Sources

A) LASER

→ Function of optical source :- to convert electrical energy in the form of a current into optical energy (light) in an efficient manner which allows the light o/p to be effectively launched or ~~comp~~ coupled into the optical fiber.

3 types of optical light sources :-

a) wideband 'continuous spectra' sources (incandescent lamps);

b) monochromatic incoherent sources (LEDs);

c) monochromatic coherent sources (LASERS).

→ Previously, the most powerful narrowband coherent light sources were necessary due to severe attenuation & dispersion in the fibers.
∴ gas lasers (helium-neon) were utilized initially.

→ afterwards, semiconductor injection laser & LEDs were introduced.

req. for optical source :-

⇒ size and configuration compatible with launching light into an optical fiber.

⇒ must accurately track the electrical i/p signal to minimize distortion & noise.

⇒ should emit light at wavelengths where the fiber has low losses & low dispersion

⇒ capable of simple signal modulation

⇒ must couple sufficient optical power. to overcome attenuation

⇒ should have a very narrow spectral BW

⇒ must be capable of maintaining a stable optical o/p

⇒ should be cheap + highly reliable

LASER (Light Amplification by Stimulated Emission of Radiation)

→ Laser is a device which amplifies light.

→ However, laser is more used as an optical oscillator.

⇒ **Basic operation** :- formation of an electromagnetic standing wave within a cavity which provides an o/p of monochromatic highly coherent radiation

Absorption + emission of radiation

→ interaction of light with matter takes place in discrete packets of energy or quanta, called photons

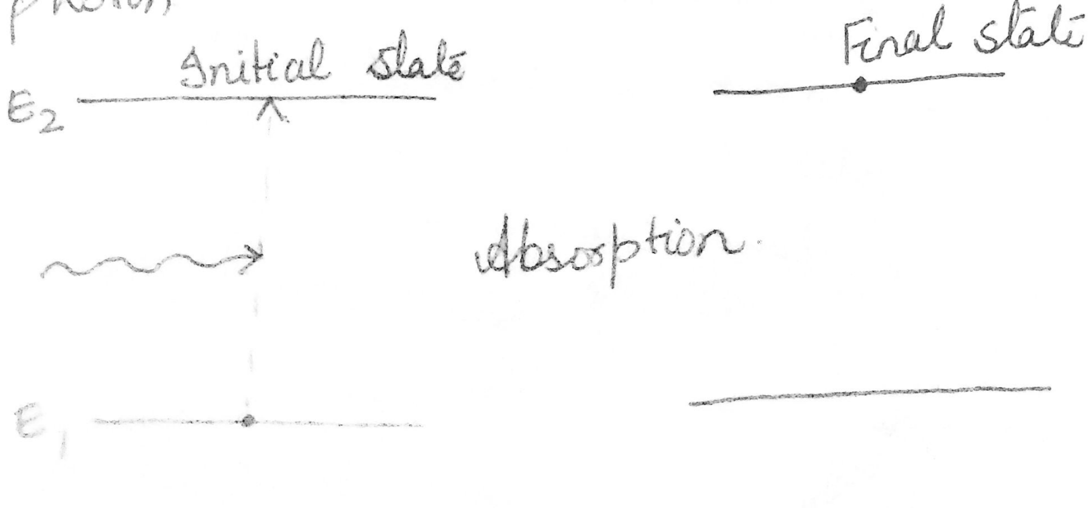
→ Acc to quantum theory, atoms exist only in certain discrete energy states such that absorption + emission of light causes them to make a transition from one discrete energy state to another freq. of the absorbed or emitted radiation f, diff. in energy E, E_2 (higher energy state) & E_1 (lower energy state);

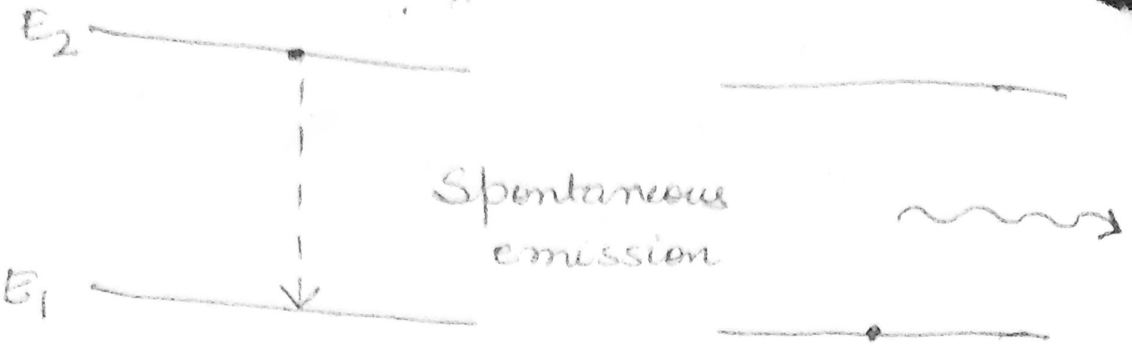
$$E = E_2 - E_1$$
$$= hf$$

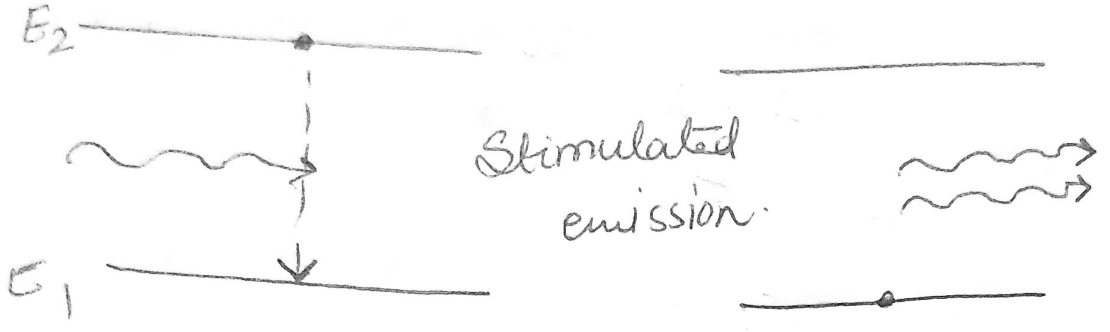
where $h = 6.626 \times 10^{-34}$ Js is Planck's constant

- → discrete energy states :- e⁻s occuring in particular energy levels relative to the nucleus.

- ∴ diff. energy states for the atom correspond to diff. e⁻ configurations, & a single e⁻ transition b/w 2 ~~ek~~ energy levels within the atom will provide a change in energy suitable for the absorption or emission of a Photon







→ 2 energy state or level atomic system where an atom is initially in the lower energy state E_1.

→ When a photon with energy $(E_2 - E_1)$ is incident on the atom it may be excited into the higher energy state E_2 through apsorption of the photon ; process is stimulated absorption.

→ When the atom is initially in the higher energy state E_2 it can make a transition to the lower energy state E_1 providing the emission of a photon. This emission can occur in 2 ways :-

a) by spontaneous emission :- atom returns to the lower energy state in random manner.

stimulated emission :- photon having an energy equal to the energy diff. b/w the 2 states $(E_2 - E_1)$ interacts with the atom in the upper energy state causing it to return to the lower state with the creation of a second photon.

⇒ In laser :- stimulated emission

The photon produced by stimulated emission is generaly of an identical energy to the one which caused it + hence the light associated with them is of the same freq, the light associated with the stimulating + stimulated photon is in phase + has the same polarization. ∴ coherent radiation.

⇒ Also, when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in a constructive manner, providing amplification.

Relati

$\exp(hf/KT)-1$

Population Inversion

→ When eqm., lower energy level E_1 contains more atoms than the upper energy level E_2.

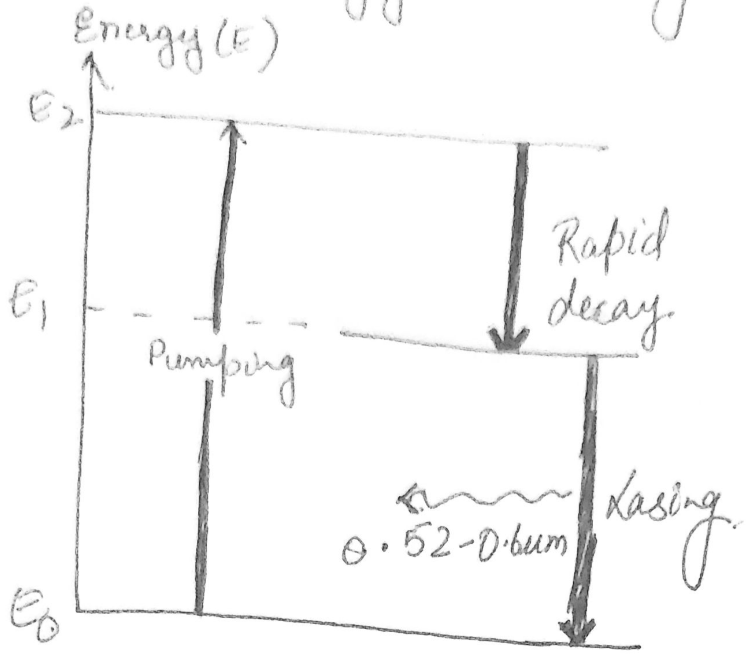
→ To achieve optical amplification it is necessary to create a nonequilibrium distribution of atoms such that the population of the upper energy levels is greater than that of the lower energy level. This is population inversion.

→ To excite atoms into upper energy level E_2, external energy source is required & the process is called as 'pumping'.

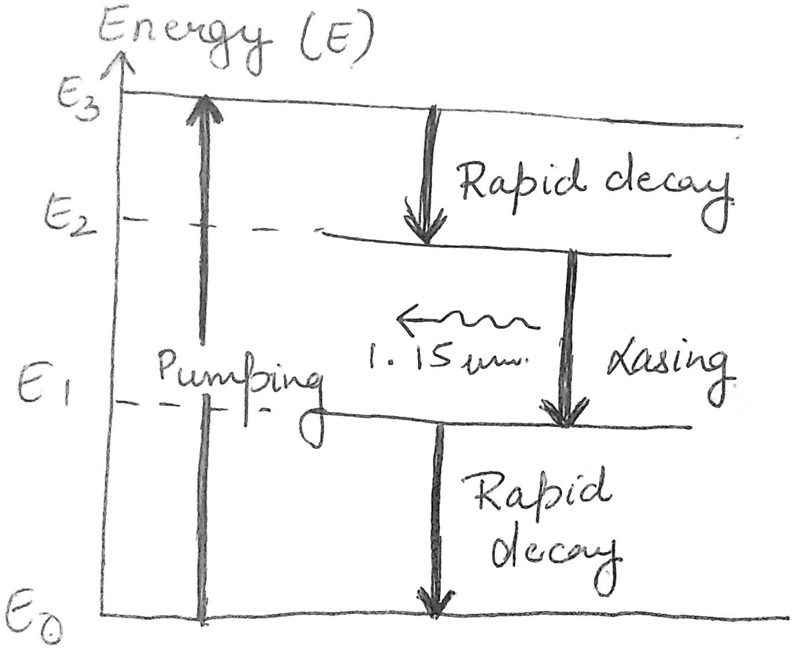
⇒ Pumping :- application of intense radiation (from optical flash tube or high-freq. radio field).

⇒ When 2 levels are equally degenerate, $B_{12} = B_{21}$ ∴ probabilities of absorption & emission are equal.

Population inversion may be obtained 3-4 energy level systems



3 level system - ruby (crystal) laser



4 level system - He-Ne (gas) laser.

→ Both systems display a central metastable state in which the atoms spend an unusually long time.

→ It is from this metastable state that the stimulated emission or lasing takes place.

the 3-level system, a ground level E_0, a metastable level E_1 & a third level above the metastable level E_2. ⑥

→ Initially, atomic distribution by Boltzmann's law. When pumping → e's in some of the atoms may be excited from the ground state into E_2. ∵ E_2 is a normal level, the e's will rapidly decay by non radiative processes to either E_1 or directly to E_0. ∴ empty states will be provided in E_2.

→ E_1 exhibits a much longer lifetime than E_2 which allows a large no. of atoms to accumulate at E_1.

→ Over a period, the density of atoms in metastable state N_1 increases above those in ground state N_0 & a population inversion is obtained.

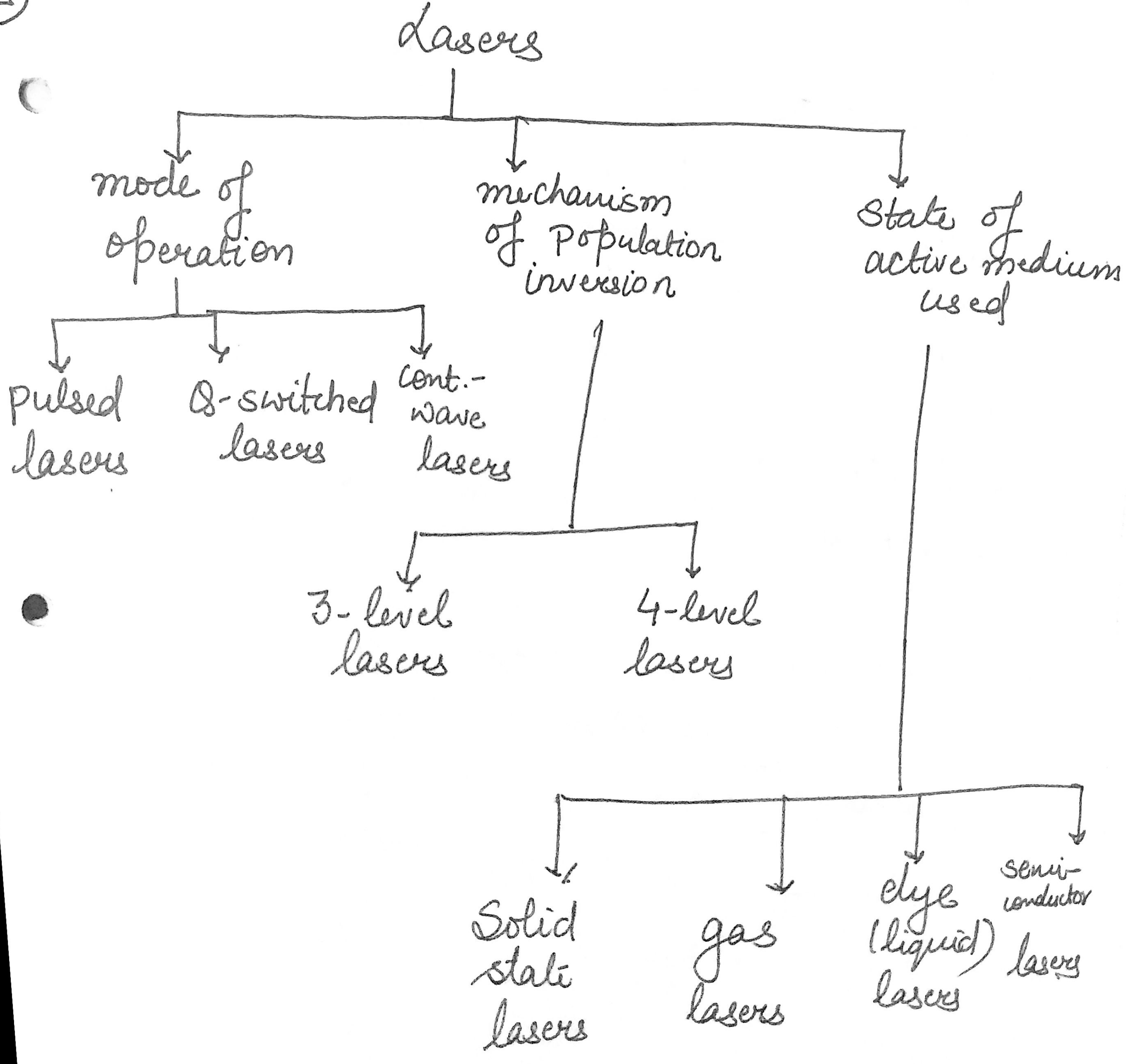
Drawback of 3-level system (Ruby laser) :- requires very high pump powers ~~because~~

⇒ Four-level system (He-Ne Laser) :- lower pumping req.; pumping excites the atoms from the ground state into energy level E_3 & they decay rapidly to the metastable level E_2. ∴ the populations of E_3 & E_1 remain essentially unchanged, a small increase in the no. of atoms in E_2 creates population inversion & lasing takes place b/w this level & E_1.

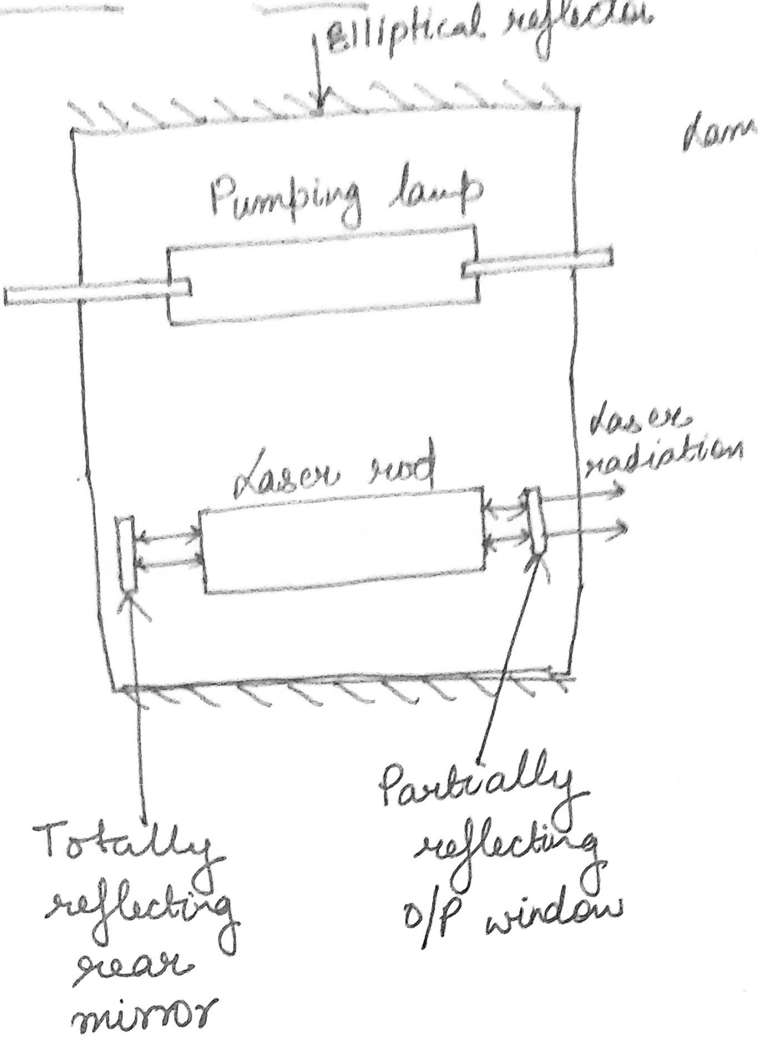
emission

Solid - state lasers

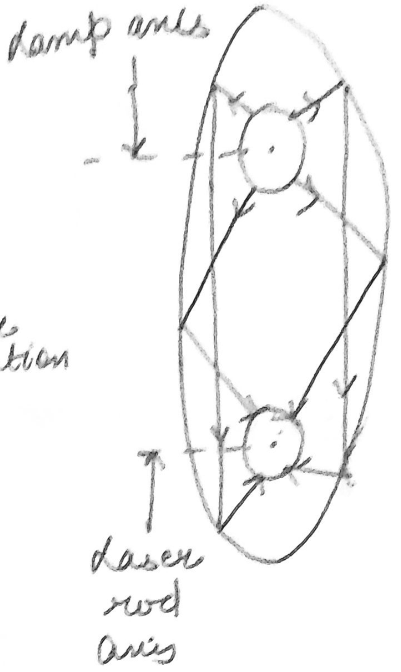
⇒



Solid-State lasers



Solid state laser with elliptical reflector

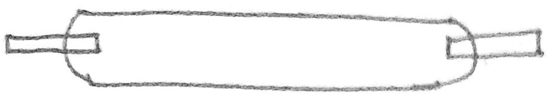


Focusing of pumping light onto the laser rod

→ A linear pumping source & the laser rod are placed || to each other inside an elliptical reflector.

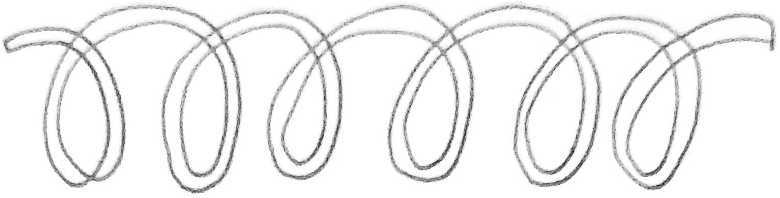
→ The pumping lamp is placed along one principal axis (focus) & the laser rod along the other.

→ ~~rods~~ lamps used for optical pumping are basically discharge tubes, whose configurations may be linear, π-shaped or helical.



linear

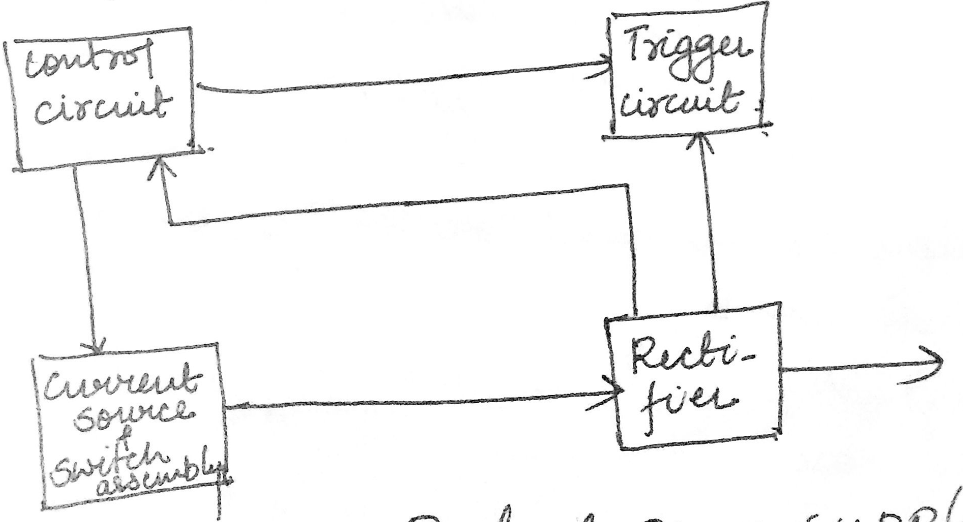
π-shaped



helical

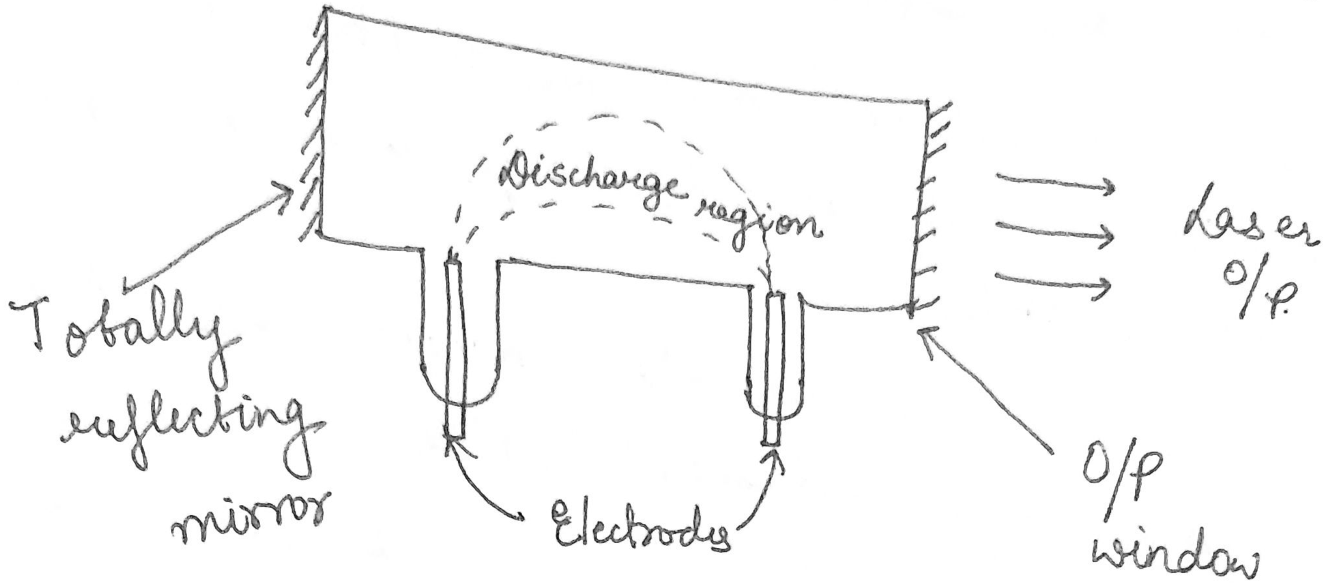
→ If a helical lamp is employed, the laser rod is placed along the axis of the helix, & the entire system is kept inside a cylindrical reflector.

→ normally operate in the pulsed mode :. use pulsed power sources to supply power to the flash tubes.



Pulsed power supply

m, helium-neon, argon ion & CO_2 lasers.



→ pumping is normally achieved through the electrical discharge b/w a pair of electrodes.

→ The discharge occurs along the axis of the laser cavity.

→ Some volume of the gas is not utilized.

→ To achieve uniform excitation of a larger volume of the gas, transverse discharge is employed.

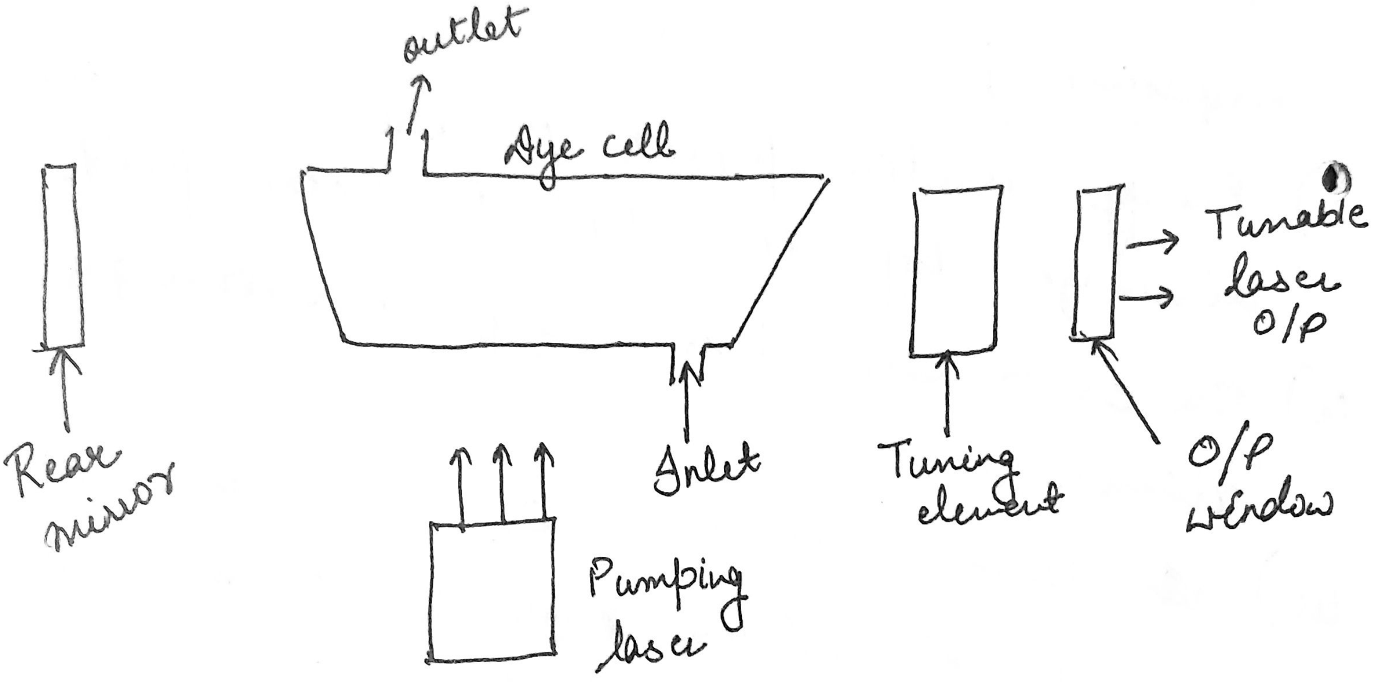
→ Excitation of gas lasers can also be carried out by e^- beams.

→ Requires rectified ac.

Dye Lasers

→ can be tuned to give a continuously variable o/p over a wide range of wavelengths.

→ They are excited either by another laser or by flash tubes.



→ spectral range :- 0.42 – 0.80 μm.

eg :- Carbostyril, coumarin, rhodamine, oxazine.

→ For CW operation, the dye is dissolved into a suitable solvent e.g. ethylene glycol & then circulated through the dye cell.

→ It is excited by another laser or some other source. The tuning is achieved by rotating the birefringent filter placed inside the optical cavity.

B) LED

→ Mechanism :- normally empty conduction band of the semiconductor is populated by e's injected into it by the forward current through the junction, and light is generated when these e's recombine with holes in the valence band to emit a photon.

→ operates at lower current densities

→ Emitted photons have random phases & the device is an incoherent optical source.

→ Energy of the emitted photons = B.Gap energy of the semiconductor material,

→ LED supports many optical modes within its structure & is ∴ often used as a multimode source.

→ Drawbacks of LASER
  - generally lower optical power coupled into a fiber.
  - usually lower modulation BW
  - harmonic distortion.

→ Advantages :-
  → Simpler fabrication

→ Cost :- reduced cost

→ Reliability :- does not exhibit catastrophic degradation ; also immune to self-pulsation + modal noise problems.

→ Generally less temperature dependence :- light o/p against current charac. is less affected by temp.

→ Simpler drive circuity :- due to the generally lower drive currents + reduced temp. dependence.

→ Linearity :- linear light o/p.

LED power and efficiency

→ absence of optical amplification through stimulated emission in the LED tends to limit the internal quantum eff.

→ power generated internally by an LED may be determined by consideration of the excess e^-s + holes in the p-type + n-type material respectively when it is f/w biased + carrier injection takes place at the device contacts.

→ excess density of e's Δn & holes Δp is equal since the injected carriers are created and recombined in pairs such that charge neutraity is maintained within the structure.

→ In extrinsic materials one carrier type will have a much higher concentration than the other & hence in the p-type region.

- Excess minority carrier density decays exponentially,

$$\Delta n = \Delta n(0) \exp(-t/\tau)$$

where $\Delta n(0)$ is the initial injected excess e^- density & τ represents the total carrier recombination lifetime.

- As Δn contains more minority carriers, the carrier recombination lifetime becomes the minority or injected carrier lifetime τ_i.

→ When there is a constant current flow into the junction diode, an eqm. condition is established.

Total rate at which carriers generated = externally supplied rate + thermal generation rate

$$[illegible] = \frac{J}{e\underset{\text{thickness of the recombination region.}}{d}}$$ e's per cubic meter per meter

current density / Square meter

them

no.

Rate of equation for carrier recombination,

$$\frac{d(\Delta n)}{dt} = \frac{J}{ed} - \frac{\Delta n}{\tau}$$

condition for eq/m is obtained by setting the derivative to zero. Hence,

$$\underbrace{\Delta n = \frac{J\tau}{ed}}_{\text{steady-state } e^- \text{ density when a constant current is flowing into the junction region}}$$

Total no. of carrier recombinations/second or the recombination rate r_t will be!

$$r_t = \frac{J}{ed} = \underbrace{r_r}_{\text{radiative recombination rate}} + \underbrace{r_{nr}}_{\text{non-radiative recombination rate}}$$

When the f/w-biased current is i, the total no. of recombinations per second R_t becomes:

$$R_t = \frac{i}{e}$$

LED internal quantum eff., (ratio of radiative recombination rate to total recombination rate)

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}}$$

$$= \frac{R_r}{R_t}.$$

R_r → total no. of radiative recombinations per second.

Sub.,

$$R_r = \eta_{int} \frac{i}{e}$$

Optical power generated by LED, P_{int}

$$P_{int} = \eta_{int} \frac{i}{e} hf$$

$$= \eta_{int} \frac{hci}{e\lambda}$$

$\left(f = \frac{c}{\lambda}\right)$

linear relationship b/w P & i

For exponential decay of excess carriers, the radiative minority carrier lifetime is $\tau_r = \frac{\Delta n}{r_r}$ & the non-radiative minority carrier lifetime is $\tau_{nr} = \frac{\Delta n}{r_{nr}}$ ∴, the internal quantum eff. is;

$$\eta_{int} = \frac{1}{1+(r_{nr}/r_t)} = \frac{1}{1+(\tau_r/\tau_{nr})}$$

The total recombination lifetime τ can be written as $\tau = \frac{\Delta n}{r_t}$ which gives:

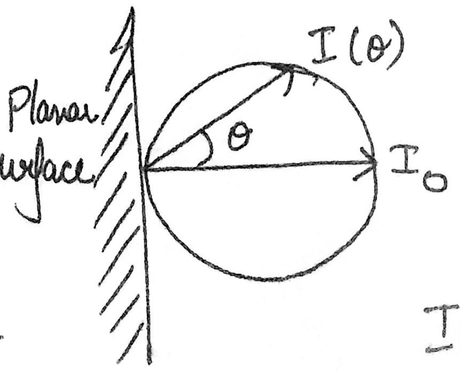
$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

∴

$$\eta_{int} = \frac{\tau}{\tau_r}$$

Radiation geometry for an LED which emits through a planar surface is Lambertian in that the surface radiance (power radiated from a unit area into a unit solid angle) is constant in all directions.

→ max. intensity I_0 is ⊥ to the planar surface but is reduced on the sides in proportion to the cosine of



$I(\theta) = I_0 \cos\theta$

angle θ as the apparent area varies with this angle. This reduces the external power eff. to a few %. as most of the light generated within the device is trapped by TIR.

external power eff., $\eta_{ep} \simeq \frac{P_e}{P} \times 100\%$

"(ratio of optical power emitted externally Pe to the electrical power provided P)

$$\underline{\underline{P_c = \frac{P_{int}\, F n^2}{4 n_x^2}}}$$

F → transmission factor of the semiconductor - external interface.

→ If it is assumed for step-index fibers that all the light incident out the exposed end of the core within the acceptance angle θa is coupled,

$$\theta_a = \sin^{-1}(n_1^2 - n_2^2)^{1/2} = \sin^{-1}(NA)$$

For a Lambertian source, the radiant intensity at an angle θ, I(θ),

$$I(\theta) = I_0 \cos\theta$$

where I_0 is the radiant intensity along the line $\theta = 0$.

Coupling efficiency, η_c.

$$\eta_c = \frac{\int_0^{\theta_a} I(\theta) \sin\theta \, d\theta}{\int_0^{\pi/2} I(\theta) \sin\theta \, d\theta}$$

Sub,

$$\eta_c = \frac{\int_0^{\theta_a} I_0 \cos\theta \sin\theta \, d\theta}{\int_0^{\pi/2} I_0 \cos\theta \sin\theta \, d\theta}$$

$$= \frac{\int_0^{\theta_a} I_0 \sin 2\theta \, d\theta}{\int_0^{\pi/2} I_0 \sin 2\theta \, d\theta}$$

$$= \frac{\left[-I_0 \cos 2\theta/2\right]_0^{\theta_a}}{\left[-I_0 \cos 2\theta/2\right]_0^{\pi/2}} = \sin^2\theta_a$$

$$\eta_c = \sin^2\theta_a = (NA)^2.$$

LED structures

6

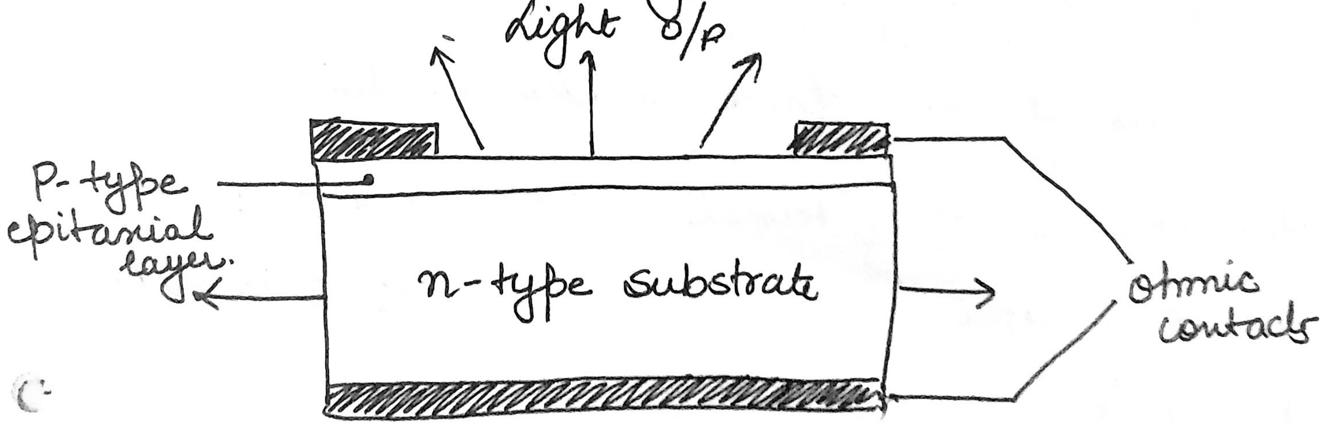
→ 6 major types of LED structure.

1) Planar LED

→ Simplest of structure.

→ fabricated by either liquid or vapor-phase epitaxial processes over the whole surface of a GaAs substrate.

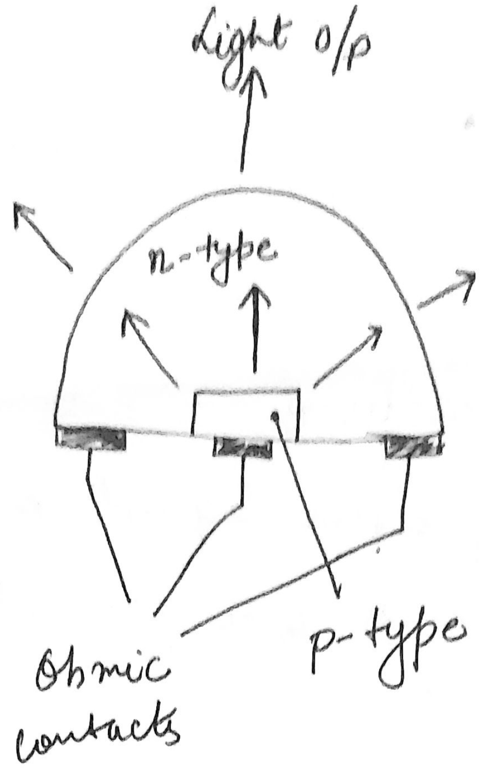
→ p-type diffusion into n-type substrate in order to create a junction.



→ F/w current flows through the junction giving Lambertian spontaneous emission & the device emits light from all surfaces.

→ only a limited amount of light escapes the structure due to total internal reflection & the radiance is low.

Dome LED



- → hemisphere of n-type GaAs is formed around a diffused p-type region.
- → diameter of the dome is chosen to maximize the amount of internal emission reaching the surface within the critical angle of the GaAs-air interface.
- ∴ → higher external power efficiency.
- → geometry of the structure is such that the dome must be far larger than the active recombination area, which gives a greater effective emission area & thus reduces the radiance.

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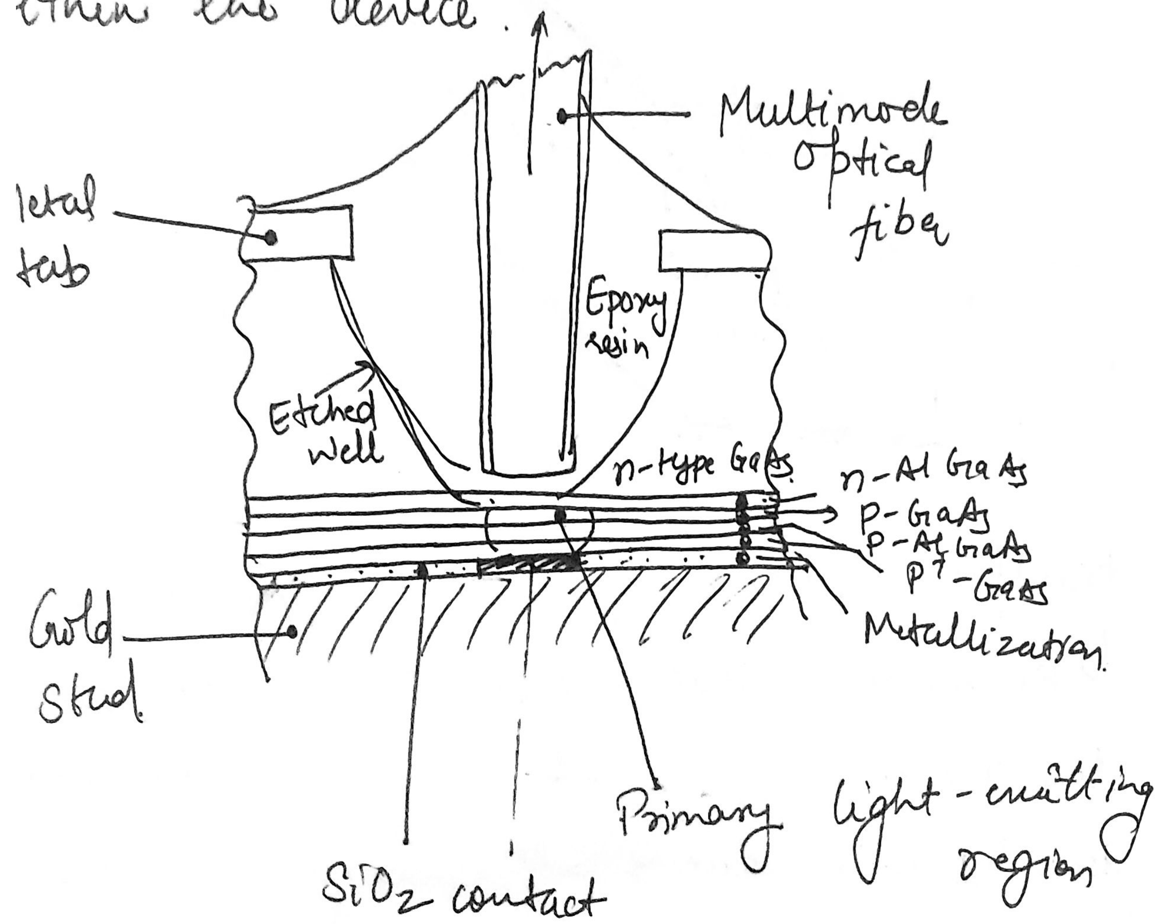
Surface emitter LED

method for obtaining high radiance is to restrict the emission to a small active region ithin the device.

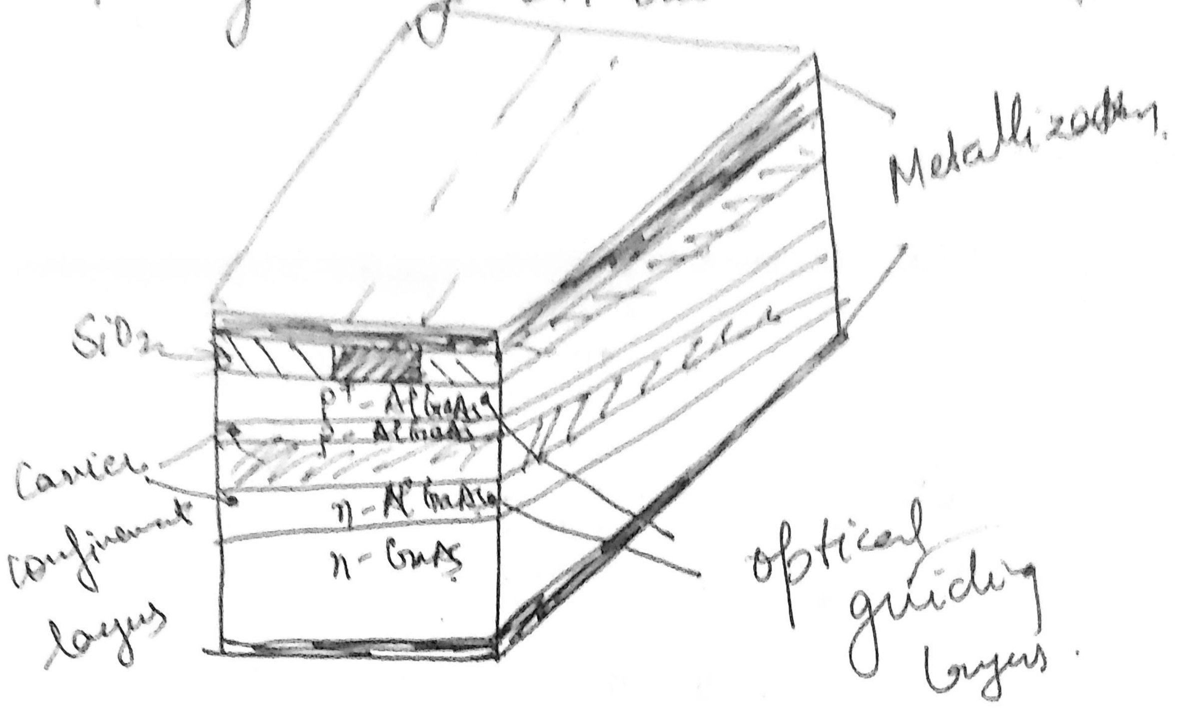


> emission from the active layer is essentially isotropic, although the external emission distribution may be considered Lambertian with a beam width of 120° due to refraction from a high to a low RI at the GaAs-fiber interface

Power coupled, $P_c = \underset{\substack{\downarrow \\ \text{Fresnel coefficient}}}{\pi(1-r)} \underbrace{A}_{\text{emission area}} \overset{\text{Radiance of the source}}{R_D} (NA)^2$

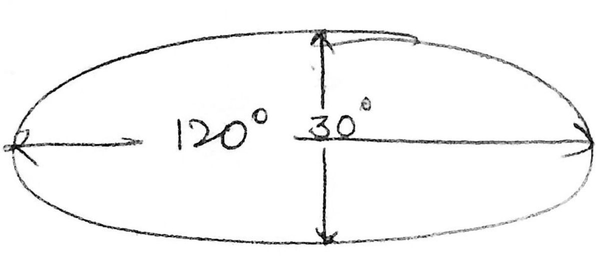
Edge - emitter LEDs

→ Stripe geometry DH emitter LED(ELED)



→ transparent guiding layers with a very thin active layer in order that the light produced in the active layer spreads into the transparent guiding layers, reducing self-absorption in the active layr.

→ consequent waveguiding narrows the beam divergence to a half-power width of around 30° in the plane ⊥ to the junction.
lack of waveguiding in the plane of the juction gives a Lambertian O/P with a ½-power width of arond 120°.

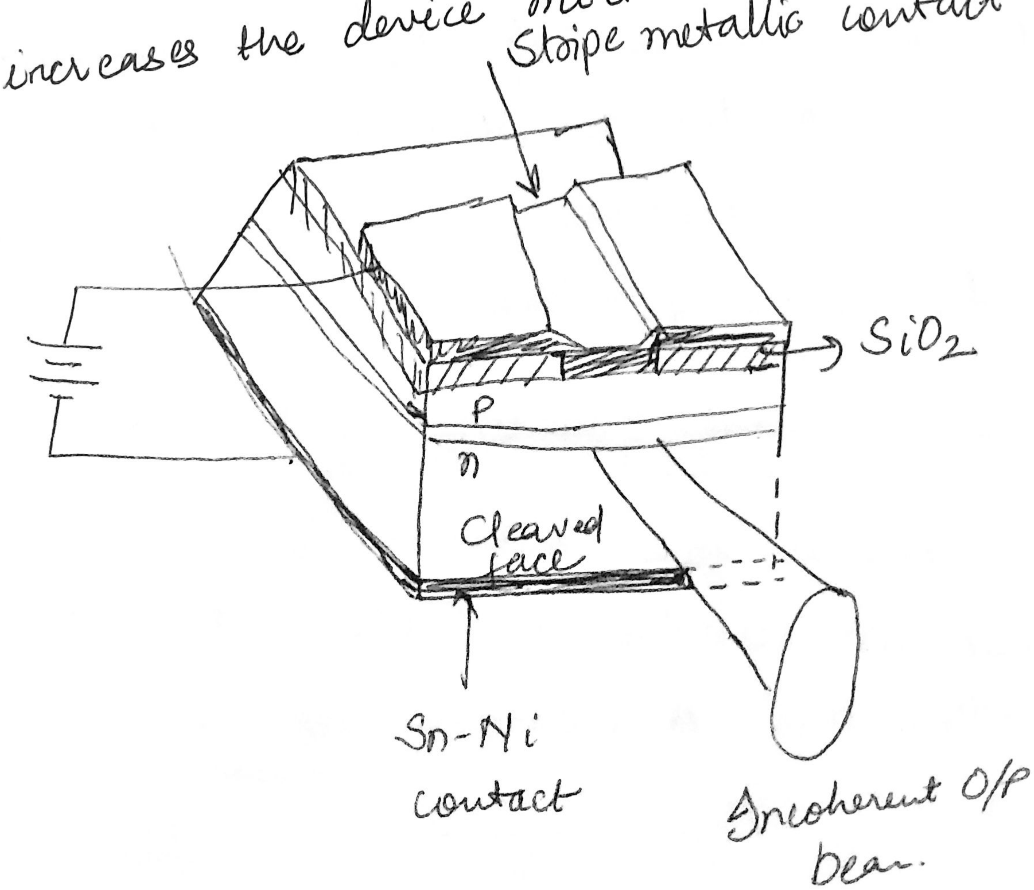


most of the propagating light is emitted at one end face only due to a reflector on the other end face and an antireflection coating on the emitting end face.

Superluminescent LEDs

→ adv :- high O/P power, directional O/P beam and a narrow spectral linewidth.

→ increases the device mod^n BW.



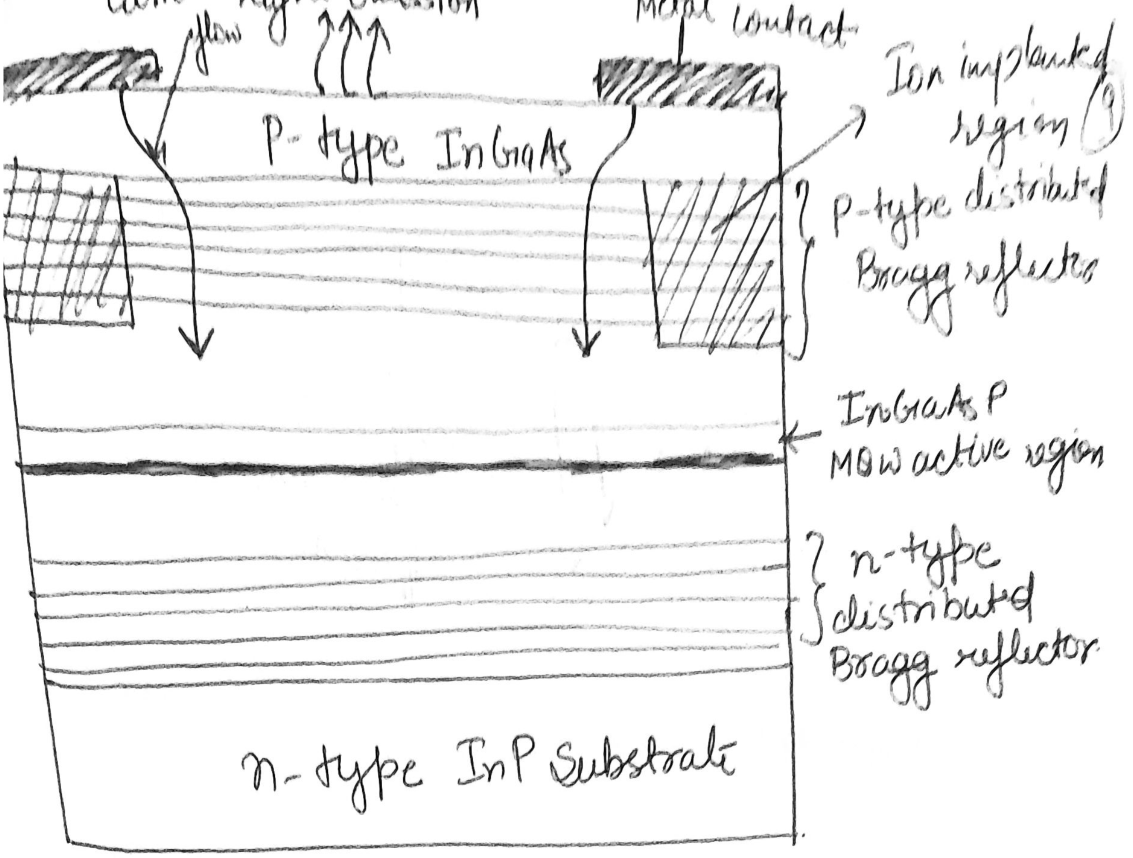
→ requires a p-n junction in the form of a long rectangular stripe, a ridge waveguide or a BH. one end of the device is made optically lossy to prevent reflection + thus supress lasing, the O/P being from the opp. end ∴

→ Operation :- the injected current is increas until stimulated emission & hence ~~op~~ amplifica occurs but because there is high loss at one end of the device, no optical f/b takes place. ∴ although there is amplification of the spontaneous emission, no laser osc. builds up. However, operation in the current region fo stimulated emission provides gain causing the device o/p to increase rapidly with increases in drive current due to what is effectively single-pass amplification. High optical power can ∴ be obtained.

Resonant cavity and quantum-dot LEDs

→ Based on planar tech. containing a Fabry-Perot active resonant cavity b/w distributed Bragg reflector(DBR) mirrors. A quantum well is then embedded in this active cavity.

→ In this, an active region consisting of InGaAsP multiquantum wells is positioned in the optical resonant cavity which is located b/w 2 DBR mirrors.

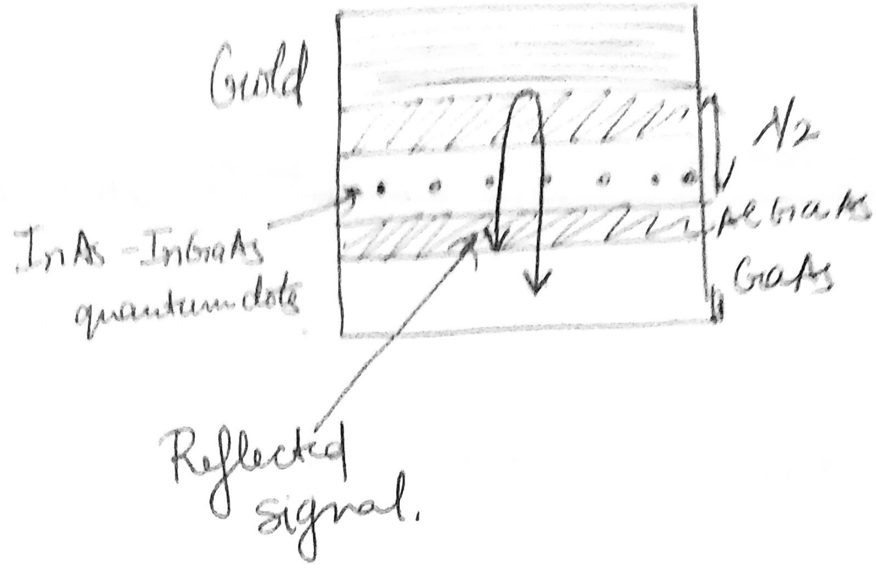


ptical cavity mode is in resonance mplifying the spontaneous emission from the ctive layer.

ne reflectivity of the bottom DBR mirror is kept to a maximum by incorporating a large no. of gratings where the surface DBR mirror is made semitransparent by introducing fewer gratings creating low facet reflectivity to allow the optical signal to exit through this mirror.

→ Light is emitted ~~as a~~ by spontaneous emission & stimulated emission does not occur.

→ In 0D- LED, an active layer comprising a layer of InAs quantum dots covered by InGaAs is positioned at a distance from a gold-coated mirror on the device surface



→ The active region comprises a single layer of quantum dots while a AlGaAs layer is grown b/w the GaAs substrate and the active region in order to confine the injected carriers.

→ To enhance O/P signal power, the quantum-dot layer is positioned at half the emission wavelength distance from the surface mirror. ∴ The optical signal reflected by mirror ∴ constructively interferes with the radiation emitted downwards from the active layer resulting in a fourfold increase in optical signal power being collected from the substrate side.

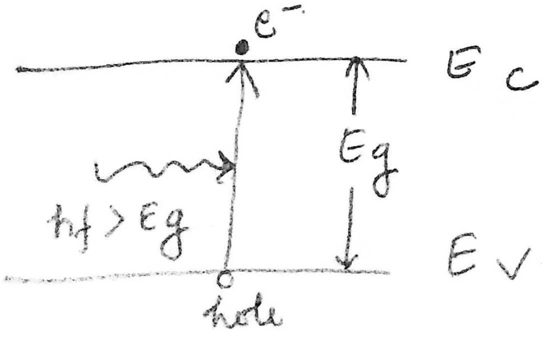
Unit 3:- Optical Detectors

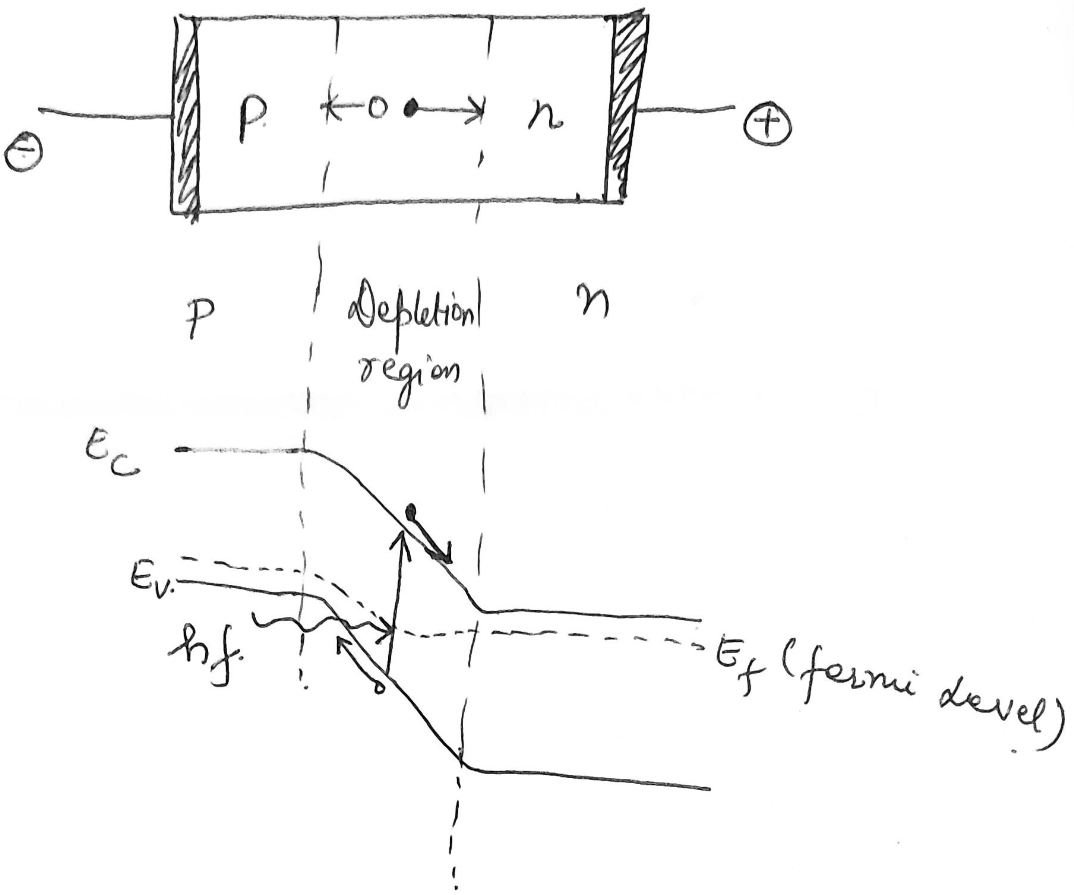
→ Function is to convert the received optical signal into an electrical signal, which is then amplified before further processing.

→ Requirements for a perfect optical detector :-

1) High sensitivity at the operating wavelengths
2) High fidelity
3) Large electrical response to the received optical signal.
4) Short response time to obtain a suitable bandwidth.
5) A min. noise introduced by the detector
6) Stability of Performance characteristics
7) Small size
8) Low bias voltages
9) High reliability
10) Low cost.

Optical Detection Principles





- p-n photodiode
- Device is reverse-biased and the electric field developed across the p-n junction sweeps mobile carriers (holes & e's) to their respective majority sides.
- A depletion layer is created.
- This barrier has the effect of stopping the majority carriers crossing the junction in the opposite direction to the field.
- the field accelerates minority carriers from both sides to the opp. side of the junction, forming the reverse leakage current of the diode.

②

photon incident in or near the depletion region of this device which has an energy greater that or equal to the BG energy Eg of the fabricating material ($hf \geq E_g$) will excite an e^- from the valence band into the conduction band. This process leaves an empty hole in the valence band & is known as the photogeneration of an e^--hole pair.

Carrier pairs so generated near the junction are separated & swept under the influence of the electric field to produce a displacement by current in the external ckt. in excess of any reverse leakage current.

→ Depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed in order to achieve max. carrier-pair generation.

Absorption

Absorption coeff:

→ absorption of photons in a photodiode to produce carrier pairs & thus a photocurrent is dependent on absorption coeff. α_0

photo current I_p, → charge

width absorption region

$$I_p = \frac{P_0\, e\,(1-r)}{hf}\,[1-\exp(-\alpha_0 d)]$$

optical power

Fresnel reflection coeff.

→ absorption coeff. of semiconductor materials are dependent on wavelength.

Direct & Indirect absorption : Si & Ge

→ Si & Ge absorb light by both direct & indirect optical transitions.

→ Indirect absorption requires the assistance of a photon so that momentum as well as energy are conserved. This makes the transition probability less likely for Indirect absorption than for direct absorption where no photon is involved.

→ Si weakly absorbs over the wavelength band of optical comm. due to transitions over this wavelength band are due only to the Indirect absorption mechanism.

Ge :- lowest energy absorption takes place by indirect optical transitions

Ge is used in the fabrication of detectors over the whole of the wavelength range of interest.

→ A photodiode material should be chosen with a BG energy slightly less than the photon energy corresponding to the longest operating wavelength of the system. This gives a sufficiently high absorption coeff. to ensure a good response, & yet limits the no. of thermally generated carriers in order to achieve a low dark current.

Ge photodiodes have relatively large dark currents due to their narrow bandgaps in comparison to other semiconductor materials. This is the disadv. of Ge.

→ Due to drawback of Ge, III-V alloys came into picture.

They are superior to Ge because their BGs can be tailored to the desired wavelength by changing the relative concentrations of their constituents, resulting in lower dark currents.

→ eg:- InGaAs , GaAlSb

Quantum efficiency (η)

→ defined as the fraction of incident photons which are absorbed by the photodetector & generate e^-s which are collected at the detector terminals.

$$\eta = \frac{\text{no. of } e^-\text{s collected}}{\text{no. of incident photons}}$$

$$= \frac{r_e}{r_p}$$

r_e → e^- rate

r_p → incident photon rate.

→ η is generally less than unity as not all of the incident photons are absorped to create e^--hole pairs.

Responsivity

$$R = \frac{I_p}{P_o} \; (AW^{-1})$$

I_p → O/P photocurrent

P_o → incident optical power

gives photocurrent per unit incident optical power.

$$E = hf.$$

∴ Incident photon rate $r_p = \frac{P_o}{hf}$

P_o → power

hf → energy.

$$\therefore \eta = \frac{r_e}{r_p} \Rightarrow r_e = \eta r_p$$

$$\therefore r_e = \frac{\eta P_o}{hf}.$$

o/p photocurrent

$$\therefore I_p = \frac{\eta P_o e}{hf}.$$

$$\therefore \boxed{R_e = \frac{I_p}{P_o} = \frac{\eta e}{hf}.}$$

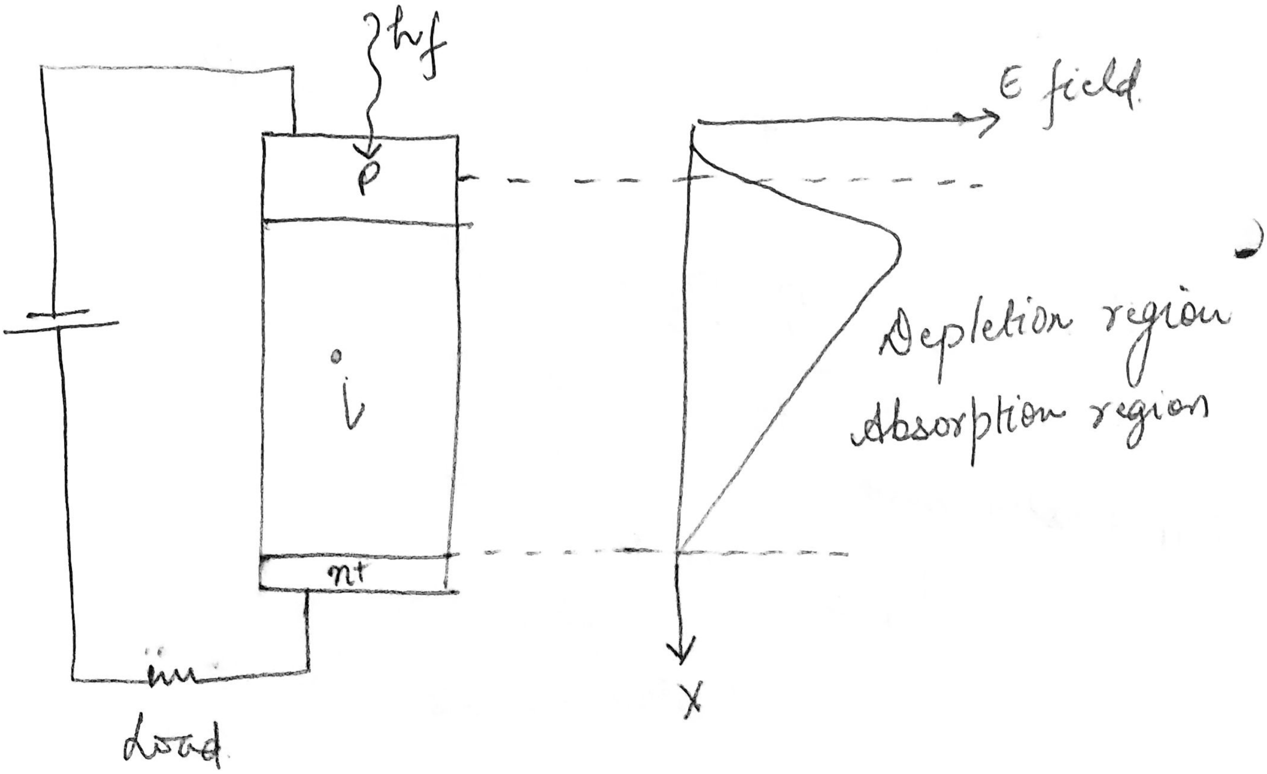
$$= \frac{\eta e \lambda}{hc}$$

Responsivity ∝ quantum eff at a particular wavelength.

P-i-n photodiode

→ operation at longer wavelength where light penetral more deeply into the semiconductor material.

→ n type material is doped so lightly that it can be considered intrinsic, a highly doped n type (n^+) layer is added.

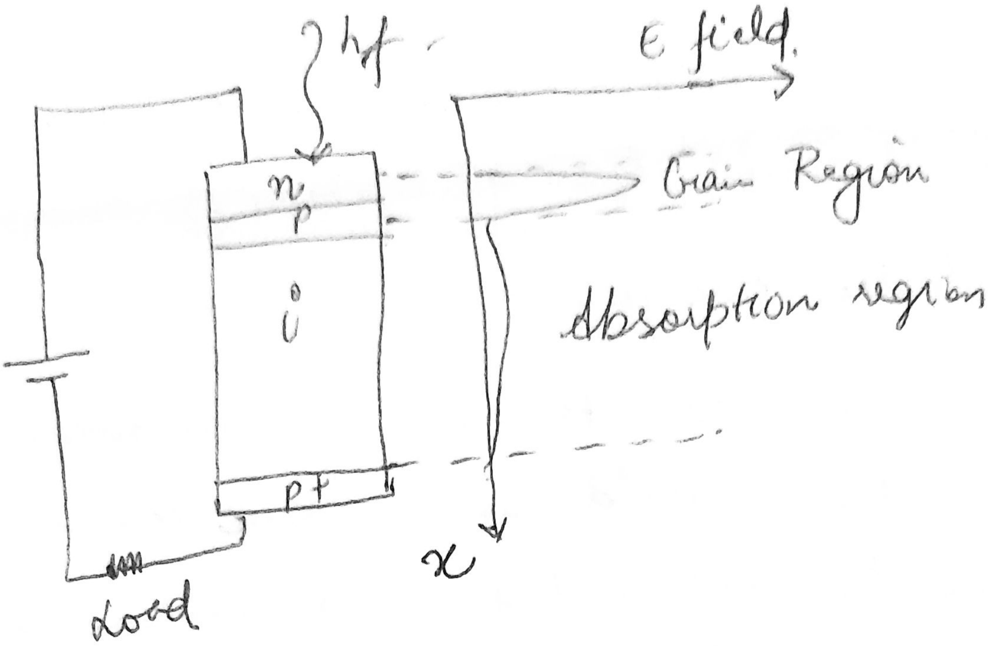


→ When a sufficient reverse voltage is applied. its res. encreases.

→ When an incident photon has an energy equal to or greater than the band gap energy of the semiconductor material, the photon can give up its energy and excite an e^- from VB to CB. This process generates mobile e^- hole pairs, these e^-s & holes are known as photocarriers.

lanche Photodiode

→ creates an extremely high electric field region



→ As well as the depletion region where most of the photons are absorbed and the primary carrier pairs generated there is a high field region in which holes + e⁻s can acquire sufficient energy to excite new e⁻ - hole pairs. This is known as <u>impact ionization</u> + is the phenomenon that leads to avlanche breakdown in ordinary reverse biased diodes.

→ Carrier multiplication factors may be obtained using defect-free materials to ensure uniformity of carrier multiplication over the entire photosensitive area.

- Light absorption takes pla
un-doped region.
avlanche region occurs b/w n + p regions.

→ Light enters the undoped region of the avlanche photodiode + causes the generation of hole-e^- pairs. Under the action of the electric field the e^-'s migrate towards the avlanche region. ∴ electric field causes their velocity to increase to the extent that collisions with the crystal lattice to create even more hole-e^- pairs. ∴ a single e^- created by light in the un-doped region may result in many more being created.

→ require a high reverse bias

Impact ionization coefficient, $\alpha = \frac{\text{No. of sec. charges generated}}{\text{Unit length}}$

Multiplication factor, $M = \frac{I}{I_p}$

Noise

→ overall sensitivity of a photodiode results from the random current & voltage fluctuations which occur at the device o/p terminals in both the presence & absence of an incident optical signal.

→ dark current :- source of noise.

→ Detector avg. current $\bar{I}$ always exhibits a random fluctuation about its mean value as a result of the statistical nature of the quantum detection process. – shot noise.

RMS value of Shot noise ⇒ $(\bar{i}_s^2)^{1/2} = (2eB\bar{I})^{1/2}$, $B \downarrow$ BW.

⇒ NEP (noise eqv power) :- incident optical power at a particular wavelength or with a specified spectral content required to produce a photodetector current equal to the rms noise current within a unit BW.

$$P_o = \frac{I_p h f}{\eta e} = \frac{I_p h c}{\eta e \lambda}$$

I_p = rms shot noise current

$= (2e\bar{I}B)^{1/2}$

photodiode avg. current $\bar{I} = I_p + I_d$

↓ dark current

$\therefore I_p = [2e(I_p + I_d)B]^{1/2}$

When $I_p >> I_d$,

$I_p \simeq 2eB$

Sub.

$$\boxed{NEP = P_o = \frac{2hc}{\eta\lambda}}$$

When $I_p << I_d$

$I_p \simeq [2e I_d B]^{1/2}$

$$\boxed{NEP = P_o = \frac{hc(2eI_d)^{1/2}}{\eta e\lambda}}$$

Detectivity, $D = \frac{1}{NEP}$

$$= \frac{\eta e \lambda}{hc(2eI_d)^{1/2}}.$$

~~$D = D_\lambda = \eta e \lambda$~~

Specific detectivity $D^* = DA^{1/2}$

$$= \frac{\eta e \lambda}{hc(2eI_d/A)^{1/2}}$$

BW $\simeq$ 1 Hz

incorporates the area of the photodetector A in order to take account of the effect of this factor on the amplitude of the device dark current.