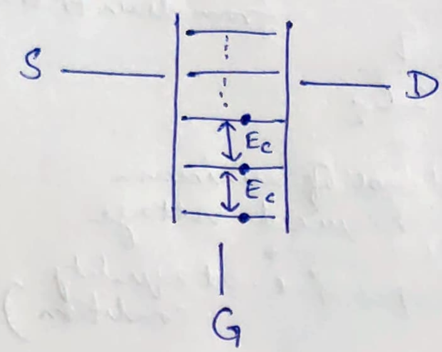
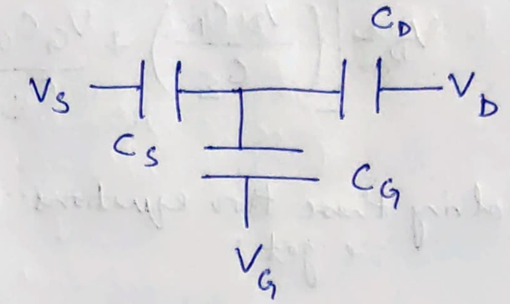
LECTURE 9 (29/01/2024)

30]

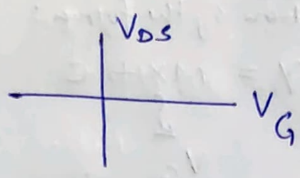




$\{ C_\Sigma = C_S + C_D + C_G \}$

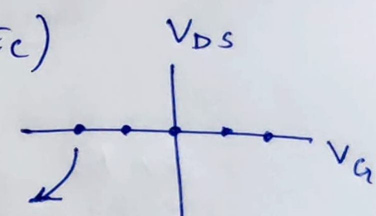
We are here going to consider the absence of a source-drain bias

we want to obtain the plot :



We can see that
↓
whenever we apply V_G such that the
↓
energy levels of dot align with source-drain
↓
Current flow occurs

These will occur at periodic intervals (of energy gaps equal to E_C)
↓
these points in the plot are called **degeneracy points** *



31] In order for flow of current to occur
↓
we know that voltage at junction needs to be $\geq \dfrac{q}{2C_\Sigma}$
↓
Now, we will also need to take into account the capacitances :

$$\textcircled{1} : \quad \therefore \frac{V_D C_D}{C_\Sigma} + \frac{V_G C_G}{C_\Sigma} \geq \frac{q}{2C_\Sigma}$$

For (Positive source drain
↓
i.e. e^-'s moving from source to drain)

For a reversed polarity case: (negative source drain ↓ i.e. e^-'s moving from drain to source)

$$② : \quad V_D - \left[\left(\frac{V_D C_D}{C_\Sigma}\right) + \frac{V_G C_G}{C_\Sigma}\right] \geq \frac{q}{2C_\Sigma}$$

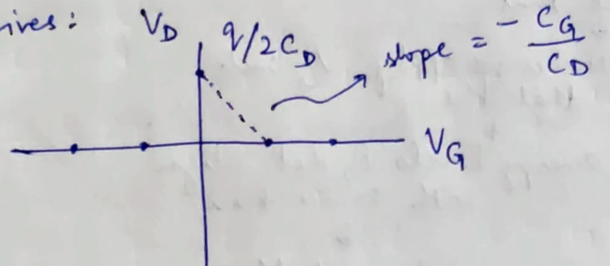
Solving these two equations (for case of minimum required voltage ↓ i.e. at equality condition) we get:

From ① :

$$\underbrace{V_D = \frac{q}{2C_D} - \frac{V_G C_G}{C_D}}_{\text{this is a linear equation of the form: } y = mx + c}$$

$y \to V_D$, $x \to V_G$

This gives:

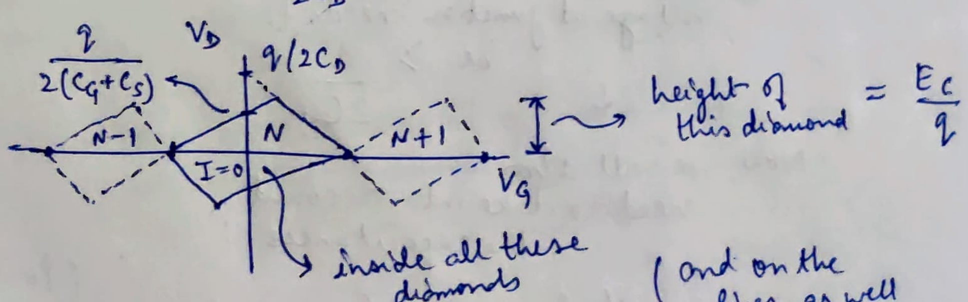


From ② :

$$V_D = \frac{\frac{q}{2C_\Sigma} + \frac{V_G C_G}{C_\Sigma}}{1 - \frac{C_D}{C_\Sigma}} = \underbrace{\frac{q}{2(C_G + C_S)}}_{} + \frac{V_G C_G}{C_G + C_S}$$

technically this value may be anywhere (above, below or equal to) in comparison to $\frac{q}{2C_D}$

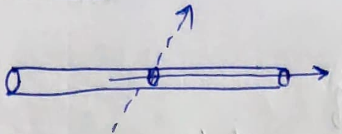
For example, let's take it to be less than $\frac{q}{2C_D}$:



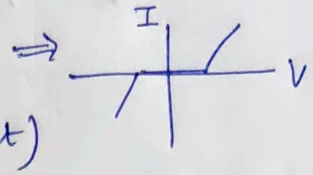
inside all these diamonds ↓ the current is zero *

(and on the lines, as well as outside ↓ current will flow)

32] <u>1D Nanowires</u>



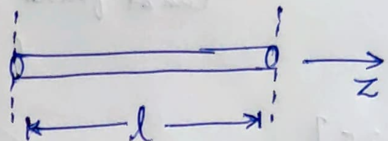
"coulomb blockade" like case in this dirⁿ
(Similar to a quantum dot)



↓

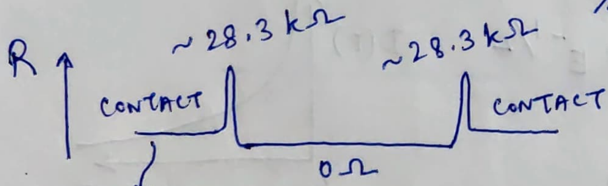
thus, nanowires show different properties in diff. directions

33] There can be two kinds of transport



Diffusive (Bulk-like)
↓
where the mean free path $= \lambda$
↓
this means that collisions occur on average at lengths of λ

Ballistic
↓
this occurs for the case when
$l < \lambda_{bulk}$
↓
so for such a case we would effectively expect there to be – <u>NO COLLISION</u>
↓
so we would expect resistance to be zero
↓
But in reality we observe a resistance of $R \sim \frac{2h}{e^2}$
⇓
This originates from $\frac{h}{e^2}$ resistance from both contacts



resistance of contact (metal)

it turns out that when we make QPCs
* (<u>quantum point contacts</u>) of a 1D material, then contact resistances are created

LECTURE 10 (31/01/2024)

34] Density of states

↓

gives an idea of how the energy states occupied by e^-s

↓

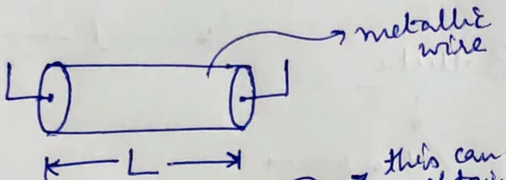
are distributed across space

For 3D : we saw in the previous course that $D(E) \propto E^{1/2}$

Similarly it can be found for 2D, and 1D

(For 0D it is more complicated)

35]



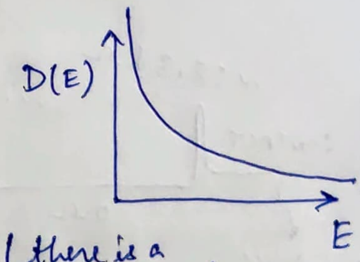
Here, $I = \Delta n \, q v$ — this can be obtained from Density of states

We can assume (for now) that Ohm's law is valid : $I = GV$

We can write :

$$\Delta n = \frac{D(E_F)}{L} q V^{\to \text{voltage}}$$

For the case of 1D, $D(E) \propto E^{-1/2}$



(there is a singularity at zero

↓

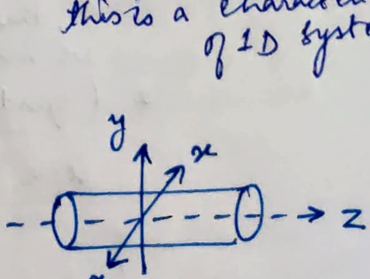
this is a characteristic of 1D systems)

{ **NOTE:** In reality, for such systems, we have a constraint in two directions, and free motion in one dir.^{n}

↓

and so energy levels are quantized only in 2 dir.^{n}s

$$E = \underbrace{E_{0z}}_{\text{free}} + \underbrace{E_{n_x, n_y}}_{\text{quantized}}$$



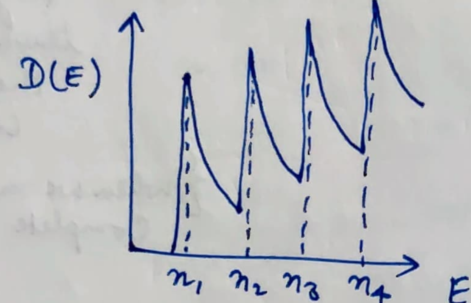
$$E = E_{0z} + \frac{n^2 h^2}{8mL^2} \qquad (n^2 = n_x^2 + n_y^2)$$

$$E - E_{0z} = \frac{n^2 h^2}{8mL^2}$$

This implies that actually:

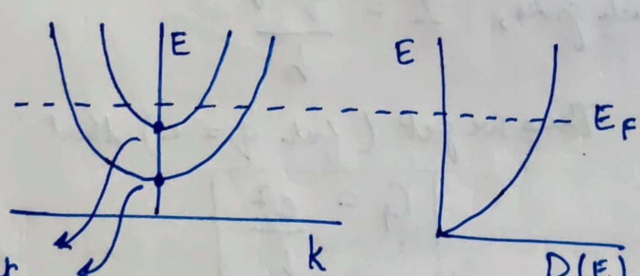
$$D(E) \propto \frac{1}{\sqrt{E - E_{0z}}}$$

Hence, there will be a singularity (divergence) at any point where system meets a quantized state:



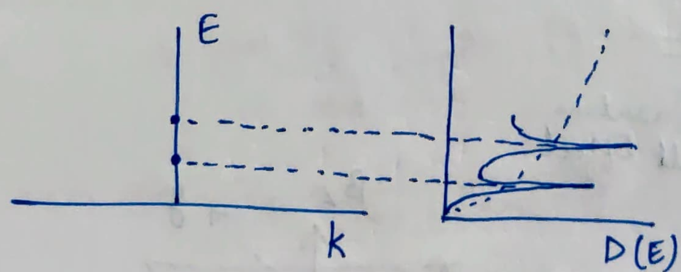
NOTE: The reason for such shapes is:

Without confinement:



but if we confine to just these places

⇓ the density of states redistribute themselves accordingly



36] Now we have that:

$$I = \Delta n\, q v$$
$$= \frac{D(E_F)}{L} qV\, q v$$
$$= \frac{q^2}{L} \underbrace{D(E_F)\, v}\, V$$

here we know this is of the form : $\frac{1}{\sqrt{E}} \cdot v$ } this expression ultimately only leaves behind the planck's constant

{ when we make the Complete calculation }

$\Leftarrow$ * **NOTE:** This L Comes from within the expression for D(E)

$\downarrow$

we have just written it here separately (because often people forget to include it inside D(E) itself)

So really we should write $\Rightarrow$ $I = q^2 D(E_F)\, v\, V$

which gives, $I = \dfrac{q^2 V}{h}$

Thus we get (for $q = e$) that:

$$\boxed{G = \frac{e^2}{h}}$$

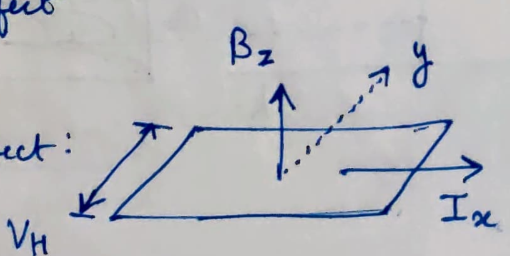
LECTURE 11 (01/02/2024)

36] **2D Systems**

$\downarrow$

involves Quantum Hall Effect

In Classical Hall Effect:



(Hall voltage) $\rightsquigarrow$ develops in such a scenario

Equation of motion of the e^- which suffers scattering: (i.e. interacts with electric & magnetic fields)

$$m\frac{d\vec{v}}{dt} = \underbrace{-\frac{m\vec{v}}{\tau}}_{\text{scattering}} - e\vec{E} - e(\vec{v}\times\vec{B})$$

(τ : Relaxation Time)

Here, $\vec{B} = (0, 0, B)$
$\vec{E} = (E_x, E_y, 0)$

We define a term called the Cyclotron frequency

$$\omega_c = \frac{eB}{m}$$

This can be expressed in two eq's:

$$m\frac{dv_x}{dt} = -\frac{mv_x}{\tau} - eE_x + ev_yB$$

$$m\frac{dv_y}{dt} = -\frac{mv_y}{\tau} - eE_y - ev_xB$$

Now, at equilibrium : $m\frac{dv_x}{dt} = 0$ and $m\frac{dv_y}{dt} = 0$

$$\Rightarrow \left.\begin{aligned} \frac{mv_x}{\tau} &= -eE_x + ev_yB \\ \frac{mv_y}{\tau} &= -eE_y - ev_xB \end{aligned}\right] \quad (1)$$

From Ohm's law, we know that:

$$\vec{J} = \sigma\vec{E} \quad , \text{where } \sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix}$$

$$ne\vec{v} = \sigma\vec{E}$$

$$\Rightarrow \vec{v} = \frac{1}{ne}\sigma\vec{E}$$

$$\Rightarrow \left.\begin{aligned} v_x &= \frac{1}{ne}\left[\sigma_{xx}E_x + \sigma_{xy}E_y\right] \\ v_y &= \frac{1}{ne}\left[\sigma_{yx}E_x + \sigma_{yy}E_y\right] \end{aligned}\right] \quad (2)$$

From our previous expressions, we get {i.e. from 1 }:

$$v_x = -\frac{e\tau}{m} E_x + \omega_c \tau v_y$$

$$v_y = -\frac{e\tau}{m} E_y - \omega_c \tau v_x$$

Simplifying:

$$v_x = -\frac{e\tau}{m} E_x - \frac{\omega_c e \tau^2}{m} E_y - \omega_c^2 \tau^2 v_x$$

$$\Rightarrow v_x = \frac{-\frac{e\tau}{m} E_x - \frac{\omega_c e \tau^2}{m} E_y}{1 + \omega_c^2 \tau^2} \quad - (3)$$

and, $$v_y = -\frac{e\tau}{m} E_y + \frac{\omega_c e \tau^2}{m} E_x - \omega_c^2 \tau^2 v_y$$

$$\Rightarrow v_y = \frac{-\frac{e\tau}{m} E_y + \frac{\omega_c e \tau^2}{m} E_x}{1 + \omega_c^2 \tau^2} \quad - (4)$$

Comparing 3 and 4 with 2 gives us:

$$\sigma_{xx} = \frac{ne^2\tau/m}{1+\omega_c^2\tau^2} \qquad \sigma_{xy} = \frac{ne^2\omega_c\tau^2/m}{1+\omega_c^2\tau^2}$$

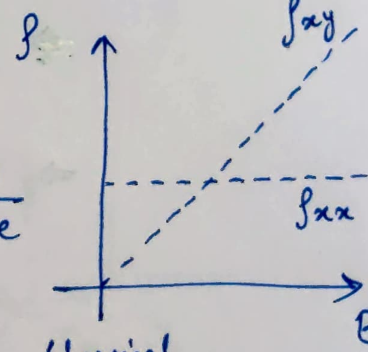
$$\sigma_{yx} = \frac{ne^2\tau/m}{1+\omega_c^2\tau^2} \qquad \sigma_{yy} = \frac{ne^2\omega_c\tau^2/m}{1+\omega_c^2\tau^2}$$

37] If we want ρ, we get it by taking the matrix inverse of σ:

$$\rho = (\sigma^{-1}) = \frac{1}{ne^2\tau/m} \begin{bmatrix} 1 & \omega_c\tau \\ -\omega_c\tau & 1 \end{bmatrix}$$

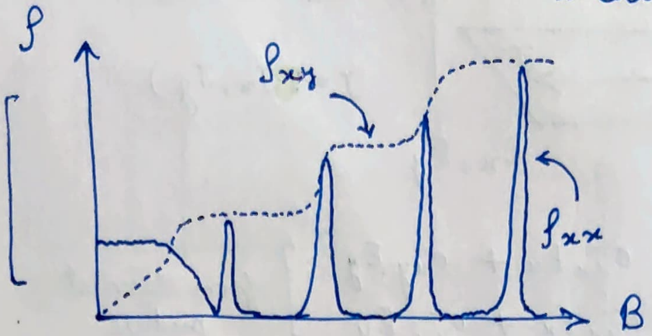
i.e. $\Rightarrow \rho_{xx} = \dfrac{1}{ne^2\tau/m}$

$$\rho_{xy} = \frac{\frac{eB}{m}\tau}{ne^2\tau/m} = \frac{B}{ne}$$



Classical picture of ρ_{xx} and ρ_{xy}

However, it turns out that at high values of magnetic field, this picture breaks down (and it can actually only be explained Quantum mechanically)



these fractional values are of the form: $\frac{h}{e^2}\cdot\frac{1}{\nu}$

where, ν is an integer [Integer Quantum Hall Effect]

NOTE: In reality plateaus may also occur on fractional values for some materials ($eg: \nu = \frac{3}{5}, \frac{2}{3}, etc\ldots$) → this is called Fractional Quantum Hall Effect

Experimentally it is found that they neither obey Bose-Einstein nor Fermi-Dirac Statistics

(one theory to explain this is by considering that the electron "splits" up into (unobservable) particles called "anyons")

[There are other theories as well]

38] We have the conductivity matrix as:

$$\sigma = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ \sigma_{yx} & \sigma_{yy} \end{pmatrix} \underset{\text{taking matrix inverse:}}{\Longrightarrow}$$

$$\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2}$$

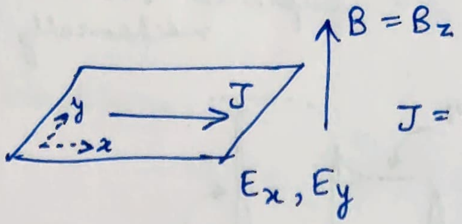
$$\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2}$$

From the plot we see that there is a region where $\rho_{xx} = 0$ and $\rho_{xy} \neq 0$ ⇒ Then, $\sigma_{xx} = 0$ also

But how is this possible?

LECTURE 12 (05/02/2024)

39] We were considering the case for a 2D material:



$$J_x = \sigma_{xx} E_x + \sigma_{xy} E_y$$
$$J_y = \sigma_{yx} E_x + \sigma_{yy} E_y$$
from classical picture

But we saw a case where

$$\left\{ \begin{array}{l} \sigma_{xx} = 0 \\ \rho_{xx} = 0 \end{array} \right. \quad (\text{where } \rho_{xy} \neq 0 \text{ and } \sigma_{xy} \neq 0)$$

↓

it turns out that this actually is possible

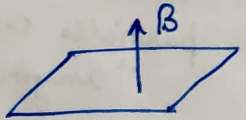
(Technically this can be seen properly only from quantum picture

↓

But conceptually, σ_{xx} being zero tells us that current flow does not occur,

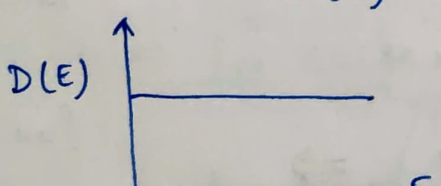
* while ρ_{xx} tells us that dissipation is zero)

40] <u>Landau Levels</u>



For 2D case the density of states is:

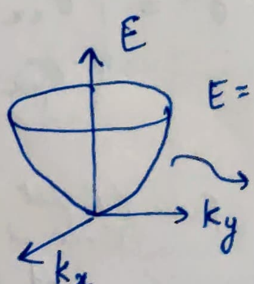
$$D(E) = \text{constant} \propto \frac{\pi m}{h^2} A$$



For the x and y directions, there is no quantization

↓

particle moves freely

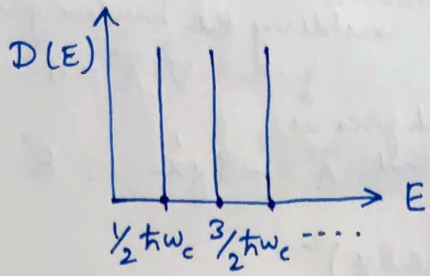


$$E = \frac{\hbar^2 k_x^2}{2m} + \frac{\hbar^2 k_y^2}{2m}$$

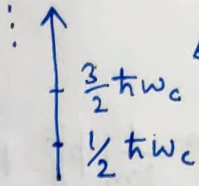
However, when we apply the magnetic field (at all values of magnetic field)

$\downarrow$

quantization occurs



{i.e. the energy levels are:



$\Leftarrow$ these are called Landau Levels *

separation b/w energy levels is $\hbar\omega_c$ }

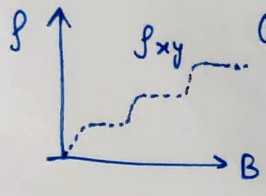
where, $\omega_c = \dfrac{eB}{m}$

$\downarrow$

i.e. increase in B leads to increase in ω_c

$\therefore$ separation will also increase

{NOTE: $k_B T \ll \hbar\omega_c$}



Conceptually, these lead to the plateau's we saw (due to filling of each of these landau levels)

41] We have:

$$\mathcal{H} = \frac{p_x^2}{2m} + \frac{p_y^2}{2m} = \frac{|\vec{p}|^2}{2m}$$

(Hamiltonian originally)

Also, we then applied a magnetic field:

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

and, $\mathcal{H}$ will change to: $\mathcal{H} = \dfrac{1}{2m}(\vec{p} + e\vec{A})^2$

We here have taken $\vec{B} = B_z\hat{k}$ or $B\hat{z}$

We will use the Landau gauge: $\vec{\nabla}\cdot\vec{A} = 0$

This will give us:

$$\boxed{\vec{A} = -By\hat{x}}$$

LECTURE 13 (07/02/2024)

42] We have :

$$\mathcal{H} = \frac{1}{2m}(\vec{p} + e\vec{A})^2 \quad , \text{ and } \vec{B} = \vec{\nabla} \times \vec{A}$$

where we are considering the Landau gauge: $\vec{\nabla} \cdot \vec{A} = 0$

↓

which gives us that $\vec{A} = -By\hat{x}$; $\vec{B} = B\hat{z}$

$$\therefore \mathcal{H} = \frac{1}{2m}p_y^2 + \frac{1}{2m}(p_x - eBy)^2$$

$$\Rightarrow \mathcal{H} = \frac{1}{2m}p_y^2 + \frac{1}{2m}(\hbar k_x - eBy)^2 \qquad \{\text{using } p_x = \hbar k_x\}$$

Now, let $y_0 \equiv \frac{\hbar k_x}{eB} \Rightarrow \mathcal{H} = \frac{1}{2m}p_y^2 + \frac{e^2B^2}{2m}(y-y_0)^2$

Finally, using $w_c = \frac{eB}{m}$:

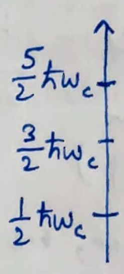
$$\boxed{\mathcal{H} = \frac{1}{2m}p_y^2 + \frac{1}{2}mw_c^2(y-y_0)^2}$$

Hamiltonian for 1D Harmonic Oscillator

⇓

The energy corresponding to this is given by:

$$E_n = \left(n + \frac{1}{2}\right)\hbar w_c$$



These quantized levels are called LANDAU ENERGY LEVELS

43] Since there is no x variable in the Hamiltonian

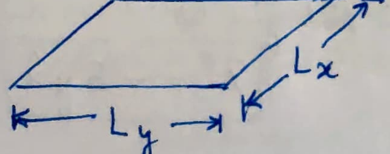
↓

we can say that the x values can have the same energy

↓

Thus, this gives us degeneracy

If y_0 is the point about which the e^- oscillates :



$l_y l_x$ = area

where, $0 \leq y_0 \leq l_y$

$$\Rightarrow 0 \leq \frac{\hbar k_x}{eB} \leq l_y$$

Thus, the max^m value for k_x is:

$$k_x = \frac{eBl_x}{\hbar}$$

Now, degeneracy will be same as density of states

i.e. all values of k_x will correspond to the same energy level $\Big] \rightarrow$ So we want to count how many values k_x can take (to determine degeneracy)

$\Rightarrow$ We know: $k_x = \frac{2\pi n_x}{L_x}$

$\Rightarrow n_x = \frac{L_x k_x}{2\pi} \Rightarrow \therefore$ No. of states with same energy is given by max^m value of n_x

$$\therefore \text{Degeneracy} = \frac{l_x k_{x_{max}}}{2\pi} = \frac{l_x eBl_y}{2\pi\hbar} = \frac{eB\overbrace{(l_xl_y)}^{A \text{ (area)}}}{h}$$

Using definition of flux, $\phi = BA$:

$$\text{Degeneracy} = \frac{e}{h}\phi$$

$\rightarrow$ this should thus have units of inverse of flux $\Rightarrow \therefore$ We can define it as: $\frac{1}{\phi_0}$

Thus, we get:

$$\boxed{\text{Degeneracy} = \frac{\phi}{\phi_0}}$$

* $\left\{ \text{where } \phi_0 \equiv \frac{h}{e} \right\}$

Hence, we see that degeneracy will depend on the magnetic field

low B $\Rightarrow$ less e^-s occupying low energy states

high B $\Rightarrow$ high no. of e^-s occupying energy states of high energy

44] We saw previously: $\rho_{xy} = \frac{h}{e^2}\cdot\frac{1}{\nu}$ $\rightarrow$ some integer, and also: $\rho_{xy} = \frac{B}{ne}$

$\Rightarrow$ Thus: $n = \frac{eB\nu}{h} = \frac{1}{A}\cdot\frac{e}{h}\cdot(BA)\nu$ $\Rightarrow \therefore n =$ density of states (i.e. states per unit area)

($\frac{e}{h} \rightarrow \frac{1}{\phi_0}$, $BA \rightarrow \phi$)

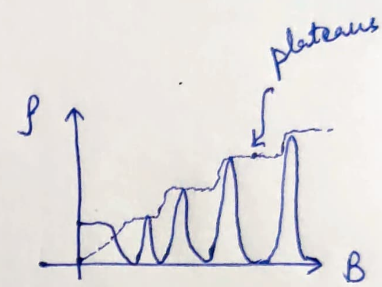
We can also define:

$$N = \frac{e}{h}\nu BA \Rightarrow N = \nu\frac{\phi}{\phi_0}$$

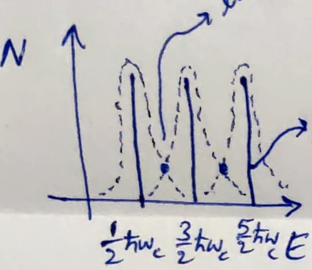
NOTE: It is the field induced quantization
↓
which leads to the collapse of energy levels

NOTE: Once the lower energy level is filled
↓
e^-s can't go anywhere until the energy cost of $\hbar\omega_c$ is paid
↓
& thus we get zero ρ state

45] Why do we observe this for a range of magnetic field values
↓
& why not only certain values of magnetic field?
⇓
Reason: These plateaus are observed due to disorders *
↓
* A clean material won't show this effect, & quantization would occur only at some integer values
⇓
The reasoning here is that these energy states start to broaden into extended states & localized states



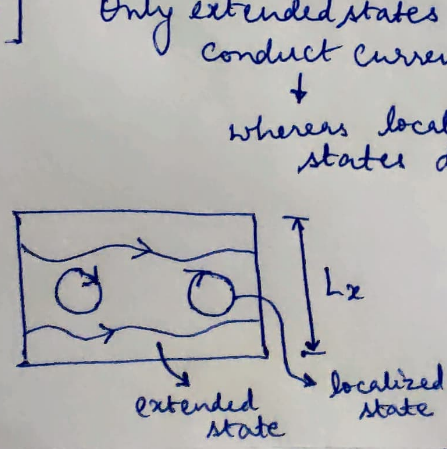
[Material with disorders]



[Material with disorder
↓
starts also developing localized states]

- extended states
  ↓
  these are close to the original
- localized states
  ↓
  these are in the middle
  ↓
  and these localized states form due to disorder & defect

46] Only extended states conduct current
↓
whereas localized states do not conduct → & thus these do NOT contribute to resistance



* Here, the no. of defects should follow the conditions:

$$\left.\begin{array}{l} \nu \ll k_B T \\ \nu \ll \hbar\omega_c \end{array}\right] \text{ where, } \nu = \text{disorder}$$

*

{ Remaining content
of this lecture
↓
is attached as a
separate sheet
on this
page itself }

[Next Lecture Continues
Below]

LECTURE 14 (08/02/2024)

46] Nanophotonics
↓
some of the most
initial observations
involving this
↓
were objects (such as glass)
with metal particles (eg: Cu, Au, Al)
embedded
↓
leading to generation
of colours when light
transmitted through
them

Consider motion under electric field: (for an electron):

$m\ddot{x} = e\vec{E}$, where $\vec{E} = E_0 e^{i\omega t}$

Trying: $x = x_0 e^{i\omega t}$

$\Rightarrow -m\omega^2 x_0 = eE_0$

$\Rightarrow x_0 = -\dfrac{eE_0}{m\omega^2}$

Now, the magnitude of dipole moment is:

$$|p| = e x_0$$

In general, $p = e x_0 e^{i\omega t}$

For n e^-s:

$$P = n e x_0 e^{i\omega t}$$

Using the expression we got for x_0, this gives:

$$P = -\frac{n e^2 E_0}{m\omega^2} e^{i\omega t}$$

Since we also know that, polarization $P = \varepsilon_0 \chi E$

$$\Rightarrow \boxed{\chi(\omega) = \frac{-n e^2}{m \omega^2 \varepsilon_0}}$$

Using which we define: $\omega_p^2 = \frac{n e^2}{m \varepsilon_0}$

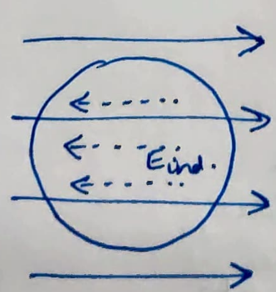
* Plasma Frequency

(Technically, this is the plasma freq. of the bulk, so we could call it ω_{pb})

[Thus, $\chi(\omega) = -\frac{\omega_{pb}^2}{\omega^2}$]

* NOTE: We will see now that, for a sphere we will get the plasma freq. as: $\omega_{sp} = \frac{\omega_{pb}}{\sqrt{3}}$

47]



E (external electric field)

$\Downarrow$

This leads to an induced electric field inside the sphere (which is a conductor*)

From electromagnetism: $\vec{E}_{ind.} = -\frac{P}{3\varepsilon_0}$

$$\therefore \vec{E}_{tot} = \vec{E} + \vec{E}_{ind.} \Rightarrow \therefore E_{tot.} = E - \frac{P}{3\varepsilon_0}$$

We have:

$$P = \varepsilon_0 \chi E_{tot.}$$
$$= \varepsilon_0 \chi \left(E - \frac{P}{3\varepsilon_0} \right)$$

Solving this for P gives us:

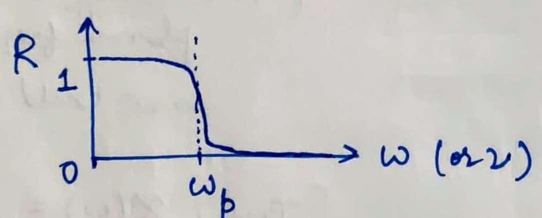
$$P = \frac{\varepsilon_0 \chi E}{1 + \chi/3}$$

$$= \frac{\varepsilon_0 \chi(\omega) E}{1 - \frac{ne^2}{3m\varepsilon_0} \frac{1}{\omega^2}}$$

From here
we get the plasma freq:

$$\omega_{sp}^2 = \frac{ne^2}{3m\varepsilon_0} = \frac{\omega_{pb}^2}{3}$$

* NOTE: The reason why the plasma freq. is related to colours, is related to reflectance vs freq. curve (for metals):



* NOTE: Technically the analysis we have performed should apply for any spherical particle (of arbitrary size, since we did not take size into any of our analysis, and it is size independent)

↓

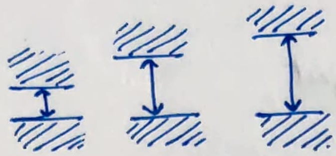
However, in reality we only observe these phenomena for Nanoparticles

↓

The reason for this is that at larger scales, certain damping effects due to electromagnetic fields occur

{ However, we won't study them here in this Course }

NOTE: In the case of semiconductors
↓
Colour variation
is explained due to
variation in band gaps



48] Near-Field Light
↓
Generally, we cannot distinguish b/w points which are arbitrarily close
↓
due to the diffraction limit
(which occurs on size $\sim \lambda$)
↓
However, near-field light allows us to go beyond this limit

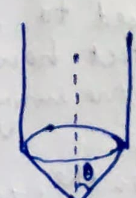
LECTURE 15 (12/02/2024)

49] We know that

Concave lens
↓
diverges light rays

Convex lens
↓
converges the light rays → But can this convergence occur
↓
upto an absolutely small size?
↓
Answer: No
(it will be limited due to diffraction)

⇐ In principle the small separation that can be resolved
↓
Can be obtained from:

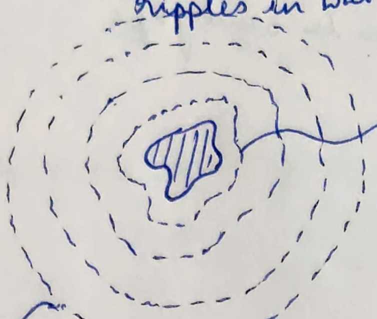


$$\Delta = \frac{1.22\lambda}{2n\sin\theta}$$

(i.e., $\Delta \sim \frac{\lambda}{2}$)

taking $\lambda \approx 400\,nm$ → $\boxed{\Delta = 200\,nm}$

NOTE: For the case of an object producing ripples in water:



extremely close to the object
⇓
the wave carry more information
(in terms of shape & topology of the object)

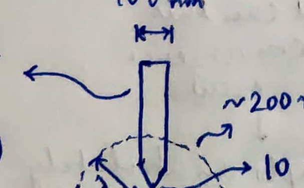
further away
↓
wave become more circular

This is the same analogy
↓
as the concept of near field light
↓
where in distances < 200 nm → light carries more information

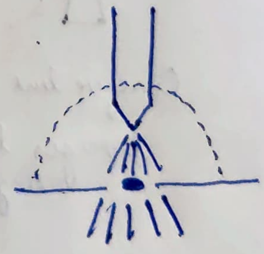
50] There are two main modes involved

Collection mode
↓
here the purpose of the probe is to collect light

Illumination mode
↓
here the purpose of the probe is to illuminate the sample



{ in either case
↓
distance between probe & sample
↓
should be within range of λ }
(For near-field light phenomena)



NOTE: STMs (Scanning Transmission Microscopes)
↓
are used to detect how close we are moving the probe to the sample.
↓
and then the tip of the STM is replaced with a probe

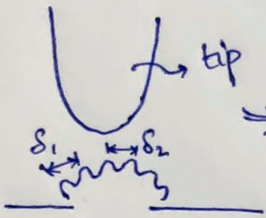
→ Since these didn't exist earlier
↓
there was no way of setting up this instrument
(i.e. moving the probe about precisely)

which is why this concept was discovered later

51] The advantage of Near Field Imaging versus AFM

In AFM also we try to get the shape (using height profiles)
↓
However if the AFM tip is larger than surface morphological features!

eg:

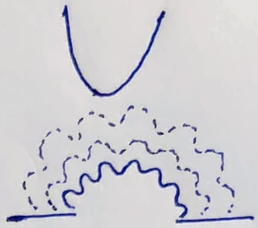


→ (Tip is much larger than δ_1 and δ_2, etc.)

⇓

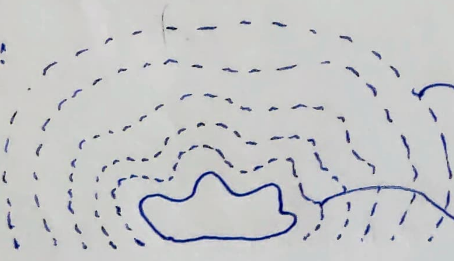
Then here AFM will not give us the information

In Near-field Imaging
↓
we directly see the light → (i.e. the wavefront itself) from the object
↓
and this contains the information of the sample surface morphology



* **NOTE:** In Near-field
↓
we go close enough
↓
such that the effects of dispersion and interference are minimized

NOTE:



→ further away
↓
becomes "circular" (due to dispersion effect)

→ closer wavefronts
↓
contain more light in higher frequency ranges as well

(whereas further away
↓
the higher freq. light
↓
diminishes)

⇓

This frequency change is what is captured by the Near-field Imaging