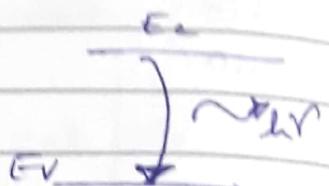


# After Midsem:

## → LED and LASERS

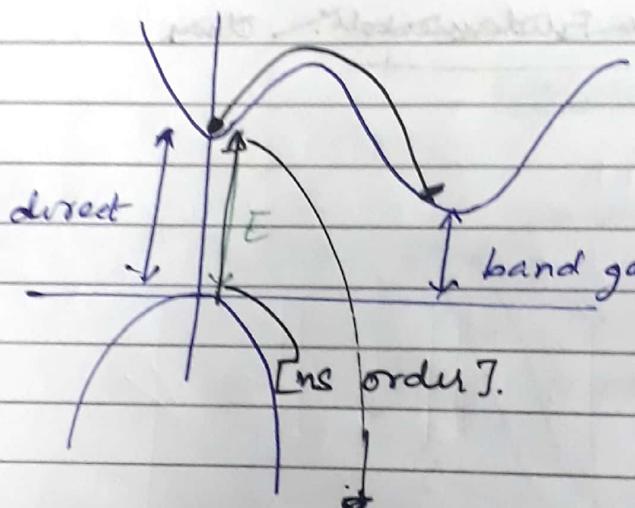
Si → Indirect Band gap semiconductor:

+  
does not give photons:



Si: absorbs photon and does not emit it.

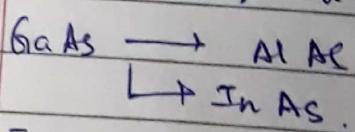
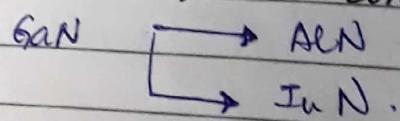
Because



If photon energy  
is equal to gap  
these are called E  
absorb photons

e- tries to minimize energy. and thus  
it immediately roles down.  
[picosecond order]

## DIRECT BAND GAP SEMICONDUCTORS:



InP

SiO<sub>2</sub>

### HETEROSTRUCTURE:

Si/SiO<sub>2</sub>:

↓  
dissimilar materials put together without much defect.  
Eg: AlAs / GaAs. ↓  
can manipulate band gap

$$x \text{ GaN} \longrightarrow 3.4 \text{ eV}$$

$$(1-x) \text{ InN} \longrightarrow 0.7 \text{ eV}$$

$$\text{AlN} \longrightarrow 6.1 \text{ eV}$$

For material -

$$\text{In}_{1-x} \text{ Ga}_x \text{ N} \longrightarrow \text{Ternary alloy}$$

$$\text{and } Eg = x(3.4) + (1-x)0.7 \rightarrow \text{Vegard's Law.}$$

Band gap changes if : Temp changes  
and basis (unit cell charges)

GaN and InN: Wurtzite structure: (checkup) HCP:

first material  
with tunable  
bandgap

$$x \text{ GaN}, y \text{ InN and } (1-x-y) \text{ AlN.}$$

Quaternary alloy

Heterostructure:

Al<sub>0.3</sub>Ga<sub>0.7</sub>N

@ GaN

no trap levels.

epitaxial

The interface must be defect free: no dangling bonds.

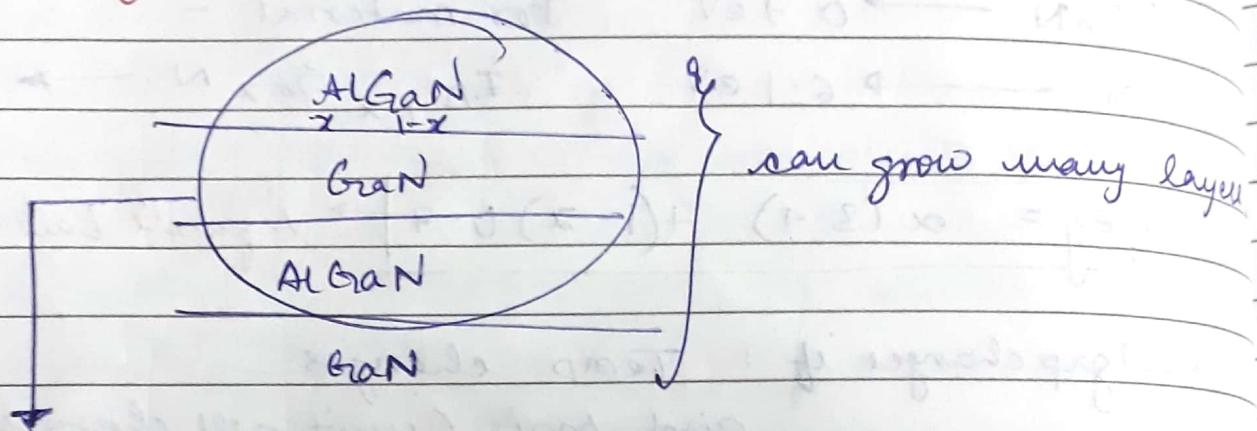
so no SRH, mobility does not decrease.

Heterostructure: bond length is (extended) or compressed

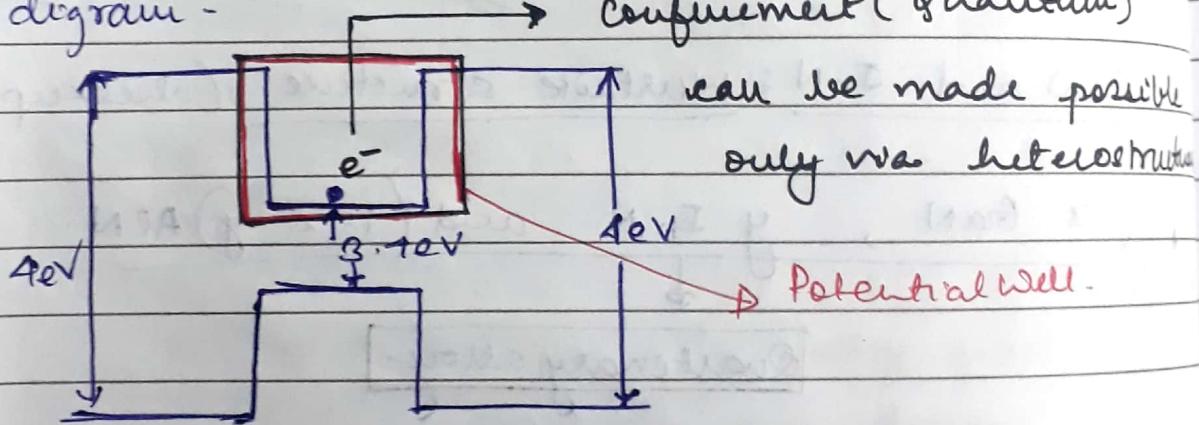
↓  
strain  
↓  
Tensile strain  
↓  
Compressive strain

Lattice constant: bond length.

Thin layer tensile or compressive strain.



Band diagram -

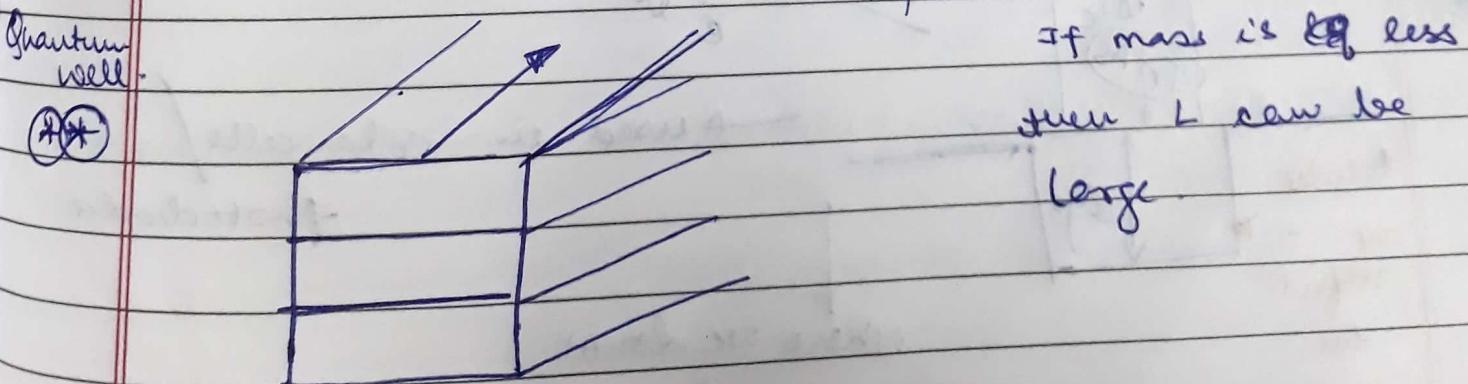
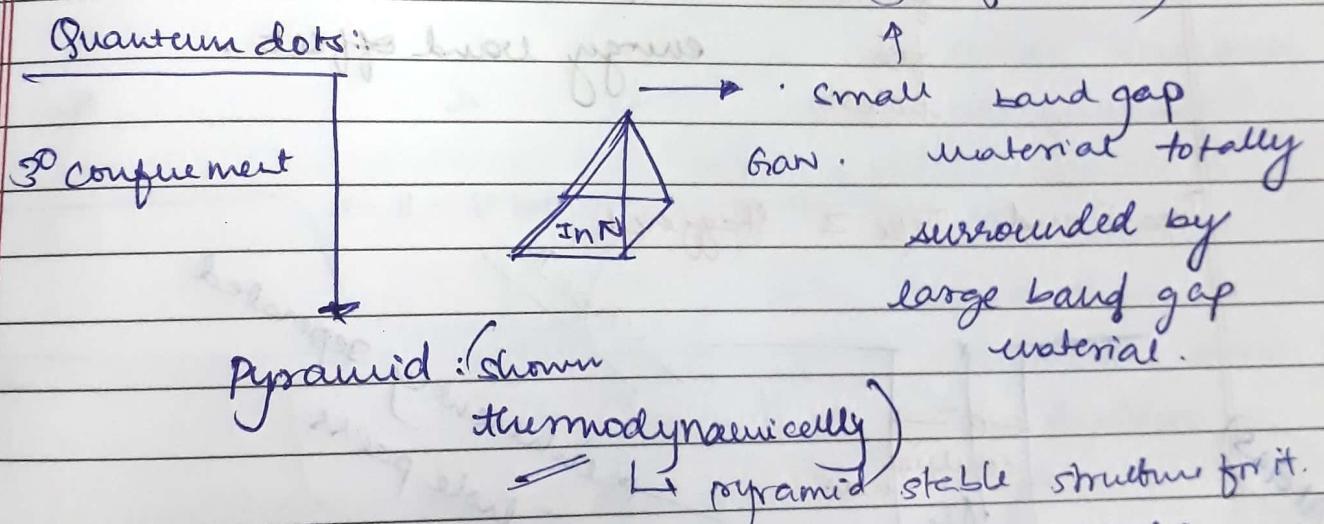
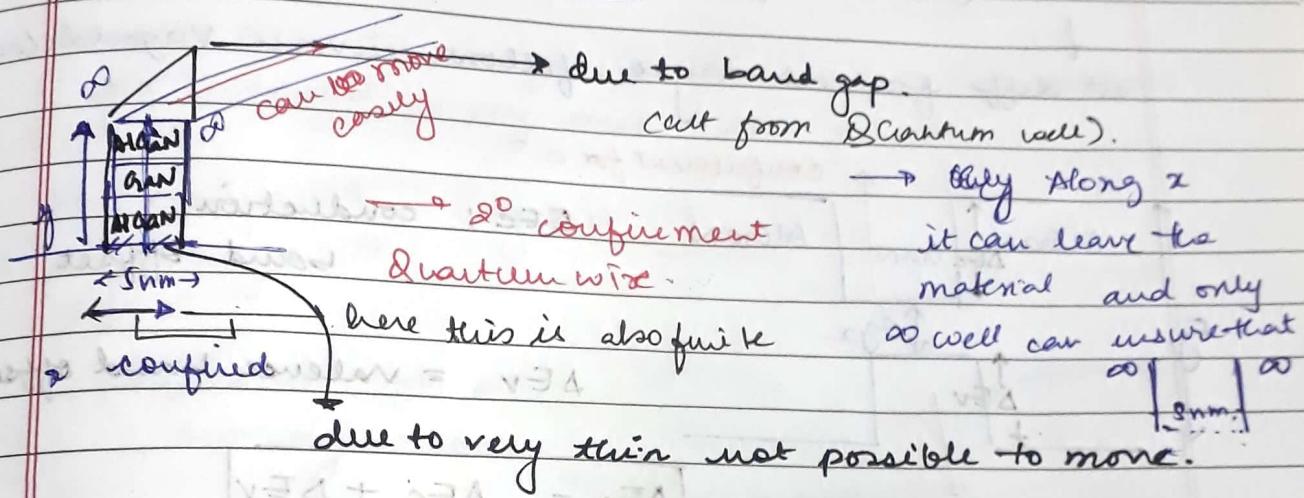
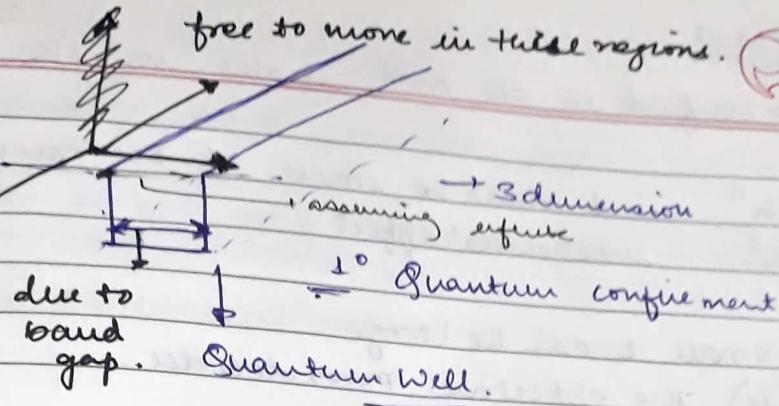


$$2(8) + (1-x)(3.1) = 4$$

~~8eV~~ 
$$0.6 = (2-3)x$$

$$x = 0.222$$

TeV ← 22% ALN AlGaN



Date \_\_\_\_\_  
Page \_\_\_\_\_

well

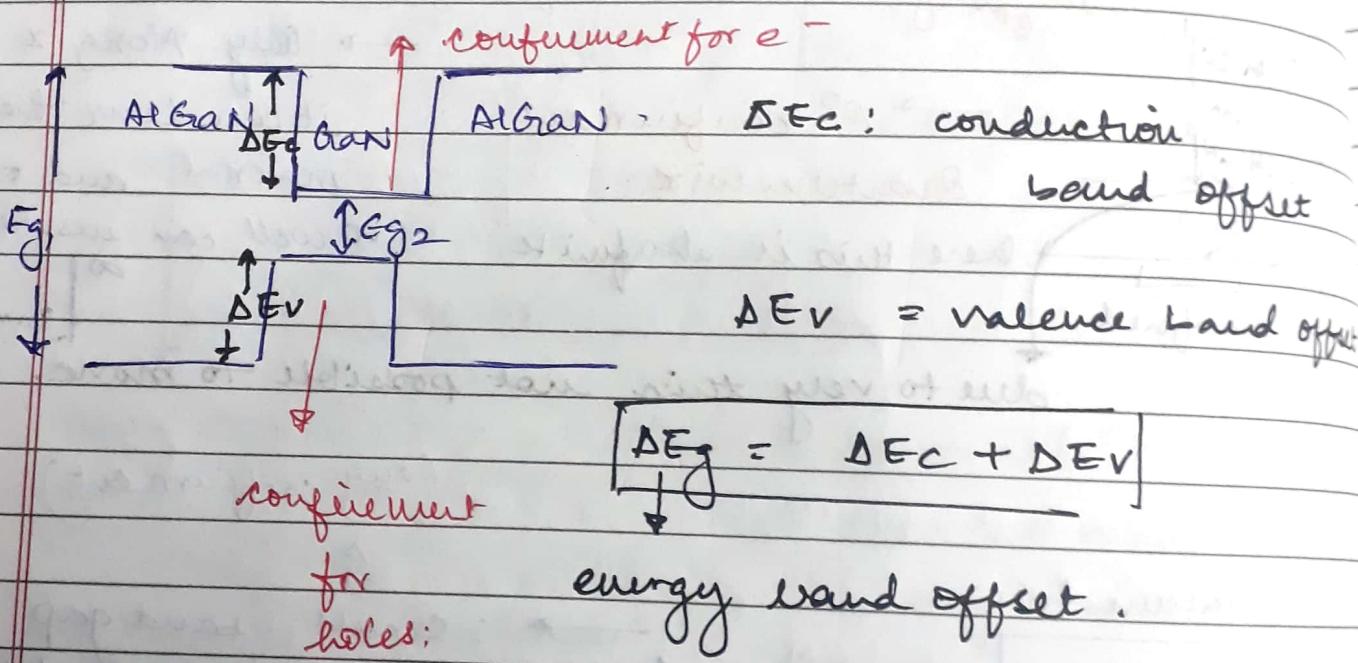
$e^-$  confined in CB and holes in V.B.

$$E_n = \frac{e^2 h^2}{8mL^2} \quad \therefore L \text{ must be small to see quantum mechanical effect.}$$

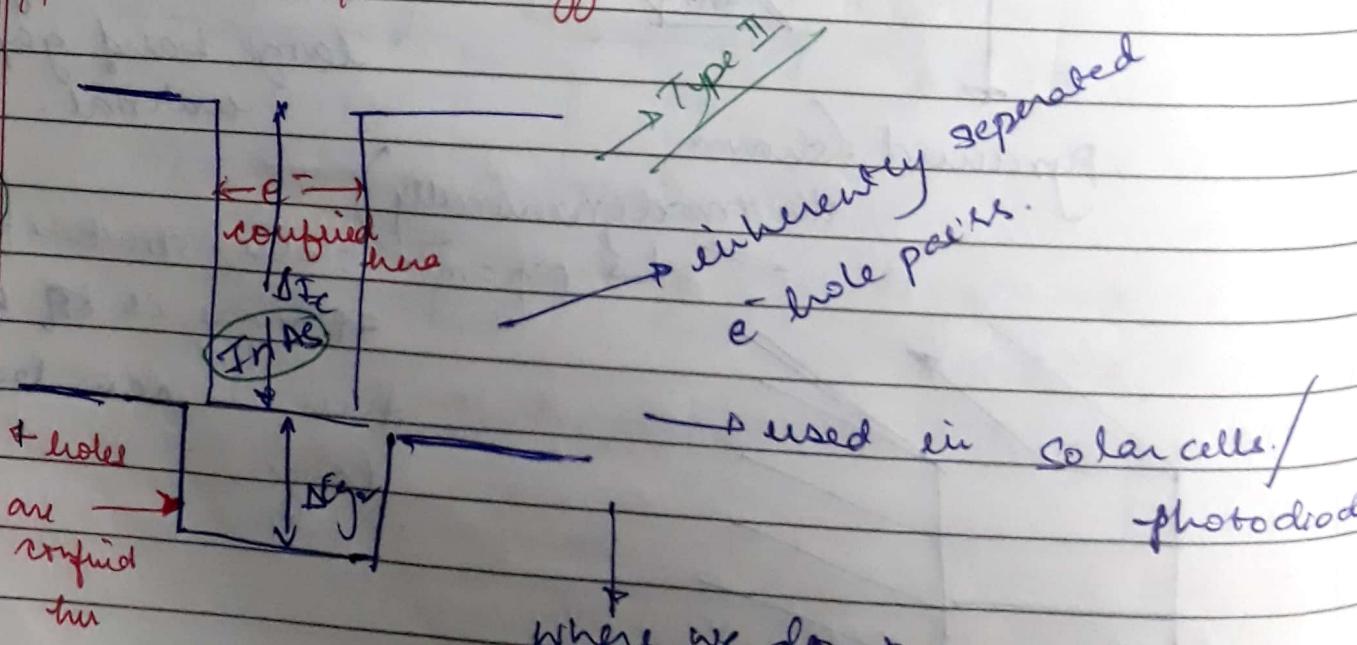
if  $m$  small  $L$  can be large

so  $m$  (ie) the effective mass decides

$m^*$  diff for each layer: follows inverse vagardile



Type I and Type II staggered.



\* Alignment of bands gap also imp.

$$[\Delta E_C = 60\% \Delta E_g]$$

and

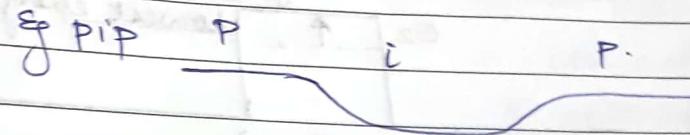
$$\Delta E_V = 40\% \Delta E_g$$

\* Band alignment cannot be tuned for a set of materials.

Homostructure: we can get confinement: - (electrostatic)  
but potential is very small and ... no use.

High doping =  $10^{19}$

Low doping =  $10^{17}$



confinement for  $e^-$

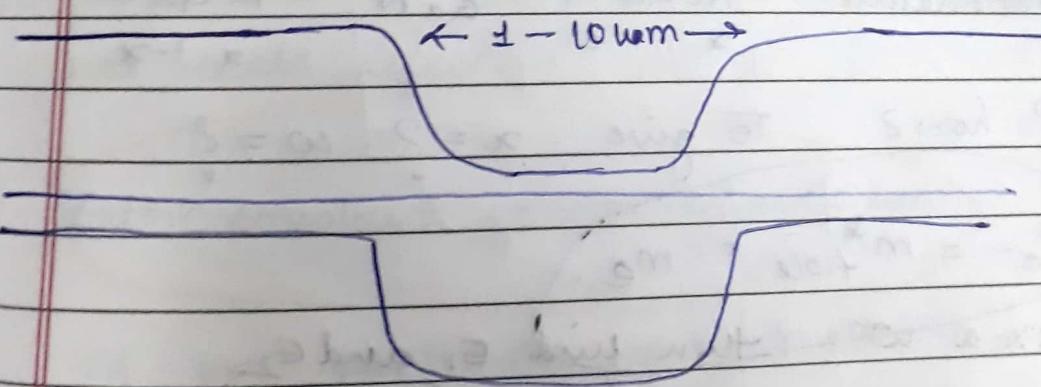
but very shallow

minority carriers.

p

n

can it do quantum  
confinement?



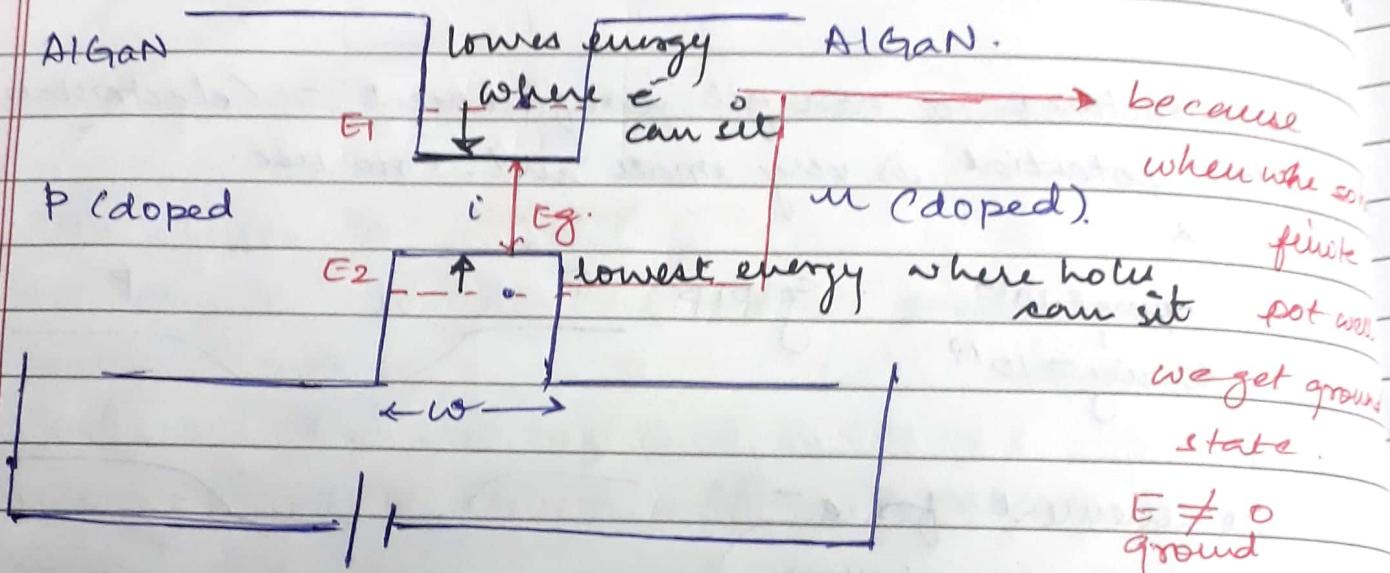
The layer is  
very thin so  
it mostly comes  
in depletion  
region.

\* confinement  $\rightarrow$  quantization in energy level.

LED =  $\lambda \rightarrow$  decales wavelength / colour = bandstructure.

Out of equilibrium case -

\* Flat band diagram: The band edges are flat:



$$Eg' = Eg + E_1 + E_2 = hc/\lambda$$

→ This is actually the true band gap.

because  $m \neq 0$

$$\begin{aligned} E_1 &\neq E_2 \\ \therefore m^*_{e^-} &\neq m^*_{\text{holes}} \end{aligned}$$

(8) Design heterostructure

AlGaN  
 $\alpha$   
 $\approx 1-x$

GaN

AlGaN  
 $\alpha$   
 $\approx 1-x$

$\lambda = 300 \text{ nm} = ?$  how? To give  $\alpha = ?$   $w = ?$

$$\text{det } m^*_{e^-} = m^*_{\text{hole}} = m_e$$

Method 1: Fix a  $w$ , then find  $E_1$  and  $E_2$  (on  $x$ )

$$\begin{aligned} \text{known} & \quad E_g + E_1 + E_2 = \frac{m_e}{2} \text{ known} \\ \downarrow & \\ \text{we get } \alpha & \end{aligned}$$

$$\lambda(\mu\text{m}) = \frac{1.24}{E_g(\text{eV})}$$

taken  $\alpha = 1$ :

$$(or) \alpha = 0.7$$

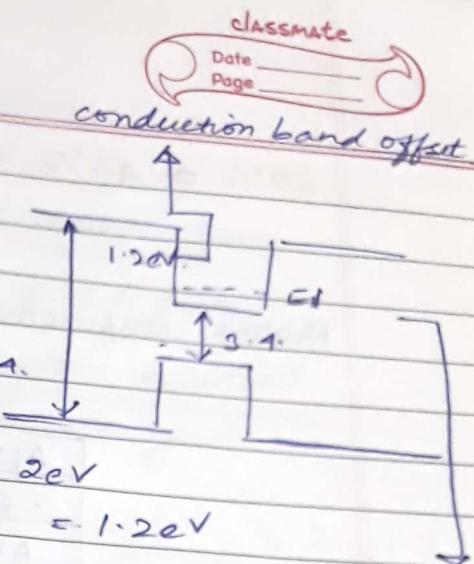
$$E_g = (6.1) \times 0.7 + (3.4)(0.3)$$

$$= 8.3 \text{ eV}$$

$$= 5.4 \text{ eV}$$

$$AlN = 6.1 \text{ eV}$$

$$GaN = 3.4 \text{ eV}$$



$$\Delta E_g = 2 \text{ eV}$$

$$60\% = 1.2 \text{ eV}$$

(Ad-hoc)

$\rightarrow \infty$  well

At the wall

comes down

$E_1$  gets closer to  $E_c$ .

$E_1$  decreases

$$E_1 = \frac{n^2 h^2}{8mL^2}$$

$$10mL^2$$

$$E_g + E_1 + E_2 = \frac{1.24}{0.3}$$

$E_1$  and  $E_2$  depend on  $L$  or depend on  $w$ .

so we get  $w$

\*  $\alpha$  depends on lattice constants such that it does not create defects.

Lattice constant follow Vegard's law.

$x \uparrow \rightarrow$  defects  $\uparrow$   
 $x \downarrow$

If  $\alpha$   $AlN = a_1$   $GaN = a_2$

$$\alpha = 1 - x$$

$\alpha$  = small.

$$a' = x a_1 + (1-x)a_2$$

so that not much mismatch.

but then  $\uparrow$

confinement

decreases.

~~8~~  
60%  $\leftrightarrow$  40% rule only for  $\text{GaN}$ ,  $\text{AlN}$ ,  $\text{InN}$ ,  $\text{GaN}$ ,  
 $\text{AlAs}$ ,  $\text{InAs}$ .

Photon confinement in planar regions. i.e.:



When refractive index diff high  $\rightarrow$  then most photons are reflected inside  $\propto (\text{say of diff})^2$  in  $n_{\text{ref}}$  index.

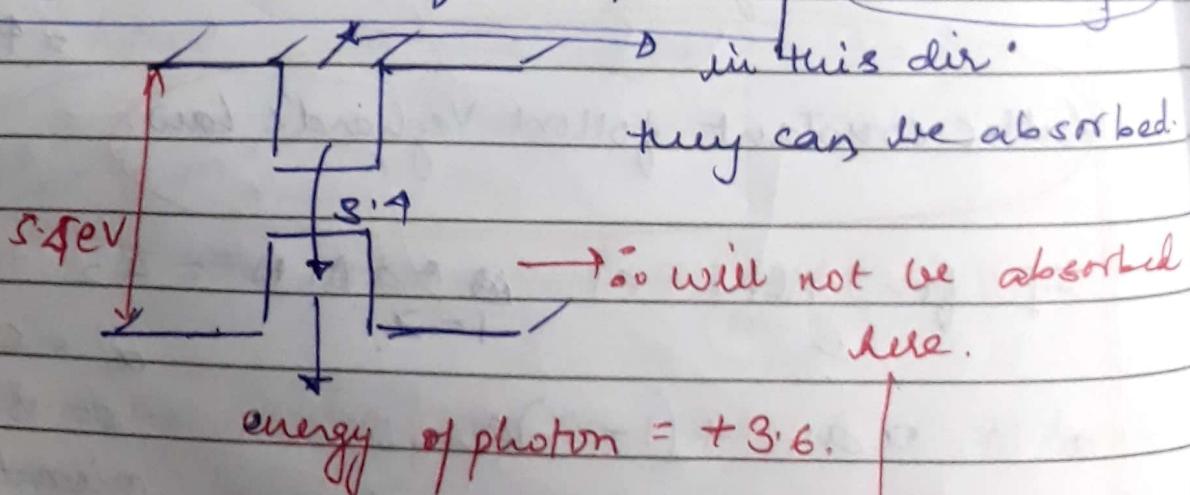
$\therefore$  The photons, are confined in the quantum well and are guided across that planar region of GaN.

Ref depends on  $\left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$

~~to be  
or cross check:~~

Quantum efficiency =  $\frac{\# \text{ of photons}}{\# \text{ of E-H pairs}}$   $\rightarrow$  coming out/will  $\rightarrow$  or  $e^-$  injects

here -



still better  
than homostructure

still better than  
homostructure

SATs : how many photons gen/injection

Internal in quantum eff =  $\frac{\text{no. of photon gen}}{\text{no. of } e-h \text{ pairs.}}$

External in quantum =  $\frac{\# \text{ of photons emitted}}{\# \text{ of photons gen}}$

→ their product must be closer to 1.

$$\eta = \eta_i \cdot \eta_e \rightarrow ①$$

$\eta$  can be changed in growth of these materials.

Why not go to the second band in well? Fermi dosage prob occupancy higher.

→ T

~~Software:~~

G-simulator  
schrodinger

Poisson B

→ professional webpage.

→ Heterostructure:

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  10 μm

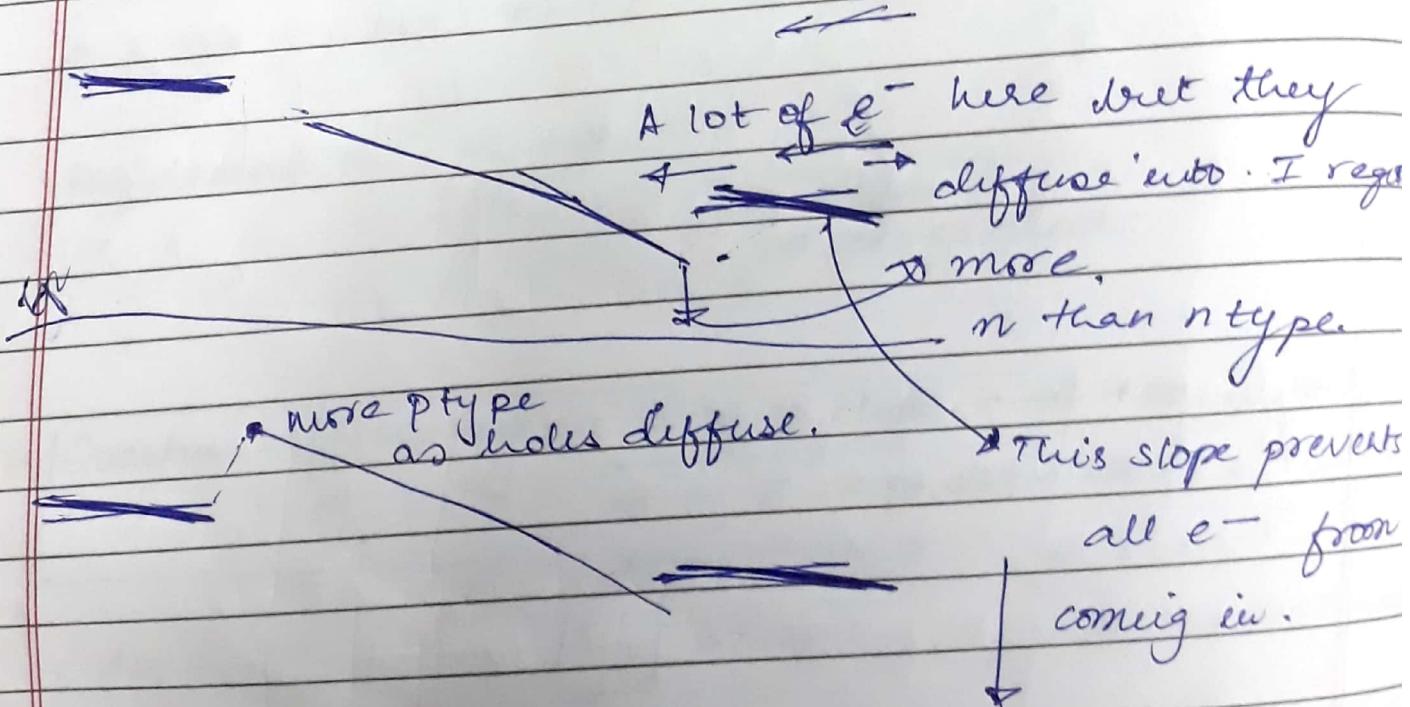
GaAs 15 nm

$\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$  10 nm

solves schrodinger and poisson eqn

\* They should get  $e^-$  be captured or confined in same region so that they can recombine.

\* PIN → In I type there is a linear slope.

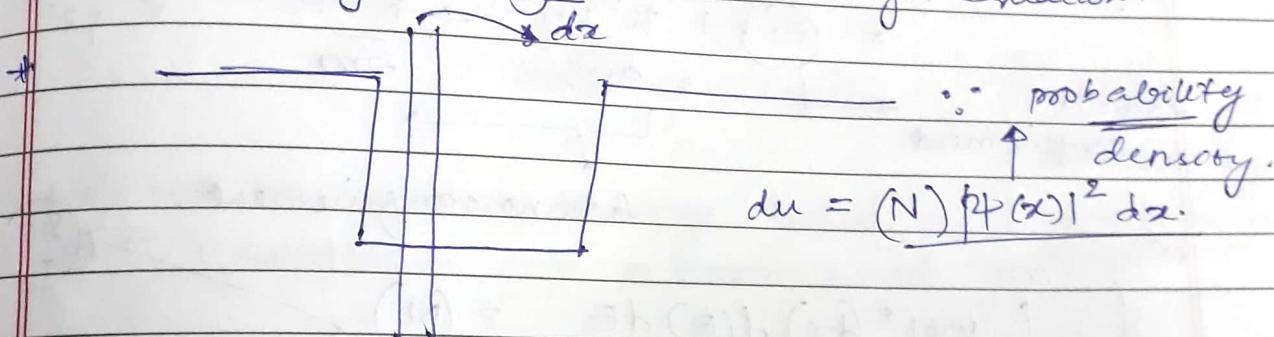


\* Band discontinuity comes from the fact that there are 2 different materials.

If it is much away from the EF then, we can say that  $n$  is very small and so simulator cannot find a bound state.

\* Prob of the region being occupied =  $\int g(E) f(E) dx$ .  
state must be present.

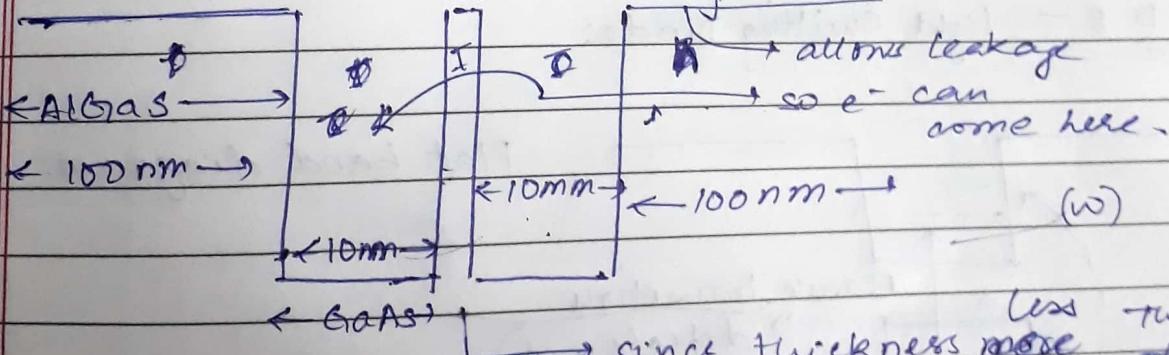
2  
 $\psi$ : probability density  $\rightarrow$  Schrodinger equation.



\* We solve the semiconductors devices mostly using -

\* ~~free~~ free  $e^-$  approximation:  $e^-$  do not interact

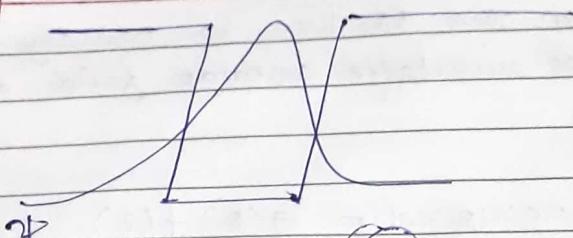
2nm: for luminescence with others



width of pot well more  $\rightarrow$  then more chance of confinement.

No. of peaks in n density = no. of quantum wells.

\* They can escape and go into the tunneling region also.



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

$\downarrow$

$$= (E_1) + \frac{\hbar^2 k_y^2}{2m} + \frac{\hbar^2 k_z^2}{2m}$$

$\downarrow$

due to confinement

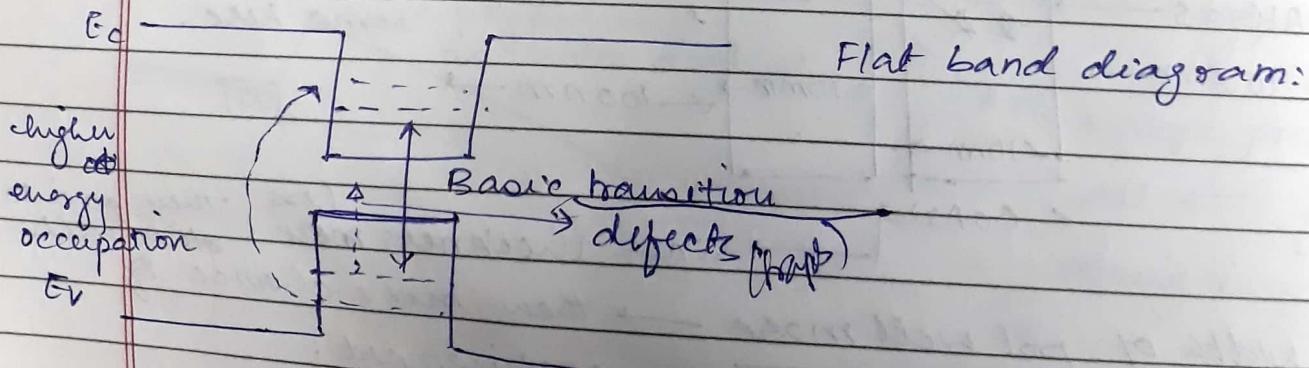
here no confinement.

$$\int_{x=0}^{\infty} \int_{E_c}^{\infty} \frac{17\pi l^2 (2x) f(E) dE}{\text{states}} = (N)$$

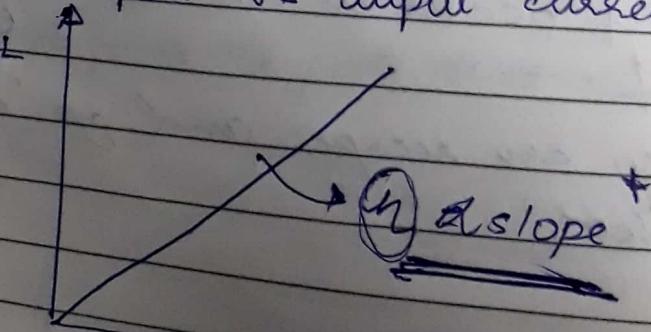
$\downarrow$

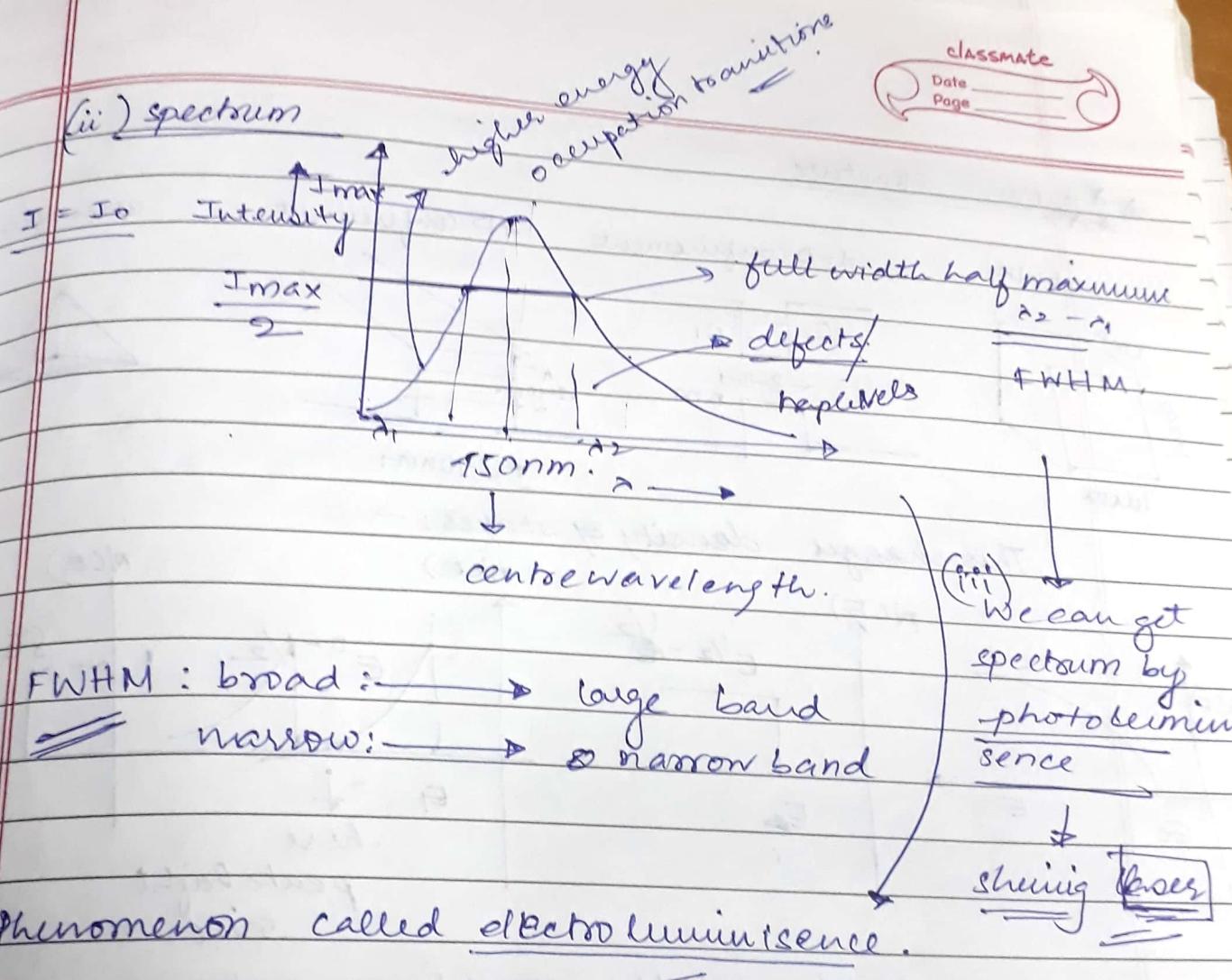
also involve density of states.

### LED 8 - Light emitting Diode:



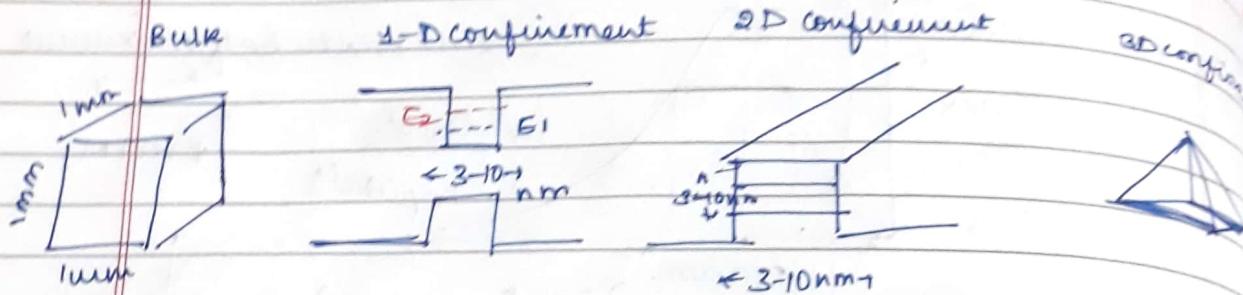
Characteristics: (i) light output vs input current.



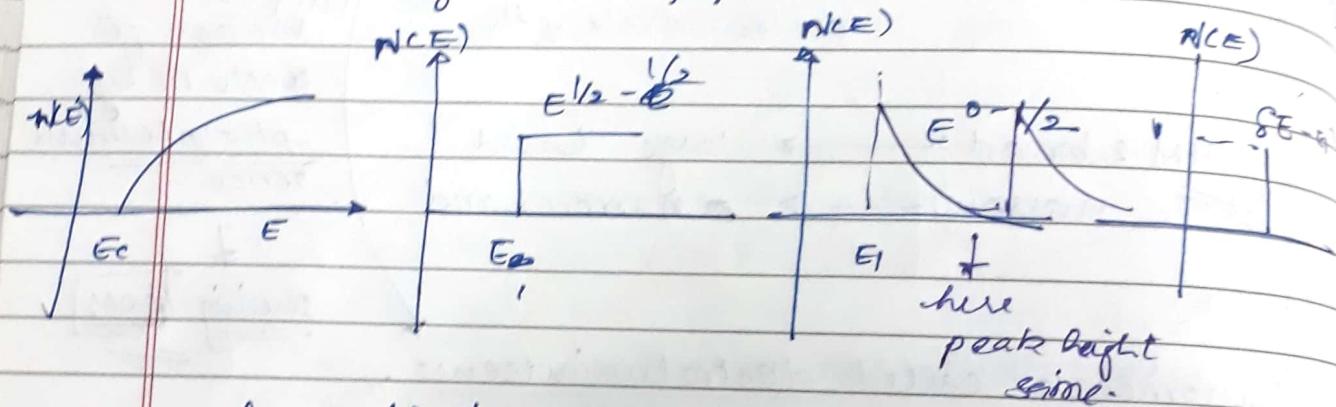


# Phenomenon called electroluminescence.

### \* \* \* Nano-structure \*

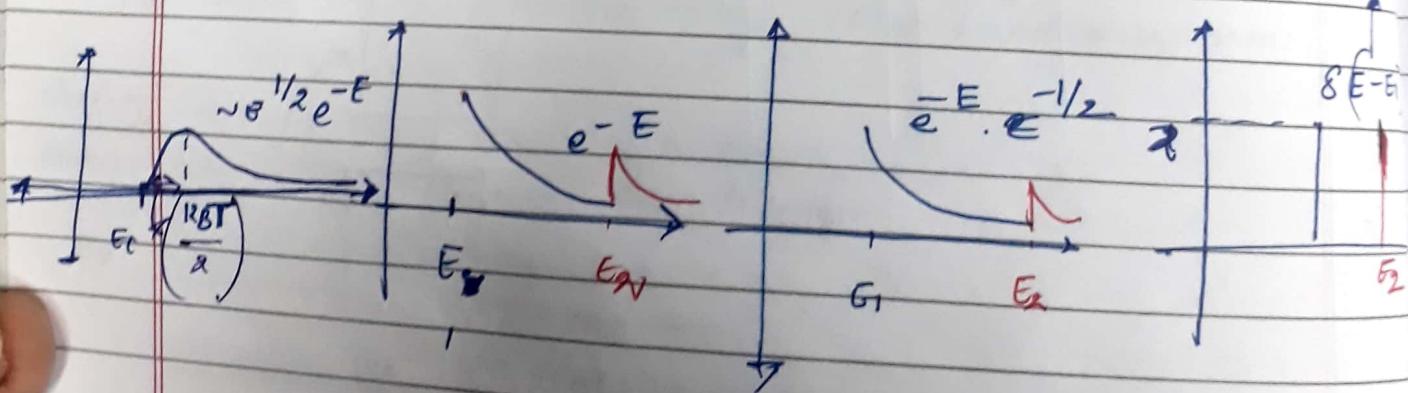


This changes density of states: -



fermi-dirac's statistics come from entropy:

occupation of  $e^-$   $N(E)f(E)$



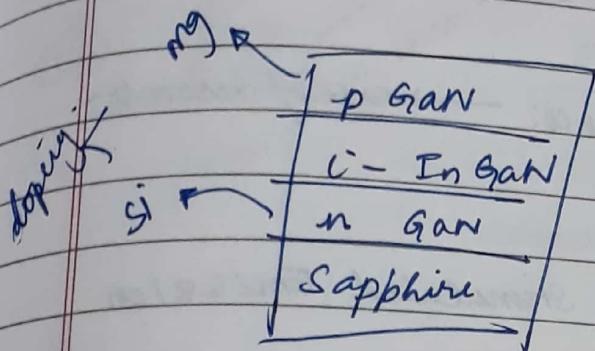
due to confinement it starts from  $E_1$ :

We control the energy levels over which the  $e^-$  are distributed.

→ decay of energy slowest in bulk and sharpest in Quantum dot:

\* For quantum well there is always a bound state.

\* But for Quantum wire and dot that need not be the case.



MOCVD

Metal organic chemical vapour deposition.

Molecular Beam Epitaxy:

pressure -  $10^{-11} - 10^{-12}$  Torr

pin → intrinsic  
region traps  
the radiative

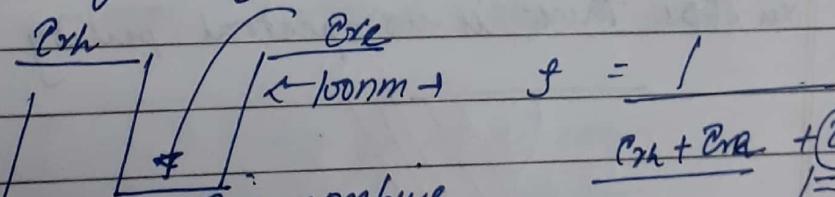
recomb.: traps. w/o

for more  
efficient.

→ higher temps helps to reduce defects as they are mitigated.

Since traps are less in intrinsic.

an increase of free of the gain t



$$\frac{R_{tr} + R_{re}}{R_{tr}} + \textcircled{2} = \text{Recomb}$$

Radiative  
time constant

$$R_{re} = \frac{100 \text{ nm}}{\tau_e}$$

$\tau_{tr}$ : after injecting  
holes how much time

$\frac{1}{e}$  → transit  
time

$$S = \frac{10}{\tau_{tr}}$$

mobility: hall measurement:

$$\tau = 50-100 \text{ femto second (fm).}$$

done by femto second spectroscopy: captures process happening at 10<sup>-14</sup> of femto second.

Time Resolved photoluminescence: → rate of recomb.

⇒ LASER: Light Amplification Stimulated Emission  
\* Phase coherence and  
\* spectral purity.

$$\sim \sqrt[3]{2} \lambda$$

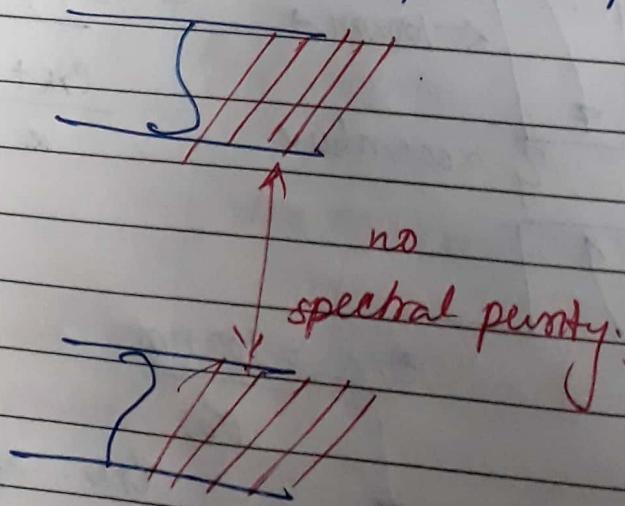
This EM generate 2 EM waves with same  $\lambda$  and same phase

so that

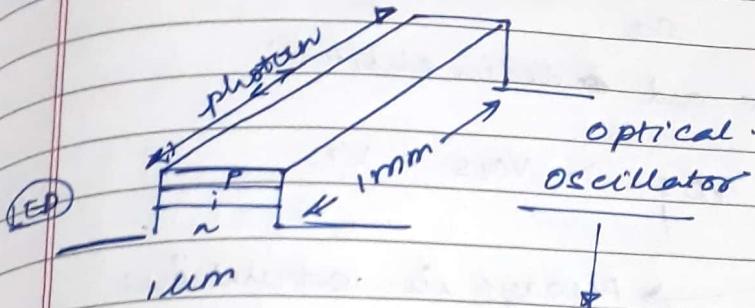
no destructive interference

=  
Monochromatic light

Spatial coherence: → same direction:  
In LEDs there is no spectral purity



- + Phase - coherence
- + Spectral purity
- + spectral coherence



classmate  
Date \_\_\_\_\_  
Page \_\_\_\_\_

famous:-  
laser of  $1.3 \mu\text{m}$   
 $1.55 \mu\text{m}$

↓  
Based on R.I.  
of quartz in  
optical fibres.

converts LED into Laser. LASER:

Model sem:

In saturation there is constant current regime:  $\Rightarrow$  first part of characteristic is linear.

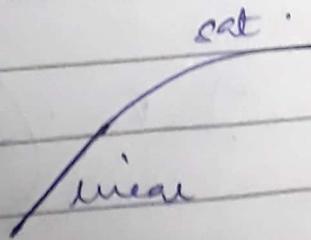
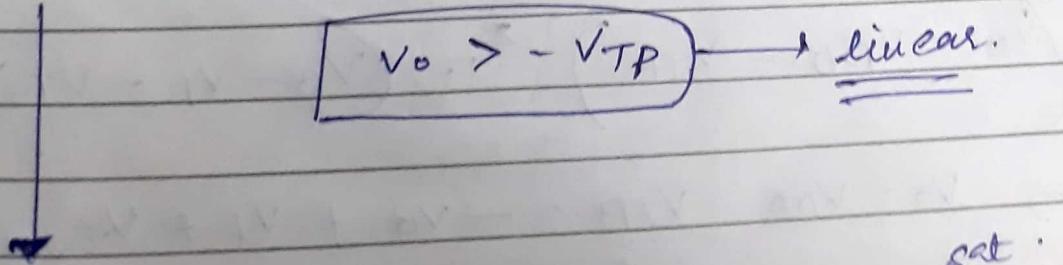
$$C_L \frac{dV_O}{dt} = \frac{1}{2L} k_P W (-V_{DD} - V_{TP})^2$$

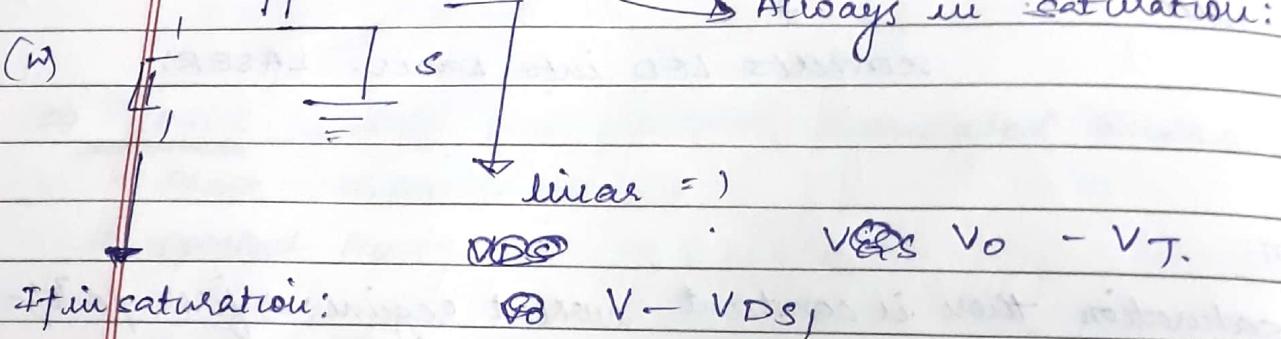
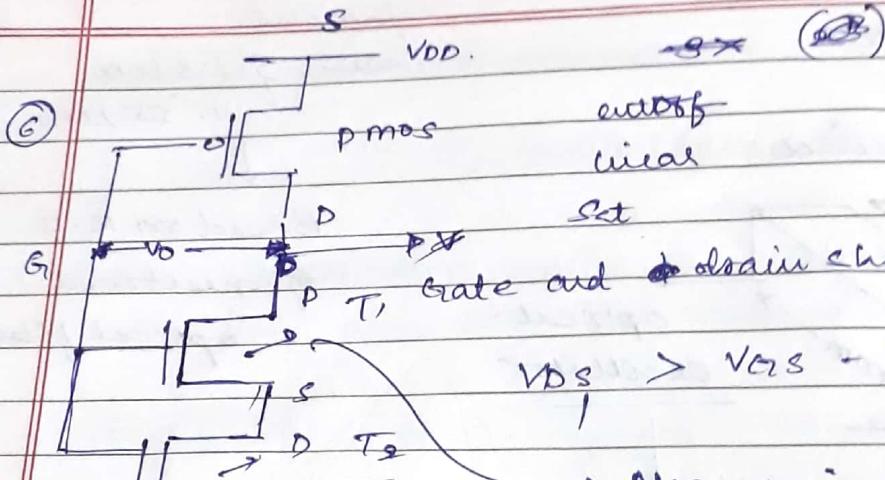
$$V_O = \frac{1}{2L C_L} \left( k_P W (+V_{DD} + V_{TP})^2 \right) (t),$$

$$V_{DS} = (V_{DD} + V_{TP}) \quad \Rightarrow \quad (V_{GS}) = (V_O) - V_{DD}$$

~~$|V_{DS}| > -V_{DD} - V_{TP}$~~

$V_O > -V_{TP}$   $\rightarrow$  linear.





$$I_{DS1} = I_{DS2}$$

Then they must have same  $V_{GS}$

$$V_{GS1} = V_{GS2} = V_o \quad \text{so Not possible in satn.}$$

so in linear.

And pmos g and s shorted  $\therefore$  satn.

now solve:-

$$(V_{GS} - V_{TP})^2 = (V_{GSn} - V_{TN})^2$$

$$(V_o - V_{DD} - V_{TP})^2 = (V_o - V_I - V_{TN})^2$$

$$\Rightarrow V_o - V_{DD} - V_{TP} = -V_o + V_I + V_{TN}$$

$$\therefore V_o = \frac{(V_I + V_{TN})}{2}$$

$$\frac{XP}{2X} \checkmark (V_o - V_{DD} - V_{TP}) = \frac{kW}{L} \left[ (V_o - V_m) v_1 - \frac{v_1^2}{2} \right]$$

$$\Rightarrow (V_o - V_{DD} - V_{TP}) =$$

$$\frac{1}{2} (V_o - 1) = (V_o - 1) v_1 - \frac{v_1^2}{2}$$

$$V_1 = 2V_o - 5 \quad \Rightarrow \frac{1}{2} (V_o - 1) = (V_o - 1) (2V_o - 5)$$

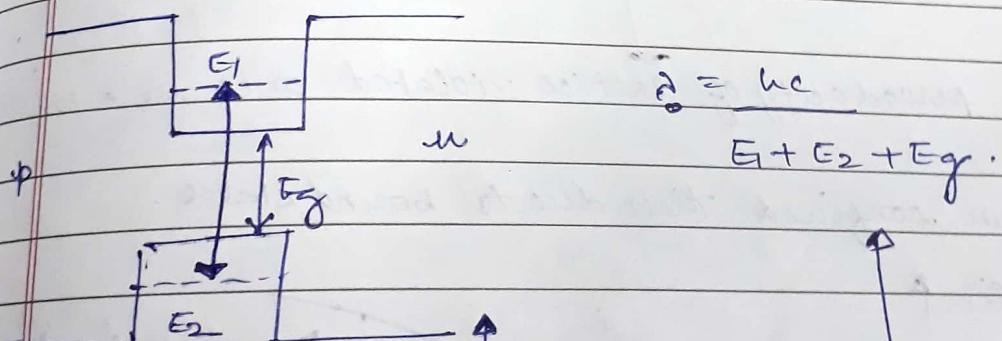
$$= \underline{\underline{2.75}}$$

Simulator:

Laser cont:

① Emission Wavelength:

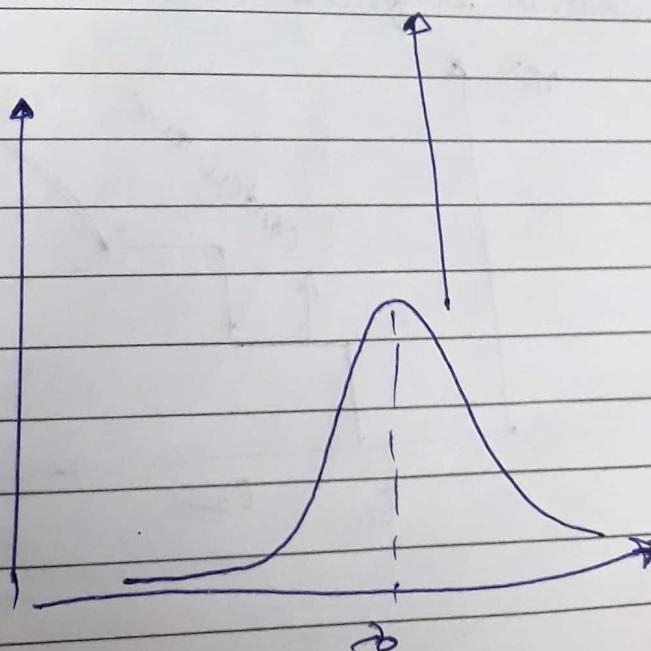
Photoluminescence:



$$\lambda = hc$$

$$E_1 + E_2 + E_g$$

Qwell =



Power Spectral Density  
Date \_\_\_\_\_  
Page \_\_\_\_\_

Bulk: homo

$\rightarrow$  I i n

called  
PSD"

$E_c$

$E_g$

$E_v$

I ↑ presence of bound states.

$I_0$

$\frac{I_0}{2}$

$A_0$

$A_0 = h c$

$(E_g + k_B T)$

traps/  
defects.

Low temp

↓ low resist.  
more noise

Lower Temp / higher confinement due to shift

Full width half maximum:

sharpener  
does  $f(E)$

It is cont as in other  
2 directions any energy  
is possible.)

Fermi-like stat: higher energy  
and lower bound states.

periodicity of lattice violated once in a while.

If quantum confined then due to bound states.

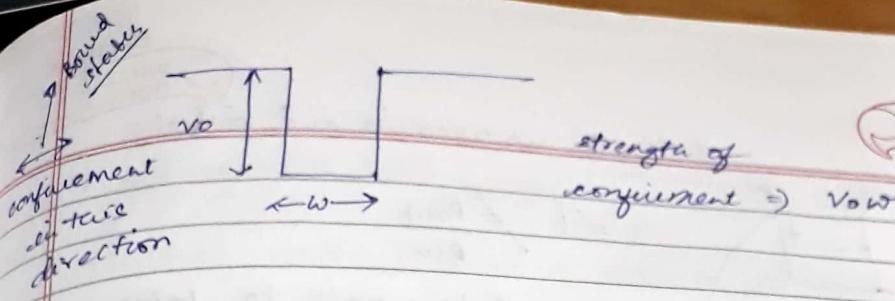
$N(E)$

continuum.

$G \quad E_2$

not confined  
but prob of  
0 to be here  
very less.

classmate  
Date \_\_\_\_\_  
Page \_\_\_\_\_



strength of confinement  $\Rightarrow V_0 w$

$$-\frac{\hbar^2}{2m} \left( \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{\partial^2 \psi}{\partial z^2} \right) + V \psi = E \psi.$$

low temp:  
less movement  
more conf.  
invariant

i) orthogonal.  $\rightarrow$  separation of variables:  
ii) 2° confinement

$$E_x = \frac{\pi^2 \hbar^2 n_x^2}{2m L_x^2}$$

$$E_y = \frac{\pi^2 \hbar^2 n_y^2}{2m L_y^2}$$

e.c.

(1, 2) and (2, 1)  $\rightarrow$  degenerate states:

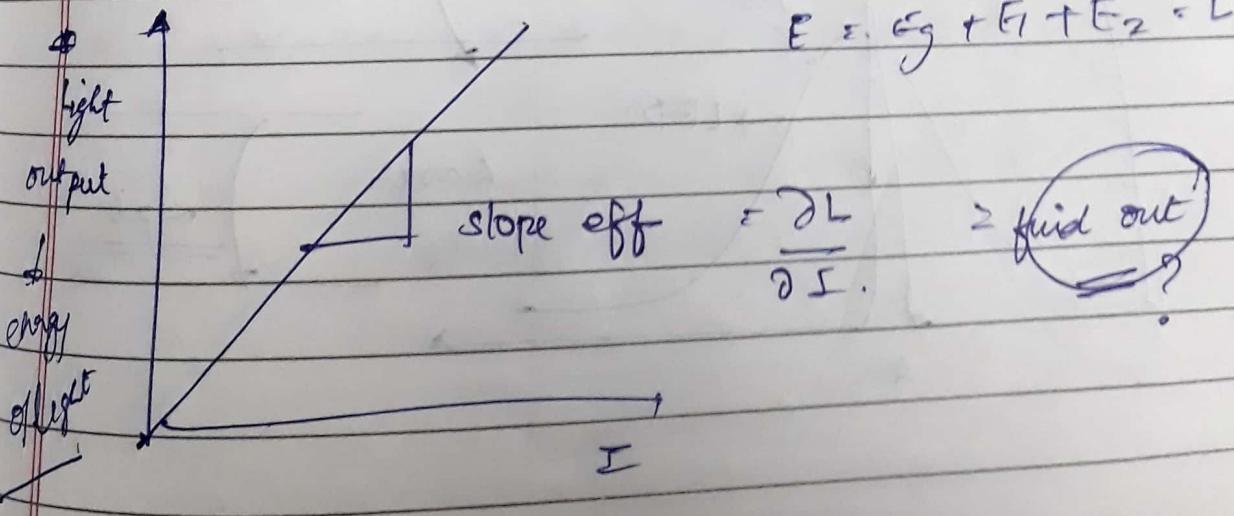
$$E_z = \frac{\pi^2 k_z^2}{2m}$$

$\rightarrow$  free particle / no confinement.

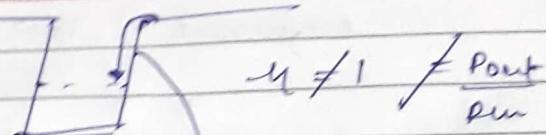
$$= \frac{\pi^2 \hbar^2}{2m} \left[ \frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} \right] + \frac{\hbar^2 k_z^2}{2m} \quad \text{Quantum wire.}$$

ie:  
Quantum well =  $\frac{\pi^2 \hbar^2}{2m} \left[ \frac{n_x^2}{L_x^2} \right] + \frac{\hbar^2}{2m} (k_x^2 + k_y^2)$

so after min E there is a continuum.

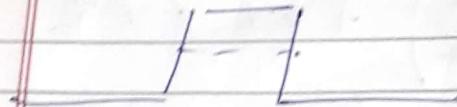


even if no recomb and diff.



$$I = 1 \text{ A} \quad P_{\text{out}} / R_n$$

because this goes to lattice.



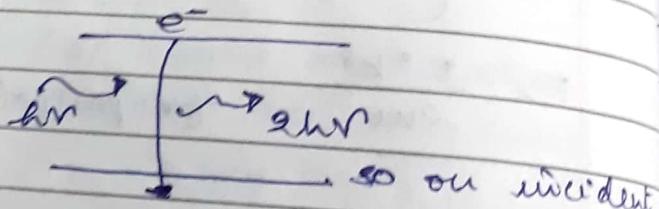
Quantum cascade LED / Quantum cascade diode: Look up??

→ Simulate:

→ Stimulated emission:

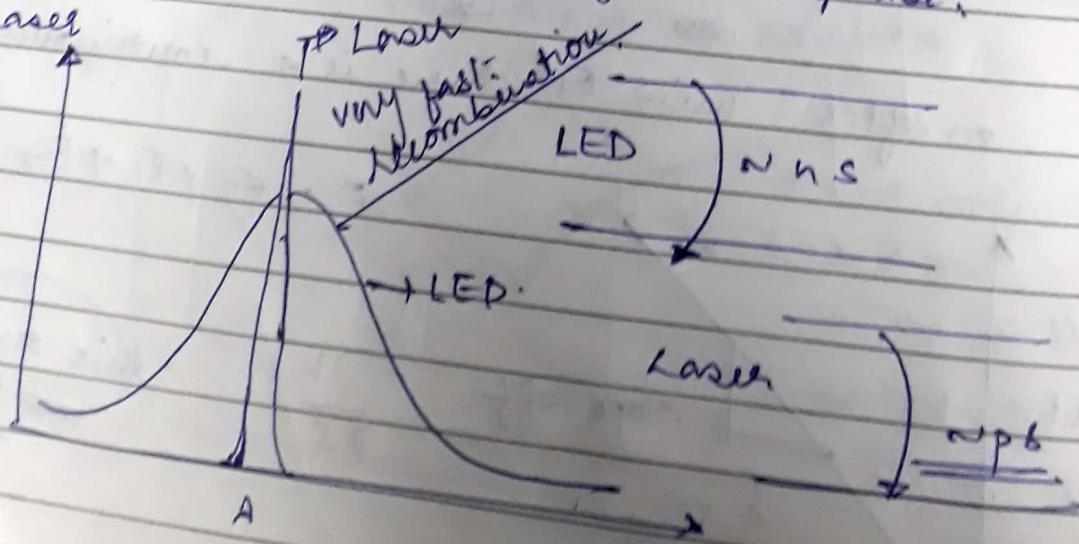
Fermi's Golden Rule

(No classical analogy.)



of a photon the max possibility of photon ~~form~~ from recombination of  $e^-$  and hole  $n$  of same wavelength and phase;

LED vs Laser



To Laser  
very fast  
Recombination

LED

$n \text{ ns}$

Laser

npb

A

### o Ideal LED and Laser

- If not worried about  $\lambda$  efficiency more or less same.
- But for wavelength, then  $\rightarrow$  laser more efficient than LED as the initial part due to fermi-dirac is still there.

### modulation of Band Width: -

- If we change freq, the intensity should also change accordingly with  $f$ .

In Laser change is faster because response limited by the recombination time  $\text{ps}$  in Laser and  $\text{ns}$  in LED.

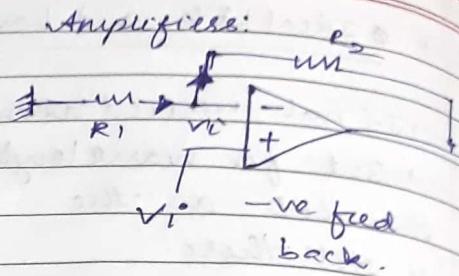
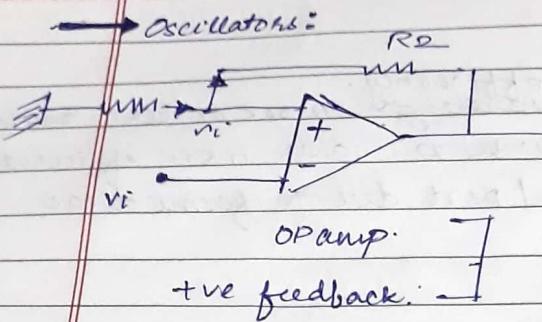
the current at which ~~leads to~~ transition from LED to Laser: .

- By putting Phosphor coating the response decreases.  
↓  
due to the additional lag in hitting the phosphor to give white light.

general lag for LED  $>$  lag for laser  
↓



because not possible to optimize it for several wavelengths.



input impedance of opamp =  $\infty$ . current into opamp = 0.

not taken in +ve feedback:

$$e_0 = A(e_+ - e_-)$$

$$\frac{e_0 - e_-}{R_1} = \frac{(e_- - e_0)}{R_2}$$

$$\Rightarrow \frac{e_0}{e_+} = \frac{A(R_1 + R_2)}{R_1 + R_2 + R_f}$$

~~$$\frac{e_0}{e_+} = \frac{R_1}{R_1 + R_2}$$~~

$$\frac{e_0}{e_-} = \frac{R_1}{R_1 + R_2} = B = \text{fraction of output coming on } e_+$$

in - ve      in + ve feedback,

$$\frac{A}{1 + AB}$$

+feed back +high gain = oscillat

here A is a function of  $\omega$

only here there can be no

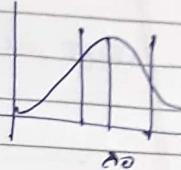
oscillator or active circuit

call pitt's oscillator

directed light in laser due to the modeling optical cavity of laser.

distance bet<sup>n</sup> 2 mirrors  $\frac{\lambda}{2}$ .

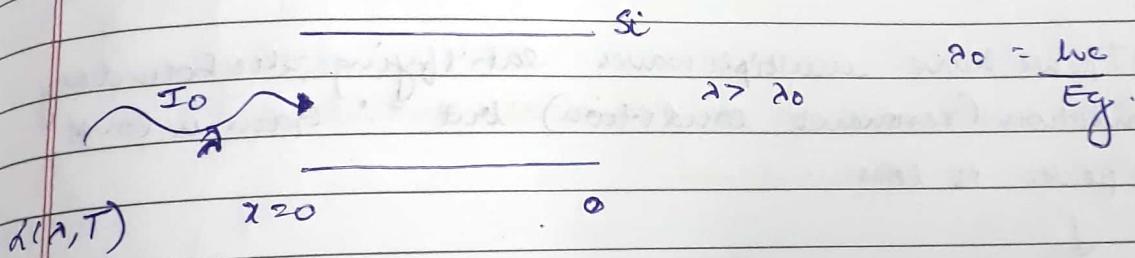
gain large and feedback factor:  
fraction of photon reflected =  $B$ .  
Total photon generated



99.9%

99.1%

Long wavelength light penetrates more in a semiconductor  
 $\lambda > \lambda_0 \therefore$  not absorbed



$$I(x) = I_0 e^{-\alpha x} \quad \frac{1}{\alpha} = \text{penetration depth.}$$

$\alpha$  = Absorption coefficient

$G = -\alpha$  = gain. Unless there is perturbation  
 $\alpha > 0$  and no gain.

Intensity might increase as it goes into the semiconductor  
eg ~~re~~ electron hole pair generation Recombination

ehp

photon generation

Optical gain

magnitude of peak increases

shift in the peak level due to -



\* since we populate higher energy state.

As injection  $\uparrow \rightarrow T^4$  increases so shift  
in ~~for~~ DOS.  $L \downarrow$  due to de- populated power

If this is cooled, then, shift less  
called chirp

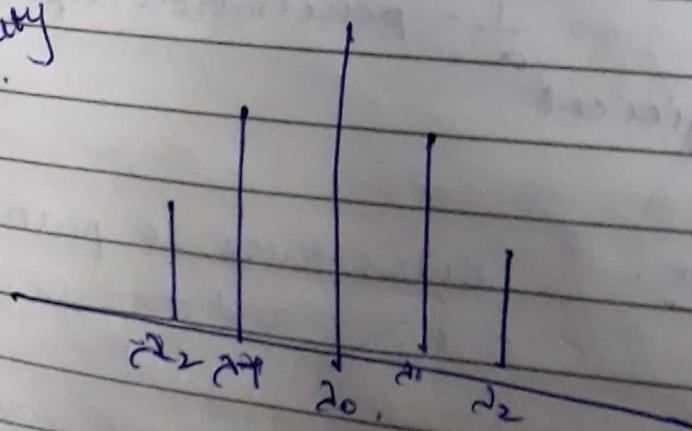
$\hookrightarrow$  check - ?

For high precision work, laser kept on for an hour  
so that it gets constant temp;

=> If we have multiple waves satisfying the boundary condition (resonant condition) but Gain is lower the peak or less.

$\downarrow$   
Multimode Laser:

Intensity  
 $V/S^2$



\* Resonant condition:

$$\frac{L}{\lambda} = \frac{n}{2}$$

Length

### LASER RATE EQUATION

$$\frac{dN(t)}{dt} = \frac{I(t)}{ava} - g_0 [N(t) - N_0] \cdot S(t) - \frac{N(t)}{Cw} \quad (1)$$

$N(t)$  = electron density

$I(t)$  = current

( $aV$ ) = charge

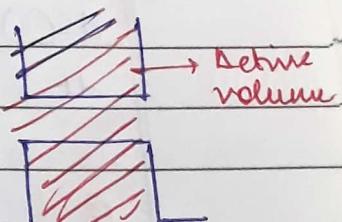
$V_0$  = active volume of device [Assuming that confinement]

$g_0$  = gain

Neglecting SRH.

Radiative recomb  $\rightarrow$  spontaneous

simulated



$I_0$

$$I = I_0 e^{-\alpha x}$$

Now if there is injection

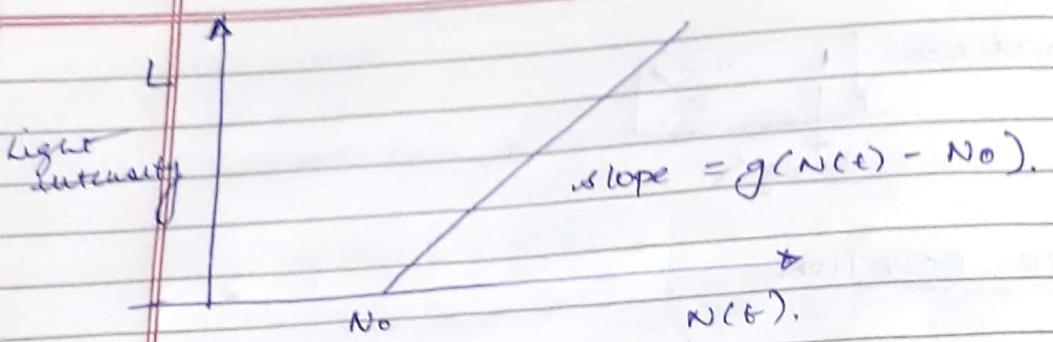
$x=0$

$$J = I_0 e^{-(\alpha - g)x} \quad \text{if } g = \alpha$$

gain

then,

$$I = I_0 (\text{Transparent carrier density})$$



$\epsilon$  = gain compression factor: decreases ~~intensity gain~~ at high photon density.

$S(t)$  = photon density.

$\Gamma'$  = fraction of photon confined and available for stimulated response

$$\frac{dS(t)}{dt} = \Gamma'(g_0) \cdot \frac{(N(t) - N_0) \kappa(t)}{1 + \epsilon S(t)}$$

↑ fraction of photons coupled

$$- \frac{S(t)}{C_P} + \frac{\Gamma'(B)}{C_n} N(t)$$

5. Stimulated emission.

↔

photon leaving  
(spontaneous).

100%

79%

LASER

→ This

loss of  
photon.

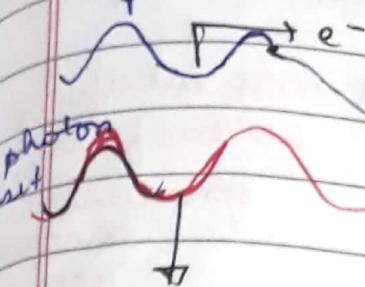
what fraction  
of spontaneous  
gives photon.

↓

all sorts of  
non-radiative  
recomb.

relaxation oscillation

e density  $\uparrow$



e- density decreases  $\therefore$  they recombined  
to give photon

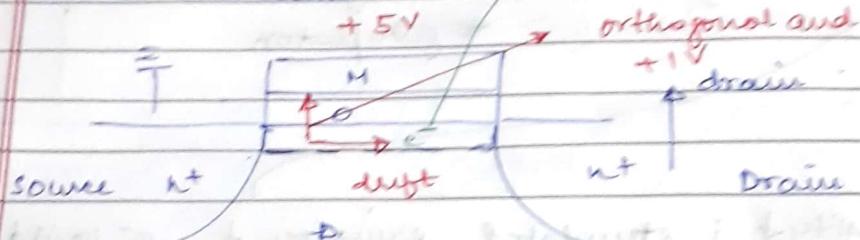
photon density  $\downarrow$   $\downarrow$  stimulated emission  $\downarrow$ , e- buildup

H1 (Hall electron mobility transistors)

HEMT

III and IV transistors:

n-MOS Transistor



stressed here

Additional friction  
→ surface scattering  
+ mouth loss.

orthogonal and non interfering  
electric field  
gradual  
changes  
opposite

$$\mu = 300 - 500 \text{ in NMOS}$$

$$\text{in Bulk Si } \mu = 1200 - 1500$$

$\mu_s$  velocity  $\rightarrow$  in nMOS

- $\mu_s$  not depends on  
doped not  
reverses.  
right
- $\mu_1 \rightarrow$  due to only this scattering and others about
  - $\mu_2 \rightarrow$  Lattice vibrations : Phonon Scattering
  - $\mu_3 \rightarrow$  Impurity Scattering: Doping
  - $\mu_4 \rightarrow$  Surface scattering
  - $\mu_5 \rightarrow$  addition friction due to gate potential.  
due to hetero interface.

III and IV transistors: get rid of impurity scattering.

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_3}$$

Mattescue Rule:

Carrier - Carrier scattering

[both  $e^-$  neglected]

$\propto$  dependence  $n^{1/3}$

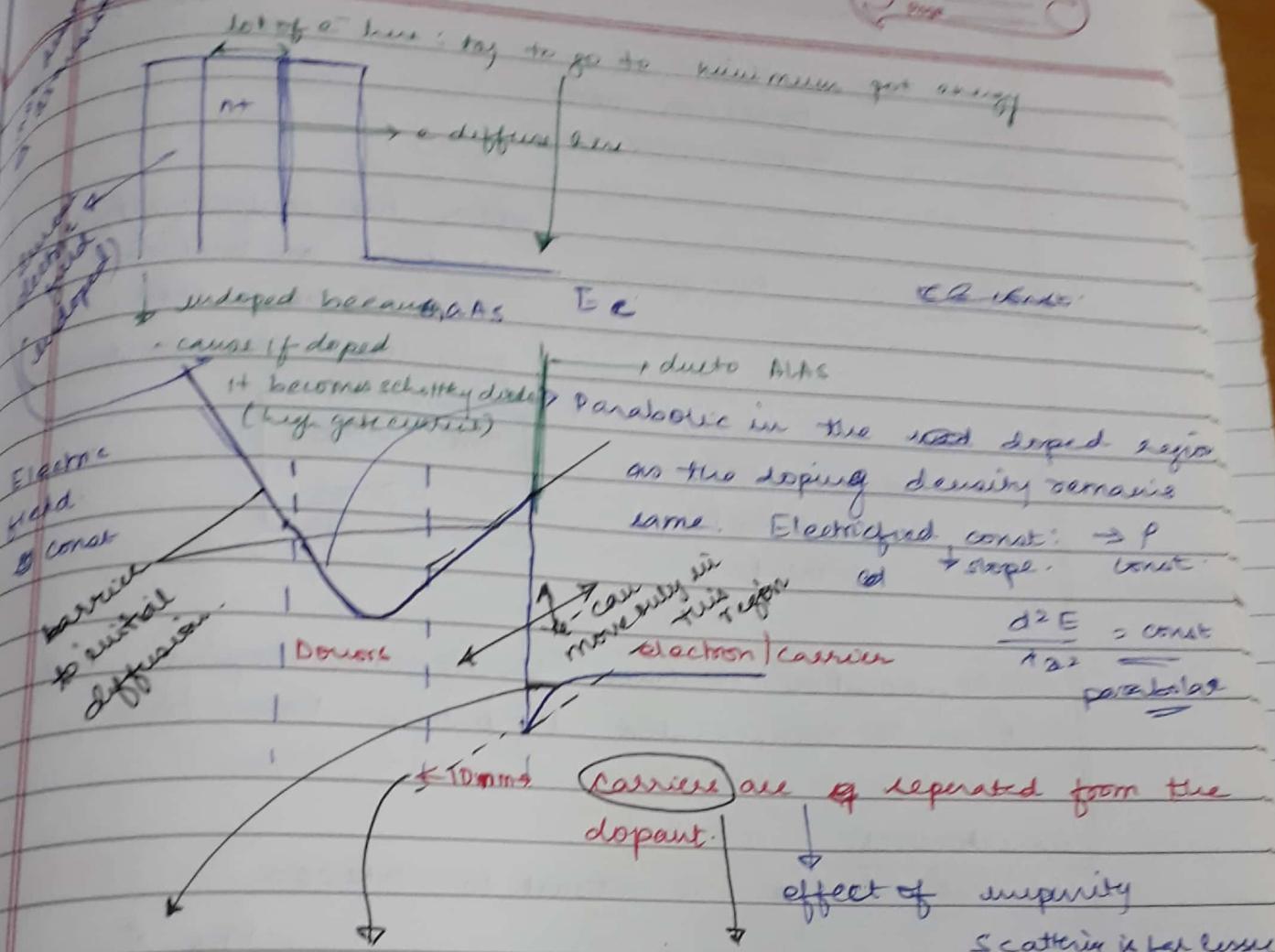
80% 10 nm AlGaAs (undoped)

30% 10 nm AlGaAs ( $n^+$  doped),

30% 10 nm AlGaAs (undoped)

GaAs (undoped)

5 nm



They are confined to left due to band offset and to right due to potential or band bending.

$2500 \text{ cm}^2/\text{V}_2$   $\leftarrow$  High and speed high

f high:

2D  $E_g$

$V_{DS} = 1\text{V}$

$V_G > 0$

Metal gate

AlGAs

n-ohmic

n-ohmic drain

To turn off this

transistor  $V_T = -V_E$

$\downarrow -2 \text{ to } -3\text{V}$

GaAs

now if  $V_G = 0$  we have 2DEG  $\therefore$  current flows

-> gate upto 600 nm 200 GHz

-> high transconductance

MOSFET: Shallow power consumption

1)  $V_T = -ve$  Depletion mode:

2)  $V_T = +ve$  Enhancement mode:

Diode and Rectifying

?

gate control  $\rightarrow$   
over S to D  
current:

2DEG the confinement must  
be thin so that can  
be modulated easily which  
gives higher transconductance.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}}$$

due to fabrication we have background doping and  
that can be compensated by putting Fe.

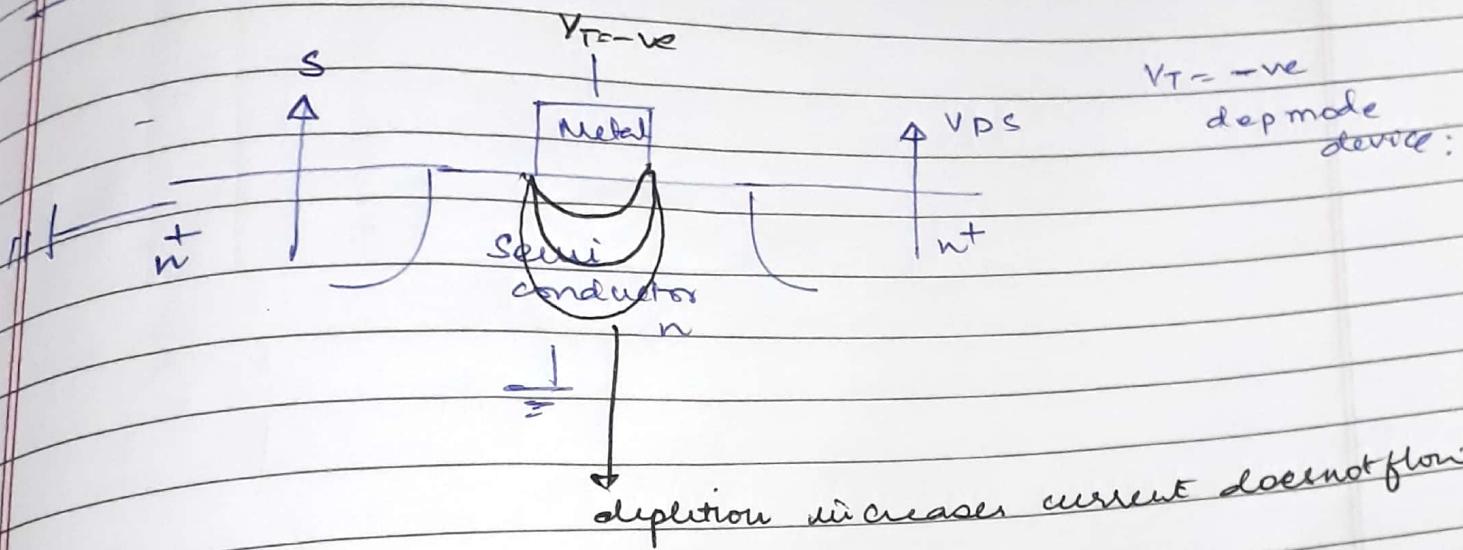
Characteristics

$V_T = -ve$   $\rightarrow$  in contrast to nMOS;

$$I_{DS} = \frac{\mu C_W}{L} \left[ (V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \quad V_{DS} < V_{GS} - V_T$$

$$= \frac{\mu C_W}{2L} (V_{GS} - V_T)^2 \quad V_{DS} > V_{GS} - V_T$$

MESFET: Metal - semi conductor field effect transistor.



- drawback:
- more gate current:  $\because$  metal on semiconductor
  - less mobility

Speed better than mosfet but less than HEM.  
 $\because$  mobility was it inherently higher in GaAs.

MOSFET use "i" due to native oxide  $\text{SiO}_2$  is  $\text{SiO}_2$