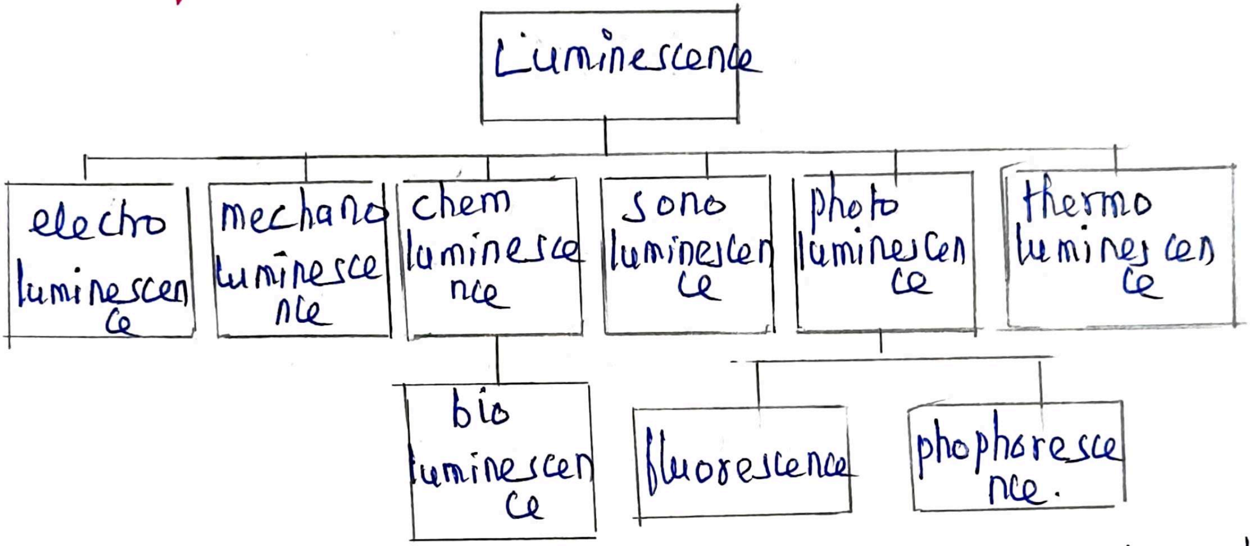
Display Devices -

Luminescence is spontaneous emission of light by a substance not resulting from heat or "cold light"

Luminescence is used to describe the emission of radiation from a solid when it is supplied with some form of energy.

Types of Luminescence:



Photoluminescence: excitation arises from the absorption of photons

Cathodoluminescence: excitation is by bombardment with a beam of electrons.

Electroluminescence: excitation results from the application of an electric field which may be either a.c or d.c.

Whatever the form of energy input to the luminescing material, the final stage in the process is an electronic transition between two energy levels E_1 and E_2 $[E_2 > E_1]$ with the emission of radiation of wavelength

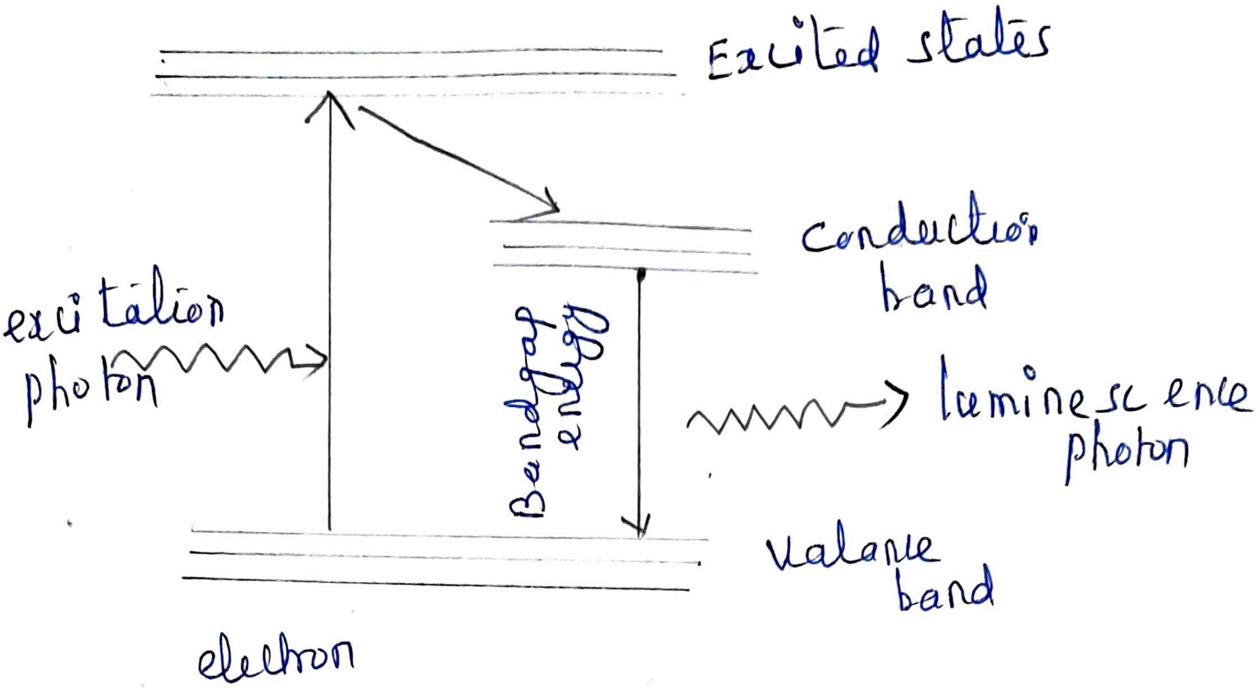
λ_0 where $\frac{hc}{\lambda_0} = E_2 - E_1$ E_1 and E_2 are part of two groups of energy levels.

when the excitation mechanism is switched off, we would expect the luminescence to persist for a time equal to the life time of the transition between the two energy levels E_1 and E_2. when this is so, we speak of fluorescence. often however the luminescence persists for much longer than expected a phenomenon called phosphorescence. phosphorescene is attributable to the presence of metastable (or very long lifetimes) states with energies less than E_2. Electrons can fall into these states and remain trapped there until thermal excitation releases them later. materials exhibiting phosphorescene are known as phosphors.

photo luminescence: PL

PL is a process in which the substance absorbs photons [Em radiation] and then re-radiates photons. The radiated light is often visible, but can also be in the ultraviolet or infrared spectral region.

In PL energy is transferred to the crystal by the absorption of a photon.



PL in semiconductors and dielectrics can occur for illumination of a substance with light which has a photon energy above the bandgap energy. The PL occurs for wavelengths around the bandgap wavelength. PL occurs only with certain dopants or impurities in a material. For example, fluorescence can occur when rare-earth-doped laser gain media are pumped with light which can excite the rare earth ions. Here the emission can occur in various wavelengths band corresponding to optical transitions of those ions. One may obtain more than one photon per absorbed photon, when there is a cascade of transitions.

PL may be largely suppressed (quenched) if there are fast non-radiative transitions to lower energy levels, leading to a very small lifetime of the excited levels.

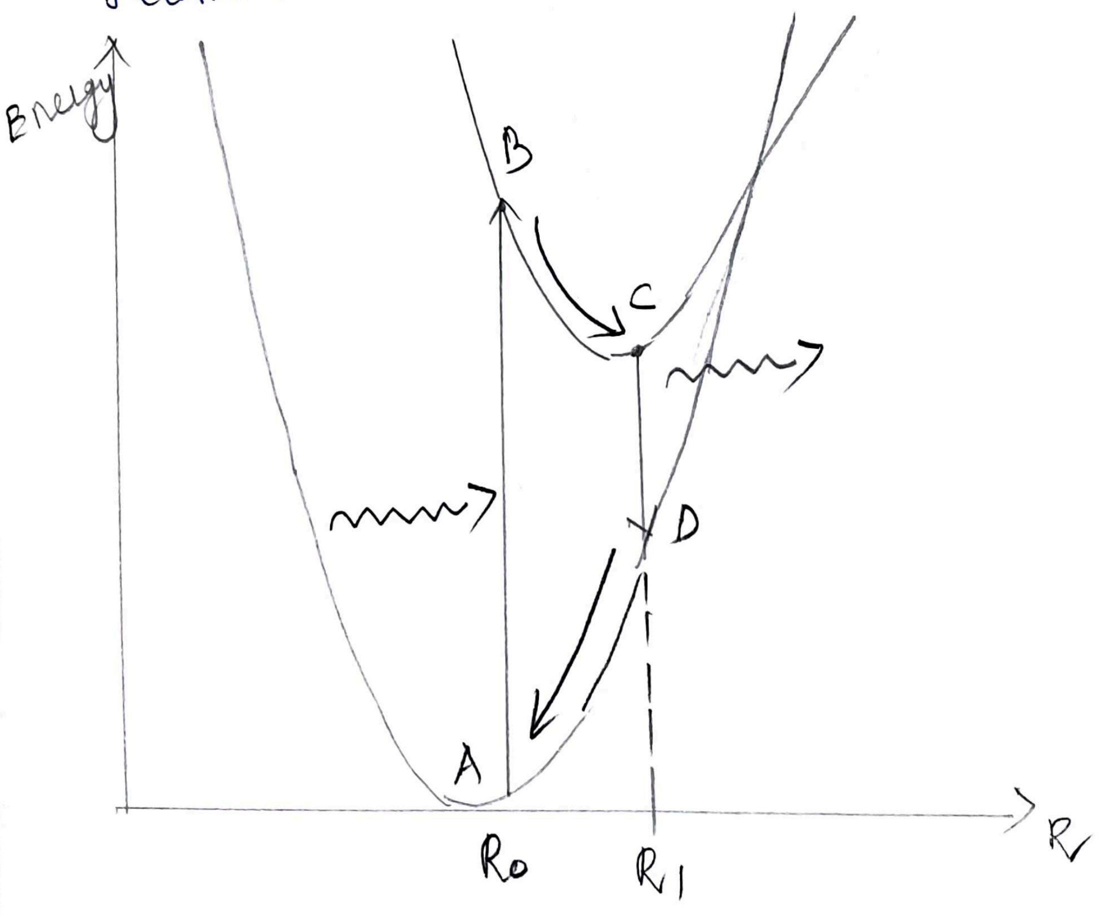
Fluorescence is a short-lived photoluminescence, excited by irradiation of a substance with light. The light hitting a sample puts atoms, ions or molecules in the sample into excited state (by absorption of photons), from where they decay into lower-lying states (eg their ground states) through spontaneous emission of fluorescence photons. This phenomenon is exploited for illumination, particularly in fluorescent lamps. It also occurs in various kind of optically pumped lasers and amplifiers eg in solid-state doped-insulator lasers and amplifiers including fiber lasers and fiber amplifiers in optically pumped semiconductor lasers and in dye lasers. The resulting radiation is called fluorescent light.

Phosphorescence is a kind of luminescence (ie a kind of light emission of a medium) which lasts long after excitation of the medium with light. The excitation energy stored in meta electronic states (excited states which have a long lifetime due to slow radiative and non-radiative decay). As the stored energy can be released only through relatively slow processes, phosphorescence is much weaker than fluorescence.

photoluminescence is used for the characterization of photonic devices. For example, one may irradiate a semiconductor wafer, on which additional layer for a semiconductor laser or a saturable absorber (light absorbers with a degree of absorption which is reduced at high optical intensities) have been fabricated with short-wavelength light for exciting photoluminescence.

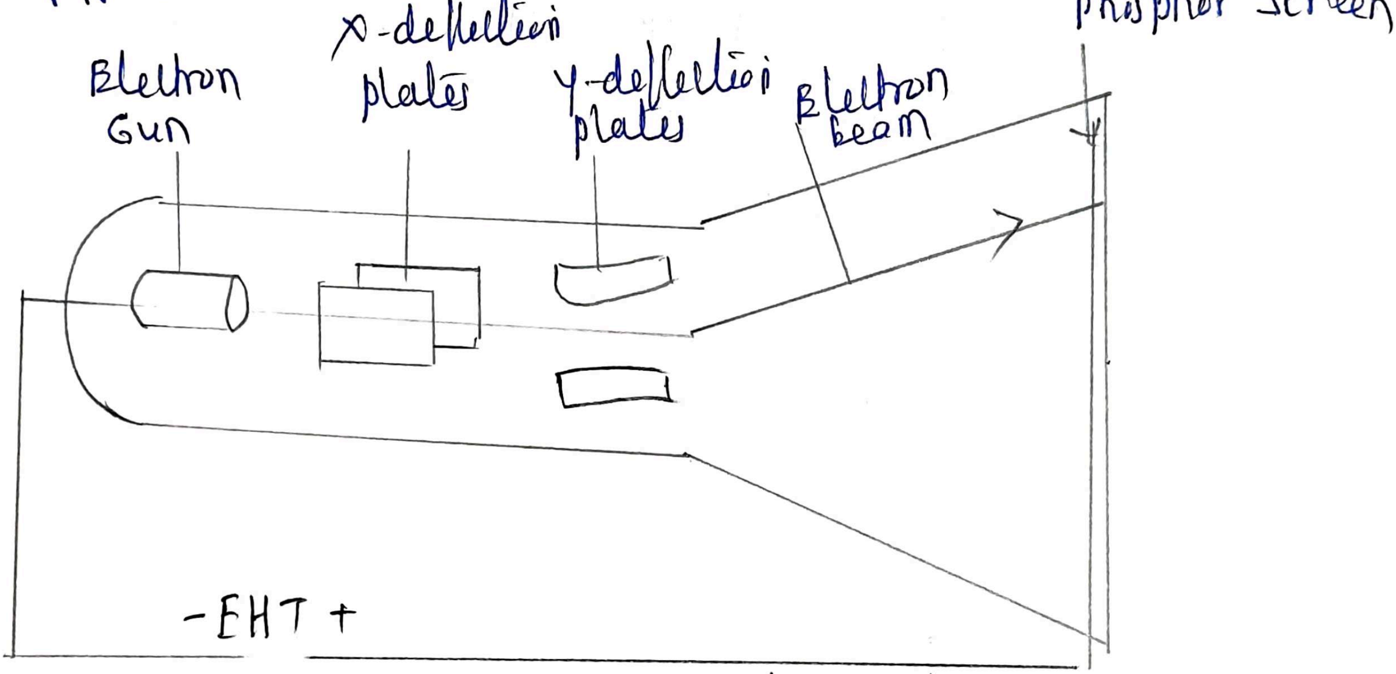
PL spectra and their intensity dependencies can allow

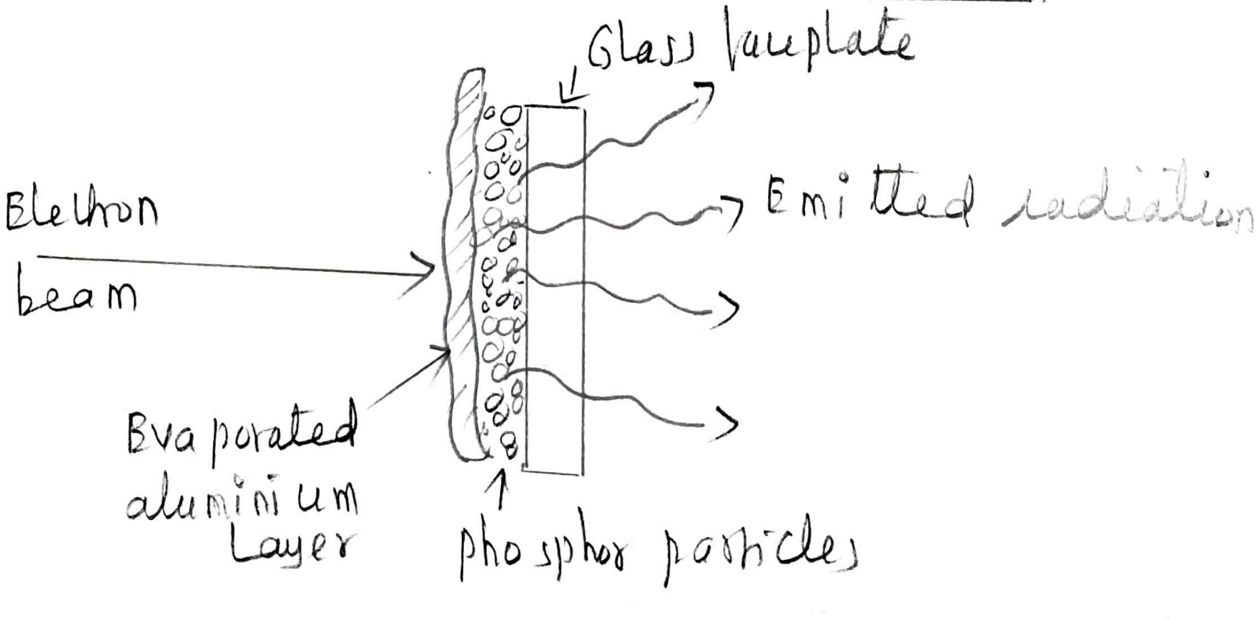
- to determine the bandgap energy
- to estimate the wavelength of maximum gain
- to determine the composition of ternary or quaternary layer
- to determine impurity levels to investigate recombination mechanisms.



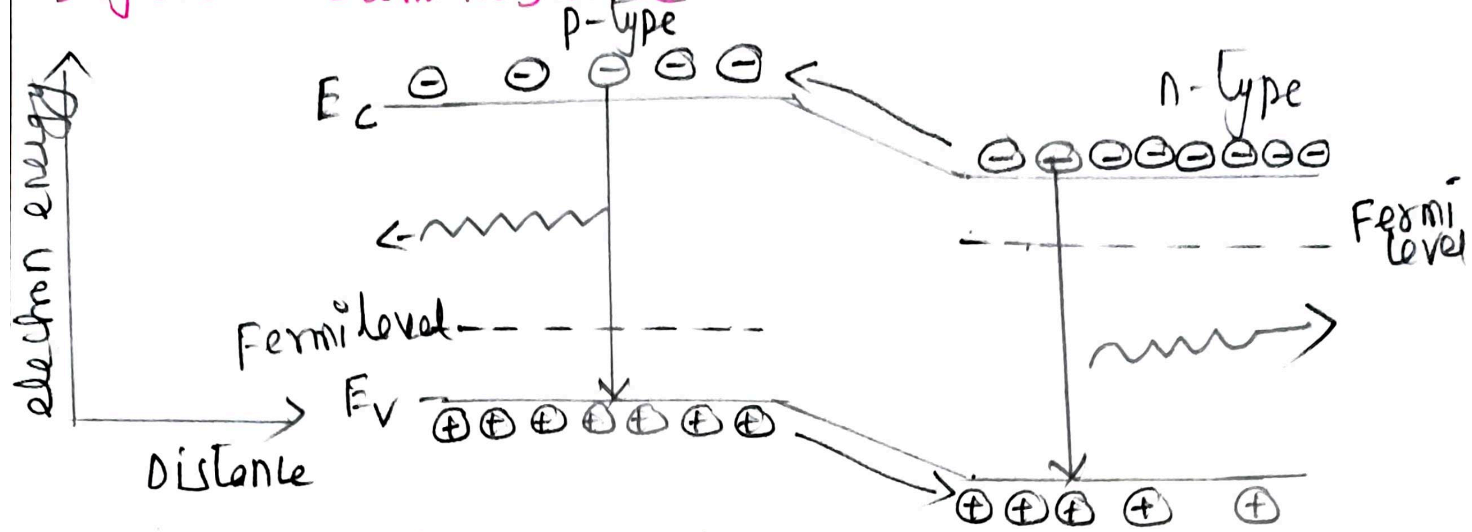
Cathodo luminescence

CL is an optical and Electromagnetic phenomenon in which electrons impacting on a luminescent material such as a phosphor cause the emission of photons which may have wavelengths in the visible spectrum.
Example is the generation of light by an electron beam scanning the phosphor-coated inner surface of the screen of a TV that uses a CRT.
Cathodoluminescence is the inverse of the photoelectric effect in which electron emission is induced by irradiation with photons.





Injection Luminescence

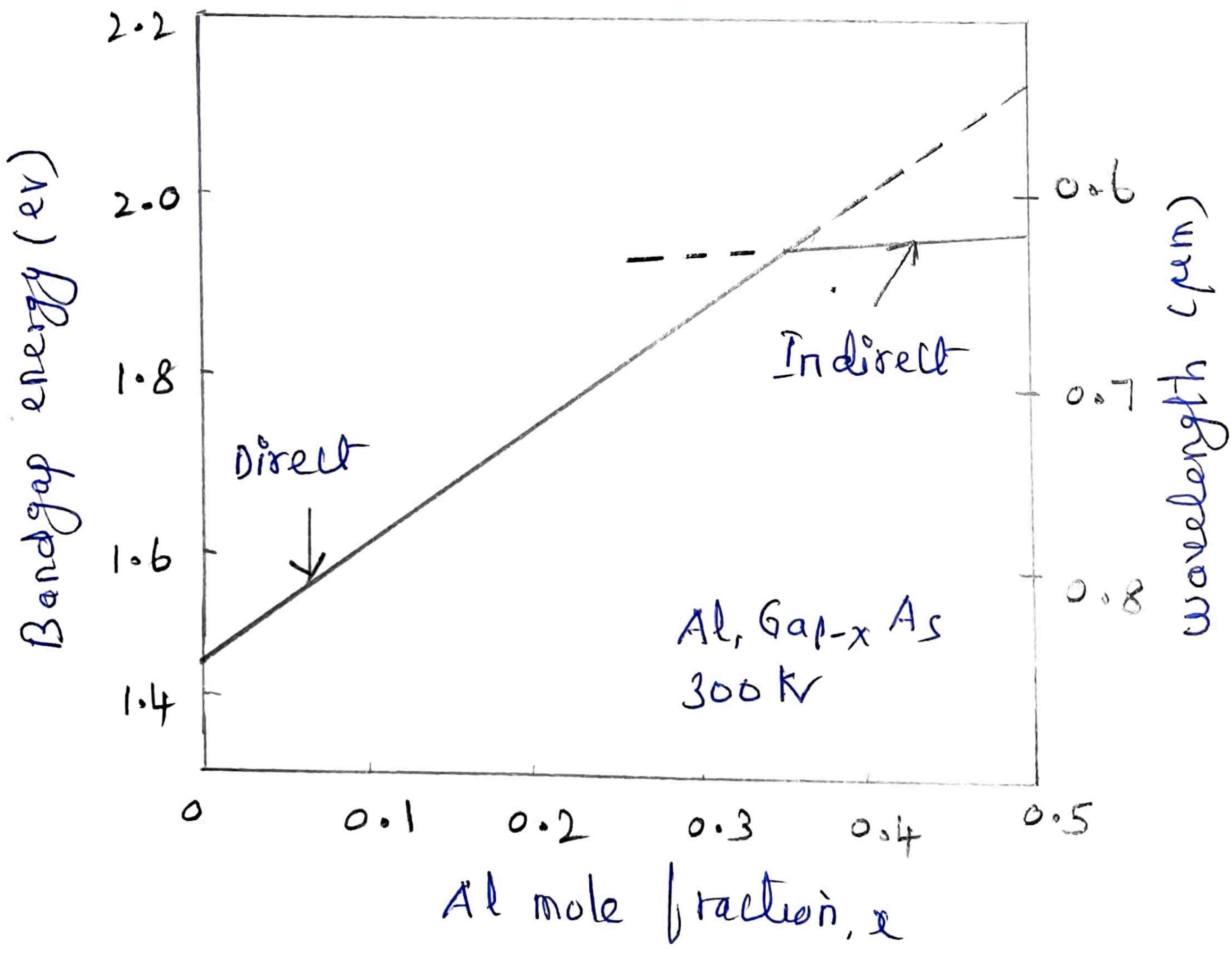


under forward bias, majority carriers from both sides of the junction cross the depletion layer and enter the material at the other side, where they are then the minority type of carrier and cause the local minority carrier population to be Larger than normal. this is described as minority carrier injection. The injected carriers diffuse away from the junction, recombining with majority carriers as they do so. This recombination of electron with holes may be either non radiative, in which the energy difference of the two carriers is released into the lattice as thermal energy or radiative in which a photon of energy equal to or less than the energy difference of the carrier is radiated.

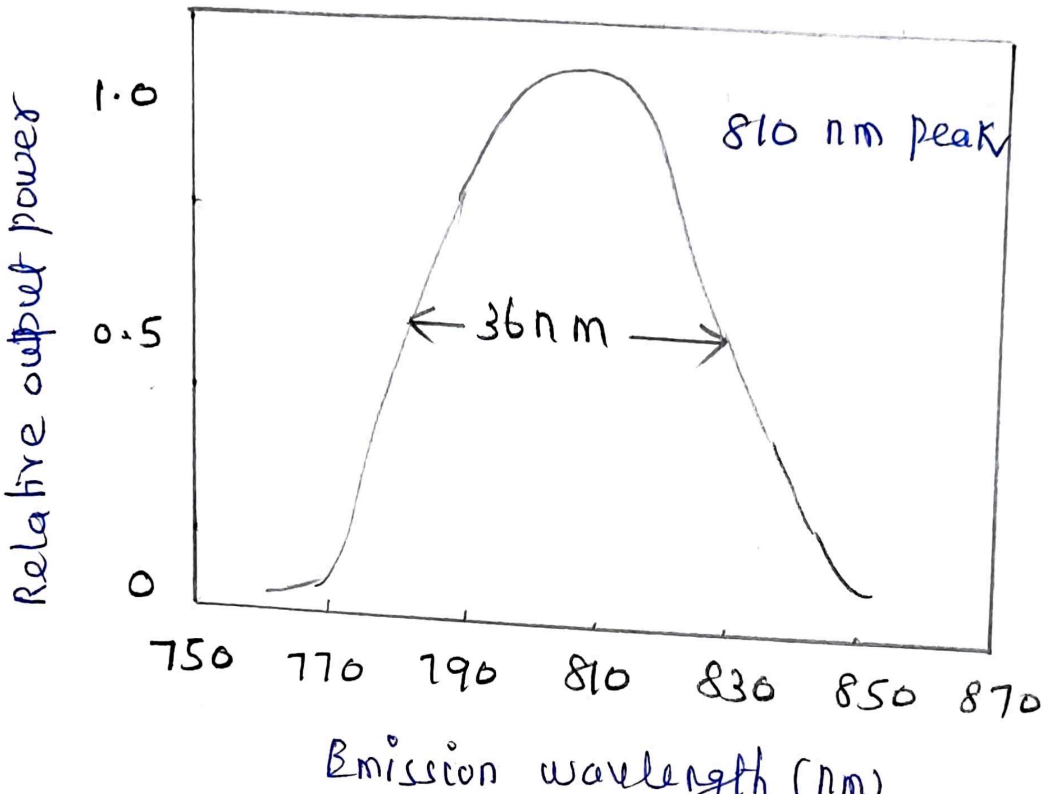
Light source materials

The semiconductor material is used for the active layer
of an optical source must have a direct bandgap.
In a direct band-gap s.c, e^- and holes can recombine
directly across the bandgap without needing a third
particle to conserve momentum. only in direct bandgap
material is the radiative recombination high to produce
an adequate level of optical emission.

For operation in the 800-to-900 nm spectrum, the
principle material is the ternary alloy $Ga_{1-x}Al_xAs$.
the ratio of x of the aluminum arsenide to gallium
arsenide determines the bandgap of the alloy and
the wavelength of the peak emitted radiation.



The value of x for the active-area material is chosen to give an emission wavelength of 800–850nm. An example of the emission spectrum of a $Ga_{1-x}Al_xAs$ LED with $x=0.08$.



The peak output power occurs at 810nm. The width of the spectral pattern at its half-power point is known as the full-width half maximum (FWHM) spectral width. This FWHM spectral width σ_λ is 36nm.

At longer wavelengths the quaternary alloy $In_{1-x}Ga_x As_y P_{1-y}$ is one of the primary material. For simplicity the notations GaAlAs and InGaAsP are used.

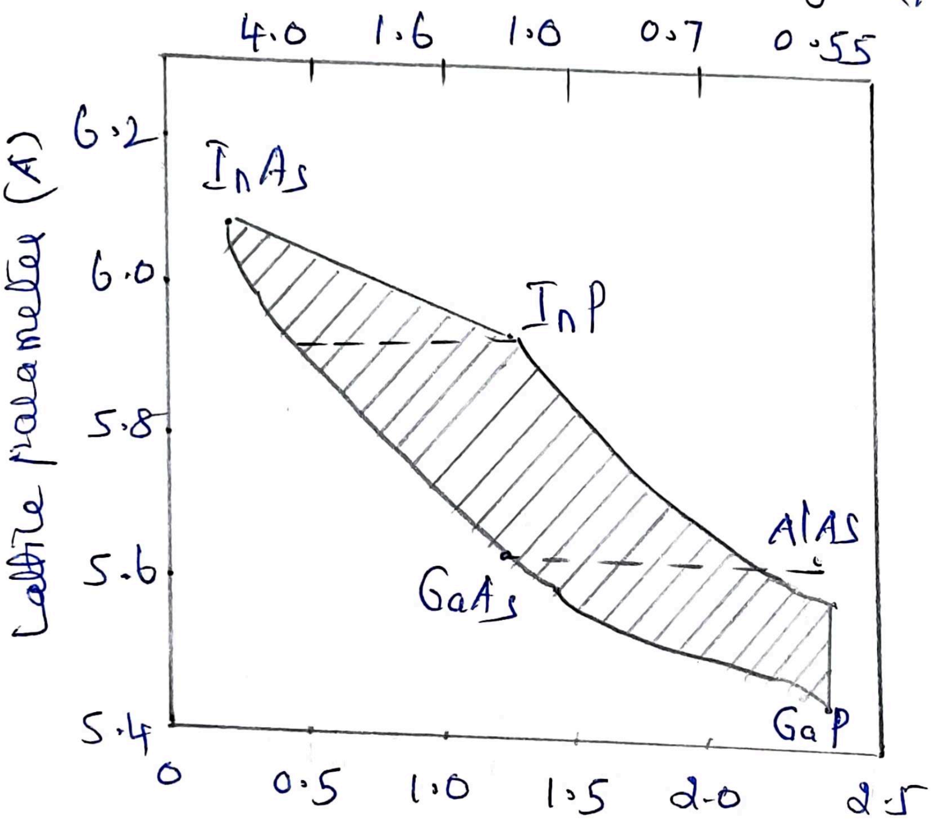
Fundamental quantum mechanical relationship between energy E and frequency ν,

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

The peak emission wavelength λ in micrometers can be expressed as a function of the band gap energy E_g in electron volts by

$$\lambda(\mu m) = \frac{1.240}{E_g(eV)}$$

The relationship between bandgap energy E_g and the crystal lattice spacing for various III-V compounds:



Band gap energies of some common semiconductor materials

Semiconductor material	Bandgap energy (eV)
Silicon (Si)	1.12
GaAs	1.43
Germanium (Ge)	0.67
InP	1.35
$Ga_{0.93}Al_{0.03}As$	1.51

LED structures:

For optical communication systems requiring bit rates less than 100-200 Mb/s with multimode fiber-coupled optical power in the tens of microwatts, semiconductor LED are the best source choice. These LED's require less complex drive circuitry than Lasers as no thermal or optical stabilization circuits are needed, they can be fabricated less expensively with higher yields.

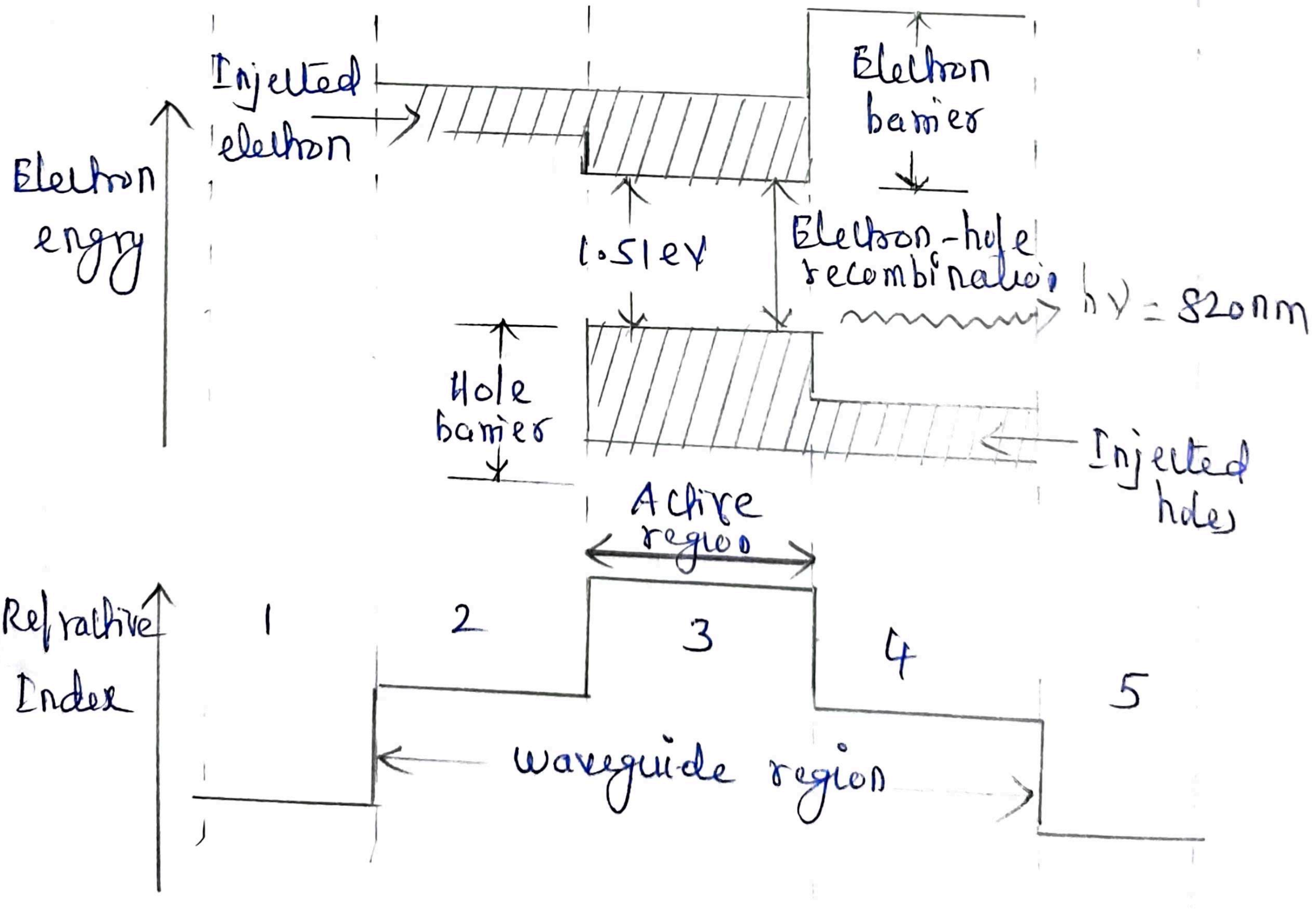
To be useful in fiber transmission application, an LED must have a high radiance output, a fast emission response time, and a high quantum efficiency. Its radiance (or brightness) is a measure in watts of the optical power radiated into a unit solid angle per unit area of the emitting surface. High radiances are necessary to couple high optical power into fiber. The emission response time is the time delay between the application of a current pulse and the onset of optical emission. This time delay is the factor limiting the bandwidth with which the source can be modulated directly by varying the injected current.

To achieve a high radiance and a high quantum efficiency, the LED structure must provide a mean of confining the ~~H~~ charge carriers and the stimulated optical emission to the active region of the pn junction where the radiative recombination takes place.

carrier confinement is used to achieve a high level of radiance recombination in the active region of the device, which yields a high quantum efficiency.
To achieve carrier and optical confinement LED configurations such as homojunctions and single and double heterojunctions have been widely used.

Double heterostructure or heterojunction device

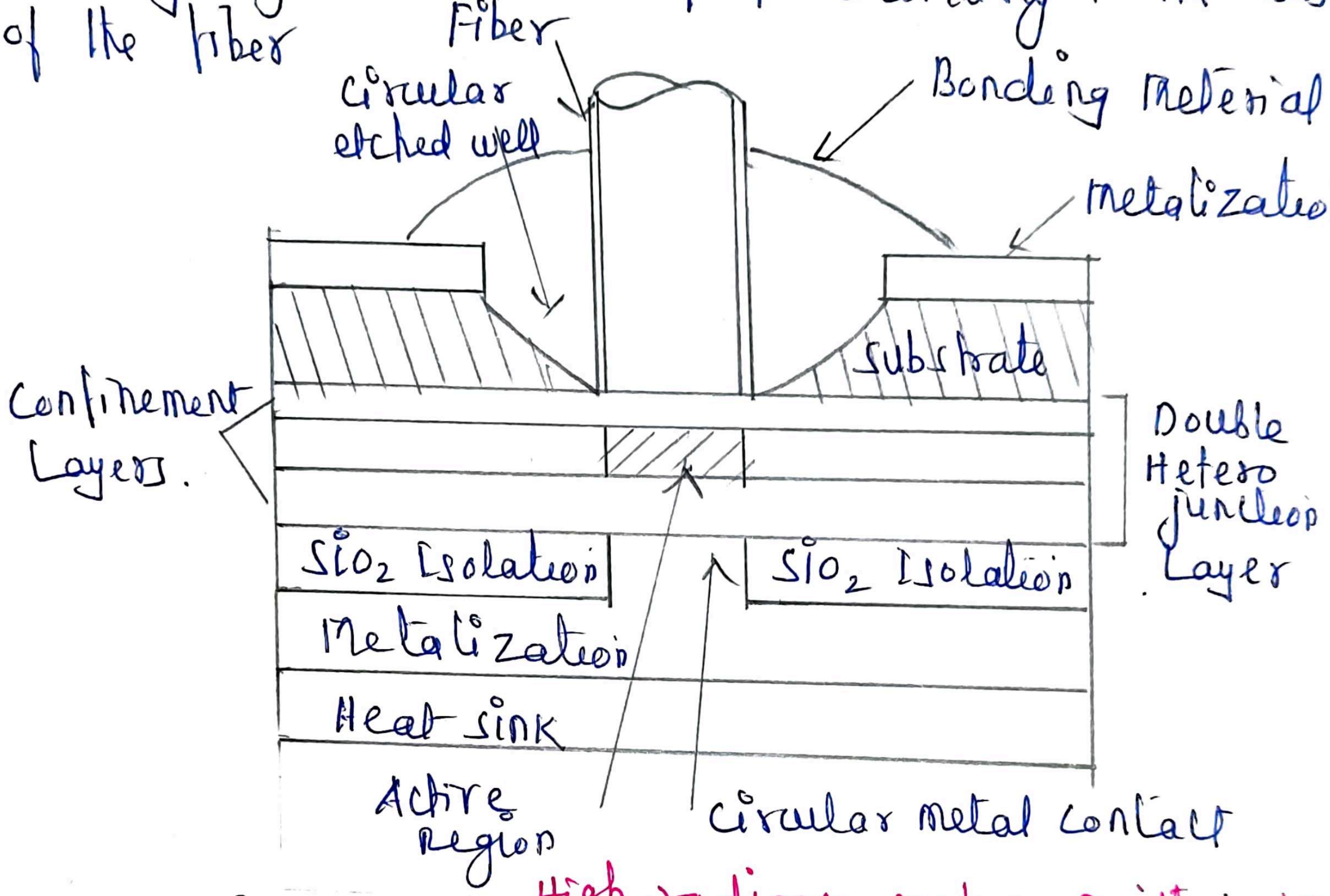
Metal Contact	n-type GaAs substrate	n-type $Ga_{1-x}Al_xAs$ Light guiding and carrier confinement ~1 μm	n-type $Ga_{1-x}Al_xAs$ Recombination region ~0.3 μm	p-type $Ga_{1-x}Al_xAs$ Light guiding and carrier confinement ~1 μm	p-type GaAs metal contact improvement layer 1 μm	metal contact



LED configuration

Two basic LED configurations being used for fiber optics are
(i) surface Emitters also called Burrus or front emitters
(ii) Edge Emitters

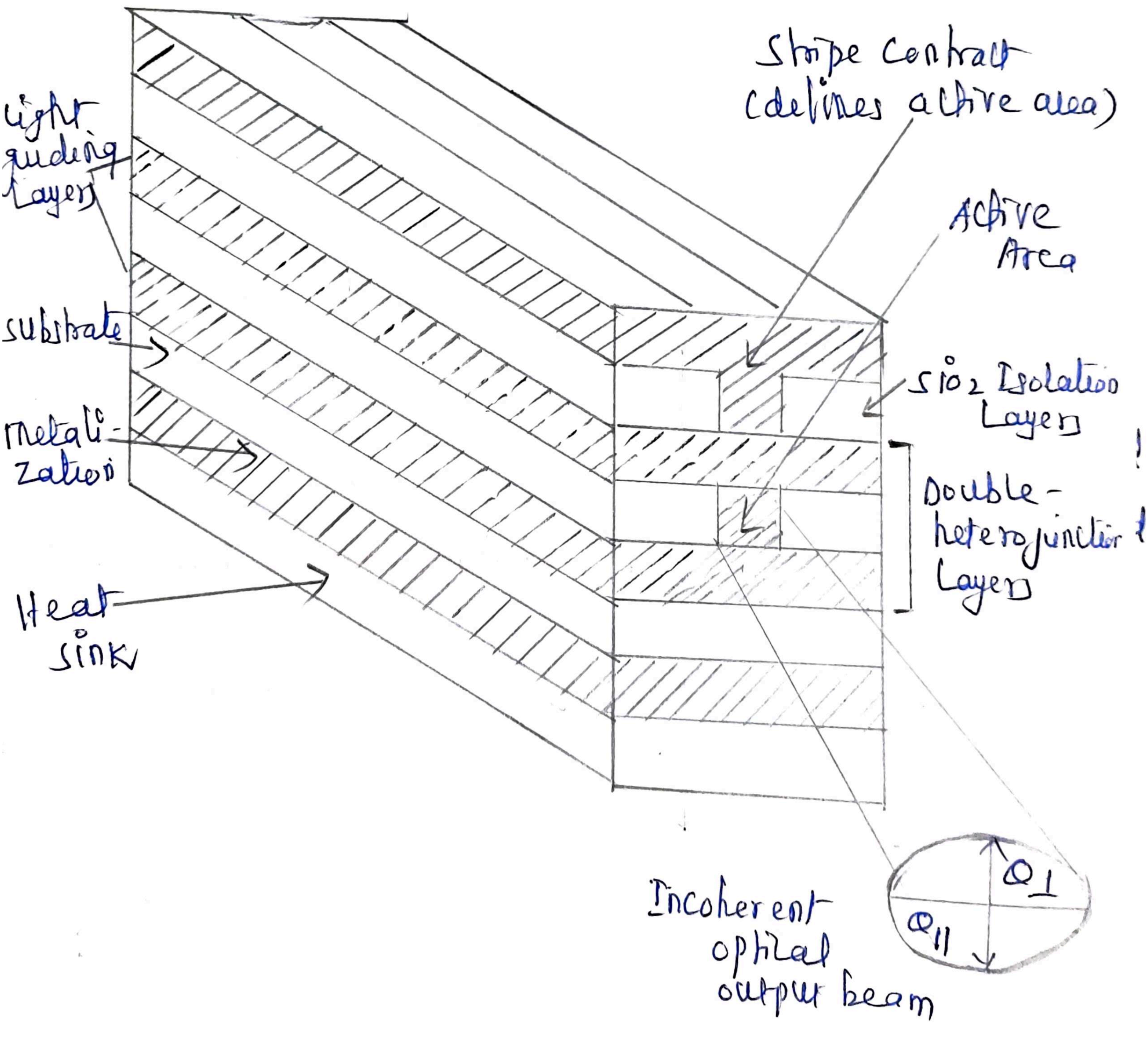
In the surface emitter, the plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber



High-radiance surface Emitting LED

The circular active area in surface emitter is 50 μm in diameter and upto 2.5 μm thick. The emission pattern is isotropic with a 120° half-power beam width. This isotropic pattern from a surface emitter is called as Lambertian pattern. In this pattern the source is equally bright when viewed from any direction but the power diminishes as $\cos\theta$ where θ is the angle between the viewing direction and the normal to the surface. The power is down to 50% of its peak when $\theta = 60°$ so that the total Half power beam width is 120°

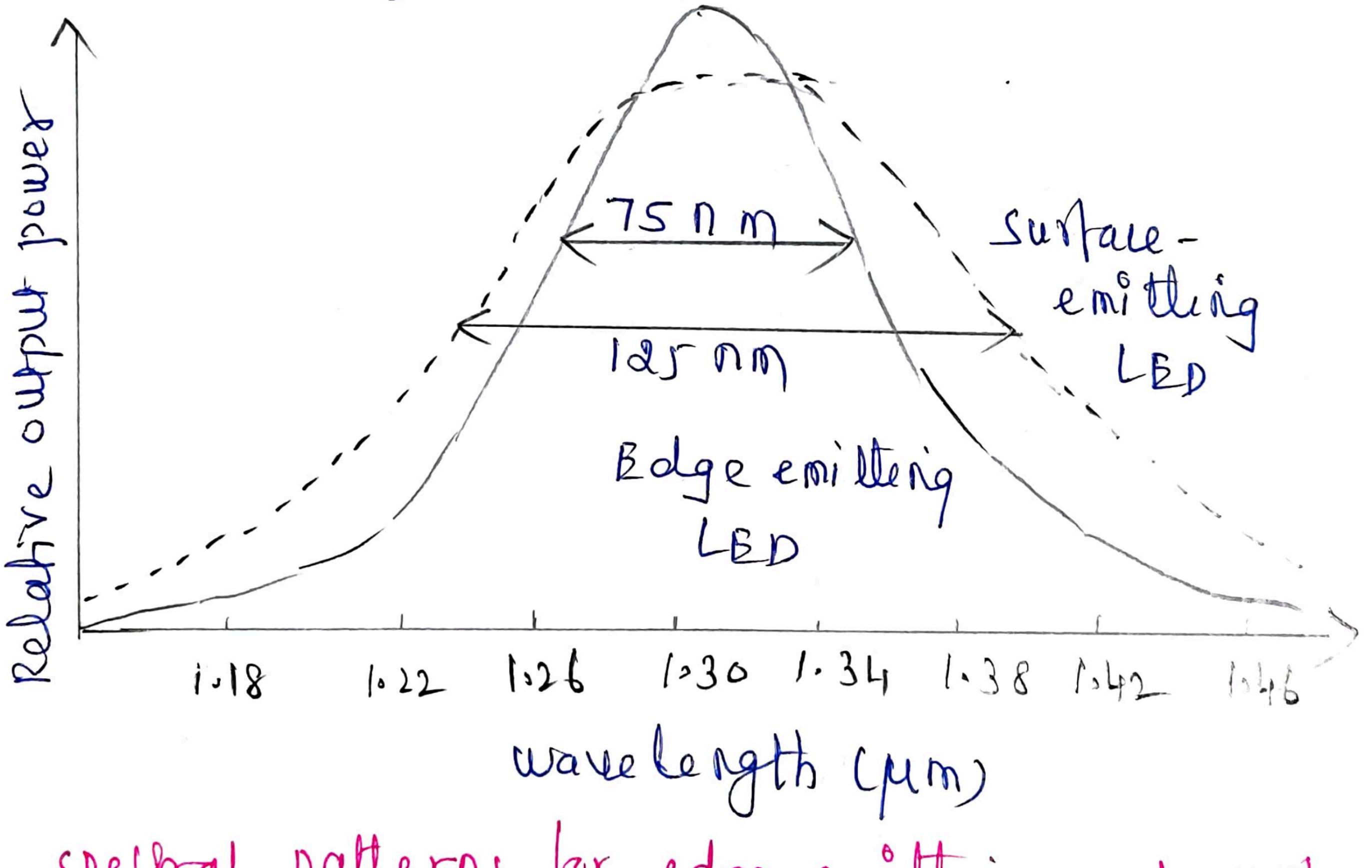
The edge emitter consists of an active region, which is the source of the incoherent light and two guiding Layers. The guiding Layers both have a refractive index lower than that of the active region and higher than the index of the surrounding material.



This structure forms a waveguide channel that directs the optical radiation toward the fiber core. To match the fiber-core diameter (50–100 μm), the contact stripes for the edge emitter are 50–70 μm wide. Length of the active region range from 100 to 150 μm.

In the plane parallel to the junction, where there is no waveguide effect, the emitted beam is Lambertian (varying as cos θ) with half power width of $\theta_{\parallel} = 120°$.

In the plane perpendicular to the junction, the half power beam width $\theta_{\perp}$ has been made as small as 25–35°.



spectral patterns for edge-emitting and surface-emitting LEDs at 1310 nm.

The patterns broaden with increasing wavelength and are wider for surface emitters.

Quantum Efficiency and LED power

An excess of electrons and holes in p and n-type material (minority carriers) is created in a semiconductor light source by carrier injection at the device contacts. The excess densities of electrons n and holes p are equal, since the injected carriers are formed and recombine in pairs in accordance with the requirement for charge neutrality in the crystal. When carrier injection stops the carrier density returns to the equilibrium value. The excess carrier density decays exponentially with time according to the relation

$$n = n_0 e^{-t/\tau}$$

where n_0 is the injected excess electron density & τ is time constant.

This lifetime is one of the important operating parameters of an electro-optic device. Its value can range from milliseconds to nanosecond depending on material composition and device defects.

The excess carriers can recombine either radiatively or nonradiatively. In radiative recombination a photon of energy $h\nu$, which is equal to the band gap energy, is emitted. Nonradiative recombination effects include optical absorption in the active region (self-absorption) when there is a constant current flow into an LED an equilibrium condition is established. The excess density of electron n and holes p is equal since the injected carriers are created and recombined in pairs. such that charge neutrality is maintained within the device. The total rate at which carriers are generated is the sum of the externally supplied and the thermally generated rates. The externally supplied rate is given by J/qd where J is the current density in A/cm^2, q is the electron charge and d is the thickness of the recombination region. The thermal generation rate is given by n/τ. Hence the rate equation for carrier recombination in an LED

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau}$$

In equilibrium condition $\frac{dn}{dt} = 0$

$$n = \frac{J\tau}{qd}$$

This relationship gives the steady state electron density in the active region when a constant current is flowing through it.

The Internal Quantum efficiency in the active region is the fraction of the electron-hole pairs recombine radiatively. If the radiative recombination rate is R_r and the non-radiative recombination rate is R_{nr} then the internal quantum efficiency η_{int} is the ratio of the radiative recombination rate to the total recombination rate

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}}$$

For exponential decay of excess carriers, the radiative recombination life time is $\tau_r = n/R_r$ and the non-radiative recombination lifetime $\tau_{nr} = n/R_{nr}$.

Internal Quantum efficiency

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

where the bulk recombination lifetime is

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

If the current is injected into the LED is I then the total number of recombination per second is

$$R_r + R_{nr} = I/q$$

$$\eta_{int} \Rightarrow R_r = \eta_{int} I/q$$

R_r is the total number of photons generated per second and each photon has an energy $h\nu$ then optical power generated internally to the LED is

$$P_{int} = \eta_{int} \, I/q \cdot h\nu = \eta_{int} \frac{hcI}{q\lambda} \quad \because \nu = c/\lambda$$

Internal quantum efficiency is 50 percent for simple homojunctions. LEDs. For double-heterojunction structures have 60-80 percentage. This high efficiency is achieved because the thin active regions;

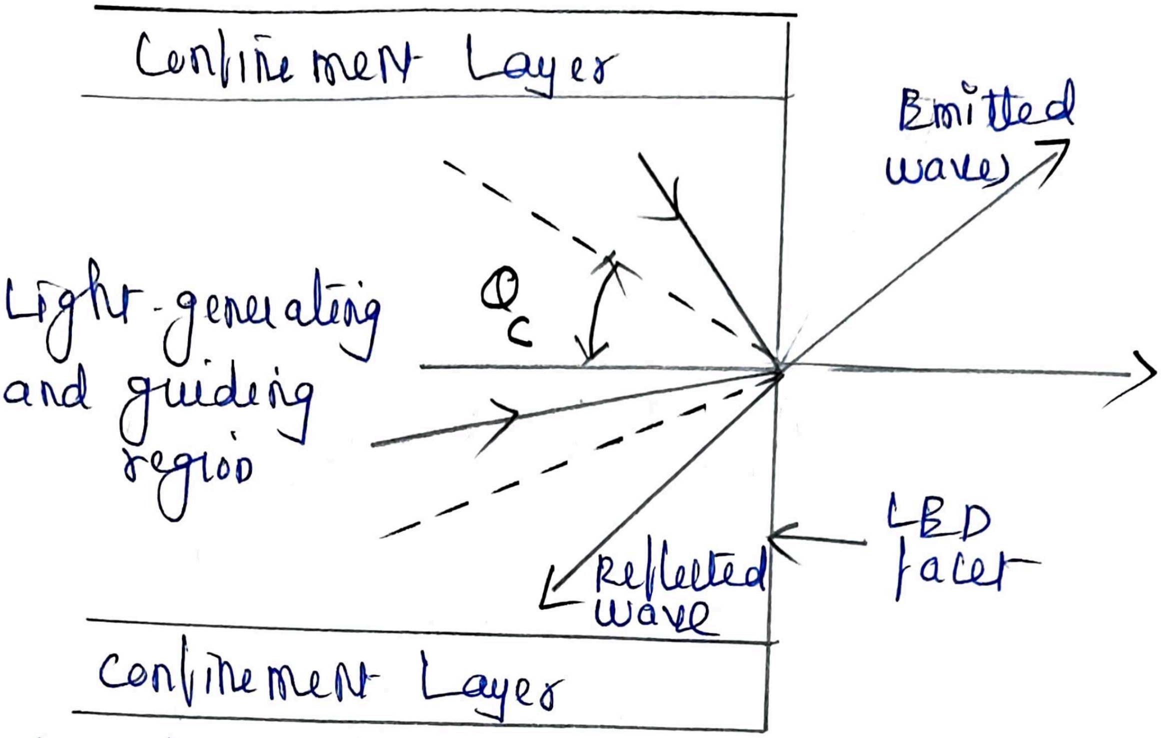
Not all internally generated photons will exit the device. To find the emitted power, need to consider external quantum efficiency. η_{ext}.

η_{ext} is defined as the ratio of the photons emitted from the LED to the number of internally generated photons. To find the external η_{ext}, we need to take into account reflection effects at the surface of the LED.

At the interface of a material boundary only fraction of light falling within a cone defined by critical angle ϕ_c will cross the interface.

$\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$ $\quad n_1 \rightarrow$ R.I of S.C material

$n_2 \rightarrow$ R.I of outside "



The external quantum efficiency η_{ext}

$$\eta_{ext} = \frac{1}{4\pi} \int_0^{\phi_c} T(\phi)\,(2\pi \sin\phi)\, d\phi.$$

$T(\phi)$ is the Fresnel transmission co-efficient or Fresnel transmissivity.

This factor depends on the incidence angle ϕ.

For normal Incidence $T(0) = \frac{4 n_1 n_2}{(n_1+n_2)^2}$

Assuming the outside medium is air and $n_1 = n$ we have $T(0) = \frac{4n}{(n+1)^2}$. The external quantum efficiency is then approximately given by

$$\eta_{ext} \simeq \frac{1}{n(n+1)^2}$$

The optical power emitted from the LED is

$$P = \eta_{ext} P_{int} = \frac{P_{int}}{n(n+1)^2}$$

LASER Diodes

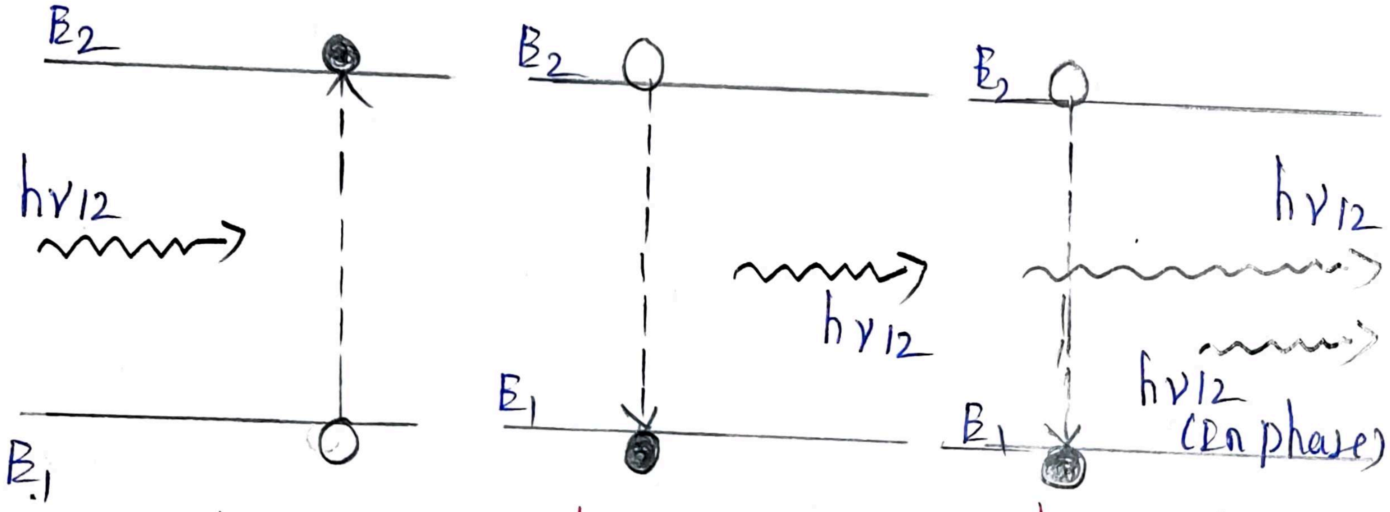
Lasers come in many forms with dimensions ranging from the size of a grain of salt to one will occupy an entire room. The Laser medium can be

- a gas
- a liquid
- an insulating crystal (solid state) or
- a semiconductor.

For optical fiber systems the laser sources used are semiconductor Laser diodes.

Laser action is the result of three key process.

- photon absorption
- spontaneous emission and
- stimulated emission



Absorption　　spontaneous Emission　　stimulated Emission

E_1 is the ground state energy

E_2 is the excited state energy

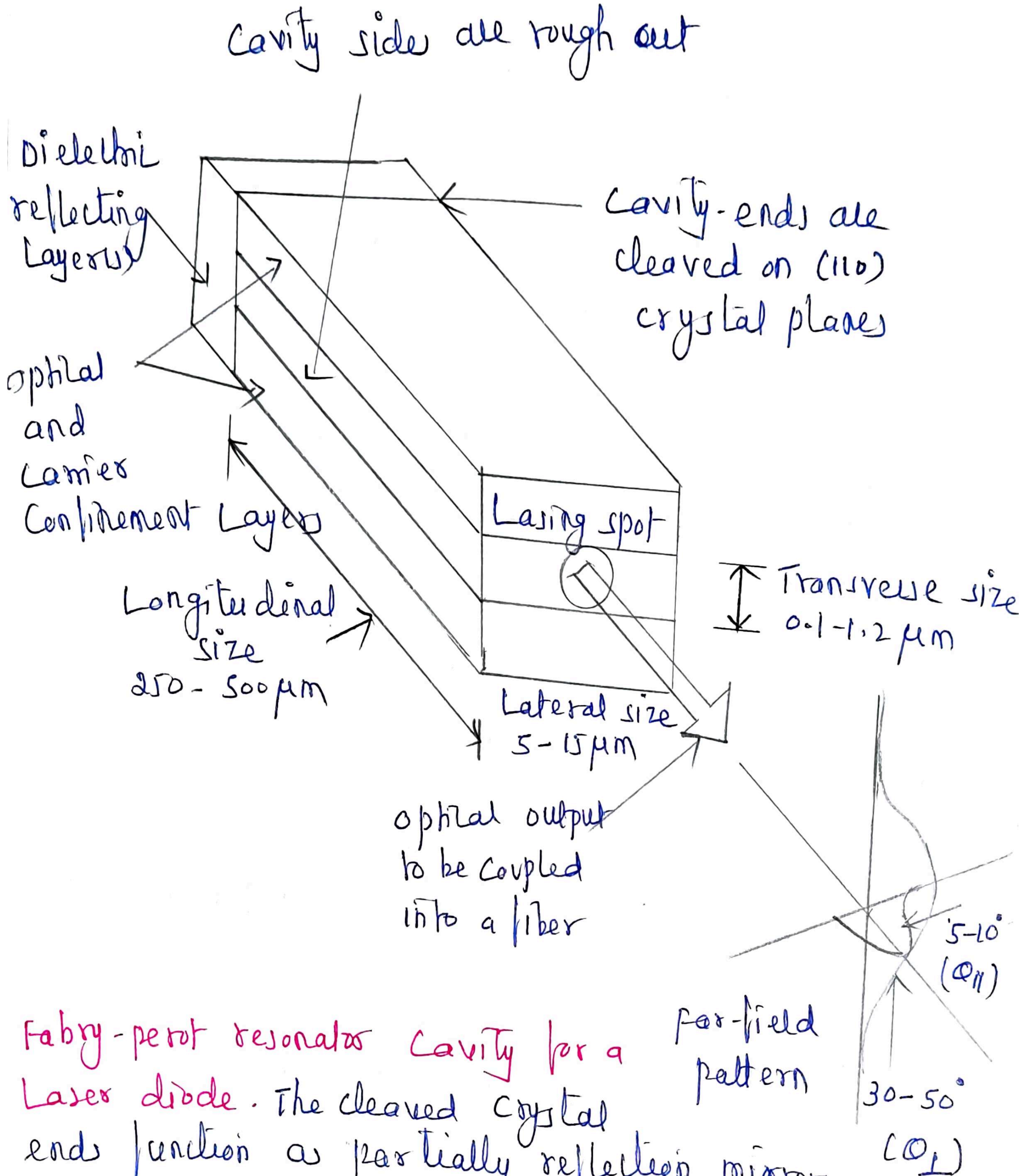
According to planck's Law, the transition between these two states involves the absorption or emission of a photon energy $h\nu_{12} = E_2 - E_1$
Normally the system is in the ground state. when a photon of energy $h\nu_{12}$ impinges on the system an electron in state E_1 can absorb the photon energy and be excited to state E_2 since this is an unstable state the electron will shortly return to the ground state there by emitting a photon of energy $h\nu_{12}$. This occurs without any external stimulation and is called spontaneous emission These emissions are isotropic and of random phase and appear as a narrowband gaussian output.
The electron can also be induced to make a downward transition from the excited level to the ground-state level by an external stimulation If a photon of energy $h\nu_{12}$ impinges on the system while the electron is still in its excited state, the electron is immediately stimulated to drop to the ground state and give off a photon of energy $h\nu_{12}$. This photo is in phase with the incident photon and the emission is called stimulated emission

Laser Diode Modes and Threshold conditions :

For optical fiber communication systems requiring B.W greater than 200 MHz, the semiconductor injection Laser diode is preferred over LED. Laser diodes have response times less than 1ns can have spectral widths of 2nm or less and are capable of coupling from tens to hundreds of milliwatts of luminescent power into optical fibers with small cores and small mode field diameters.

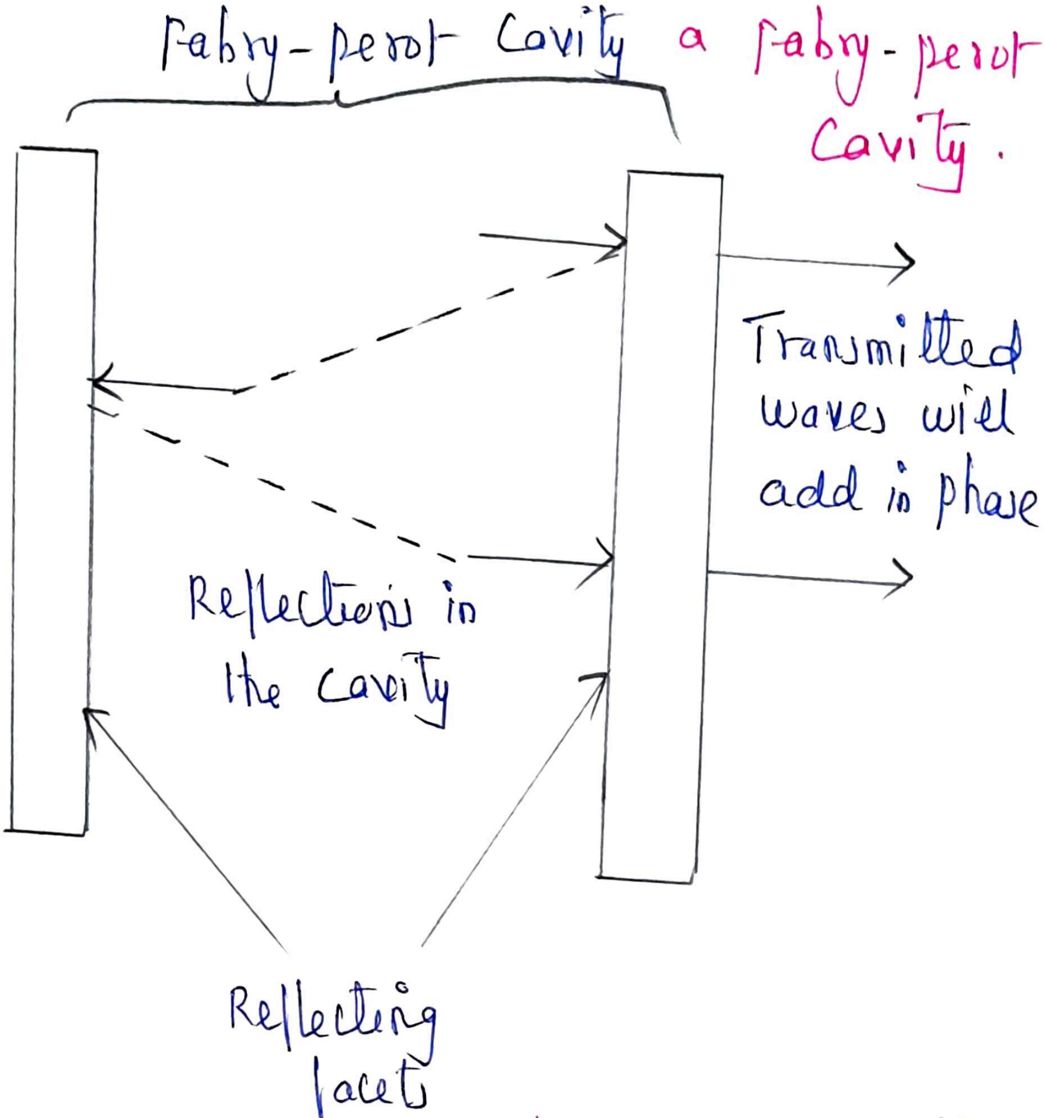
Stimulated emission in semiconductor lasers arises from optical transitions between distributions of energy states in the V.B and C.B. This differs from gas and solid-state lasers, in which radiative transitions occur between discrete isolated atomic or molecular levels. The radiation in one-type of laser diode configuration is generated within a Fabry-perot resonator cavity.

The cavity is approximately 250-500 μm long, 5-15 μm wide and 0.1-0.2 μm thick. These dimensions are referred to as the Longitudinal, Lateral and transverse dimensions of the cavity.



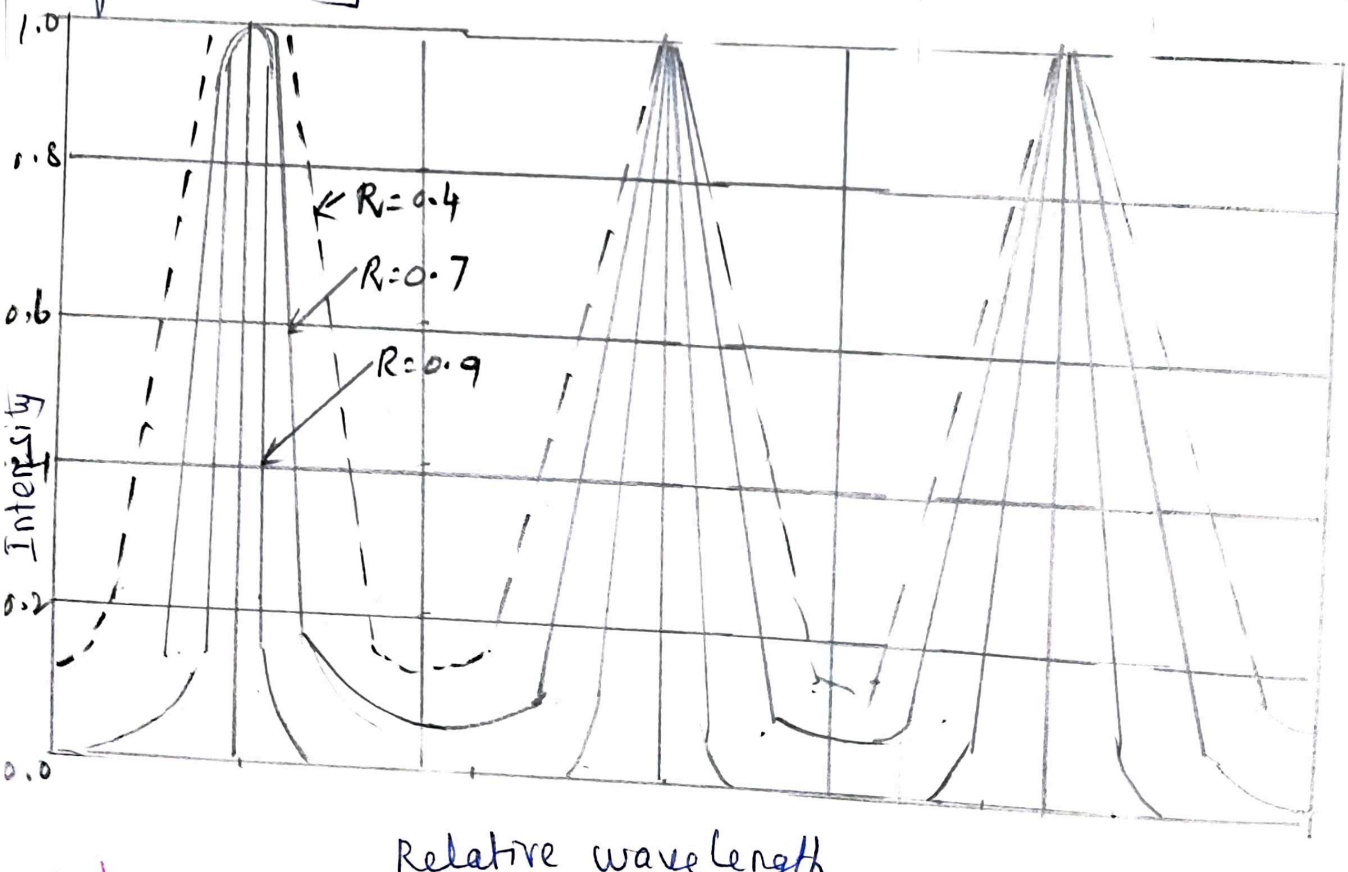
Fabry-perot resonator cavity for a Laser diode. The cleaved crystal ends function as partially reflection mirrors. The unused end (the rear facet) can be coated with a dielectric reflector to reduce optical loss in the cavity.

Two parallel light-reflecting mirrored surfaces define a Fabry-Perot resonator cavity.



Two flat partially reflecting mirrors are directed toward each other to enclose the Fabry-Perot resonator cavity. The mirror facets are constructed by making two parallel clefts along natural cleavage planes of the s.c crystal. The purpose of the mirrors is to establish a strong optical feedback in the longitudinal direction. This feedback mechanism converts the device into an oscillator (and hence a light emitter) with a gain mechanism that compensates for optical losses in the cavity at certain resonant optical frequencies. The sides of the cavity are simply formed by roughing the edges of the device to reduce unwanted emissions in the lateral directions.

As the light reflects back and forth within the Fabry-perot cavity the electric fields of the light interfere on successive round trips. Those wavelengths are integer multiples of the cavity length interfere constructively so that their amplitudes add when they exit the device through the right-hand facet. All the wavelengths interfere destructively and thus cancel themselves out. The optical freq at which constructive interference occurs are the resonant frequencies of the cavity. The resonant wavelengths are called the longitudinal modes of the cavity because they resonate along the length of the cavity.

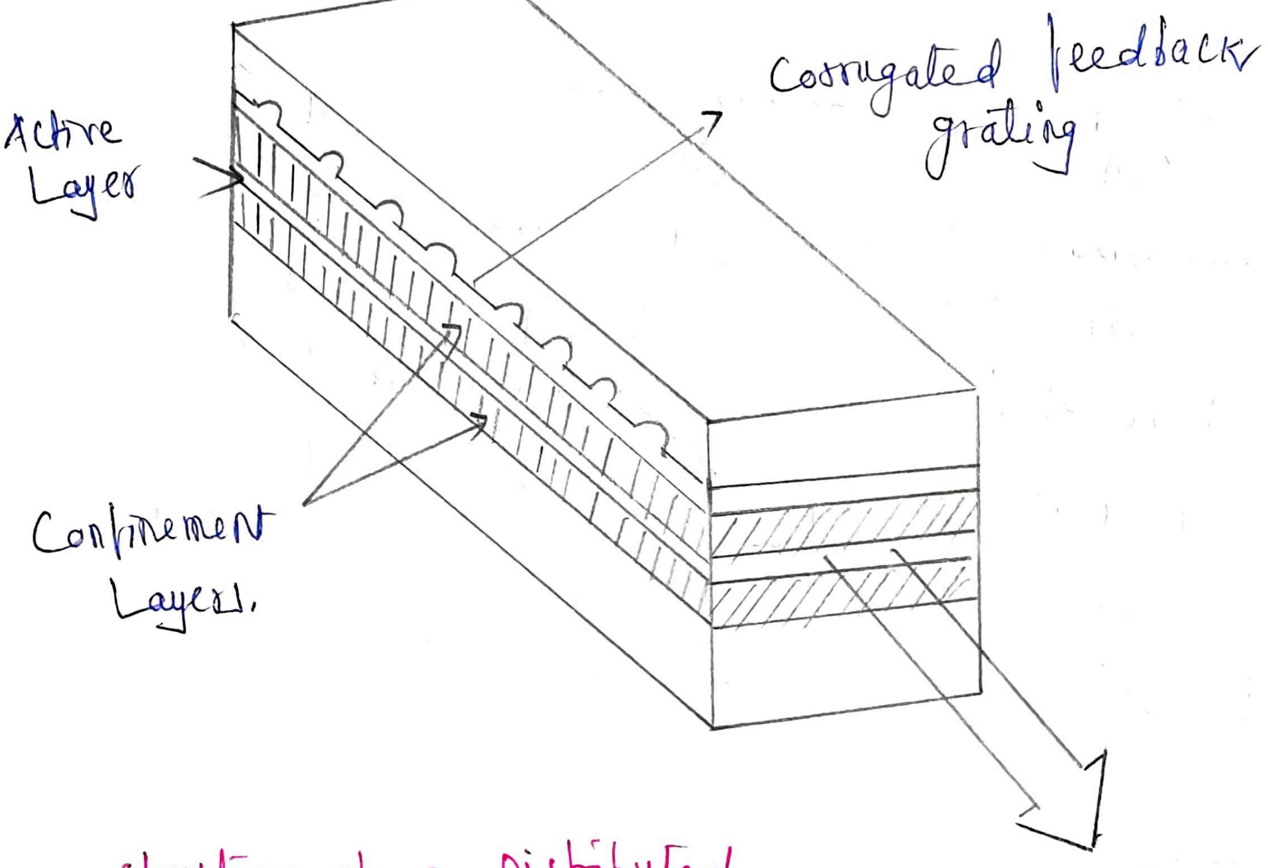


Behavior of the resonant wavelengths in a Fabry-perot cavity

The behaviour of the resonant wavelengths for three values of the mirror reflectivity as shown in fig. The plot gives the relative intensity as a function of the wavelength relative to the cavity length., the resonances become sharper as the reflectivity increases.

Distributed Feedback (DFB) Laser

The cleaved facets are not required for optical feedback. The fabrication is similar to the fabry-perot types, except that the lasing action is obtained from Bragg reflectors (gratings) or periodic variation of the R.I [Called distributed feedback corrugations]



Structure of a Distributed Feedback (DFB) Laser Diode

The optical radiation within the resonance cavity of
a Laser diode sets up a pattern of electric and
magnetic field lines called the modes of the cavity.
These can be separated into two independent sets
of transverse electric (TE) and transverse magnetic
(TM) modes.
Each set of modes can be described in terms of the
Longitudinal, Lateral and transverse half-sinusoidal
variations of the electromagnetic fields along the
major axes of the cavity. The Longitudinal modes
are related to the Length of the cavity and determine
the principal structure of the frequency spectrum of the
emitted optical radiation. Since L is much larger than
the Lasing wavelength of $\simeq 1\mu m$, many Longitudinal
modes can exist. Lateral modes lie in the plane of the
pn junction. These modes depend on the side wall
preparation and the width of the cavity and determine
the shape of the Lateral profile of the Laser beam.
Transverse modes are associated with the electromagnetic
field and beam profile in the direction perpendicular
to the plane of the pn junction. These modes are important
as they determine Laser characteristics as the radiation
pattern and the threshold current density.

Photo detectors:

At the output end of an optical transmission line, there must be a receiving device that interprets the information contained in the optical signal. The 1st element of this receiver is a photodetector. The photo detector senses the luminescent power falling upon it and converts the variation of this optical power into a varying electric current. Since the optical signal is weekened and distorted when it emerges from the end of the fiber, the photo-detector must meet very high performance requirements

Requirements

- High sensitivity at the operating wavelength of the source
- short response time to obtain a desirable bandwidth
- minimum noise contribution
- Compatible size for efficient coupling and packaging
- Linear response over a wide range of light intensity
- stability of performance characteristics
- Low bias voltage
- Low cost, Long operating life.

Types of photo detectors:

Photomultipliers, pyroelectric detectors, photo transistors, photo diodes and semiconductor-based photo conductors.

Two distinct photo detection mechanisms.

1. External photoelectric effect
   Photomultiplier Tubes [PMT]
2. Internal photo electric effect
   PN junction photodiodes
   PIN photodiodes
   Avalanche photodiodes

External photo electric effect
Electrons become free from the metal surface by energy absorption obtained by stream of incident photons.

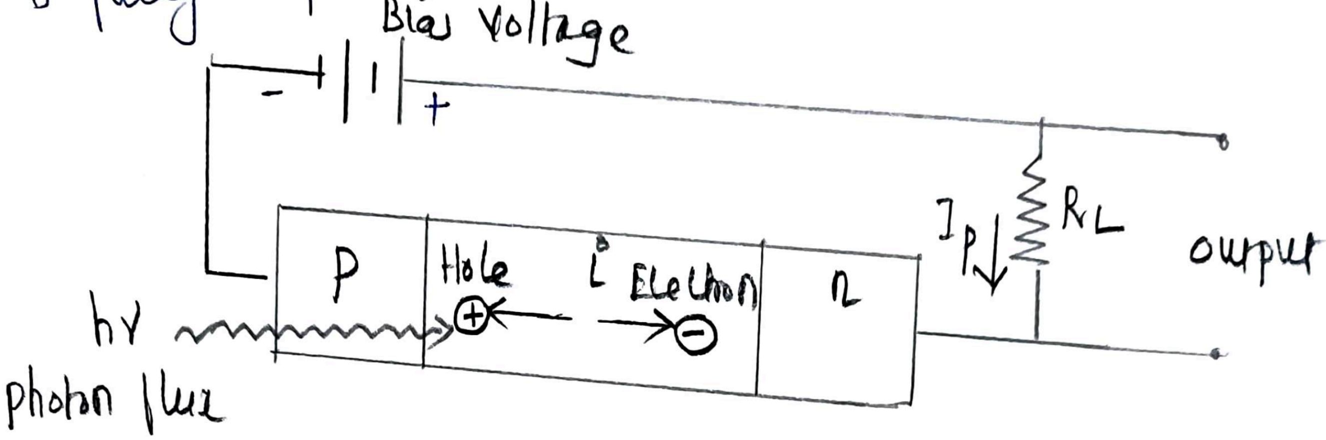
Internal photo electric effect
Free charge carriers are generated by absorption of incident photons in semiconductor junction detectors.

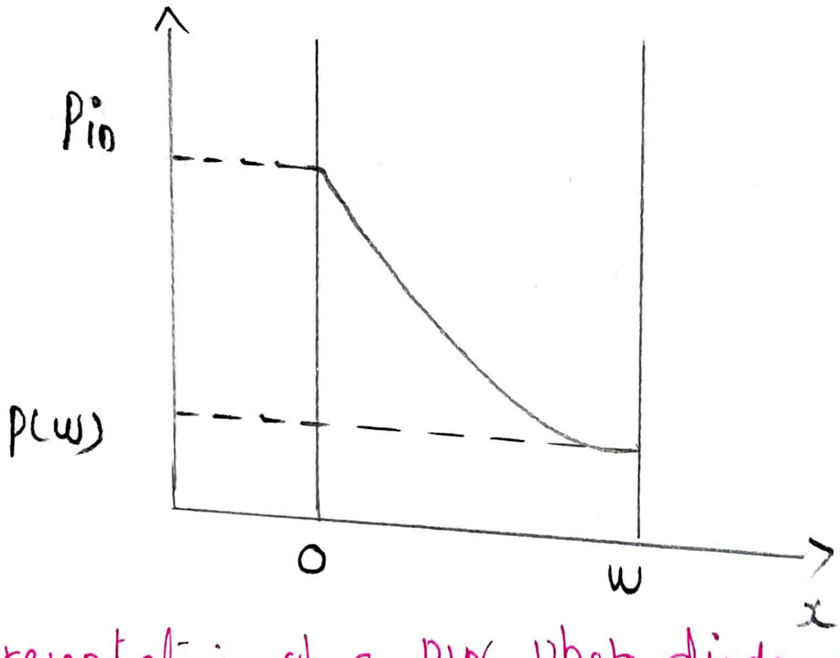
Photomultipliers consisting of photocathode and an electron multiplier packaged in a vaccum tube are capable of very high gain and very low noise. but their large size and high voltage requirements make them unsuitable for optical fiber systems.

Pyroelectric photodetectors involve the conversion of photons to heat. photon absorption results in a temperature change of the detector material.

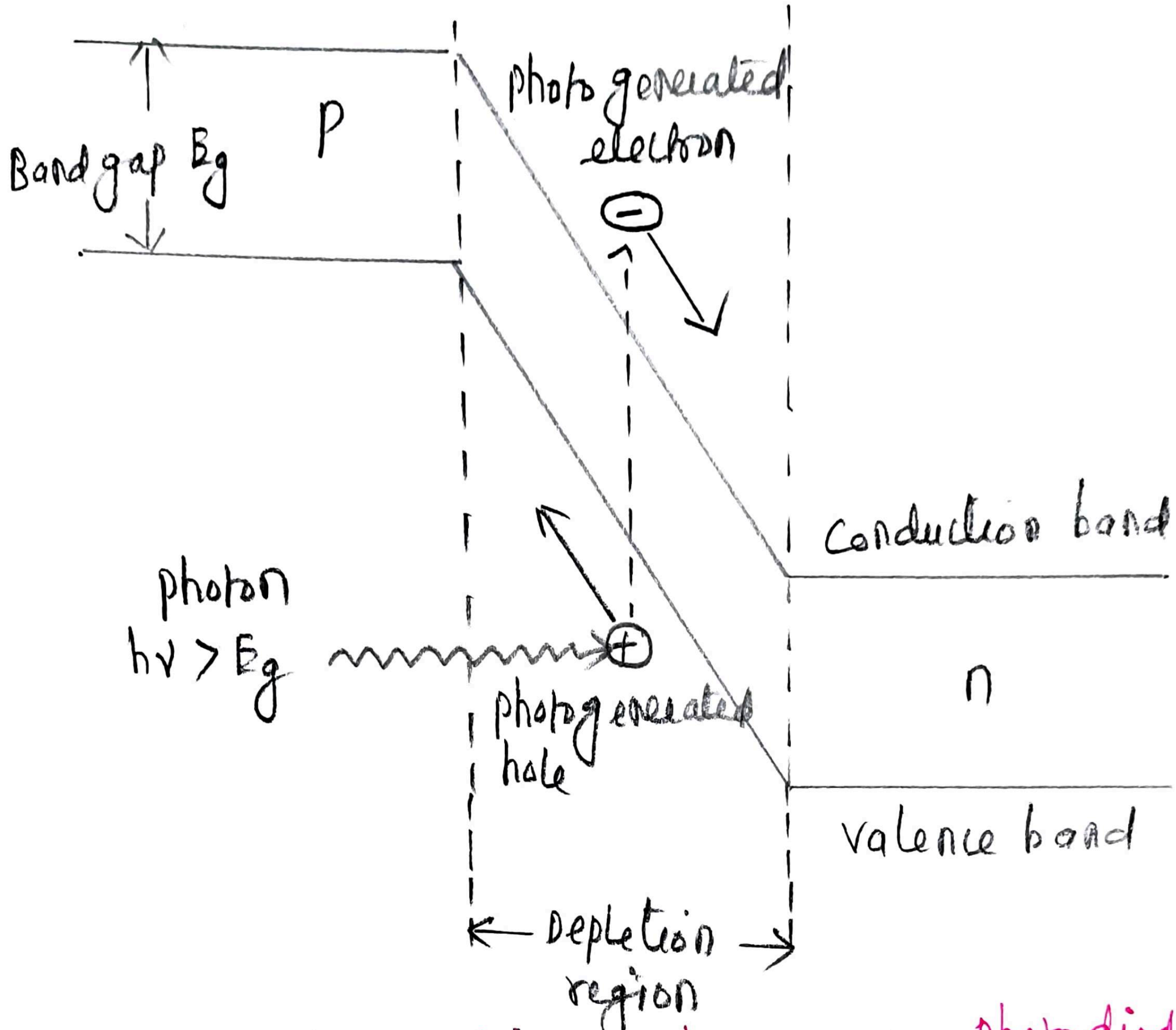
PIN photo detector:

The device structure consists of p and n regions separated by a very lightly n-doped intrinsic (i) region. In normal operation a large reverse-bias voltage is applied across the device so that the intrinsic region is fully depleted of carriers.





Representation of a PIN photo diode circuit with an applied reverse bias. An incident optical power level decays exponentially inside the device.



simple energy-band diagram for a PIN photodiode

photons with energy greater than or equal to the bandgap energy E_g can generate free electron-hole pairs that act as photocurrent carriers.

As a photon flux ϕ penetrates into a s.c, it will be absorbed as it progresses through the material
suppose P_{in} is the optical power level falling on the photodetector at $x=0$ and $p(x)$ is the power level at a distance x into the material. Then the incremental change $dp(x)$ in the optical power level as this photon flux passes through an incremental distance dx in the

semiconductor is given by $dp(x) = -\alpha_s(\lambda)\, p(x)\, dx$
where $\alpha_s(\lambda)$ is the photon absorption co-efficient at a wavelength λ. Integrating this relationship gives the power level at a distance x into the material as

$$p(x) = P_{in} \exp(-\alpha_s x)$$

As the charge carriers flow through the material some electron-hole pairs will recombine and hence disappear. On the average, the charge carriers move a distance L_n or L_p for electrons and holes. This distance is known as the diffusion length. The time it takes for an electron or hole to recombine is known as the carrier lifetime and is represented by τ_n and τ_p. The lifetimes and the diffusion lengths are related by the expression

$$L_n = (D_n \tau_n)^{1/2} \text{ and } L_p = (D_p \tau_p)^{1/2}$$

where D_n and D_p are the electron and hole diffusion coefficients (or constants)

The upper wavelength cutoff λ_c is determined by the bandgap energy E_g of the material. If E_g is expressed in units of electron volts (eV) then λ_c is given in units of micrometers (μm) by

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

If the depletion region has a width w,
the total power absorbed in the distance w is

$$P_{absorbed}(w) = \int_0^w \alpha_s P_{in} \exp(-\alpha_s x)\, dx$$

$$= P_{in} [1 - e^{-\alpha_s w}]$$

If we take reflectivity R_f at the entrance face of the photodiode, then the photocurrent I_p

$$I_p = \frac{q}{h\nu} P_{in} [1 - e^{-\alpha_s w}] (1 - R_f)$$

where P_{in} is the optical power incident on the photo-detector q is the electron charge and $h\nu$ is the photon energy.

Quantum Efficiency η is the number of electron-hole carrier pairs generated per incident-absorbed photon of energy $h\nu$ and is given by

$$\eta = \frac{\text{number of electron-hole pairs generated}}{\text{number of incident-absorbed photons}}$$

$$= \frac{I_p / q}{P_{in} / h\nu}$$

Responsivity R

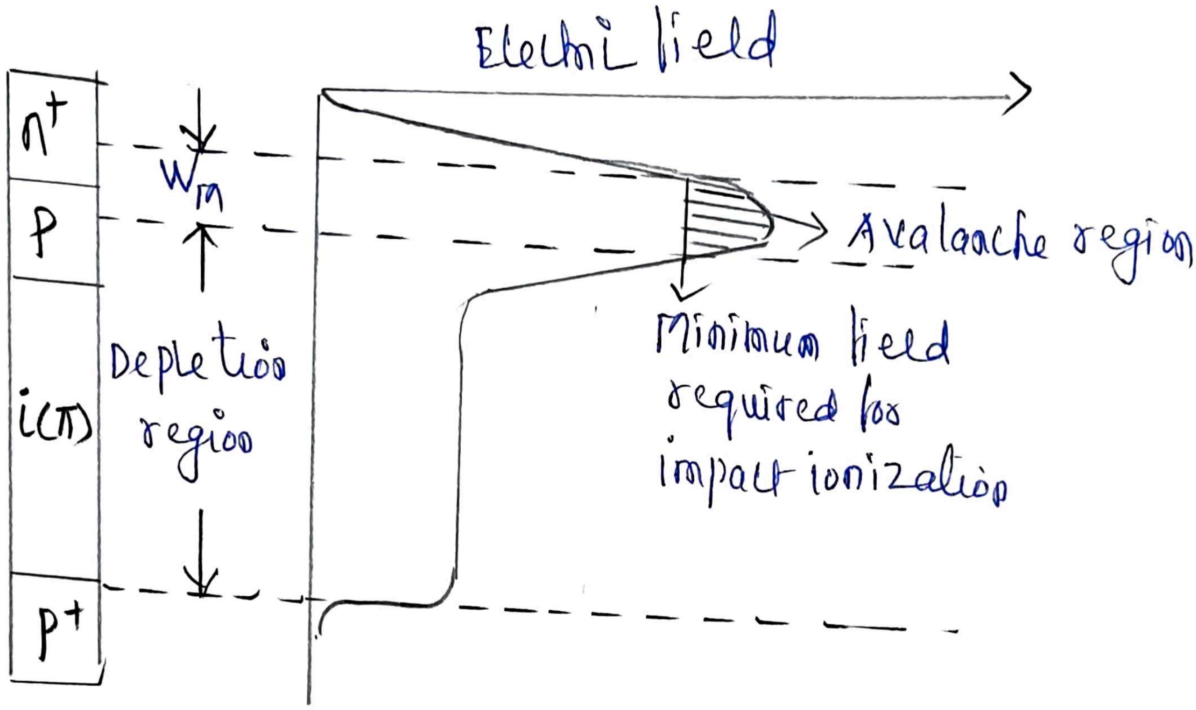
$$R = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}$$

Avalanche photo diode [APD]:

APD's internally multiply the primary photocurrent before it enters the input circuitry of the amplifier. This increases receiver sensitivity, since photo current is multiplied before encountering the thermal noise associated with the receiver circuit. In order for carrier multiplication to takes place, the photo generated carriers must traverse a region where a very high electric field is present. In this high-field region, a photogenerated electron or hole can gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them. This carrier multiplication is known as impact ionization. The newly created carriers are also accelerated by the high electric field thus gaining enough energy to cause further impact ionization. This is known as avalanche effect. Below the diode breakdown voltages a finite total number of carriers are created, whereas above breakdown the number of carriers can be infinite.

A commonly used structure for achieving carrier multiplication is with very little excess noise is the reach-through construction. The RAPD is composed of a high resistive p-type material deposited as an epitaxial layer on a p+ (heavily doped p-type) substrate

A p-type diffusion or ion implant is then made in the high-resistivity material followed by the construction of an n^+ (heavily doped n-type) layer.



This configuration is referred to as $p^+\pi p n^+$ reach-through structure.
The π layer is an intrinsic material that has some p doping because of imperfect purification. The term reach through arises from the photodiode operation. When a low reverse bias voltage is applied most of the potential drop is across pn^+ junction. The depletion layer widens with increasing bias until a certain voltage is reached at which the peak electric field at the pn^+ junction is 5-10% below that needed to cause avalanche breakdown. At this point, the depletion layer just "reaches through" to the nearly intrinsic π region.

In normal usage, the RAPD is operated in the fully depleted mode. Light enters the device through the p^+ region and is absorbed in the π-material, which act as the collection region for the photo generated carriers. upon being absorbed, the photon gives up its energy thereby creating electron-hole pairs, which are then separated by the electric field in the π-region. The photogenerated electrons drift through the π-region in the pn^+ junction, where a high electric field exists. It is in this high-field region that carrier multiplication takes place.

The average number of electron-hole pairs created by a carrier per unit distance traveled is called the ionization rate.

The multiplication M for all carriers generated in the photodiode is defined by $M = \frac{I_M}{I_p}$.

where I_M is the average value of the total multiplied output current and

I_p is the primary unmultiplied photocurrent.

performance of an APD is characterized by its responsivity R_{APD}

$$R_{APD} = \frac{\eta q}{h\nu} M = R \cdot M$$

R is the unity gain responsivity

Photo detector Noise :

In fiber optic communication system, the photodiode is to detect very weak optical signals. Detection of the weak optical signal requires that the photodetector and its amplification circuitry be optimized. so that a given signal-to-noise ratio is maintained.

The power signal-to-noise ratio S/N at the output of an optical receiver is defined by

$$SNR = \frac{S}{N} = \frac{\text{signal power from photocurrent}}{\text{photodetector noise power + amplifier noise power}}$$

The noise sources in the receiver arise from the photodetector noises resulting from the statistical nature of photon-to-electron conversion process and the thermal noise associated with amplifier circuitry

To achieve a high signal-to-noise ratio,

1. The photodetector must have high quantum efficiency to generate a large signal power
2. The photodetector and amplifier noises should be kept as low as possible.

The principal noise source associated with photodetectors

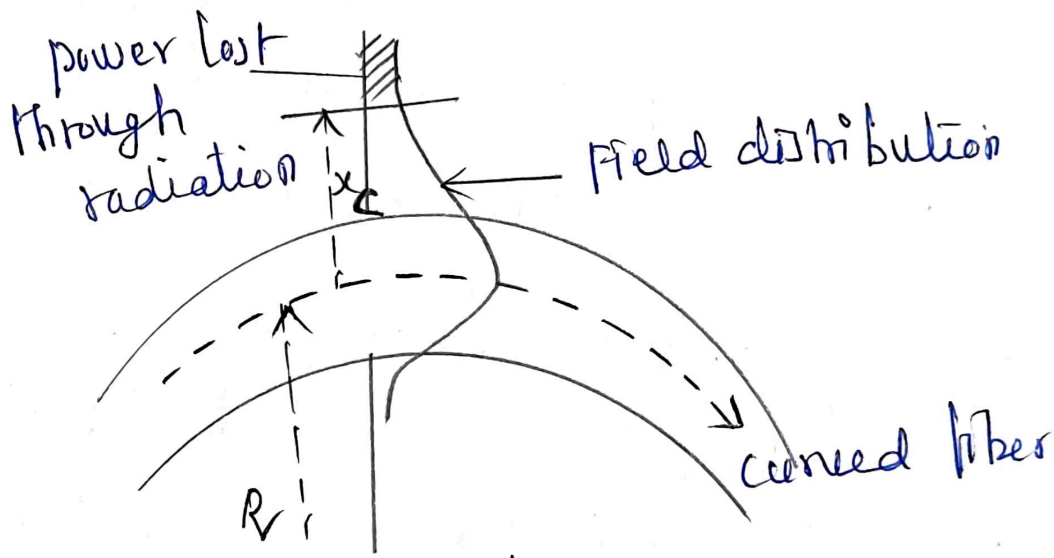
1. Quantum (shot) Noise : arises from statistical nature of the photo-generated electron upon optical illumination
2. Dark current Noise : is the current that continues to flow through the bias circuit in the absence of the light

Bending Losses:

Radiative losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. Fibers can be subject to two types of curvature

a) macroscopic bends having radii that are large compared with the fiber diameter

b) microscopic bends of the fiber axis that can arise when the fiber are incorporated into cables.



Larger-curvature radiation losses are known as macrobending losses or simply bending losses. For slight bends the excess loss is extremely small and is unobservable. As the radius of curvature decreases the loss increases exponentially until at a certain critical radius the curvature loss becomes observable. If the bend radius is made a bit smaller once this threshold point has been reached the losses suddenly become extremely large.

Consider the material alloy $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$, that is, x = 0.26 and y = 0.57 in the general formula $In_{1-x}Ga_xAs_yP_{1-y}$. Find (a) the bandgap of this material; (b) the peak emission wavelength.

Solution: For $In_{1-x}Ga_xAs_yP_{1-y}$ Composition the bandgap in eV

$$E_g = 1.35 - 0.72y + 0.12y^2$$

$$E_g = 1.35 - 0.72(0.57) + 0.12(0.57)^2$$

$$= 0.97\,eV$$

using this value of the bandgap energy in

$$\lambda(\mu m) = \frac{1.240}{E_g(eV)} = \frac{1.240}{0.97} = 1.27\,\mu m$$

$$= 1270\,nm$$

A double hetero junction InGaAsP LED emitting at a peak wavelength of 1310 nm has radiative and nonradiative recombination times of 30 and 100 ns, respectively. The drive current is 40 mA. Find (a)the bulk recombination time; (b) the internal quantum effi ciency; and (c) the internal power level.

Solution: Bulk recombination lifetime is

$$\tau = \frac{\tau_r \tau_{nr}}{\tau_r + \tau_{nr}} = \frac{30 \times 100}{30 + 100}\,ns = 23.1\,ns$$

Internal quantum efficiency is

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{23.1}{30} = 0.77$$

Internal power level

$$P_{int} = \eta_{int} \cdot \frac{hcI}{q\lambda}$$

$$= \frac{0.77\,(6.6256 \times 10^{-34}\,J \cdot s)(3 \times 10^8\,m/s)(0.040\,A)}{(1.602 \times 10^{-19}\,C)(1.31 \times 10^{-6}\,m)}$$

$$= 29.2\,mW$$

Consider the following parameter values for GaAs at 300 K:

Electron rest mass $m = 9.11 \times 10^{-31}$ kg, Effective electron mass $m_e = 0.068\ m = 6.19 \times 10^{-32}$ kg Effective hole mass $m_h = 0.56\ m = 5.10 \times 10^{-31}$ kg, Bandgap energy $E_g = 1.42$ eV What is the intrinsic carrier concentration?

Solution: First we need to change the bandgap energy to unit of joules: $E_g = 1.42\,eV \times 1.60 \times 10^{-19}\ J/eV$

Intrinsic Carrier Concentration $n_i = K \exp\left[-\frac{E_g}{2K_BT}\right]$

where $K = 2\left[\frac{2\pi K_BT}{h^2}\right]^{3/2}[m_em_h]^{3/4}$

I.C.C $n_i = 2\left[\frac{2\pi(1.381 \times 10^{-23})300}{(6.626 \times 10^{-34})^2}\right]^{3/2}\left[(6.19 \times 10^{-32}) \times (5.10 \times 10^{-31})\right]^{3/4} \exp\left[-\frac{1.42 \times 1.60 \times 10^{-19}}{2(1.381 \times 10^{-23})300}\right]$

$= 2.62 \times 10^{12}\ m^{-3}$

$= 2.62 \times 10^{6}\ cm^{-3}$

A particular $Ga_{1-x}Al_xAs$ laser is constructed with a material ratio $x = 0.07$. Find

(a) the bandgap of this material; (b) the peak emission wavelength.

Solution: In the ternary alloy GaAlAs the bandgap energy E_g is given by

$$E_g = 1.424 + 1.266x + 0.266x^2$$

given $x = 0.07$

$E_g = 1.424 + 1.266(0.07) + 0.266(0.07)^2 = 1.51\,eV$

using this value of the bandgap energy, peak emission wavelength $\lambda(\mu m) = \frac{1.240}{E_g(eV)}$

$= \frac{1.240}{1.51} = 0.82\ \mu m$

$= 820\ nm$

Assume for GaAs that $R_1 = R_2 = R = 0.32$ for uncoated facets (i.e., 32 percent of the radiation is reflected at a facet) and α a 10 cm–1. What is the gain threshold for a 500-mm long laser diode?

Solution: $g_{th} = \bar{\alpha} + \frac{1}{2L} \ln\left[\frac{1}{R^2}\right]$

$= 10 + \frac{1}{2(500 \times 10^{-4})} \ln\left[\frac{1}{(0.32)^2}\right]$

$= 33 \ cm^{-1}$

If the absorption coefficient of $In_{0.53}Ga_{0.47}As$ is 0.8 mm^{-1} at 1550 nm, what is the penetration depth at which P(x)/Pin = l/e = 0.368?

Solution: $P(x) = P_{in} \exp(-\alpha_s x) \Rightarrow \frac{P(x)}{P_{in}} = \exp(-0.8)x$

$= 0.368$

Therefore $-0.8x = \ln 0.368 = -0.9997$

which yields $x = 1.25 \mu m$.

A high-speed $In_{0.53}Ga_{0.47}As$ pin photo detector is made with a depletion layer thickness of 0.15 mm. What percent of incident photons are absorbed in this photo detector at 1310 nm if the absorption coefficient is 1.5 mm^{-1} at this wavelength?

solution $P(x) = P_{in} \exp(-\alpha_s x)$

$\frac{P(0.15)}{P_{in}} = \exp(-\alpha_s x) = \exp(-1.5)(0.15)$

$= 0.80$

Therefore only 20 percent of the incident photon are absorbed.

Assume a typical value of n = 3.5 for the refractive index of an LED material. What percent of the internally generated optical power is emitted into an air medium?

Solution: The percentage of the optical power that is generated internally in the device that is emitted into an air medium $\eta_{ext} = \frac{1}{n(n+1)^2} = \frac{1}{3.5(3.5+1)^2} = 1.41\%$.

This shows that only a small fraction of the internally generated optical power is emitted from the device.

What is the FSR at an 850-nm wavelength for a 0.8-mm long GaAs Fabry-Perot cavity in which the refractive index is 3.5?

Solution: If D is the distance between the reflecting mirrors in a device of R.I n, then at a peak wavelength λ the FSR [free spectral range] is given by

$$FSR = \frac{\lambda^2}{2nD} = \frac{(0.85 \times 10^{-6})^2}{2(3.5)(0.80 \times 10^{-3})} = 0.129 \text{ nm}$$

Assume that the cleaved mirror end faces of a GaAs laser are uncoated and that the outside medium is air. What is the reflectivity for normal incidence of a plane wave on the GaAs-air interface if the GaAs refractive index is 3.6?

Solution: R_1 and R_2 are the mirror reflectivities or Fresnel reflection co-efficient

$$R = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2$$

$n_1 = 3.6$ for GaAs

$n_2 = 1.0$ for air

$$R_1 = R_2 = \left[\frac{3.6 - 1}{3.6 + 1}\right]^2$$

$$= 0.32$$

A given silicon avalanche photodiode has a quantum efficiency of 65 percent at a wavelength of 900 nm. Suppose 0.5 μW of optical power produces a multiplied photocurrent of 10 μA. What is the multiplication M?

Solution $I_p = R P_{in} = \frac{\eta q}{h\nu} P_{in} = \frac{\eta q \lambda}{hc} P_{in} = 0.235\ \mu A$

The multiplication M for all carriers generated

$$M = \frac{I_M}{I_p} = \frac{10\ \mu A}{0.235\ \mu A} = 43$$

Thus the primary photocurrent is multiplied by a factor of 43.

An InGaAs pin photodiode has the following parameters at a wave length of 1300 nm: $I_D = 4$ nA, $\eta = 0.90$, $R_L = 1000\ \Omega$, and the surface leakage current is negligible. The incident optical power is 300 nW (–35 dBm), and the receiver bandwidth is 20 MHz. Find the various noise terms of the receiver.

Solution First we need to find the primary photocurrent

$$I_p = R P_{in} = \frac{\eta q}{h\nu} P_{in} = \frac{\eta q \lambda}{hc} P_{in}$$

$$= \frac{(0.90)(1.6 \times 10^{-19} C)(1.3 \times 10^{-6} m)}{(6.625 \times 10^{-34} J.s)(3 \times 10^{8} m/s)} = 0.282\ \mu A$$

mean-square shot noise current

$$\langle i^2_{shot} \rangle = 2 q I_p B_e = 2 \times 1.6 \times 10^{-19} C \times 0.282 \times 10^{-6} A \times 20 \times 10^{6} Hz$$

$$= 1.80 \times 10^{-18} A^2$$

mean square dark current is

$$\langle i^2_{DB} \rangle = 2 q I_D B_e = 2 \times 1.6 \times 10^{-19} \times 4 \times 10^{-9} \times 20 \times 10^{6}$$

$$= 2.56 \times 10^{-20} A^2$$

mean-square thermal noise current for the receiver is

$$i^2_T = \frac{4 K_B T}{R_L} . B_e = \frac{4 \times 1.38 \times 10^{-23} \times 293}{1 \times 10^{3}} 20 \times 10^{6}$$

$$= 323 \times 10^{-18} A^2$$

A photodiode is constructed of GaAs, which has a bandgap energy of 1.43 eV at 300 K. What is the cutoff wavelength of this device?

Solution: cut off wavelength $\lambda_c(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)}$

$$\lambda_c = \frac{hc}{E_g} = \frac{(6.625 \times 10^{-34} J.s)(3 \times 10^8 m/s)}{(1.43\, eV)(1.6 \times 10^{-19} J/eV)} = 869\, nm$$

This GaAs photodiode will not operate for photons of λ greater than 869 nm.

In a 100 ns pulse, 6 = 10^6 photons at a wavelength of 1300 nm fall on an InGaAs photo detector. On the average, 5.4 = 10^6 electron–hole (e–h) pairs are generated. The quantum efficiency is found

Solution: Quantum efficiency $\eta = \frac{\text{number of e-h pairs generated}}{\text{number of incident photons}}$

$$= \frac{5.4 \times 10^6}{6 \times 10^6} = 0.90$$

The quantum efficiency at 1300 nm is 90 percentage

Photons of energy 1.53 = 10^{-19} J are incident on a photodiode which has a responsivity of 0.65 A/W. If the optical power level is 10 μW, then the photocurrent generated is

Solution: Responsivity $R = \frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}$

$$I_p = R P_{in}$$

$$= (0.65\, A/W)(10\, \mu W)$$

$$= 6.5\, \mu A$$

Quantum Noise current

$$\langle i_Q^2 \rangle = \sigma_Q^2 = 2q I_p B M^2 F(M)$$

B - Bandwidth, $F(M)$ is the Noise Figure

I_p - photocurrent

Bulk Dark current Noise

$$\langle i_{DB}^2 \rangle = \sigma_{DB}^2 = 2q I_D B M^2 F(M)$$

I_D - bulk dark current

Surface dark current Noise

$$\langle i_{DS} \rangle^2 = \sigma_{DS}^2 = 2q I_L B$$

I_L is surface current

Total rms photodetector Noise current is

$$i_N^2 = \sigma_N^2 = i_Q^2 + i_{DB}^2 + i_{DS}^2$$

$$= 2q (I_p + I_D) B M^2 F(M) + 2q I_L B$$

The thermal noise of amplifier connected to the photodetector is

$$i_T^2 = \sigma_T^2 = \frac{4 K_B T B}{R_L}$$

R_L - resistance of the amplifier

$K_B = 1.38 \times 10^{-23}$ J/K is Boltzmann Constant.