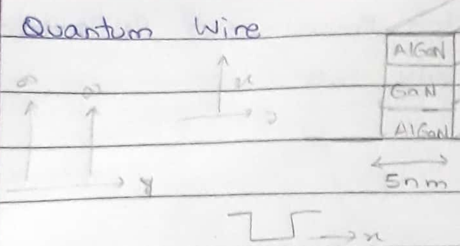
$\lambda(\mu m) = \frac{1.24}{E_g(eV)}$

Quantum Wire

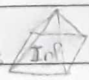


2D confinement → Q wire

5nm ← for energy discretisation

Quantum Dots – 3D confinement → (0-D system)

from thermodynamics

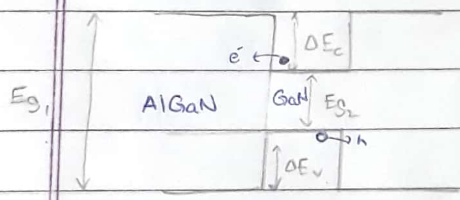


GaN

minimizing surface energy

ΔE_c = Conduction band offset ΔE_v = Valence band Offset

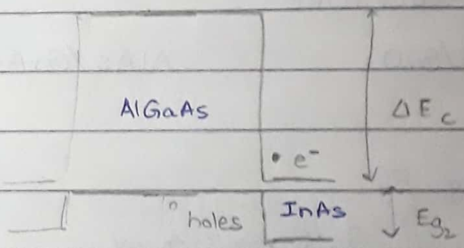
$\Delta E_g = E_{g_1} - E_{g_2} = \Delta E_c + \Delta E_v$



Type I

$\Delta E_c = 0.6 \Delta E_g$

$\Delta E_v = 0.4 \Delta E_g$

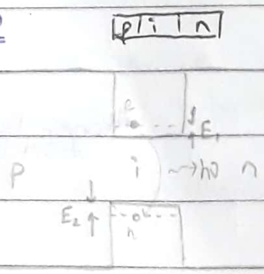


Type II (staggered)

- e^- are holes are physically separated
  - give very ~~go~~ high performance photodiodes

LED

$\boxed{p \mid i \mid n}$



$\}E_g$

flatband diagram

AlGaN - GaN - AlGaN

GaN - InGaN - GaN

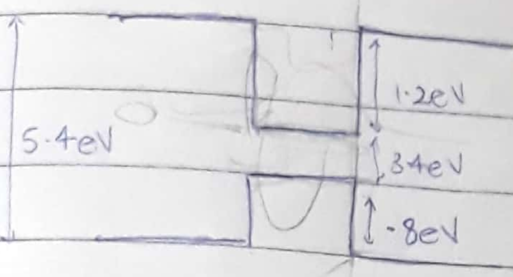
$E_1 \neq E_2$ (due to m^*)

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

~~λ = 50~~ $\lambda = 300nm$, $Al_xGa_{1-x}N - GaN - Al_xGa_{1-x}N$ $W = ?$, $x = ?$

$m_e = m_p = m_0$

$Al_{.7}Ga_{.3}N \rightarrow 5.29 \approx 5$



$E_1 = \frac{n^2h^2}{8mL^2}$ ~~[illegible]~~

Ad-hoc $E_1 = \frac{h^2}{10m_e L^2}$

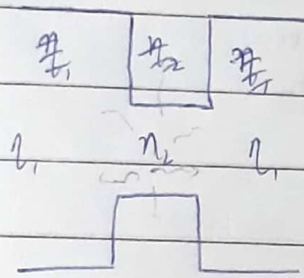
$E_2 = \frac{h^2}{10m_h L^2}$

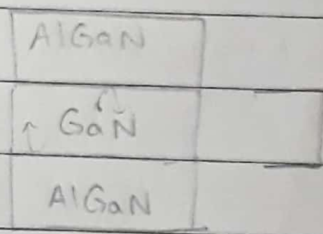
$3.4 + E_1 + E_2 = \frac{1.25}{.3} \approx 4.1 \Rightarrow$

<u>Chosing x</u> : lattice constant → we have to grow the material (minimize defects)

$xa_1 + (1-x)a_2$: large x → low defects but no quantum ... ~~low x →~~ trade-off

- carriers can't leave well → greater recombination rate ⇒ more





most light travels in p...

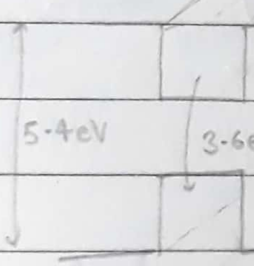
* photon 'trapping' is due to refractive indices NOT potential (electric) well

DIELECTRIC WAVEGUIDE
↳ for monolithic circuits

to 1st order ph... are not a... electric p...

* Quantum efficiency : $\frac{\text{\# of photons}}{\text{\# of EHP injected}}$ (less recombination

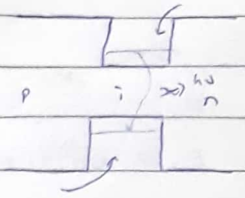
$= \eta_i \times \eta_E$



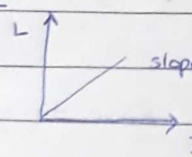
$\eta_I = \frac{\text{\# of photons generated}}{\text{\# of EHP}}$

$\eta_E = \frac{\text{\# of photons emitted}}{\text{\# of photons generated}}$

LED : ~~L-I~~

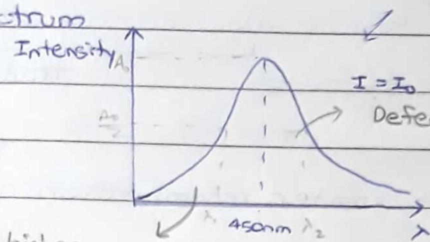


① L-I



slope ~ η = slope efficiency = $\frac{\partial L}{\partial I}$

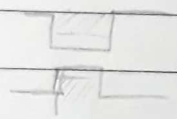
② Spectrum ELECTROLUMINISCENCE



$I = I_0$
Defects

Full width at half maxima ($\lambda_2 - \lambda_1$)
↳ Broadband emission
↳ Narrowband emission

higher energy occupation (kinetic energy



Power Spectral Density

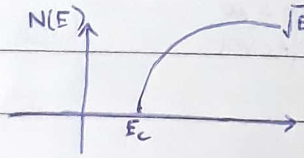
③ PHOTOLUMINISCENCE

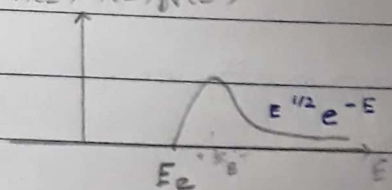
· Optical generation of carriers

Density of States

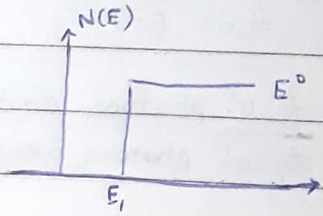
$n(E) = f(E)N(E)$

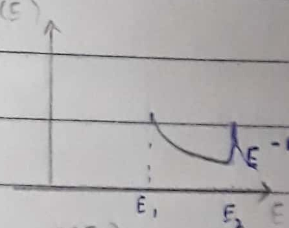
Bulk



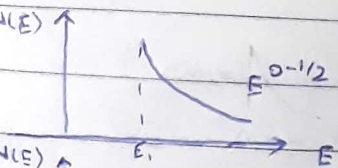


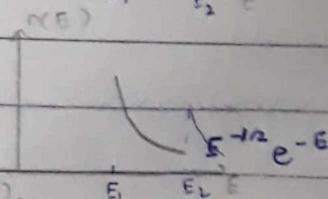
Q. Well



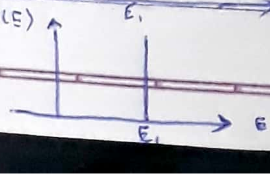


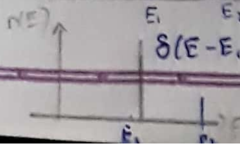
Q. Wire





Q. Dot





- p-i-n diode has greater breakdown voltage than p-n
- for LED and LASER p-i-n ensures radiative recom. (defect free :)

• Fermi-Dirac Statistics is from maximizing entropy

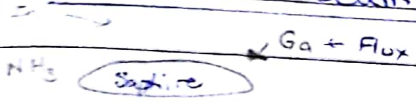
• Quantum Dot enables extremely narrow band emissions

For Quantum Well : ∃ atleast one bound state

Wire/Dot : not necessary.

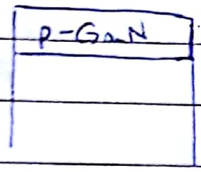
LED FABRICATION

- Molecular Beam Epitaxy



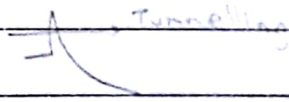
$10^{-11} - 10^{-12}$ tor

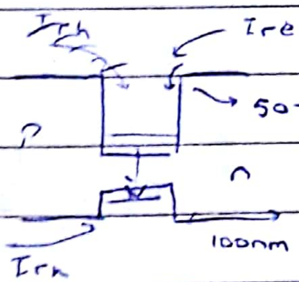
- MOCVD : metal organic chemical vapour deposition



ICP - RIE
↳ inductive coupled plasma Reactive etching
(Ar/Cl)

n-ohmic   Ti/Al/Ni/Au ⟶ TiN





$$f = \cancel{\tau_r + \tau_{rh}} \quad \frac{1}{\frac{\tau_{rh}+\tau_{re}}{2} + \tau_r}$$

$$\tau_{re} = \frac{100nm}{v_e} \sim 1ns$$

$$\tau_{rh} \sim 1ns$$

$$\tau_r \sim 5\text{-}10\,ns$$

. Mobility : Hall effect

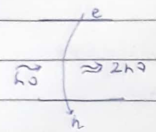
Femtosecond Spectroscopy (can resolve any ~~of~~ event 10-50fs)

Time Resolved Photoluminiscence

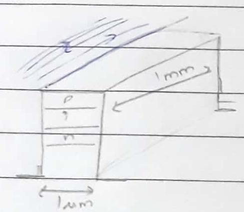
LASER

- 1.3 μm
- 1.55 μm

Lasers → refractive index of quartz s.t transmission is high



- phase coherence
- spectral purity (monochromatic light)
- spatial coherence

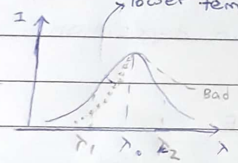


Optical oscillator

RECAP of LED

lower temp or greater degree of confinement

Q.W

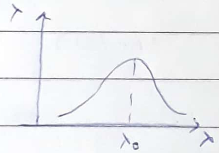


$$\lambda_0 = \frac{hc}{E_1 + E_2 + E_g}$$

$$\frac{hc}{E_1 + KE_1 + E_2 - KE_2 + E_g}$$

mp mp

Bulk



$$\lambda_0 = \frac{hc}{E_g + k_B T}$$

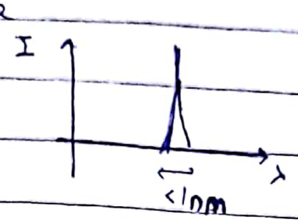
2 degree of confinement

$$E_x = \frac{\pi^2 \hbar^2 n_x^2}{2m L_x^2} \qquad E_y = \frac{\pi^2 \hbar^2 n_y^2}{2m L_y^2} \qquad E_z = \frac{\hbar^2 k_z^2}{2m}$$

Fermi's Golden Rule

↳ the emitted ~~wa~~ photon ~~is~~ will have max. probability of having same phase as the

LASER



LED ~ns

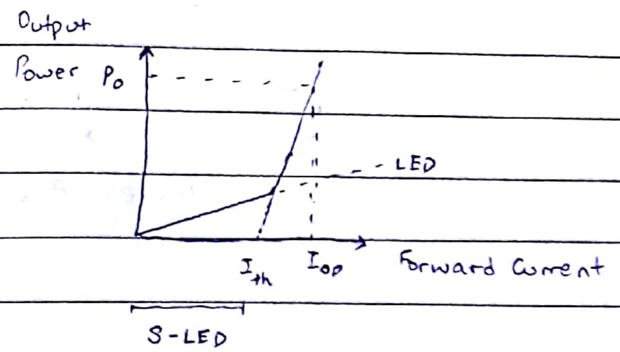
~ps LASER

- higher power
- less ~~step~~ time
  also constructive interference
- more efficient
- Modulation bandwidth

- ~~LED~~ speed is limited by recombination process
  (LED → ~ns ⇒ GHz LASER → ps ⇒ 4 THz)

LASER — Gaussian

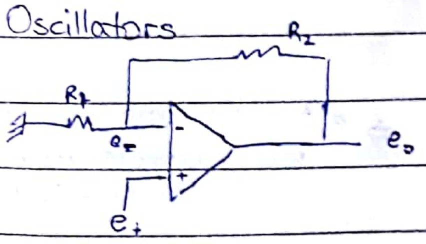
LED → Lambert's Cosine Law



S-LED : superluminiscent LED
↳ some stimulated emission but not enough for lasing action

Normalised Response : $\dfrac{\partial(L/L_o)}{\partial(I_{ac}/i_o)}$

Oscillators



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

$\cancel{e_o = e}$

$\dfrac{0 - e_-}{R_1} = \dfrac{e_- - e_o}{R_2}$

$\Rightarrow \dfrac{e_o}{e_+} = \dfrac{A}{\dfrac{AR_1}{R_1+R_2} + 1} = \dfrac{A}{1+A\beta}$ $\left(\beta = \dfrac{R_1}{R_1+R_2}\right)$ ← feedback factor

-ve	+ve
$\dfrac{A}{1+A\beta}$	$\dfrac{A}{1-A\beta}$ ← voltage could go to max ⇒ Saturation
	$\dfrac{A(\omega)}{1-A(\omega)\beta(\omega)}$

$A\beta > 1$ as circuit will 'adjust' to make $A\beta = 1$

← Amplifier becomes an oscillator

Collpit's , Hartley Oscillator

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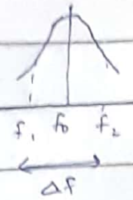
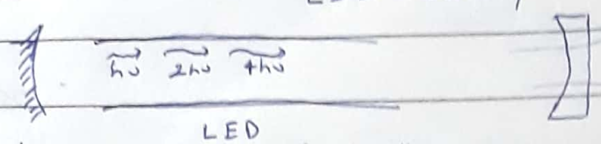


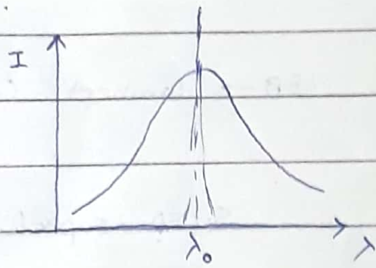
Quality Factor : $\frac{f_0}{\Delta f}$

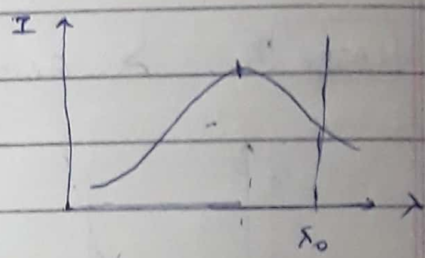
LED + Cavity



~~$\beta = \frac{L_{out}}{L_{reflect}}$~~ $\beta = \frac{\text{fraction of reflected}}{\text{fraction of input}}$

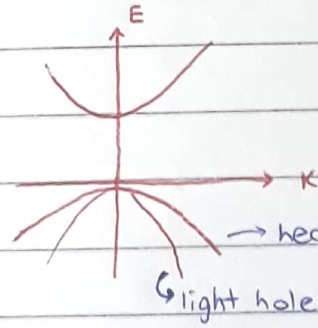
$L = \frac{\lambda_0}{2}$.



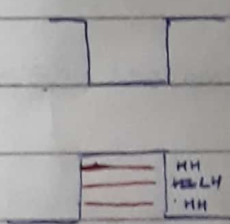


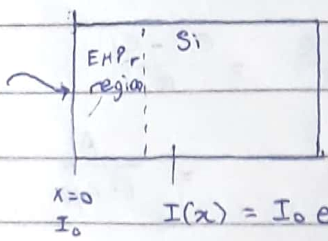
lower A ⇒ need larger β

#



$m^* \propto \frac{1}{\partial^2 E/\partial K^2}$





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

~~$\alpha = \alpha(\lambda)$~~
$\alpha = \alpha(\lambda, T)$

⇒ Any wavelength longer than E_g, will penetrate more (material is more transparent)

$\frac{1}{\alpha}$ = penetration depth

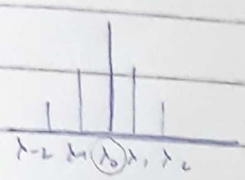
~~Min~~ Pumping in more carriers

→ Gain increases due to greater recombination

→ Peak shifts to higher energy ⇒ wavelength shifts ⇒ CHIRP

-  higher energy tail is also occupied
- temp increases 

* for precision use, LASER is left on ~~for~~ (idle) to result in eq^n temp (no chirp)



Peak is due to maxima of gain

(λ_i satisfies boundary condition)

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

Multimode LASER

↓ optical filter

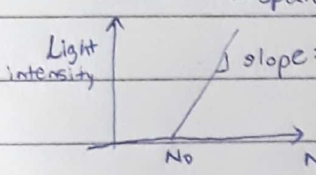
Single mode LASER

LASER RATE EQ^N

$N = e^-$ density $I(t)$ = current V_a = active volume of device

$$\frac{dN(t)}{dt} = \frac{I(t)}{qV_a} - \underbrace{g_0 \frac{[N(t) - N_0] \cdot S(t)}{1 + \varepsilon \cdot S(t)}}_{\text{stimulated emission}} - \underbrace{\frac{N(t)}{\tau_n}}_{\text{spontaneous emission}}$$

N_0 = transparency carrier density [$I(x) = I_0$ ($g=0$)]



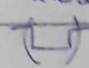
$L = g(N(t) - N_0)$

$S(t)$ = photon density

ε = gain compression factor (if too many photons, gain is slightly lesser)

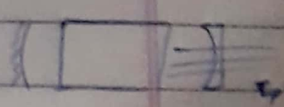
$$\frac{dS(t)}{dt} = \Gamma \cdot g_0 \frac{[N(t) - N_0] \cdot S(t)}{1 + \varepsilon S(t)} - \frac{S(t)}{\tau_p} + \frac{\Gamma \cdot \beta}{\tau_n} N(t)$$

τ_p ↳ rate at which photons leave the system



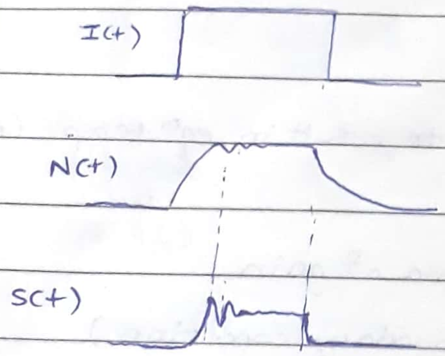
Γ : photon confinement factor

β : ~~a~~ fraction of recombination that is radiative



Relaxation Oscillation

· More e^- $\longrightarrow$ more photons $\longrightarrow$ stimulated emission $\longrightarrow$ e^- bulids up
stops
photons decrease



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