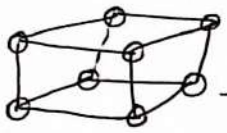
Lec 2 Energy bands in Solids

> (Crystalline) semiconductors.



		No. of atoms per unit cell.
• Cubic lattice →	Simple cubic (SC)	1
→	BCC	2
→	FCC	4

> What is the no. of valence electrons per unit volume?

$a \rightarrow$ inter-atomic spacing = 3-7 Å . Say 5 Å.

$\Rightarrow$ volume of unit cell = $125\ Å^3 = 125 \times 10^{-24}\ cm^3$.

$\Rightarrow$ No. of atoms per unit cell = 0.8×10^{22} /cc

$\simeq 10^{22}$ /cc.

> Since semiconductors have 4 electrons (valence), the no. of valence electrons electrons per unit volume is

$\boxed{4 \times 10^{22}/cc} \rightarrow$ Si & Ge.

Gallium - 31 & Arsenic - 33.

$\Rightarrow$ Answer: $10^{22} - 10^{23}$ /cc.

Solid → state of matter
↳ collection of atoms or molecules.
↓ Given by Schrödinger Eq

$$H\psi = E\psi$$

Hamiltonian.

Total energy operator.

$$KE + PE$$

$$\frac{p^2}{2m} + V \rightarrow \left(-\frac{\hbar^2\nabla^2}{2m} + V\right)\psi = E\psi.$$

$$\Rightarrow \boxed{\nabla^2\psi - \frac{2m}{\hbar^2}(E-V)\psi = 0.}$$

↳ For a given potential we can find an Energy (E) eigenvalue.

Eg: H-atom : $V = \frac{kq_1q_2}{r} = -\frac{e^2}{r}k.$

Solving SE using V ⇒ $E_n = -\left(\frac{me^4}{8\epsilon_0^2 h^2}\right)\frac{1}{n^2}$

↳ discrete E vals (energy levels).

$n=\infty$

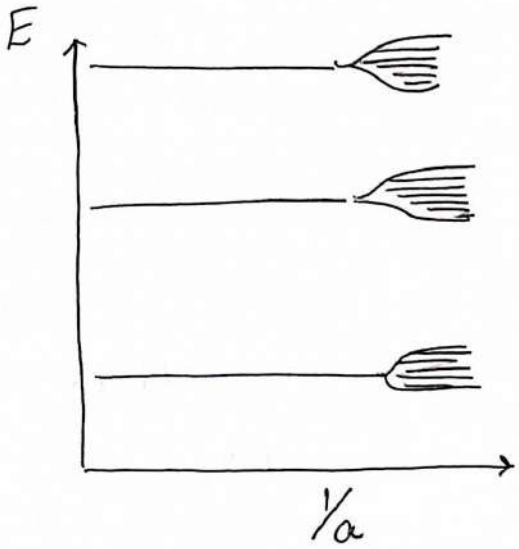
$$= -13.6\left(\frac{1}{n^2}\right) eV$$

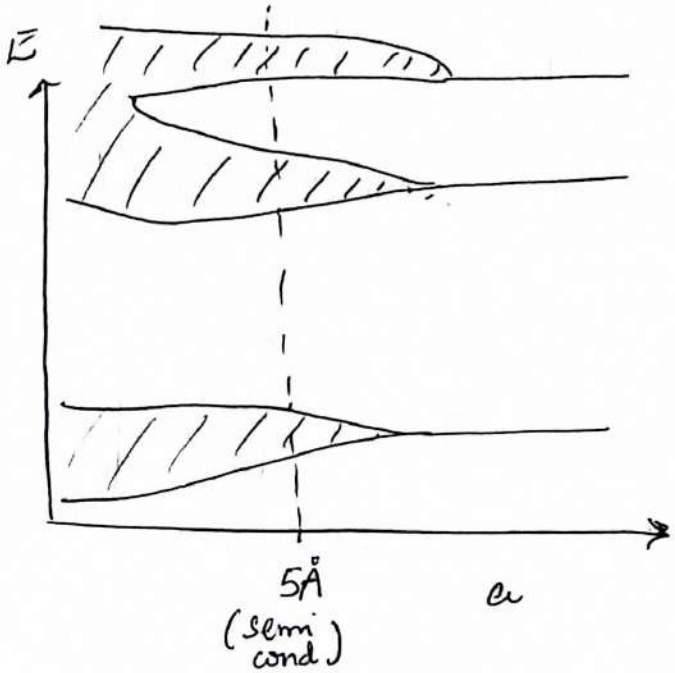
$n=2$

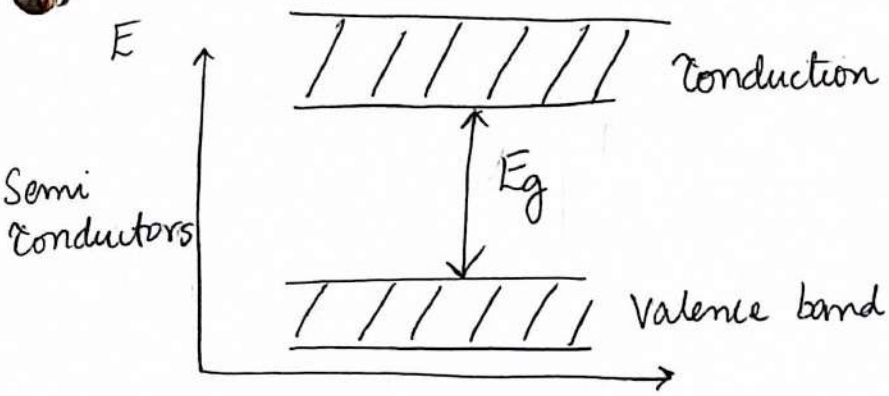
$-13.6eV$ $n=1$ → Ground state for isolated H-atom.

In a gas : $a \sim 100\,\text{Å} - 1\,\mu m$.

> Band splitting when two atoms come closer (Pauli's)

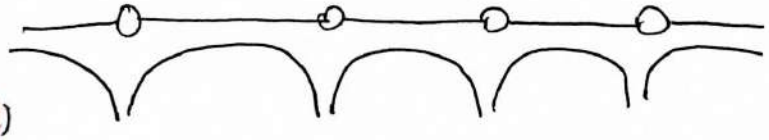






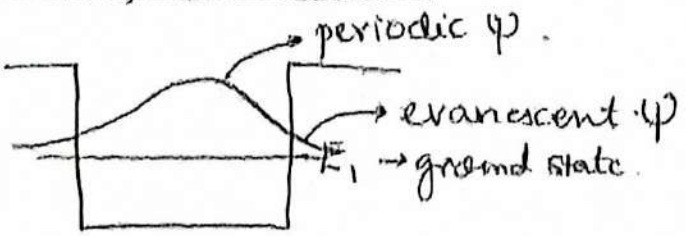
Kronig Penney Model.

A 1-D lattice has a potential distribution like.

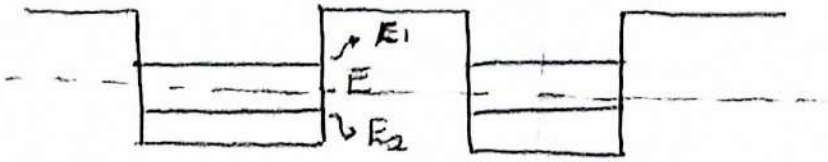


↓ Approx. as periodic potential well.

1-D potential well.

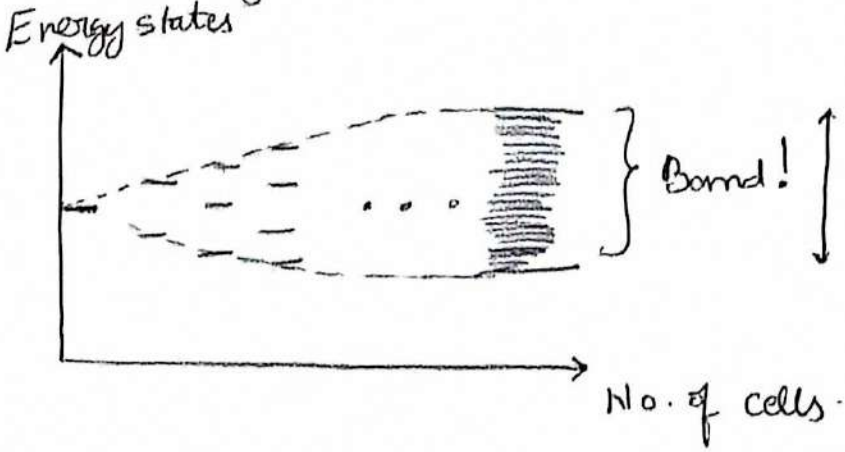


> When 2 wells are brought in close proximity.



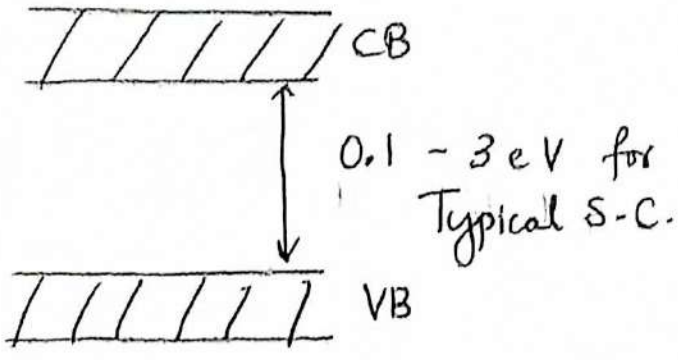
→ Solving the problem leads to mode splitting + each well has 2 solutions.

> N interacting wells gives N states.

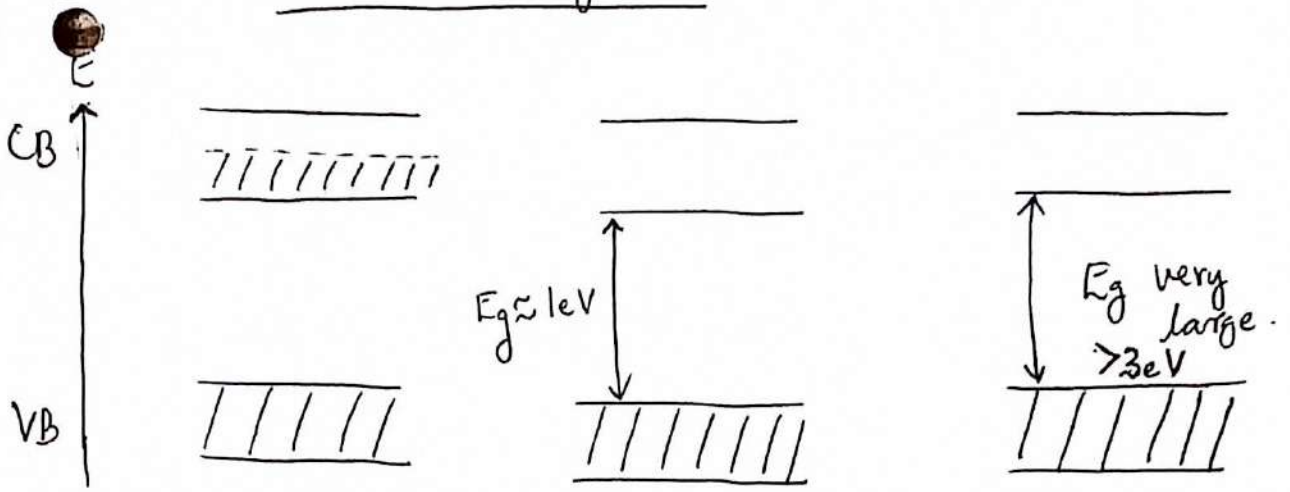


→ same as that from Kronig Penny Model.

Summary



Lec 3 E - k Diagram



metals
(bands could also overlap)

Semiconductor

At 300k

Ge - 0.67eV - 10^{13}/cc

Si - 1.1 eV - 10^{10}/cc

GaAs - 1.42 eV - 10^{6}/cc

$E_e \simeq 0.025$ eV (avg. kinetic energy of an electron).

How are so many electrons reaching the conduction band?

> Since a 1-D lattice is periodic, F. Bloch postulated that ψ must also be periodic.

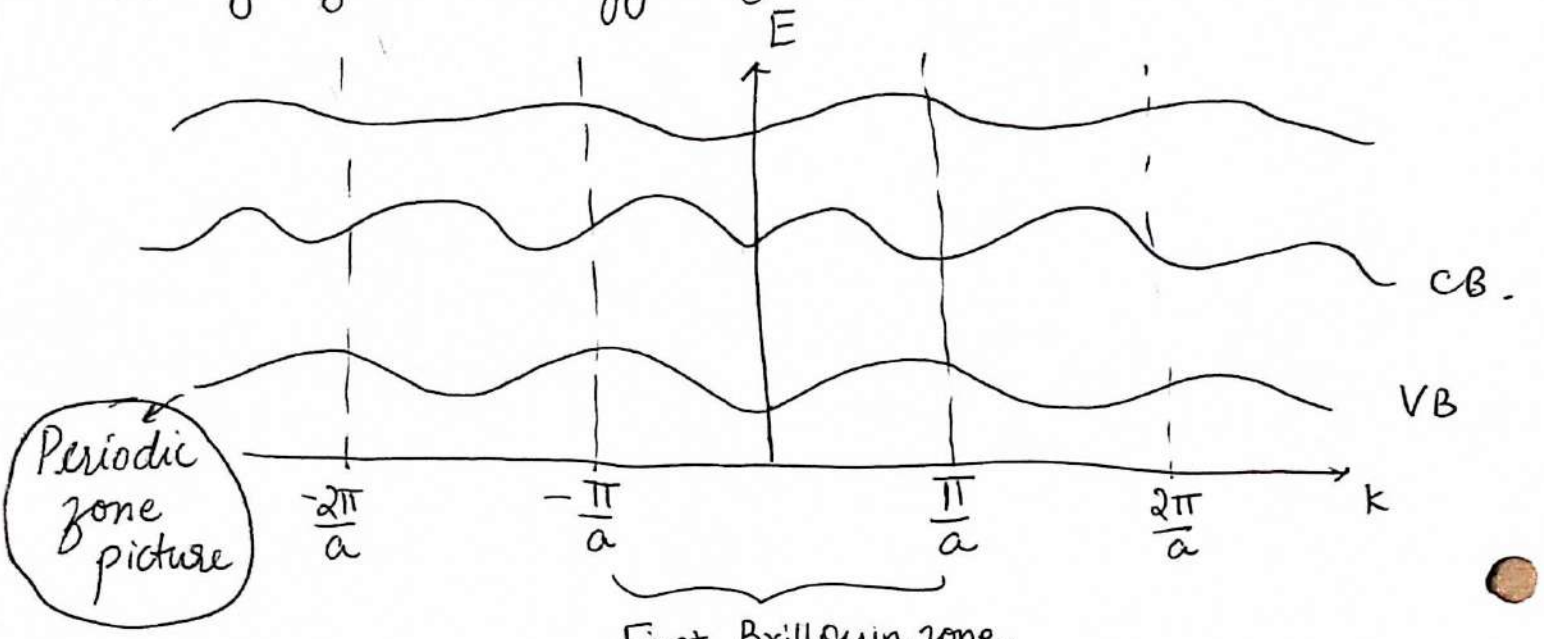
$$\psi_k(r) = u_k(r)\, e^{i\vec{k}\cdot\vec{r}} \quad \text{where } u_k(r) = u_k(r+a).$$

↳ Periodic cell function

Sustituting into Schrödinger,

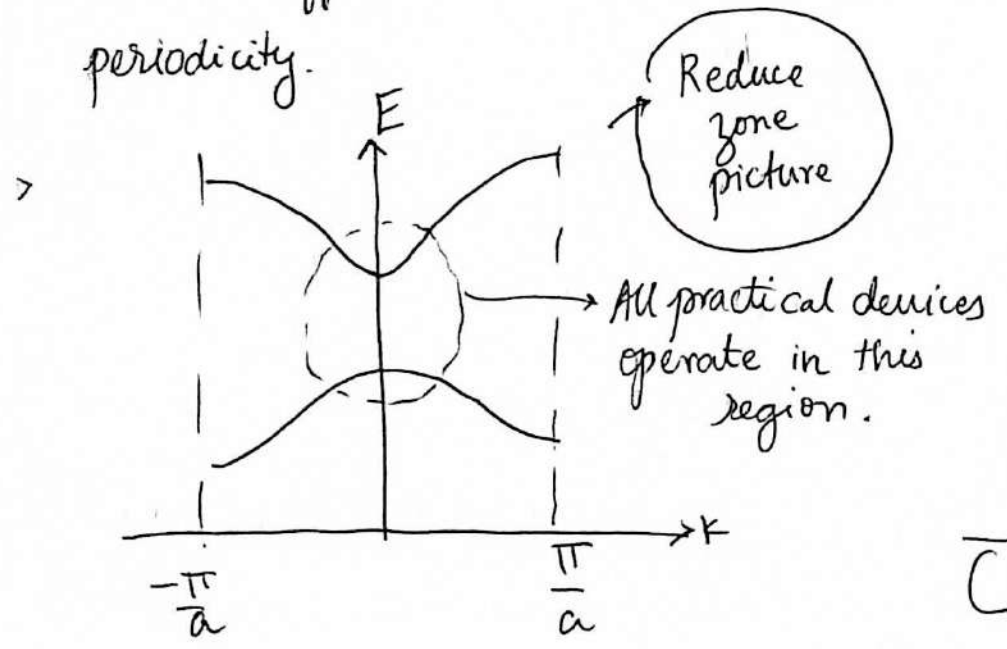
$$\nabla^2\psi + \frac{2m}{\hbar^2}(E-V)\psi = 0$$

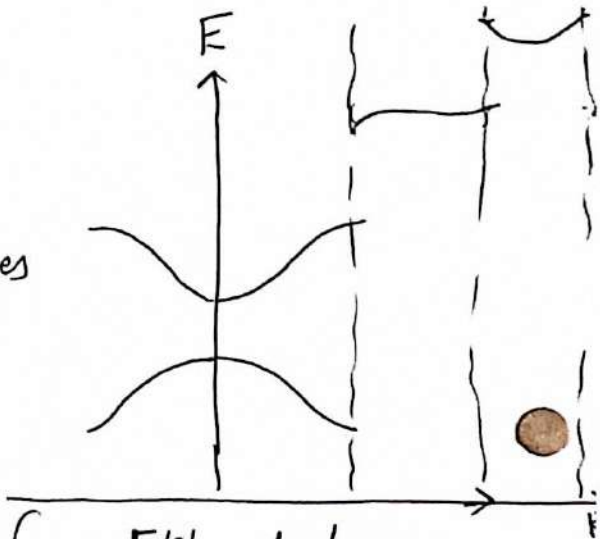
Solving gives energy eigenvalues that are also periodic!



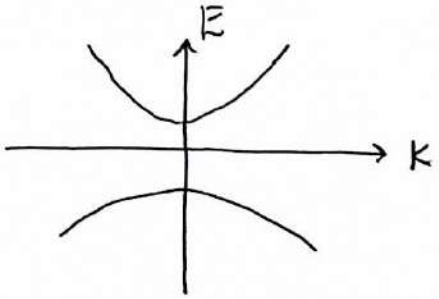
> In the First Brillouin zone, $k=0$ is the Γ- point.

> It is sufficient to study the first Brillouin zone due to periodicity.

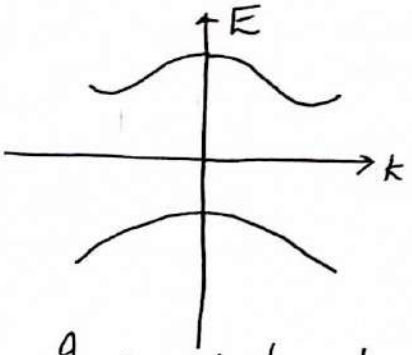




↳ Extended zone picture.

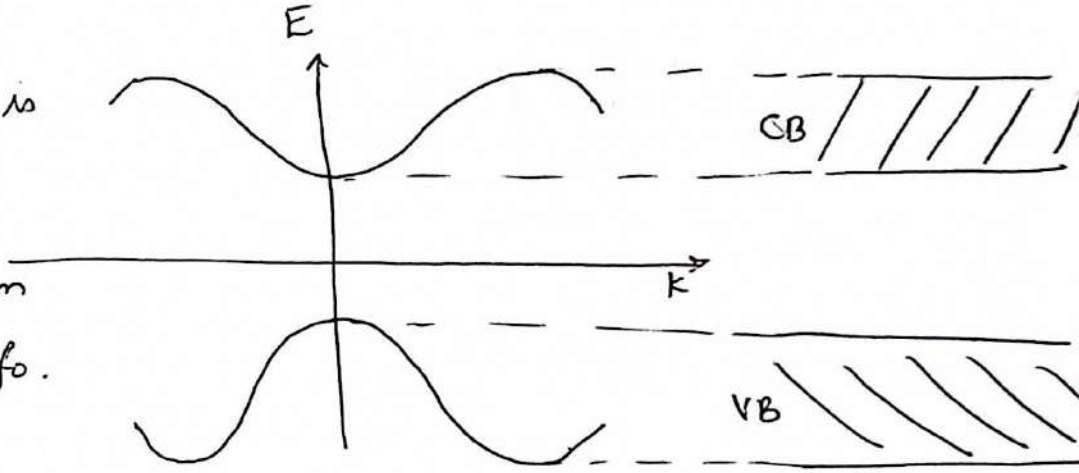


Direct band-gap semiconductors



Indirect band-gap semi-conductors.

> E-k diagram is related to the Band-gap diagram & gives more info.



> $|\vec{k}| = \frac{2\pi}{\lambda}$ → de Broglie wavelength.

$\vec{p} = \hbar \vec{k}$ → "crystal momentum".

But what is $\vec{k}$?

> $\vec{k}$ is the "crystal momentum". If an external E-field is applied to the crystal, the electron moves under the influence of the external field & the internal field. The internal field is from the other electrons & ions, but $\vec{k}$ is defined by the momentum due to E_{ext} alone.

i.e $\frac{dp}{dt} = F_{ext} = -e\,\mathcal{E}_{ext}$.

> The electron is therefore assumed to move as a free particle with an effective mass "m^*"

$$m^* = \left(\frac{1}{\hbar^2}\frac{d^2E}{dk^2}\right)^{-1}$$ ← This comes from the E-k diagram. ↳ Super imp!

> Using this m^* mass, we can assume e^- is free.

Why does this matter?

(What is the current under an applied field?)

$I = JA$ ← area.

$J = n\,q\,\mu_e\,\mathcal{E}$

$n \rightarrow$ carrier concentration.
$q \rightarrow$ charge.
$\mu_e \rightarrow$ mobility
$\mathcal{E} \rightarrow$ Applied field.

$$n = \int_{E_c}^{\infty} n(E)\,dE$$ ← For CB

where $n(E) \rightarrow$ Carrier density

$n(E) = \rho(E)\,f(E) \longrightarrow$ probability of occupation.

↳ density of states. ↳ (next lecture)

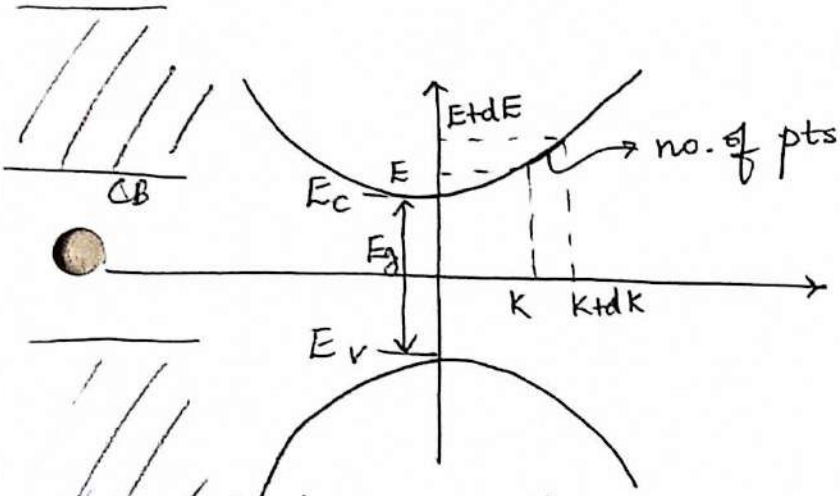
$$\mu_e = \frac{e\,\tau_c}{m^*}$$ ← charge; $\tau_c \rightarrow$ carrier recombination time; $m^* \rightarrow$ effective mass (from E-K diagram).

Lecture 4 Density of States

Density of States: $\rho(k)$ & $\rho(E)$

$\rho(k)dk \rightarrow$ no. of states between k & $k+dk$ per unit volume of the material.

$\rho(E)dE \rightarrow$ "



→ no. of pts. here is same ⇒ $\boxed{\rho(k)dk = \rho(E)dE}$

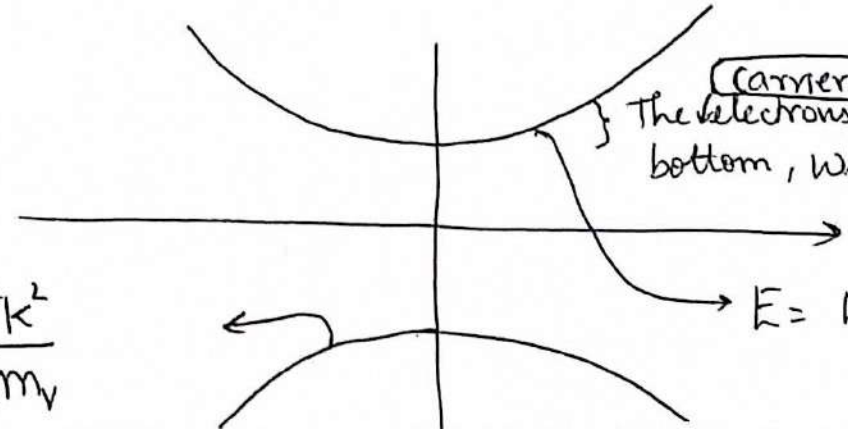
total electrons. → 10^{22}/cc

(doped in Si ~ 10^{15}/cc $\bar{e}$ are available in C.B.)

h^+ " " " V.B.

⇒ Carriers are much smaller than total no. of electrons in that band

(10^{15} carriers vs. 10^{22} electrons)



Effective mass

$$m_{c,v} = \left(\frac{1}{\hbar^2} \frac{d^2E}{dk^2} \right)^{-1}$$

	m_c	m_v	μ_c	μ_v
Si	$0.98 m_0$	$0.49 m_0$	1450	450
GaAs	$0.07 m_0$	$0.45 m_0$	8500	400
Ge	$0.08 m_0$	$0.28 m_0$	3900	1900

$m_0 = 9.1 \times 10^{-31}$ kg.

($\mu \uparrow$ since $m \downarrow$).

What values can k have?

Bloch's Theorem $\psi_k = \underbrace{u_k(r)}_{\text{periodic Bloch cell function}} \underbrace{e^{i\vec{K}\cdot\vec{r}}}_{\text{plane wave}}$

Probability $= |\psi|^2$.

For standing waves inside a cubic crystal we need

$\Rightarrow 2\vec{K}\cdot\vec{r} = N \cdot 2\pi$. Let $\vec{k} = k_x \hat{x} + k_y \hat{y} + k_z \hat{z}$. $= (k_x, k_y, k_z)$

$\Rightarrow 2 k_x L_x = m \cdot 2\pi$

$2 k_y L_y = p \cdot 2\pi$

$2 k_z L_z = q \cdot 2\pi$

Where L_x, L_y, & L_z are the side length of the crystal. Each component must form a standing wave.

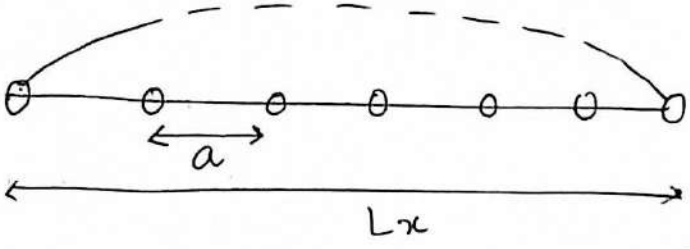
$\Rightarrow$ $k_x = \left(\frac{\pi}{L_x}\right) m$; $k_y = \left(\frac{\pi}{L_y}\right) p$; $k_z = \left(\frac{\pi}{L_z}\right) q$.

$\Rightarrow$ $\vec{k}$ is discrete!

Eg:
Let $L_x = L_y = L_z = 1mm$.

$\Rightarrow$ $k_x = \frac{\pi}{1mm} m = 10^3 \pi\ m^{-1}$ (smallest).

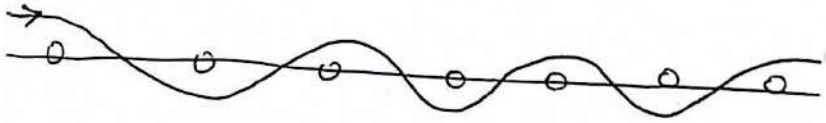
What is its largest value?



→ lowest mode.

Λ → deBroglie wavelength

$\Lambda = 2L_x$ & $k = \frac{2\pi}{\Lambda} = \frac{\pi}{L_x}$



→ Highest mode.

Electron entering from left can "at most" be scattered such that it bends around each atom. In this case, deBroglie $\Lambda = 2a$ $\Rightarrow$ $k = \frac{\pi}{a}$ → which is also the edge of the first Brillouin zone! $k_{x_{max}} = 2 \times 10^9 \pi\ m^{-1}$

Therefore k_x varies from $10^3\pi$ — $\sim 10^9\pi$ in steps of $10^3\pi$.

⇒ There are 10^6 states in each of k_x, k_y, k_z.

⇒ There are 10^{18} states for k!

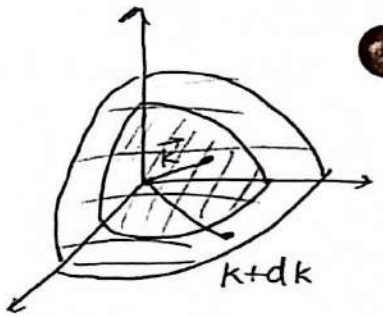
Lec 5 Density of States (contd.)

› Since spacing of states is $\frac{\pi}{L_x}$, $\frac{\pi}{L_y}$ & $\frac{\pi}{L_z}$, the volume occupied by one state is $\left(\frac{\pi^3}{L_x L_y L_z}\right)$.

› Volume between k & k+dk

$$= \frac{1}{8} \cdot 4\pi k^2 \cdot dk$$

↳ only need consider one octant in k-space since -ve k_x, k_y, k_z are already present in a standing wave.



› No. of states b/w k & k+dk = $\dfrac{\frac{1}{8} \cdot 4\pi k^2 dk}{\left(\frac{\pi}{L_x}\right)\left(\frac{\pi}{L_y}\right)\left(\frac{\pi}{L_z}\right)} \times 2$ ↓ due 2 spin states.

⇒ $\rho(k)\,dk = \dfrac{\pi k^2 dk}{\pi^3} \dfrac{(L_x L_y L_z)}{(L_x L_y L_z)} = \boxed{\dfrac{k^2}{\pi^2} dk}$ // $\rho(k)$

$$\Rightarrow \boxed{\rho(k) = \frac{k^2}{\pi^2}}$$

$$\Rightarrow \rho(E) = \frac{\rho(k)}{(dE/dk)} = \frac{k^2}{\pi^2} \cdot \frac{1}{(dE/dk)}$$

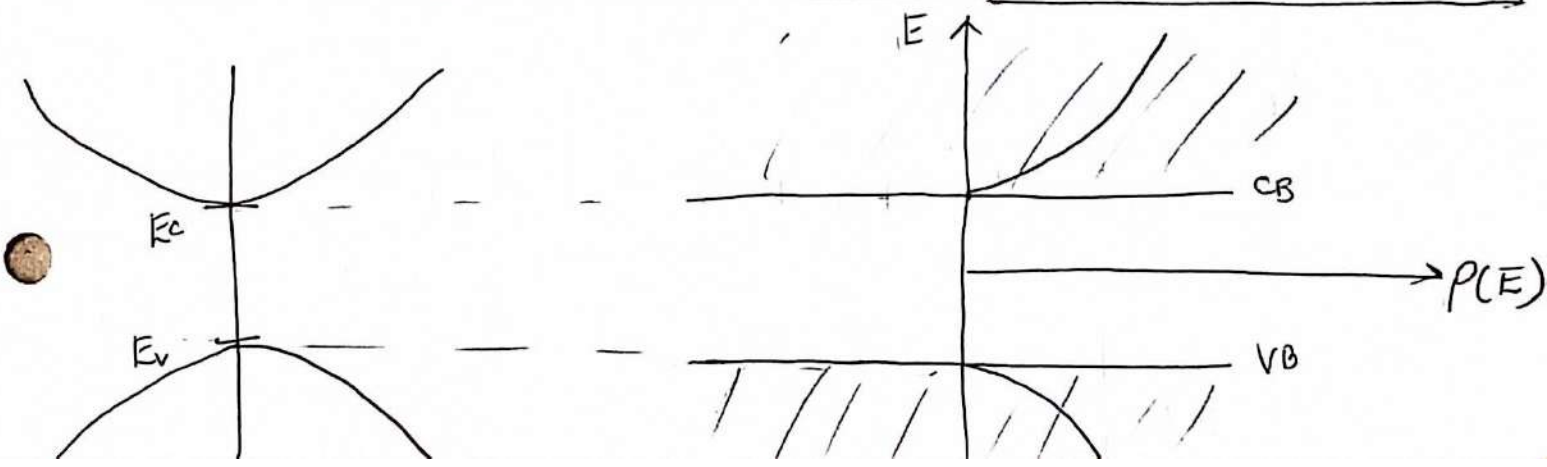
Parabolic approx. $\Rightarrow$ $E = E_c + \frac{\hbar^2 k^2}{2m_c}$ $\rightarrow$ conduction band.

$$\Rightarrow \frac{dE}{dk} = \frac{\hbar^2}{2m_c} 2k = \frac{\hbar^2}{2m_c} \cdot 2\left[(E-E_c)^{1/2}\left(\frac{2m_c}{\hbar^2}\right)^{1/2}\right]$$

$$\Rightarrow \rho(E) = \frac{m_c}{\pi^2\hbar^2}(E-E_c)^{1/2}\left(\frac{2m_c}{\hbar^2}\right)^{1/2}$$

$$\Rightarrow \boxed{\rho(E) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E-E_c)^{1/2}} \rightarrow \boxed{\frac{1}{2\pi^2}\left(\frac{2m_v}{\hbar^2}\right)^{3/2}(E_v-E)^{1/2}}$$

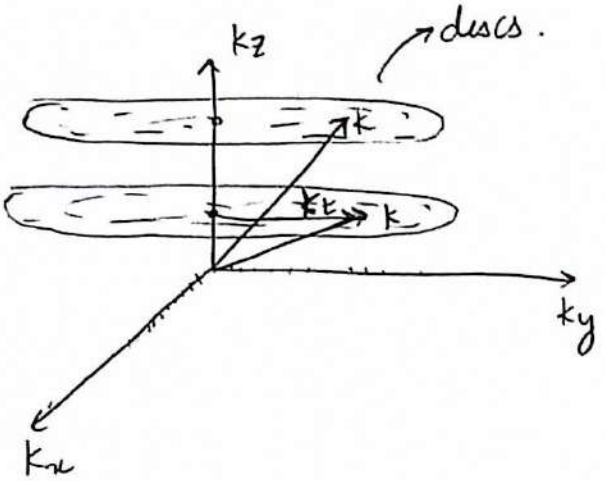
for CB for VB

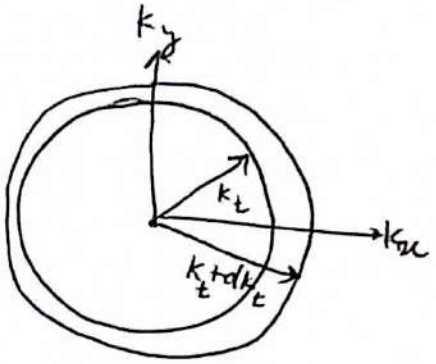


Lec 6 Density of States in a Quantum Well Structure.

> When one dimension of the semiconductor becomes very small, then the discreteness in that dimension's k becomes important.

K-spaces





$$\vec{k} = \vec{k_t} + k_z \hat{z}$$

$$E = E_c + E(q=1) + \frac{\hbar^2 k_t^2}{2m_c} \qquad \left(\frac{\hbar^2 k_z^2}{2m_c}\right)$$

$\Rightarrow \rho(k)dk = \rho(k_t)dk_t$ & we only consider one quadrant!

$\Rightarrow$ Area of quadrant annulus is $\frac{1}{4} \cdot 2\pi k_t \, dk_t$. (↳ quadrant.)

$$\Rightarrow \rho(k_t)dk_t = \frac{\frac{1}{4} \cdot 2\pi k_t \, dk_t \times 2}{\left(\frac{\pi}{L_x}\right)\left(\frac{\pi}{L_y}\right)} \Big/ L_x L_y L_z$$

(2 spins. ; $L_x L_y L_z$ ↳ total volume.)

$$\Rightarrow \boxed{\rho(k_t) = \frac{k_t}{\pi L_z}}$$

$$\frac{dE}{dk_t} = \frac{\hbar^2 k_t}{m_c}$$

$$\Rightarrow \rho(E) = \frac{\left(\frac{k_t}{\pi L_z}\right)}{\frac{\hbar^2 k_t}{m_c}}$$

$$\Rightarrow \boxed{\rho(E) = \frac{m_c}{\hbar^2 \pi L_z}}$$

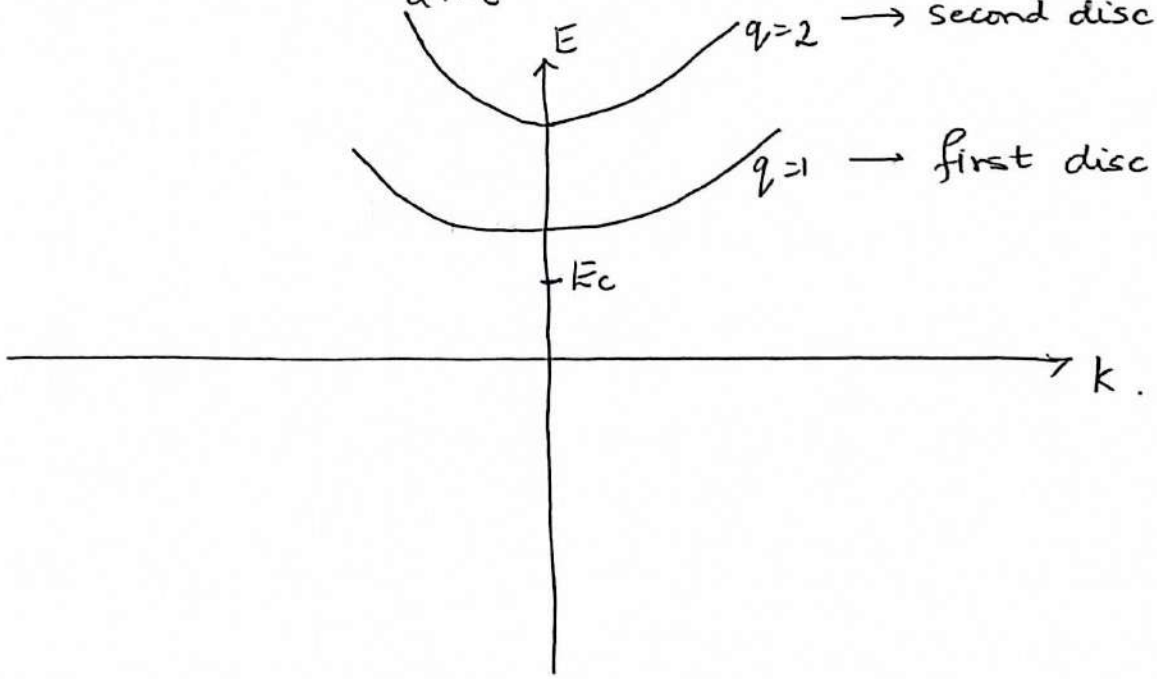
→ Such thin semiconductors are also called quantum well → (will make sense later).

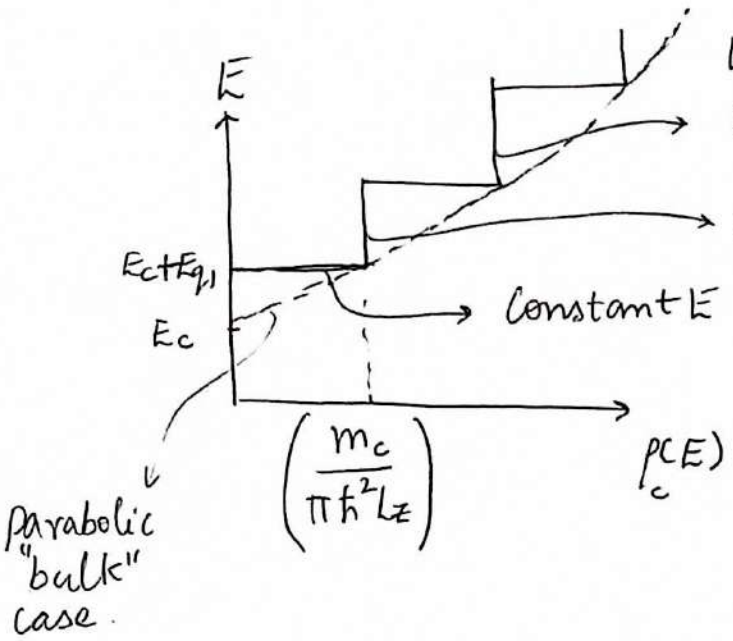
↓

no energy dependance!

$$E = E_c + E_{q1} + \frac{\hbar^2 k_t^2}{2m_c} \quad \text{when } q = 1$$

$$E = E_c + E_{q2} + \frac{\hbar^2 k_t^2}{2m_c}$$





When E ↑, k is large & can lie on 2 discs ⇒ ρ doubles!

density of states is fixed on first disc

> Note that bandgap increases, it is more than $E_c - E_v$..

> Number of states: $N_c = \int_{E_c}^{E_2 = E_c + 0.1eV} \rho_c(E)\,dE = \frac{1}{3\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E-E_c)^{3/2}\Big|_{E_c}^{E}$

⇒ $N_c = \frac{1}{3\pi^2}\cdot\left(2\cdot\frac{m_c}{\hbar^2}\right)^{3/2}(0.1eV)^{3/2}$ let $m_c = 0.067\,m_0$

$\simeq 10^{18}$ /cc

> n = total no. of carriers = $\int_{E_c}^{E_2} n(E)\,dE$ → density of carriers.

↳ $\rho(E)\,f(E)$

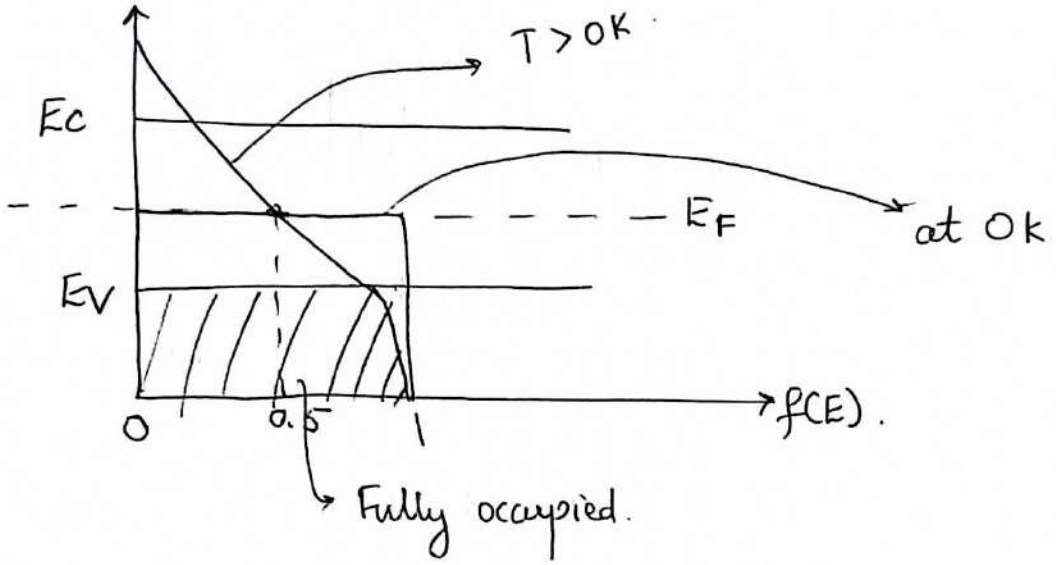
↳ Probability of occupation. (Fermi Function)

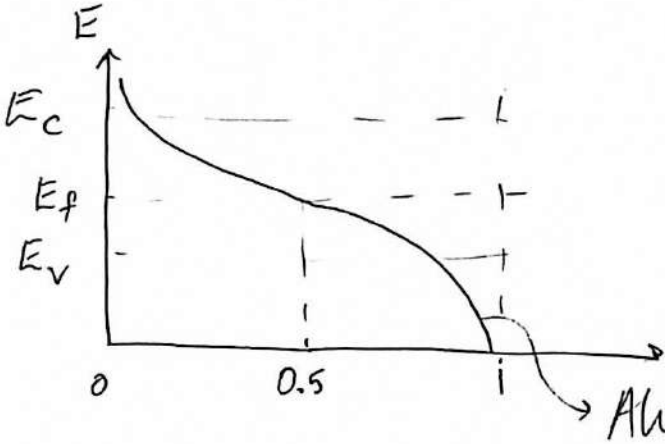
> Basically each electron occupies a single "resonant mode" of the crystal & 2 electrons must occupy different modes/states.

Lec 7 Occupation probability and Carrier Concentration.

Fermi function → $f(E) = \dfrac{1}{e^{(E-E_f)/kT} + 1}$

E_f → Fermi energy.





(1 - f(E)) is the probability of occupation of a hole.

Total number of carriers : $n = \int_{E_c}^{\infty} \rho(E) f(E) dE$ → (since f(E) → 0 quickly)

$$\Rightarrow n = \int_{E_c}^{\infty} \frac{1}{2\pi^2} \left(\frac{2m_c}{\hbar^2}\right)^{3/2} (E - E_c)^{1/2} \cdot \frac{1}{e^{(E-E_f)/kT} + 1} \, dE.$$

$$\Rightarrow n = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}\int_{E_c}^{\infty}(E-E_c)^{1/2}\cdot\frac{1}{e^{(E-E_f)/kT}+1}\,dE.$$

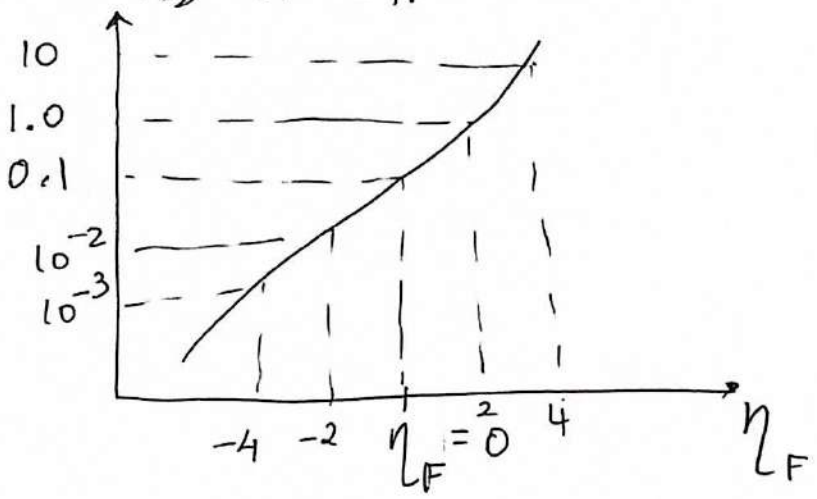
Let $\eta = (E-E_c)/kT$ & $\eta_F = \dfrac{E_c - E_f}{kT}$

$$\Rightarrow n = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(kT)^{3/2}\underbrace{\int_0^{\infty}\frac{\eta^{1/2}\,d\eta}{\left[e^{(\eta-\eta_F)}+1\right]}}_{F_{1/2}(\eta_F)}$$

$F_{1/2}(\eta_F) \longrightarrow$ Fermi Half Integral.

$$\Rightarrow \boxed{n = \left(\frac{1}{2\pi^2}\right)\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(kT)^{3/2}\,F_{1/2}(\eta_F)}$$

$F_{1/2}(\eta_F) \rightarrow$ (approx numbers)



Boltzmann approx.

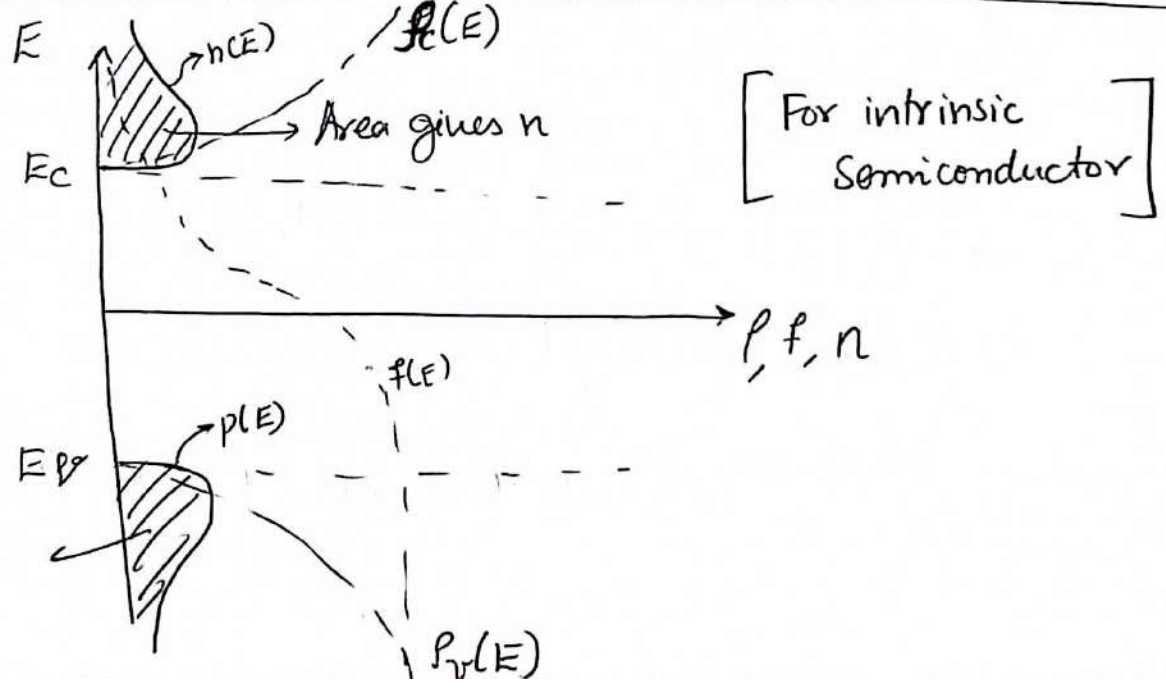
$$f(E) = \frac{1}{e^{(E-E_f)/kT}+1} \approx e^{-(E-E_f)/kT} \quad \text{when } E-E_f \gg kT.$$

$$\Rightarrow n = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-(E-E_f)/kT}\, dE.$$

$$\Rightarrow \boxed{n = 2\left(\frac{m_c kT}{2\pi\hbar^2}\right)^{3/2} e^{(E_f-E_c)/kT}} \rightarrow \text{Conduction band.}$$

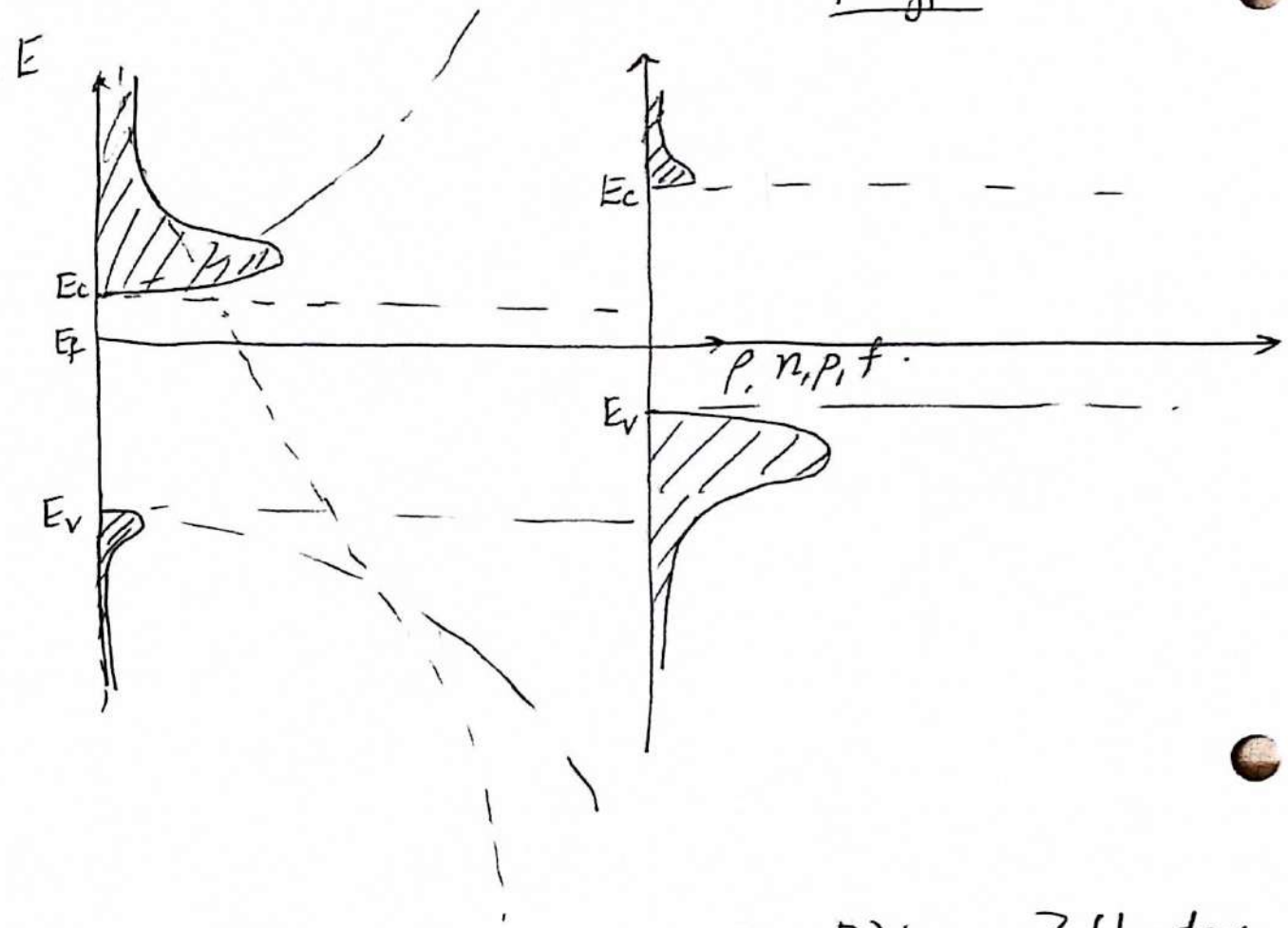
$$\boxed{p = 2\left(\frac{m_v kT}{2\pi\hbar^2}\right)^{3/2} e^{(E_v-E_f)/kT}} \rightarrow \text{Valence band.}$$

Lec 8:



N type S.C

P type



$$P = N_V e^{(E_V - E_f)/kT} \qquad n = N_C e^{(E_f - E_c)/kT}$$ } Under Boltzmann

$$np = N_C N_V e^{-E_g/kT}$$

For intrinsic semiconductor $n = p = n_i$

$$\Rightarrow n_i^2 = N_C N_V e^{-E_g/kT}$$

$$\Rightarrow \boxed{np = n_i^2}$$ → Under Boltzmann approx. (∀ semiconductor)

↳ Law of mass action.

$n_i = (N_c N_v)^{1/2} e^{-E_g/2kT}$ $\Rightarrow$ n_i depends on E_g.

Typical Values

	Si	GaP	GaAs.
N_c	2.9×10^{9}	5.4×10^{17}	4.4×10^{17}
N_v	1.1×10^{19}	1.2×10^{19}	8.2×10^{18}
n_i	1.0×10^{10}	1.2×10^{7}	2.5×10^{6}
E_g	1.1eV	1.35eV	1.42eV

(After some algebra ...)

$$E_{fi} = \frac{E_c + E_v}{2} + \frac{3}{4} kT \ln\left(\frac{m_v}{m_c}\right)$$

(E_{fi}: intrinsic)

$\rightarrow$ usually very small.

For n type, $E_f = E_c + kT \ln\left(\frac{n}{N_c}\right)$

P type $E_f = E_v - kT \ln\left(\frac{P}{N_v}\right)$

These approx. are under Boltzmann, i.e. when lightly doped.

In general, (w/o Boltzmann).

$$n = M \cdot F_{1/2}(\eta_F).$$

↳ constant

& $\eta_F = \left(\frac{E_f - E_c}{kT}\right)$

$$\Rightarrow \quad E_f = E_c + kT\eta_F = E_c + kT\, F_{1/2}^{-1}\left(\frac{n}{M}\right) //$$

Joyce-Dixon approximation of E_F (Empirical)

$$E_f = E_c + kT\left[\ln\left(\frac{n}{N}\right) + \frac{1}{\sqrt{8}}\frac{n}{N_c}\right]$$

$$E_f = E_v - kT\left[\ln\left(\frac{p}{N}\right) + \frac{1}{\sqrt{8}}\frac{p}{N_v}\right]$$

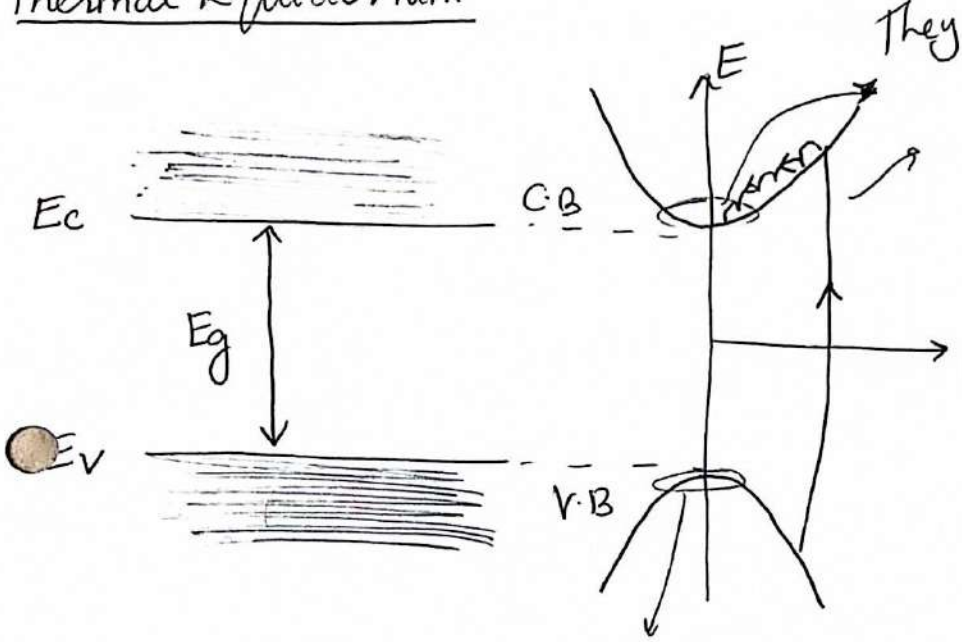
Quasi Fermi Levels

> When both CB & VB have a large number of free carriers, we need QFLevels. //

Lec 9 Quasi Fermi Levels

It refers to the 2 fermi levels which describe the probability of occupation in the conduction band and the valence band in "Quasi Equilibrium".

Thermal Equilibrium.



They accumulate here.

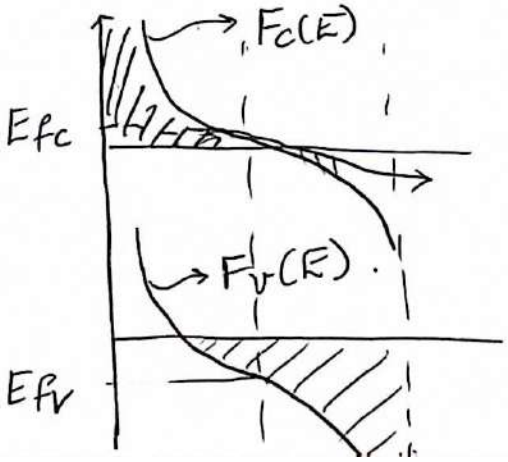
Electrons excited to higher Energy states quickly decay to lower E-states in the C.B by the process of thermalization by releasing phonons ↓ quanta of lattice vibrations.

Holes accumulate here.

> Phonon transitions are very fast $\tau \simeq 10^{-12} - 10^{-13}$ s. (Intraband lifetime)

> Interband transitions $\tau \simeq 10^{-8} - 10^{-9}$ s.

>



Two different Fermi functions $F_C(E)$ & $F_V(E)$ are used when an additional "pump" to move electrons to CB is present.

$$f_c(E) = \frac{1}{\left[e^{(E-E_{fc})/kT} + 1\right]}$$

$$f_v(E) = \frac{1}{\left[e^{(E-E_{fv})/kT} + 1\right]}$$

At thermal Equilibrium, Boltzmann approx was

$$n = N_c e^{(E_f - E_c)/kT}$$

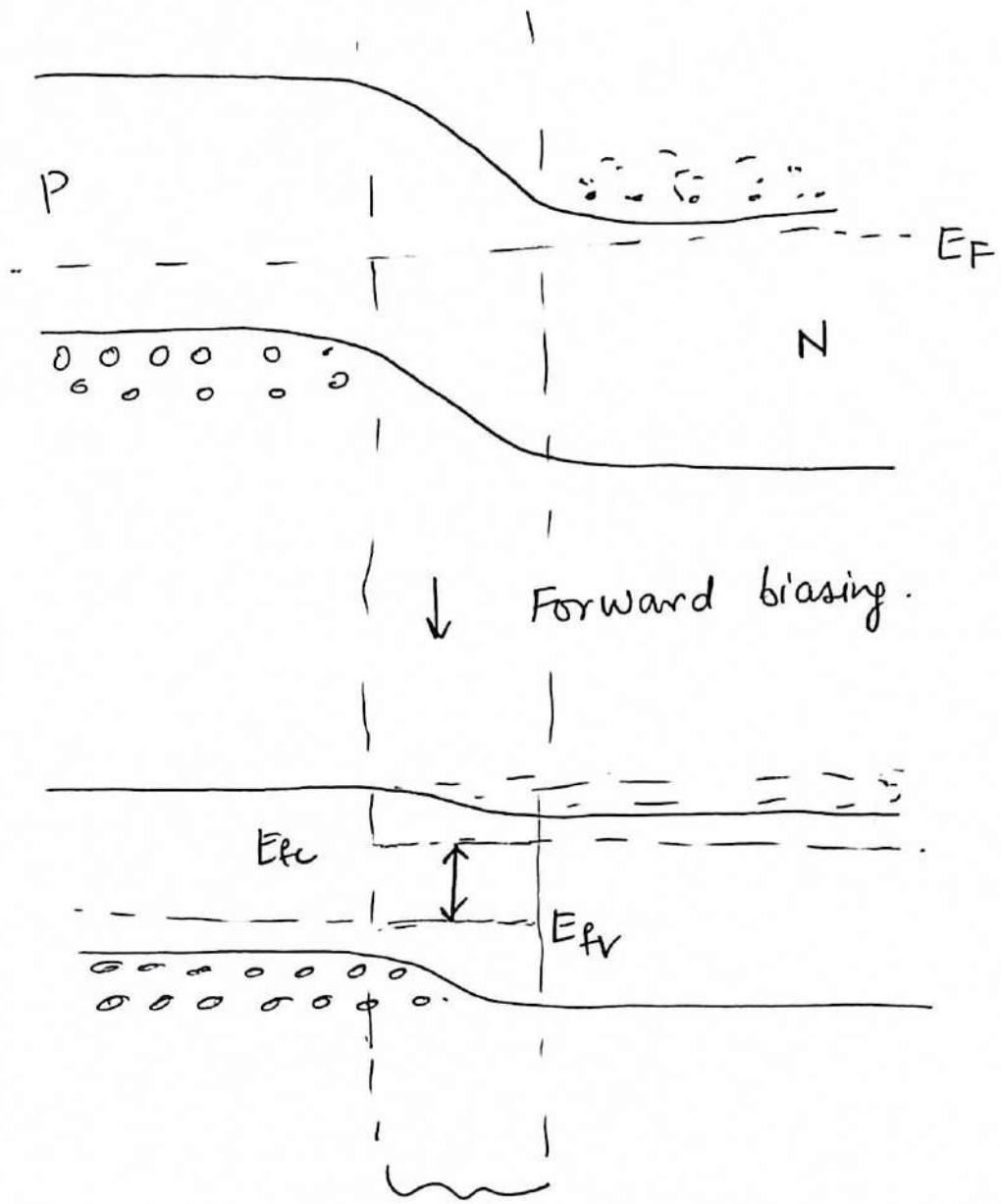
At Quasi Equilibrium,

$$n = N_c e^{(E_{fc}-E_c)/kT} \quad \& \quad p = N_v e^{(E_v - E_{fv})/kT}$$

$$\Rightarrow np = N_c N_v e^{-E_g/kT} \cdot e^{(E_{fc} - E_{fv})/kT}$$

$$\boxed{np = n_i^2 e^{(E_{fc} - E_{fv})/kT}} \rightarrow \text{(Under Boltzmann approx} \Rightarrow \text{lightly doped)}$$

PN junction (preview)



In this region now the carrier concentrations have gone up! Both electrons & holes. There are now 2 Fermi functions E_{Fv} & E_{Fc}. Here $E_{fc} - E_{fv} > 0$ & $np > n_i^2$. If reverse biased we get $E_{fv} - E_{fc} > 0$ & $np < n_i^2$.

Lec 10 Semiconductor Materials.

① Elemental Semiconductors: Si, Ge, Sn → Group IV

② Binary Semiconductors (III - V semiconductors).

or (II - VI semiconductors).

$\lambda_g = \frac{hc}{E_g}$ → Bandgap wavelength.

↳ Largest wavelength that can cause band transition.

$$\lambda_g \,(\text{in } \mu m) \cong \frac{1.24}{E_g(eV)}$$

$\lambda_g (GaN) \simeq \frac{1.24}{3.39} \simeq 0.35 \mu m$ ⇒ Important for blue light.

③ Ternary Compounds & Quaternary Compounds

(Allows continuous variation in bandgap E_g).

→ $\underbrace{Al}_{III}\,Ga\,\underbrace{As}_{V}$ → $\underbrace{Al_x Ga_{1-x} As}_{Alloy}$. → Alloy semiconductors.

→ $In\,Ga\,As\,P$ → $\underbrace{In_{1-x} Ga_x}\,\underbrace{As_y P_{1-y}}$

$In_{1-x} Ga_x As_y P_{1-y}$ → InP is the starting material since x, y are usually less than 0.5.

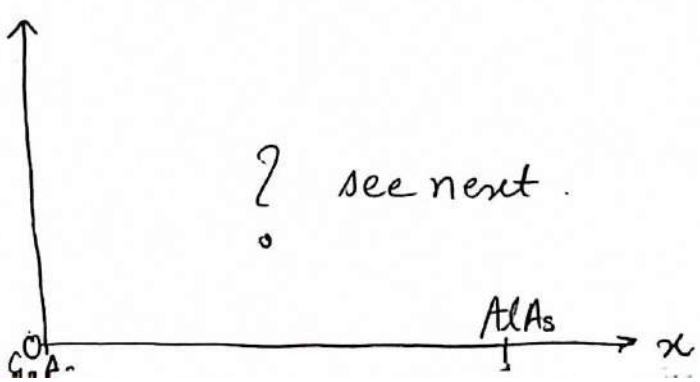
Why Ternary & Quaternary compounds?

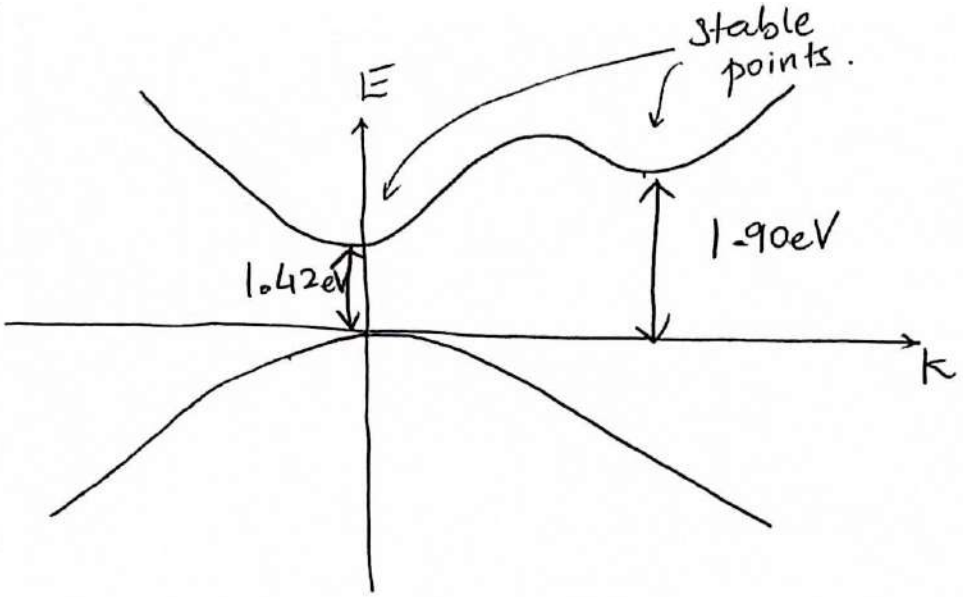
1. For bandgap modification.
2. Enables formation of lattice matched heterostructures.

Bandgap modification.

$Al_x Ga_{1-x} As / GaAs$ → means GaAs is the starting material & Al is added to it.

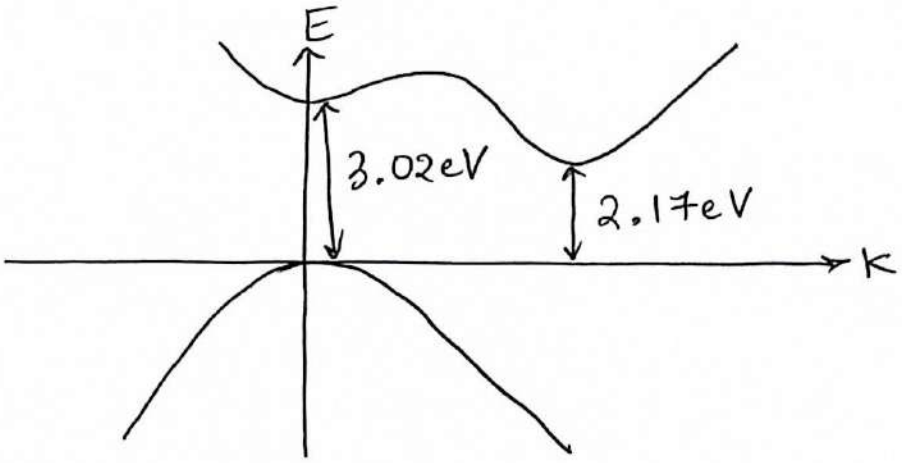
- $\lambda_g \simeq 780nm$ & is the most widely used photonic semiconductor (laser diodes).
- For optical comm. λ_g is 1550nm & InGaAsP is used. Because this is the low loss window of optical fibers.





GaAs

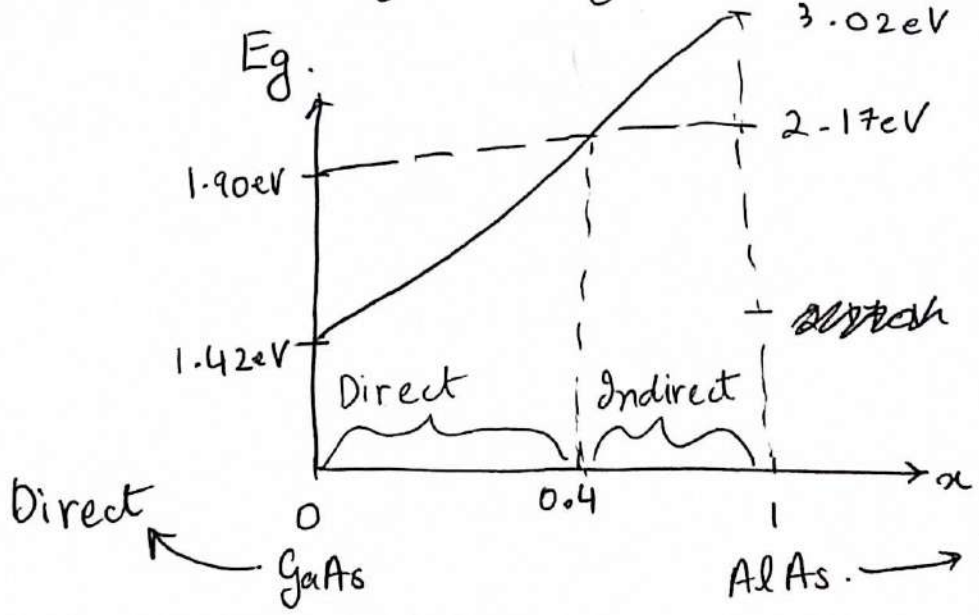
This is a Direct Bandgap material since the global min is at $K=0$.



AlAs.

This is an indirect bandgap semiconductor.

At $K=0$ there is always a maxima in valence band but conduction band may or may not have a local minima.



Lec 11 Semiconductor Heterostructures - & - Lattice Matched Layers.

Doping vs. Alloy

Doping vs Alloy: > Substitutional element is from the adjacent group whereas alloys are from the same group.

> Doping is to change the conductivity & alloying is for bandgap modification.

> Alloys are much higher in concentration in terms of the substitutional elements concentration.

Doping 10^{12}-10^{19}/cc & Alloys 10^{22}/cc.

> **Fabrication of Devices** → Optoelectronics → much larger.
→ Electronics

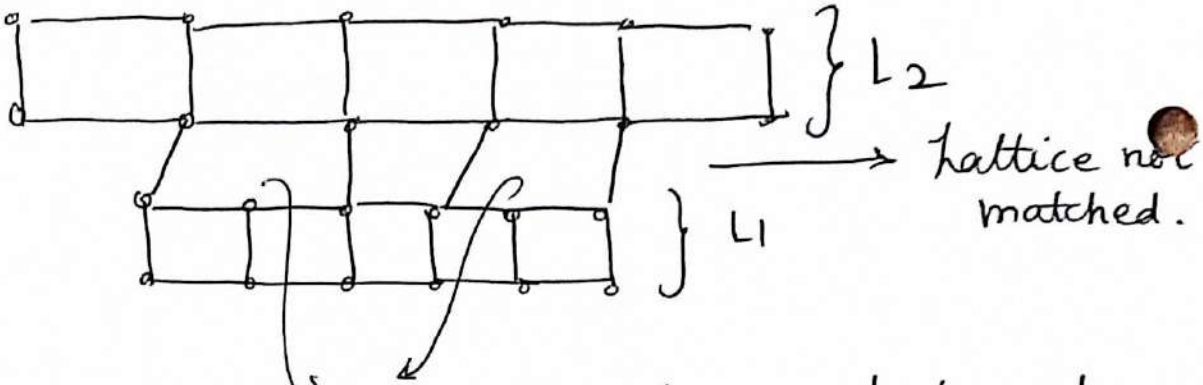
> Electronics uses diffusion (P, n, p^+, n^+ ...) & epitaxy
↳ deposition of SiO_2 & other layers

> Photonics mostly uses epitaxy
- LPE Liquid phase epitaxy
- VPE Vapour phase epitaxy or CVD - chemical vapor dep.
- MBE Molecular beam epitaxy.

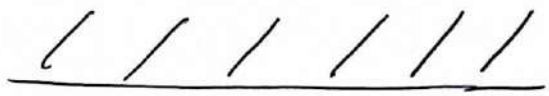
> Hetero structure: Device using material layers of different bandgaps.

p^+ GaAs		
p GaAs	→ Hetero junction	} Double Hetero Structures.
n AlGaAs	→ Hetero junction	
n^+ GaAs	→ Homo junction	
n GaAs		

> lattice matching is required for the Hetero junction to be free of defects. (i.e. $a_{L1} = a_{L2}$).
↳ (very bad!! for optoelectronics)

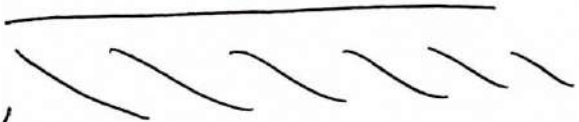


Dangling bonds → electrons here have different energy → form trap states.



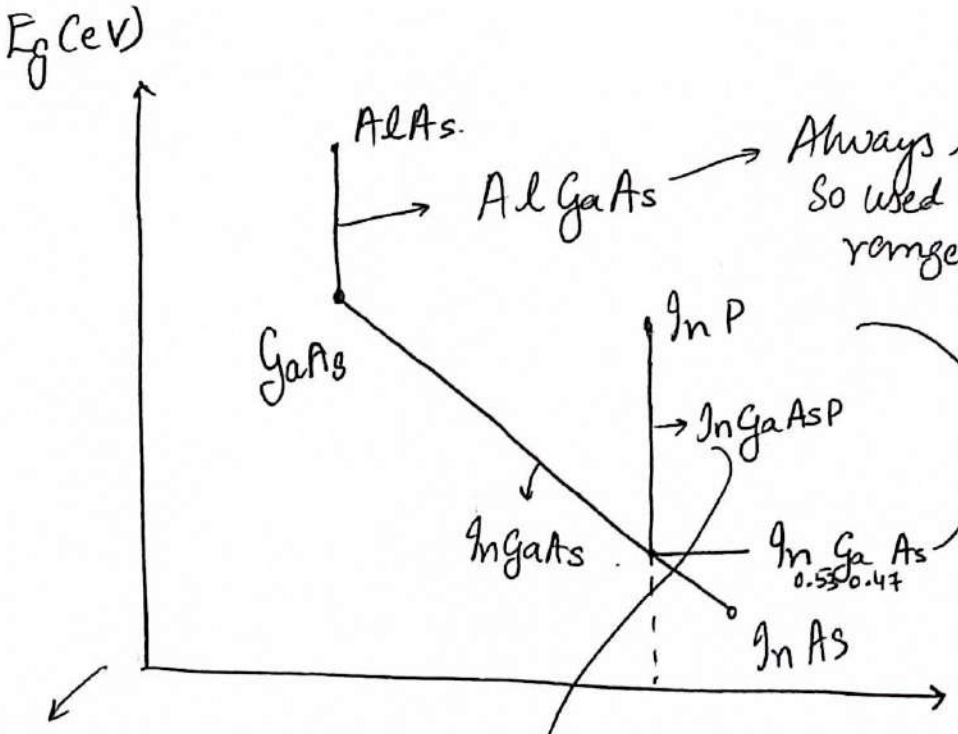
→ trap states.

→ trap states



Therefore, trap states can be formed even with 2 pure materials. They increase nonradiative transitions.

These transitions happen using phonon emission/absorption.



Always lattice matched so used for lasers over range of frequencies.

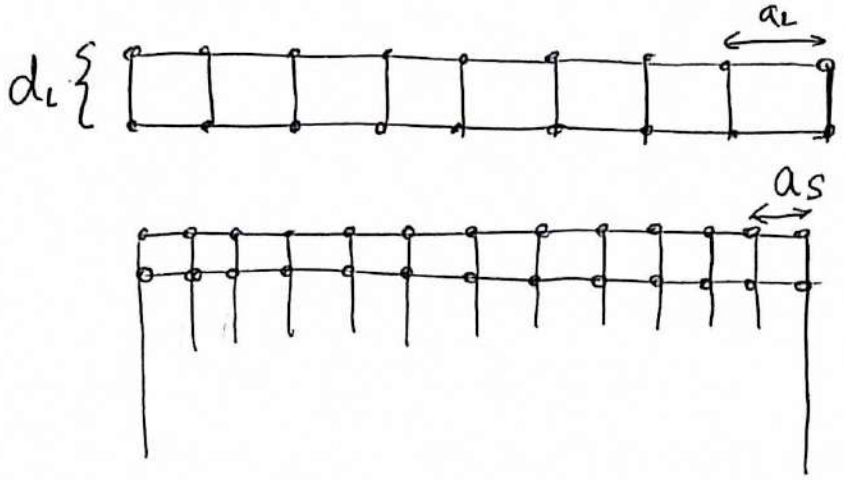
lattice matched & used as high speed photo detectors for optical comm.

Vertical lines are lattice matched.

This vertical line defines all optical comm. photodetectors from 1.3-1.55μ

Lec12 Strained layer Epitaxy and Quantum Well Structure

> Strained layer epitaxy.



→ These atoms are "squeezed" or strained in ↔ axis to match with a_L. They also experience a tensile strain in ↕ axis to compensate. This is only possible for thin layers.

If $d_L < d_c$ → critical thickness.

$$d_c \simeq \frac{a_s}{2|\epsilon|} \quad \text{where } \epsilon = \frac{a_L - a_s}{a_L}$$

↳ mismatch parameter.

High mismatch ⇒ d_c is low.

> $d_L \sim 100\,\text{Å}$ ⇒ Quantum well structures

↳ If $d_L \leq \Lambda_{deBroglie}$ → (de Broglie wavelength)

Thermal energy of electrons $E \simeq kT \simeq 0.025eV$

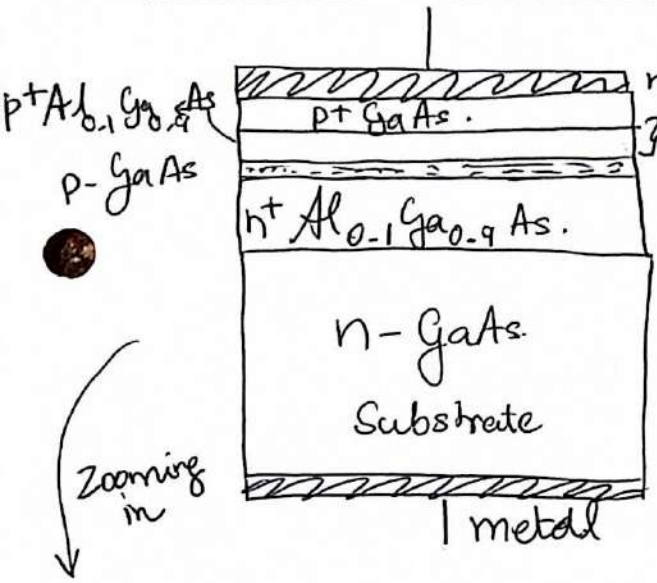
& $E = \frac{p^2}{2m^*}$ ⇒ $p = \sqrt{2m^*E}$ & $\Lambda = \frac{h}{p} = \frac{h}{\sqrt{2m^*E}}$

> For GaAs, $m^* = 0.067\, m_0$.

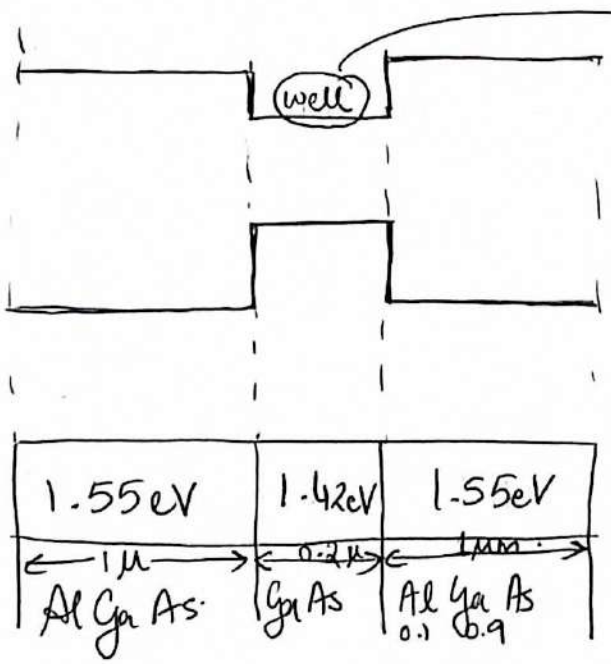
$$\Rightarrow \Lambda_{dBr} = \frac{6.6 \times 10^{-34}}{\sqrt{2 \times 0.067 \times 9.1 \times 10^{-31} \times 0.025 \times 1.602 \times 10^{-19}}}$$

$$\simeq 300\ \text{Å}.$$

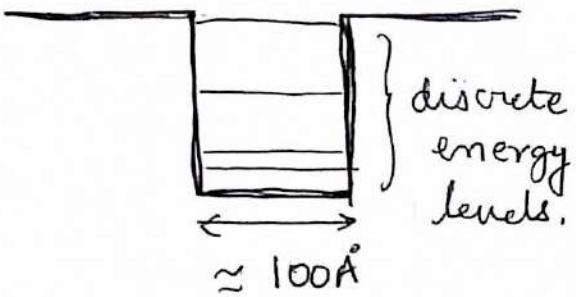
> Double Hetero Structure



If this < d_c then this becomes a quantum well structure.



→ when this becomes small, we see discrete modes as in a quantum well.

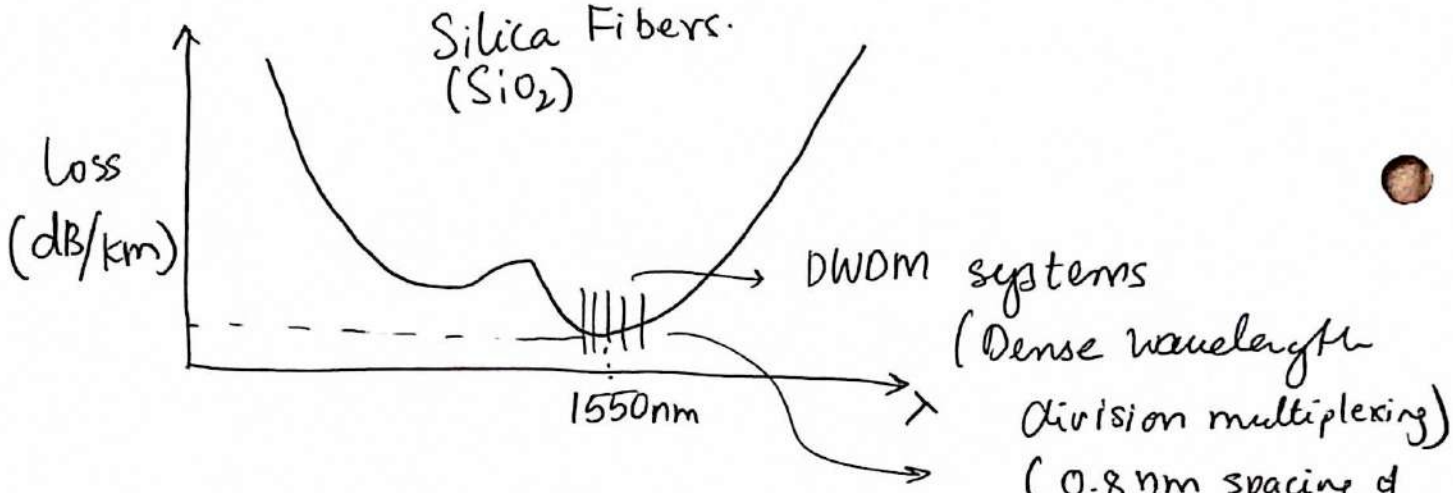


Lec 13: Bandgap Engineering.

1. Alloy semiconductors
2. Use of Quantum well structures
3. Use of Strained Layer materials (Pseudomorphic materials).

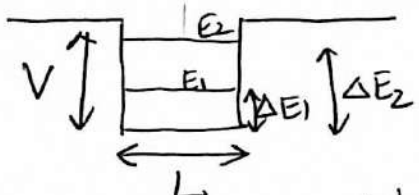
Why do we need Bandgap Engineering.?

Optical Fibers.



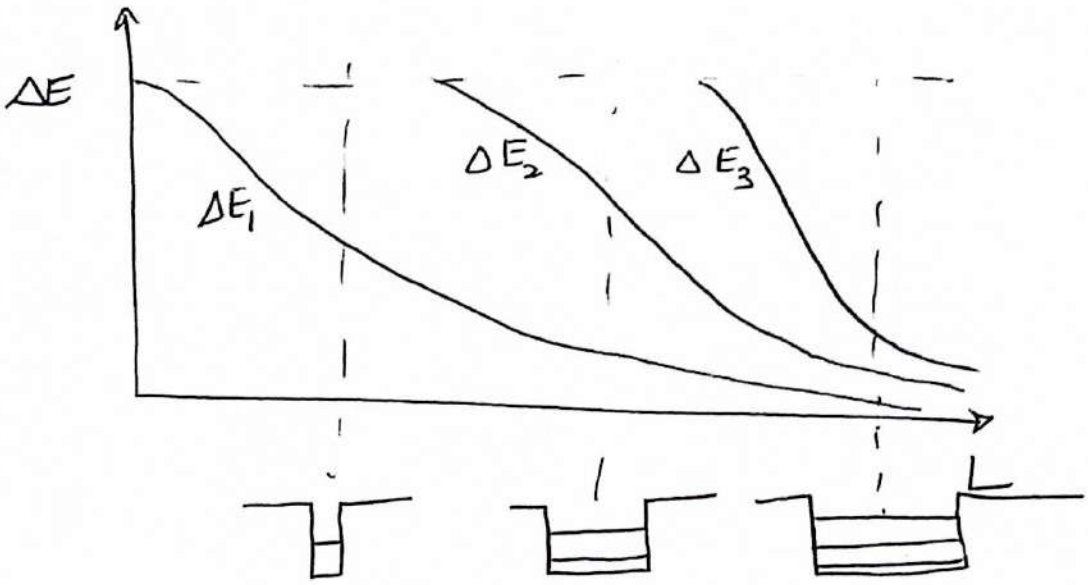
> Tailoring the bandgap gives a very fine control on the λ to realize DWDM.

Going back to Quantum Wells

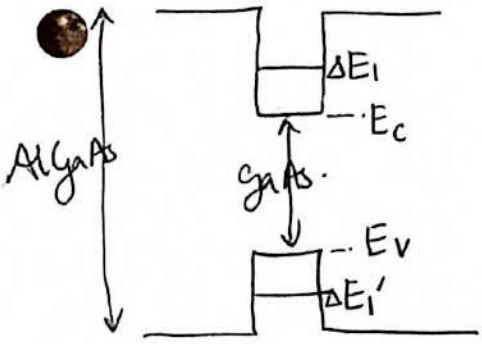


$$\tan kL = \frac{\gamma}{k} \Rightarrow \boxed{kL = \tan^{-1}\left(\frac{\gamma}{k}\right) + n\pi}$$

where $k^2 = \frac{2mE}{\hbar^2}$ & $\gamma^2 = \frac{2m}{\hbar^2}(V-E)$



What is the effective bandgap in a quantum well?



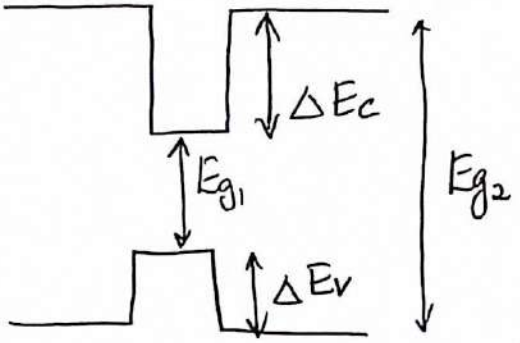
Since ΔE_1 & $\Delta E_1'$ are the first possible occupiable states, the effective bandgap is now

$$E_g^{eff} = (E_c - E_v) + \Delta E_1 + \Delta E_1'.$$

> MBE allows monolayer deposition so thickness control is very practical.

Example $Al_{0.35}Ga_{0.65}As$ & $GaAs$. $\longrightarrow$ 1.42eV.
$\hookrightarrow$ 1.860eV.

$\Rightarrow \Delta E_g = 0.436eV$. How much λ tuning this gives.



$\Delta E_c \approx 0.65\ \Delta E_g$

$\Delta E_V \simeq 0.35\ \Delta E_g$

These numbers are typical for opto-electronic materials.

$\Delta E_c \approx 0.29eV$

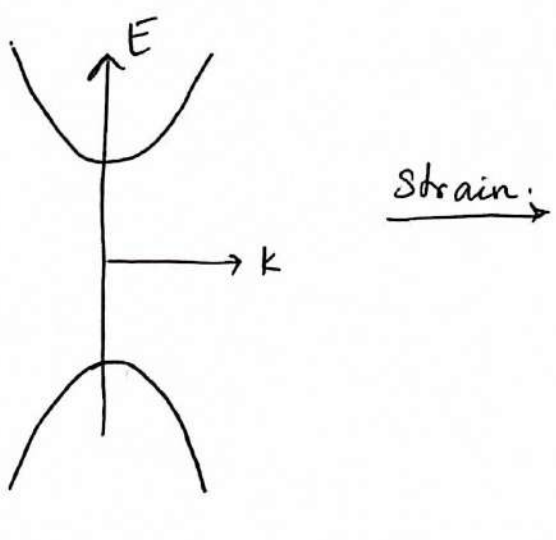
$\Delta E_V \simeq 0.15eV.$

$\Rightarrow \lambda_g \rightarrow 1.424 \rightarrow 0.88\mu m$

$\lambda_g \rightarrow 1.86 \rightarrow 0.65\mu m.$

$\Rightarrow \Delta\lambda_g = 230nm.$ & if $\delta\lambda_g$ is 0.8nm in DWDM we can have over 250 channels!

(3) Use of Strained layers

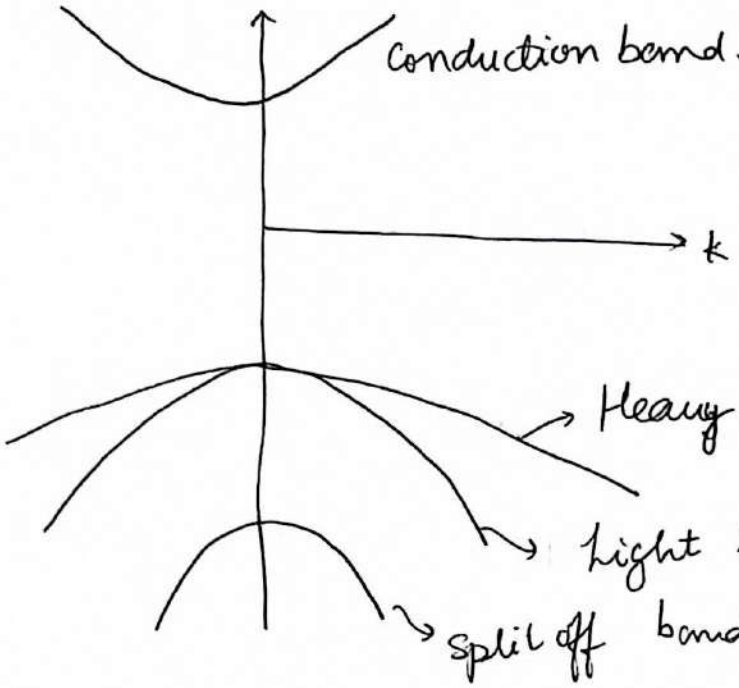


> Strain affects bandgap.

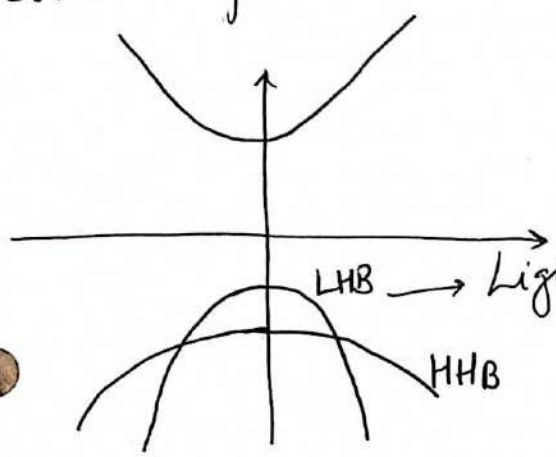
=> Bandgap can be controlled by changing the lattice mismatch.

> Why use composition changes to induce strain for bandgap engineering when composition changes can directly change the bandgap? Reality is more complex.

Valence band is more complex.

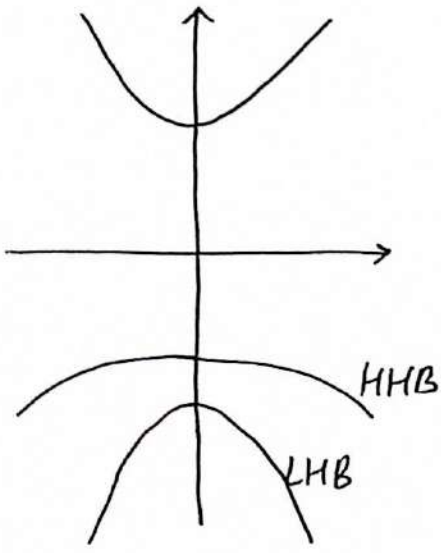


When strain is applied, Heavy hole & light hole bands split.



Compressive strain.

Light holes have more mobility. & now they are dominant.



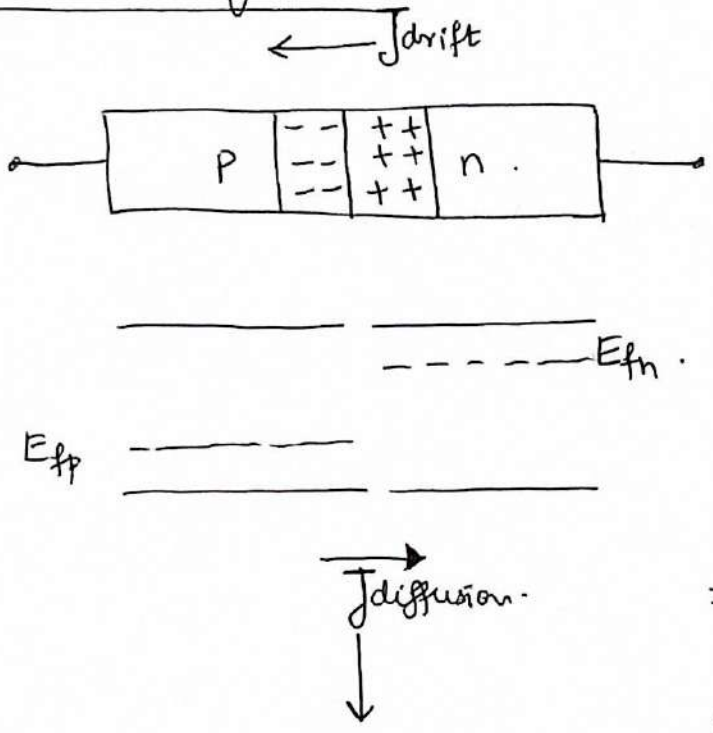
Lec 14 - Heterojunction PN junctions.

- p-n junction devices for active control.

- Fabrication → Diffusion. } of dopants. } lead to graded junctions
  → Ion implantation. }
  → Epitaxy → abrupt junctions.

- Classification → Homojunction
  → Heterojunction.
  → Schottky junction.

- Energy Band diagrams.



At equilibrium,

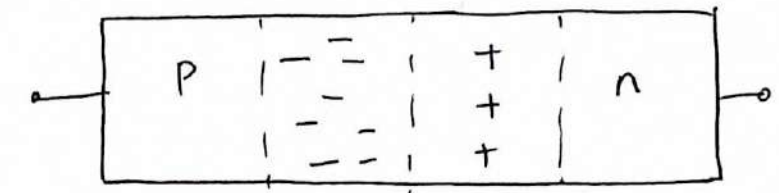
$J_{diff} + J_{drift} = 0$

⇒ Can be shown that

$\frac{dE_f}{dx} = 0$

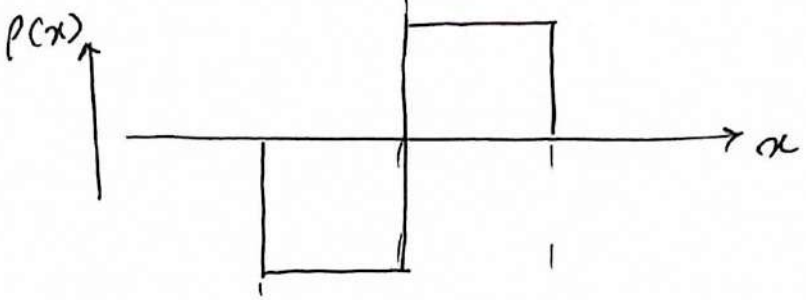
⇒ E_f is constant throughout.

⇒ Band must bend.

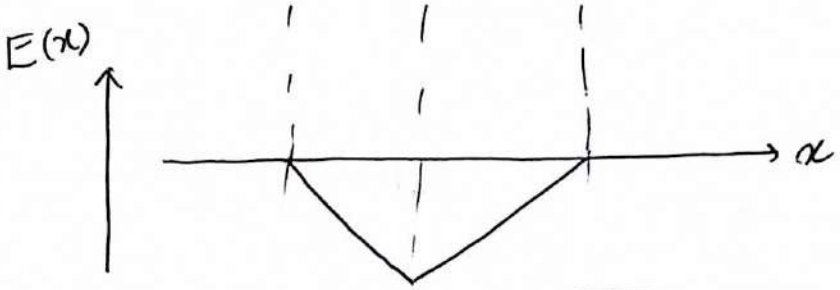


Since $\nabla \cdot E = \frac{\rho}{\epsilon}$

$\Rightarrow E = \int \frac{\rho(x)dx}{\epsilon}$

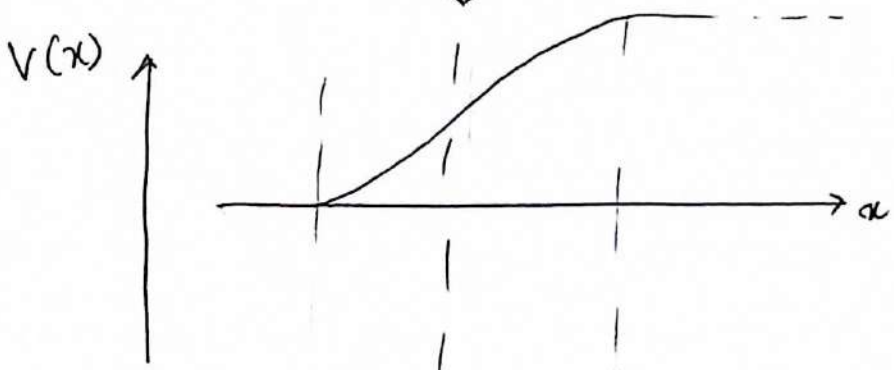


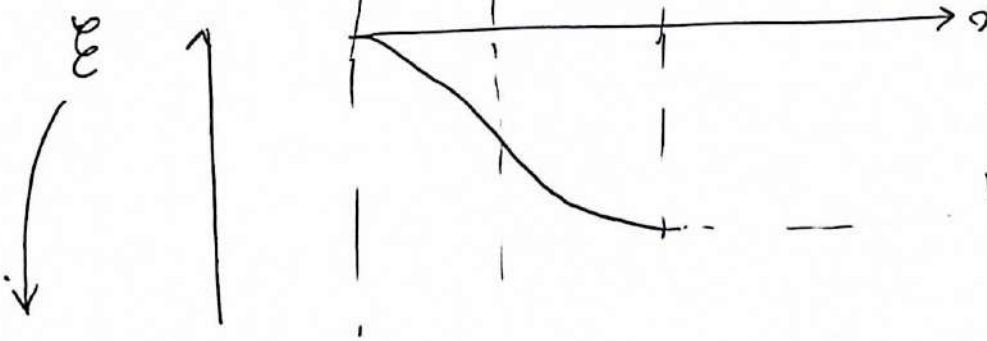
$V = -\int E(x)dx$



$\mathcal{E} = -eV$

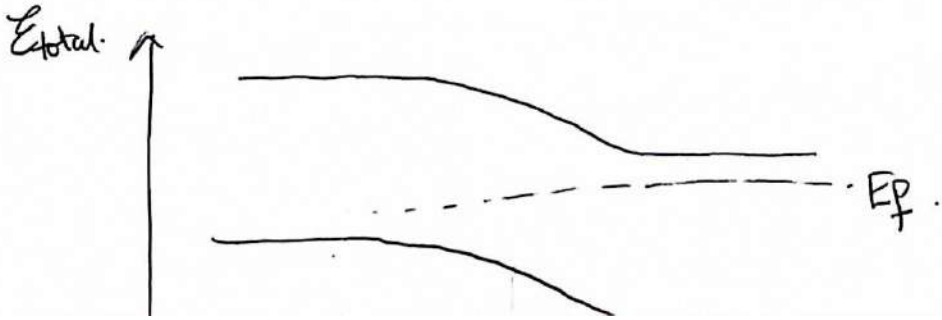
pot energy



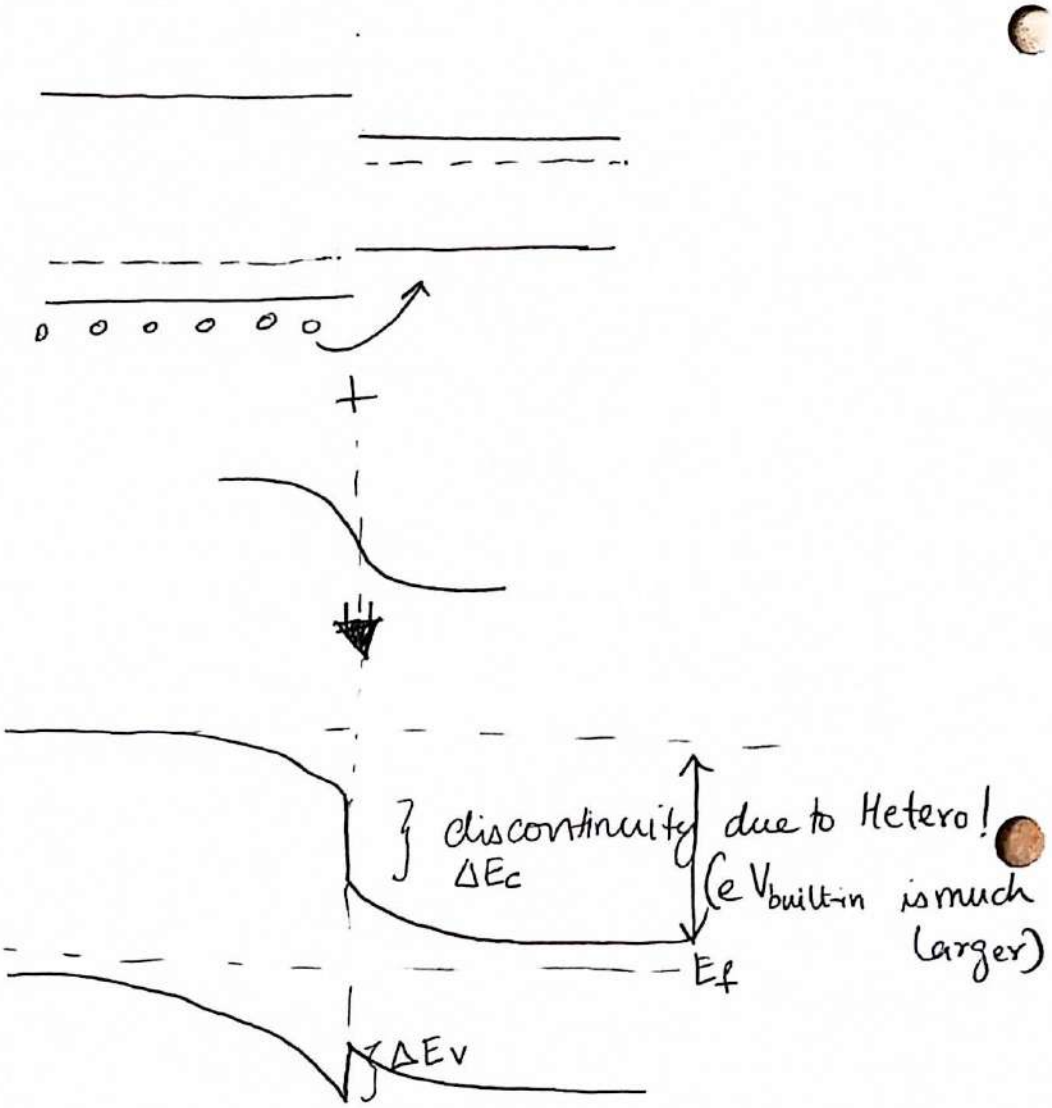


Note that the n-type material's energy drops since hole enters it $\Rightarrow V \uparrow \Rightarrow \mathcal{E} \downarrow$.

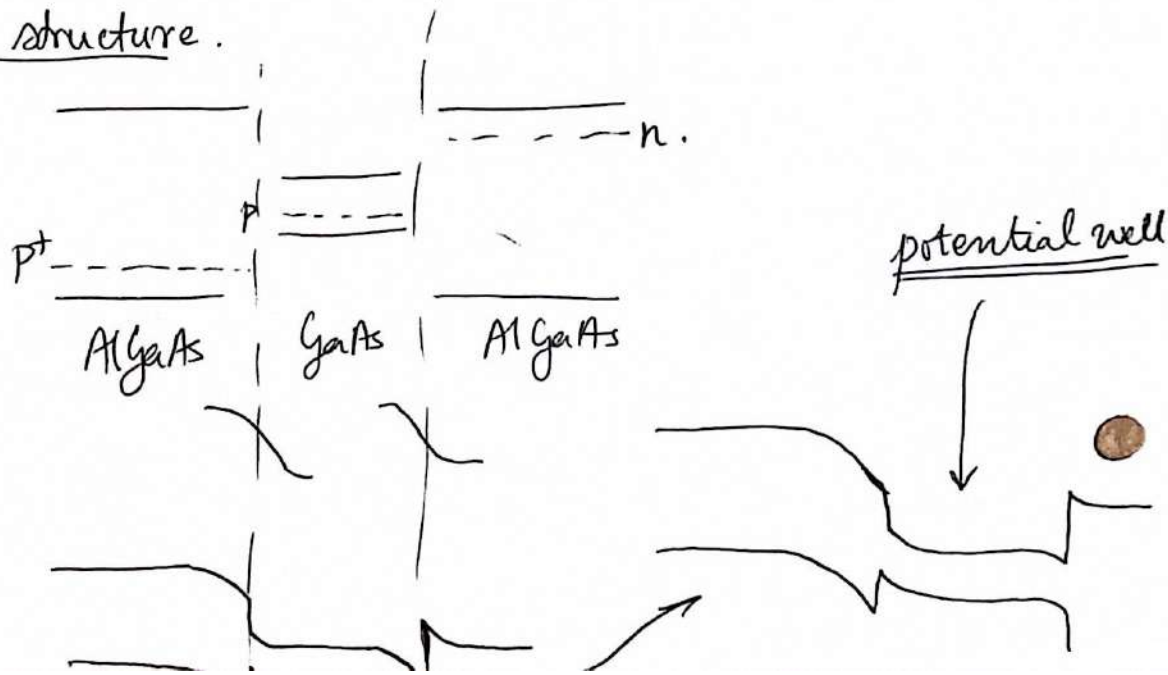
add this to band diagram.



Heterojunction p- $Al_{0.3}Ga_{0.7}As$ | n- GaAs.

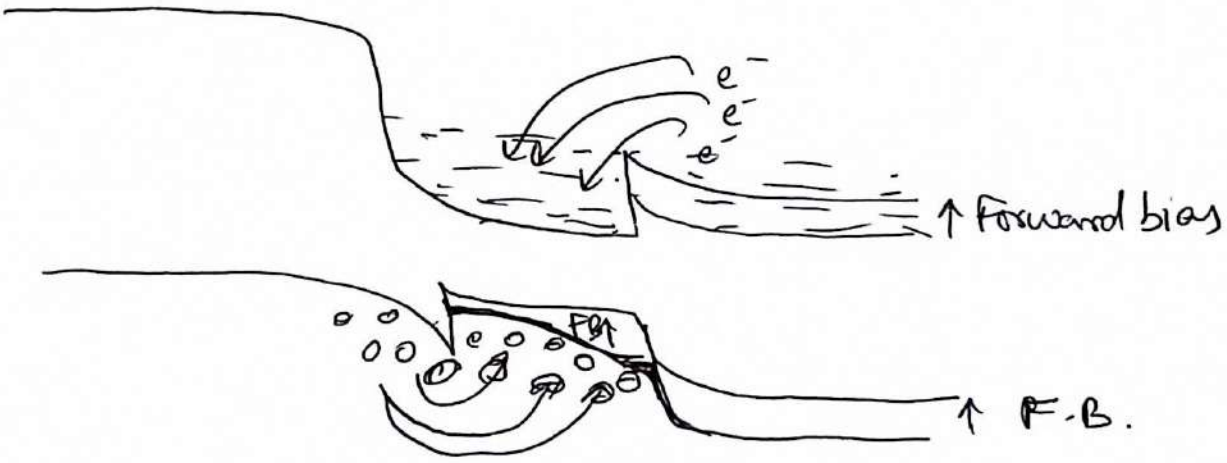


Double Hetero structure.



Why double hetero structures are important?

- When a forward bias is added, a largen number of carriers are poured into the central quantumwell. These carriers don't constitute a current since there is still a large potential barrier. We therefore endup with a large carrier concentration in a very narrow region. In PN jns. the width of the depletion region is not designed explicitly, but the q-well width can be controlled.
- **Carrier confinement** is the big advantage.

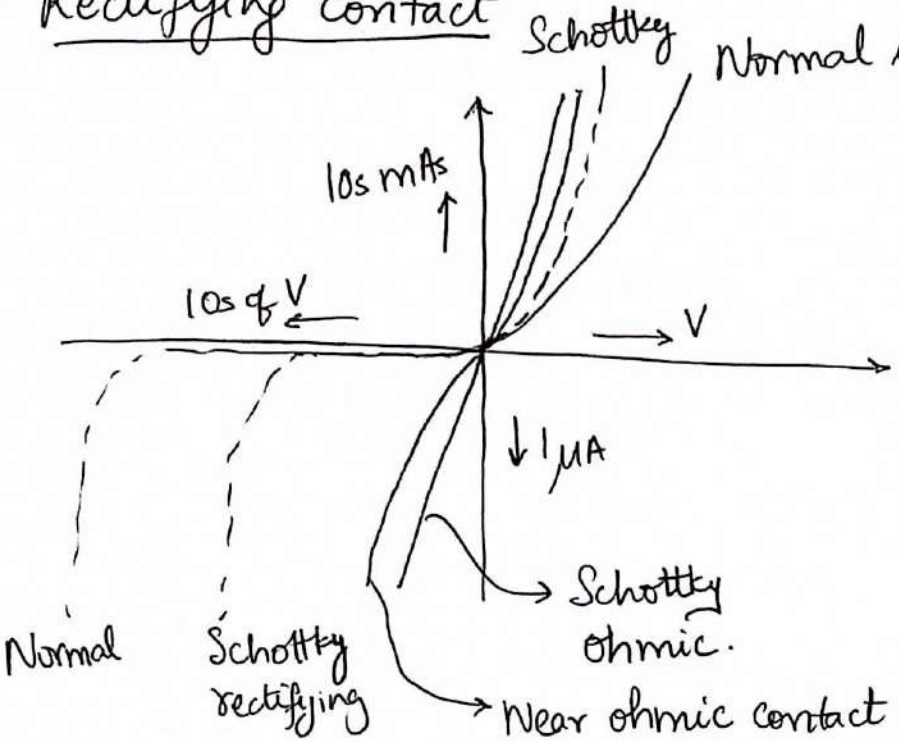


Lec 15 : Schottky Junction & Ohmic Contacts.

↳ jn. b/w metal & semiconductor.

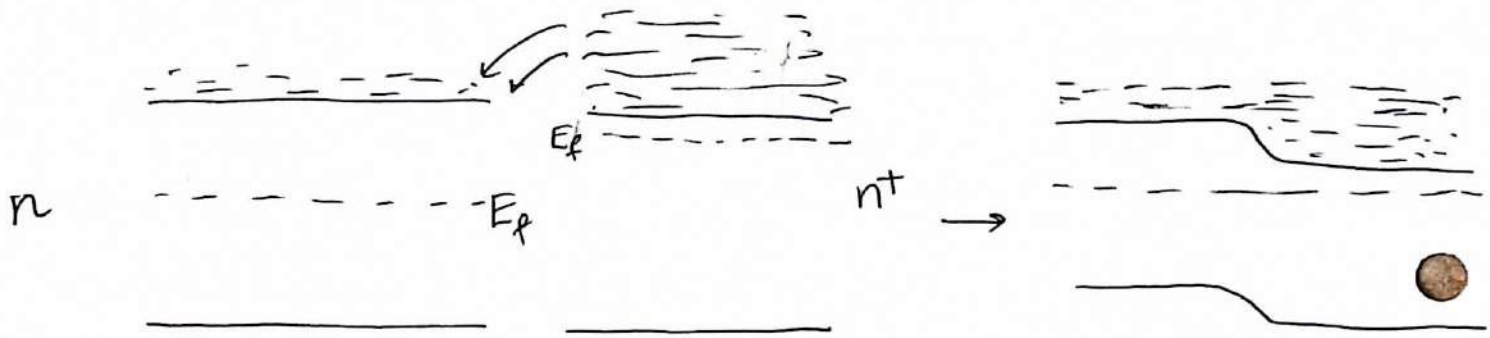
→ Could be rectifying or Ohmic.

> Rectifying contact



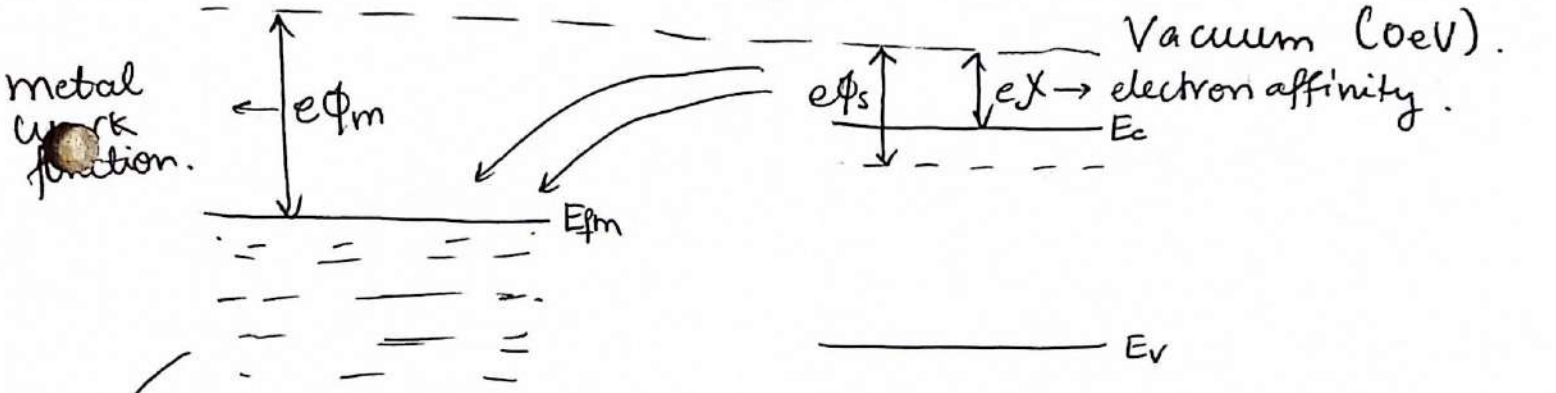
> There is always a n^+ & p^+ between metal & semiconductor.

> n- n+ Junction



> Under both forward & reverse bias conditions, the current ~~oxdg~~ flows both ways since carrier concentration is high on both sides. ~~Slight~~ Slight imbalance due to the small potential barrier. Current flows mainly by one type of carrier.

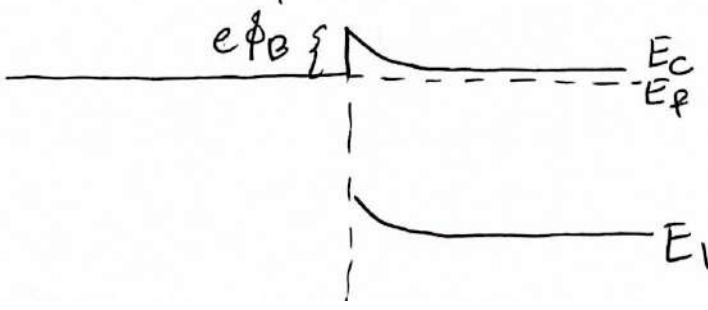
> Schottky Junction. [Metals have overlapping bands or half filled bands, ⇒ many vacant states that are easily accessible]



Typical values: ~4.4eV for Al/Silver. Ag
~5eV for Au
~5.7eV for Pt.

$e\chi$	~4.0eV GaAs
	~4.0eV Si
	~4.3eV InP
	~4.1eV Ge.
	~4.9eV InAs

Schottky barrier.



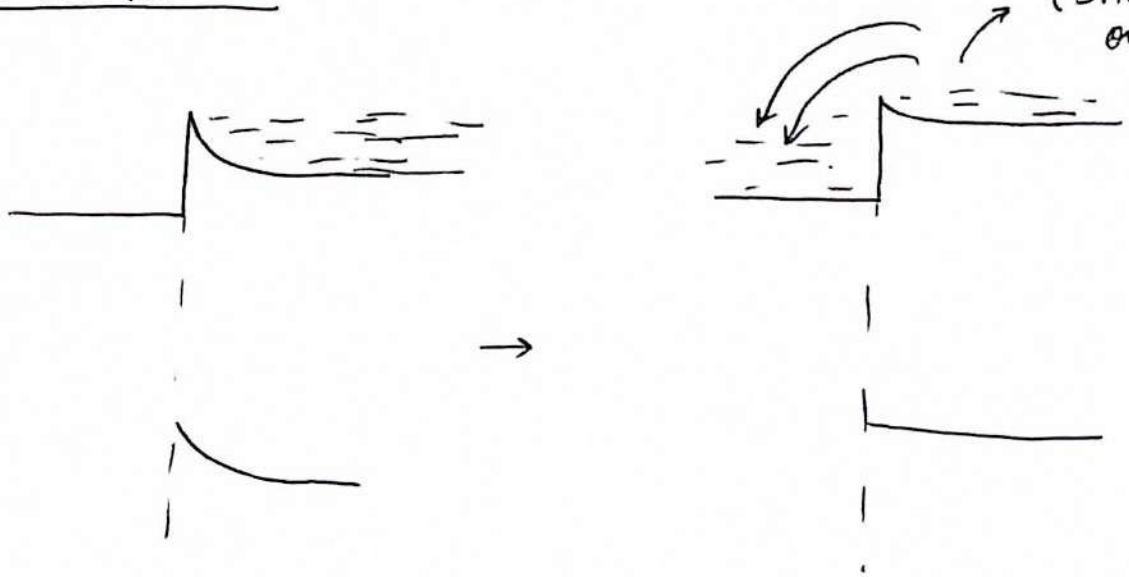
$e\phi_B = e(\phi_m - \chi)$

~0.6-0.8eV for n Si

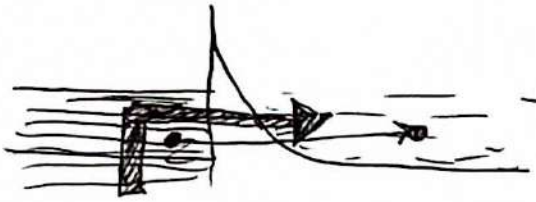
~0.7-0.9eV for n GaAs

Forward bias

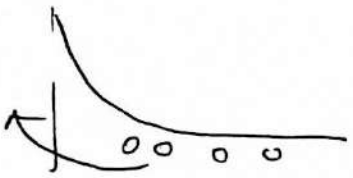
Thermionic emission.
(since electrons jump over the barrier).



Reverse bias.



(Also electron tunneling takes place i.e. evanescent coupling).



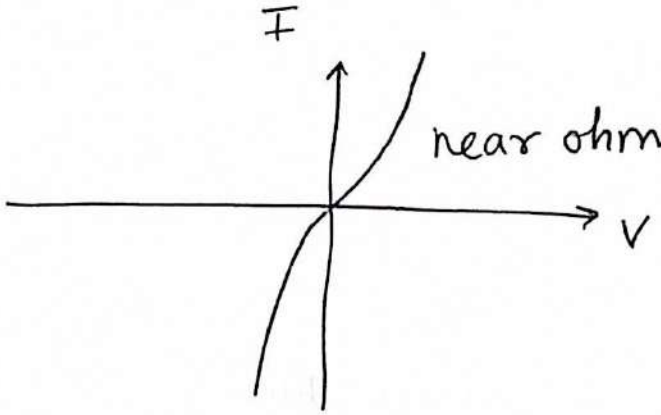
(Hole current is increased)

> To increase tunneling current, we need to dope the s-c heavily. This is the reason for always using n^+ or p^+ contact with metal junctions!!

> High doping => hight $P(x)$ & after 2 integrals $\mathcal{E}$ is very narrow.

> Forward current: Thermionic emission + Tunneling. (dominant).

Reverse bias : Hole current + Tunneling. (dominant)

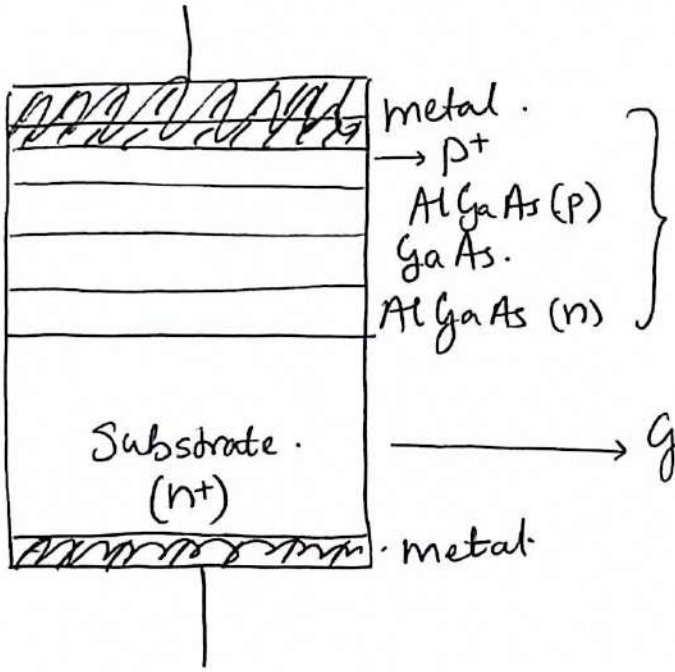


> how doping ⇒ Rectifying contact

High doping ⇒ Ohmic contact.

Lec16 Fabrication of Heterojunction Devices.

1. S.M. Sze
2. J. Singh.
3. P. Bhattacharya



Grown by epitaxy → Liquid phase Ep
→ Vapour phase Epi (CVD)
→ Molecular beam Ep

Substrate (n+) → Grown by Bulk crystal growth.

- Bridgman method. (Furnace).
- Czochralski method.

Czochralski method.

> Seed crystal is inside a melt & slowly pulled up.

Bridgman method.

> polycrystalline boat is pulled through a temp gradient to create the ingot.

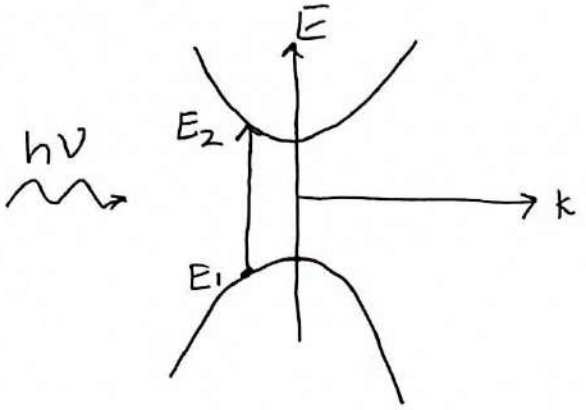
> Watch video for LPE, VPE(or CVD) & MBE.

Lec 17 Interaction of Photons with Electrons & Holes in a Semiconductor.

> Matter interacts with radiation via emission & absorption.

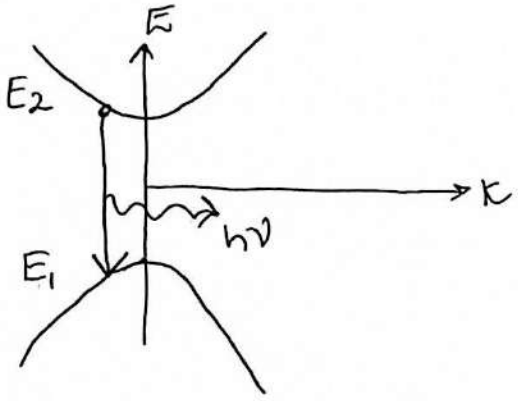
Spontaneous Stimulated.

1) Absorption. (Photodetectors)

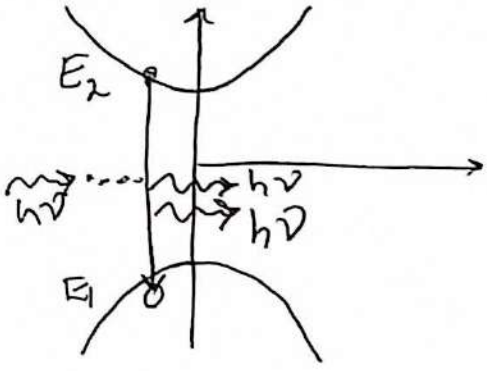


$E_2 - E_1 = h\nu$

2) Spontaneous emission (LEDs)

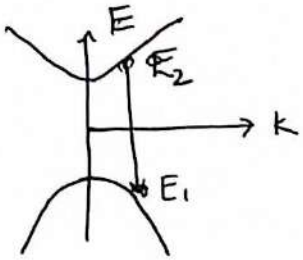


3) Stimulated emission. (Lasers)



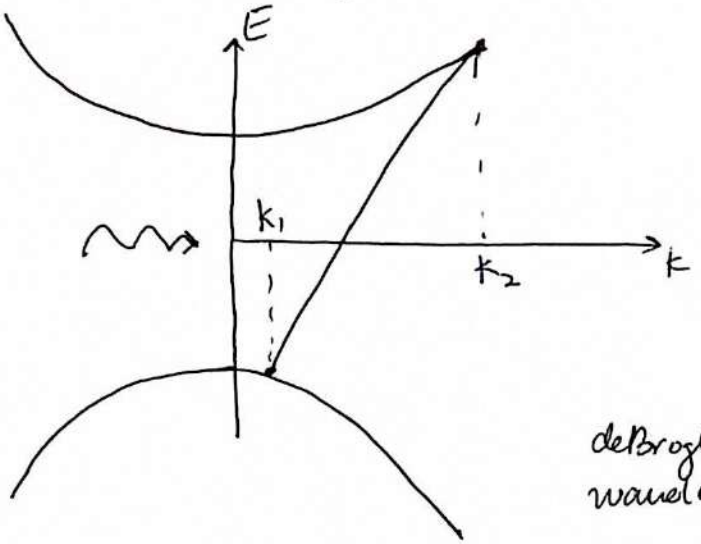
Basic laws

① Conservation of Energy.



$h\nu = E_2 - E_1$

2. Conservation of momentum



$$\hbar k_1 + \hbar k_{photon} = \hbar k_2$$

$$\Rightarrow k_1 + k_{photon} = k_2$$

$k_1 \rightarrow \frac{2\pi}{\lambda_1}$ ← deBroglie wavelength.

$k_{photon} \rightarrow \frac{2\pi}{\lambda}$

$k_2 \rightarrow \frac{2\pi}{\lambda_2}$

assuming $\lambda \simeq 1\mu m = 10^4 \text{Å}$

Edge of first Brillouin zone : $\frac{\pi}{a} = k$

$$\Rightarrow \frac{\pi}{L} < k_e < \frac{\pi}{a}$$

$\frac{\pi}{L}$ ← dim of S.C ↑ 1mm

$\frac{\pi}{a}$ ↑ 5Å

Assuming (Typically) $\lambda_e \simeq 10 - 100 \text{Å}$

$$\Rightarrow \lambda_e \ll \lambda_{photon} \Rightarrow k_e \gg k_{photon}.$$

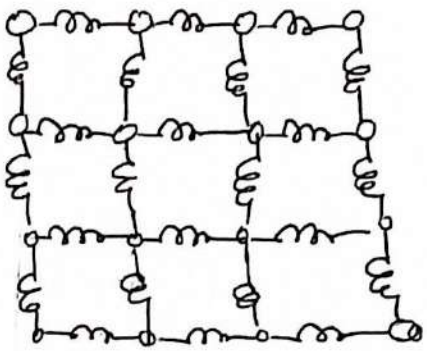
$$\Rightarrow \boxed{k_1 \simeq k_2} \Rightarrow \text{transitions are vertical.}$$

What happens during Non-radiative transitions? (Later)

- Phonon-assisted radiative transitions can occur where the phonon can carry away the large Δk in oblique transitions.

Phonon : Quanta of lattice vibrations

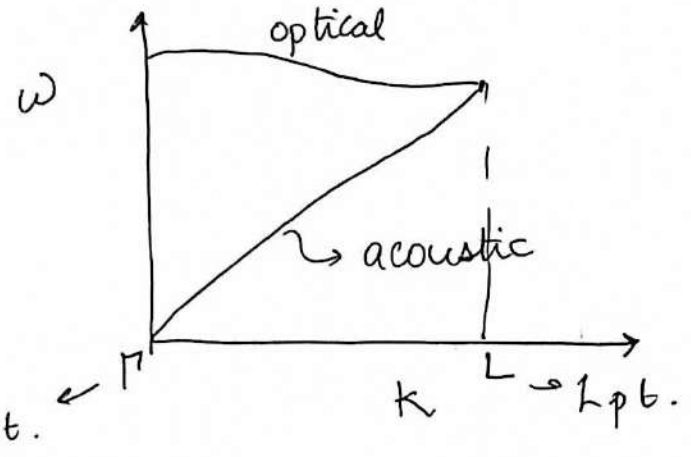
- → Acoustic phonons
- → Optical phonons.



(Optical phonons) → adjacent atoms are displaced in opposite direction. → Always high frequency.

→ Can be from low to high.

(acoustic phonons) → adjacent atoms move together.



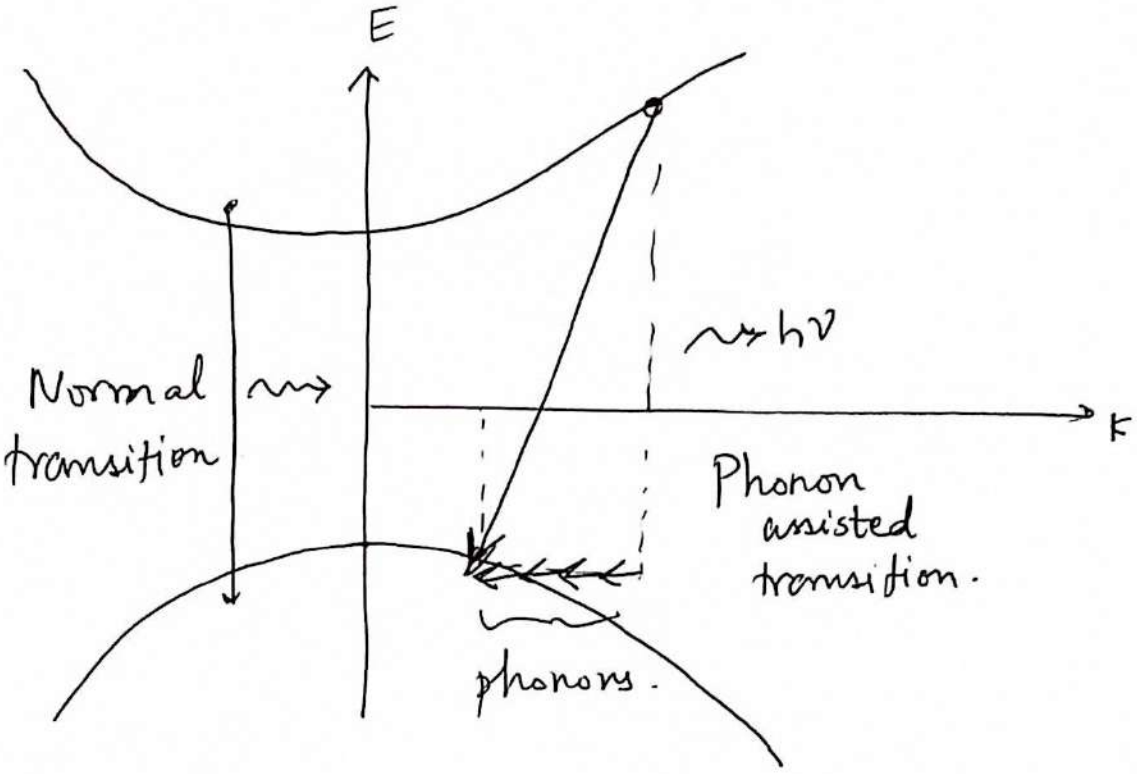
typical energies in s-c.

0.01 – 0.1 eV

- Clearly $K_{phonons}$ can be on the of electrons.
- But their energies are much lower.

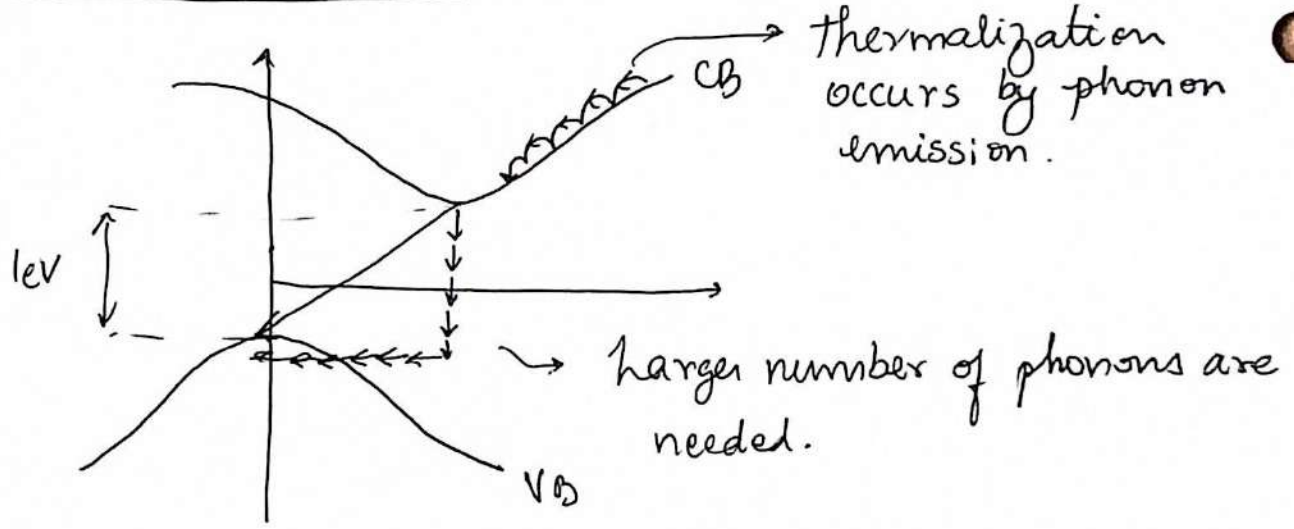
Therefore a combination of photon + phonon can allow for oblique transitions.

"Phonon assisted radiative transitions" → probability is lower du



Non-radiative Transitions.

Recall. (Silicon is indirect B-G S-C)



- More common in indirect B-G S.C (like Si) since Δk needed is also large. Also, in this case they are quite frequent since photons are not participating. This is the main recomb. phenomena during forward bias, & can generate a lot of heat. IDBGSC are still good for photon absorption devices since upward transitions have many

Lec 18 : Optical Joint Density of States.

> What is the number of emissions per unit volume?

Recall,

$$n = \int n(E)\,dE = \int \rho_c(E)\, f(E)\, dE$$

- n: carrier concentration.
- $n(E)$: carrier density of e in CB
- $\rho_c(E)$: density of states
- $f(E)$: probability of occupation.

& $$P = \int p(E)\,dE = \int \rho_v(E)\,[1 - f(E)]\,dE.$$

Here the density of states $\rho_c(E)$ & $\rho_v(E)$ are independant. However, during photon interactions (emission or absorption), the probability of photon ~~or~~ interaction depends on both ρ_c & ρ_v. Therefore, we need a joint density of states.

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} \rightarrow \text{parabolic approx}$$

$$E_1 = E_v - \frac{\hbar^2 k^2}{2m_v}$$

$$\Rightarrow E_2 - E_1 = E_g + \frac{\hbar^2 k^2}{2}\underbrace{\left(\frac{1}{m_c} + \frac{1}{m_v}\right)}_{\frac{1}{\mu} \rightarrow \text{reduced mass.}}$$

$$\Rightarrow \quad h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

$$\Rightarrow \quad k^2 = \frac{2m_r}{\hbar^2}\left(h\nu - E_g\right).$$

Recall

$$\Rightarrow \quad E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} = E_c + \frac{\hbar^2}{2m_c} \cdot \frac{2m_r}{\hbar^2}(h\nu - E_g)$$

$$\Rightarrow \quad E_2 = E_c + \frac{m_r}{m_c}\left(h\nu - E_g\right).$$

Since E_2 is directly proportion to ν (all other terms are constants),

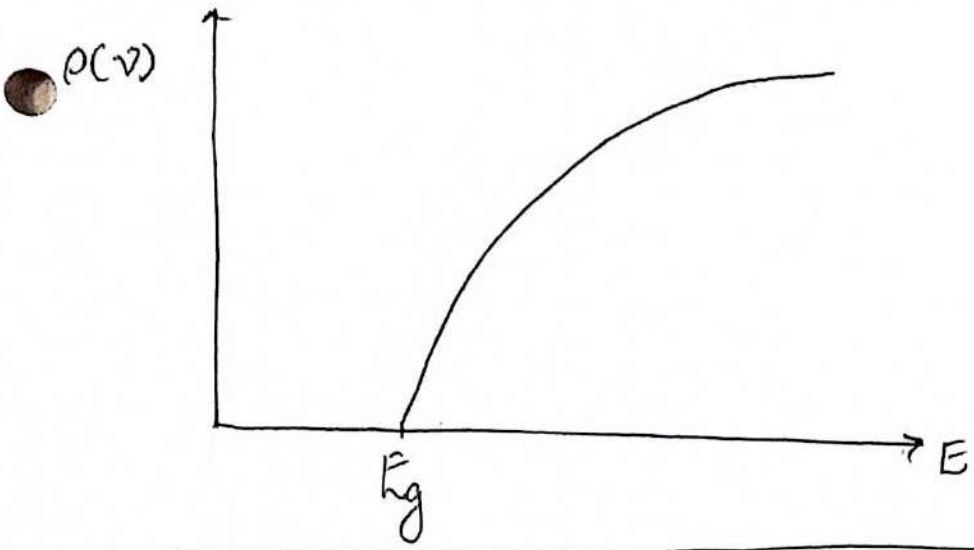
we have $\rho_c(E_2)\,dE_2 = \underbrace{\rho(\nu)\,d\nu}$ (per unit volume)

↳ No. of states for photons of energy b/w $h\nu$ & $h(\nu+d\nu)$ to interact with.

$$\Rightarrow \quad \rho(\nu) = \rho_c(E_2)\frac{dE_2}{d\nu} = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}\underbrace{(E_2 - E_c)^{1/2}}_{\frac{m_r}{m_c}(h\nu - E_g)} \cdot \frac{h m_r}{m_c}.$$

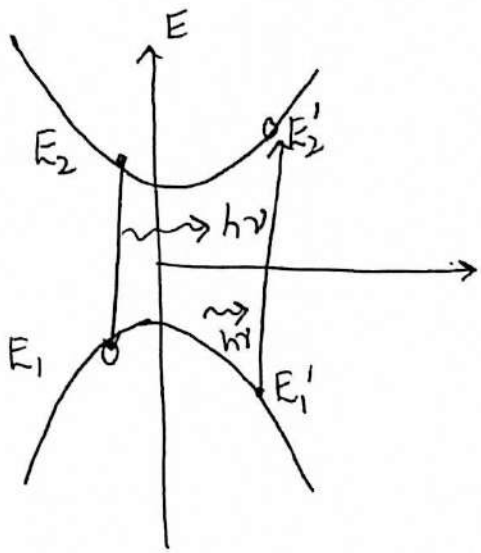
$$= \frac{1}{\pi\hbar^2}(2m_c)^{3/2}\frac{m_r}{m_c}\left(\frac{m_r}{m_c}\right)^{1/2}(h\nu - E_g)^{1/2}$$

$$\Rightarrow \boxed{\rho(\nu) = \frac{1}{\pi\hbar^2}(2m_r)^{3/2}(h\nu - E_g)^{1/2}.}$$



$$\rho(\nu) = \frac{1}{\pi\hbar^2}(2m_r)^{3/2}(h\nu - E_g)^{1/2}$$

Probabilities of Emission and Absorption.



$h\nu = E_2 - E_1$

emission $P_e = f(E_2)\cdot[1 - f(E_1)]$

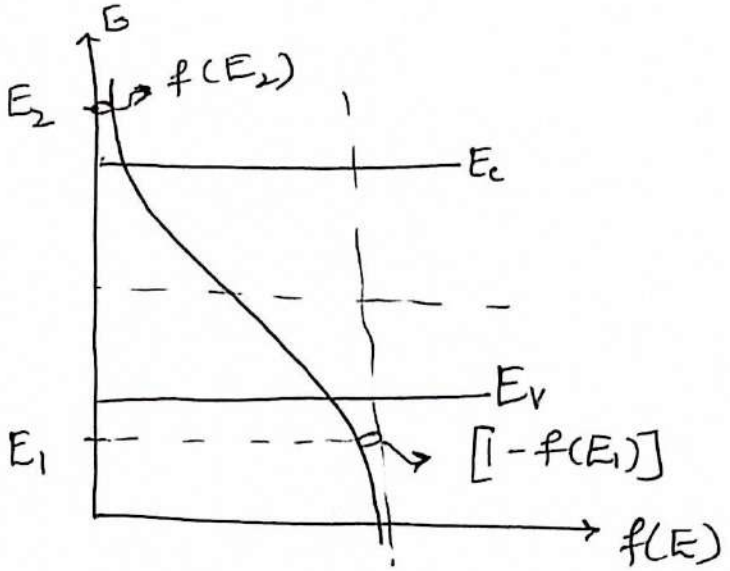
absorption $P_a = f(E_1')\,[1 - f(E_2')]$

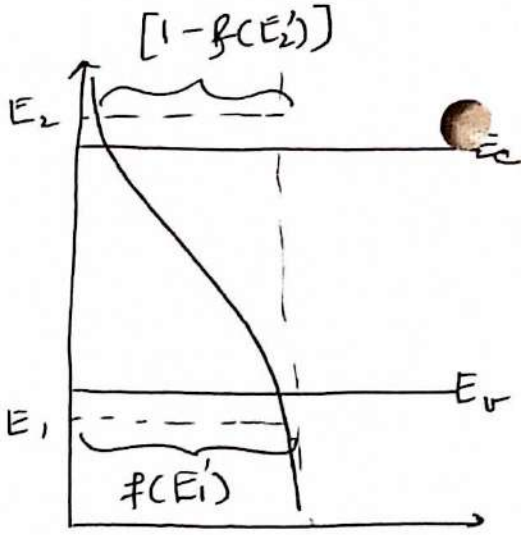
} Prob. of E_2 & A

(If $P_e > P_a \Rightarrow$ emitter)

Case 1 : Thermal Equilibrium.

In this case, one Fermi function describes the prob. of occupation of an in both VB & CB.

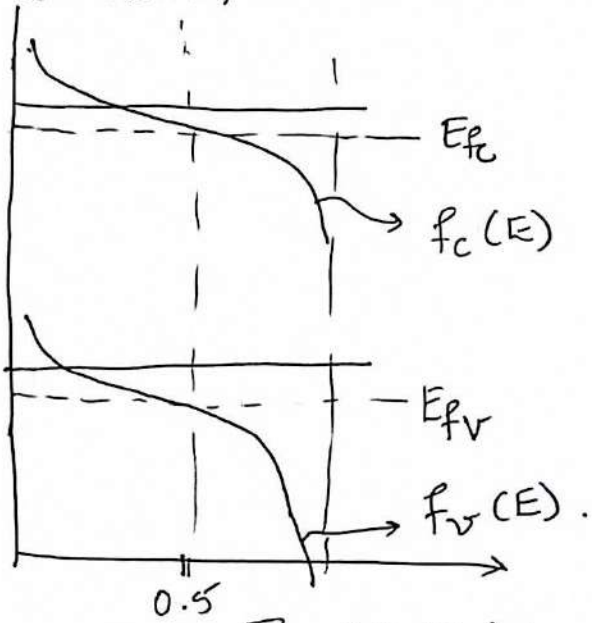




> Clearly $P_e \ll\ll P_a$. Therefore at Thermal Equilibrium it is impossible for emissions to occur.

Case 2): Quasi Equilibrium.

There are now 2 Fermi functions f_c & f_v.



$$P_e(\omega) = \frac{1}{\left[e^{(E_2-E_{fc})/kT}+1\right]} \cdot \left[\frac{e^{(E-E_{fv})/kT}}{1+e^{(E-E_{fv})/kT}}\right]$$

$$P_a(\nu) = \frac{1}{1 + e^{(E_1 - E_{fv})/kT}} \cdot \frac{e^{(E_2 - E_{fc})/kT}}{\left[1 + e^{(E_2 - E_{fc})/kT}\right]}$$

For $P_e(\nu) > P_a(\nu)$ we need, $E_1 - E_{fv} > E_2 - E_{fc}$

$$\Rightarrow \quad (E_{fc} - E_{fv}) > E_2 - E_1 = h\nu$$

$$\Rightarrow \quad \boxed{E_{fc} - E_{fv} > E_g} \quad \rightarrow \text{Requirement for Emissions \& also for Lasers.}$$

Lec 19 Rates of Emission and Absorption.

> $\rho(\nu)$, $f_e(\nu)$, $f_a(\nu)$.

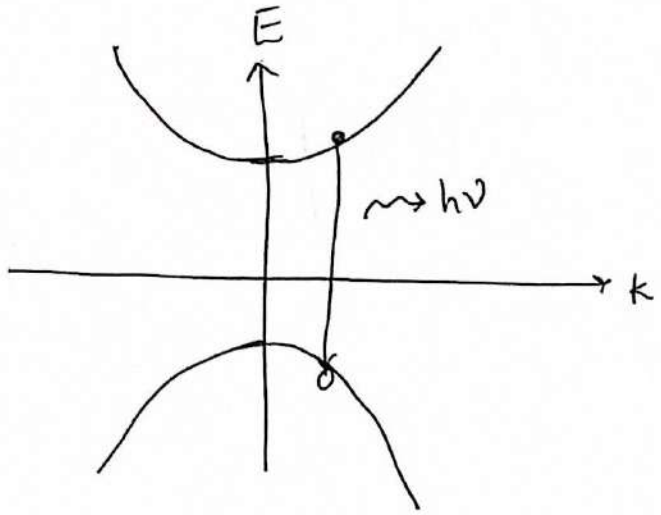
$\rho(\nu)$: optical joint density of states

$f_e(\nu)$, $f_a(\nu)$: emission/absorption probability

$\Rightarrow$ $\rho(\nu) f_e(\nu)$ $\longrightarrow$ no. of emission / unit volume / unit time

$\Rightarrow$ $r_{sp} \propto \rho(\nu) f_e(\nu)$ (r_{sp}: rate of spontaneous emission.)

$\Rightarrow$ $r_{sp} \propto A\, \rho(\nu) f_e(\nu)$ ($\frac{1}{C_r}$ = radiative recombination time.)



Total no. of spontaneous downward transition

= radiative + non-radiative transitions.

⇒ Total rate constant T

$= A + S$

$= \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$

⇒ $T = \frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$

τ → Spontaneous recombination time.

In DBGSC, $\tau_r \approx \tau_{nr}$.

⇒ 50% prob. of photon emission for each $\bar{e}$ transition.

In IDBGSC, $\tau_{nr} \ll \tau_r$

⇒ almost no radiative transitions.

Atomic system (analogy)

E_2 ——— N_2 → no. of atoms per unit vol. → excited state.

$h\nu$ → u_ν

E_1 ——— N_1 → ground state.

$r_{sp} \propto N_2$

⇒ $r_{sp} = AN_2$

If u_ν is the energy density ⇒ $r_{st} = BN_2 u_\nu$

i.e $\frac{nh\nu}{V} = u_\nu$ $r_{ab} = BN_1 u_\nu$

$g(\nu)$ → atomic lineshape function.
(strength of interaction at ν)

⇒
$$\mu_{sp}(\nu) = A N_2 g(\nu)$$
$$\mu_{st}(\nu) = B N_2 U_\nu g(\nu)$$
$$\mu_{ab}(\nu) = B N_1 U_\nu g(\nu).$$

Here A, B are the Einstein coefficients.

$A = \frac{1}{t_{sp}}$ → spontaneous emission lifetime.

$$\frac{A}{B} = \frac{8\pi h\nu^3}{(c/n)^3}$$
(n → ref. ind.)

Going back to ~~electronic~~ semiconductors.

$$\mu_{sp}(\nu) = A \rho(\nu) f_e(\nu)$$
$$\mu_{st}(\nu) = B \rho(\nu) f_e(\nu) U_\nu.$$
$$\mu_{ab}(\nu) = B \rho(\nu) f_a(\nu) U_\nu.$$

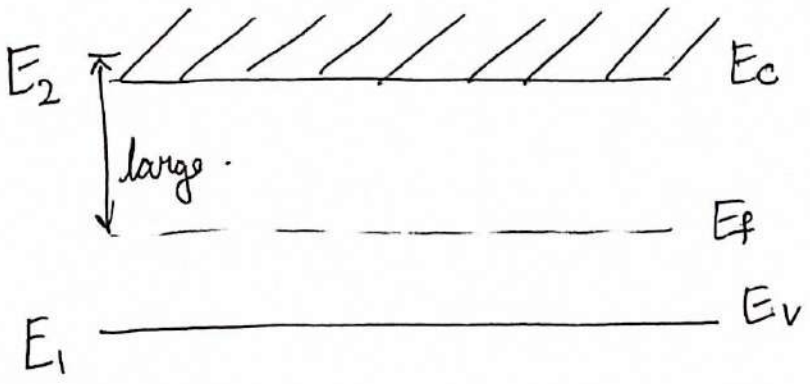
Where $A = \frac{1}{\tau_r}$ ∝ $\boxed{\frac{A}{B} = \frac{8\pi h\nu^3}{(c/n)^3}}$

Rate of Spontaneous Emission.

$$\mu_{sp}(\nu) = \frac{1}{\tau_r} \cdot \frac{1}{\pi\hbar^2} (2m_r)^{3/2} (h\nu - E_g)^{1/2} f_e(\nu).$$

∝ $f_e(\nu)$ at Thermal Equilibrium $= f(E_2)[1 - f(E_1)]$

$$= \frac{1}{1 + e^{(E_2 - E_F)/kT}} \cdot \left[\frac{e^{E_1 - E_F/kT}}{1 + e^{(E_1 - E_F)/kT}}\right]$$

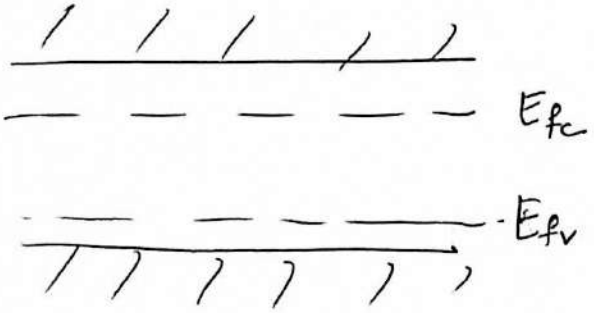


$$\Rightarrow f_e(\nu) \simeq e^{-(E_2-E_f)/kT} \cdot e^{(E_1-E_f)/kT}$$

$$\simeq e^{-(E_2-E_1)/kT}$$

$$\boxed{f_e(\nu) \simeq e^{-h\nu/kT}} \rightarrow \text{very small! } \Rightarrow \text{no emission at Thermal Eq.}$$

At quasi equilibrium,



$$\Rightarrow f_e(\nu) = e^{-(E_2-E_{fc})/kT} e^{(E_1-E_{fv})/kT}$$

$$\boxed{f_e(\nu) = e^{-h\nu/kT} \cdot e^{(E_{fc}-E_{fv})/kT}}$$

large!

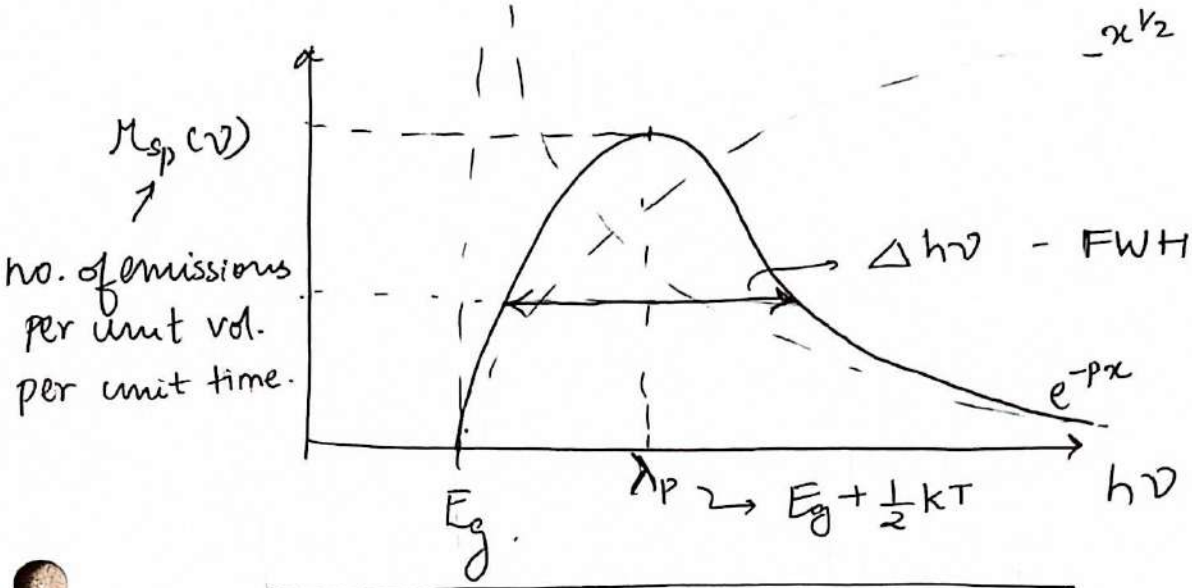
$\Rightarrow$ At Thermal equilibrium

$$R_{sp}(\nu) = \frac{1}{\tau_r} \frac{1}{\pi\hbar^2} (2m_r)^{3/2} (h\nu - E_g)^{1/2} e^{-h\nu/kT}$$

$$= \frac{1}{\tau_r} \frac{1}{\pi\hbar^2} (2m_r)^{3/2} e^{-E_g/kT} \cdot (h\nu - E_g)^{1/2} e^{-(h\nu-E_g)/kT}$$

$$= D_0 (h\nu - E_g)^{1/2} e^{-(h\nu - E_g)/kT}$$

$$\left\{ r_{sp} \simeq D_0 x^{1/2} e^{-px} \right\}$$



$$\boxed{\Delta\lambda \{\text{from } \Delta(h\nu)\} = 1.45\, kT\, \lambda_p^2}$$

$\Delta\lambda \sim 2\text{-}3$ nm for Fabry Perot LDs.

$\Delta\lambda \sim 20$ nm for LEDs.

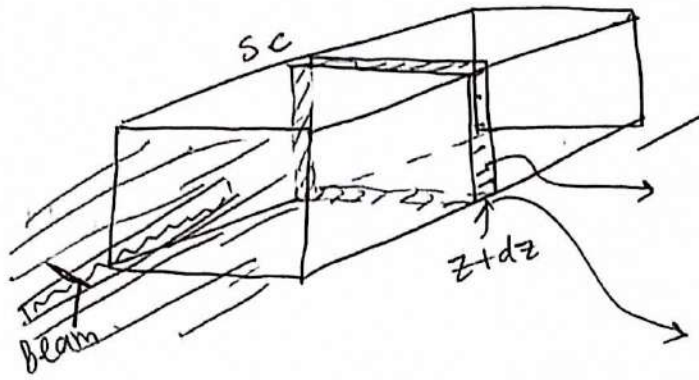
Lec 20 - Amplification by Stimulated Emission.

Recall,

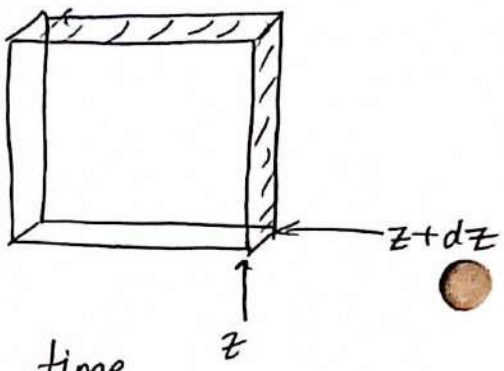
$$r_{sp}(\nu) = A\rho(\nu) f_e(\nu)$$

$$\sim D_0 (h\nu - E_g)^{1/2} e^{-(h\nu - E_g)/kT}$$

Rates of Stimulated Emission and Absorption.



Let S be the area.



$$r_{st}(\nu) = B\rho(\nu) f_e(\nu) U_\nu$$

$$r_{abs}(\nu) = B\rho(\nu) f_a(\nu) U_\nu$$

No. of stimulated emissions per unit time, in the volume element Sdz = $r_{st}(\nu) S dz$.

⇒ Energy generated / unit time in the vol element Sdz } $= r_{st}(\nu) Sdz\, h\nu$.

III^{ly} Energy absorbed / unitime in the vol element Sdz } $= r_{ab}(\nu) Sdz \cdot h\nu$

⇒ Net energy generated $= (r_{st} - r_{ab})\, Sdz \cdot h\nu$ — (1)

- Incident irradiance → Energy flux / unit time.

Energy entering per unit time into the volume element is

$$I_\nu(z)\, S.$$

Energy leaving per unit time at $z+dz$ is

$$I_\nu(z+dz)S.$$

⇒ Net energy generated per unit time $= \left[I_\nu(z+dz) - I_\nu(z)\right]S.$ — ②

Equating ① & ②,

$$\left[I_\nu(z+dz) - I_\nu(z)\right]S = (\kappa_{st} - \kappa_{ab})\, S dz * h\nu.$$

⇒ $I_\nu(z) + \frac{\partial I_\nu}{\partial z} dz$

⇒
$$\boxed{\frac{\partial I_\nu}{\partial z} = (\kappa_{st} - \kappa_{ab})\, h\nu} \quad — ③$$

$$= B\rho(\nu) u_\nu \left[f_e(\nu) - f_a(\nu)\right] h\nu$$

$\frac{I_\nu}{v}$ → velocity.

$\times \frac{A}{B} = \frac{8\pi h\nu^3}{c^3}$

$$\Rightarrow B = \frac{v^3}{c\, 8\pi h\nu^3}$$

$$\Rightarrow \frac{\partial I_\nu}{\partial z} = \frac{v^3}{8\pi h\nu^3} \frac{\rho(\nu)}{\tau_r} \frac{I_\nu}{v} \left[f_e(\nu) - f_a(\nu)\right] h\nu .$$

$$\Rightarrow \frac{\partial I_\nu}{\partial z} = \underbrace{\frac{v^2}{8\pi\nu^2} \frac{\rho(\nu)}{\tau_r} \cdot \left[f_e(\nu) - f_a(\nu)\right]}_{\gamma_0(\nu)} \cdot I_\nu$$

$$\Rightarrow \boxed{I_\nu(z) = I_\nu(0) \cdot e^{\gamma_0(\nu) z}}$$

$\Rightarrow$ Gain $= e^{\gamma_0(\nu) L}$ ← Gain coefficient!

$$\gamma_0(\nu) = \frac{v^2}{8\pi\nu^2} \frac{\rho(\nu)}{\tau_r} \left[f_e(\nu) - f_a(\nu)\right] I_\nu$$

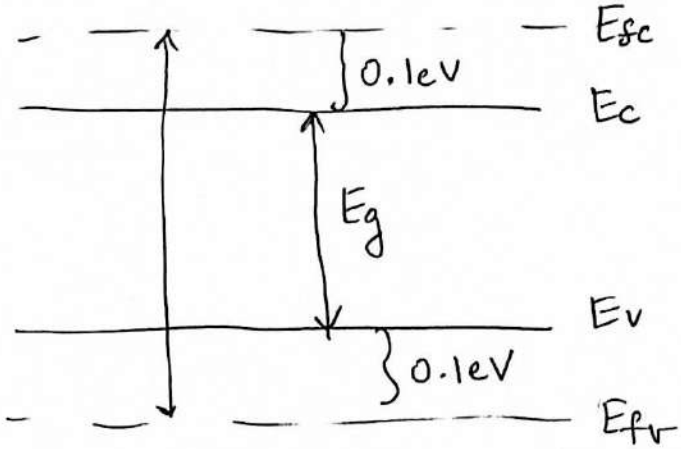
Gain exists when $f_e(\nu) > f_a(\nu)$ & recall that this occurs when $\boxed{\left(E_{fc} - E_{fv}\right) > h\nu}$ → Analogous to population inversion.

If seperation between quasi Fermi levels is larger that $h\nu$, we get gain! (Note that $E_{fc} > E_c$ & $E_{fv} < E_v$ is necessary implicitly)

Lec 21 Semiconductor (Laser) Amplifier

$$\gamma = \frac{(c/n)^2}{8\pi\nu^2}\,\frac{1}{\tau_r}\,\rho(\nu)\,\left[f_e(\nu) - f_a(\nu)\right]$$

$\rho(\nu)$ → optical joint DOS.

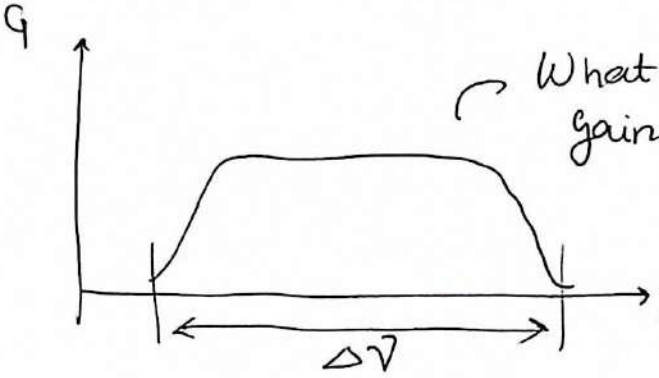


$$\Rightarrow \Delta E = h\Delta\nu = 0.2\,eV$$

$$\Rightarrow \Delta\nu = \frac{0.2 \times 1.6 \times 10^{-19}}{6.6 \times 10^{-34}}$$

$$= 5 \times 10^{13}\ Hz.$$

↑ Bandwidth.



What about the gain profile.

Expt. at OK

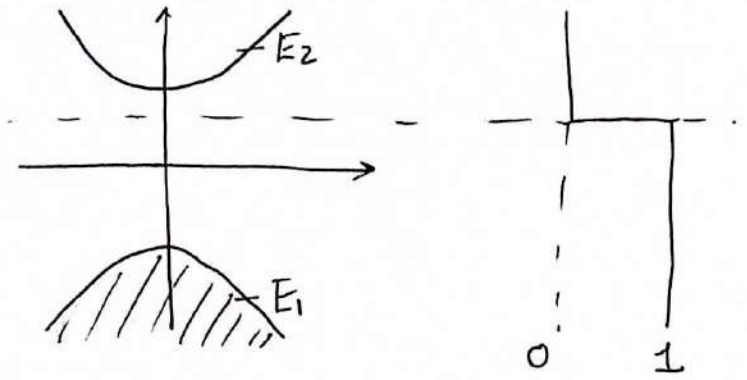
Case 1 : Thermal Equilibrium.

$$\rho(\nu) = \frac{1}{\pi^2\hbar^3}\,(2m_r)^{3/2}\,(h\nu - E_g)^{1/2}$$

$$\Rightarrow \gamma = \left[\frac{(c/n)^2}{8\pi^2\tau_r}\,(2m_r)^{3/2}\right]\frac{(h\nu - E_g)^{1/2}}{\nu^2}\,f_g(\nu)$$

→ Fermi inversion factor.

$$\Rightarrow \gamma(\nu) = K \frac{(h\nu - E_g)^{1/2}}{\nu^2} f_g(\nu).$$

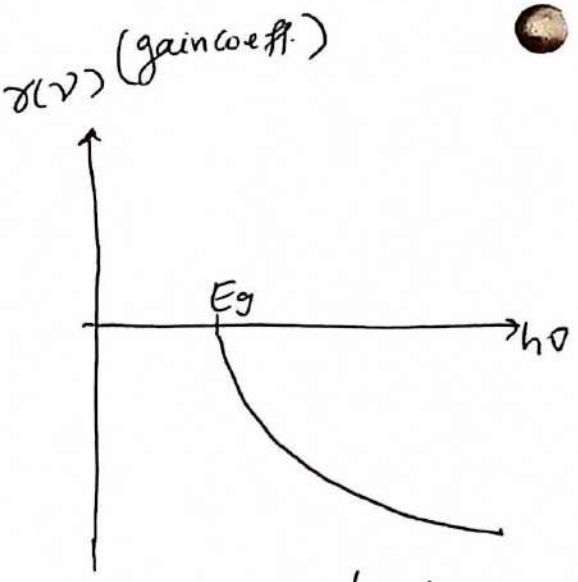


at $T = 0k$

$f(E_2) = 0$

$f(E_1) = 1$

$\Rightarrow f_g(\nu) = -1$



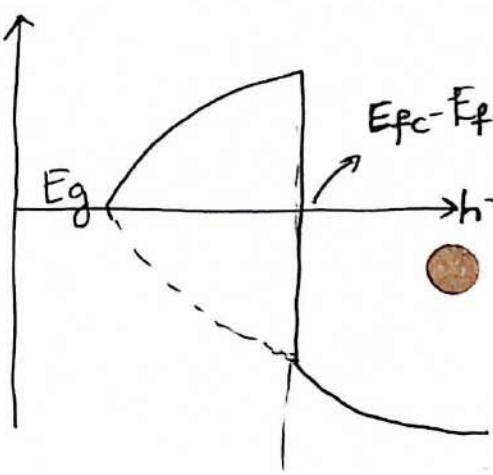
↳ Loss.

Typically $\Delta\nu$ is 0.1 × value of $\nu \Rightarrow \nu^2$ is almost constant over $\Delta\nu$.

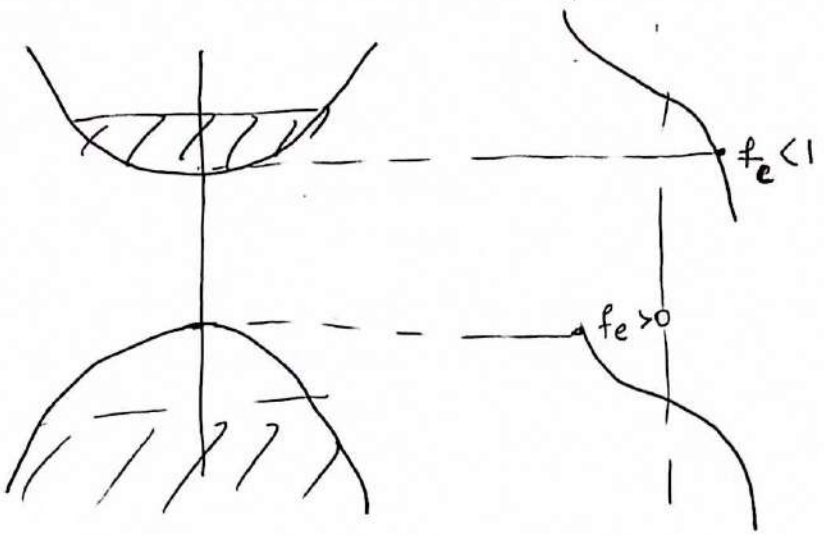
$\Rightarrow \gamma(\nu) \sim -K_0 (h\nu - E_g)^{1/2}$ (from $f_g(\nu)$)

Case 2 Quasi Equilibrium (at T=0)

$\Rightarrow f_g(\nu) = 1$

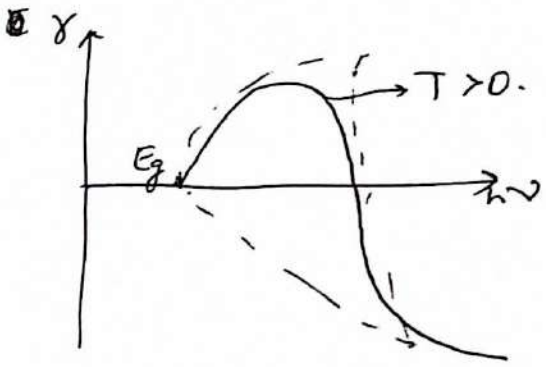


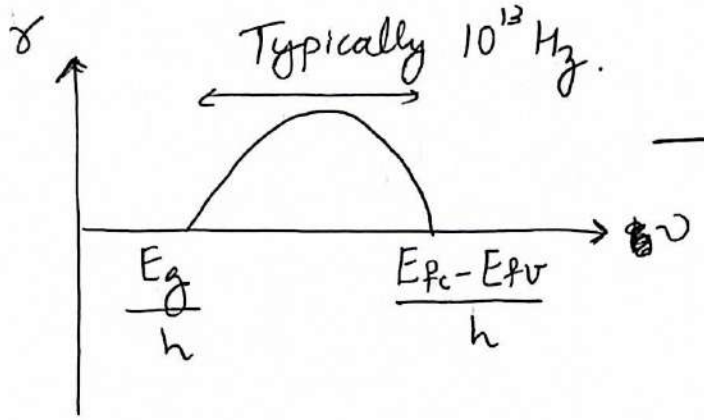
Case 3 Quasi Equilibrium at T>0K



at $h\nu = E_{fc} - E_{fv}$

$f_g(\nu) = 0$.

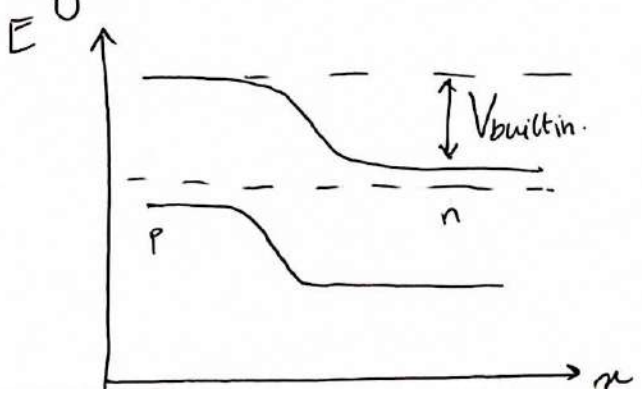


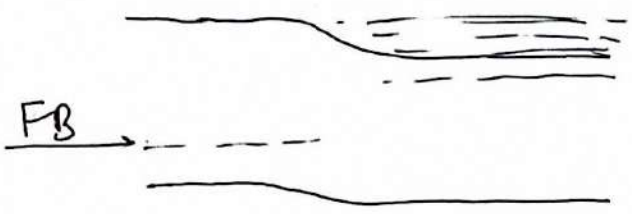


→ Gain profile is not flat!

- How to maintain $E_{fc} - E_{fv} > E_g$, or how to pump an amplifier?

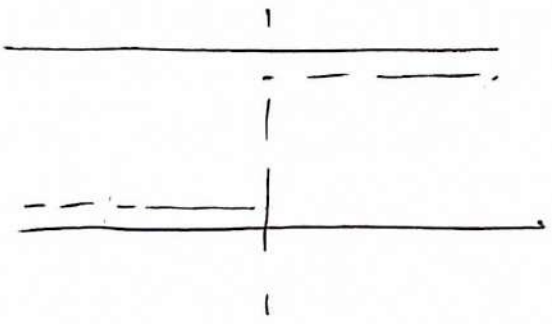
  - By current injection in a forward biased p-n junction





> Even after heavy F-B note that $E_{fc} - E_{fv} < E_g$.

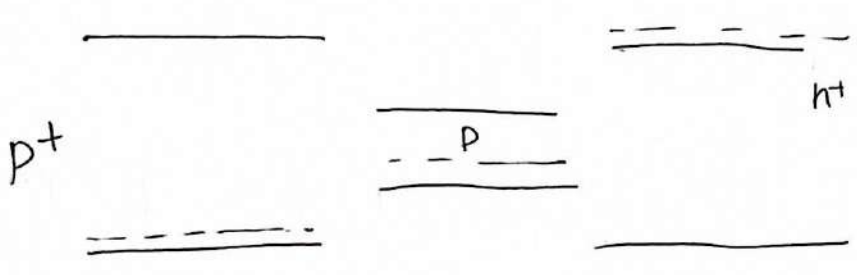
Extreme FB :

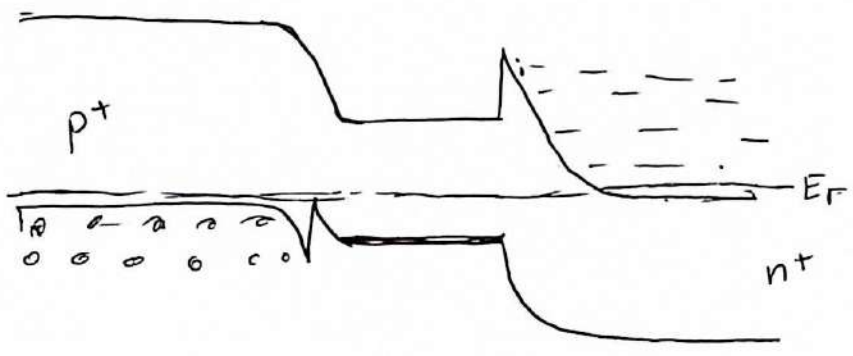


Energy levels are back to where the original "seperate" p & n were.

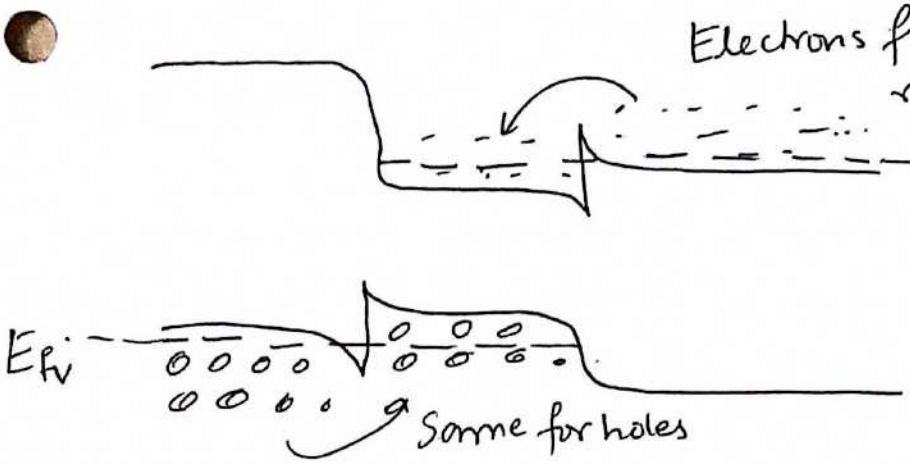
> Therefore if we start with a p & n that already have $E_f > E_c$ & $E_f < E_v$ (i.e highly doped "degenerate" semiconductors) there is a possibility under extreme FB to achieve $E_{fc} - E_{fv} > E_g$. But it is not practical.

> Use of Double Hetero Structures for Amplification.





After forward biasing,



$E_{fc} - E_{fv} > E_g$

Also $\Delta n \rightarrow$ very large.

$\Delta p \rightarrow$ very large.

Recall,

$$E_{fc} = E_c + kT\left[\ln\frac{n}{N_c} + \frac{1}{\sqrt{8}}\frac{n}{N_c}\right]$$

$$E_{fv} = E_v - kT\left[\ln\frac{p}{N_v} + \frac{1}{\sqrt{8}}\frac{p}{N_v}\right]$$

$\Rightarrow E_{fc} \uparrow\uparrow \quad E_{fv} \downarrow\downarrow$

Lec 22 Absorption Spectrum of Semiconductors.

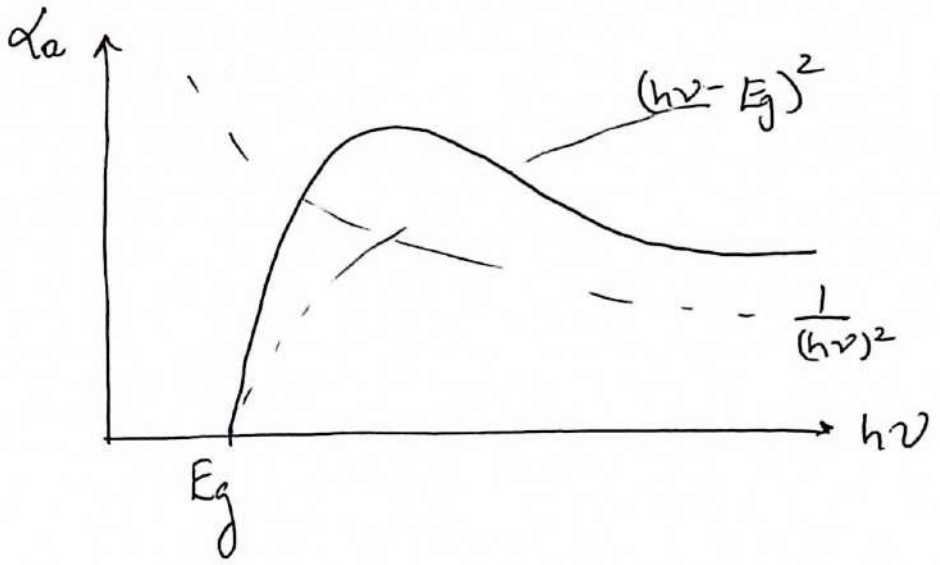
Recall,

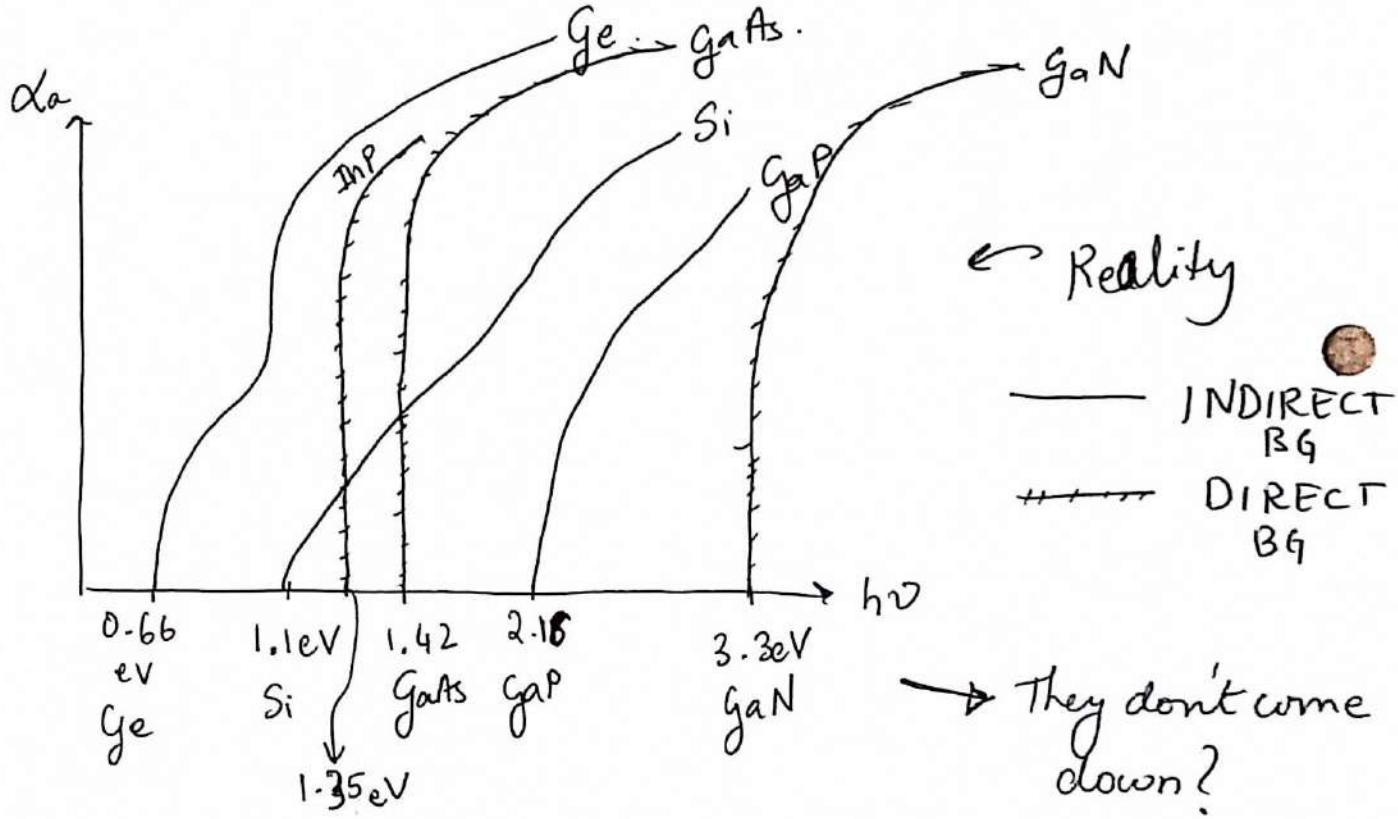
$$\gamma = \frac{(\zeta_n)^2}{8\pi\nu^2} \cdot \frac{1}{\tau_r} (2m_r)^{3/2} \cdot \frac{1}{\pi\hbar^2} (h\nu - E_g)^{1/2} f_g(\nu).$$

If $f_g(\nu) < 0$,

$$\gamma = -\alpha_a \Rightarrow \boxed{\alpha_a = \frac{(\zeta_n)^2}{2\tau_r} (2m_r)^{3/2} f_0(\nu) \frac{(h\nu - E_g)^{1/2}}{(h\nu)^2}}$$

attenuation coefficient.



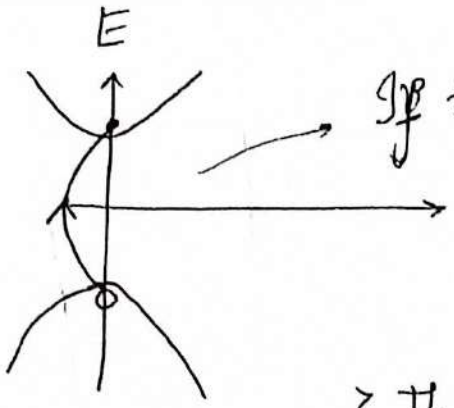


> Because of parabolic approx. & the assumption of DBG SC.

There are also many other effects

- Intraband transitions. (Low energy)
- Excitonic transitions.
- Phonon transitions.

Excitonic Transitions



If this e-h pair are close in space, they form a single localized entity due to the Coloumb force.

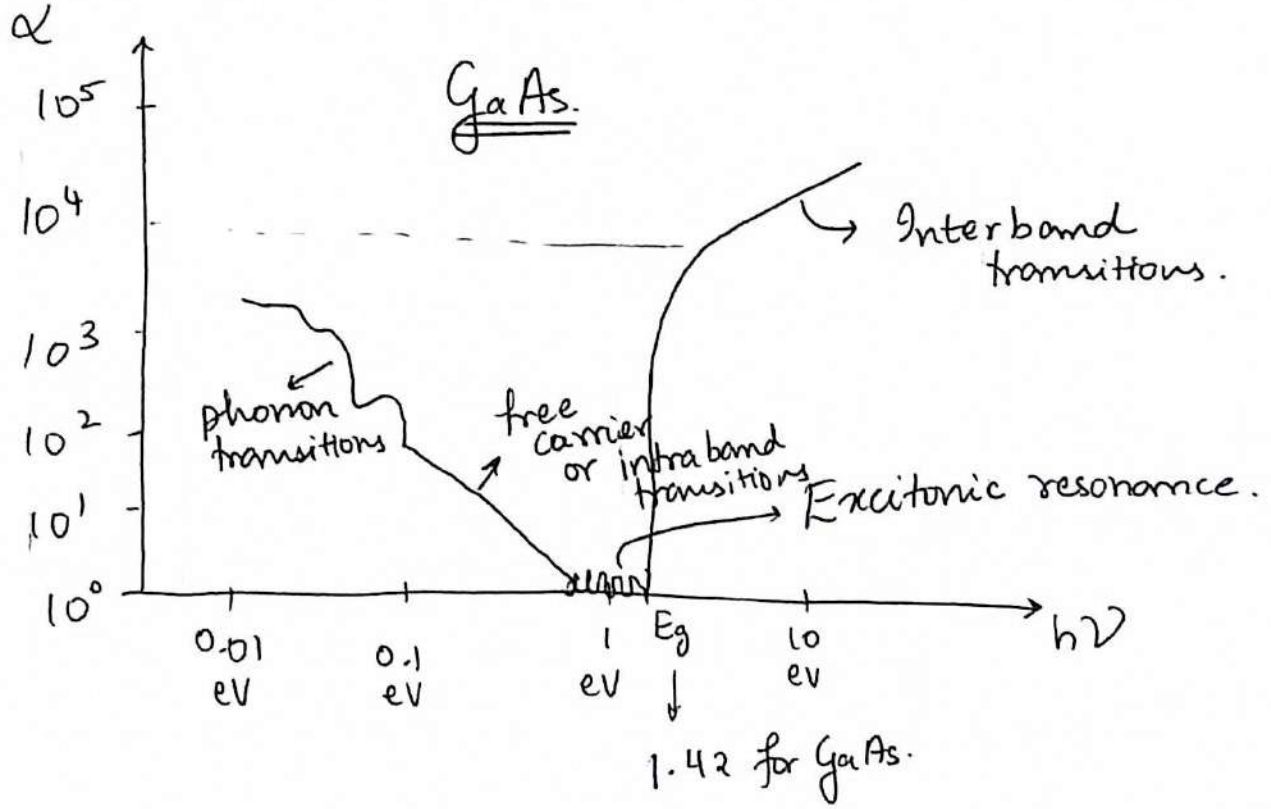
> This is called an exciton.

> They have low binding energy $\simeq$ 10meV.

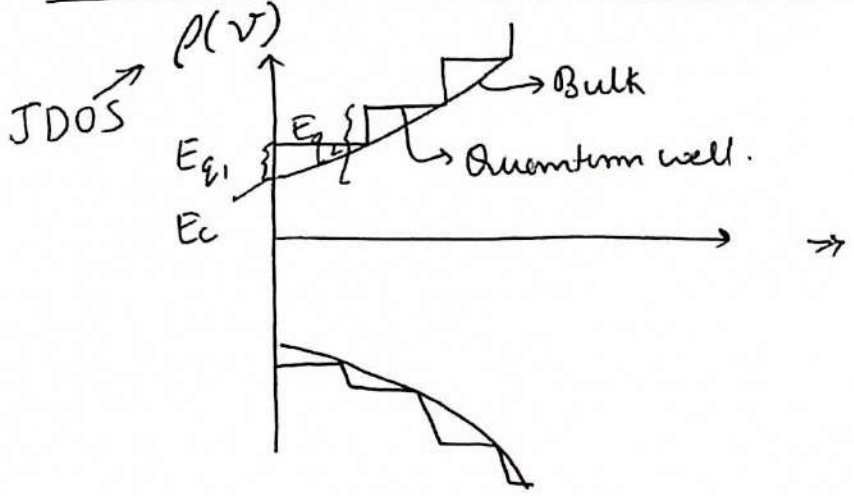
(H atom for example has a binding energy of >10eV)

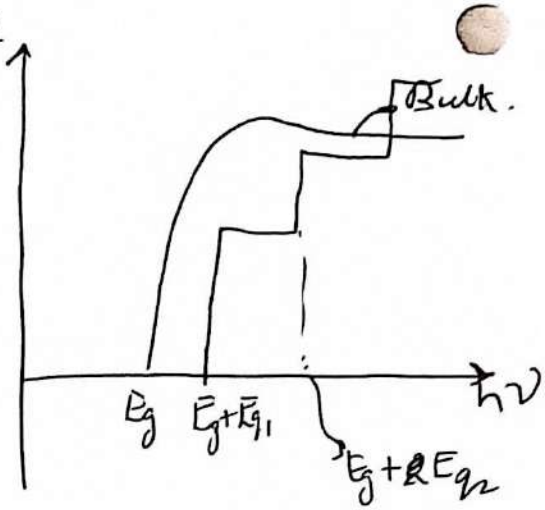
> Excitons don't usually occur in S-C at room temp since $KT \sim 25meV$.

> Exciton transitions have slightly lower energy than Eg.



> Quantum Well absorption spectrum





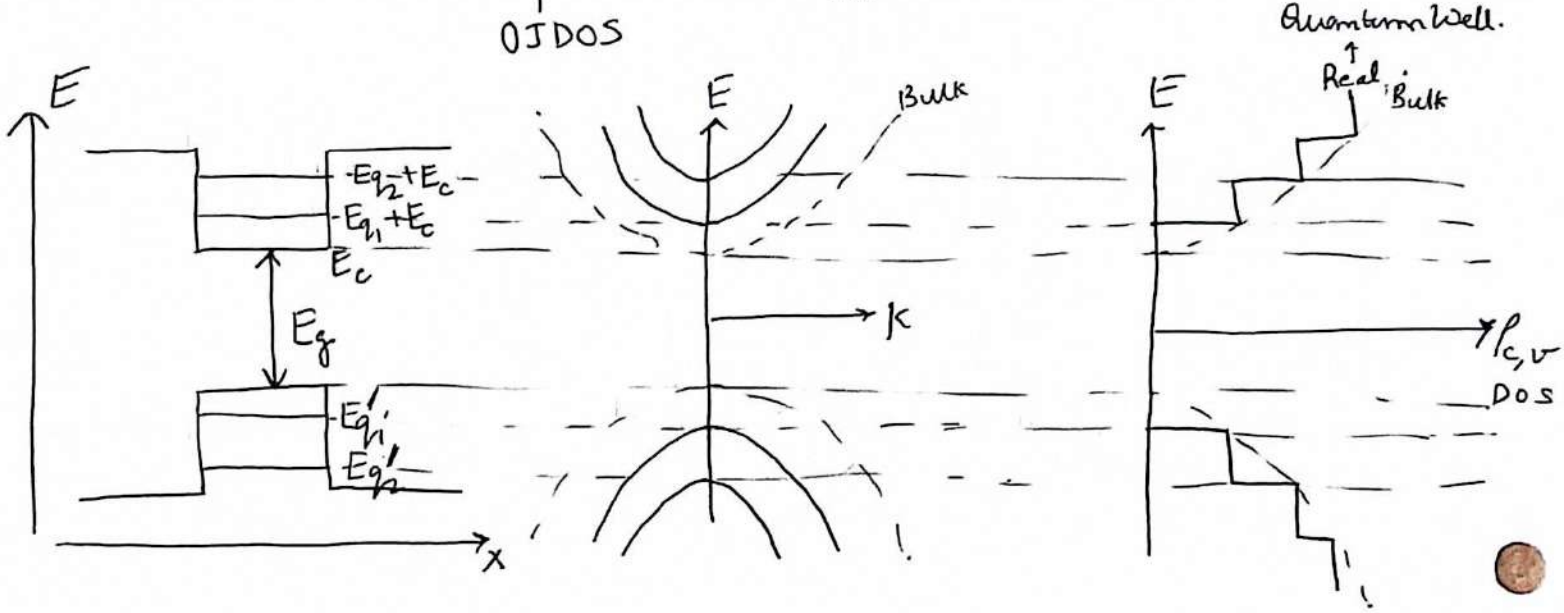
⇒ Abrupt transitions in absorption spectra due to quantized energy levels & quantized JDOS.

Lec 23 Gain and Absorption Spectrum of Quantum Well Structures.

$$\gamma = \frac{(c/n)^2}{8\pi\nu^2}\,\frac{1}{\tau_r}\,\rho(\nu)\,f_g(\nu)$$

$\rho(\nu)$ ↑ JDOS

$f_g(\nu) \rightarrow f_e(\nu) - f_a(\nu)$



$\Rightarrow \rho_c = 0 \qquad E_c < E < E_c + E_{q,1}$

$= \dfrac{m_c}{\pi \hbar^2 L_z} \qquad E_c + E_{q,1} < E < E_c + E_{q,2}$

$= \dfrac{2m_c}{\pi \hbar^2 L_z} \qquad E_{q,2} + E_c < E < E_c + E_{q,2}$

$E_{gq_1} = E_g + E_{q,1} + E'_{q,1} \leq h\nu$ for photon interactions.

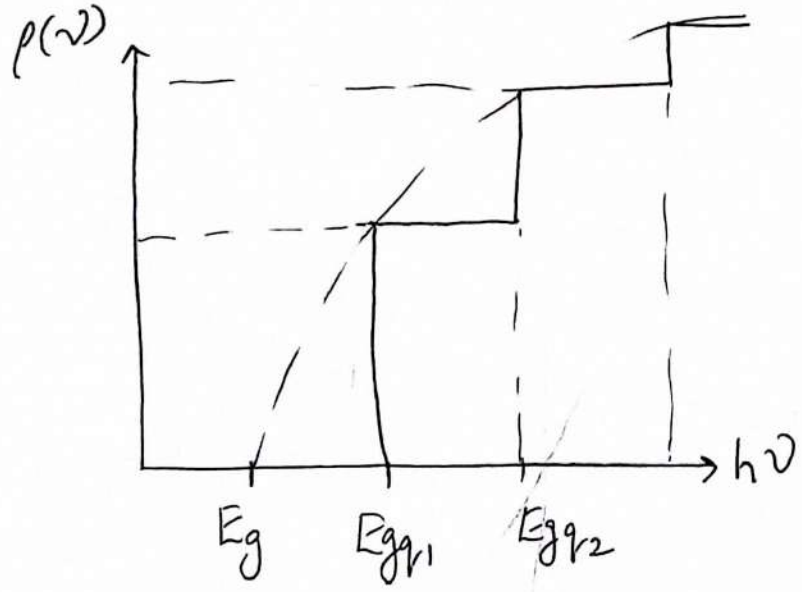
$\rho(\nu) = \rho_c(E_2) \cdot \dfrac{dE_2}{d\nu}$, $E_2 = E_c + \dfrac{m_r}{m_c}(h\nu - E_g)$ → Bulk.

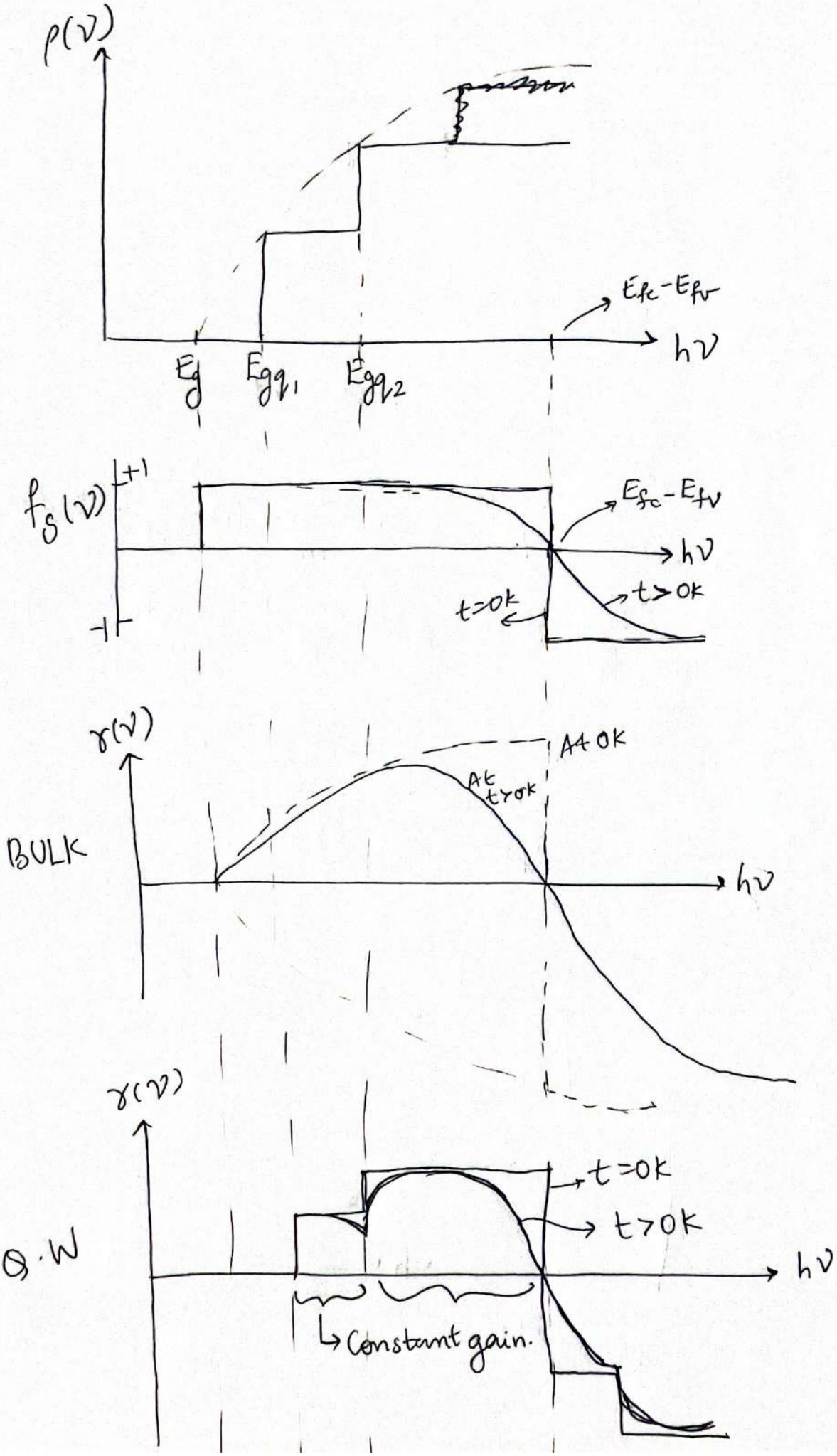
$= E_c + E_{q,1} + \dfrac{m_r}{m_c}(h\nu - E_{gq_1})$.

↳ Q-Well

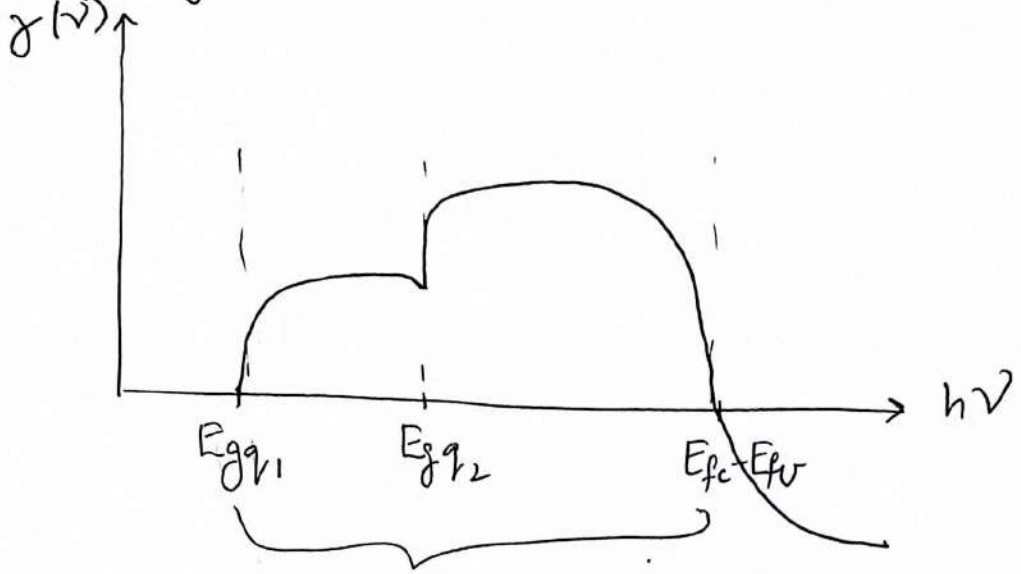
$= \dfrac{m_c}{\pi \hbar^2 L_z} \times \dfrac{m_r}{m_c} \cdot h.$

$= \dfrac{2m_r}{\hbar L_z}$ for $E_{gq_1} < h\nu < E_{gq_2}$.



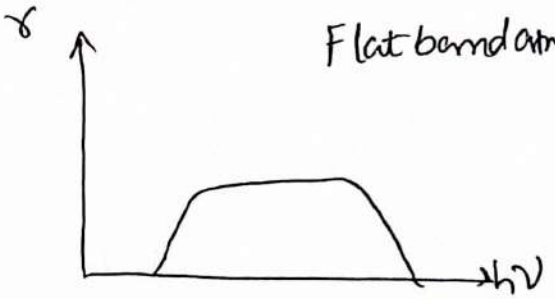

P(ν)
$E_{fc}-E_{fv}$
hν
E_g
E_{g_1}
E_{g_2}
$f_s(\nu)$
+1
-1
$E_{fc}-E_{fv}$
hν
t=0k
t>0k
γ(ν)
BULK
At 0k
At t>0k
hν
γ(ν)
Q.W
t=0k
t>0k
hν
↳ Constant gain.

Redrawing,



Amplification bandwidth.

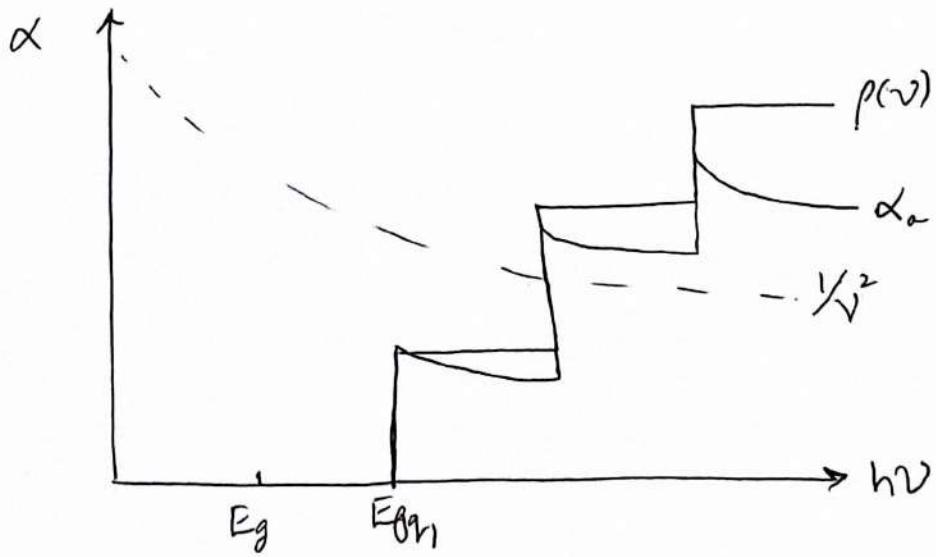
If $E_{fc} - E_{fv} = E_{gq_2}$

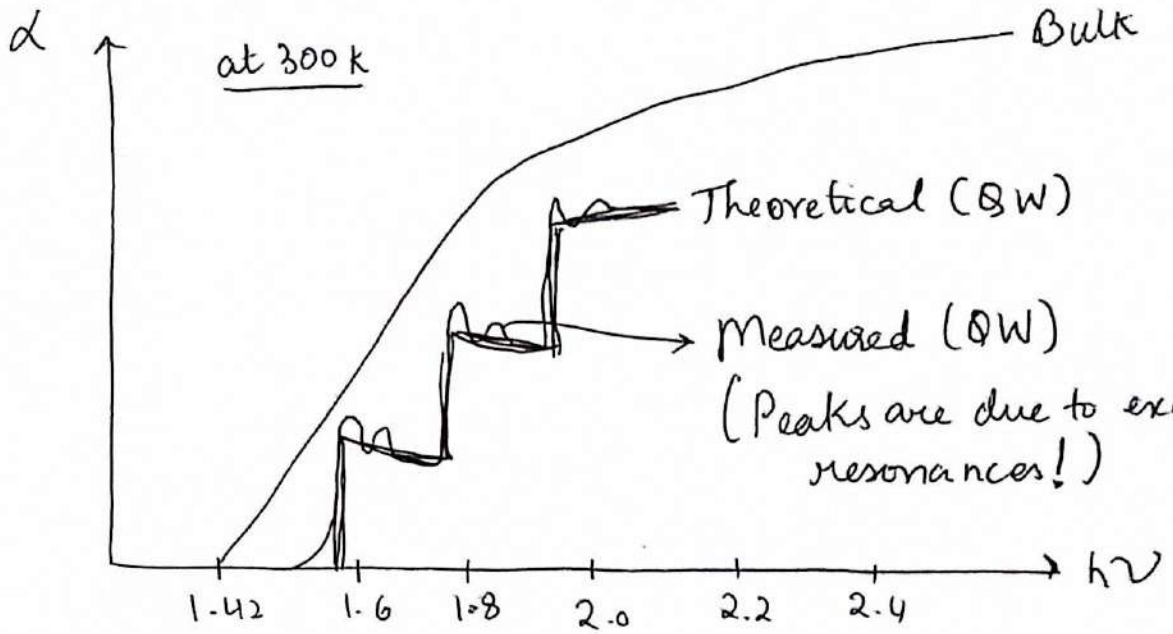


Flat band amplifier.

Loss spectrum.

$$\alpha_a \simeq \frac{(\gamma_n)^2}{8\pi \tau_r} \cdot \frac{\rho(\nu)}{\nu^2}$$





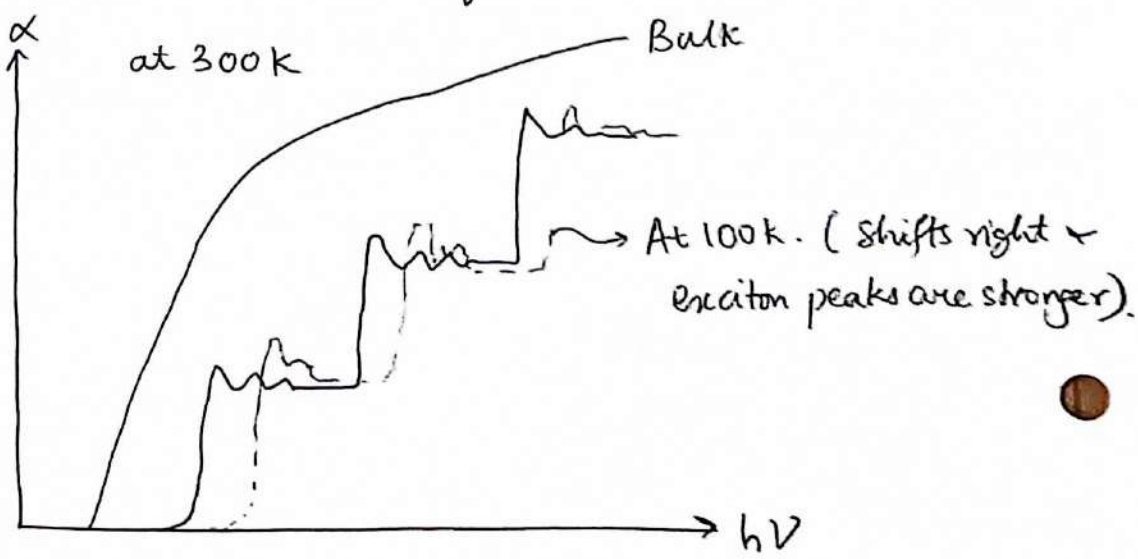
Lec 24 Electro Absorption Modulator

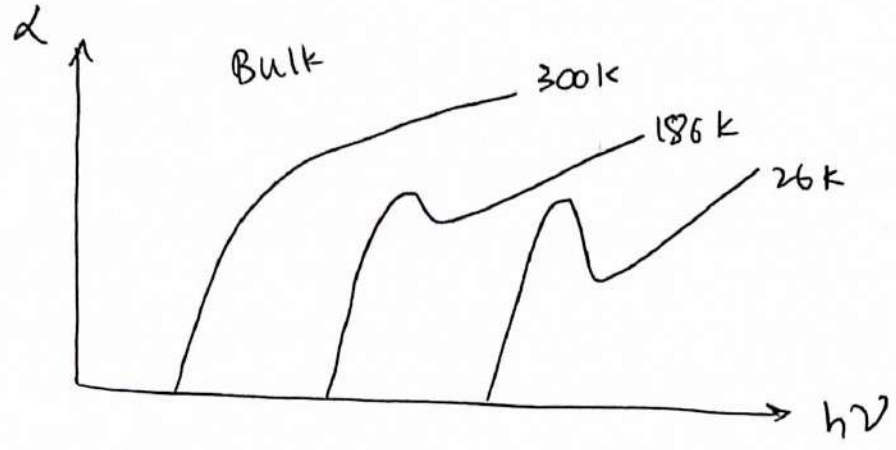
Quantum Well Modulators.

↳ Quantum Confined Stark Effect (QCSE)

↓

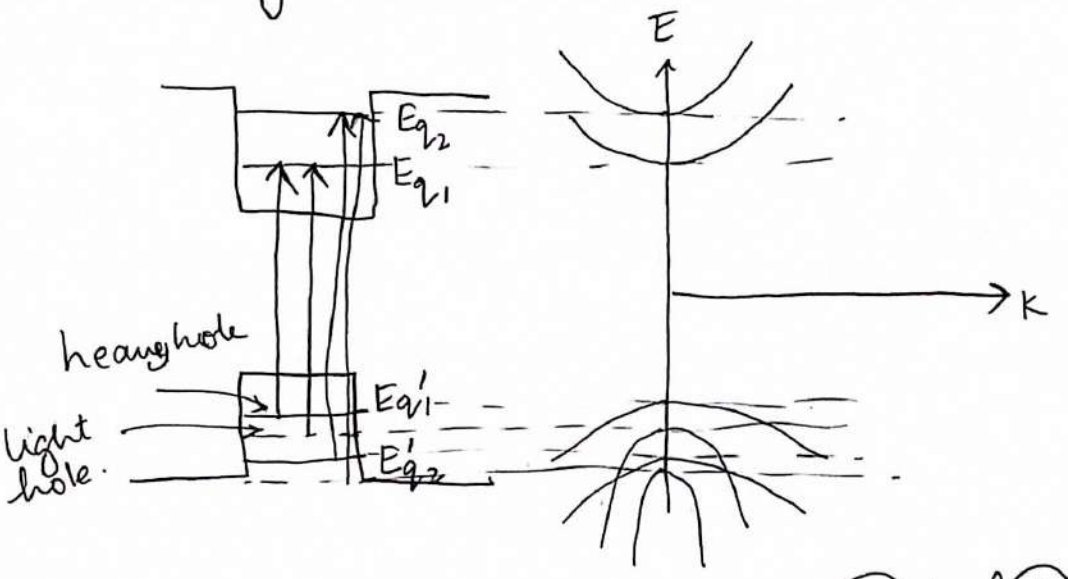
Shift in absorption spectrum due to external electric field. } Originally in absorption spectrum of H atom





> Binding energy of excitons is ≈ 4-5meV. kT at room temperature is ≈ 25meV. So at lower temperature excitons can exist stably.

> Why do excitons exist in QW at 300K?



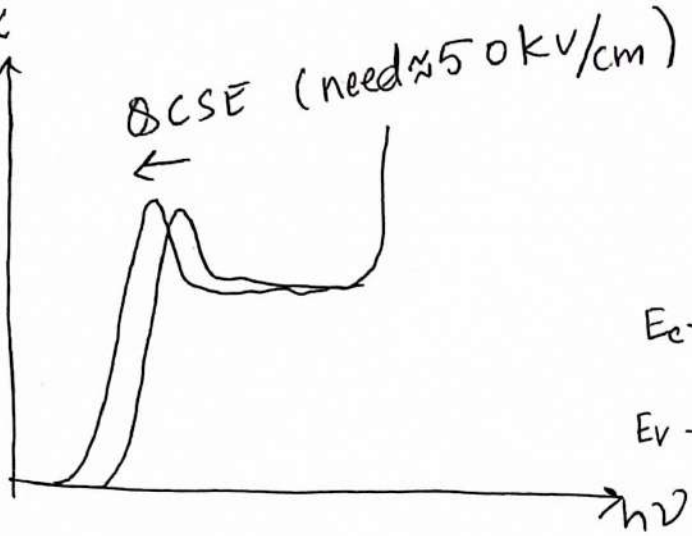
> Note that excitonic energy in QW is higher due to the quantized state.

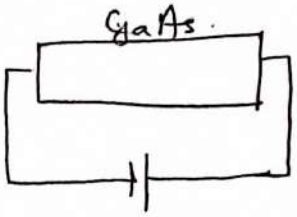
> In a quantum well the electron & hole are confined,

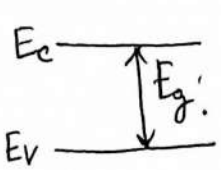
⇒ they "line-up" strongly which leads to strong coupling & higher binding energy. BE is 3-4 times higher.

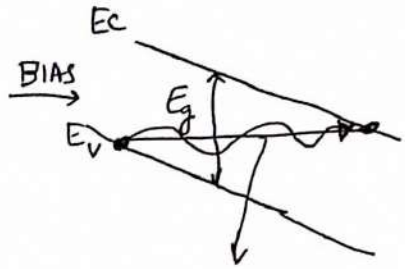
Quantum Confined Stark Effect.

GaAs
T=300K

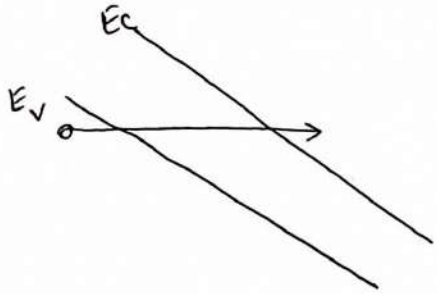




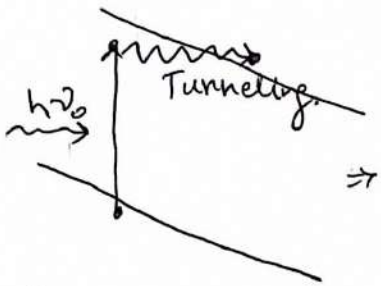




Electrons can tunnel!
(Since Energy States are same)



BM tunnelling.



⇒ $h\nu_0 < E_g$

Photon assisted tunneling

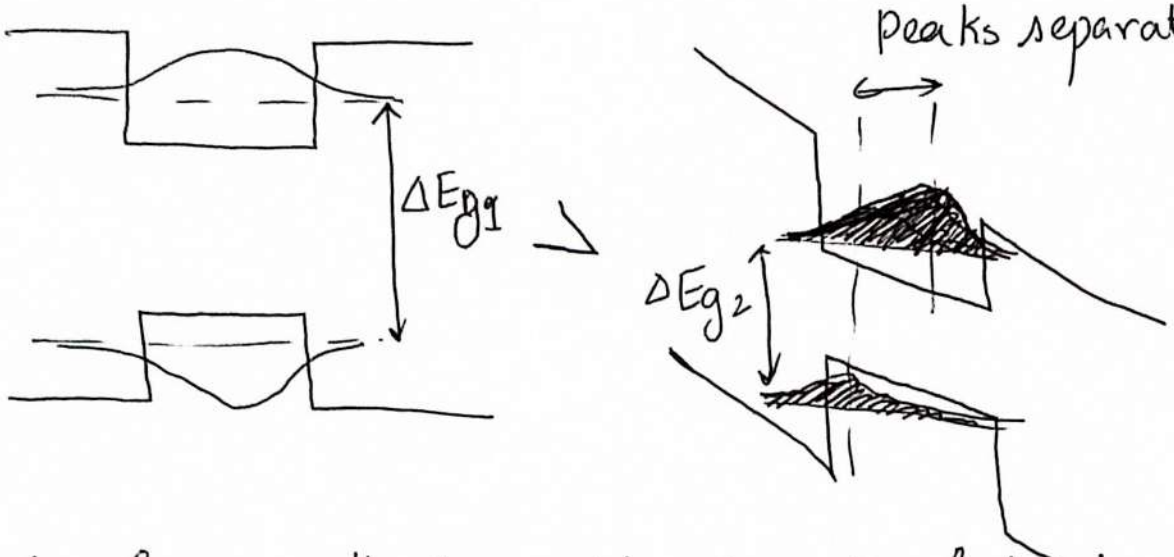
} Absorption starts even before E_g.

Franz Keldysh Effect

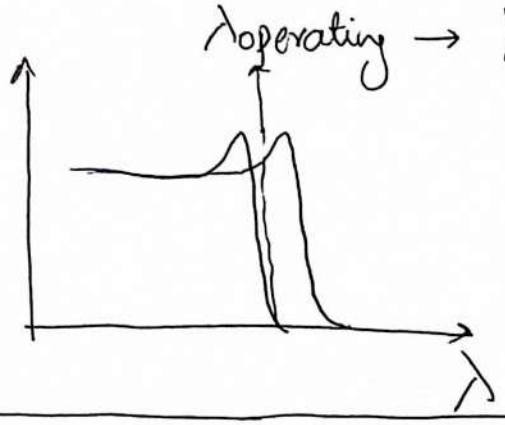
This was made possible because of band tilting.

⇒ Absorption edge shifts down in Energy (i.e. Red Shift of the absorption edge) → Photon Assisted Tunneling!

→ In a quantum well the same thing happens and is called QCSE!

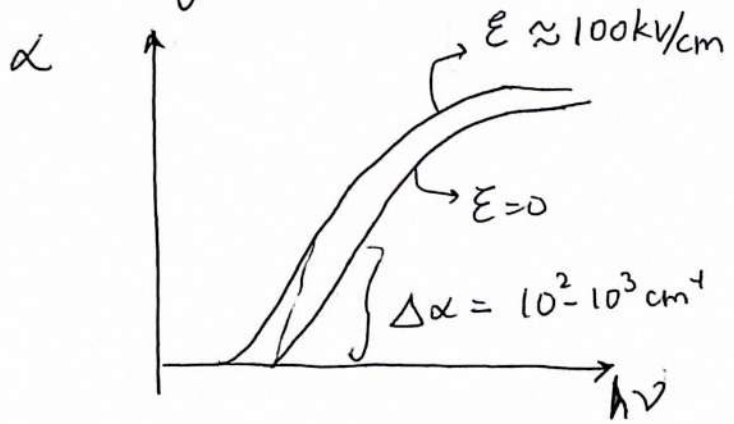


> Note further that exciton is still held in place despite the applied E-field due to the confinement by the well.

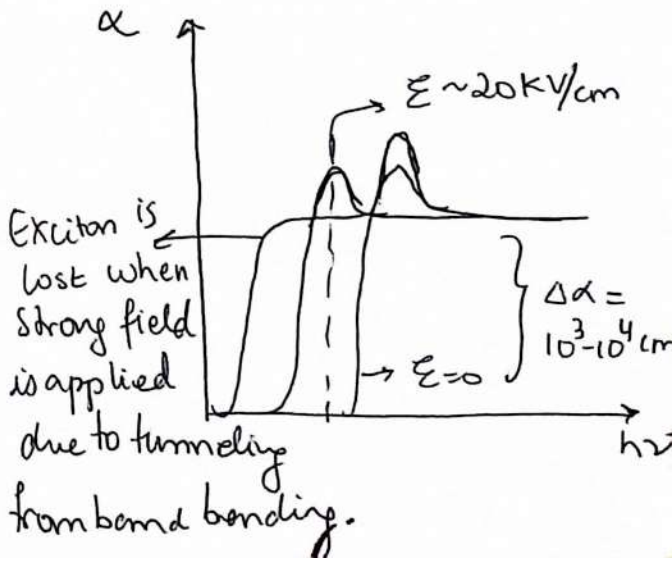


Lec 25 - Electro Absorption Modulator - II

Franz Keldysh Effect (Bulk)



QCSE

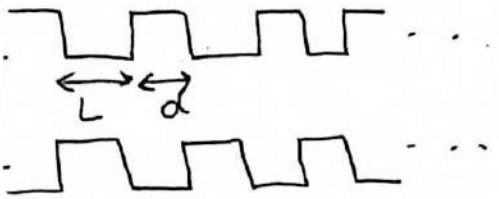


> $\mathcal{E} = 20\,kV/cm = 2\times10^4\,V/cm = 2\,V/\mu m$.

~~Reflection~~

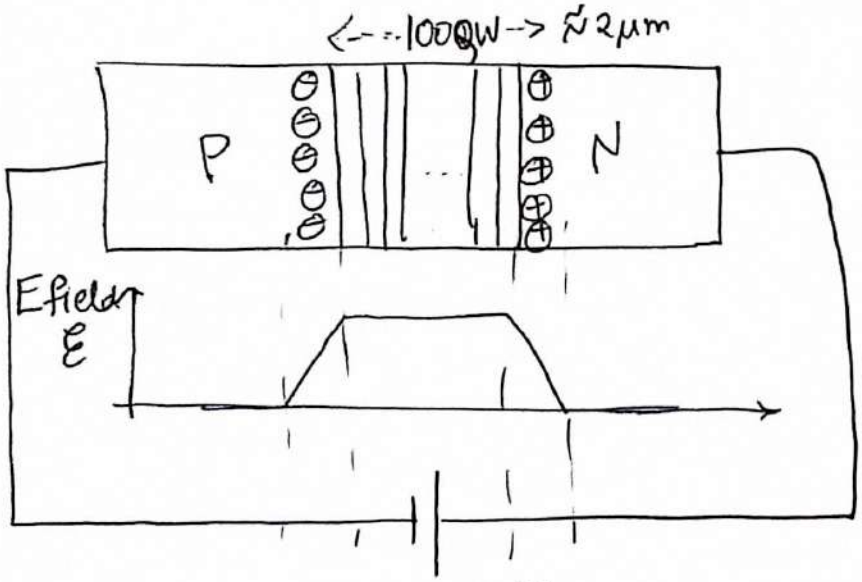
> How many quantum wells are needed for significant attenuation? About ~~100~~ 100.

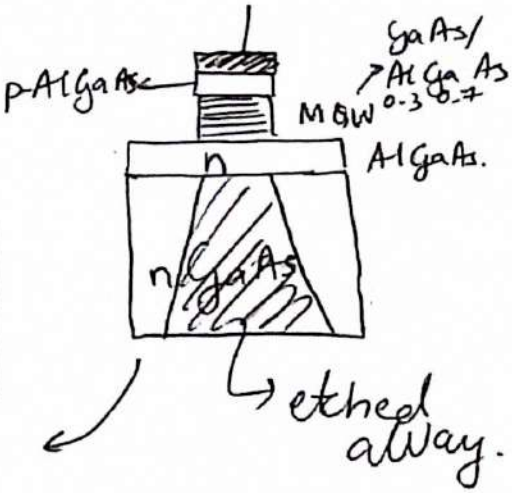
$d \sim 100\text{Å}$ & $L \sim 100\text{Å}$

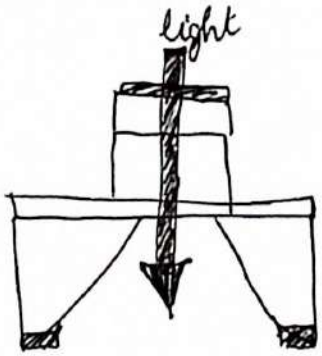


⇒ 50 ~ 100 wells are needed.

Reverse biased PIN MQW (multiple)





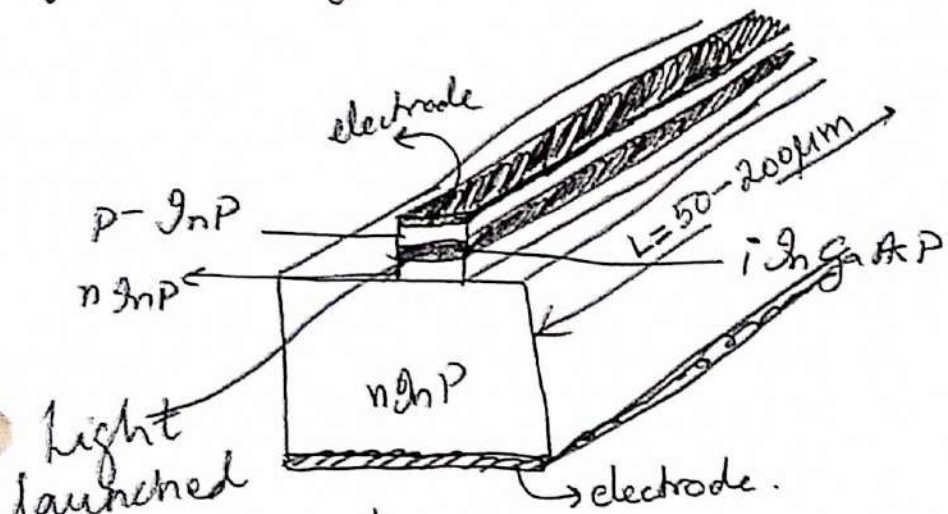


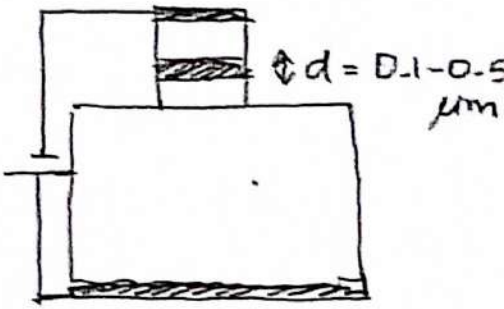
$\lambda_{op} \sim 800\,nm$.

Extinction Ratio or Modulation index

$$E\text{-}R = \frac{I_{out}(E_p)}{I_{out}(E=0)} = e^{-\Delta\alpha L}$$

If L is large, even Franz Keldysh effect can be used.





→ Ridged waveguide. Uses Franz keldysh effect.

→ Waveguide configuration of EAM.

$$\alpha_{eff} = \alpha_a \Gamma$$

→ Confinement factor (How much of the mode is inside the absorbing region)

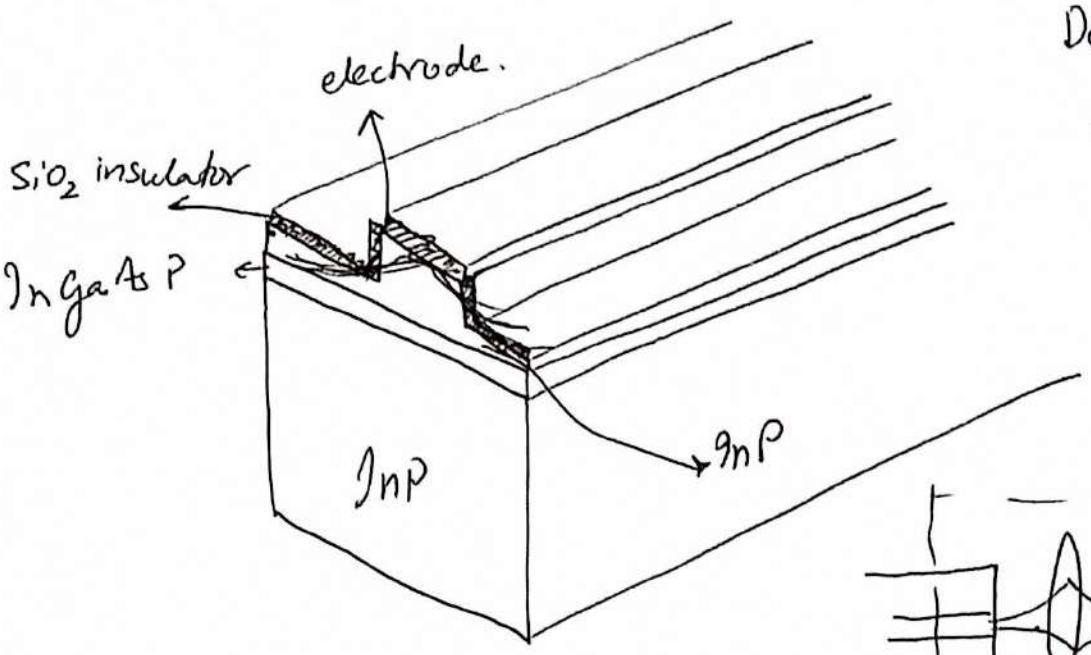
- Requires only 1-2 volts since height is small.

Lec 26 - Semiconductor optical Amplifiers (SOA)

Other amplifiers → Doped fiber amplifier (DFA)
→ Raman Fiber Amplifier

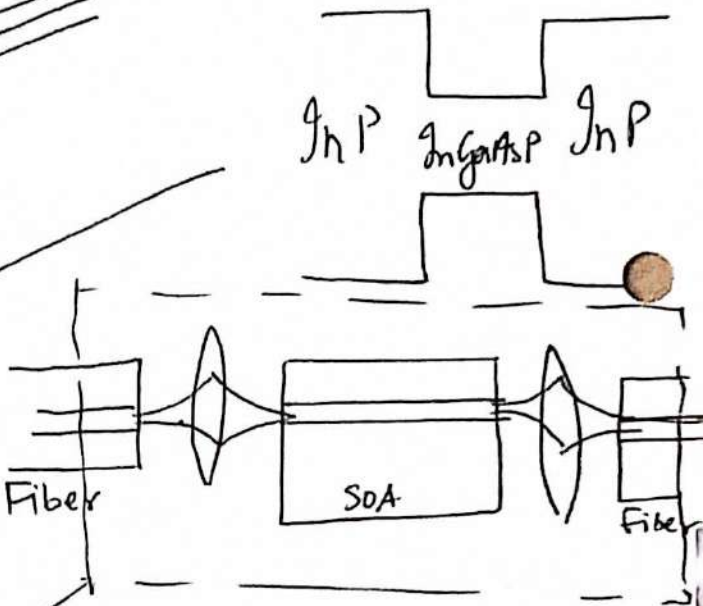
DFA → Erbium DFA (EDFA)

SOA

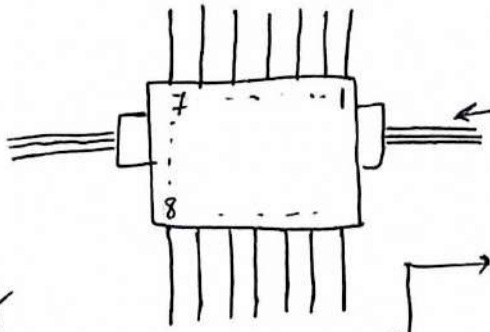


Double Hetero structure

Ridge waveguide config.



Stand alone SOA, Fiber pigtailed



14 pin Butterfly package.

Connected pins →
- Anode & cathode
- Thermistor
- TEC → Thermo-electric cooler
- Case Ground

Amplifier Characteristics

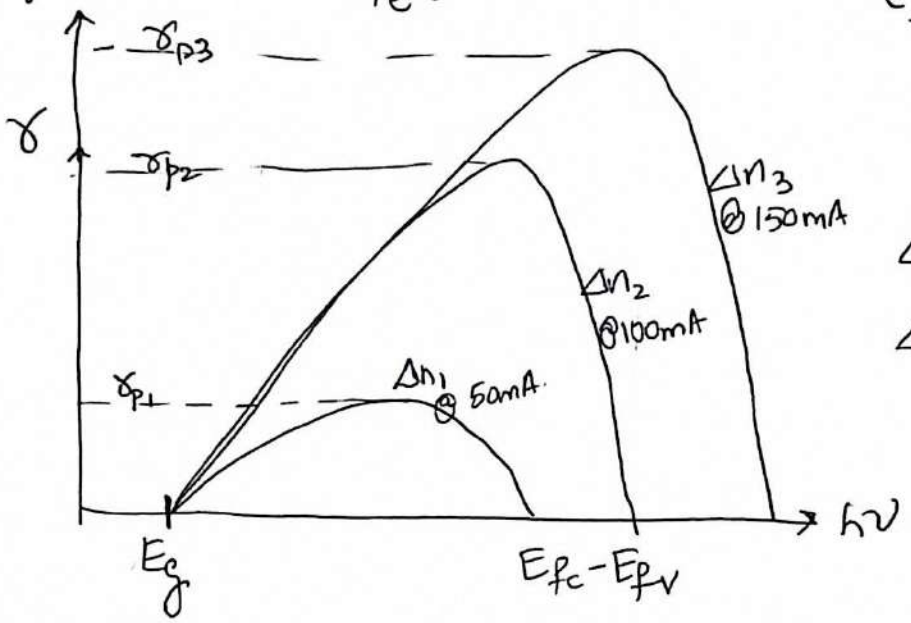
- Gain characteristics → Peak Gain, Gain spectrum, BW, P_{sat}
- Noise
- Polarization dependent gain
- ⋮ etc

Recap: $\gamma_0(\nu) = \frac{(c/n)^2}{8\pi\nu^2\tau_r} \rho(\nu)\left[f_e(\nu) - f_a(\nu)\right]$

↑ small signal gain coefficient.

$f_e(\nu) - f_a(\nu) > 0 \Leftarrow (E_{fc} - E_{fv}) > h\nu$

↳ Forward Bias — p-n heterojunction.



$\Delta n \rightarrow$ excess carrier conc.

$\Delta n_3 > \Delta n_2 > \Delta n_1$

Saturated Gain Coefficient

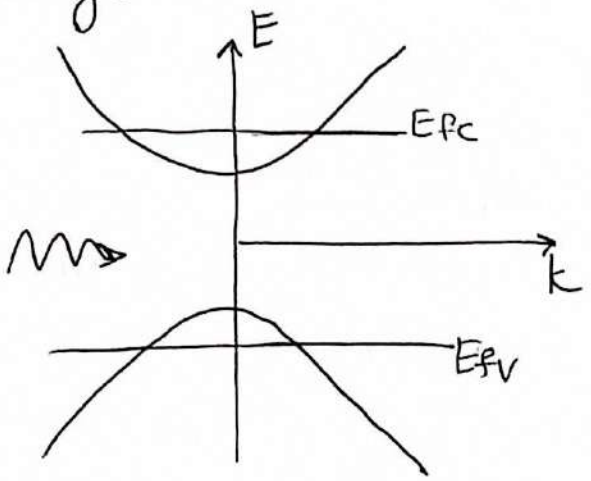
$\gamma_0 = \frac{\gamma_p}{1 + 4\pi^2\tau^2(\nu - \nu_p)^2}$ → homogeneously broadened line shape function.

↑ small signal

$\gamma(\nu) = \frac{\gamma_p}{1 + 4\pi^2\tau^2(\nu - \nu_p)^2 + P_\nu/P_s}$ → Saturation power.

↑ Large signal.

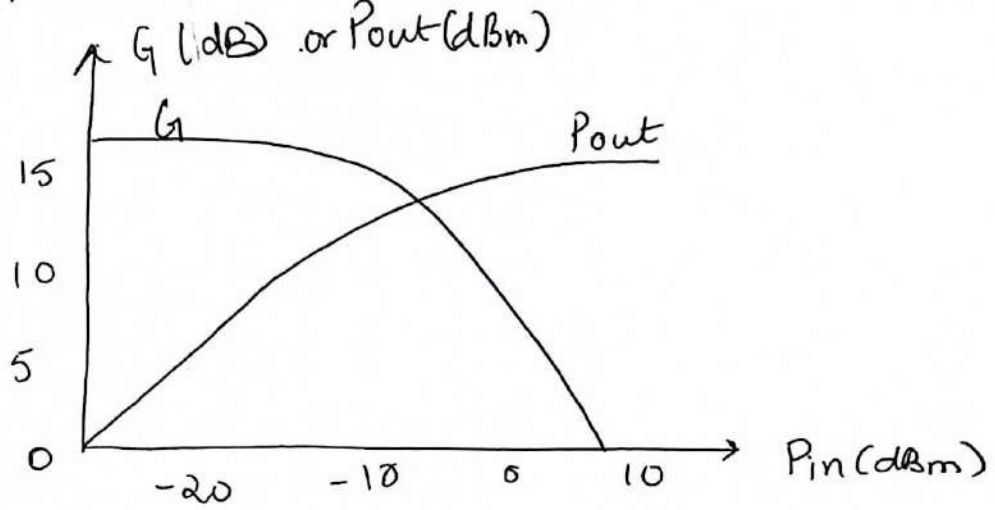
Why does



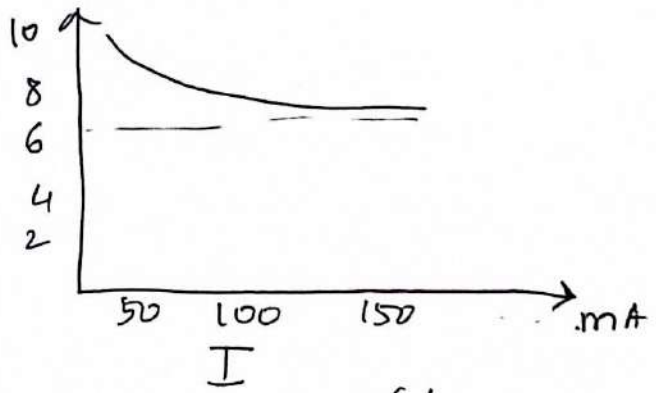
> When large Input power is used, a lot of electrons are brought down & E_{fc} ↓ & E_{fv} ↑.

At low power, pumping can replenish the lost carriers. This is the reason for saturation.

If $G = e^{\gamma_0 L}$



$$NF = 10\log \frac{SNR_{o/p}}{SNR_{i/p}}$$



Typical numbers (SOA)

Gain : 20-30dB
BW : 50-100nm
Psat : ~10dBm
NF : ~6dB

↓

[All optical switching & logic gates & wavelength converters]

vs

EDFA → (long range communication)

30-50dB
30-40nm
>20dBm
≈ 3dB - 3.5dB

Lec 27 Semiconductor light Sources.

Electroluminescence. (Injection electroluminescence)

Thermal Equilibrium

$n_0 = n_i + N_D$ & $p_0 = p_i + N_A$. } Carrier concentrations.

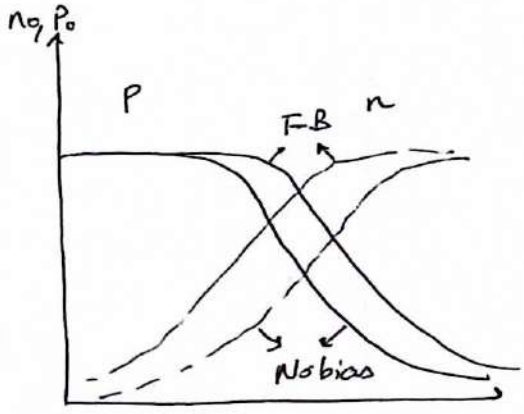
$G_0 \propto n_0 p_0$ → rate of generation.

$R_0 \propto n_0 p_0$ → rate of recombination.

$= \mu n_0 p_0$

↳ rate constant. (depends on material)

At thermal equilibrium, $G_0 = R_0 = \mu n_0 p_0$.



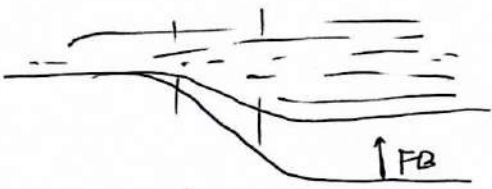
Assuming some bias is now added.:

R → rate of injection.

Δn, Δp → excess carrier concentration.

& $\Delta n = \Delta p$ since e-h come in pairs.

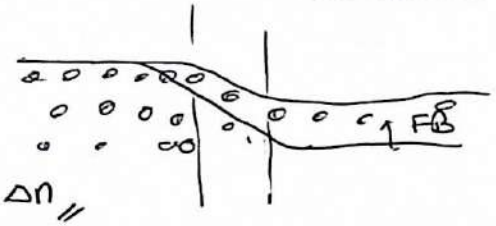
& $n = n_0 + \Delta n$; $p = p_0 + \Delta p$.



$\Rightarrow (G_0 + R) \propto np = \mu n p$

$= \mu (n_0 + \Delta n)(p_0 + \Delta p)$

$= \mu n_0 p_0 + \mu (n_0 + p_0 + \Delta n) \Delta n$



or $R = \underbrace{\mu(n_0 + p_0 + \Delta n)\Delta n}_{\tau}$ ↳ per c.c. ⇒ μ has unit cc/s.

↙ per cc per sec.

$\Rightarrow R = \tau^{+}\Delta n$ where $\tau = \frac{1}{\mu(n_0+p_0+\Delta n)} \overset{\text{if } \Delta n \leq n_0, p_0}{\simeq} \frac{1}{\mu(n_0+p_0)}$

$\Rightarrow \boxed{R = \frac{\Delta n}{\tau}}$

↳ excess carrier recombination time.

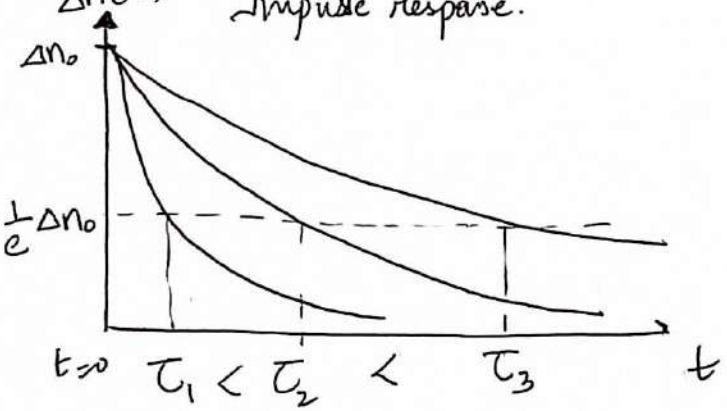
$\mu \rightarrow$ rate constant of recombination: → radiative
→ non-radiative.

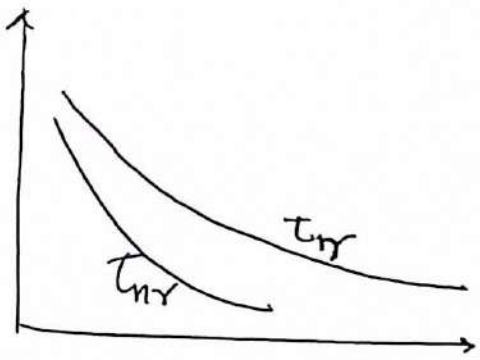
$\Rightarrow \mu = \mu_r + \mu_{nr}$

$\Rightarrow$ Rate of Recomb $= \mu_r np + \mu_{nr} np.$

Let $\tau_r \propto \frac{1}{\mu_r}$ & $\tau_{nr} \propto \frac{1}{\mu_{nr}}$.

· $\Delta n(t)$ → Impulse response.





	τ_r	τ_{nr}
Si	10ms	100ns
GaAs	100ns	100ns
GaN	10ns	0.1ns

Small lifetime $\tau \Rightarrow$ it is dominant!

⇒ Si is a poor radiator.

Internal Quantum Efficiency (η_i)

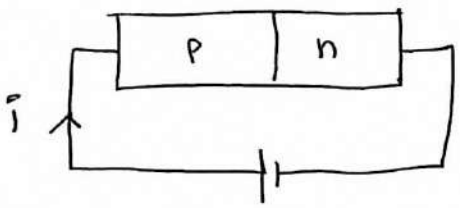
$$\eta_i = \frac{\text{radiative recombinations per sec}}{\text{Total recombinations per sec}}$$

$$= \frac{R_r}{R_r + R_{nr}} = \frac{\tau}{\tau_r}$$

η_i of GaAs $\cong$ 0.5

η_i of Si $\cong$ 10^{-5}

} In general direct bandgap materials have $\eta_i \simeq 0.2$–0.9 & indirect are very low.



R → no. of recombinations per unit time per unit vol.

$$R = \frac{\Delta n}{\tau}$$

i = charge / time.

⇒ no. of carriers per unit time.

Rate of recombination of carriers = Rate of injection of carriers.

$RV = (i/e)$

↳ volume.

$$\Rightarrow \frac{i}{e} = \frac{\Delta n}{\tau} \cdot V$$

What is the optical power generated

$\eta_{ph} \cdot h\nu \longrightarrow$ total power generated.
↳ no. of photons.

$V \cdot R \rightarrow$ rate of recombinations.

$\eta_i VR \rightarrow$ no. of photons generated

$\Rightarrow \eta_i RV\, h\nu \rightarrow$ optical power generated.

$$P_{gen}^{opt} = \eta_i \left(\frac{i}{e}\right) h\nu$$

$\Rightarrow$

$$\boxed{P_{gen}^{opt} = \eta_i \left(\frac{h\nu}{e}\right) i} \longrightarrow \text{power vs. applied current!}$$

Lec 28 LED I - Device structure & Parameters.

Let $\eta_e \rightarrow$ extraction efficiency.

$\Rightarrow$

$$P_{out} = \underbrace{\eta_e \eta_i}_{\eta_{ext}} \left(\frac{i}{e}\right) h\nu$$

$\eta_{ext} \rightarrow$ external efficiency.

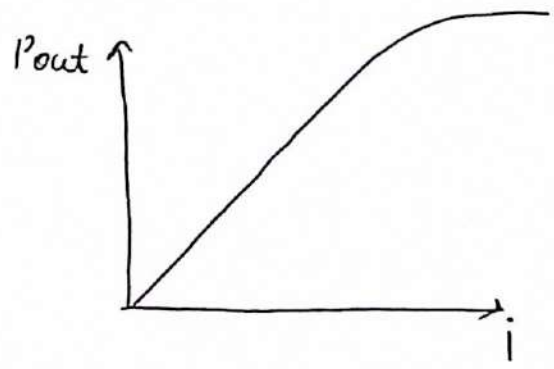
$\Rightarrow$

$$\boxed{P_{out} = \eta_{ext} \left(\frac{i}{e}\right) h\nu}$$

$$P_{out} = \eta_{ext}\left(\frac{i}{e}\right)\frac{hc}{\lambda}$$

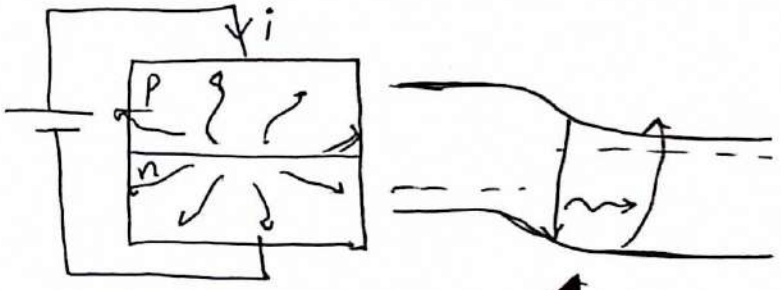
$$= \eta_{ext}\left(\frac{hc}{e}\right)\frac{i}{\lambda}$$

$$\boxed{P_{out} = \eta_{ext}\left(\frac{1.24}{\lambda}\right) i} \quad \Rightarrow P_{out} \propto i$$



LED

- Surface emitting LED (SLED)
- Edge emitting LED (ELED)



> Some light is reflected back due to air-dielectric interface.

$$R = |r|^2 = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

$$= \left(\frac{3.6 - 10}{3.6 + 1.0}\right)^2$$

$$\simeq 0.32$$

r → reflection coeff for Power at normal incidence

Sources of loss

① > Reabsorption of generated photons

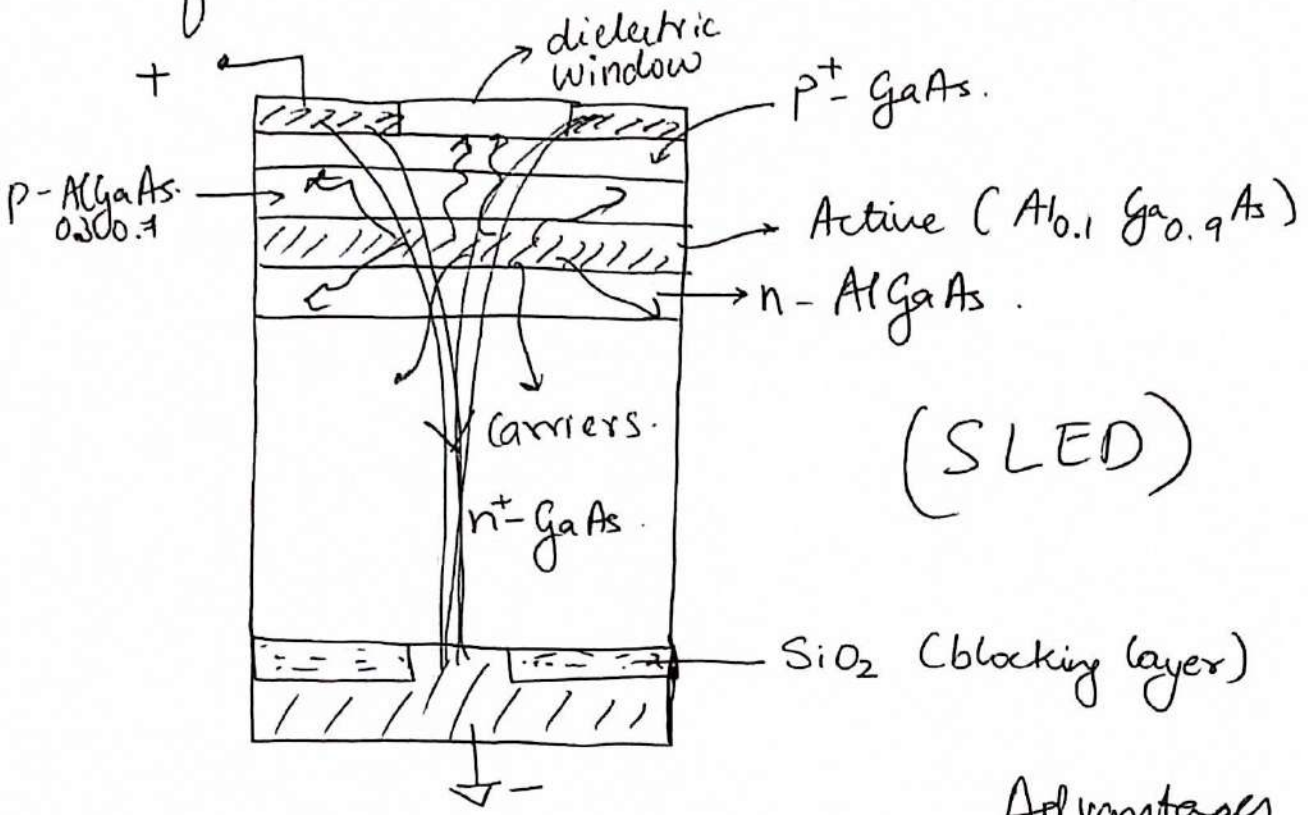
② > Reflection loss at S.C-air interface.

③ > Total internal reflection loss.

Typically $\eta_e \simeq 0.2 - 0.3$

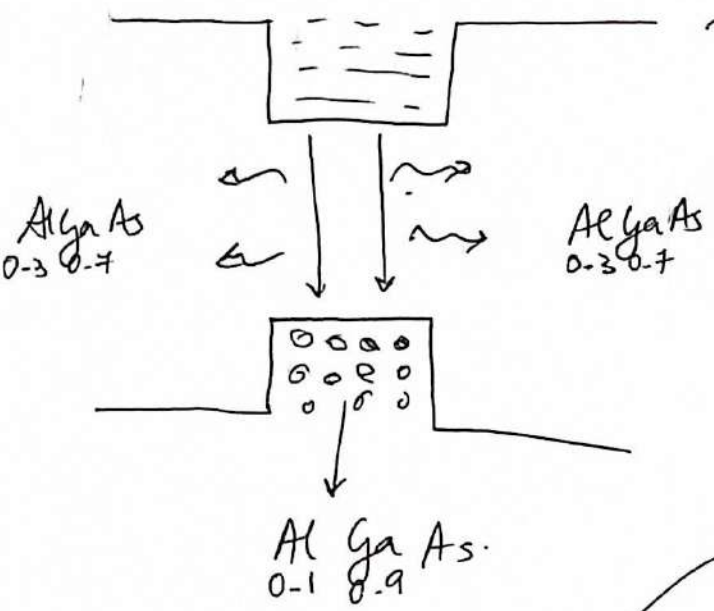
How to reduce? Double Hetero Structures //

Use of Double Hetero Structures to mitigate losses.



(SLED)

Advantages

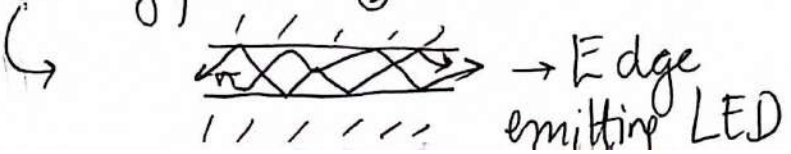


① Avoids re-absorption losses since bandgap outside active region is higher.

② Carrier confinement causes very high charge concentration.

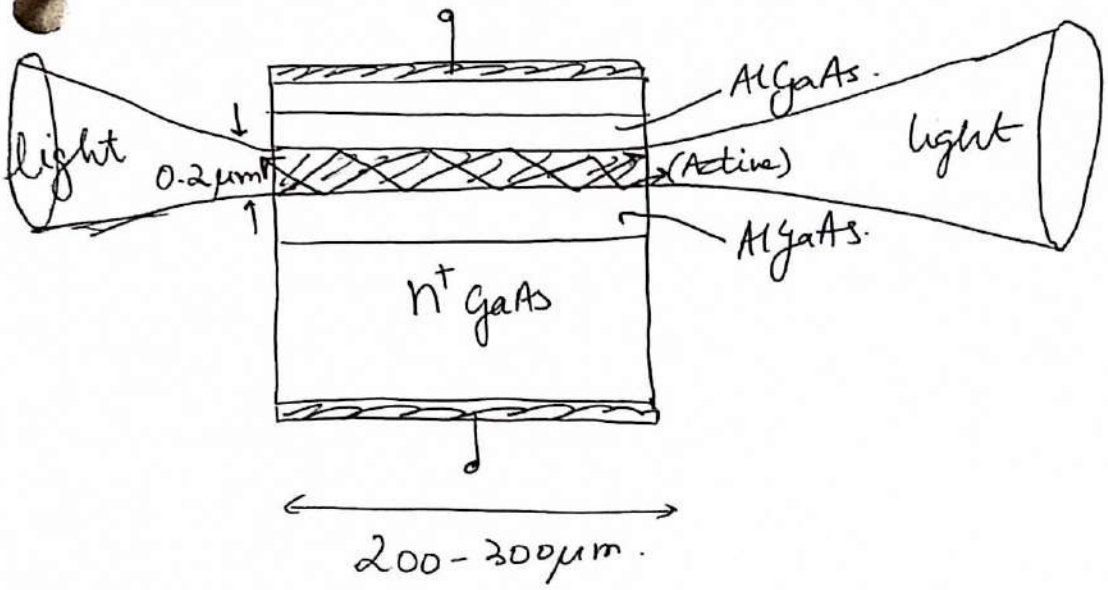
③ Optical confinement (not relevant for surface emitting LED)

Refractive index is higher when bandgap is ~~high~~ low!!



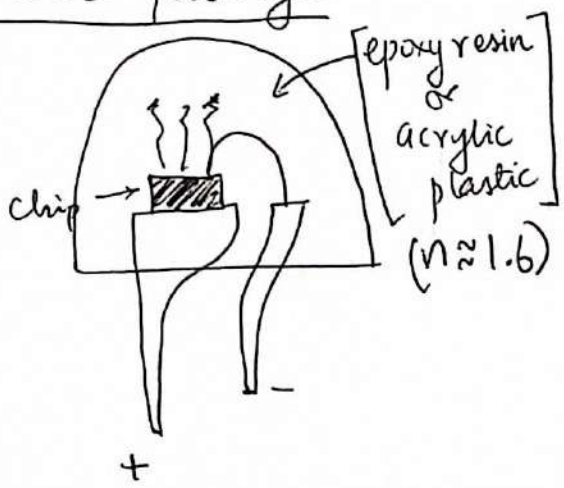
→ Edge emitting LED

ELED



Higher directionality in output light compared to SLED.

SLED package



1) To protect the chip & reduce reflection losses.

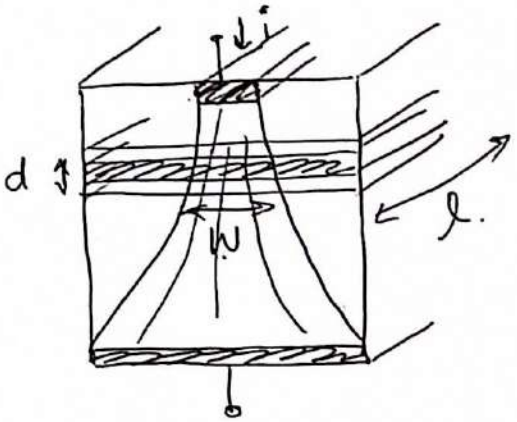
> Bragg reflectors in n^+ GaAs can reflect light up.
> Texturizing the surface can reduce Total internal reflection

---

Lec 29 LED II — Device Characteristics

$$\Delta n = \frac{(i/e)\,\tau}{l \times w \times d} \quad \& \quad \frac{i}{l \times w} = J \leftarrow \text{current density.}$$

$$\Rightarrow \boxed{\Delta n = \frac{J\tau}{ld}}$$



LED device characteristics

1. current power — voltage.
   $i-P$ & $i-V$ characteristic

aka $L-I$ characteristic
light current

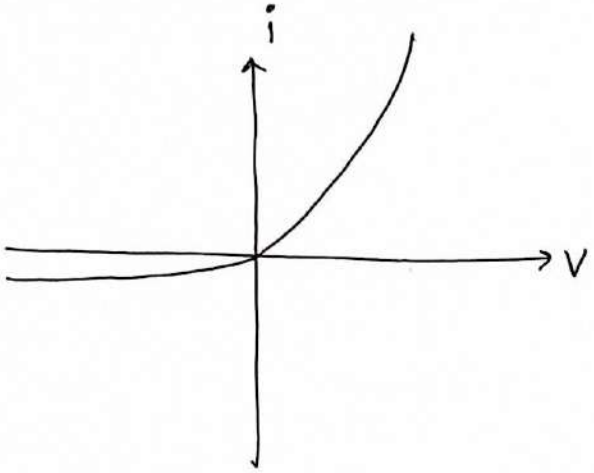
2. Wavelength spectrum (spectral distribution)

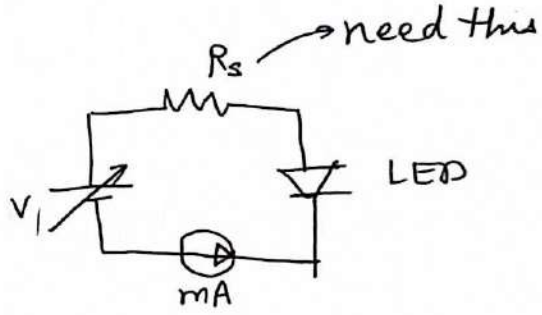
3. Emission pattern (angular spectrum or radiation pattern)

4. Modulation bandwidth.

---

1. IV characteristics

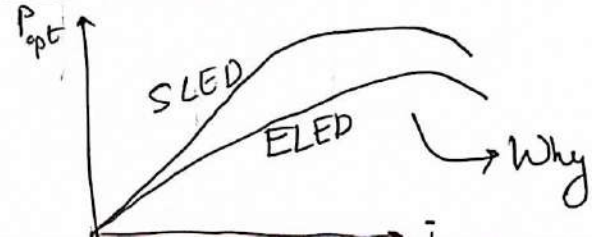




R_s is needed to ensure current does not exceed $I_{F_{max}}$ → data sheet!

max supply voltage. ← $\frac{V_{max}}{I_{Fmax}} = R_s$.

LI characteristic



→ Why saturation?

$P_{out} = \eta_{ext} \left(\frac{i}{e}\right) h\nu$

Why saturation occurs?

1. Joule heating i^2R

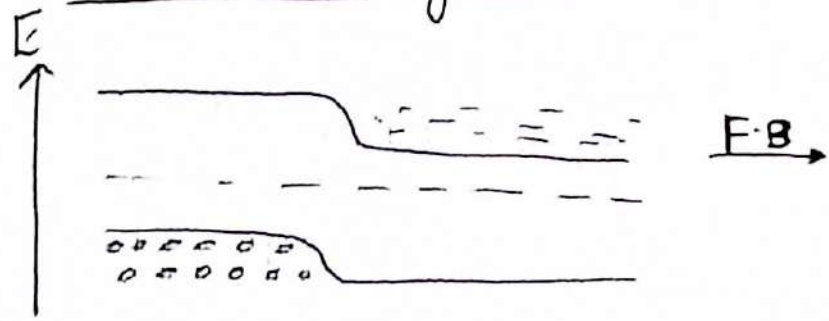
As temp ↑ η_i (internal quantum efficiency) decreases since too many phonons exist.

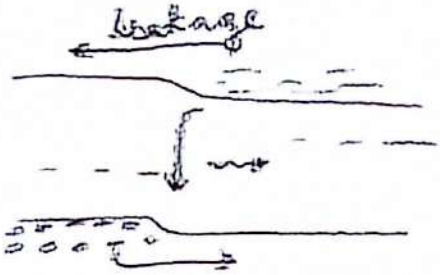
2. Carrier leakage loss

3. Stimulated emission loss.

Lec 30 - LED III - Output Characteristics

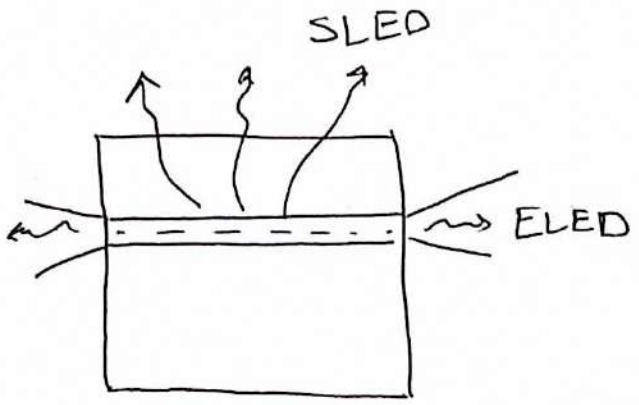
2. Carrier leakage loss

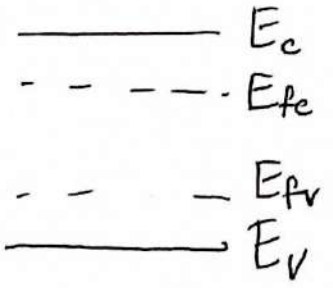




Instead of recombining in the depletion region, they pass by the barrier & directly to the electrode

3. Stimulated Emission loss





As FB ↑, $E_{fc} - E_{fv}$ ↑ ⇒ stimulated emission starts increasing

⇒ stimulated emission occurs along ELED direction.

⇒ it is a loss for SLED & gain for ELED.

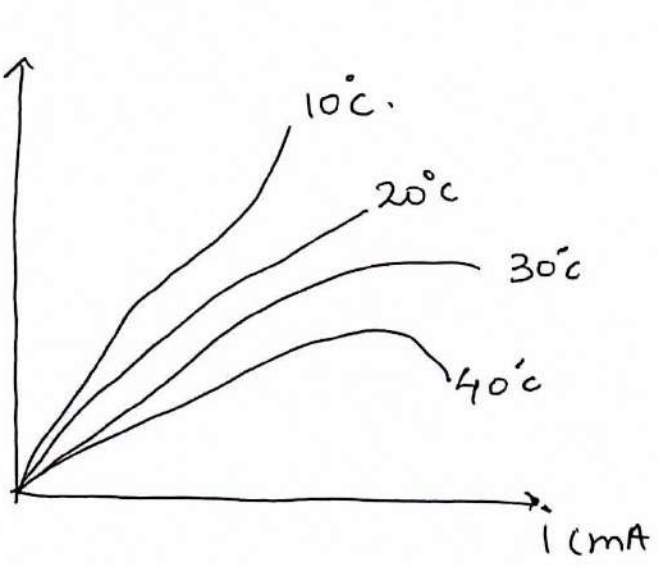
> However, even for ELED, the 1.) & 2). loss mechanisms dominate at room temp.

> At lower temperatures it is possible to see "gain" in ELEDs. Such diodes are called SLDs.

↳ Superluminescent diodes.

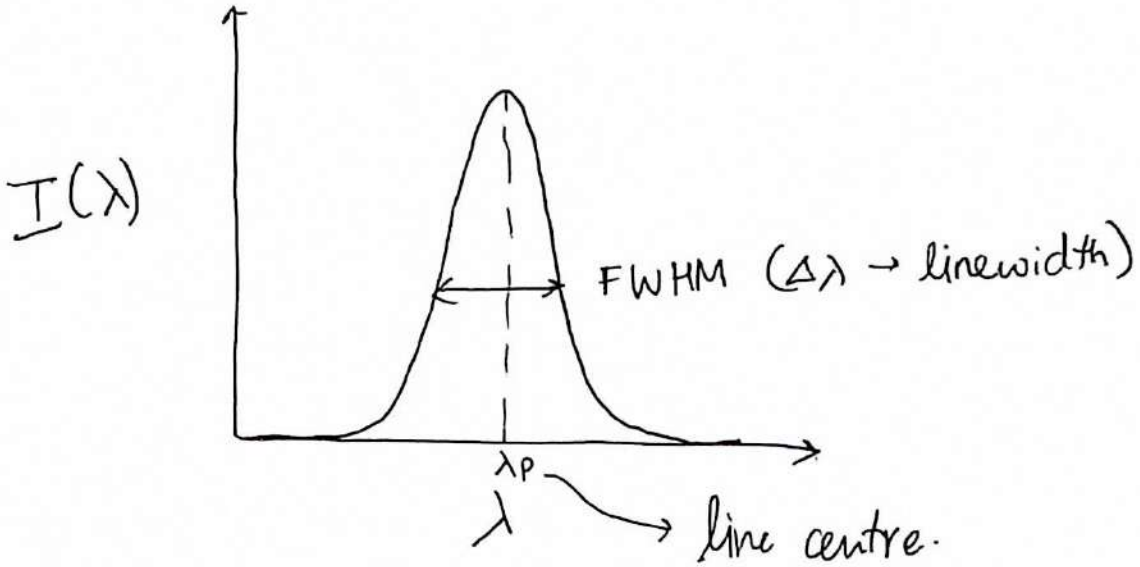
↓

ELEDs that are much longer to increase Stimulated gain.



Lec 30 LED-III - Output Characteristics (contd.)

Wavelength Spectrum (Spectral distribution)



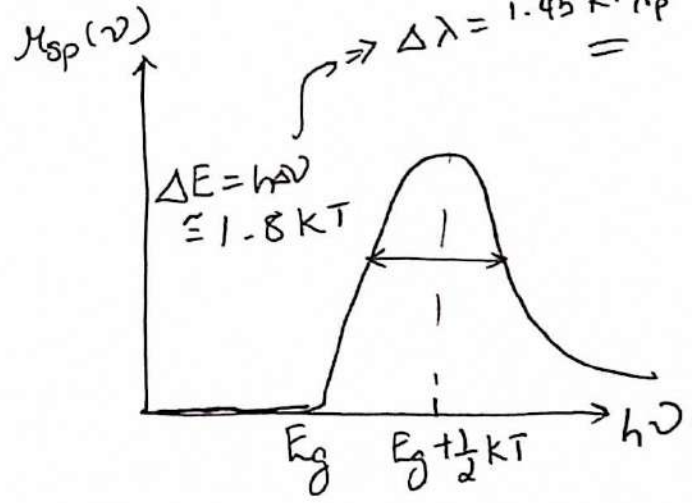
Recall,

$$M_{sp}(\nu) = D_0 (h\nu - E_g)^{1/2} \cdot e^{-(h\nu - E_g)/kT}$$

$$= D_0 x^{1/2} e^{-ax}.$$

$$h\nu_p = E_g + \frac{1}{2}kT$$

$$\Delta\lambda \simeq 1.45\, kT\, \lambda_p^2$$

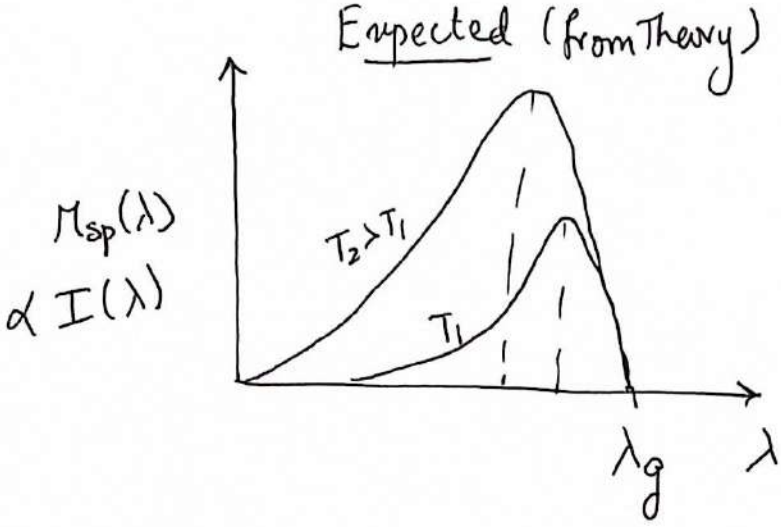


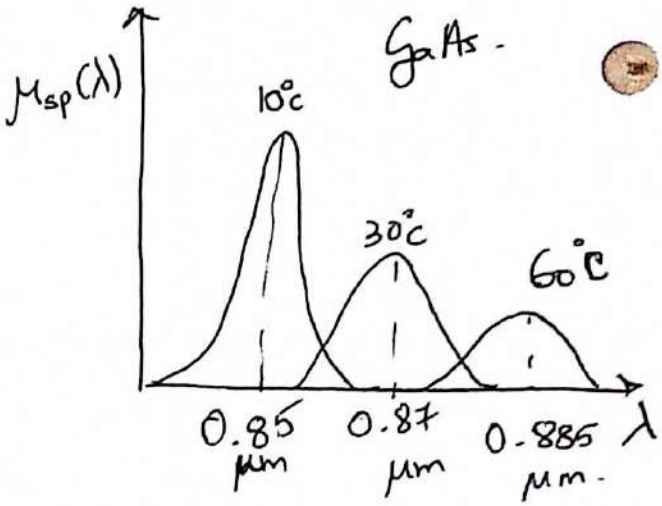
Example: $kT \simeq 0.025$ & let $\lambda_p = 800\text{nm}$ (GaAs)

$$\Rightarrow \Delta\lambda = 1.45 \times 0.025 \times 0.64 \cong 0.023\,\mu\text{m}.$$

Typically $\Delta\lambda \sim$ [illegible] visible.

Measurements





* peak goes up in λ instead of lower.
* Also peak goes down in M_{sp} instead of higher.

Why the discrepancy?

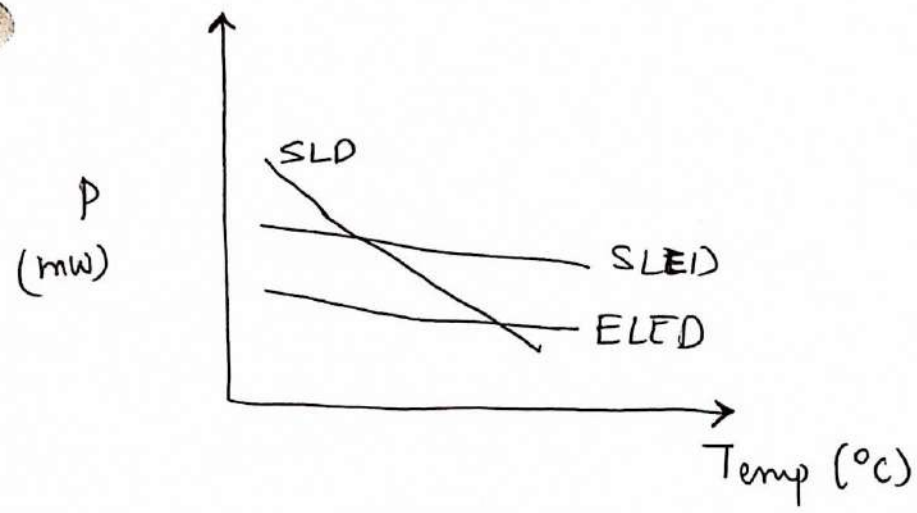
1) Bandgap is temperature dependant.

	0k	300k
GaAs:	1.52eV	1.42eV

Empirical formula for GaAs: $E_g(T) = 1.519 - \frac{5.405 \times 10^{-4} T^2}{(T + 204)}$

2) Peak decreases since η_i goes down exponentially with T. due to increase in phonon transitions.

Lec 31 1) L-I characteristics (review)



3) Angular distribution. (Radiation pattern)

$$I(\theta) = I_0 (\cos\theta)^m \quad - \text{LED}.$$

$m = 1, 2, 3 \ldots$

Planar LEDs (no encapsulation)

$I(\theta) = I_0 \cos\theta \cdot \rightarrow$ Lambertian distribution. ($\Delta\theta = 120°$)

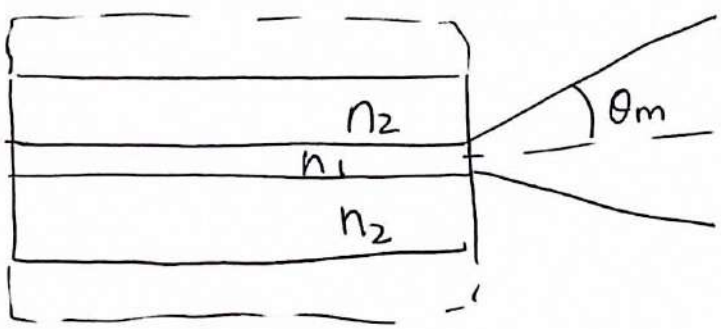
> Typically m is between 2 & 3.

> m should be low for display LEDs for wide angle viewing.

> ELEDs have higher directivity.

Numerical aperture.

$$\sin\theta_m = N.A = \sqrt{n_1^2 - n_2^2}$$



— Typically $\Delta\theta \simeq 30°$.

HPBW in elevation

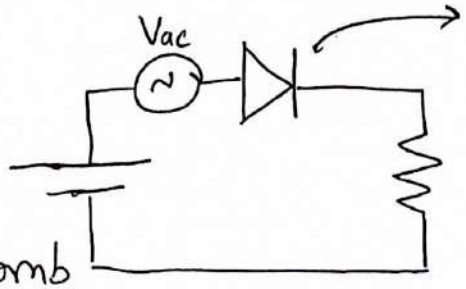
$\Delta\theta$ in azimuth is higher in ELEDs.

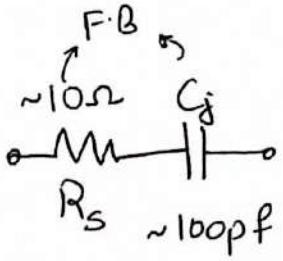
$\simeq 120°$

4. Modulation Bandwidth

- Carrier recombination time.
- RC time constant

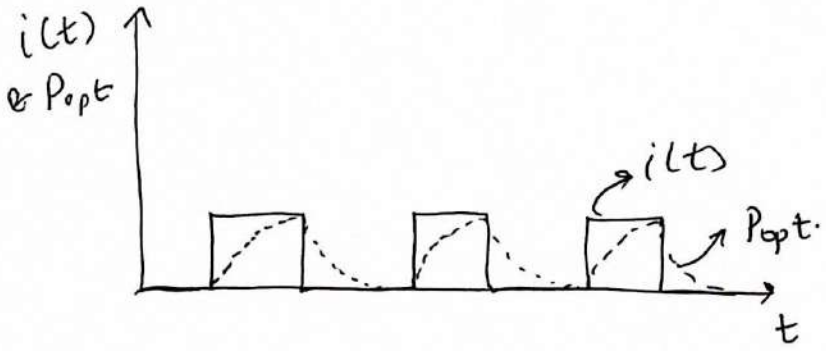
$$f_{BW} = \frac{1}{2\pi RC}$$

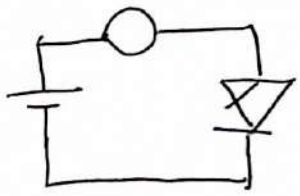




$\Rightarrow f_c \simeq 100MHz.$

1) Carrier recomb





Due to finite recombination time, Popt is limited.

$$\tau \simeq 10^{-6} - 10^{-9} s.$$

display ↑ ↖ communication.

$$i(\omega) = \frac{i_0}{(1+\omega^2\tau^2)^{1/2}}$$

↑ current in LED

LED-V Materials & applications

Responsivity

$$R = \frac{P_{opt}}{i} = \eta_{ext} \frac{1.24}{\lambda} \quad \text{Watt/Amp}$$

Typical numbers: $50\,\mu W/mA$.

$\Rightarrow 100mA \longrightarrow 5mW$

Light conversion efficiency or wall-plug efficiency

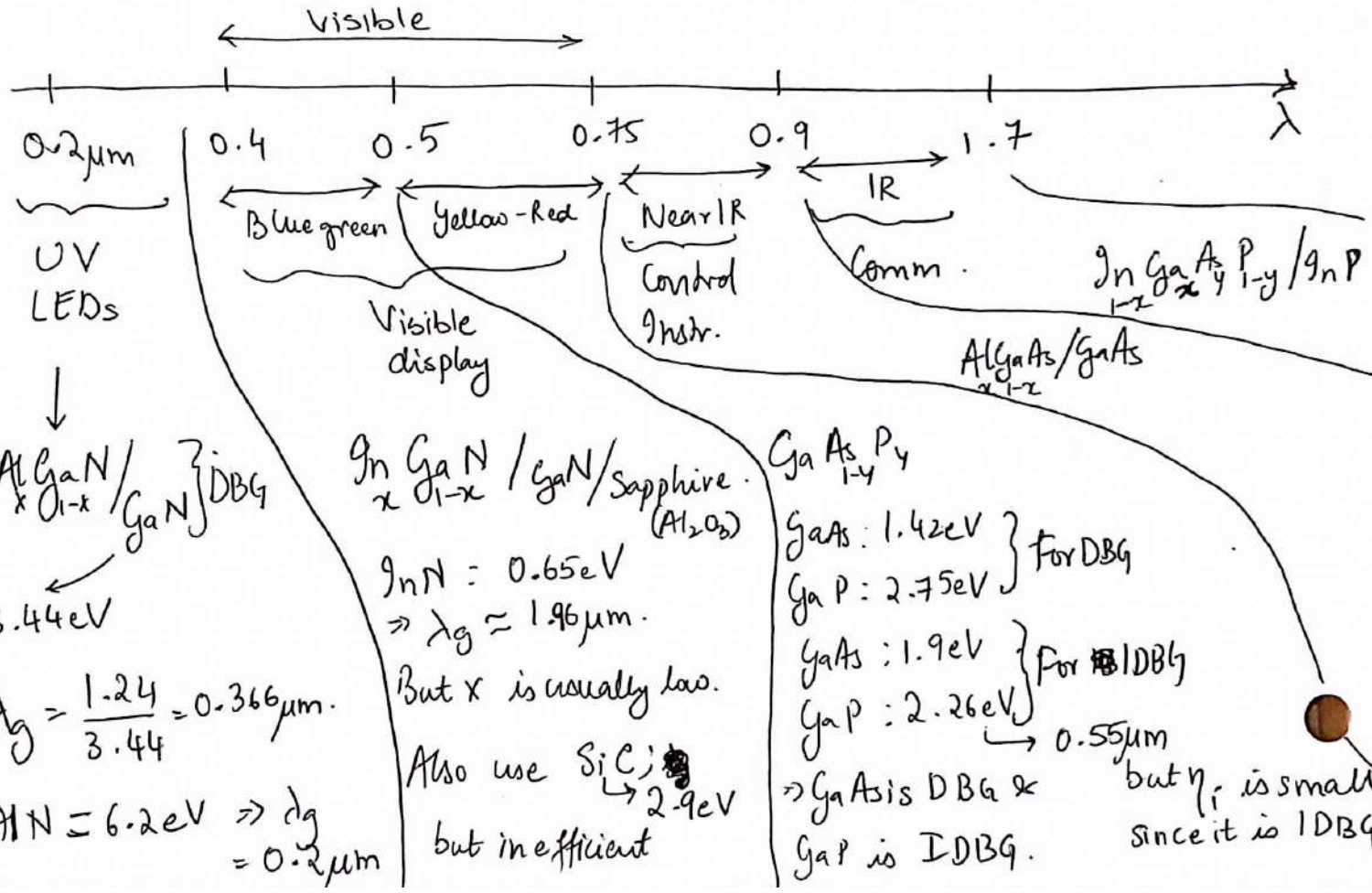
$$\eta = \frac{P_{opt}}{P_{elec}} = \frac{\eta_{ext} \cdot i \cdot \frac{1.24}{\lambda(\mu m)}}{iV} = \eta_{ext} \frac{1.24}{V\lambda}$$

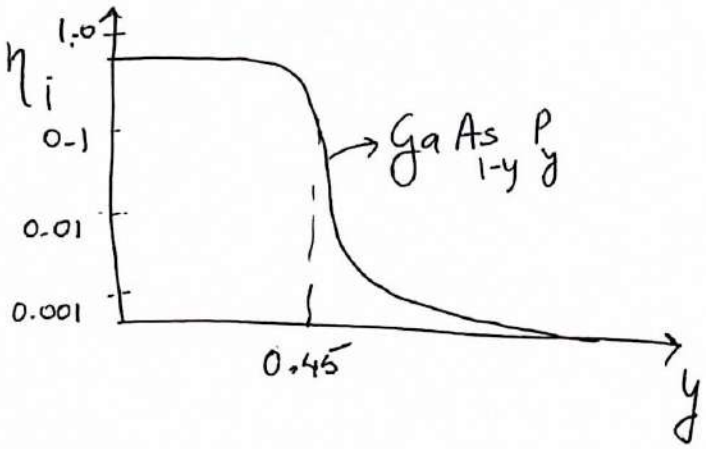
$V \rightarrow$ voltage across diode.

internal quantum		external	wallplug	
η_i	η_e	η_{ext}	η	Typical numbers.
	~~External~~ extraction	0.03-0.2	0.02-0.2	
0.3-0.6	0.1-0.3			

Applications

1) Display.
2) Communication (low data rate MM fiber & cheap).
   (upto 100 Mbps)
3) UV LEDs for purification/decontamination of water.
   - Security
   - Epoxy resin curing.
4) Control & instrumentation. (remote controls etc.)
   (opto isolators).
5) White light LEDs.

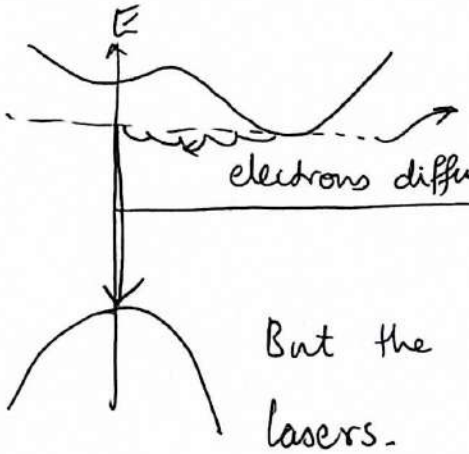




How to make 0.55μm LED without dropping η_i?

Iso-electronic centers

GaP:N



States due to N doping.

electrons diffuse & move to a "location" where radiative transition can occur.

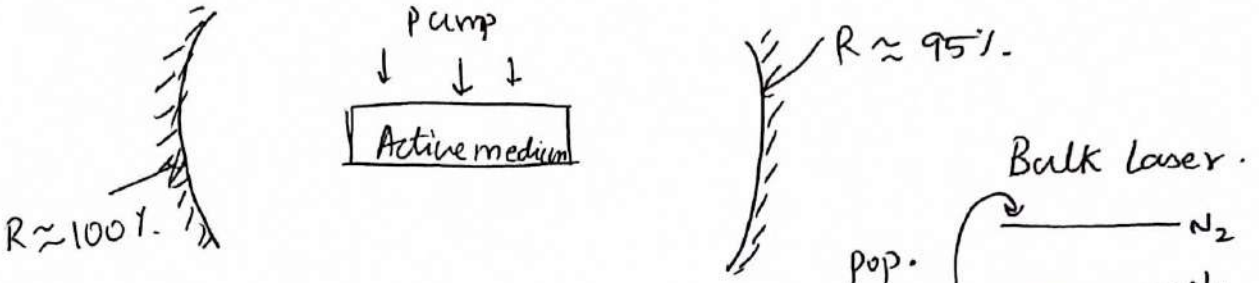
↳ created by N doping

But the process is slow ⇒ cannot be used for lasers.

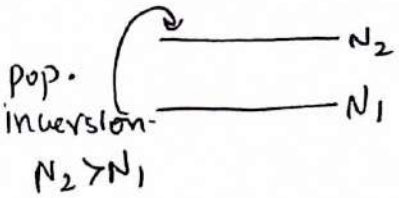
Lec 33 Laser Basics

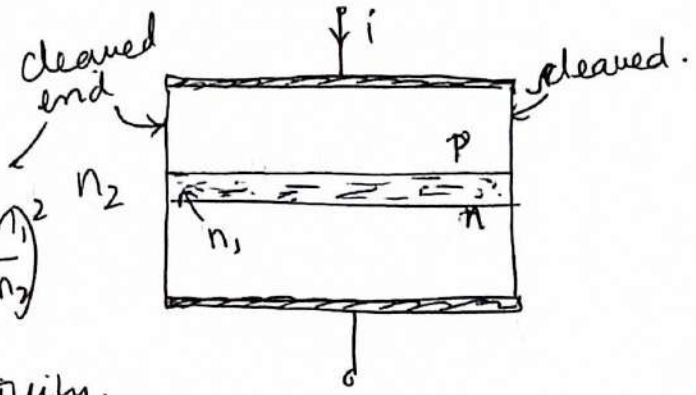
3 components of a Laser.

1) Gain medium
2) Pump or power supply
3) Optical Feedback unit.



Bulk Laser.





Semiconductor laser.

$$R = \left(\frac{n_2 - n_1}{n_1 + n_2}\right)^2$$

↖ reflectivity.

$$\Delta n = \frac{(i/e)\tau}{l \times w \times d}$$

$E_{fc} - E_{fv} > E_g$.

> If the reflecting mirrors are spherical, the modes inside are Hermite-Gauss or Laguerre-Gauss. Fundamental mode is Gaussian TEM_{00}.

↖ Bulk laser.

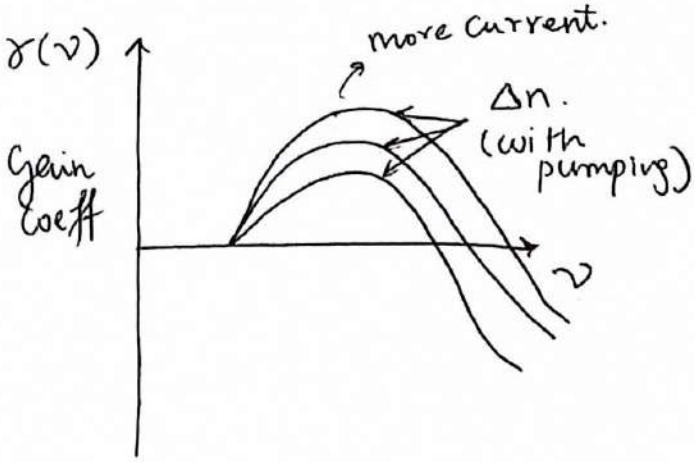
Laser dynamics (steady state).

Gain = loss

Gain in active medium

loss in resonator.

Recall, gain ↓



loss mechanisms

- Reflectivity of mirrors.
- Scattering loss inside medium.
- Diffraction losses due to finite beam extent.

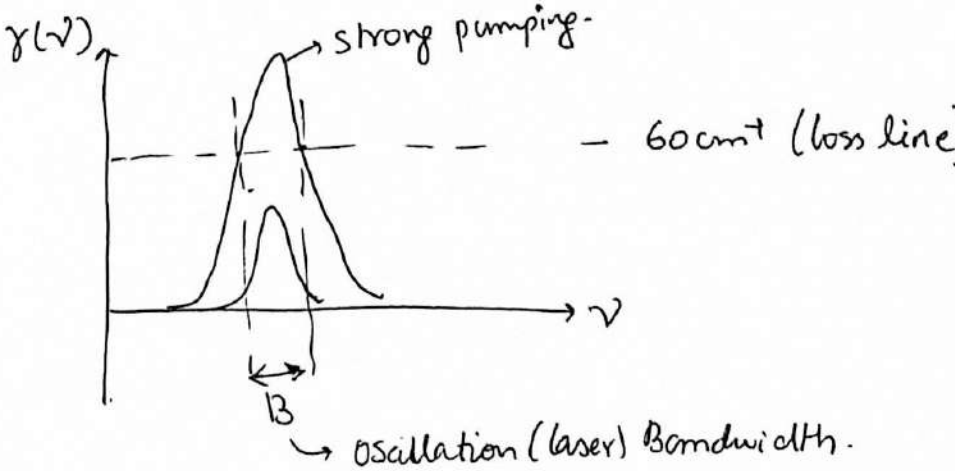
$$\underset{\text{loss coeff}}{\alpha} = \underset{\text{scattering}}{\alpha_s} + \underset{\text{mirrors}}{\alpha_m} = \alpha_s + \frac{1}{2l}\ln\left(\frac{1}{R_1 R_2}\right)$$

α_s: 10–50 cm^{-1}

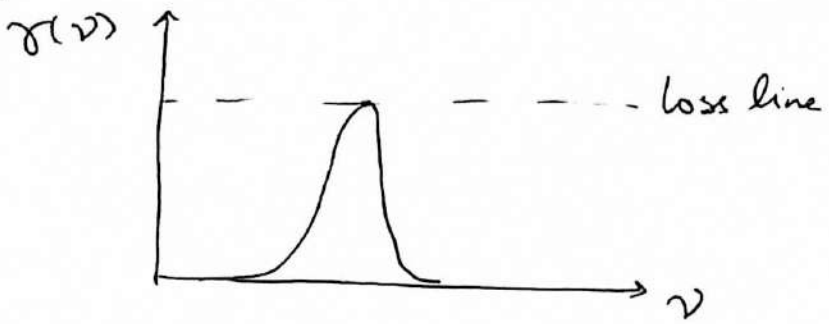
$2l \simeq 300\mu m$ → 38 cm^{-1}

$R_1 R_2$ → 0-32

$\Rightarrow \quad \alpha \simeq 60\text{cm}^{-1} \quad \gg \quad \gamma(\nu) = \alpha_r$ for laser action.



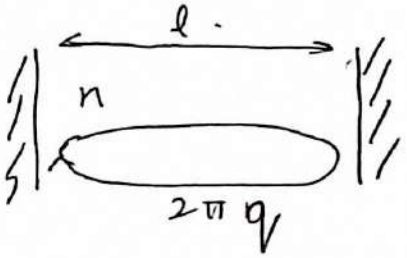
> To ensure gain = loss, the laser action changes the gain profile to be:



> Many dynamic mechanisms contribute to this steady state condition.

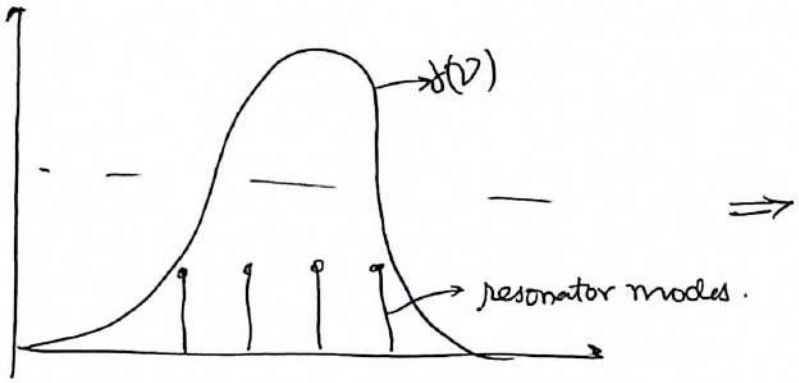
Optical Resonator

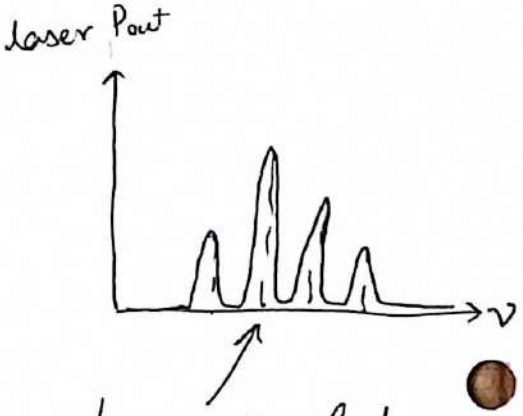
- Longitudinal modes → Resonance frequencies
- Transverse modes → Field distribution.



$$\Rightarrow k_0 n \times 2l = q \cdot 2\pi$$

$$\Rightarrow \boxed{\nu_q = \frac{q \cdot c}{2nl}}$$





Longitudinal laser modes.

Lec 34

Semiconductor Lasers - 1 Device Structures (shown in PPTs)

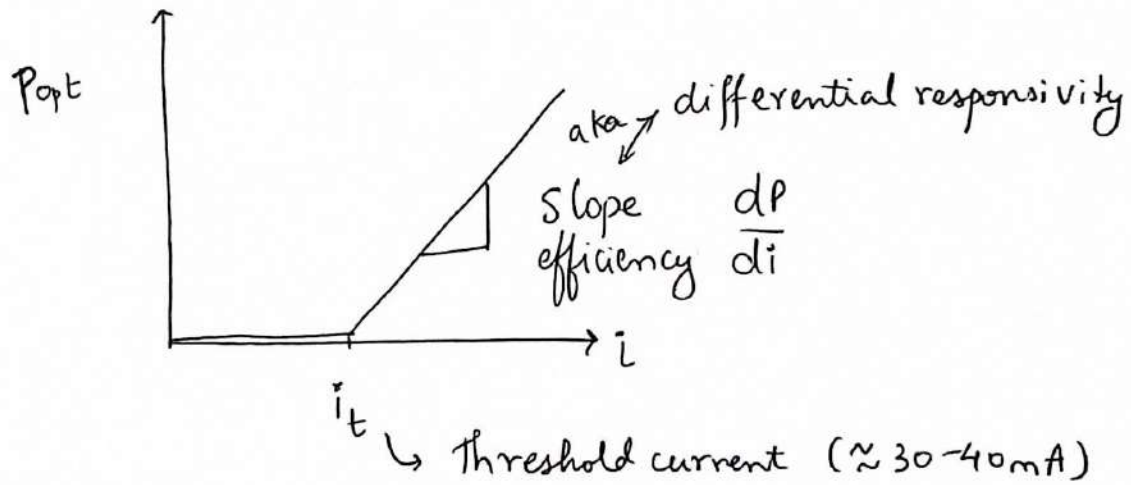
- Semiconductor lasers can be "directly modulated" (i.e modulate power supply), atleast upto few GHz.
- Basic structure
  - Forward bias p-n junction of a direct bandgap S-C.

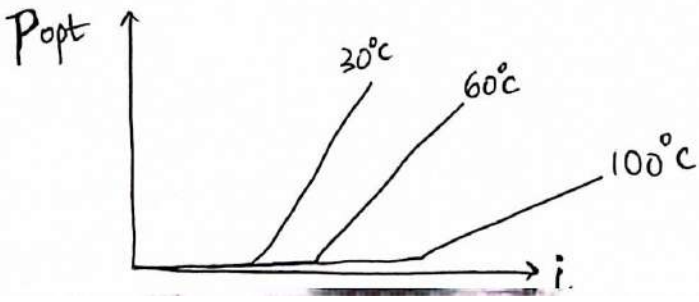
$$\gamma(\nu) = \frac{(c/n)^2}{8\pi\nu^2} \frac{1}{\hbar^2\tau} (h\nu - E_g)^{1/2} \left[f_c(E_2) - f_v(E_v) \right]$$

$h\nu = E_2 - E_1$

(slides are used for remaining lecture).

[Gain guided vs. Index guided lasers]





~~become~~ because recombs are very frequent
↑
→ very temperature sensitive.

Lec 35 Laser II - Output Characteristics

Recap: $\gamma_p = \alpha_a \left(\frac{\Delta n}{\Delta n_T} - 1 \right)$

Lasing condition: Gain = Loss.

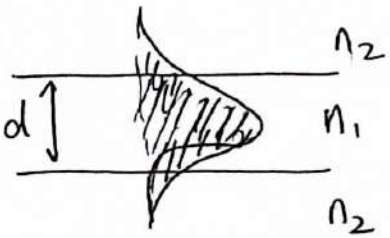
$\Rightarrow \gamma_{pt} = \alpha_r$.

$\Rightarrow \alpha_r = \alpha_a \left(\frac{\Delta n}{\Delta n_T} - 1 \right) = \alpha_a \left(\frac{J_t}{J_T} - 1 \right)$

or $\boxed{J_t = J_T \left(1 + \frac{\alpha_r}{\alpha_a} \right)}$

Confinement Factor Γ

$\Gamma \rightarrow$ Fractional energy in the active region. Only this experiences gain.



$\Rightarrow$ Cavity gain $= \Gamma \gamma_p$

$\Rightarrow$ Really we have $\Gamma \gamma_p = \alpha_r$.

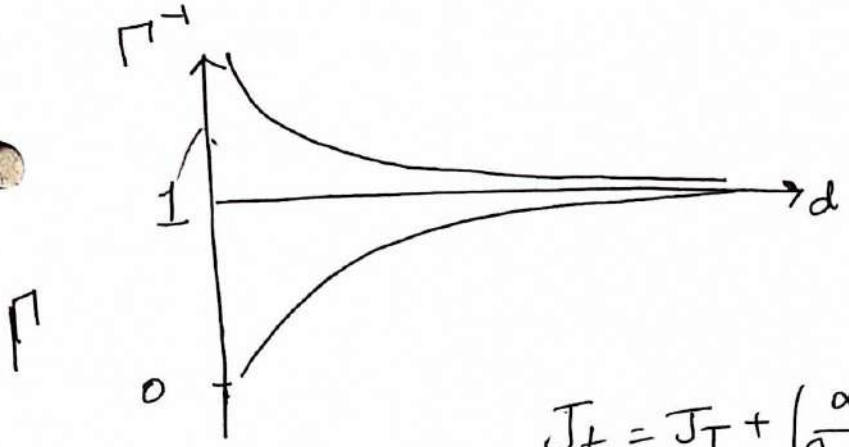
$\Rightarrow \boxed{J_t = J_T \left(1 + \frac{\alpha_r}{\Gamma \alpha_a} \right)}$

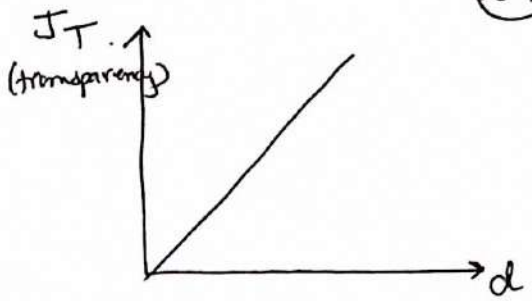
J_t ↑ Threshold

$V = \frac{2\pi}{\lambda} d \sqrt{n_1^2 - n_2^2}$ if d is small, evanescent energy ↑

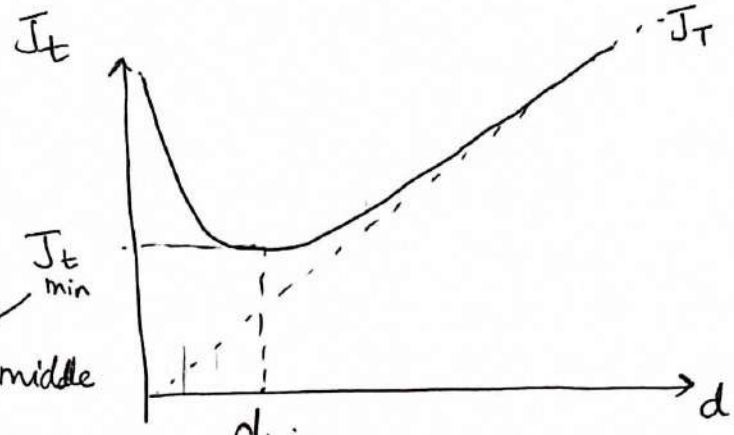
V-number

$\Rightarrow \Gamma \downarrow$ which is bad.





$$J_t = J_T + \left(\frac{\alpha_r}{\Gamma d_a}\right) J_T$$



This is the reason for middle layer to have $\approx 0.1 - 0.2\,\mu m$ thickness.

d_{min} → $\approx 0.1 \sim 0.2\,\mu m$

Spectral linewidths

$\Delta\lambda \approx$ 20–40 nm for LEDs

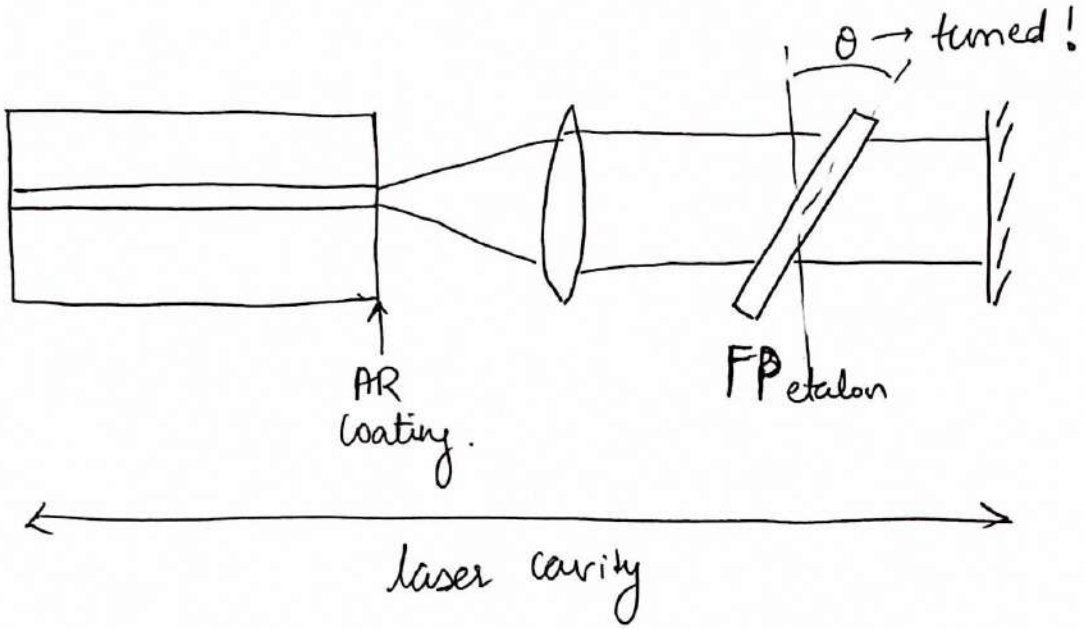
2–3 nm for F.P. laser diodes

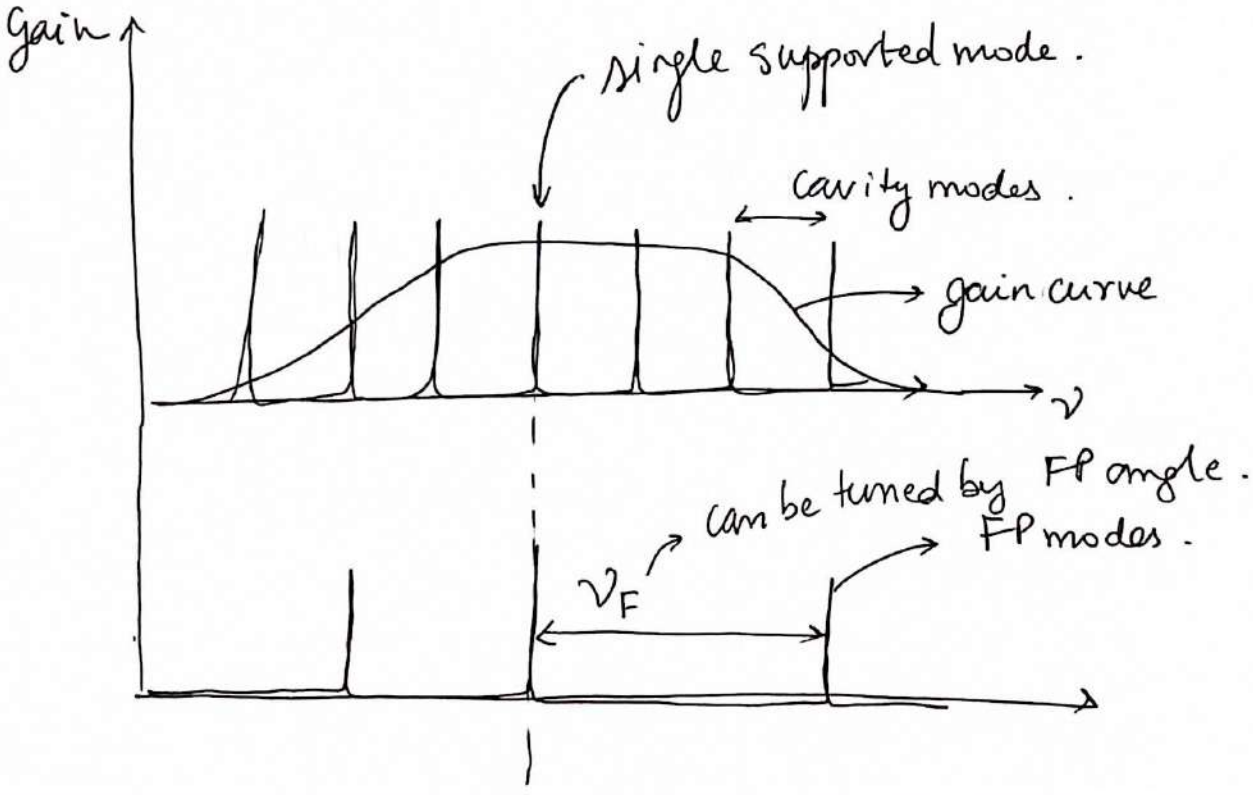
≤ 0.1 nm for DFB lasers & VCSELs.
(distributed feedback)

Lec 36 - Laser III - Single Frequency Lasers

Fabry Perot Etalon (ECL - external cavity laser).

$\nu_F = \frac{c}{2nl}$ → Free spectral range or freq. spacing b/w modes.

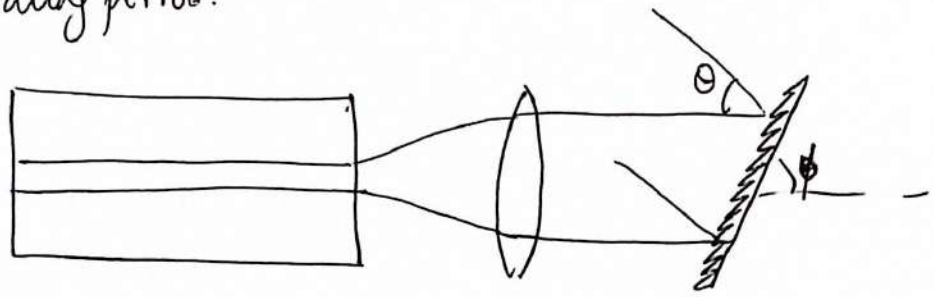




> ECL can also be made using a grating.

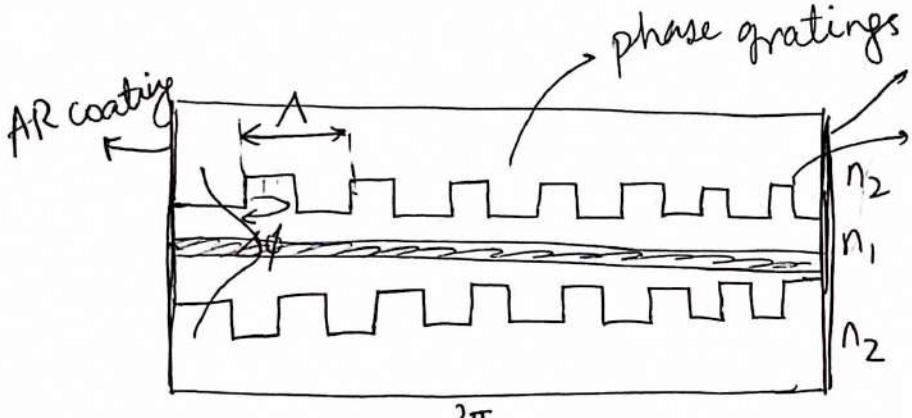
$2d \sin\theta = n\lambda$

d → grating period.



at some λ, get full reflection.

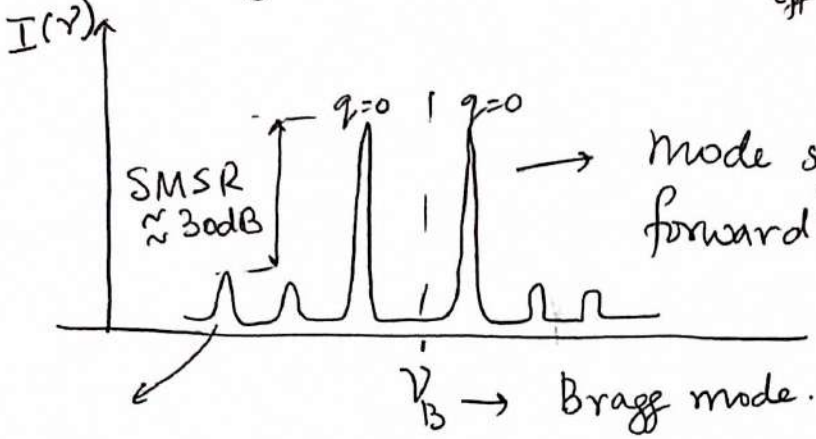
Distributed feedback laser (DFB) (Fixed frequency lasers)



$\Delta\phi = 2 k_0 \bar{n} \frac{\Lambda}{2} = \pi$ ($k_0 = \frac{2\pi}{\lambda_B}$) → not 2π since π happens already at an interface.

$$\lambda_B = 2 n_{effective} \Lambda$$

In reality $\nu_L = \nu_B \pm \left(\frac{c}{2n_{eff}L}\right)\left(q+\frac{1}{2}\right)$



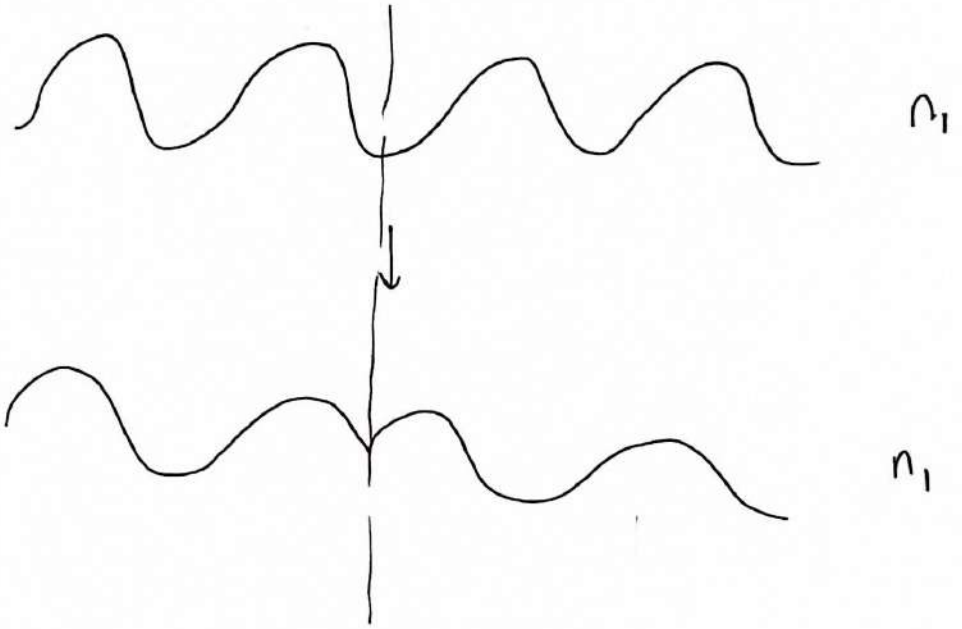
→ Mode splitting occurs because the forward & backward modes interact.

ν_B → Bragg mode.

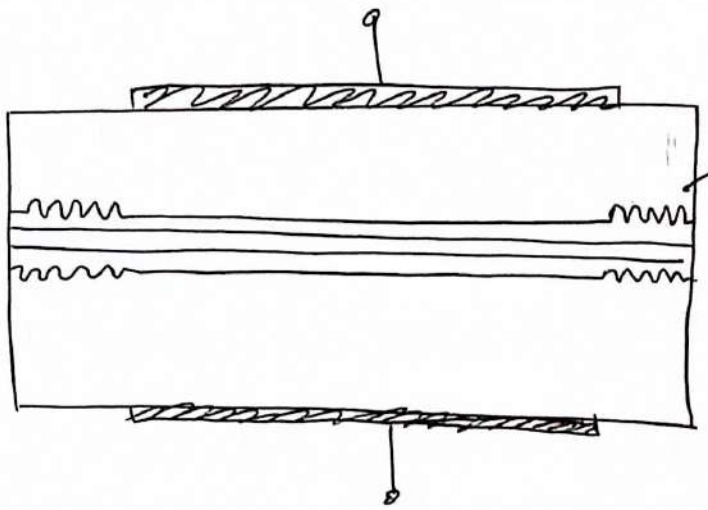
SMSR → sidemode suppression ratio.

because it is not a perfect sinusoid grating.

> The degeneracy can be broken by introducing a 1/4 shift in the cavity. This shift is introduced at the center of the grating & causes a strong reflection at ν_B.



DBR Distributed Bragg Reflector laser



> DBR lasers are much more stable than DFB. Why?

$n_{eff} = n_r - j n_i$ → $n_i < 0 \Rightarrow$ gain. { n_r & n_i are related by Kramers Kronig }

↳ The imaginary part is a function of electrical current since it depends on medium gain.

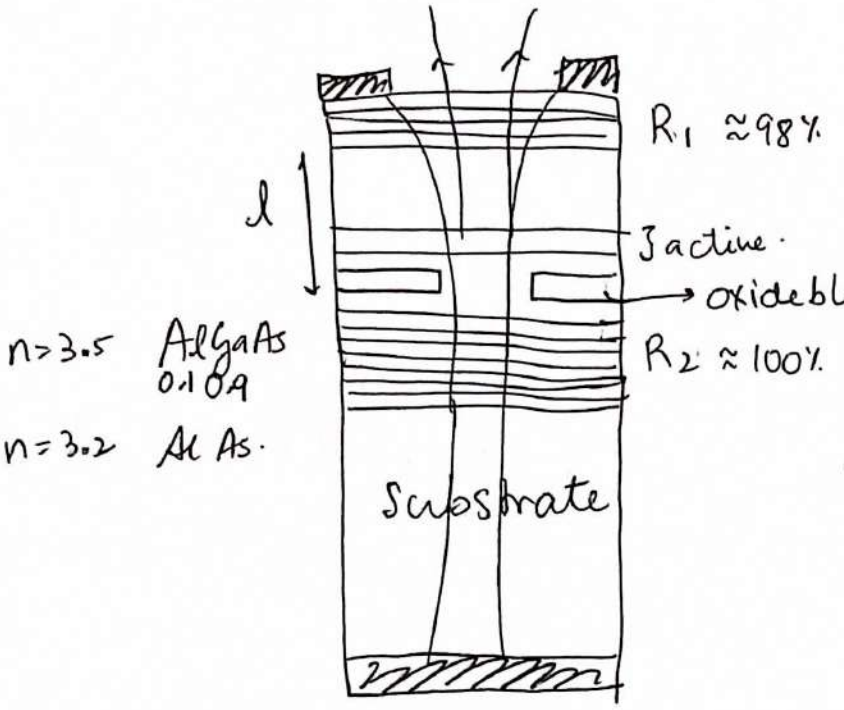
> So n_{eff} is a function of applied current ⇒ $\lambda_B = 2 n_{eff} \Lambda$

how depends on current.

> In DBR, current does not flow through reflecting part.

Lec 37 VCSEL : Vertical Cavity Surface Emitting Lasers.

(Vertical DBR laser).



> Useful for array of lasers.

> High density data interconnects in computer chips.

> Can be directly modulated upto many GHz

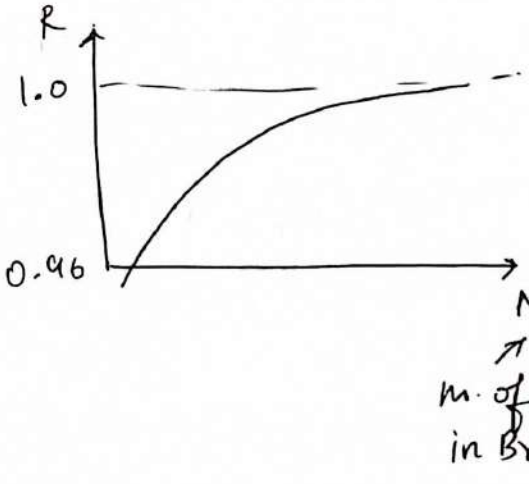
When $R \approx 0.9 \rightarrow l = 285\mu m$

$R \approx 0.98 \rightarrow l \approx 10\mu m$

$R \approx 0.99 \rightarrow l \approx 2.5\mu m$

$R \approx 0.998 \rightarrow l \simeq 0.2\mu m$

$$l \approx \frac{1}{(\alpha - \alpha_s)} \ln\left(\frac{1}{R}\right)$$

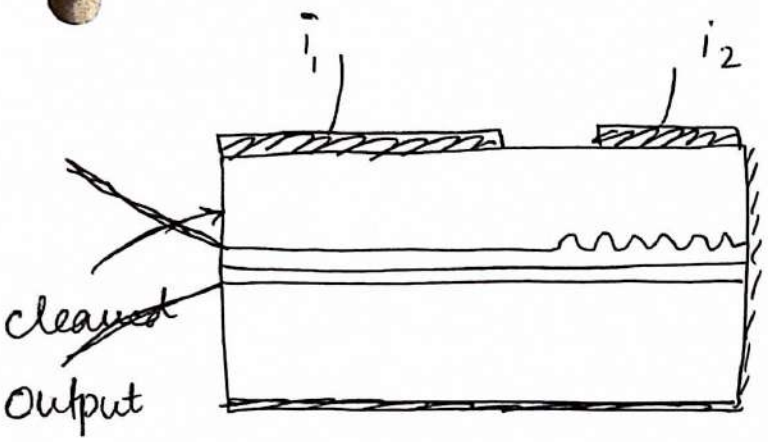


> $l \approx 10\mu m \Rightarrow \nu_f$ is large & therefore only one mode exists!

> Output rad patter is also symmetric.

> Controlling transverse modes is very difficult → Current research.

Tunable laser based on DBR structure.



i_1 controls laser power.

i_2 controls laser frequency

$$\nu_q = \frac{c}{\lambda_B} = \frac{c}{2 n_{eff} \Lambda}$$

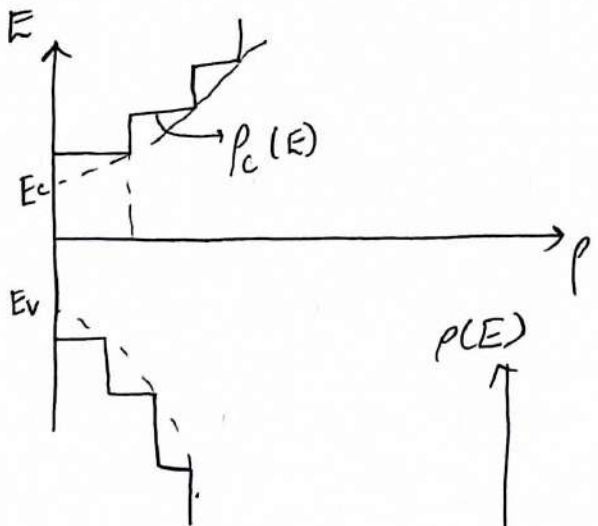
Tunable range $\simeq$ 5 - 10nm

- ECL tuning range $\simeq$ 50nm.
- DFB lasers can be tuned by temperature ($\simeq$ 1 - 3nm).

$$\Delta\lambda \rightarrow \left(0.1 \text{ nm}/^{\circ}\text{C}\right)$$

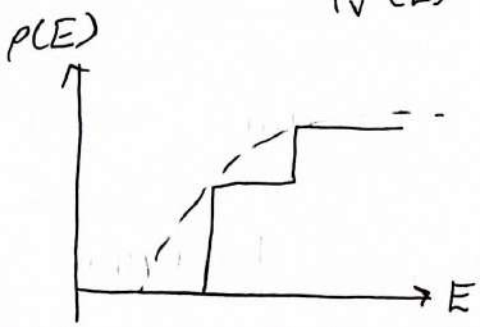
Lec 38 : Quantum Well Lasers.

Recall from lec ⑥, Density of states in Quantum Wells.

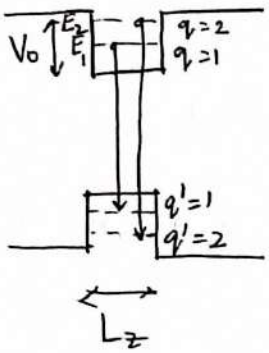


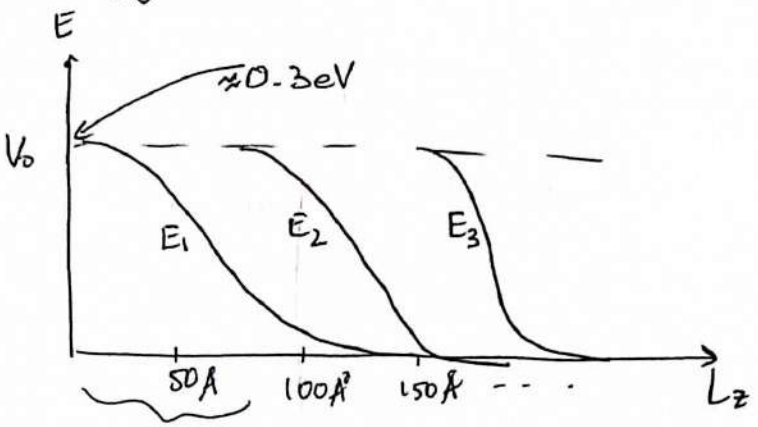
$$\rho_c(E) = \frac{m_c}{\pi \hbar^2 L_z}$$

$$\rho_v(E) = \frac{m_v}{\pi \hbar^2 L_z}$$



In Lec ⑫ & ⑬, → Energy states in Quantum Well Structures.



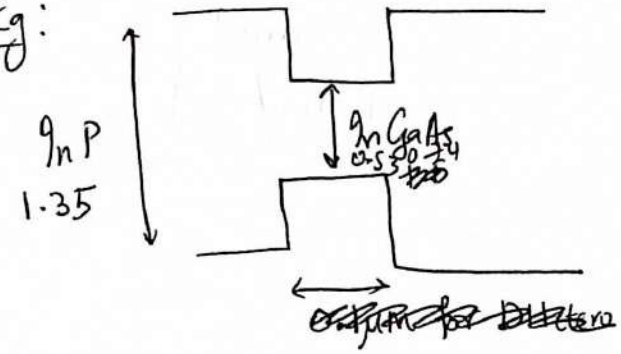


↳ only one mode allowed

- Therefore control of λ_{opt} can be more easily achieved by changing L_z.

⇒ Effective bandgap changes with L_z!

Eg:



$InGaAs/InP$ ⇒ $\Delta E_g = 0.61eV$

0.74eV 1.35eV

$\Delta E_c \simeq 0.4eV$ $\Delta E_v \simeq 0.21eV$

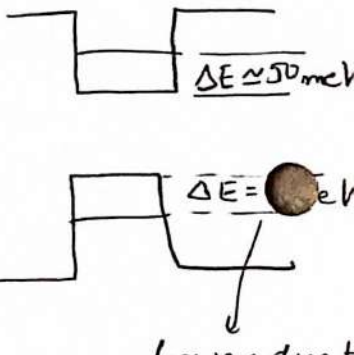
QWL: Quantum Well laser is a Sc Double Hetero laser, where the thickness of active layer ≤ de Broglie wavelength of electrons.

$$\lambda_g (InGaAs) = \frac{1.24}{E_g} = \frac{1.24}{0.74} \simeq 1.67\mu m. \text{ at } L_z = 1000nm$$

However when QWL dimensions are used,

$$\Rightarrow \lambda_g = \frac{1.24}{0.8} = \underline{1.55\mu m} \quad \text{when } L_z \simeq 100nm.$$

at 80nm, $\lambda_g \simeq 1.46\mu m$



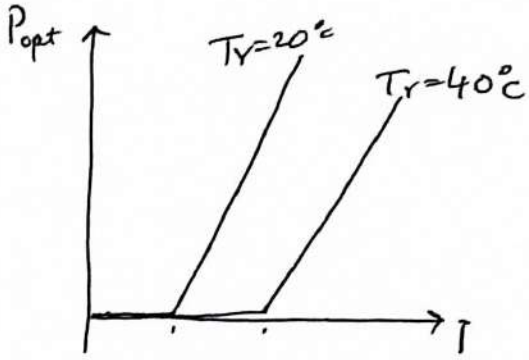
Advantages of QWL

→ lower thresholds

→ less temperature sensitivity.

> $i_t(T) = i_0(T_r)\, e^{+\frac{(T-T_r)}{T_0}}$

↳ reference.



$T_0 \sim 140K$ for GaAs FP lasers.

$T_0 \sim 400k$ for „ QW lasers.

Why is this so?

> Since only one (or few) modes exist; phonon transitions are less likely to occur. Therefore carrier distribution is much more stable.

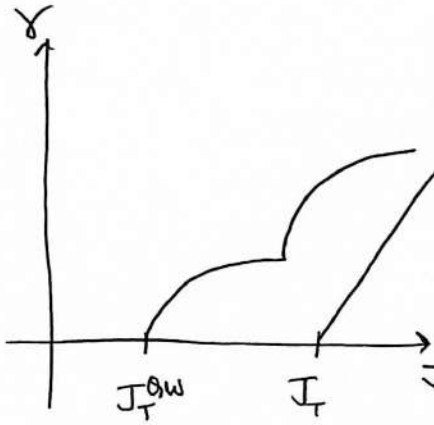
> Furthermore, the number of allowed non radiative transitions are fewer (across band).

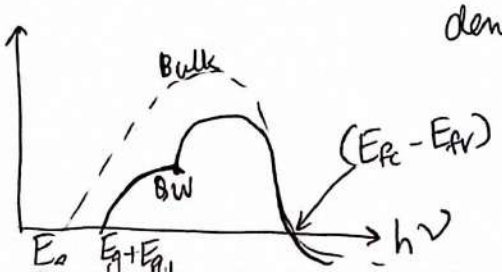
Why Low Threshold?

Recall, $\Delta n_T = \frac{J_T \tau}{ed}$ or $J_T = \frac{\Delta n_T\, ed}{\tau}$.

$$\gamma = \alpha_a\left(\frac{J}{J_T} - 1\right) = \frac{\lambda^2}{8\pi\tau}\,\rho(\nu)\, f_g(\nu)$$

density of states.





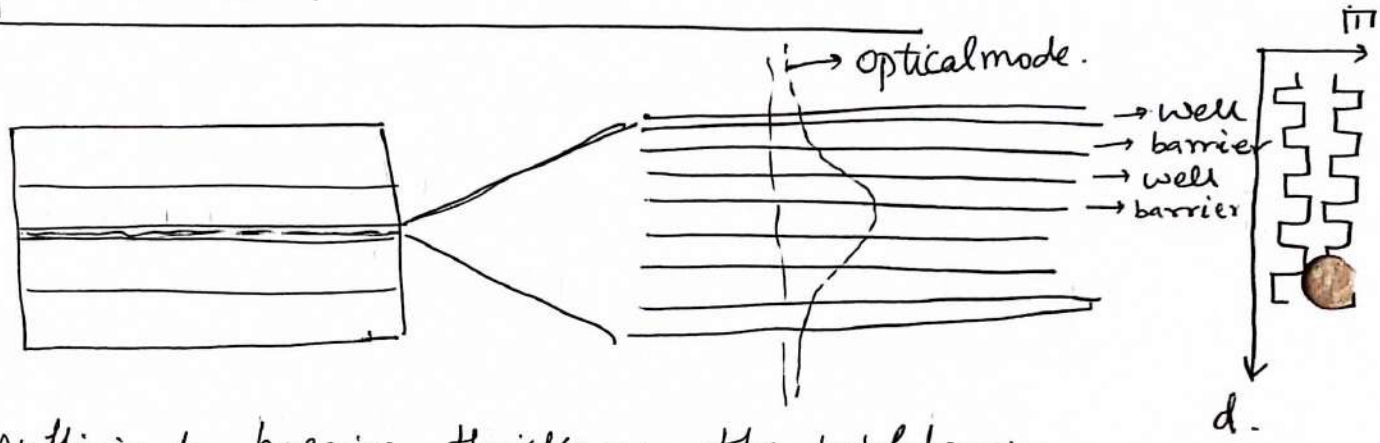
Confinement Factor (Γ) → discussed earlier. (Amt. of energy in core).

$$i_t = i_T \left(1 + \frac{\alpha_r}{\Gamma \alpha_a}\right)$$

> In QWL Γ is lower. ($\simeq 0.4$)

Despite $\Gamma \downarrow$, gain is larger at lower currents & therefore threshold is low.

Multiple Quantum Well (MQW) lasers.

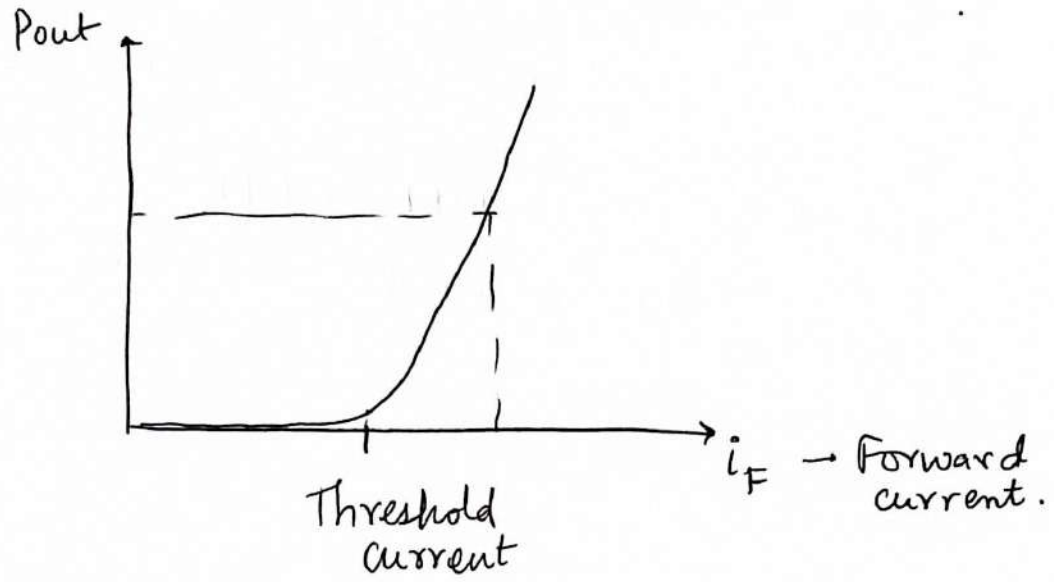


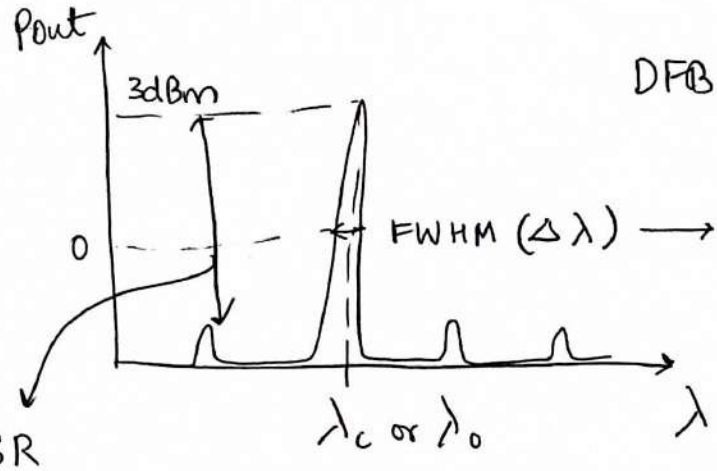
> With sufficient barrier thickness, the neighbouring electron wells do not interact.

> A single optical mode propagates in all the wells & therefore γ is high (gain ↑↑) ⇒ higher optical output power.

Lec 39 : Practical Laser Diodes and Handling.

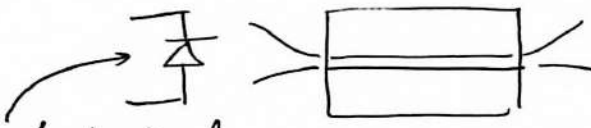
Characteristics (Data sheet)





DFB laser.

SMSR (Sidemode suppression ratio)



> Monitor current → current in monitor photodiode.

> Thermistor TCR → Temperature coefficient of resistance.

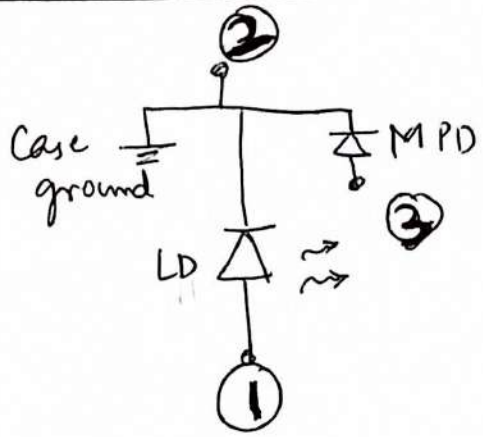
> TEC Power → Thermo electric cooler power.

↳ used to control TEC to maintain constant T.

Device Packages

- Free space output (TO-3 Window can & SOT-148 window can)
- Fiber pigtail (14 Pin DIL or DIP package & 14 Pin Butterfly package).

TO 3 & SOT 148



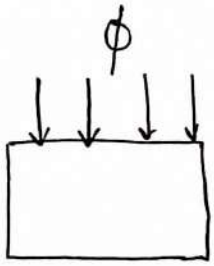
Lec 40 General Characteristics of Photodetectors.

Photodetectors
- Photo-emissive (Photo-multiplier tube) PMT
- Photo-conductive
  - ↳ Change in conductivity due to incident photons.
    - Photoconductors
    - Photodiodes
      - PIN diodes
      - APDs.
      - Others: CCDs, Solar cells.
    - Phototransistor

Thermopiles
- Temp change with incident photon.

General Characteristics of Photodetectors.

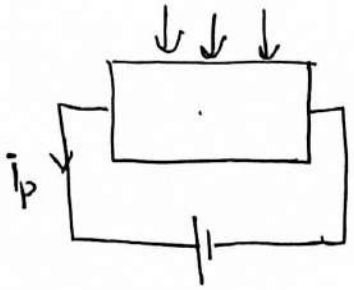
1) $\eta \rightarrow$ quantum efficiency
2) $R \rightarrow$ responsivity
3) $t_r \rightarrow$ rise time / impulse response / bandwidth.
4) $P_{Noise} \rightarrow$ Noise power / Dark current.



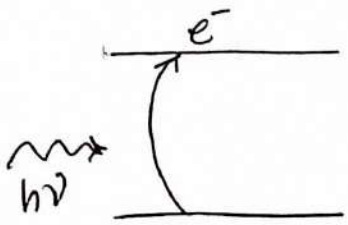
ϕ = photon flux = $\frac{P_{opt}}{h\nu}$

η = $\frac{\text{Carrier flux generated which contribute to the photocurre}}{\text{Incident photon flux}}$

$$\eta = \frac{(i_p/e)}{(P/h\nu)}$$



$$0 < \eta < 1$$



"Generation of 1 e-h pair in the semiconductor is equivalent to 1 charge moving in the external circuit." → Ramo's theorem?

Responsivity

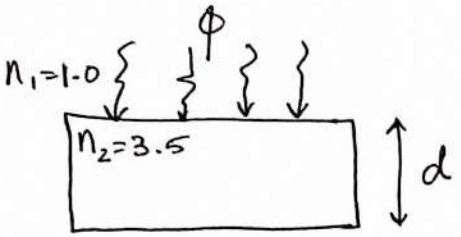
For LEDs, $R = \frac{P_{opt}}{j}\left(\frac{h\nu}{A}\right)$

For Photodetectors, $R = \frac{i_p}{P_{opt}}\left(\frac{A}{W}\right)$

$$\Rightarrow R = \frac{i_p}{P_{opt}} = \eta \cdot \frac{e}{h\nu} = \eta \cdot \frac{\lambda\,(\mu m)}{1.24}$$

$$\Rightarrow \boxed{R = \eta \cdot \frac{\lambda(\mu m)}{1.24}}$$

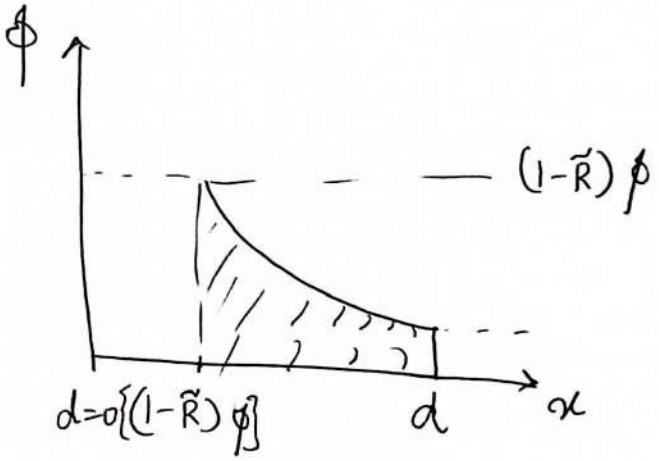
> $\eta = ?$ & how to maximize it?



$\tilde{R}$ → reflectivity due to air-dielectric interface.

photon flux entering detector : $\phi(1-\tilde{R})$

Inside the medium photon flux decays exponentially due to absorption.



fractional number of photons absorbed = $\phi(1-R)(1-e^{-\alpha d})$

> If ζ is the fractional number of photons that lead to electrical current. It has 2 components: i) photons lost to phonons or trapped states ii) generated e–h pairs may recombine immediately.

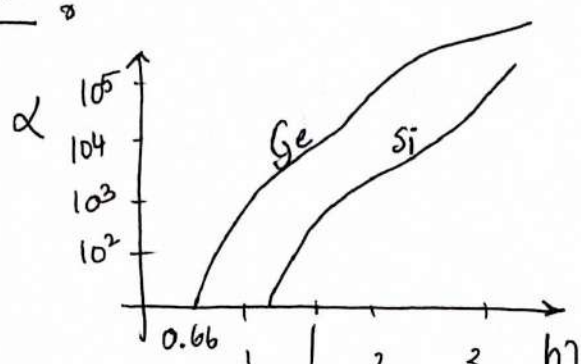
> If N photons are incident, ζN photons contribute to current in external circuit.

$\Rightarrow \phi \longrightarrow \underbrace{\phi(1-R)(1-e^{-\alpha d})\zeta}$

$\Rightarrow \boxed{\eta = (1-R)(1-e^{-\alpha d})\zeta}$ How to maximize η now?

$R=0$? AR coating.

$\alpha d \to \infty$?



Si $\xrightarrow{E_g}$ 1.1 eV

Ge → 0.66 eV

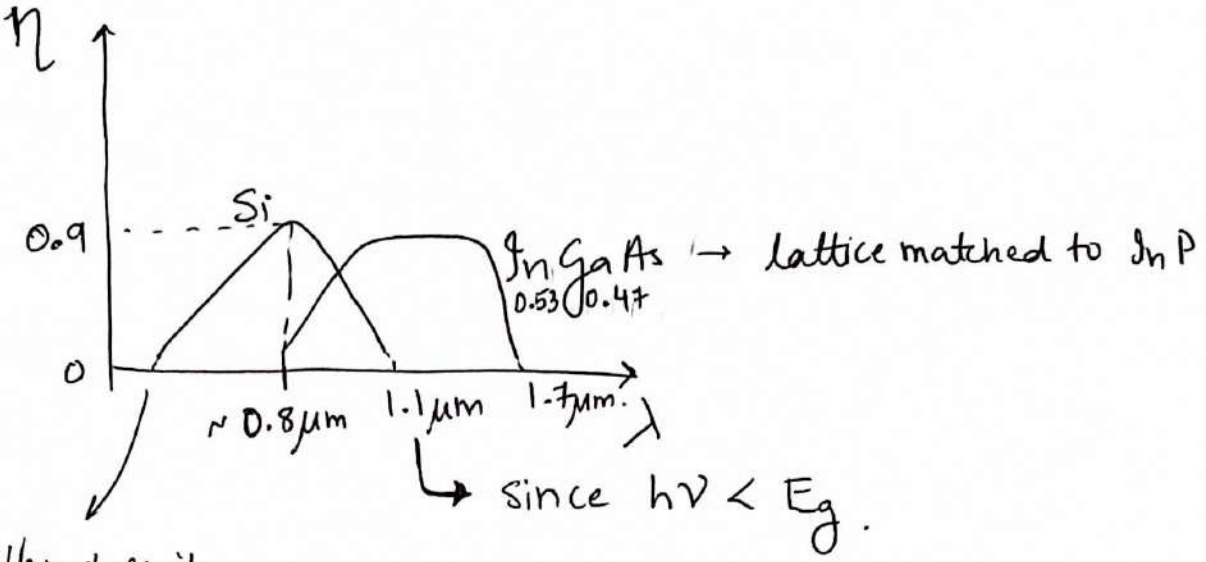
→ 1.5 eV AlGaAs/GaAs laser.

Choose d based on α to maximize η.

$\zeta \to 1$?

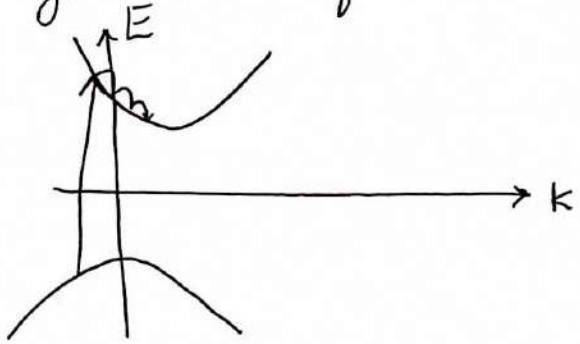
1) > Bias needs to be applied to pull e-h pairs into circuit.
   > PN junction should be reverse biased.
2) > Make sure no defects exist → very careful fabrication.

Lec 41 Responsivity and Impulse Response.



Why does it drop here?

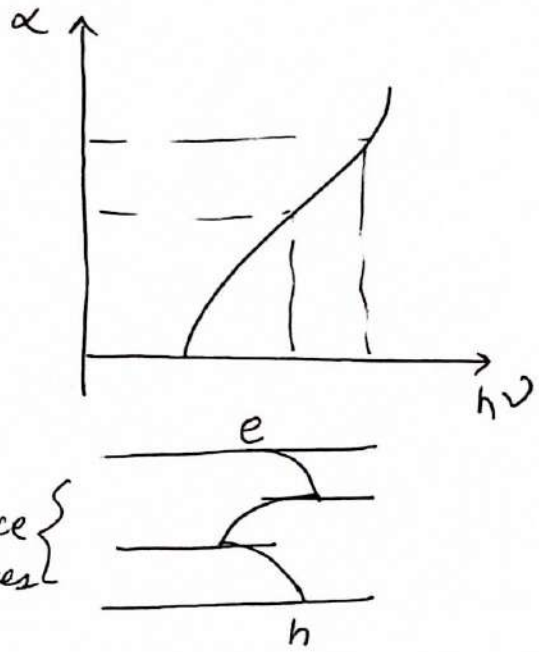
1) Generation of hot carriers.

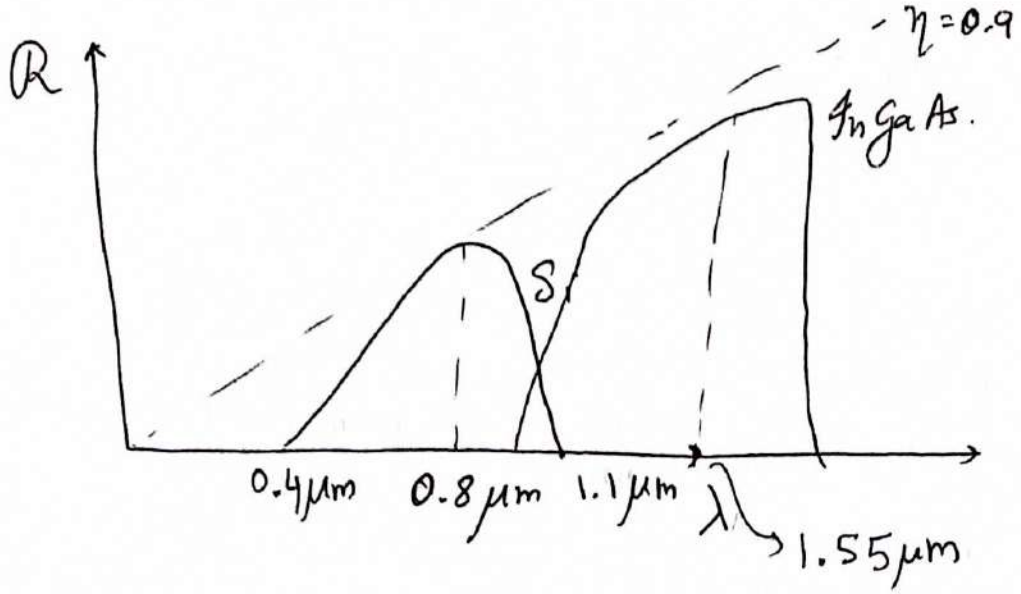


↳ These hot carriers quickly thermalize & generate a large number of phonons which facilitate e-h recombinations, reducing η.

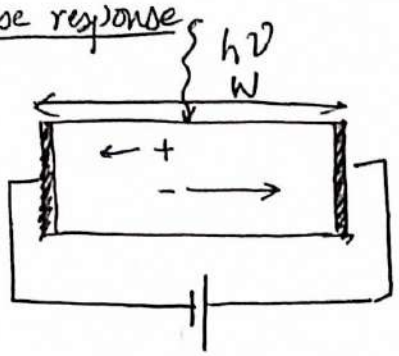
2) Absorption near the surface.

- Since α is large, most absorption occurs near surface. However, Surfaces have dangling bonds & surface states which facilitate e-h recombinations.





> Impulse response



$i_h(t)$ & $i_e(t)$
(hole) (electron)

Ramo's Theorem

$$i(t) = \frac{-q}{W} v(t)$$

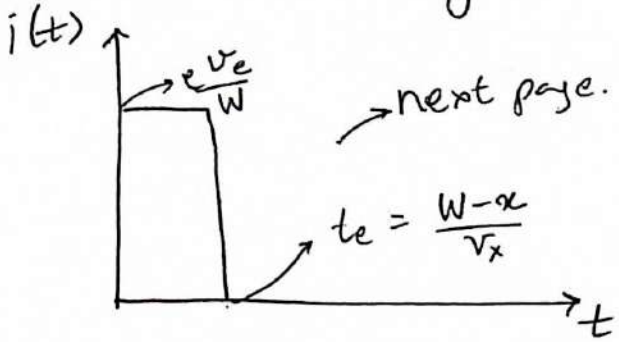
↳ instantaneous velocity of carrier.

$v = \mu E$ → E-field
↑ mobility

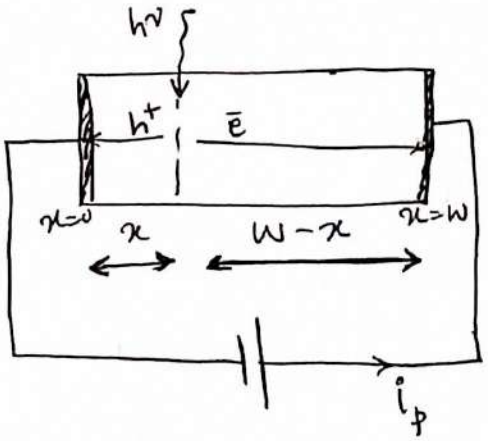
$$i_e(t) = -\frac{(-e)v_e}{W} = \frac{e v_e}{W}$$

$$i_h(t) = -\frac{e(-v_h)}{W} = \frac{e v_h}{W}$$

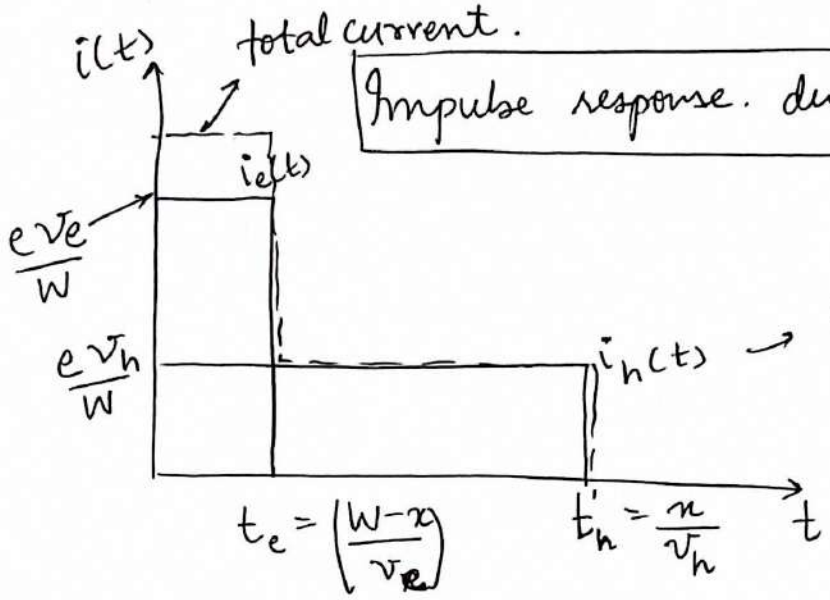
$$\Rightarrow \boxed{i(t) = \frac{e(v_e + v_h)}{W}}$$



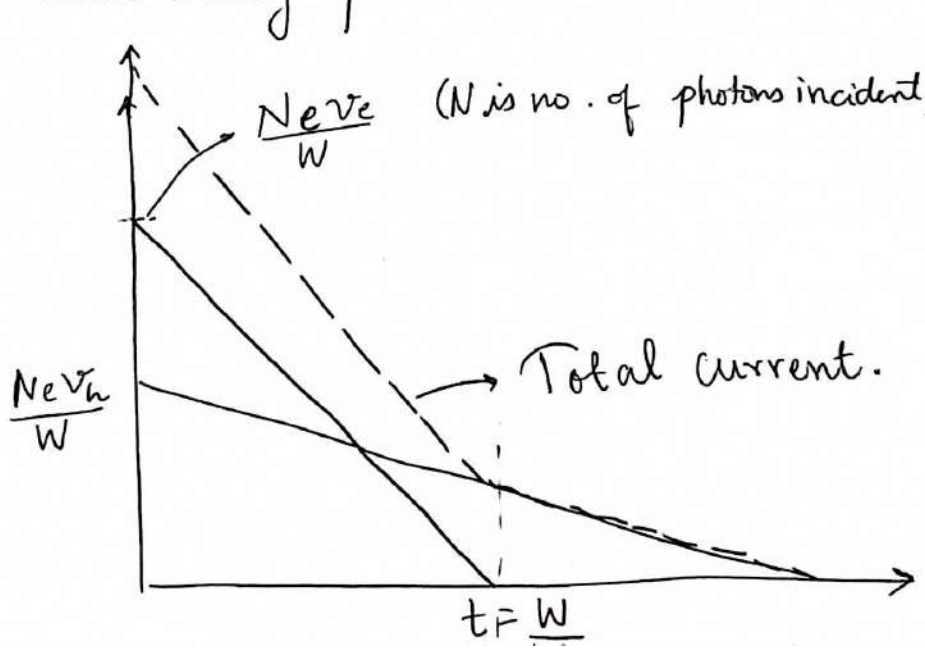
Material	μ_e	μ_h	(cm^2/Vs)
Si	1500	450	
Ge	3900	1900	
GaAs	8500	400	
I-P	4600	150	



> When e-h pair is generated, current in external circuit persists until the electron & hole are absorbed into the electrodes.



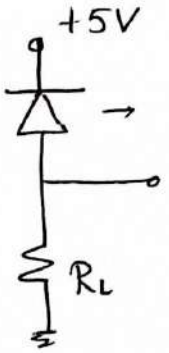
> What happens when many photons are incident all over the sc?



Impulse response is determined by

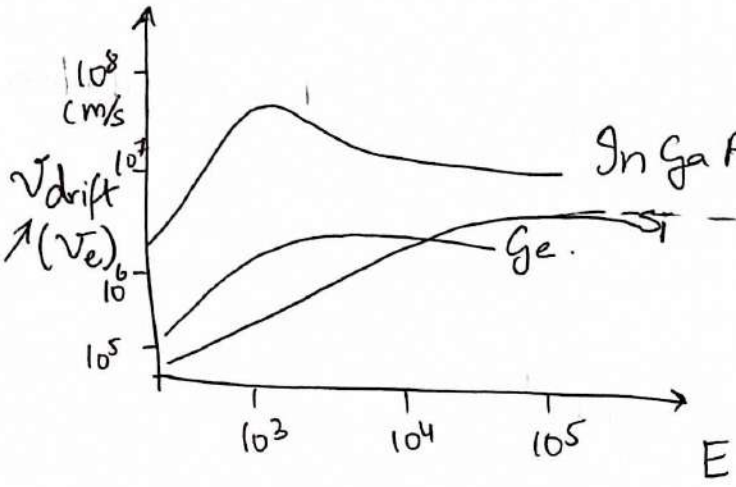
i) Transit time of carriers

2) RC time constant of circuit.



$\Rightarrow \tau = R_L C$.

$f_c = \frac{1}{2\pi R_L C}$



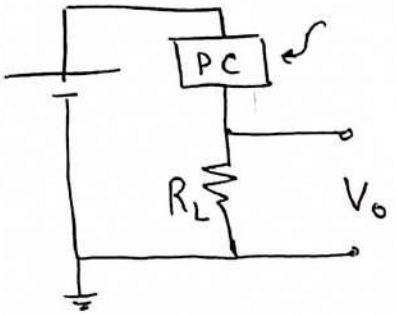
→ V_{sat} → Apply E-field at V_{sat}!

Lec 42 Photo conductors.

aka photoresistors
or light dependent resistors (LDRs).

> Conductivity of a semiconductor changes with incident photon flux.

>



$$J = J_{dark} + J_{photo}$$

$$\Rightarrow J = \sigma \mathcal{E} \quad ; \quad \sigma \text{ - conductivity}$$

$$= \rho \mu \mathcal{E} \qquad \rho \text{ - charge density}$$

$$J = ne\mu\mathcal{E} \qquad \mu \text{ - mobility}$$

$$n \text{ - carrier conc.}$$

If n_o & p_o are the concentrations when $\phi = 0$, then

$$\sigma = (n_o \mu_e + p_o \mu_h) e \quad . \quad \text{Or} \quad J_{dark} = (n_o \mu_e + p_o \mu_h) e \mathcal{E}.$$

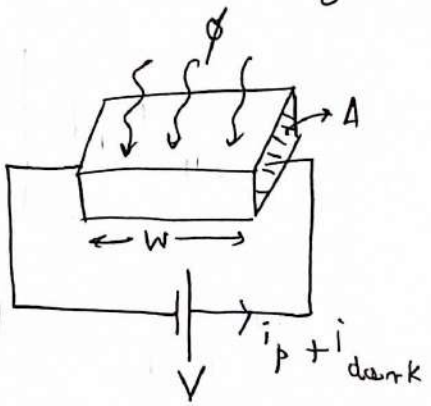
If $\Delta n \rightarrow$ excess carrier concentration of electrons due to ϕ.

ϕ ↑ photon flux

$$\Delta p = \Delta n$$

$$\Rightarrow J_{photo} = (\Delta n \mu_e + \Delta p \mu_h) e \mathcal{E}$$

$$= (\mu_e + \mu_h) \Delta n e \mathcal{E}$$



If R → rate of generation of excess carriers/unit volume.

$$R = \frac{\eta \phi}{WA} \qquad \text{but recall} \quad R = \frac{\Delta n}{\tau} \rightarrow \text{excess carrier recomb. time.}$$

↑ rate of recomb.

$$\Rightarrow \quad \Delta n = \frac{\eta \phi \tau}{WA}$$

$$J_{photo} = \frac{\eta \phi \tau_e}{WA} (\mu_e + \mu_h) \mathcal{E}.$$

$$\Rightarrow \quad i_p = J_{photo} A = \frac{\eta \phi \tau}{W} e (v_e + v_h)$$

$$\Rightarrow \quad i_p = \eta \phi \tau e \left(\frac{1}{t_e} + \frac{1}{t_h}\right)$$

$\frac{1}{t_e}$, $\frac{1}{t_h}$ → transit time across W.

$\frac{1}{t}$

$$\phi = \frac{P_{opt}}{h\nu} = \frac{P_{opt}}{hc} \lambda.$$

$$\phi_e = \frac{P_{opt}}{\left(\frac{hc}{e}\right)} \lambda = \frac{P_{opt}}{1.24} \lambda \ (\mu m).$$

$$\Rightarrow \boxed{i_p = \eta \left(\frac{\tau}{t}\right) \frac{\lambda}{1.24} P_{opt}}$$

$$\Rightarrow \boxed{\mathcal{R} = \frac{i_p}{P_{opt}} = \eta \frac{\lambda}{1.24} \left(\frac{\tau}{t}\right)} \quad \text{Amp/watt}$$

τ → carrier recombination time. $(10^{-12} - 10^{-3}\ s)$

t → transit time. (i.e if $W = 1mm$, & $v_e \approx 10^7 \frac{cm}{s}$ ⇒ $\approx 10^{-8} s$)

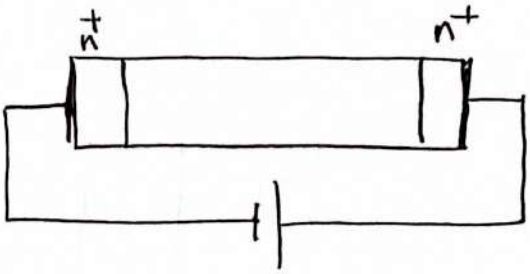
$$\frac{1}{t} = \frac{1}{t_e} + \frac{1}{t_h}$$

$$\frac{1}{t} \simeq \frac{1}{t_e}$$

Responsivity of a photoconductor.

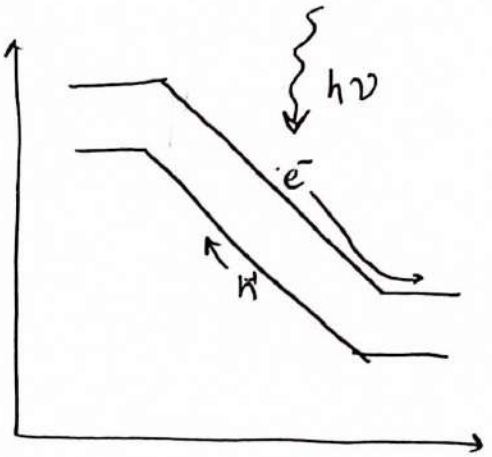
usually $\left(\frac{\tau}{t}\right)$ from 10^{-4} to 10^{5} //

Where is this gain coming from?



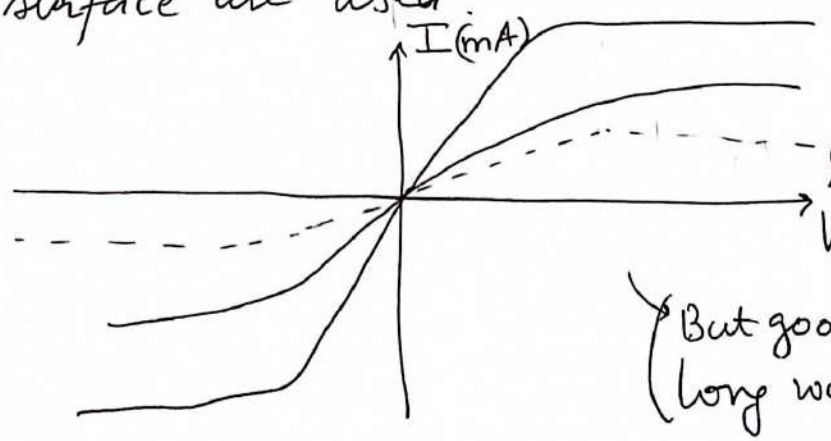
> When a single photon is incident, an electron hole pair is generated.

The electron moves quickly & is absorbed at the contact. The hole takes longer. ~~As the hole is in the dep~~ But to maintain charge neutrality electrons are sequentially pumped into the S.C until either the hole is absorbed or until $e^- - h^+$ annihilate. From Ramo's theorem we can conclude that a persistent current flows as long as the hole exists, with just 1 photon!!



> Impulse response is long though. Gain-bandwidth product remains constant.

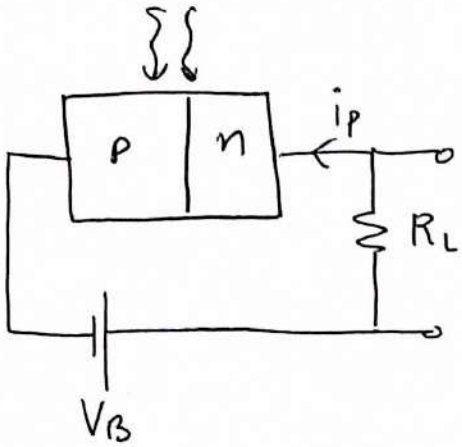
> For high speed applications, interdigitated electrodes on the surface are used.



→ large dark current (BAD)

(But good for long wavelengths)

Lec 43 Semiconductor Photodiodes



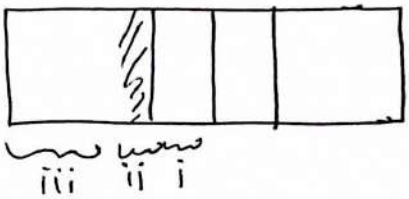
Why PIN?

Three regions

i) Depletion region (drift current)

ii) Diffusion region (edge of depletion).

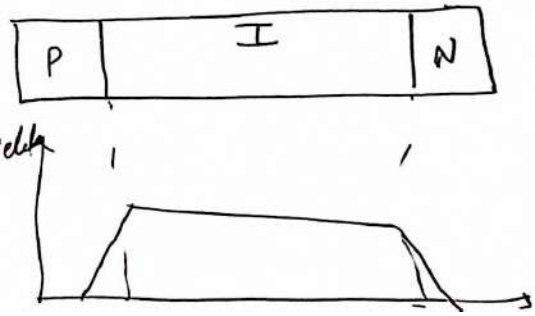
iii) Away from depletion region.



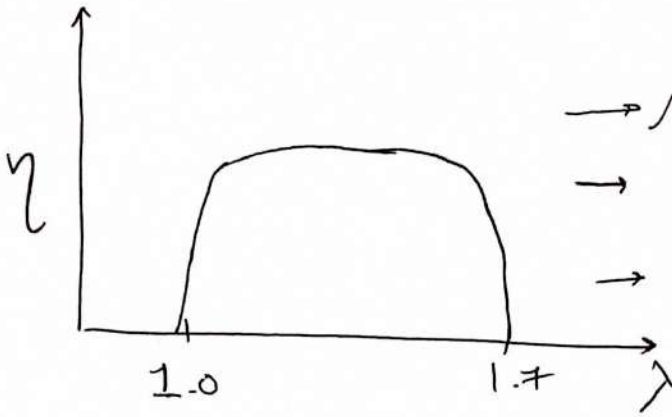
> Field only exists in i).

> Carriers generated in iii & ii are not swept away, only generate noise & not current.

> In PIN diode, region i) is enhanced! Also junction capacitance is reduced. Also more area for light to be captured.



→ All optical comms use $In_{0.53}Ga_{0.47}As/InP$.



→ large responsivity.
→ low loss at 1.55 μm window.
→ Has very large V_{sat} & high mobility μ_e.
⇒ Very sharp impulse response.

→ At 32:00 show a plot of η vs λ for Si & InGaAs.

Reverse Current Characteristics (✱)

Curve shifts down because current from photon flux adds to existing current.

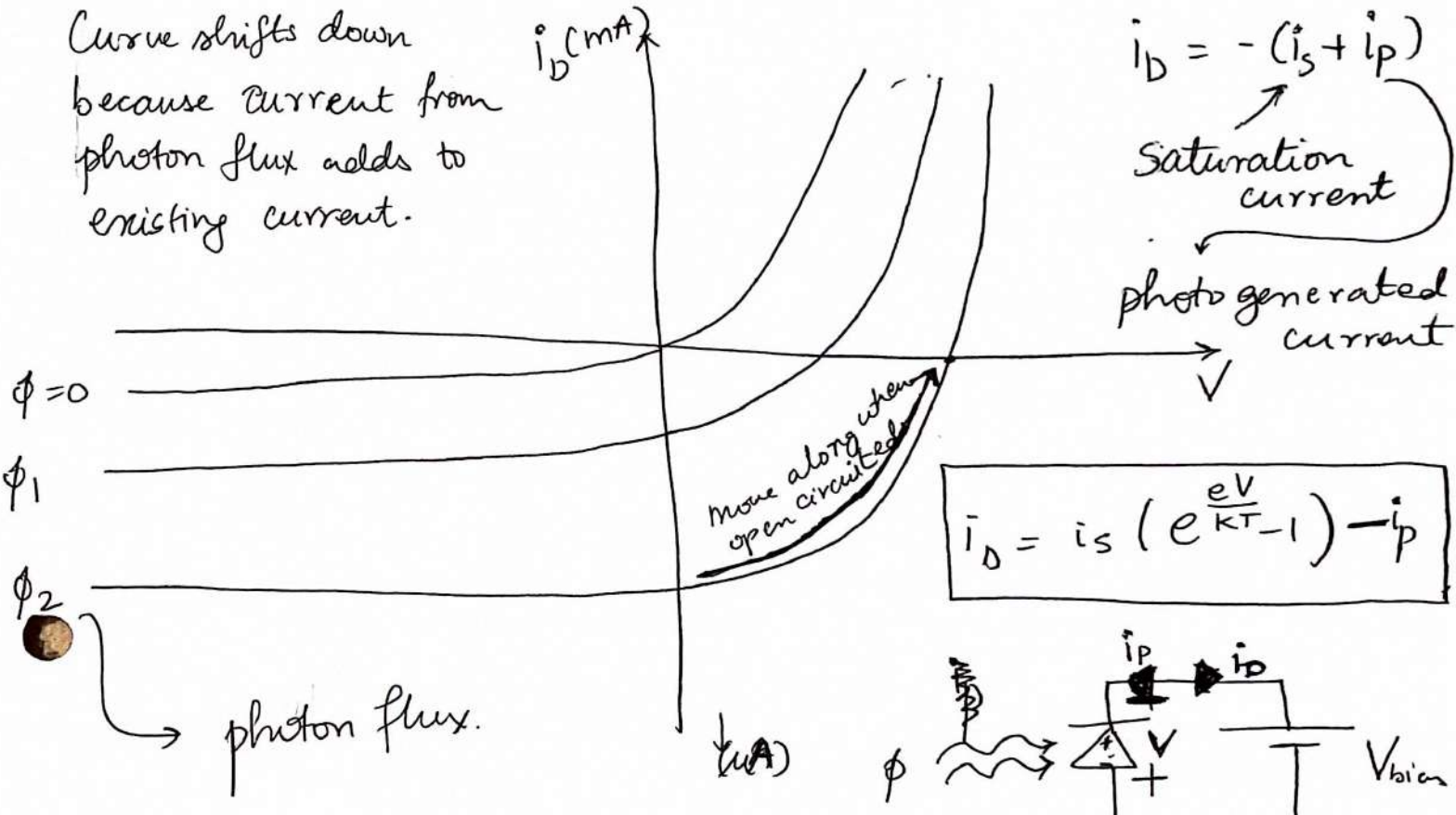
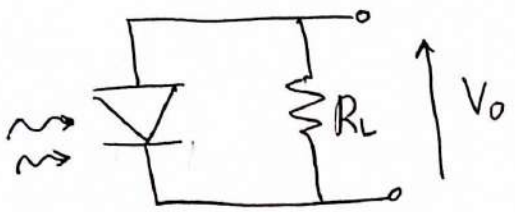
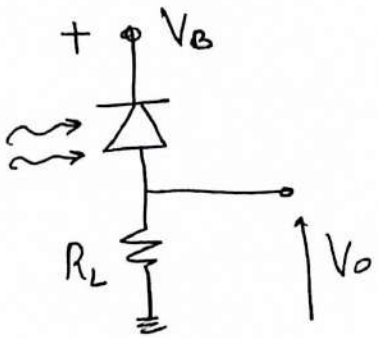


Photo voltaic



Slow

Photo conductive.



Fast

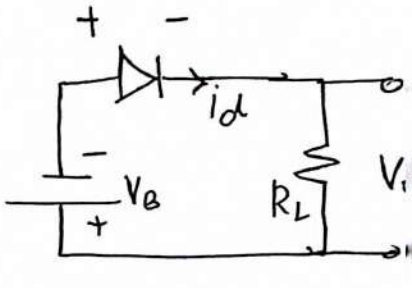
Characteristics

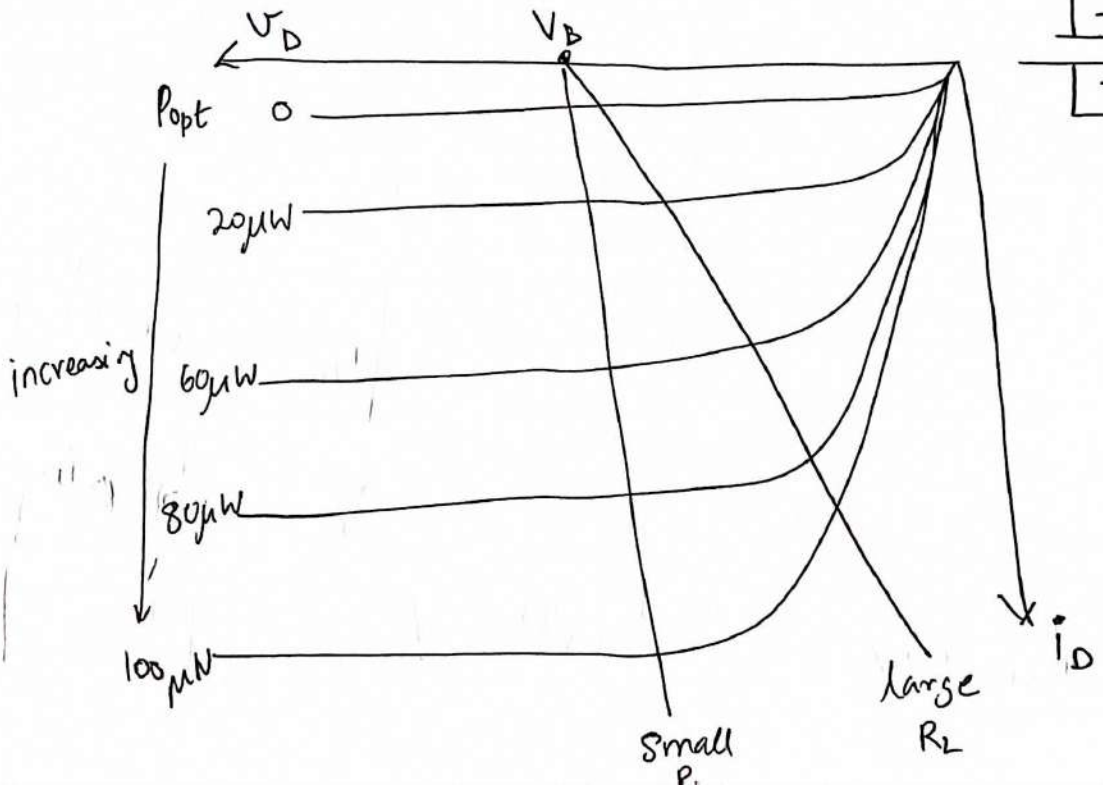
> Dynamic Range & Linearity. & Sensitivity.

Dynamic Range → $P_{out\,max} - P_{out\,min}$.

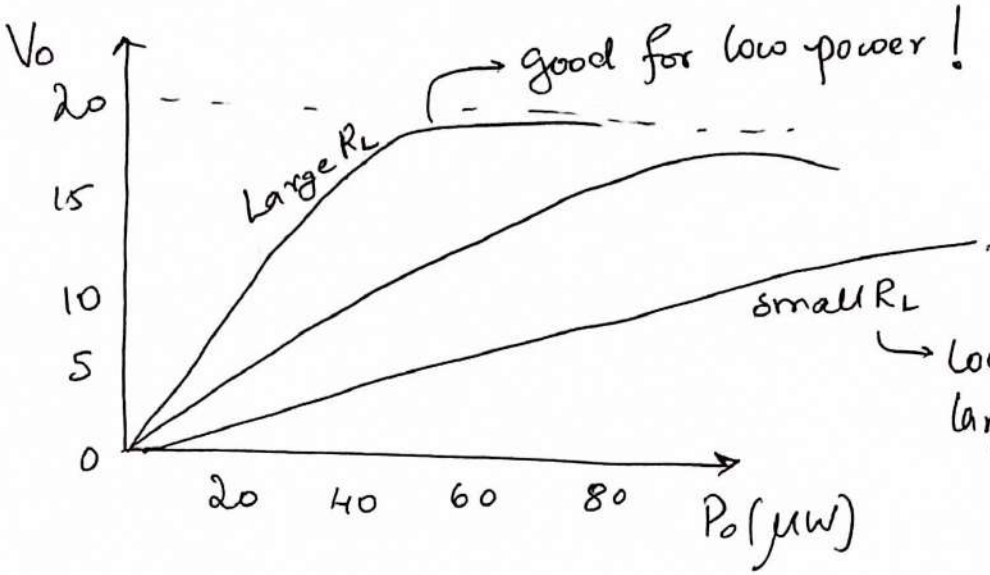
Linearity → (V_{out} vs. P_{opt})

Load line behaviour





Linearity vs. Sensitivity.



↳ Low sensitivity
large linearity.
(dyn. range)

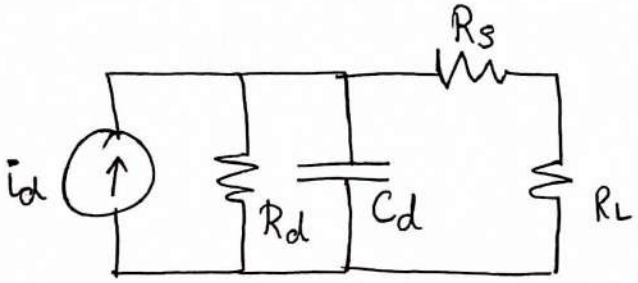
↓

Good for high speed.

$$BW = \frac{1}{2\pi R_L C_d}$$

Lec 44 Avalanche Photo Diodes (APDs)

Equivalent Circuit of Photodiodes



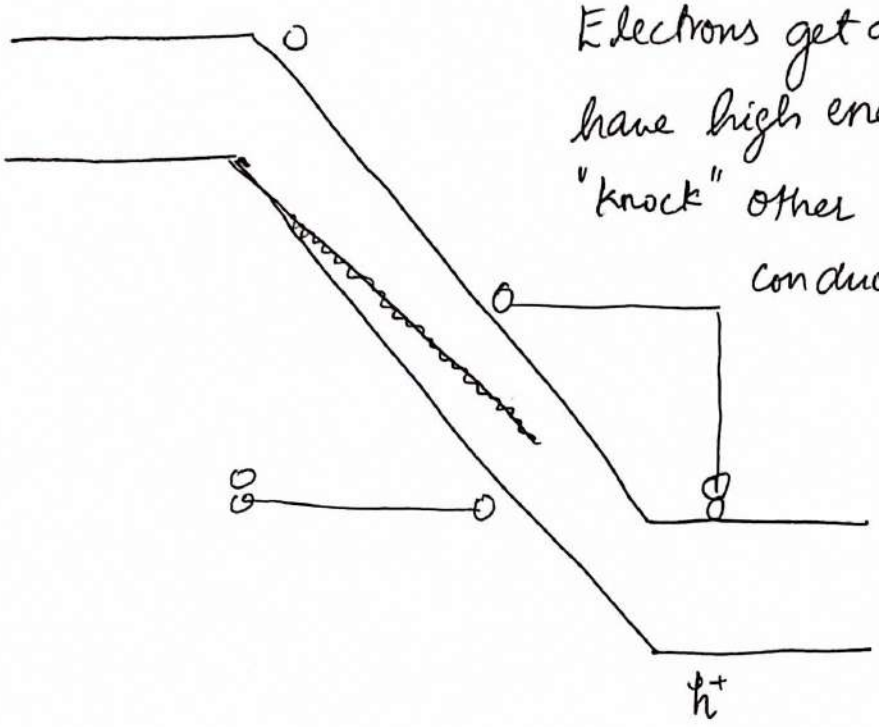
$$t_r = 2.19\, R_L C_d$$

$$f_{3dB} = \frac{0.35}{t_r} \simeq \frac{1}{2\pi R_L C_d}$$

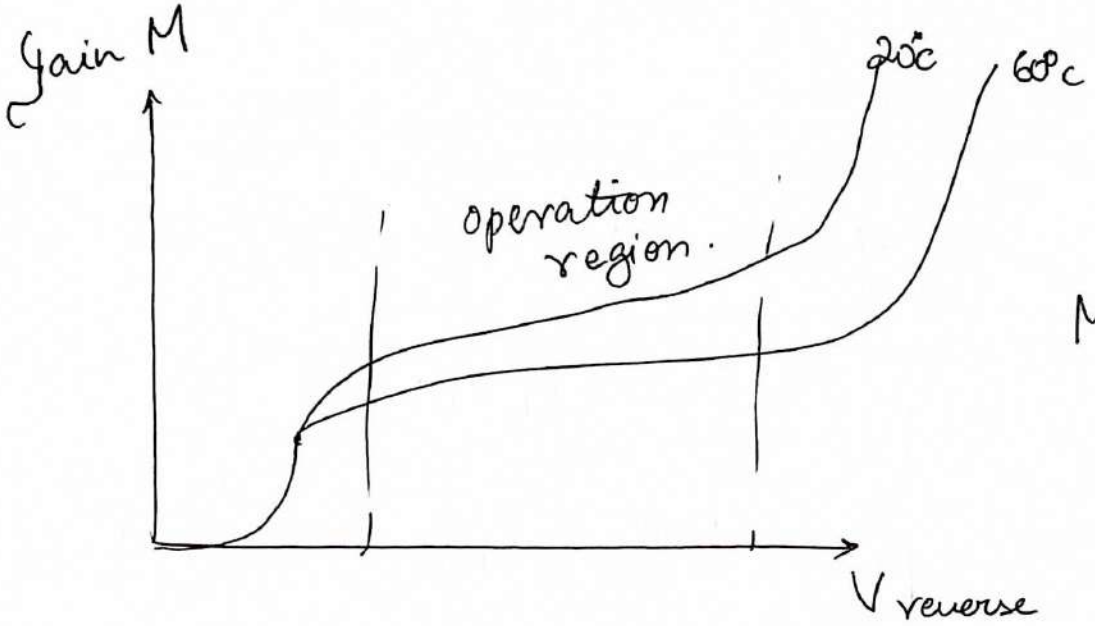
> APDs → PIN with large reverse bias.

- > Built in device gain due to avalanche multiplication.
- > High sensitivity, more noisy.
- > High current gain.

Carrier multiplication.



Electrons get accelerated & have high energy, which then "knock" other electrons into conduction band & so on.



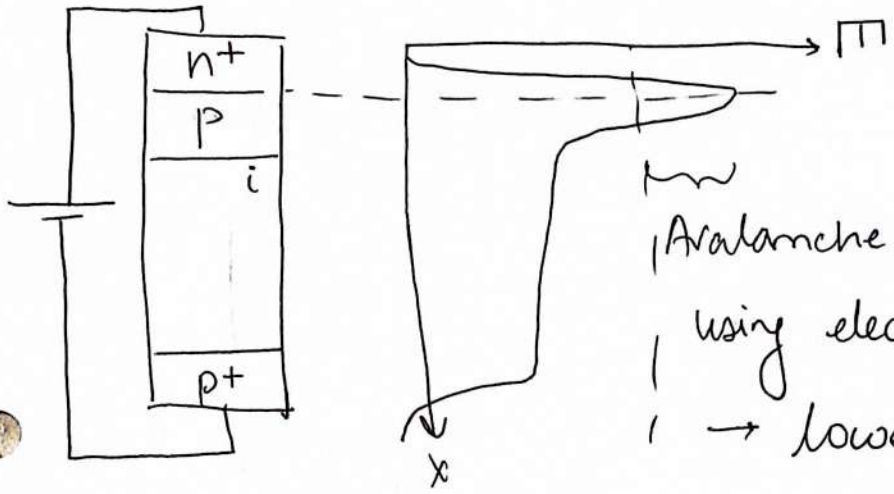
$$M = \frac{i_M}{i_P}$$

$$\alpha = \frac{1}{(\lambda_{int})_{av}} \rightarrow \text{impact ionization coeff.}$$

↳ avg. dist b/w 2 successive collisions

- In silicon, $\frac{\alpha_e}{\alpha_h} \sim 30$ for $E \sim 10^5$ V/cm.

⇒ Reach through APD.



Avalanche is done only here using electrons alone.

→ lower noise figure.

→ Faster device too since avalanche process does not continue through the entire device length. Impulse response is faster!

M → gain in circuit current vs. photocurrent.

Lec 45 Other Photodetectors.

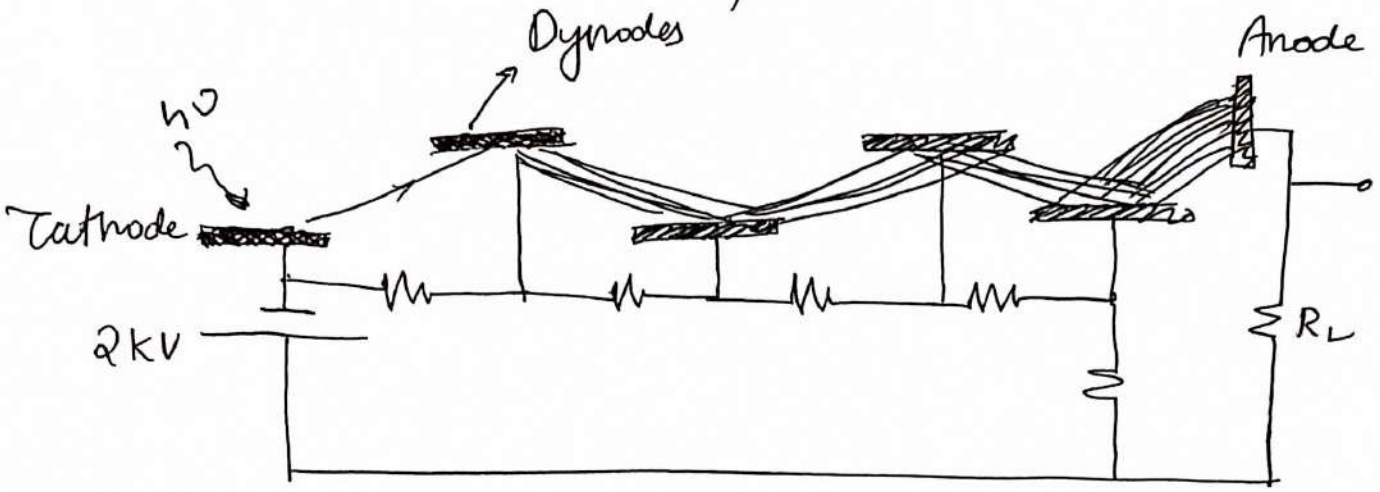
1) PMT
2) phototransistors
3) Solar cells
4) QWIP
5) Thermal detectors.

Photo multiplier tube.

Basic principle: Photoelectric effect + avalanche multiplication.

↳ $h\nu = e\phi_m + \text{Kin En.}$

ϕ_m → work function



- One incident electron generates δ (4–6) scattered electrons.

$N \rightarrow$ no. of dynodes

$\Rightarrow G = \delta^N$

$G \simeq 10^7$

If $P_{opt} = I_p W$;

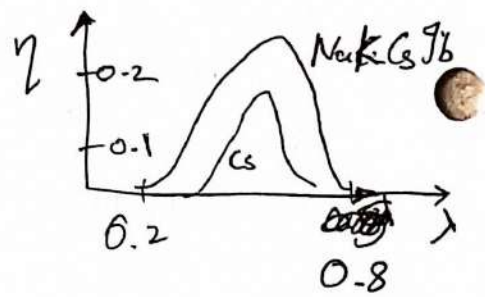
$\eta = \frac{i/e}{P_{opt}/h\nu} \Rightarrow i = \frac{\eta P_{opt} e}{h\nu}$

$\Rightarrow i = \eta P_{opt} \frac{\lambda(\mu m)}{1.24}$

Photocathode: $W = e\phi_m < h\nu$

Cesium $\simeq$ 2eV $\Rightarrow \lambda_g <$ 620nm can work!

NaKCsIb $\simeq$ 1.42eV $\Rightarrow \lambda_g \simeq 0.88\mu m$.

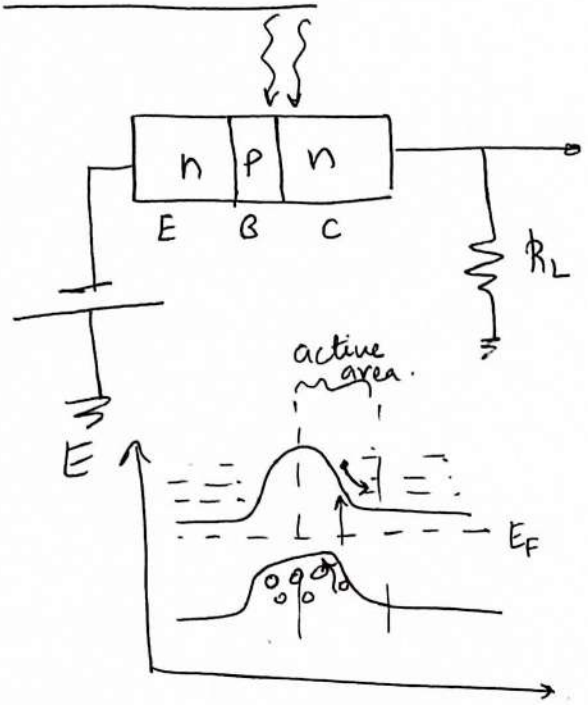


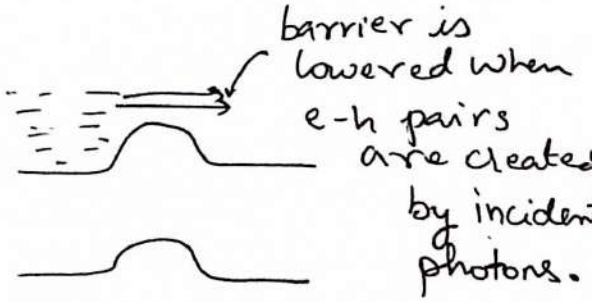
$\Rightarrow i \simeq 10^{-13} A \rightarrow$ primary current.

$$G = \frac{i_{load}}{i_p} = 10^7 \Rightarrow i_{load} = 10^{-6} A = 1\mu A$$

At $R_L = 10^6 \Omega \Rightarrow V = \underline{1V} \longrightarrow$ Super sensitive!

Phototransistor.

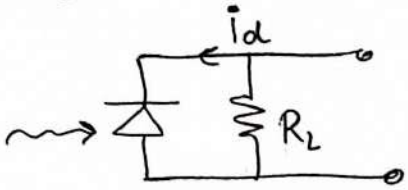




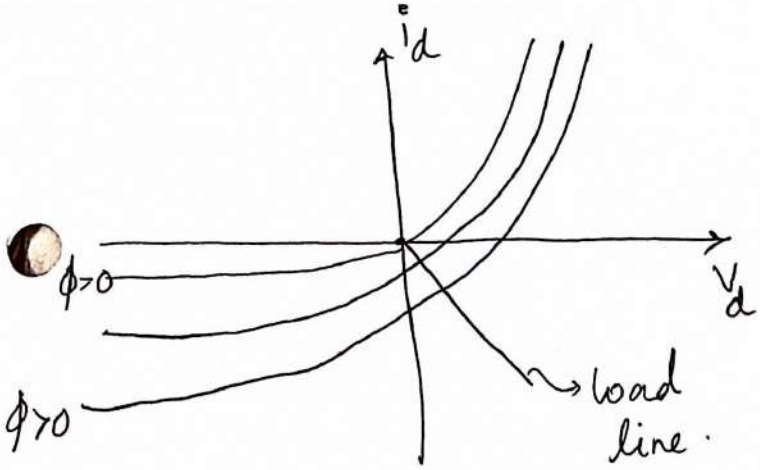
- Charge accumulation in the base limits the speed.

Gain is due to barrier lowering.

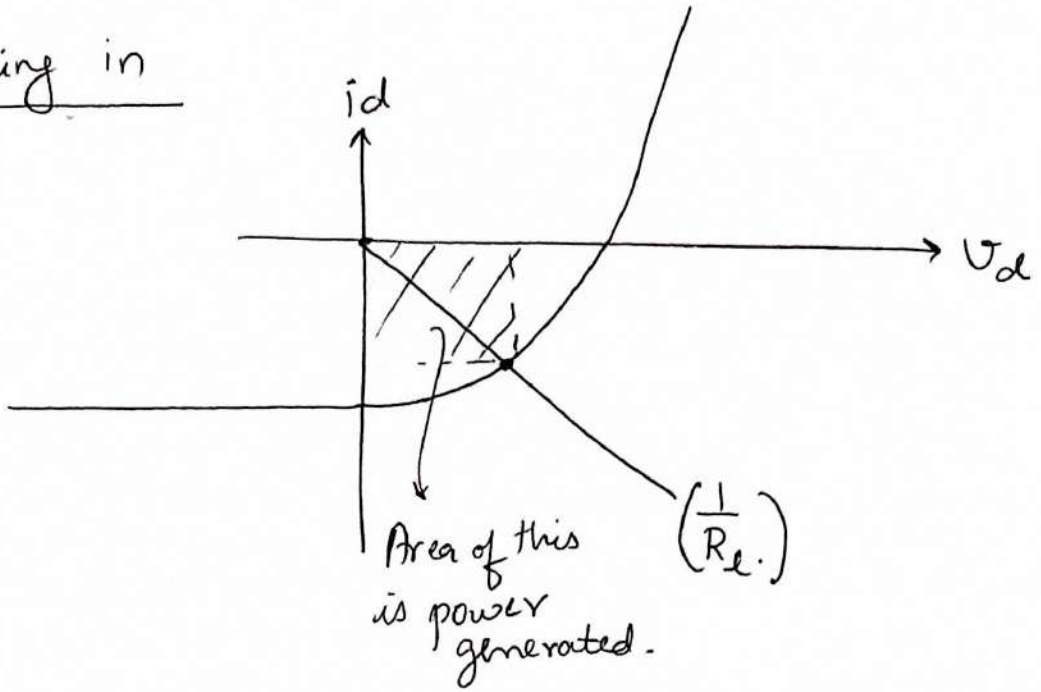
Solar Cell – (PN or PIN diode)



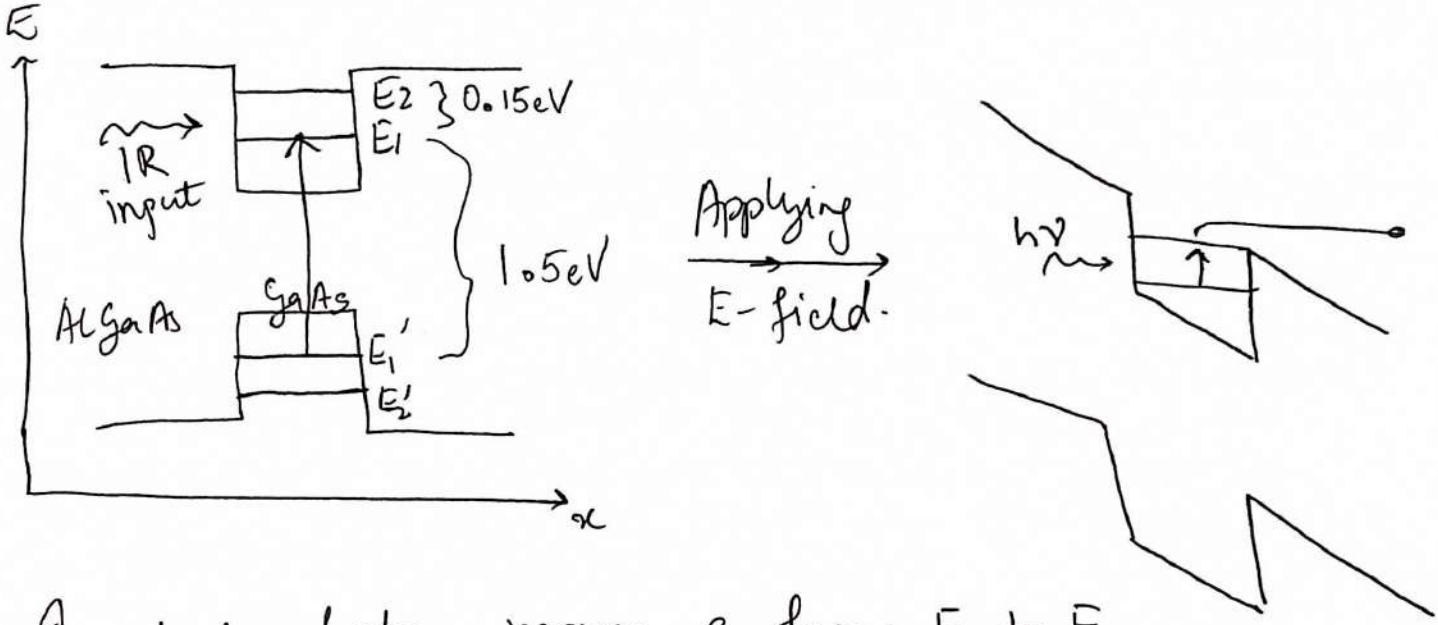
[Photo Voltaic.



Zooming in



QWIP Quantum Well Infrared Photodetectors.



Incident photon moves e from E_1 to E_2 which tunnels or escapes out to generate a current. How energy input photons are used for the intraband transitions. Typically multiple quantum wells are used.