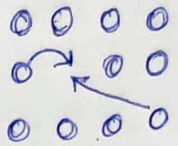
We have: $\mu_{ion} = \dfrac{eD}{k_B T}$ *(Einstein relationship for μ_{ion} and D and T)

{ NOTE: N_{ion} (no. of point defects) $\xrightarrow[\text{on}]{\text{depends}}$ T and Gibbs Free Energy }

Now, $\sigma_{ion} = N_{ion} \mu_{ion} q_{ion}$ → charge on an ion

$= N_{ion} \dfrac{eD}{k_B T} q$

Hopping Transport



(Diffusion dominated)

In general, we know : $D = D_0 e^{-\Delta Q / k_B T}$

Thus, $\sigma_{ion} = \dfrac{N_{ion} e D_0}{k_B T} q e^{-\Delta Q / k_B T}$

→ * due to this damping effect of T
↓
at any T above 200 K or so
↓
the conductivity "freezes"
↓
and is thus not too large

For Semi-conductors : $\sigma_{semi} \propto T^{3/2} e^{-\Delta E_g / k_B T}$

LECTURE-16

52] { NOTE: For Minor Exam — Formula sheets are NOT permitted }

Amorphous Semiconductors

↓

Positional disorder

→ Interstitial vacancies

→ breakdown of periodicity
↓
eg: (metallic) glasses ~→ i.e. they are made of metals (often rare earth metals)
↓
become glasses since there is no order in them

General picture of amorphous material :

Si {aSi-H} (amorphous Silicon)

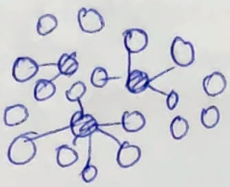
NOTE: {In practice it is very easy to create an amorphous material
↓
& v. hard to make something crystalline}

It hard to say exactly how many bond are made by a Si atom on average

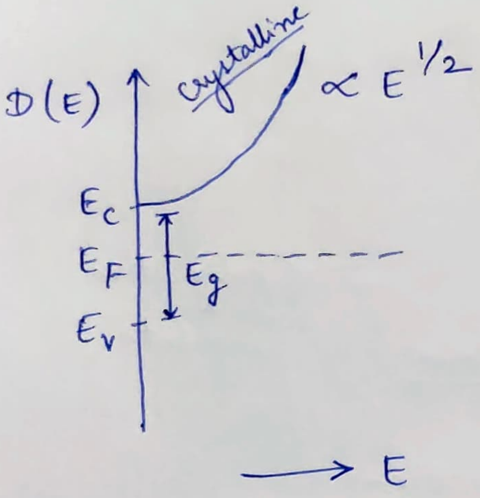
Generally on avg. it is :

$(N_b)_{avg} \approx 4$

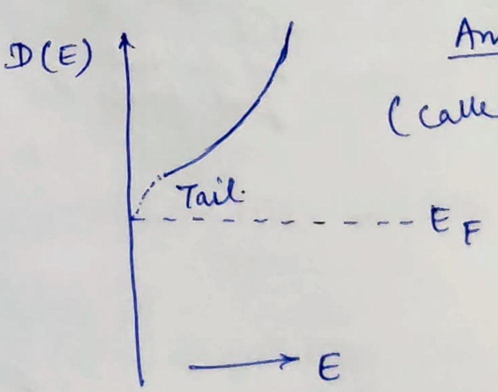
but
↓
there is also a concept of <u>Dangling bonds</u>
↓
also leads to <u>localization</u> of atoms → hence even the free e^-s may be bound to certain local regions with certain Energy, or a certain clump of atoms



53]



But due to localization
↓
there will be some states in the band gap as well
(due to destruction of the crystal order)
↳ leading to <u>tail-like features</u>

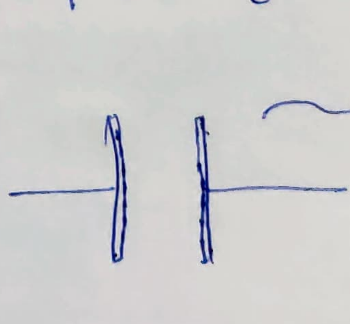


<u>Amorphous</u>

(called Tail because they are only in a v. small fraction)

54] <u>Insulators</u>
↓
Dielectric properties

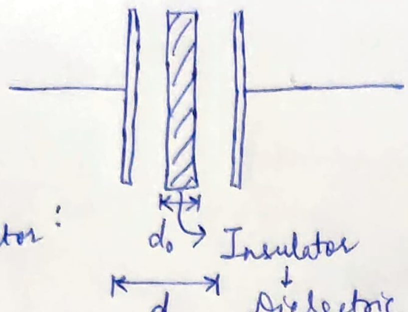
eg:



→ for this we say:

$$C = \frac{\varepsilon_0 A}{d}$$

Now we insert an insulator:



d_0 → Insulator → Dielectric constant K

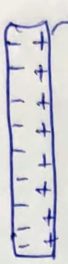
d

Here, we get:

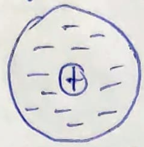
$$C' = \frac{\varepsilon_0 K A}{d}$$

(for the case when $d_0 = d$)

This increase comes from <u>Polarization of Insulator</u>



these are NOT free charges



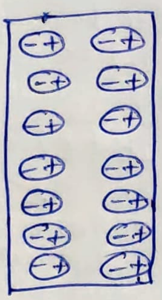
e^- cloud gets distorted

Not v. clear picture

- electronic
- ionic
- molecular

any of these 3 contributions are responsible for polarization

instead draw this way:



55] There will be a <u>Frequency Dependence</u> of polarization in an insulator

↓

thus we do not just probe the polarization

↓

to check behavior

↓

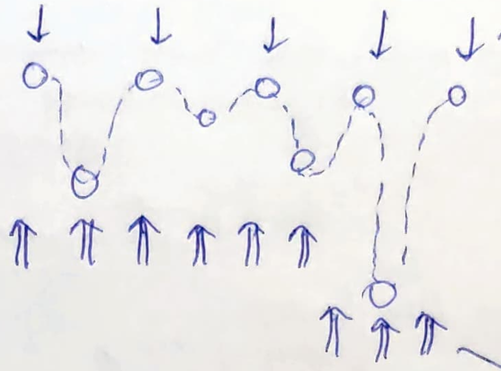
we don't use static electric fields

↓

instead, alternating electric fields are used

i.e. we change freq. to see different behavior at different frequencies eg:

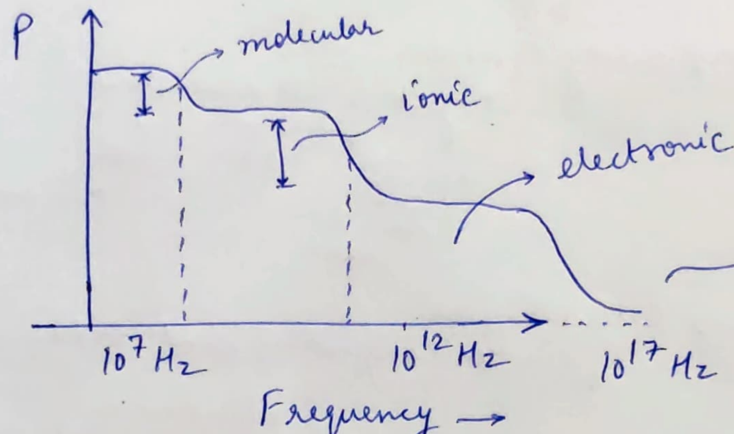
{ An analogy with frame rate of camera } ⇒



low "frame rate" → gives linear picture of balls

high "frame rate" → shows different trajectory

For Polarization, the following frequency dependence is observed



ultimately at v. high frequencies → even electronic will stop showing effect → * P will drop to essentially zero

{ By changing freq. → we change sampling → & by looking at the jumps we can observe the molecular, ionic & electronic contributions respectively }

LECTURE-17

* **For Minor:** (Syllabus)

0. Distinguish b/w Metals, insulators and Semiconductors.
1. Classical Theory
   - Derivation of σ
   - Obtaining different quantities using σ
     (NOTE: successive parts of a question get harder)
     eg: (c) > (b) > (a)
     (c) toughest, (a) easiest
   - Numericals
     (eg: Calculating & defining sheet resistance (R_s) resistivity (ρ) and simple crystal structure calculations)

eg: Knowing no. of atoms in unit cell structure

Simple cubic structures (like BCC, FCC, ...)

→ Application-based numericals
(eg: like Antenna design of assignment
(i.e. design based problems)
↓
these problems
will require simple
formulae & concepts

→ Drawbacks
of classical theory

2. Quantum Theory

→ Fermi-Dirac distribution function
(eg: Numericals in Assign. 2)
↓
and calculating E_F
(for 3D)

→ Density of States
(Calculating it in all dimensions)
↓ eg: 3D case done in class
↓ 2D
↓ 1D → in assignment

→ Calculating no. of e^-s in Conduction band ⇒ N_c
↓
also done in
content of semiconductors

3. Semiconductors

→ n & p type
→ Band Diagrams
→ Junctions → should be able to distinguish b/w {Ohmic / Schottky / Blocking} → using band diagrams (IV characteristic)
→ Bond bending

→ Diode equation for P-N Junction
*(needs to be memorized)

looks something like: $I = I_s + I_0 e^{-eV/k_BT}$

{ NOTE: Every other equation except this
you should know
how to derive them }

4. Semiconductor Devices

→ Diodes
→ Solar cells { should know why diode cannot be used as a solar cell }

→ Conducting polymers, ionic conduction, amorphous materials } → Read book for this portion as well
*

i.e. around 2 line answers ⇐ Can expect v. short answer questions

5. Superconductors

↳ Type I and Type II
(defining them & distinguishing them & their graphs, etc.)

6. Insulators

↳ Expressions for Capacitance
↳ Frequency dependence
(eg: why does dielectric const. depend on freq.)

[*NOTE: These all are going to be text-based questions
↓
Also marks for a question will be proportional to the time reqd. to write the solution to those questions

Questions that will be complicated are going to have a star next to them
(so they most likely won't have a simple short answer)]

Reference : Rolf E. Hummel
↳ Chapters 7, 8, 9
↳ Chapter 6 (to some extent, mainly Density of States)
↓
For practice you can check numericals given at the end of the chapters in the book