UNIT - IV

OPTOELECTRONIC DEVICES:

- LED
- LASER
- Photo detectors
- Solar cell.

LASER: less divergent, coherent beam, monochromatic, unidirectional.

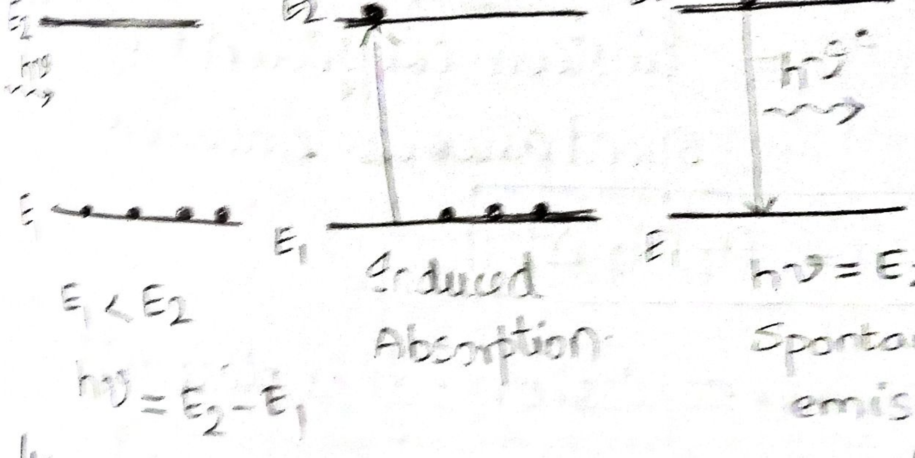
Light Amplification by Stimulated Emission of Radiation.

- Laser is highly directional monochromatic intense beam of light.
- This theory is given by Einstein.

INTERACTION OF RADIATION WITH MATTER: ~~Metal~~

→ Absorption → Induced
→ Spontaneous Emission
→ Stimulated Emission.

- Electrons try to occupy only lower energy state.



Life time of a state is the time in which the e^- can stay in excited state.
Eg: 10^{-8} sec to 10^{-9}.

* All the sources which illuminate light undergoes spontaneous emission i.e. all photons released are widely separated with a wide beam.

* Rate of absorption $\propto N_1 \rho(\nu)$ ⇒ Dependent on introduced photon.

N_1 = No. of e^-s in E_1

$\rho(\nu)$ = Energy density of incident light.

$$\boxed{\text{Rate of absorption} = B_{12} N_1 \rho(\nu)}$$

B_{12} = Einstein coefficient of induced absorption

$$\boxed{N_{ab} = B_{12} N_1 \rho(\nu) \Delta t}$$

* Rate of spontaneous emission $\propto N_2$

N_2 = No. of e^-s in the excited state.

$$\boxed{\text{Rate of spontaneous emission} = A_{21} N_2}$$

A_{21} = Einstein coefficient of spontaneous emission.

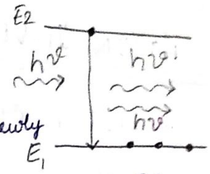
$$\boxed{N_{ab} = A_{21} N_2 \Delta t}$$

* Spontaneous emission takes place after 10^{-9} sec.

Photons are in different direction with diff wavelengths in spontaneous emission.

Stimulated Emission:

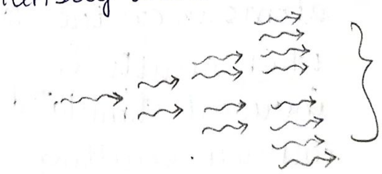
Forced Emission.



- The photon emitted after the disturbance created by the newly entered photon is having the same phase, direction and amplitude as that of initial one.
- The photon introduced will disturb the E_2 due to which photon is emitted & e^- drops down to lower energy state.
- These 2 photons trigger other 2 and this process is continued till all the atoms drop down.

This results in emission of large no. of photon and it results in amplification of light.

- Since this takes place in only one direction; intensity increases



} unidirectional

Rate of stimulated Emission $\propto N_2 \rho(\nu)$

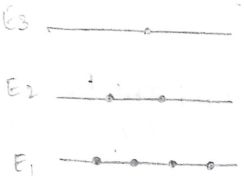
$$\boxed{\text{Rate of stimulated Emission} = N_2 B_{21} \rho(\nu)}$$

B_{21} = Einstein coefficient of stimulated emission.

$$\boxed{N_{st} = N_2 B_{21} \rho(\nu) \Delta t}$$

* POPULATION INVERSION:

The concentration of atoms in a particular energy level.



$E_1 \rightarrow$ max population

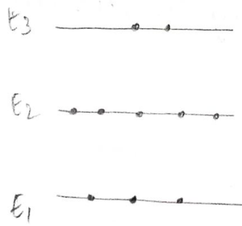
$E_3 \rightarrow$

At equilibrium

LASER's ultimate condition is undergo stimulated emission and emit large no. of atoms & ↑se light.

The process of making more no. of atoms in excited state as compared to lower energy state is called population inversion

*



Population Inversion.

* This is done to make more no. of atoms in excited state; which results in increased stimulated emission; resulting in high light

$$\boxed{N_i = N_0 e^{-E_i/KT}}$$

$$\boxed{\frac{N_2}{N_1} = e^{-(E_2-E_1)/KT}}$$

PUMPING:

The method to achieve population is called PUMPING.

The method of providing energy to a system so as to get more no. of atoms in the excited state as compared to the lower energy state is called PUMPING.

Methods of Pumping:

→ Optical Pumping: use somesort lightflash(xe)

→ Electrical / by applying $\vec{E}$ field

→ chemical reaction.

→ Direct conversion.

• Optical Pumping: Uses some sort of lightflash(Xe) or Krypton light to pump the e^-s from low E to high E.

Eg: Ruby Laser. : Solid State Lasers.

• Electrical Pumping: Applying high voltage; ↑ses the electrical field, due to which e^-s in lower energy state accelerate to higher energy state.

Eg: Gas laser: He-Ne laser, CO_2 laser etc.
(harmless) (intense beam) used for welding, cutting

• Energy released during any chemical
... this method

• Direct Conversion:

Uses semi-conductor lasers such as GaAs semi-conductor lasers.

* META STABLE STATES:

It is state which has life time greater than that of excited state. [10^{-6} to 10^{-3} sec]

Population inversion can be achieved in b/w metastable states & lower energy states.

→ Metastable state can be ~~seen~~ introduced by adding impurities.

IN RUBY LASER: Cr ions.

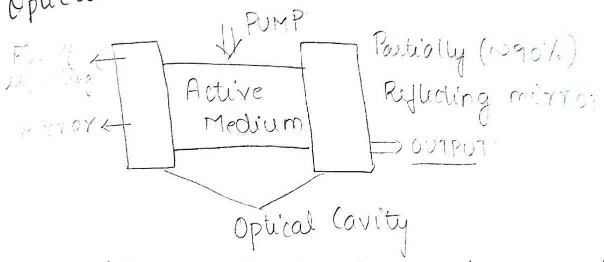
• He-Ne: Ne ions.

Pumping itself will act as absorption

MATERIAL → ADDING IMPURITY (Metastable state) → PUMPING → e's are excited to higher energy state $\xrightarrow{\text{Population inversion}}$ Spontaneous Emission → Stimulated Emission

* COMPONENTS OF LASER:

1) Active Medium → solid / gas / liquid   Ruby → Al doped with Cr ions
2) Pump
3) Optical Resonator.



Active medium decides the type of laser used.

Host	Active center
→ The original material/medium in which active centres are present.	→ Transitions take place. → metastable state is ~~created~~ introduced.

• In SC laser: Si → host; V/III → active centers

• In Ruby laser: Al → host; Cr → active centres

*Optical Resonator consists of 2 mirrors i.e. fully reflecting & partially reflecting mirrors.

Active medium is between the 2 mirrors.

→ Output is through partially reflecting mirrors.

02/03/2022

* Active medium is the medium where energy is supplied & transitions take place.

photons in diff. direction are eliminated.

* Requirements for lasing:

1) Population inversion → Pump
2) Metastable state
3) Spontaneous emission.
4) Stimulated emission.

} Active Medium

5) ~~Aplication~~ Amplification → Optical resonator.

Optical resonator acts as +ve feedback; we get an intense, amplified beam of light.

* Characteristics of LASER:

1) highly Monochromatic – single wavelength:
2) Highly directional – sharp & focussed.
3) intense → remains same throughout.
4) coherent → photons have same phase, amplitude same direction.
5) Less divergence – very negligible.

* Because of being highly ~~divergent~~ directional lasers are used to cut the glass.

* Less divergent property of laser makes it useful to ~~use~~ ~~in~~ ...

the surgeries.

* Intensity ↓ses with ↑se in distance.

* $\boxed{I = \left(\frac{10}{\lambda}\right)^2 P}$

* Nearly monochromatic → Na light
coherence ~ 0·3mm.

Coherence length He-Ne laser : 100mm

03/03/2022

* TYPES OF LASER:

1) ACTIVE MEDIUM:

- Solid State Lasers
  - → in which active medium is solid.
  - → optical pumping
  - * Eg: Ruby Laser, Nd-YAG laser
- Gas Lasers
  - → in which active medium is gas
  - → electric discharge.
  - * Eg: He-Ne laser, CO_2 laser.
- Semi-conductor Lasers.
  - → in which PN junction diode is active medium
  - → direct pumping
  - * Eg: GaAs, GaInP, AlGaAs.

2) MODES:

- Pulsed mode
- Continuous Wave

3)

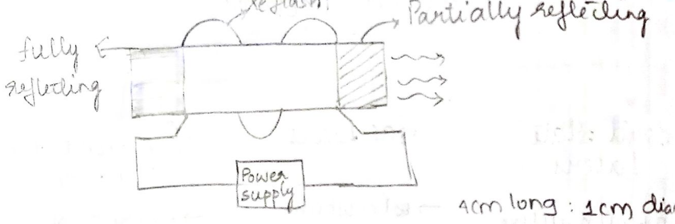
PUMPING:

2 level pumping

4-level pumping

*RUBY LASER: first ever laser.

1) Invented in the year 1960.
2) Solid State laser
3) It uses 3 level pumping scheme.
4) $\lambda \sim 694.3$ nm.



4cm long : 1cm diameter

*Active medium: Al_2O_3, doped with 0.05% Cr ions.

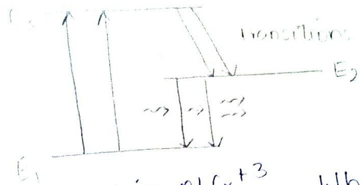
* Active centers: Cr ions : undergo transitions

* Pump: Optical Pumping
  Xenon flash lamp.

* Optical resonator:
  Front part: Reflecting (Partially)
  Back part: Fully Reflecting.

→ Opposite ends of Ruby rod are ~~~~ p' cut and well polished to act as mirrors.

Energy Band diagram:



When population of Cr^{+3} in E2 > When population of Cr^{+3} in E1.

The photons emitted ~~in~~ after stimulated emission; move to & fro in the optical resonator; this leads to amplified ~~&~~ light.

Salient Features:

→ 3-level pumping.

→ Cr^{+3} ions are the active centers.

→ Pulsed Mode.

* He-Ne LASER:

1) first ever gas laser.
2) 4 level-pumping
3) $\lambda = 632.8$ nm.

Glass discharge tube should be narrow.

30cm long
1cm diameter

*Active medium: He-Ne : 10:1 ratio

* Active centers: Ne is used in transitions

* Pump: Electrical discharge.

* Optical resonator: Two mirrors on opposite

partially reflecting.

→ When high voltage is applied and ionisation energy is developed ⇒ e^-s are developed in glass tube; these e^-s do not collide with Ne as it is larger than He and when these e^-s collide with He; energy is transferred to He.

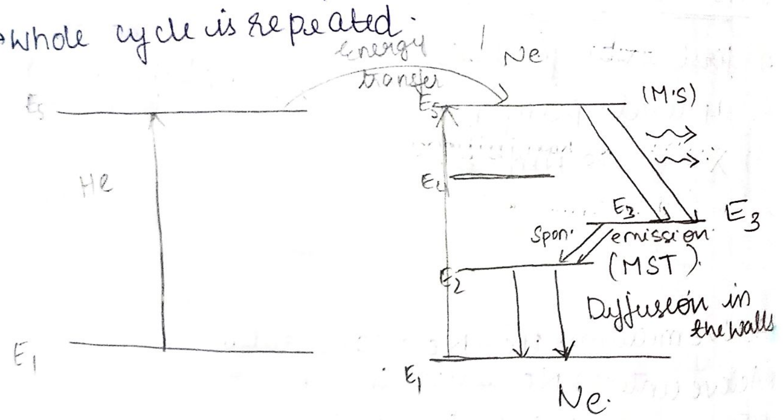
→ Due to this energy; He atoms get excited to higher energy level ($E = 20.65\,eV$).

→ This energy is transferred to Ne atoms by resonate energy ~~level~~ transfer. Same energy state

Role of He is to excite Ne atoms.

Helium reaches to ground state.

→ Whole cycle is repeated.



Ruby & He-Ne lasers ~~a~~ gives only 1 – 2% efficiency.

04/03/2022

* SEMICONDUCTOR LASER:

→ Uses direct band semi-conductor materials are used i.e. which emit light on the recombination of free e^- & hole.

→ First semiconductor laser is GaAs ~~[illegible]~~ manufactured in 1962. $\boxed{\lambda \sim 8200 - 8500\,\text{Å}}$

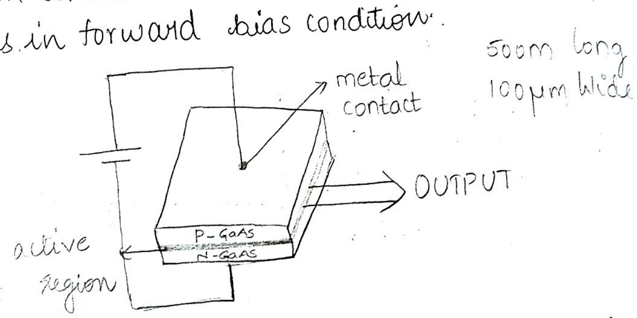
→ made up of PN junction diode.

→ Uses compound semi-conductor i.e. GaAs.

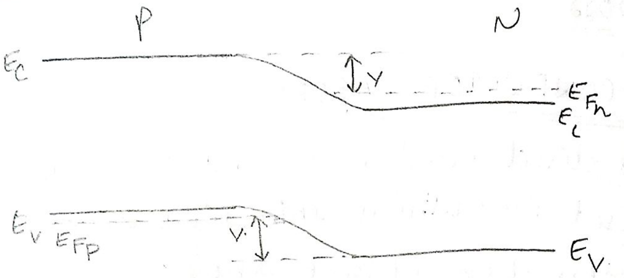
→ They emit light in range UV to IR rays.

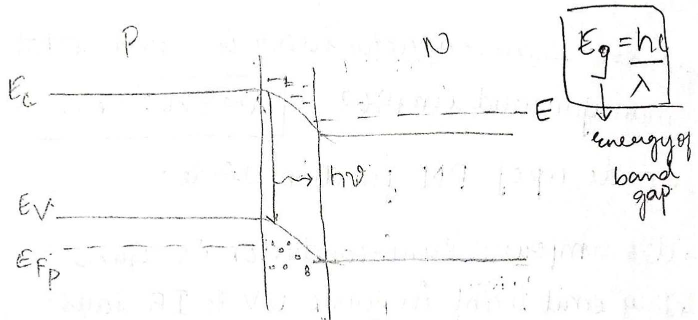
→ Small and portable; compact; low power, 40% effic

→ In direct conversion; the PN Junction diode is in forward bias condition.



* The PN junction diode used in SC laser is heavily doped which ~~[illegible]~~ implies the fermi level ~~[illegible]~~ is in CB and VB.





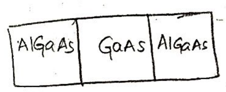
→ Due to heavy doping; the fermi-level is present in the CB and VB; due to which the barrier is not present; then ~~which~~ e⁻s ~~free~~ & holes will be present in barrier.

⇒ When e⁻s are in Ec (higher energy level) and holes are in Ev (lower energy level) which is called as population inversion.

→ Electron present in excited state falls down and recombines with hole emitting a photon (spontaneous emission) which trigger stimulated emission and leads to formation of a monochromatic & amplified light.

* The junction ... formed by ~~[illegible]~~ the same type of materials and same band gap energy is called HOMOJUNCTION.
* The junction which is formed by the different type of materials and have different band gap energy is called HETEROJUNCTION.
  - → Single Heterojunction (SH)

  - → Double Heterojunction (DH)



→ Hetero-junction is a better one.

APPLICATIONS:

→ Cutting, welding; trimming the chips
→ Alignment purposes.
→ cosmetic surgeries, medical treatment
→ Cancer treatment
→ Used as pain killers; quickly heals the wounds.
→ Laser printing, optical fiber communication; Satellite communication.
→ In defence and military purposes.

* LED

08/03/2022.

LIGHT EMITTING DIODE: (1960)

- → Forward Bias
- → Emits light.
- → PN Junction diode.
- → spontaneous emission.
- → Incoherent light.
- → electroluminiscence

SPONTANEOUS EMISSION	STIMULATED EMISSION
→ Do not need an external agent.	→ Needs an external agent.
→ The beam is scattered & emitted in all directions	→ The beam is unidirectional
→ ~~I~~Coherent beam is emitted	→ Coherent beam is emitted
→ Not monochromatic	→ Monochromatic
→ Low intensity beam.	→ High intensity beam
→ Not same phase & frequency	→ same phase
→ Eg: LED, CEFL	→ Laser.

- , efficiency is good
- , Low input power
- , Heat is not dissipated.
- , They do not have any warmup time.
- → cheaper.

*APPLICATIONS:

- , Displays in mobile ⟺ battery is longlasting.
- → Traffic signals.
- , White LED used at home
- → Colour LEDs used for decorations
- → calculators & digital clocks.

* Electroluminiscence: light emitted by the excitation of e^- ~~by~~ on the action of external electric field. is called electroluminiscence.

10/03/2022

*Luminescence: Emission of optical radiation ~~of~~ by e^- excitation.

CHARACTERISTIC TIME:

- Fluroscence: $T \leq 10^{-8}$ sec
- Phosphoroscence: $\tau \geq 10^{-8}$ sec

* Recombination mechanisms:

1) Interband transitions
2) Defect transitions
3) Intraband transitions.

* The traps formed in forbidden region:
when they are close to E_c (or) E_v ~~it is~~ those traps are called SHALLOW TRAPS.

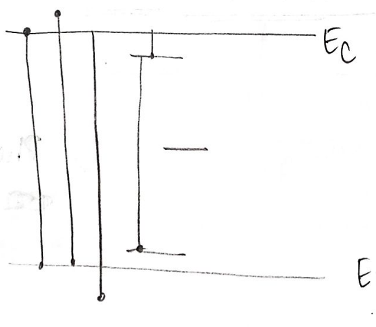
* The trap formed at the centre of forbidden gap is called deep ~~e~~ trap.

→ Interband Transition:

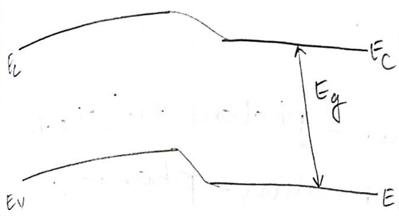
When the recombination of hole & e^- takes place; between CB & VB; it is called interband transition

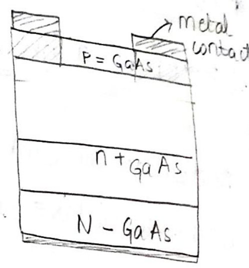
→ Intraband transition:

When the recombination of holes & e^-s takes place either only in CB (or) VB is called intraband trancition:

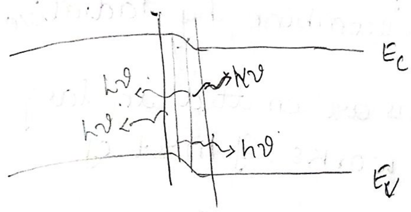


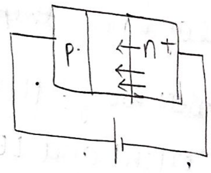
* Construction and working of LED:





at equilibrium





P-region is thin; so as to avoid any kind of losses so as to avoid reabsorption.

$$E_g = h\nu = \frac{hc}{\lambda}$$

$$\boxed{\lambda = \frac{hc}{E_g}}$$

Emits light in all possible directions

11/03/2022

* On forward biasing ~~a~~ upto a suitable rate; flow of e^-s and holes increases; due to which injection current is formed; due to which photons are emitted; by spontaneous emission.

Injection → Recombination → Extraction
(forward biasing)

→ TYPES:
- Surface emitting LED: emits light in all directions
- Edge emitting LED: emits in the form of cones.

* LOSSES IN LED:

1) Recombination losses:

radiative recombination = photons emitted.

non-radiative recombination = phonons.

* On recombination of e⁻s and holes, when majority of them recombine by radiative way; photons are emitted in large extent and LED works; if most of them recombine by non-radiative way; phonons are emitted in large extent; & LED do not work.

2) Reflection losses:

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

n_1 = refractive index of material

n_2 = refractive index of air

Eg: GaAs (n_1) = 3.6.

air (n_2) = 1

$$R = \left(\frac{3.6 - 1}{3.6 + 1}\right)^2 = 0.32$$

$$\boxed{R = 32\%}$$

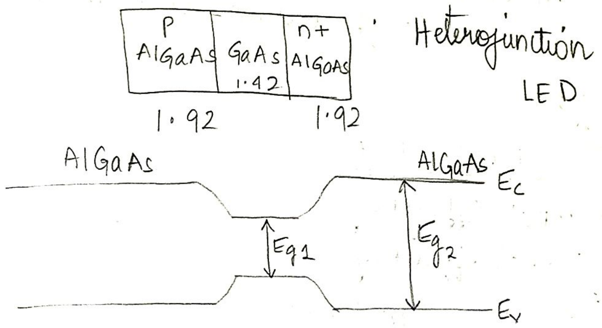
⇒ Only 68% of light is only coming out. Heterojunction LEDs are brighter.

3) TIR losses:

⇒ due to TIR of light; some of the light rays go back to the device and there are losses.

* ADVANTAGES OF LED:

1) Avoid reabsorption losses.
2) charge carrier confinement.
3) optical confinement.



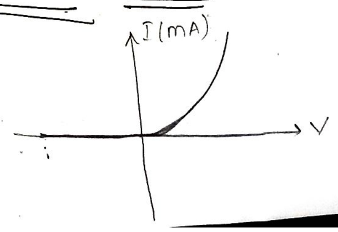
* Electrons & holes present in the middle region do not have a scope to go out; hence they should recombine in that region ⇒ Charge carrier confinement

⇒ $\boxed{\text{higher } E_g \longrightarrow \text{lower R.I.}}$

* CHARACTERISTICS OF LED:

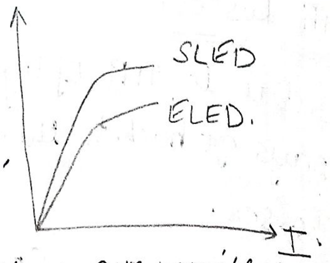
I-V-P:

1) I-V.



2) Light Output (Power) v/s I:

(i) Joule's law of heating.
(ii) Carrier leakage
(iii) Stimulated emissions. (in SLED)



Because in SLED; photons are emitted in different directions and reabsorption takes place: and in the case of ELED: stimulated emissions are advantageous so as to emit photons in uni-directional way.

12/03/2022

TYPES OF EFFICIENCIES:

1) Internal efficiency no. of EHPs ; no. of photons
2) External efficiency
3) Exteraction efficiency.

$$\boxed{I.F = \frac{\text{no. of photons produced}}{\text{no. of EHPs produced}}}$$

* Internal efficiency depends on the type of material used.

* External efficiency depends on the device structure.

* LED is encapsulated with a cap of certain refractive index.

Internal Quantum Efficiency: (η_i)

$$(\eta_i) = \frac{\text{no. of photons generated internally}}{\text{no. of EHPs produced}} \quad (40-50\%)$$

$$(\eta_i) = \frac{\text{no. of photons generated internally}}{\text{no. of carriers passing through junction}}$$

$$\eta_i = \frac{\phi_{ph}}{I/e} = \frac{P_{int}/h\nu}{I/e} = \frac{P_{opt}}{h\nu}\left(\frac{e}{I}\right)$$

$$* \boxed{\eta_i = \frac{P_{int}e}{h\nu I}}$$

Input Power = electrical = $P_{int} = VI$

$$\eta_i = \frac{\text{no. of radiative recombination}}{\text{total no. of recombinations}} = \frac{R_r}{R_r + R_{nr}}$$

$$\boxed{\eta_i = \frac{R_r}{R_r + R_{nr}}}$$

$$R_r \propto \frac{1}{\tau_r}$$

$$* \boxed{\eta_i = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}} = \frac{\tau_r^{-1}}{\tau^{-1}} = \frac{\tau}{\tau_r}}$$

Output Power = Optical Power

External efficiency: (η_e)

→ conversion of electrical energy into emitted optical energy.

$$\eta_{ext} = \frac{\text{no. of photons emitted outside}}{\text{no. of carriers passing junction}}$$

$$= \frac{P_o/h\nu}{I/e}$$

$$\boxed{\eta_e = \frac{P_o e}{h\nu I}}$$

$$\boxed{\eta_i > \eta_e}$$

$$\boxed{P_o = \eta_{ext} \frac{h\nu I}{e}} \quad P_o = \eta_{ext} \frac{hc}{\lambda} \cdot \frac{I}{e}$$

$$P_o = \eta_{ext} \cdot \left(\frac{hc}{e}\right) \frac{I}{\lambda}$$

$$\boxed{P_o = \eta_{ext} \left(\frac{1.24}{\lambda(\mu m)}\right) I}$$

→ Extraction efficiency (η_{ee}):

Fractional power that is extracted from the total generated power

$$\eta_{ee} = \frac{\text{photons emitted externally from device}}{\text{photons emitted internally by device}}$$

$$\boxed{\eta_{ee} = \frac{P_o / h\nu}{\eta_{int}(I/e)} = \frac{P_o / h\nu}{P_{int} / h\nu}}$$

$$\boxed{P_o = \eta_{ee}\, \eta_{int} \left(\frac{I}{e}\right) h\nu}$$

$$\boxed{\eta_{ext} = \eta_{ee} \cdot \eta_{int}}$$

Q: $\lambda = 900nm$ $I = 20mA$ $P_o = ?$ $\eta_{int} = 2\% = 0.02$

$$P_o = \eta_{int} \frac{1.24}{900 \times 10^{-3}} \times 20 \times \cancel{m}$$

$$P_o = 0.02 \times 1.24 \times \frac{\cancel{2}}{\cancel{90}\,45}$$

$$= 5.51 \times 10^{-4} = \underline{\underline{0.55mW}} \Rightarrow \text{Inside the device}$$

Q: n^+p GaAs LED; optical power = ? $I = 1mA$
$\lambda = 0.87\mu m$ $\eta = 50\%$

$$P_o = \frac{0.5 \times 1.24}{0.87} \times 10^{-3}$$

$$\boxed{P_o = 0.71\,mW}$$

Q: Radiative & Non-radiative recombination are $\tau_r = 60ns$ $\tau_{nr} = 100ns$. $\tau = ?$
$\lambda = 0.87\mu m$ $I = 40mA$ $P_{int} = ?$

$$\frac{1}{\tau} = \frac{1}{60} + \frac{1}{100}$$

$$\tau = \frac{600\cancel{0}}{16\cancel{0}} = 3.75nsec$$

$$\underline{\underline{\tau = 37.5ns}}$$

$$P_{int} = \frac{1.24}{0.87} \times \eta_{int} \times 40 \times 10^{-3}$$

$$= \eta_{int}(57.011 \times 10^{-3})$$

$$= \frac{37.5}{60} \times 57.011 \times 10^{-3}$$

$$\underline{\underline{P_{int} = 35.6mW}}$$

Q: $\eta_{int} = ?$ $\quad T_r = 80ns.$
$T = 40ns$

$$\eta_{int} = \frac{T}{T_r} = \frac{40}{80} = 0.5$$

Q: $\eta_{int} = 64.5\%$
$I = 40mA.$ $\quad \lambda = 0.82\mu m$
$P_{int} = ?$

$$P_{int} = \frac{64.5}{100} \times \frac{1.24}{0.82} \times 40 \times 10^{-3}$$

$$= 3901.46 \times 10^{-5}$$

$$= 39.01\ mW$$

15/03/2022

APPLICATIONS OF LED:

1) Display
- → Instrumental panel
- → traffic signals
- → TV/mobile screen.

} visible light

2) Communication: IR LEDs are used $\boxed{InGaP}$ for optical fibre communication.

3) Water decontamination/sterilization: UV LEDs are used.

*ADVATAGES OF LED:

1) Low power loss
2) long life span
3) ecofriendly because made up of PN-junction diode.
4) Less warm up time.
5) compact and small in size.

PHOTO DETECTORS:

- photoemissive (emission of e^-s)
  eg: PMT (photo multiplier)
- photoconductive (Change in conductivity)
  - photoconductors
  - photo diodes
  - photo transistors.

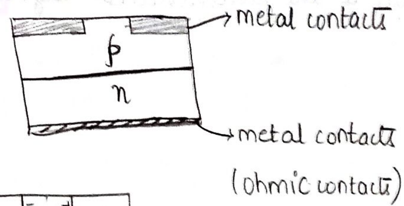
Photo diodes
- → PIN diode
- → APD (Avalanche Photodiode)

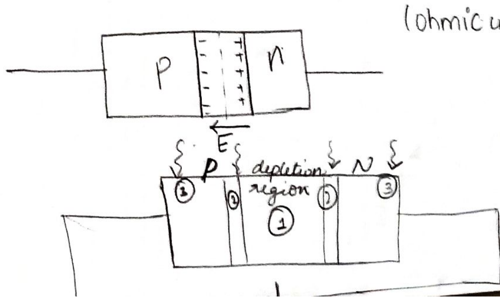
*PIN DIODE:

I/P photons → $\boxed{\text{Photo (PIN) diode}}$ → O/P Current

→ Principle: Internal Photoelectric Effect:

*Construction:





* Different regions:

1) Depletion region
2) Diffusion region
3) far away region.

When light is illuminated on the PN junction diode; EHPs are generated.

Carriers in depletion region move to respective majority charge carrier side.

When external voltage is applied, the charge carriers.

* DARK CURRENT: Reverse leakage current when no light is incident.

The current flowing in the circuit is called photo current because it is generated due to the illuminated light.