INJECTION ELETROLUMINESCENCE

Electroluminescence refers to luminescence in the presence of an electric field, i.e, generation of light in the presence of an electric field.

Injection electroluminescence refers to generation of light in the presence of an injection current, so this injection refers to injection current.

Semiconductor

$n_0 = n_i + N_D$

$p_0 = p_i + N_A$

$G_0 \propto n_0 p_0$

$R_0 \propto n_0 p_0$

(Thermal Equilibrium) $R_0 = r \cdot n_0 \cdot p_0 = G_0$

Where,

r = rate constant (depends on material)

n_0, p_0 = Steady state carrier conc^n.

$p_i = n_i$ = intrinsic carrier conc^n.

N_D = Donor conc^n.

N_A = Acceptor ion conc^n.

G_0 = Rate of Generation

R_0 = Rate of recombination.

Assume that now we separately but a beam of light from outside, which creates additional electrons and holes, so we are now moving to Quasi Equilibrium.

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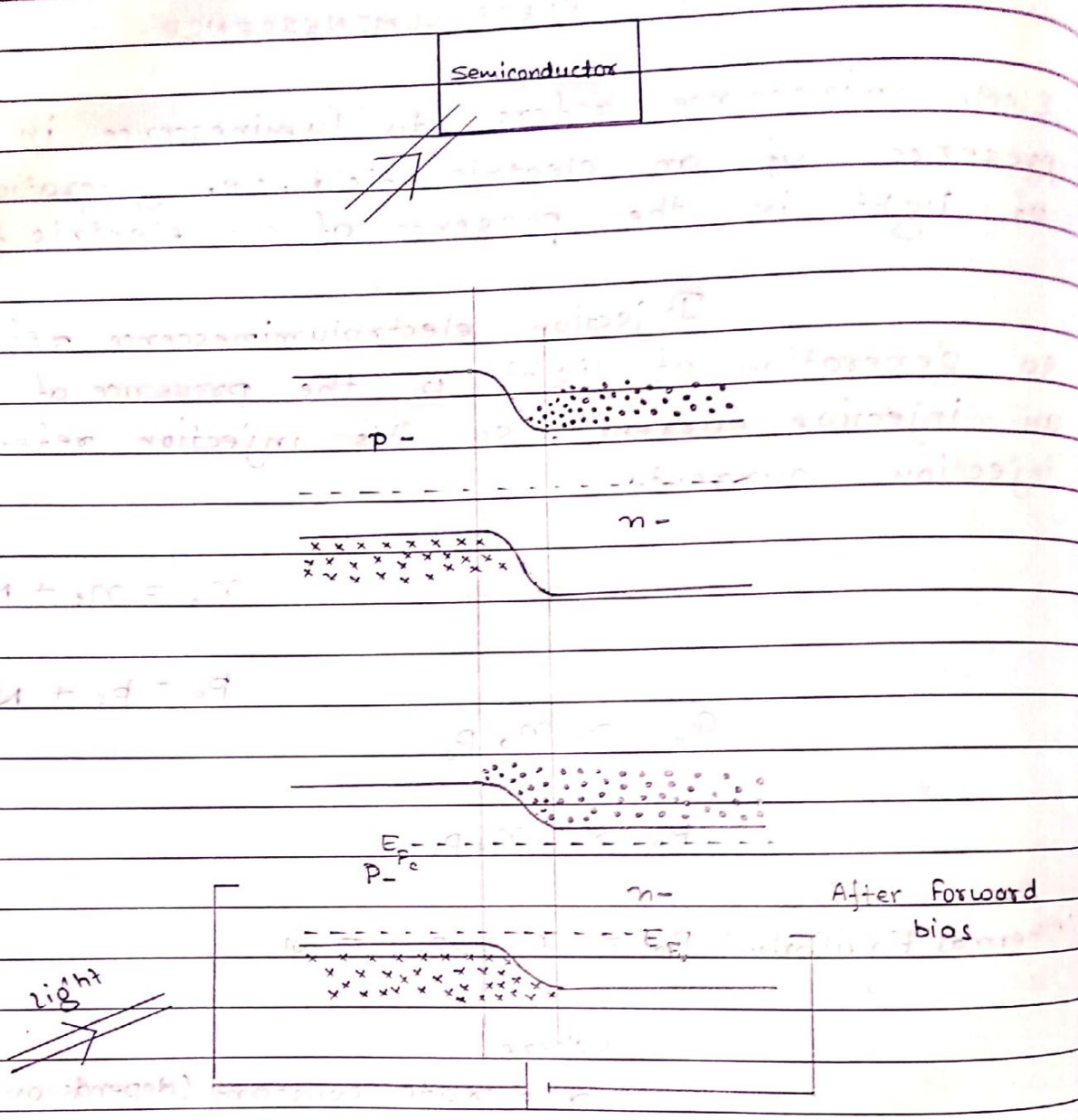

R = rate of injection of carriers.

So, In the junction region we have excess carrier concentration, excess of electrons and holes, because of the injection.

$$n = n_0 + \Delta n$$

$$p = p_0 + \Delta p$$

where,

Δn & Δp = Excess carrier conc^n.

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If we think of light incident, then for every electron generated here, 1 hole will be left behind. Similarly, when we inject current, for every e^- which is coming from the negative side, 1 hole will be released here.

$$\therefore \quad \Delta n = \Delta p.$$

Now,

$$(G_0 + R) \propto n\,p$$

or,
$$(G_0 + R) = \gamma \cdot n \cdot p$$

or,
$$(G_0 + R) = \gamma\,(n_0 + \Delta n)\cdot(p_0 + \Delta p)$$

or,
$$(G_0 + R) = \gamma\, n_0 p_0 + \gamma\,(n_0 + p_0 + \Delta n)\,\Delta n$$

{$\Delta n = \Delta p$ (use)}

or,
$$R = \gamma\,(n_0 + p_0 + \Delta n)\,\Delta n$$

R → /cc/sec; $(n_0 + p_0 + \Delta n)$ → /cc; Δn → /cc

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

where,

$$\tau = \frac{1}{\gamma\,(n_0 + p_0 + \Delta n)}$$

↑ Excess carrier recombination time

γ = cc/sec. (unit)

If the injection rate is relatively small; so, $\Delta n << n_0$, then

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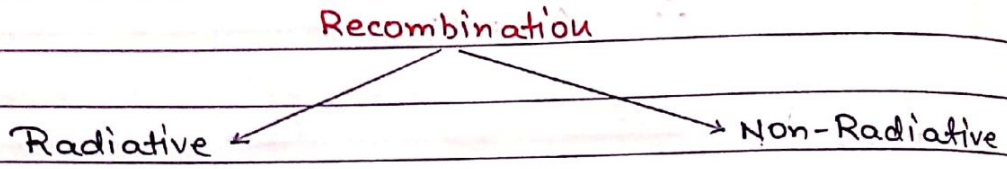
$$\tau = \frac{1}{\gamma(n_0 + p_0)}$$

Now, γ is the rate constant for recombination,



So, $\gamma = \gamma_r + \gamma_{nr}$

γ_r : radiative ; γ_{nr} : non-radiative

(Recombination rate) $R = \gamma . np = \gamma_r . np + \gamma_{nr} . n.p$

$$\therefore \tau_r \propto \frac{1}{\gamma_r} \quad ; \quad \tau_{nr} \propto \frac{1}{\gamma_{nr}}$$

LIFE TIME:

Say at $t = 0$, we inject a certain carrier conc^n Δn_0 & Δp_0 (by burst of light). Then it is only instantaneous, it is like an impulse which has created excess carrier conc^n Δn_0 & Δp_0. with time, because of recombination, this continuously drop down. If they recombine faster, the rate will fall faster. If they recombine slowly, then this will go very slowly.

$$\text{rate of recombination} = \frac{d\,\Delta n}{dt}$$

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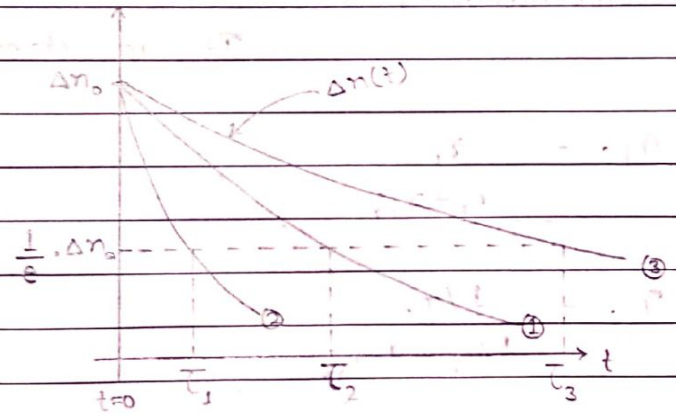
By integrating; we get

$$\Delta n(t) = \Delta n_0 \, e^{-t/\tau}$$

where,

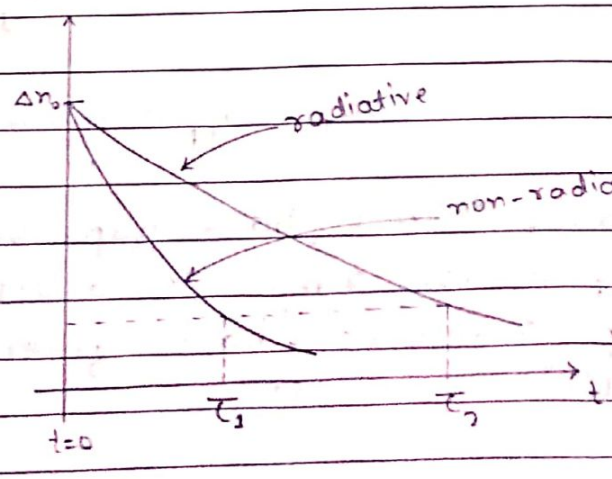
τ is the time where the excess carrier conc^n falls to $1/e * \Delta n_0$.

For e.g. If a particular material has variation like the radiative lifetime τ_r is very large, and the non-radiative lifetime τ_{nr} is very small, it means the carriers combine very quickly mostly by non-radiative transitions.



recombination rate; (2) > (1) > (3)

$\Rightarrow$ life time; (2) < (1) < (3)



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Hence, most of the recombination is done by non-radiative recombination. (in above graph)

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

INTERNAL QUANTUM EFFICIENCY:

It is the ratio of radiative recombinations to the total recombinations, per second.

It is denoted by η_i.

$$\eta_i = \frac{\gamma_r}{\gamma_r + \gamma_{nr}}$$

$$\text{or, } \eta_i = \frac{1/\tau_r}{1/\tau_r + 1/\tau_{nr}}$$

$$\text{or, } \eta_i = \frac{\tau}{\tau_r}$$

For e.g. GaAs $\eta_i = \frac{1/100}{1/100 + 1/100} = 0.5$

$$\text{or, } \eta_i = 50\%$$

In general, Direct band gap semiconductor have η_i in the rang 0.2 to 0.9. and indirect Bandgap materials have generally very low like 10^{-4}, 10^{-3}, etc.

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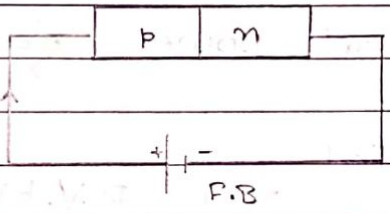
NOTE: If we want to realize a source, we should choose a material which is direct bandgap, which has a large η_i.

GaN is also a direct band gap material, but this does not have a large η_i.

So, for LED (blue) generally InGaN is used which has $\eta_i = 0.3$

OPTICAL POWER



As, carriers are recombining at junction region;

Rate of recombination = Rate of injection

i.e, $R_o = R$

We know,

R_o per unit time per unit volume (V)

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

As, $$i = \frac{q}{t} = \frac{e}{t} \Rightarrow \frac{i}{e} = \frac{1}{t}$$

$$\Rightarrow \text{no. of carrier injected per unit time} = \frac{i}{e}$$

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

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Every radiative recombination will give us one photon. If η_{ph} is the number of photons generated per unit time, the power generated is,

$$\eta_{ph} \cdot h\nu$$

No. of photons generated

$$\eta_i \cdot RV = \eta_i \frac{\Delta n}{\tau} \cdot V$$

So, the optical power generated

$$P_{gen.}^{optical} = \eta_i \cdot R.V.h\nu = \eta_i \cdot \frac{i}{e} \cdot h\nu$$

or,

$$\boxed{P_{gen.}^{optical} = \eta_i \left(\frac{h\nu}{e}\right) \cdot i}$$

where,

$$\nu = \frac{c}{\lambda}$$

$$e = 1.6 \times 10^{-19} \text{ C}$$

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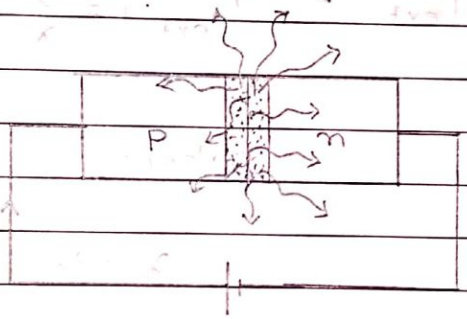
LIGHT EMITTING DIODE:
DEVICE STRUCTURE AND PARAMETERS

As, $P_{gen}^{optical} = \eta_i \left(\frac{i}{e}\right) \cdot h\nu$

where,

$\eta_i \left(\frac{i}{e}\right)$ = Photon flux $\cdot (\phi)$

In a F.B. semiconductor; spontaneous recombinations are taking place and light is generated.



When photon or the radiation is coming out, therefore the actual power output will be less than the power generated.

η_e = Extraction efficiency

which means out of the generated power, the fractional power that is being extracted out, then

$$P_{out} = \eta_e \cdot P_{gen}^{optical}$$

$$\Rightarrow P_{out} = \eta_e \cdot \eta_i \cdot \left(\frac{i}{e}\right) \cdot h\nu$$

$$\Rightarrow P_{out} = \eta_{ext} \cdot \left(\frac{i}{e}\right) \cdot h\nu \quad \{\because \eta_e \eta_i = \eta_{ext.}$$

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Where,

η_i = Property of material

η_e = depend on device structure

As, $P_{ext} = \eta_{ext} \cdot \left(\frac{i}{e}\right) \cdot \frac{hc}{\lambda}$ $\left\{\because \vartheta = \frac{c}{\lambda}\right\}$

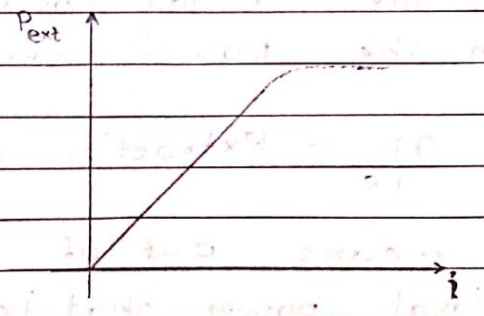
$\Rightarrow P_{ext} = \eta_{ext} \cdot \left(\frac{hc}{e}\right) \frac{i}{\lambda}$

$\Rightarrow P_{ext} = \eta_{ext} \cdot \left(\frac{1.24}{\lambda}\right) \cdot i$

Where,

λ is in μm

or, $P_{ext} \propto i$



So, η_e can be maximized by choosing appropriate device structure.

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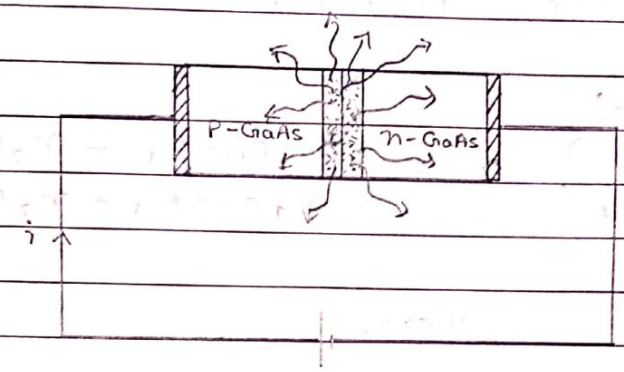
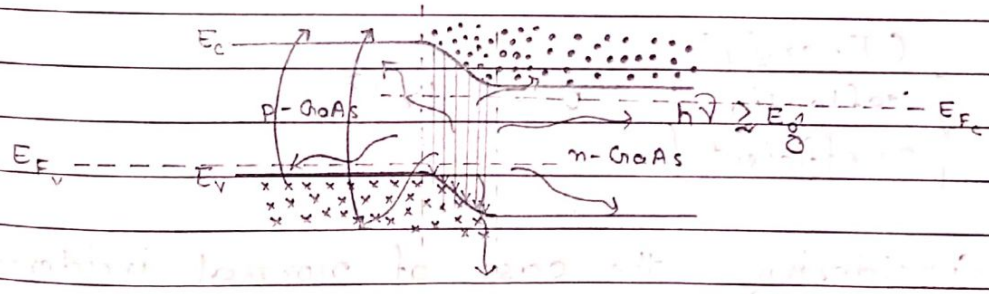
LED TYPES

1. SURFACE - EMITTING LED (SLED)
2. EDGE - EMITTING LED (ELED)

BASIC STRUCTURE OF LED



HOMOJUNCTION LED



LOSSES:

1. REABSORPTION LOSSES: As the recombination taking place at active region; and generating photon. The generated photon is now propagating through the rest of the semiconductor, beyond the active region. An electron in V.B absorbs the photons and makes upward transition, so, the generated photon can be reabsorbed by the same material. This major loss is called Reabsorption Loss.

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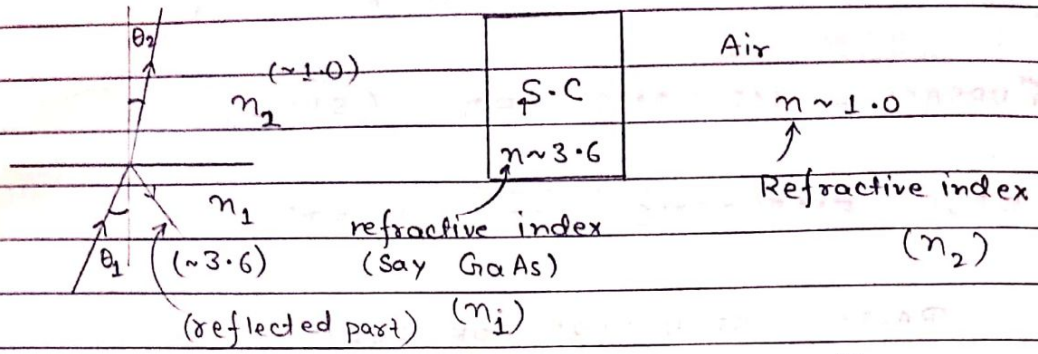
2. REFLECTION LOSS :



By Fresnel Reflection coefficients;

$$\left\{\begin{matrix}\text{(Amplitude)}\\ \text{reflection}\\ \text{coefficient}\end{matrix}\right\} \quad r = \left(\frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2}\right)$$

where,

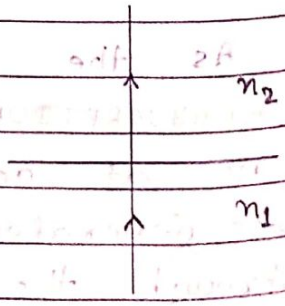
θ_1 = Angle of incidence

θ_2 = Angle of refraction

$$\left\{\begin{matrix}\text{(Energy)}\\ \text{reflection}\\ \text{coefficient}\end{matrix}\right\} \quad R = |r|^2$$

Considering the case of normal incidence for simplicity.

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



$$\Rightarrow R = \left(\frac{3.6 - 1}{3.6 + 1}\right)^2$$

$$\Rightarrow R = 0.32$$

or, Reflectivity is 32% for normal incidence.

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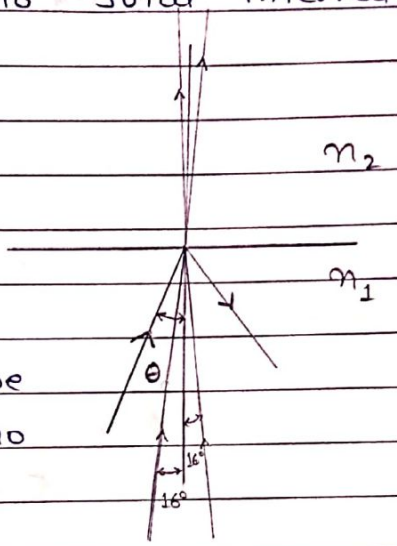
i.e, 32% of the light which is trying to come out is reflected back at the interface (n_1).

3. TOTAL INTERNAL REFLECTION LOSS:

As, the light is going from a denser medium to rarer medium. which leads to Total internal reflection.



$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

If $\theta > \theta_c$, then light will be totally reflected and there is no light coming out.

So, $\theta_c = \sin^{-1}\left(\frac{1.0}{3.6}\right)$

or, $\theta_c = 16°$

i.e, the cone of light that is coming out is within 16° angle or else totally reflected.

In other words, A major portion of the generated light will get totally reflected from the semiconductor interface.

There are additional losses as well that, impurity of material, defects, carrier losses due to trapping.

So, Above are optical losses.

To reduce these losses we use double Heterostructure.

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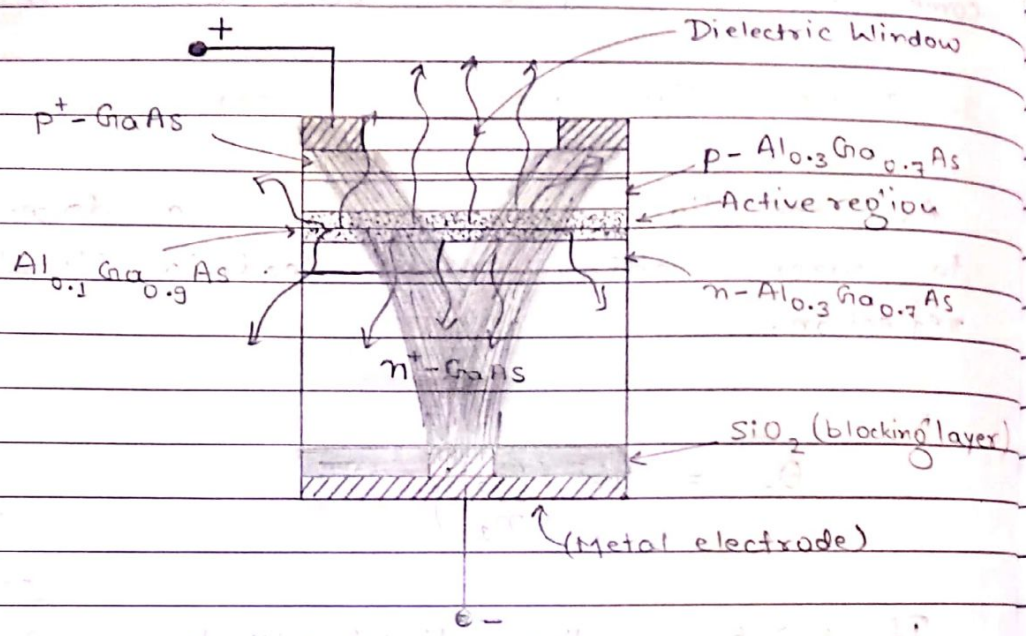
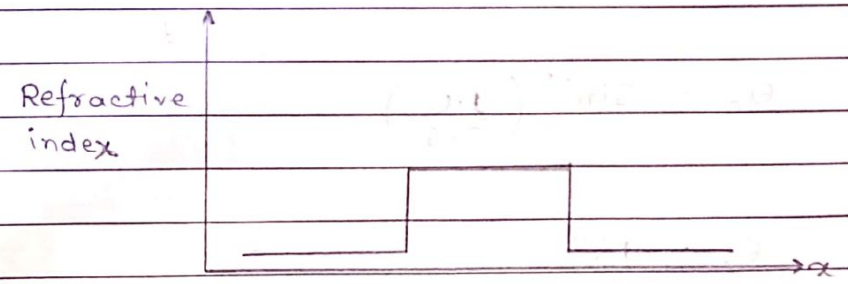
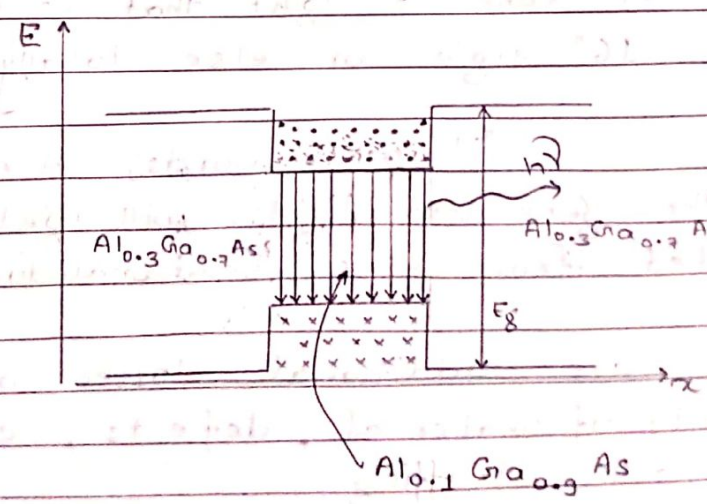
DOUBLE HETEROSTRUCTURE IN LED :



Angular Cross-Section of front view of a SLED's chip. (Surface LED)





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As, the photons generated by recombination which are taking place. Photons of energy $h\nu$ which are generated, as they come out, they see material which has larger band gap and therefore they will not be absorbed. i.e, heterostructure avoid reabsorption losses.

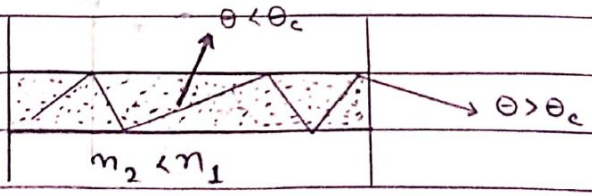
When we Forward bias the material, the carrier density becomes very large in the active region. i.e, carrier confinement.

As there is a fortunate in nature that, larger would bandgap lesser will be refractive index and vice-versa.

So, the light generated get trapped inside, if it comes at an angle greater than critical angle, and the structure will behave like an optical waveguide, and light comes out from the edges.

This optical confinement property is made use of in realizing Edge-Emitting LED(s).

Optical Confinement : It refers to the optical energy which is generated in the active region being confined because of optical wave guiding action.



NOTE:

We use block layer because, we want the light to be generated at centre, so that it comes out from dielectric window.

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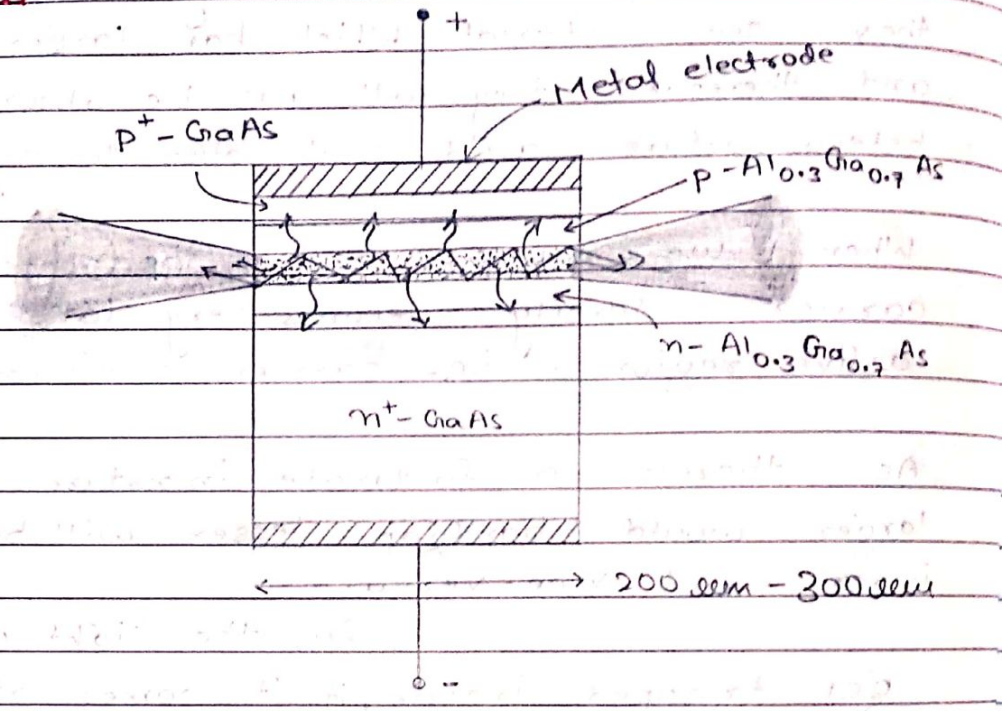
The EDGE - EMITTING LED has a similar structure, which makes use of the point optical confinement.

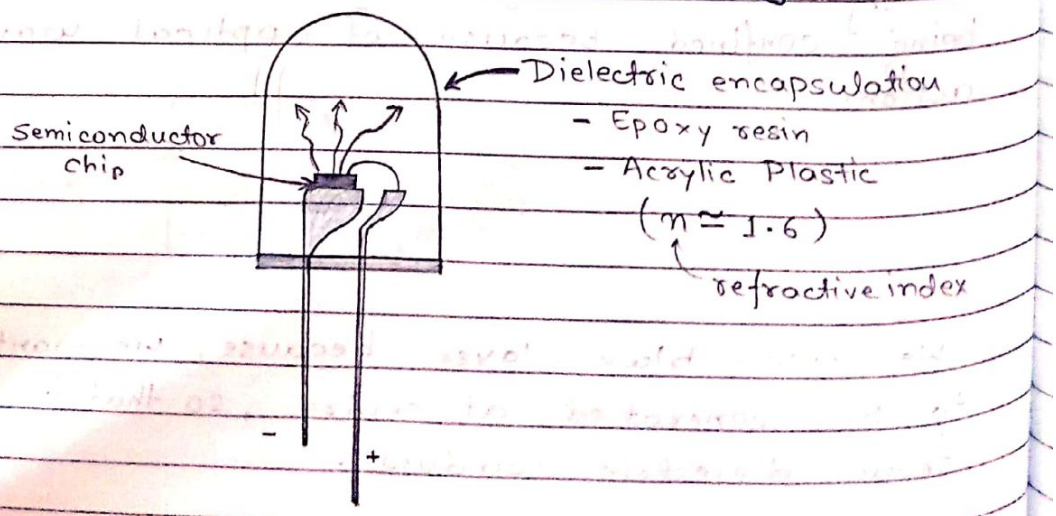


Typically, Active layer ~ 0.2 μm

Substrate thickness ~ 60 μm

Outside cladding layer ~ 0.4 to 0.6 μm

NOTE: In ELED the light is not parallel, but directional, because it's already divergent.



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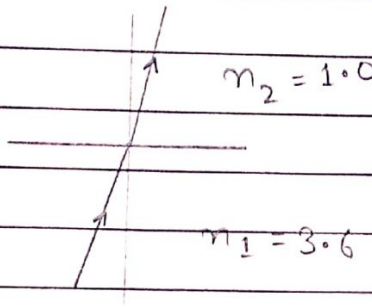
Dielectric Encapsulation

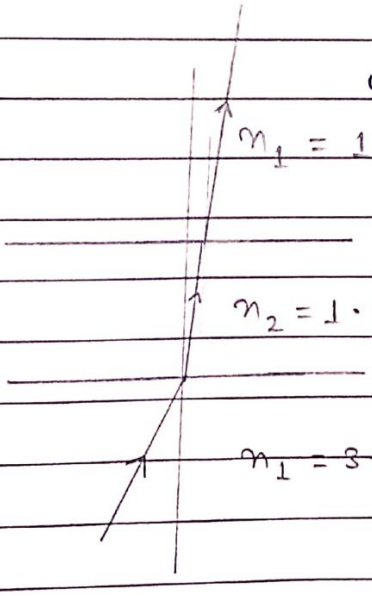
- To protect semiconductor chip
- To reduce reflection losses*

* Reflection losses:



⇒ 32 % loss and 68 % light transmitted.

using Dielectric encapsulation



⇒ ≃ 18 % loss only 82 % light will be transmitted.

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