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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – III

OPTICAL SOURCES AND OPTICAL DETECTORS

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UNIT - III

Optical Sources: The Laser

5.1 INTRODUCTION

Optical Sources

*Optical sources are **active components** whose fundamental function is to convert an **Electrical energy** into an **Optical energy (light)** i.e. E/O conversion in an effective manner. Hence, the optical sources are also called as **transducers**. The optical signal is then launched or coupled into an optical fiber.*

- Semiconductor optical source is the major component in an optical transmitter. The popularly used optical sources are,

  (i) *Wideband 'continuous spectra' sources – Incandescent lamps.*

  (ii) *Monochromatic incoherent sources – LEDs.*

  (iii) *Monochromatic coherent sources – Lasers.*

5.1.1 Requirements of Optical Sources

An optical source should ideally meet the following requirements in order to use in the transmitter unit of an optical fiber communication system:

(i) Compact Size:

Size of the emitting optical source must be ***compatible*** to the size of the optical fiber.

(ii) Highly Directional:

The emitted light should be preferably directive for easy launching of light from the source to the fiber.

(iii) High E/O Conversion Efficiency.

The light output (optical power) must vary linearly with an electrical input for the faithful E/O conversion.

(iv) Low Attenuation:

The emission wavelength should match with the attenuation window of the fiber. i.e. *wavelength at which the fiber offers low attenuation.*

(v) Minimum Dispersion:

The ***spectral width*** of the source should be ***small*** in order to reduce chromatic dispersion during propagation through the fiber.

(vi) High Modulation Capacity:

The source should have a large bandwidth in order to meet the large information carrying capacity of the fiber.

(vii) Long Life:

The source should have moderately long life.

(viii) Cheap and Reliable:

It is essential that the source is comparatively cheap and highly reliable in order to compete with conventional transmission techniques.

- Almost all these requirements are satisfied by ***semi – conductor laser diodes*** and ***LEDs***, where both operate in ***forward – biased mode.***

5.2 BASIC CONCEPTS: PRINCIPLE OF OPERATION

5.2.1 Introduction

- LASER is an acronym for ***Light Amplification by Stimulated Emission of Radiation.***
- Semiconductor laser sources are generally known as ***Laser Diode (LD)*** or more specifically known as ***Injection Laser Diode (ILD).***
- The ***lasing medium*** can be a ***gas***, a ***liquid***, an ***insulating crystal*** (solid state), or a semiconductor.

- Especially for long distance communication, ***semiconductor laser diodes*** are used as an optical source. This is mainly because, its output radiation is ***highly monochromatic*** and also the light beam is ***very directional.***
- Ideal laser light has ***single-wavelength*** only. This is related to the ***molecular characteristics*** of the material being used in the laser. It is formed in parallel beams and both are ***in the single phase.*** Therefore, it is called as ***coherent.***

5.2.2 Absorption and Emission of Radiation

- Laser action is the result of ***three key*** processes:

  (i) *Photon absorption,*

  (ii) *Spontaneous emission, and*

  (iii) *Stimulated emission.*

- These processes are represented by the simple ***two–energy–level diagrams.***

where, E_1 is the ***lower energy state level***, and

E_2 is the ***higher energy state level***. ($E_2 > E_1$)

(1) Photon Absorption

Definition:

When photon with an energy $hf_{12} = E_2 - E_1$ is incident on an atom. An atom is initially in the lower energy state E_1 gets excited into the higher energy state E_2 (Excited state) through the ***absorption*** *of photon. This process is sometimes referred to as* ***stimulated absorption.***

$$\text{Incident photon energy, } E = E_2 - E_1 = hf = \frac{hc}{\lambda}$$

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

c – *Velocity of light in free space,*

f – *Frequency of the light, and*

λ *is the corresponding wavelength.*

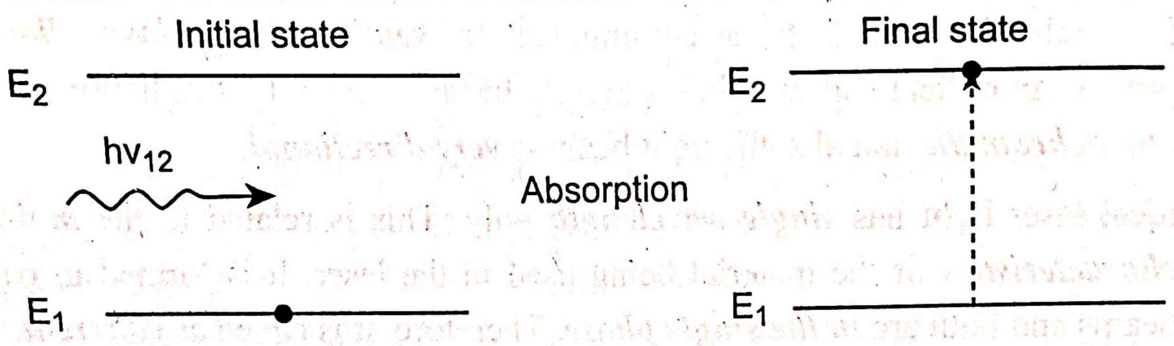

Fig 5.1 Absorption

- When an atom is at the higher energy state E_2, makes a transition to the lower energy state E_1 and thus, the emission of ***photon takes*** place. This emission process can occur in two ways:

  (i) Spontaneous emission, and

  (ii) Stimulated emission.

(2) Spontaneous Emission

Definition:

*Spontaneous emission occurs when an atom in higher energy state level (E_2) returns to the lower energy state in a **random manner**, by its own and releasing the difference in energy in the form of a photon such that $(E_2 - E_1) = hf_{12}$ = frequency of the emitted photon. It gives an **incoherent radiation.***

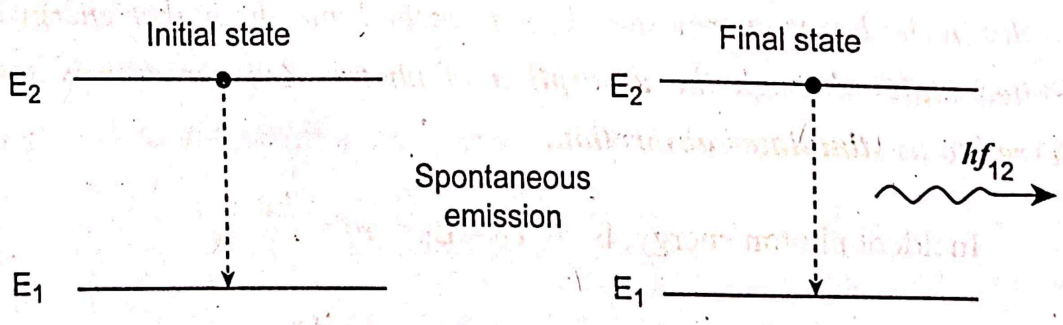

Fig 5.2 Spontaneous emission

(3) Stimulated Emission

Definition:

The stimulated emission is one which occurs when a photon having an equal energy difference between the two states ($E_2 - E_1$) interacts with an atom causing *it to the lower state with the creation of the second (emitted) photon. It gives the* ***coherent radiation.***

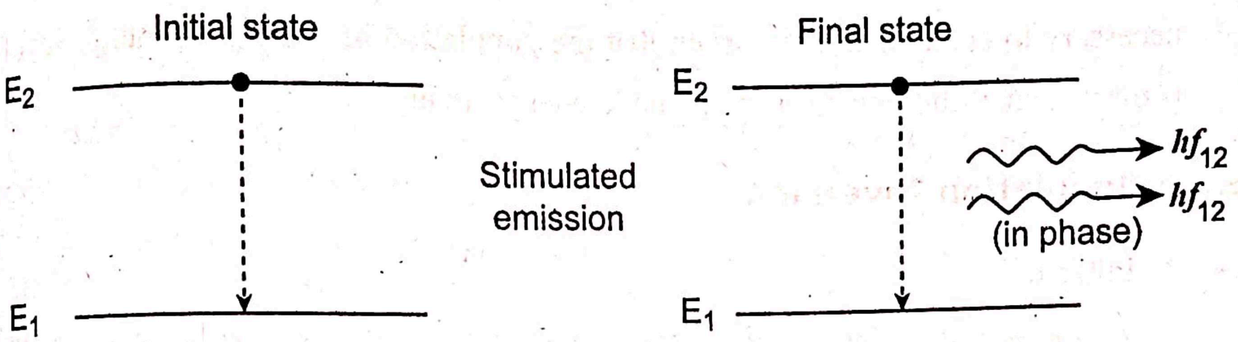

Fig 5.3 Stimulated emission

- *The light associated with an emitted photon is of* ***same frequency*** *of an incident photon and in the* ***same phase*** *with* ***same polarization.***
- ***Coherent*** means that, when an atom is stimulated to emit light energy by an incident wave, the liberated energy can be added to the wave in a constructive manner and provides amplification.
- The ***ratio*** of the ***stimulated emission rate to the spontaneous emission rate*** is given by,

$$\frac{Stimulated\ emission\ rate}{Spontaneous\ emission\ rate} = \frac{1}{exp\left(h\nu\ /kT\right)-1} \qquad \text{...... (1)}$$

- In general, the spontaneous emission rate is far more dominant than the stimulated emission when an atomic system is in the thermal equilibrium state.
- Spontaneous emission results in photons with random phase relationship and LED acts as an incoherent source.
- In order to make stimulated emission dominant, it is necessary to ensure the presence of an intense radiation field. This is generally achieved by making use of an optical cavity resonator to provide an optical feedback.
- The ***ratio*** of ***stimulated emission rate to the absorption rate*** under thermal equilibrium can be expressed as,

$$\frac{Stimulated\ emission\ rate}{Absorption\ rate} = exp\left[-\left(E_2 - E_1\right)/\ kT\right] \qquad \text{...... (2)}$$

- The rate of stimulated emission under thermal equilibrium is less than the absorption. In order to make stimulated emission dominates over absorption it is necessary to create a situation such that the population in the higher energy level is more than at the lower (ground) stable energy level.

5.2.3 Population Inversion

Definition:

At the thermal equilibrium, the density of excited electrons is very small. Most photons incident on the system will be ***absorbed,*** *so the stimulated emission is* ***essentially negligible.*** *Stimulated emission will exceed absorption only if the* ***population*** *of the* ***excited states*** (E_2) *is greater than that of the* ***ground state*** (E_1). *This condition is known as* ***population inversion.***

- At a non-equilibrium condition, the population inversion can be achieved by various ***"pumping"*** techniques.
- Pumping involves the use of ***intense radiation of short duration*** such as optical flash lamp or a radio frequency field so that the atoms can gain sufficient energy from the external source to be excited from the higher energy state.

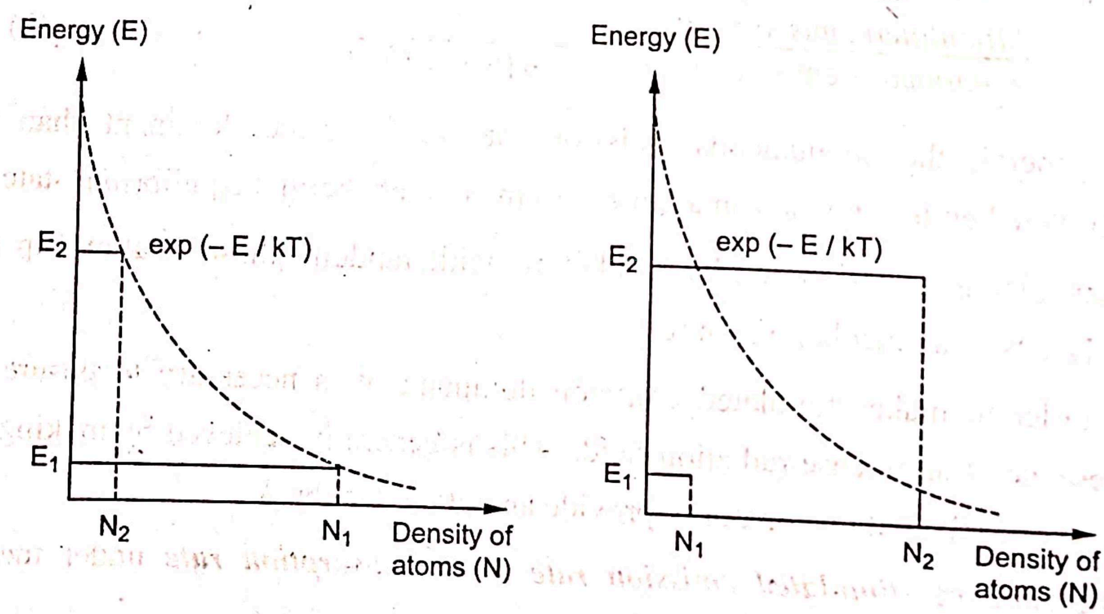

Fig 5.4 Populations in a two – energy – level system: (a) Boltzmann distribution for a system in thermal equilibrium; (b) a non-equilibrium distribution showing population inversion

- The population inversion may be obtained in systems with ***three or four energy levels.*** The energy-level diagrams for two such systems, which correspond to two non-semiconductor lasers, are illustrated in Fig 5.5.

- The attainment of population inversion both systems display a ***central metastable state*** in which the atoms spend an unusually long time. It is from this metastable level that the stimulated emission or lasing tasks place.

- In the Fig 5.5 (a), the three – level system consists of a ground level E_0, a metastable level E_1, and a third level above the metastable level is E_2.

- Initially, the atomic distribution will follow Boltzmann's law and with suitable pumping the electrons in some of the atoms may be excited from ground state into the higher level E_2.

- E_2 is a normal level where the electrons will rapidly decay by nonradiative processes to either E_1 or directly to E_0. Hence empty states will always be provided in E_2.

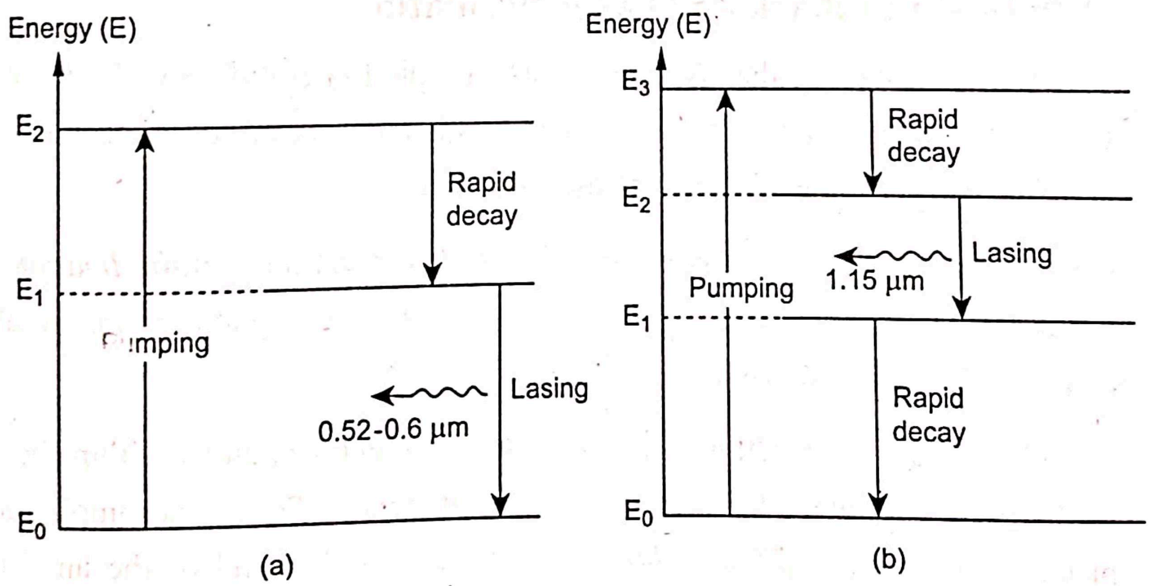

Fig 5.5 Energy – level diagrams showing population inversion and lasing for two non-semiconductor lasers: (a) three – level system – ruby (crystal) laser; (b) four – level system – He – Ne (gas) laser

- The metastable level E_1 exhibits a much longer lifetime than E_2 which allows a large number of atoms to accumulate at E_1. Over a period the density of atoms in the metastable state N_1 increases above those in the ground state N_0 and a population inversion is obtained between these two levels.

- Stimulated emission and hence lasing can then occur and is creating ***radiative electron*** transitions between levels E_1 and E_0.

☒ Drawback:

A drawback with the three – level system such as the ruby laser generally requires very high pump powers because the terminal state of the laser transition is the ground state. Hence more than half the ground state atoms must be pumped into the metastable state to achieve population inversion.

- A four – level system such as the He – Ne laser illustrated in figure 5.5 (b) is characterized by much lower pumping requirements.

5.2.4 Optical Feedback and Laser Oscillation

- Light amplification in the laser occurs when a photon colliding with an atom in the excited energy state that causes the stimulated emission of a second photon and then both of these photons release two more.

- Continuation of this process effectively creates ***avalanche multiplication***, and when an electromagnetic waves associated with these photons are in phase, amplified coherent emission is obtained.

- To achieve this laser action it is necessary to contain photons within the laser medium and maintain the conditions for coherence. This is accomplished by placing or forming mirrors ***(plane or curved)*** at either end of the amplifying medium, as illustrated in Fig 5.6.

- An optical cavity formed is more analogous to an oscillator than an amplifier as it provides ***positive feedback of the photons*** by reflection at the mirrors at either end of the cavity.

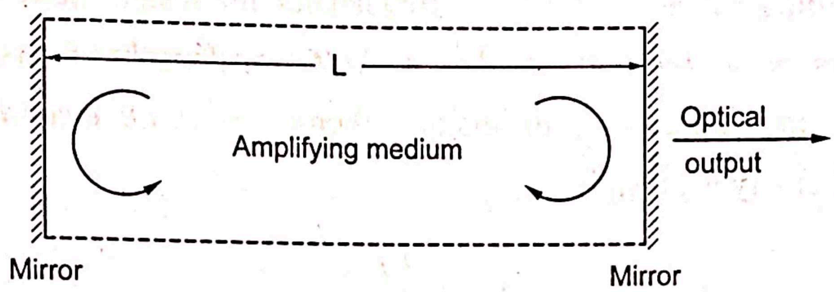

Fig 5.6 The basic laser structure incorporating plane mirrors

- Then an optical signal is fed back many times while receiving amplification as it passes through the medium. The structure therefore acts as a ***Fabry-Perot resonator***. After multiple passes of an optical signal the net gain can be large.
- If one mirror is made partially transmitting, useful radiation may escape from the cavity.
- A stable output is obtained at saturation when the optical gain is exactly matched by the losses. The major losses result from the following factors:
  (i) Absorption and scattering in the amplifying medium.
  (ii) Absorption.
  (iii) Scattering and diffraction at the mirrors.
  (iv) Nonuseful transmission through the mirrors.
- Oscillations occur in the laser cavity over a small range of frequencies where the cavity gain is sufficient to overcome the above losses.
- The amplification within the laser medium results in a broadened laser transition or gain curve over a finite spectral width as illustrated in Fig 5.7. The spectral emission from the device therefore lies within the frequency range dictated by the gain curve.
- The resonant cavity structure forms, when sufficient population inversion exists in the amplifying medium, then the radiation builds up and becomes established as standing waves between the mirrors.

- These standing waves exist only at frequencies for which the distance between the mirrors is an ***integral number of half wavelengths.*** Consider when the optical spacing between the mirrors is L, then the ***resonance condition*** along the axis of the cavity is given by

$$L = \frac{\lambda q}{2n} \quad \dots (3)$$

where, λ is the emission wavelength,

n is the refractive index of the amplifying medium, and

q is an integer.

- Alternatively, the discrete emission frequencies 'f' is defined as,

$$f = \frac{qc}{2nL} \quad \dots (4)$$

where, c is the velocity of light.

- The different frequencies of oscillation within the laser cavity are determined by the various integer values of q and each constitutes a resonance or mode.
- Equations (3) and (4) apply, when L is along the longitudinal axis of the structure (Fig 5.6) and the frequencies given by equation (3) are known as the ***longitudinal (or) axial modes.***
- From equation (4), the axial modes are separated by a frequency interval δf is expressed as,

$$\delta f = \frac{c}{2nL} \quad \dots (5)$$

- The ***mode separation*** in terms of the ***free space wavelength*** and assume

$\delta f << f$ and $f = \frac{c}{\lambda}$ and is given by

$$\delta\lambda = \frac{\lambda \delta f}{f} = \frac{\lambda^2}{c}\,\delta f \quad \dots (6)$$

By substituting equation (5) for δf in equation (6)

$$\delta\lambda = \frac{\lambda^2}{2nL} \qquad \text{... (7)}$$

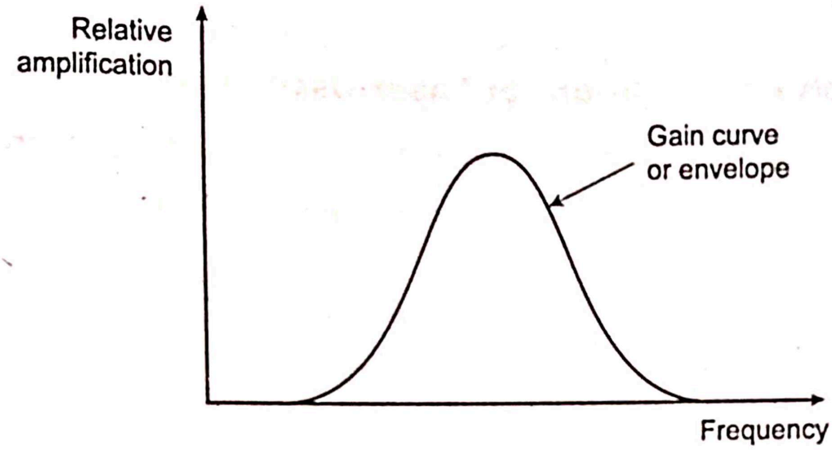

Fig 5.7 The relative amplification in the laser amplifying medium showing the broadened laser transition line or gain curve.

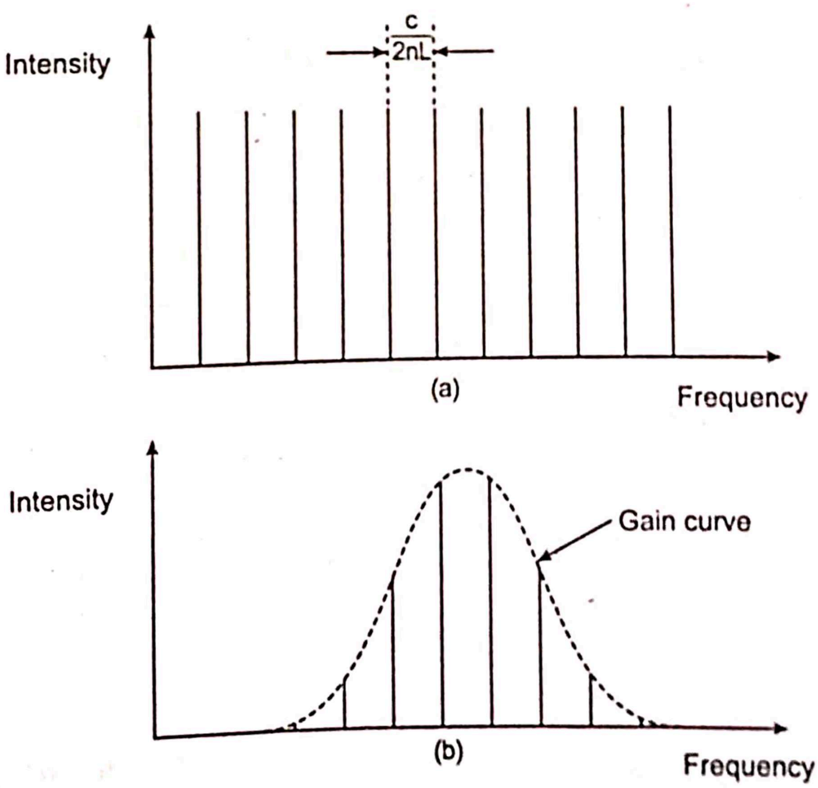

Fig 5.8 (a) The modes in the laser cavity.
(b) The longitudinal modes in the laser output

- The laser emission will only include the longitudinal modes contained within the spectral width of the gain curve which is illustrated in Fig 5.8 where several modes are shown to be present in the laser output. Such a device is said to be ***multimode.***

5.2.5 Threshold Condition for Laser Oscillation

- To determine the ***lasing conditions*** and the ***resonant frequencies,*** an electromagnetic wave propagating in the ***longitudinal direction*** is expressed as,

$$E(z,t) = I(z)\, e^{j(\omega t - \beta z)} \quad \ldots\ldots (8)$$

where $I(z)$ - *Optical field intensity,*

ω - *Angular frequency of the radiation field, and*

β - *Propagation constant.*

Lasing

Lasing is the condition at which ***light amplification*** *becomes possible in the laser diode. The condition for lasing is that a* ***population inversion*** *can be achieved.*

- The stimulated emission rate for a particular mode is proportional to the ***intensity of the radiation*** in that mode.
- The radiation intensity at a photon energy ***"hf" varies exponentially with the distance z,*** that is, it transverses along the lasing cavity according to the relationship as,

$$I(z) = I(0) \exp\{\Gamma g(hf) - \bar{\alpha}(hf) z\} \quad \ldots\ldots (9)$$

where $\bar{\alpha}$ - *Effective absorption coefficient of the material in the optical path,*

Γ - *Optical-field confinement factor or* ***fraction of optical power in the active layer,***

g - *Gain coefficient,*

hf - *Photon energy, and*

z - *Distance travels along the lasing cavity.*

- Optical amplification of selected modes is provided by the feedback mechanism of an optical cavity.
- In the repeated passes between the two partially reflecting parallel mirrors, a portion of the radiation associated with those modes that have the highest optical gain coefficient is retained and further amplified during each trip through the cavity.
- Lasing occurs when the gain of guided modes exceeds above an optical loss during one round trip through the cavity i.e. $z = 2L$.

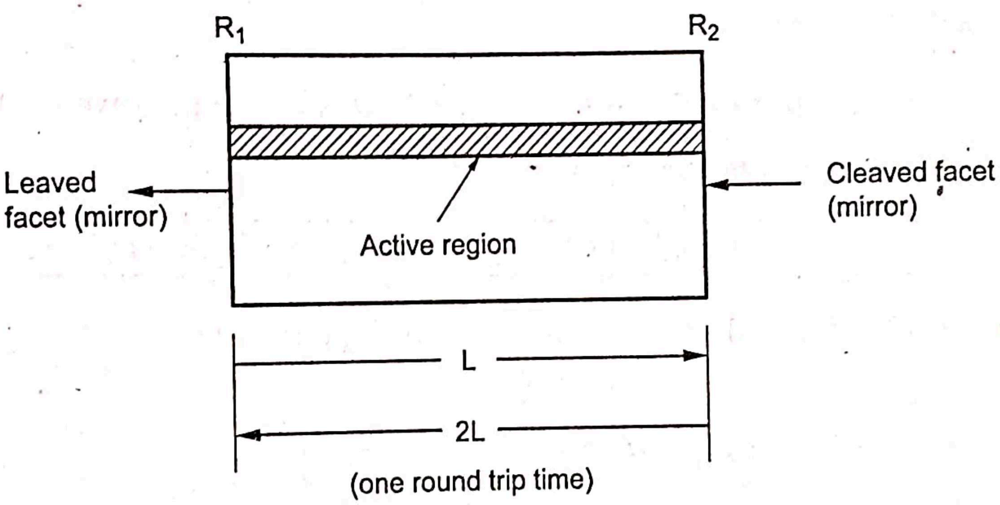

Fig 5.9 Round trip time in the optical cavity

- During this roundtrip, only the fractions R_1 and R_2 of an ***optical radiation*** are reflected from the two laser ends 1 and 2, respectively, where R_1 and R_2 are the ***mirror reflectivities*** or ***Fresnel reflection coefficients*** and it is commonly given by

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \quad \text{...... (10)}$$

- Now the expression (9) for this ***lasing condition*** is modified as

$$I(2L) = I(0)\, R_1 R_2 \exp\{2L(\Gamma g(hf) - \overline{\alpha}(hf))\} \quad \text{...... (11)}$$

Lasing Condition

- *At the lasing threshold, a steady – state oscillation takes place, and the* ***magnitude and phase of the returned wave must be equal to those*** *of an* ***original wave.***
- *The condition of lasing threshold is then given as,*

(i) *For amplitude* : $I(2L) = I(0)$ ...... (12a)

(ii) *For phase* : $e^{-j2\beta L} = 1$ ...... (12b)

- Equation (12b) gives an ***information concerning*** the resonant frequencies of the Fabry – Perot cavity.

♣ The condition to just reach the ***lasing threshold*** is the point at which the optical gain is equal to the total loss α_t in the cavity.

Lasing threshold = Optical gain = Total loss in the cavity (α_t)

♣ From equation (12a), the above conditions are expressed as,

$$\Gamma g_{th} = \alpha_t = \bar{\alpha} + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right) \quad \text{...... (13a)}$$

$$\Gamma g_{th} = \bar{\alpha} + \alpha_{end} \quad \text{...... (13b)}$$

where, α_{end} corresponds to the ***end loss of the cavity*** and it is determined by reflectivities of the mirrors. For 100 percent confinement, $\Gamma = 1$, and equations (13a) can be expressed as,

$$g_{th} = \bar{\alpha} + \frac{1}{2L}ln\left(\frac{1}{R_1 R_2}\right) \quad \text{...... (14)}$$

♣ For lasing to occur, one must ensure that the ***gain of the cavity*** must exceed the ***threshold gain***. i.e.,

$$g \geq g_{th} \quad \text{...... (15)}$$

5.2.6 Advantages and Disadvantages of LASER

Laser diode has several advantages and some disadvantages over LEDs are listed as,

Advantages

(i) Laser diode emits ***coherent light***, whereas LEDs emit ***incoherent light***. Therefore, laser have a more ***direct radian pattern***, which makes it easier to couple light emitted by the laser diode into an optical fiber cable. This ***reduces*** the ***coupling losses*** and allows smaller fibers to be used.

(ii) The ***radiant output power*** from laser is ***greater than*** that for an LED.

(iii) Lasers can be used at ***higher bit rates*** than LEDs.

(iv) Lasers generate monochromatic light, which ***reduces either chromatic or wavelength dispersion.***

(v) ***Good spatial coherence*** which allows an output to be focused by a lens into a spot which has a greater intensity than the dispersed unfocused emission. This permits efficient coupling of an optical output power into the fiber even for the fibers with low numerical aperture.

Disadvantages

*(i) Lasers are typically **10 times more expensive** than LEDs.*

*(ii) Lasers operate at higher powers, they typically have a **much shorter lifetime** than LEDs.*

*(iii) Lasers are **more temperature dependent** than LEDs.*

7.1.4 Comparisons of LED and LASER Diode

Sr.No	*Parameter*	*LASER*	*LED*
1.	*Output Beam*	Coherent	In-coherent
2.	*Coupling Efficiency*	High	Very low
3.	*Principle of operation*	Stimulated Emission	Spontaneous Emission
4.	*Output Power*	High	Low
5.	*Data Rate*	High	Low
6	*Cost*	Expensive	Less

Sr.No	*Parameter*	*LASER*	*LED*
7.	*Life Time*	10^4 hours	10^5 hours
8.	*Circuit Complexity*	Complex	Simple
9.	*Temperature Dependent*	More temperature Dependent	Less temperature Dependent
10.	*Applications*	Long distance with higher data rate.	Moderate distance with lower data rate.

5.3 OPTICAL EMISSION FROM SEMICONDUCTORS

5.3.1 The p-n Junction

♣ *A perfect semiconductor crystal containing **no impurities** or **lattice defects** is called as **intrinsic**.* An energy band structure of an intrinsic semiconductor is illustrated in Fig 5.10 (a) which shows the valence and conduction bands separated by a forbidden energy gap (or) bandgap E_g and its width varies for different semiconductor materials.

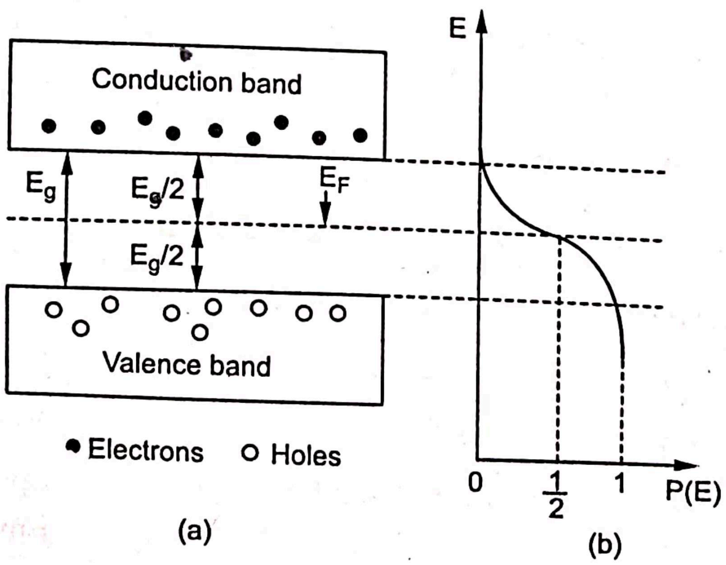

Fig 5.10 (a) The energy band structure of an intrinsic semiconductor at a temperature above absolute zero. (b) The Fermi – Dirac probability distribution corresponding to (a).

- Fig 5.10 (a) shows the energy band structure of an intrinsic semiconductor at a temperature above absolute zero showing an equal number of electrons and holes in the conduction band and the valence band respectively.
- The thermal excitation raises some electrons from the valence band into the conduction band and leaving empty hole states in the valence band.
- The thermally excited electrons in the conduction band and the holes left in the valence band allow conduction through the material. These ***electrons*** and ***holes*** are called ***carriers***.
- The probability ***P(E)*** that an electron gains sufficient thermal energy at an absolute temperature '*T*' which is occupying a particular energy level ***E*** and is given by Fermi-Dirac distribution as:

$$P(E) = \frac{1}{1 + exp\,(E - E_F)/KT} \quad \dots (1)$$

where,

K is Boltzmann's constant, and

E_F is the Fermi energy (or) Fermi level.

Fermi Level:

Fermi level is only a mathematical parameter which gives an indication of the distribution of carriers within the material.

- Fig 5.10 (b) shows the Fermi level is at the center of the bandgap that indicates there is small probability of electrons occupying energy levels at the bottom of the conduction band and a corresponding number of holes occupying energy levels at the top of the valence band.
- To create an extrinsic semiconductor the material is doped with impurity atoms which create either more *free electrons **(donor impurity)*** or *holes **(acceptor impurity)***. These two situations are shown in Figure 5.11 where the ***donor***

impurities form energy levels just ***below the conduction band*** while ***acceptor impurities*** form energy levels just ***above the valence band.***

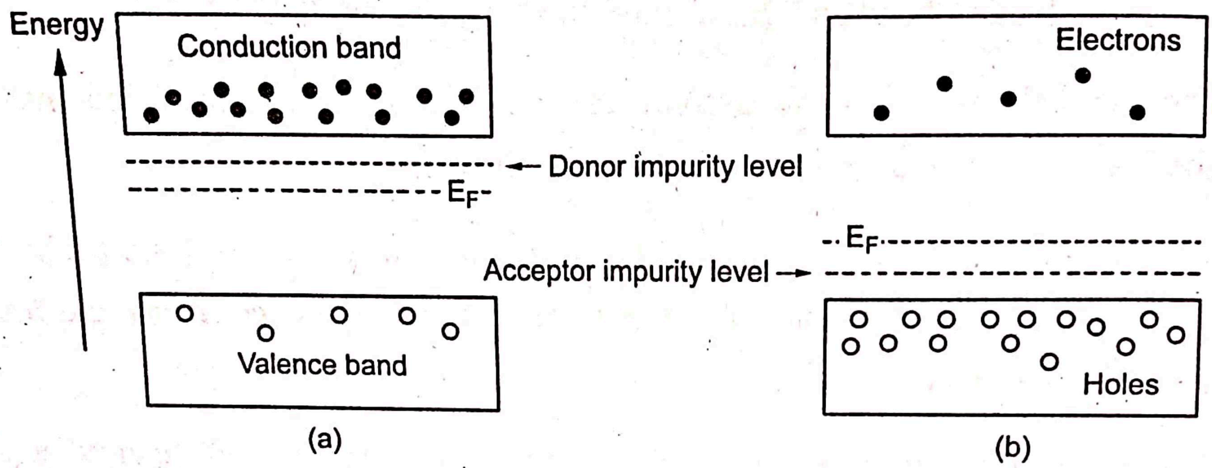

Fig 5.11 Energy band diagrams: (a) n – type semiconductor (b) p – type semiconductor

- When the donor impurities are added, then thermally excited electrons from the donor levels are raised into the conduction band to create an excess of ***negative charge carriers.*** This type of semiconductor is called as ***n-type*** and the majority carriers are ***electrons.***

- The Fermi level corresponding to this carrier distribution is raised to a position above the center of the bandgap, as illustrated in Fig 5.11(a).

- When the acceptor impurities are added, as shown in Fig 5.11(b), then thermally excited electrons are raised from the valence band to the acceptor impurity levels leaving an excess of positive charge carriers in the valence band and creating a ***p-type semiconductor*** where the majority carriers are ***holes.*** The Fermi level is lowered below the center of the bandgap.

- *The* ***p – n junction diode*** *is formed by creating adjoining p – and n – type semiconductor layers in a single crystal*, as shown in figure 5.12 (a). A ***thin depletion region (or) layer*** is formed at the junction through ***carrier recombination*** which effectively leaves it free of mobile charge carriers *(both electrons and holes).*

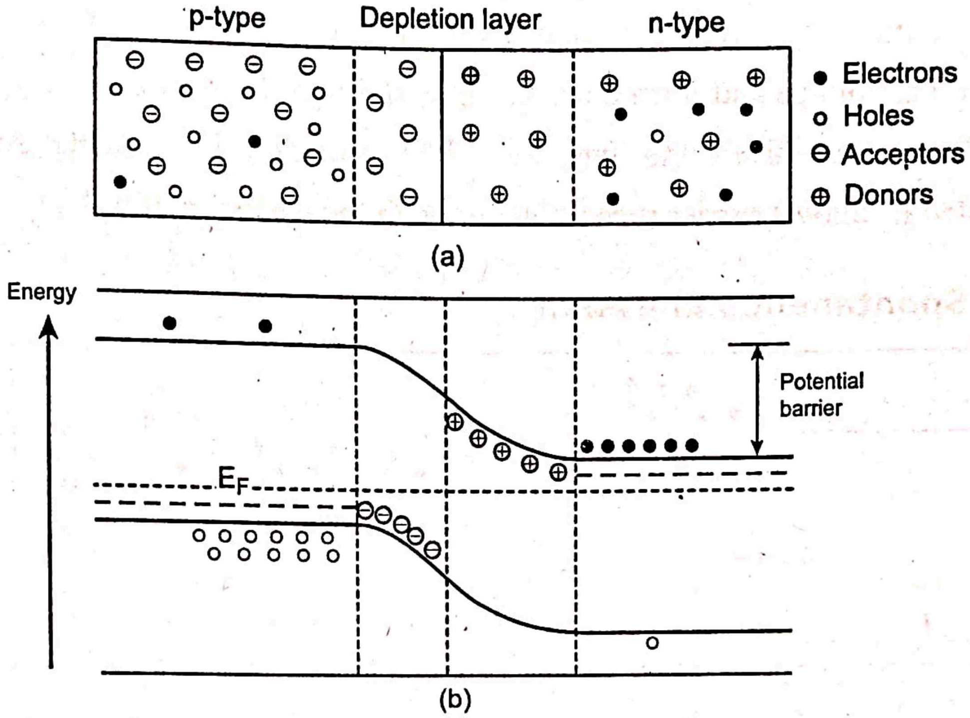

Fig 5.12 (a) The impurities and charge carriers at a p – n junction.
(b) The energy band diagram corresponding to (a)

- This establishes a potential barrier between the p – and n – type regions which restricts the inter diffusion of majority carriers from their respective regions, as illustrated in figure 5.12 (b).
- In the absence of an externally applied voltage, no current flows as the potential barrier that prevents the net flow of carriers from one region to another. When the junction is in this equilibrium state the Fermi level for the p – and n – type semiconductor is the same as shown in figure 5.12 (b).
- The ***width of the depletion region*** and the ***magnitude of the potential barrier*** are dependent upon the ***carrier concentrations (doping)*** in the p – and n – type regions and any external applied voltage.
- When an ***external positive voltage*** is applied to the p – type region with respect to the n – type, both the depletion region width and the resulting potential barrier are reduced and then the diode is said to be ***forward biased.*** Electrons from the n – type region and holes from the p – type region can flow more readily across the junction into the opposite type region.

- These minority carriers are effectively injected across the junction by apply the external voltage and form a current flow through the device as they continuously diffuse away from the interface. This situation in suitable semiconductor materials allows carrier recombination with the emission of light.

5.3.2 Spontaneous Emission

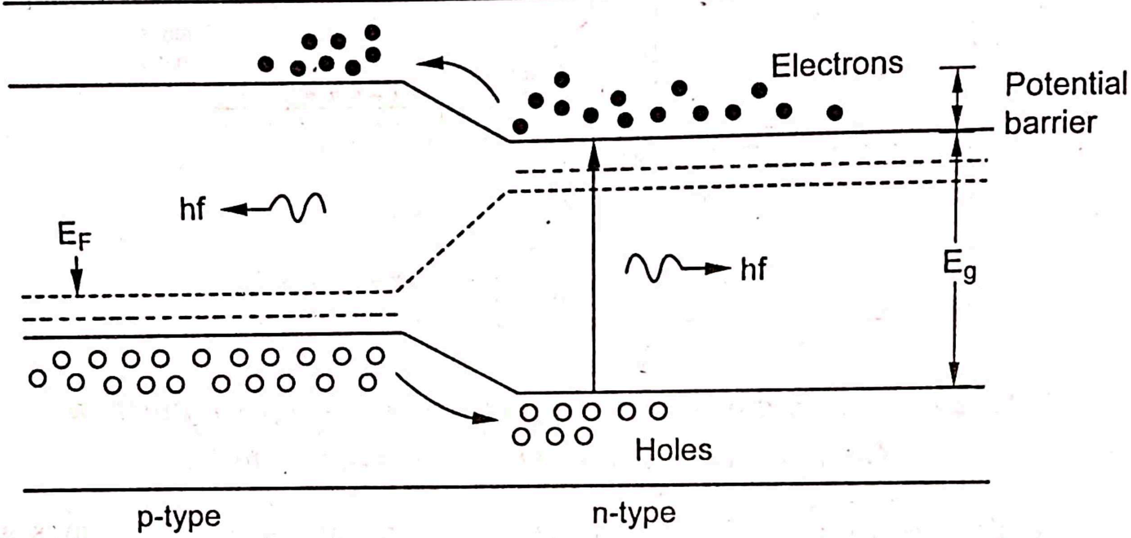

Fig 5.13 The p – n junction with forward bias giving spontaneous emission of photons

- The increased concentration of minority carriers in the opposite type region in the forward – biased $p - n$ diode leads to the recombination of carriers across the bandgap.
- This process is shown in figure 5.13 for a direct band gap semiconductor material where the normally empty electron states in the conduction band of the p – type material and the normally empty hole states in the valence band of the n – type material are populated by injected carriers which recombine across the bandgap.
- The energy released by this ***electron-hole recombination*** is approximately equal to the bandgap energy E_g. Excess carrier population is therefore decreased by recombination which may be ***radiative*** or ***nonradiative.***
- In ***non-radiative recombination***, the energy released is dissipated in the form of ***lattice vibrations*** and thus heat. In band-to-band radiative recombination, the

energy is released with the creation of photon and the energy is approximately equal to the bandgap energy E_g in eV. as:

$$E_g = hf = \frac{hc}{\lambda} \quad \text{... (2)}$$

where,

c is the velocity of light in a vacuum, and

λ is the optical wavelength in μm.

By substituting the appropriate values for h and c in Equation (2) becomes,

$$\lambda = \frac{1.24}{E_g} \quad \text{... (3)}$$

- *This spontaneous emission of light from within the diode structure is known as* ***electroluminescence.*** The light is emitted at the site of carrier recombination which is primarily close to the junction and the recombination may take place through the hole diode structure as carriers diffuse away from the junction region as shown in Fig 5.14.
- The amount of radiative, recombination and the emission area within the structure is dependent upon the semiconductor materials used and the fabrication of the device.

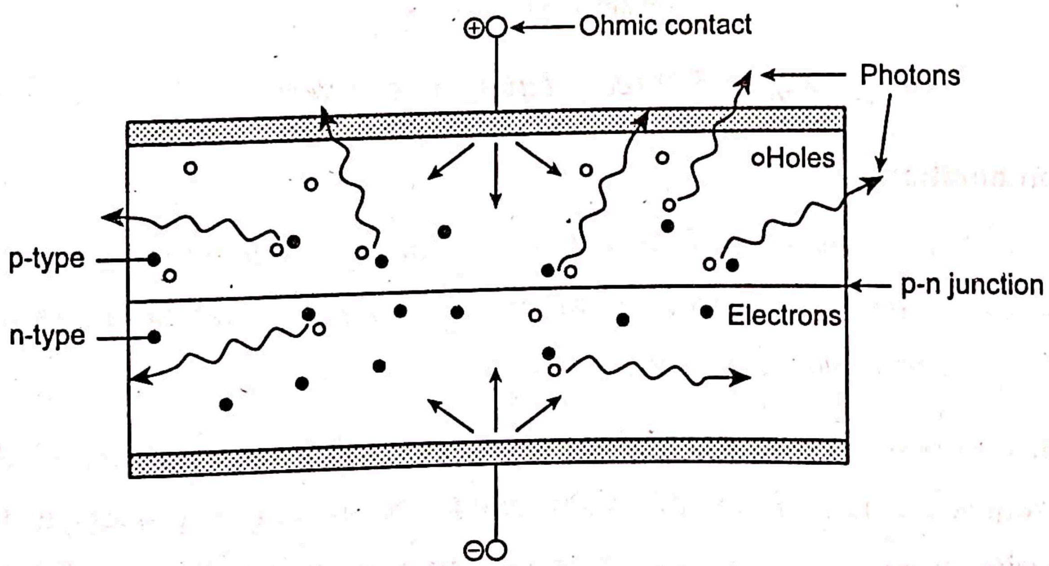

Fig 5.14 An illustration of carrier recombination giving spontaneous emission of light in a p – n junction diode

5.3.3 Carrier Recombination

5.3.3.1 Direct and Indirect Bandgap Semiconductors

(1) Direct Band Gap Material

Definition:

In direct band- gap material, an electron from the conduction band can recombine with a hole in the valence band directly by emitting a light photon of energy 'hf'. Here, an electron and hole have the same momentum value. The ***direct recombination*** *is possible.*

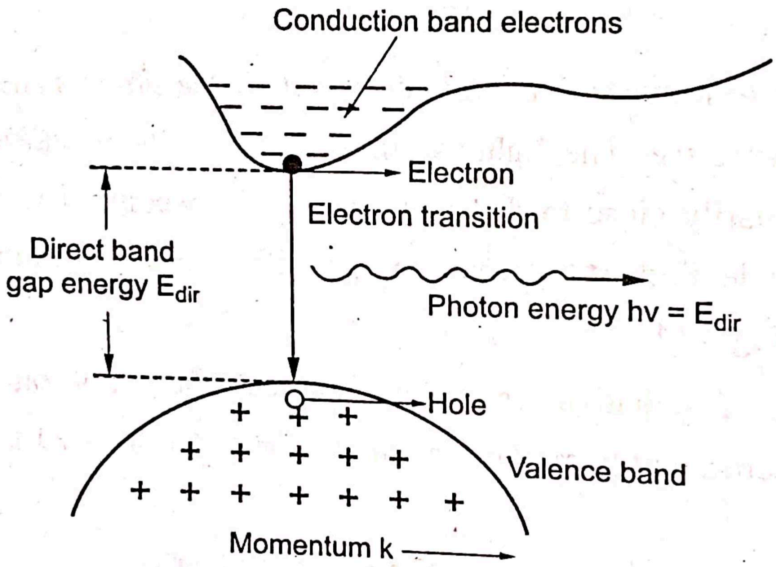

Fig 5.15 Direct – band – gap material

Recombination

The process in which an electron from the conduction band jumps to occupy a vacant electron position (hole) in the valence band is called the ***recombination*** *and one electron-hole pair is generated.*

- In this process, we lost one electron from the conduction band and a hole from the valence band. From this view point, recombination process is just the opposite of generation process. If the recombination is not successful it would result into a ***scattering process.***

- The life time *(i.e. Recombination time)* of charge carriers is very less. They are used to ***fabricate the LEDs*** and ***laser diodes.***

- Direct bandgap semiconductor devices in general have much ***higher internal quantum efficiency.***

(2) Indirect Band Gap Material

Definition:

- *For indirect band gap materials, the conduction band **minimum** and the valence band **maximum** energy levels occurs at the **different values of momentum.***

- *To perform band to band recombination, it must involve a third particle **phonons** (i.e., crystal lattice vibrations) to conserve momentum, since the photon momentum is very small.*

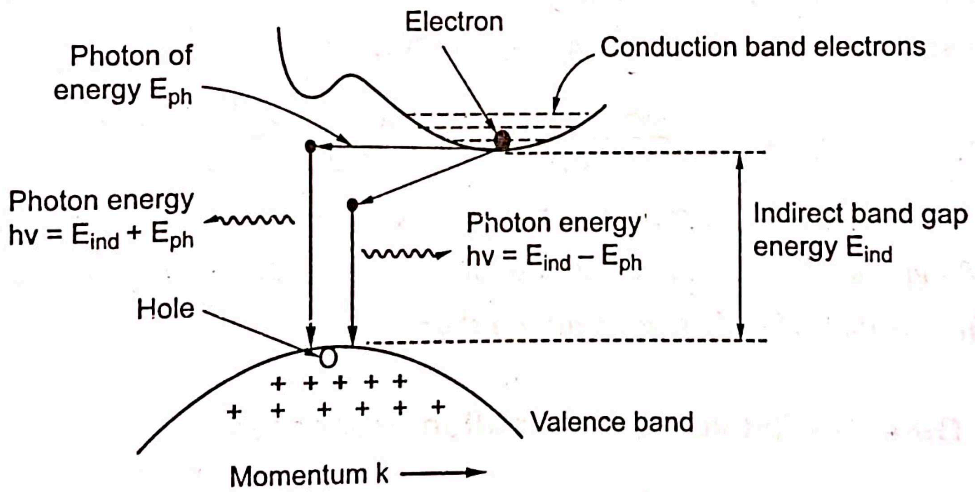

Fig 5.16 Indirect band – gap material

- Here, the life time of charge carriers is more. Due to its ***longer recombination life time*** of charge carriers (≈ 10 ms to 0.1 ms), these are used to ***fabricate the rectifier diodes*** and ***transistors*** which are used to make amplifiers, switches and integrated circuits.

- Both Si and Ge fall in the category of indirect bandgap semiconductor along with some III-V materials. ***Indirect recombination process*** is generally ***slow*** as compared to ***direct recombination***. As the recombination in an indirect bandgap semiconductor is dominated by a ***non-radiative transitions***.

- In general, both direct and indirect recombination is possible in any semiconductor. In a direct semiconductor, ***radiative recombination*** is generally dominant over non-radiative recombination.
- The ***recombination coefficient*** (B_t) is obtained from the measured absorption coefficient of the semiconductor and the ***radiative minority carrier lifetime*** τ_t is expressed as,

$$\tau_t = [B_t(N+P)]^{-1} \qquad \text{.........(1)}$$

where *N and P are the respective **majority carrier concentrations** in the n – and p – type regions.*

Internal Quantum Efficiency:

- Generally, the direct bandgap semiconductor devices have a much higher internal quantum efficiency and it is defined as,

$$\eta_i = \frac{\text{Number of photons created in the laser cavity}}{\text{Number of injected carriers}}$$

- The value of an internal quantum efficiency is very high ranging from ***50 to 70 percent.*** Here, number of photons created in the laser cavity is nothing but ***the number of radiative recombination***.

5.3.3.2 Other Radiative Recombination Processes

- Major radiative recombination processes at 300 K are shown in Figure 5.17.
  - *(i) Band-to-band transition: conduction band to valence band.*
  - *(ii) Conduction band to acceptor impurity transition.*
  - *(iii) Donor impurity to valence band transition.*
  - *(iv) Donor impurity to acceptor impurity transition.*
  - *(v) Recombination from an isoelectronic impurity to the valence band.*

- An ***indirect band gap semiconductor*** may be made into a more useful electroluminescent material by the addition of impurity centers which will effectively convert it into a ***direct band gap material.***

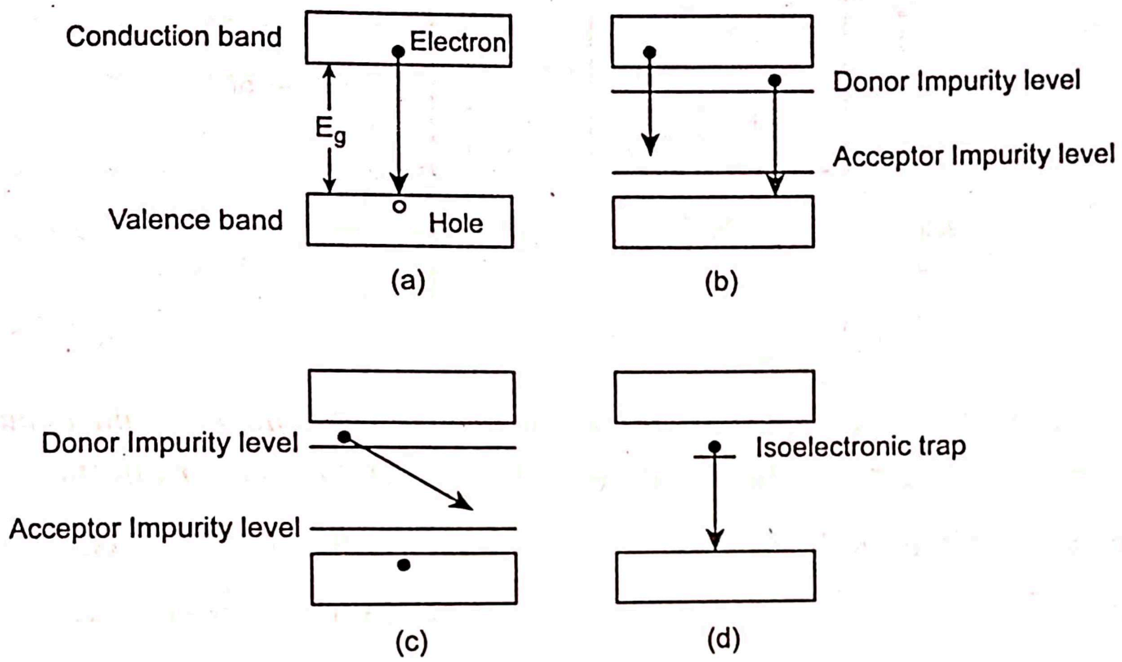

Fig 5.17 Major radiative recombination processes at 300 K (a) Band – to – band transition (b) Band to acceptor impurity, and donor impurity to band transition (c) Donor to acceptor transition (d) Recombination from an isoelectronic impurities

5.3.4 Stimulated Emission and Lasing

- Carrier population inversion is achieved in an intrinsic *(undoped)* semiconductor by the injection of electrons into the conduction band of the material which is illustrated in Figure 5.18 where the electron energy and the corresponding filled states are shown.

- Figure 5.18 (a) shows the situation at absolute zero when the conduction band contains ***no electrons.*** Electrons injected into the material fill the lower energy states in the conduction band upto the injection energy or the quasi – Fermi level for electrons.

- A charge neutrality is conserved within the material and an equal density of holes created in the top of the valence band by the absence of electrons, as shown in Fig 5.18 (b).

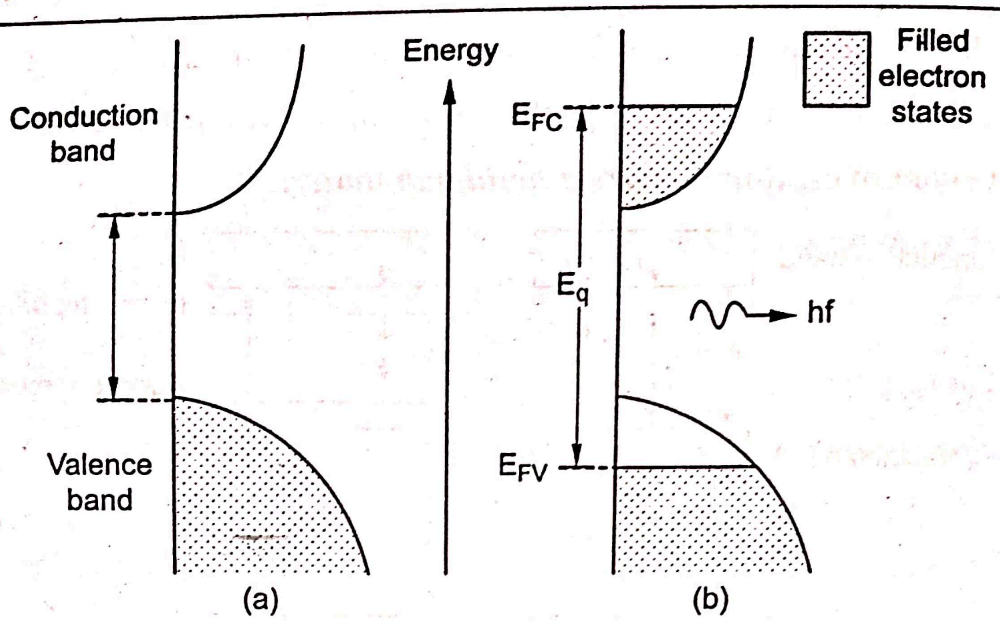

Fig 5.18 The filled electron states for an intrinsic direct band gap semiconductor at absolute zero. (a) In equilibrium; (b) With higher carrier injection

- Incident photons with energy E_g which is less than the separation energy of the quasi – Fermi levels $E_q = E_{Fc} - E_{Fv}$ cannot be absorbed because the necessary conduction band states are occupied.
- These photons can include a downward transition of an electron from the filled conduction band sates into the empty valence band states and thus stimulating the emission of another photon.
- The basic condition for stimulated emission is dependent on the quasi – Fermi level separation energy as well as the band gap energy and is defined as:

$$E_{Fc} - E_{Fv} > hf > E_g$$

- Population inversion may be obtained at a $p - n$ junction by heavy doping ***(degenerative doping)*** of both the p – and n – type material. Heavy p – type doping with acceptor impurities causes ***lowering*** of the Fermi level (or) boundary between the filled and empty states into the valence band.
- Similarly, degenerative n – type doping causes the Fermi level to enter the conduction band of the material. Energy band diagrams of a degenerate $p - n$ junction are shown in Figure 5.19.

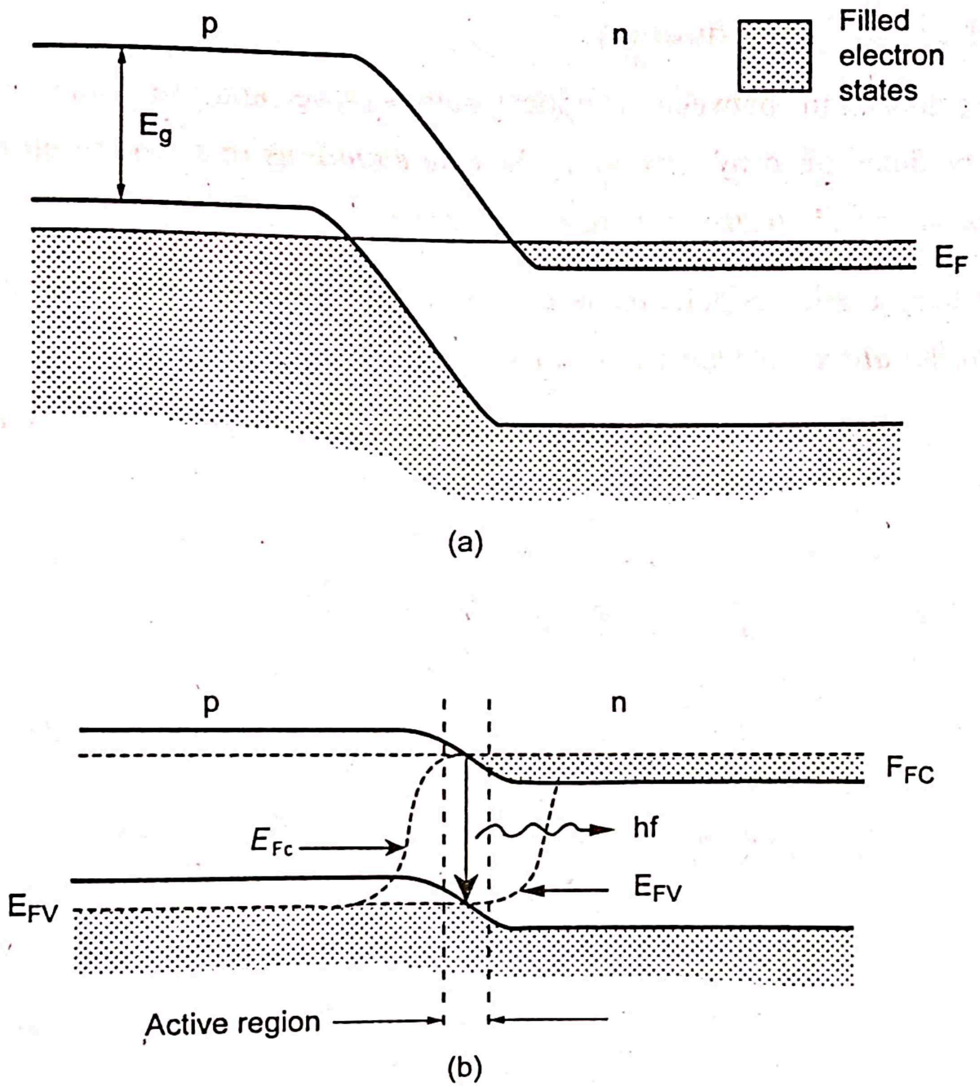

Fig 5.19 The degenerate p-n junction (a) With no bias applied (b) With strong forward bias.

- The position of the Fermi level and the electron occupation ***(shading)*** with no applied bias are shown in Figure 5.19 (a). The junction is in thermal equilibrium, the Fermi energy has the same value throughout the material.

- Figure 5.19 (b) shows the $p-n$ junction when a forward bias nearly equal to the bandgap voltage is applied and hence there is direct conduction. At high injection carrier density in such a junction there exists an active region near the depletion layer that contains simultaneously degenerate populations of electrons and holes ***(doubly degenerate).***

(1) Laser Diode Rate Equations:

- The relationship between an optical output power and the diode drive current can be determined by examining the ***rate equations*** that ***govern an interaction of photons*** and ***electrons in an active region.***
- The total carrier population is determined by ***carrier injection, spontaneous recombination*** and ***stimulated emission.***
- For a *pn* junction with a ***carrier – confinement region of depth d,*** the rate equations are given as,

  (i) In terms of number of photons (ϕ) as,

$$\frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}} \; m^{-3} s^{-1} \quad \text{...... (1)}$$

= *Stimulated emission + Spontaneous emission + Photons loss*

  (ii) In terms of number of electrons (n) as,

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\phi \; m^{-3} s^{-1} \quad \text{...... (2)}$$

= *Injection + Spontaneous recombination + Stimulated emission*

where

C - *Coefficient describing the strength of the optical absorption and emission interactions,*

R_{sp} - *Rate of spontaneous emission into the lasing mode,*

τ_{ph} - *Photon lifetime,*

τ_s - *Spontaneous recombination lifetime, and*

J - *Injection – current density.*

- Solving the equation (1) and (2) for a ***steady – state condition*** that is, $\frac{d\phi}{dt} = 0$ and $\frac{dn}{dt} = 0$, when n and ϕ have non zero values and it gives an expression for the output power.

- In equation (1), assume R_{sp} is negligible and $\frac{d\phi}{dt}$ must be positive when ϕ is small, then we have,

$$\frac{d\phi}{dt} = Cn\phi + R_{sp} - \frac{\phi}{\tau_{ph}}$$

$$0 = Cn\phi - \frac{\phi}{\tau_{ph}}$$

$$Cn - \frac{1}{\tau_{ph}} \geq 0 \quad \text{...... (3)}$$

- From equation (3) it is clear that '*n*' must ***exceed*** a ***threshold value n_{th}*** in order for ***ϕ to increase*** and this threshold value ***for an electron*** density n_{th} from equation (3) is obtained by substituting $n = n_{th}$ in the steady state and it can be expressed as,

$$\boxed{n_{th} = \frac{1}{C\,\tau_{ph}} \ (m^{-3})} \quad \text{...... (4)}$$

- From equation (2), the above threshold value (n_{th}) can be expressed in terms of the ***threshold current J_{th}***, when the number of photons $\phi = 0$ as,

$$\frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} = 0$$

$$\frac{n_{th}}{\tau_{sp}} = \frac{J_{th}}{qd}\, m^{-3}\, s^{-1} \quad \text{...... (5)}$$

- The threshold current defined by an equation (5) accounts for the bias current density required sustaining the decay of carriers through spontaneous emission in the absence of photon flex density.

- Next, consider the photon and electron rate equations in the ***steady – state condition*** at the lasing threshold and it is given as,

$$Cn_{th}\,\phi_s + R_{sp} - \frac{\phi_s}{\tau_{ph}} = 0 \qquad \text{...... (6)}$$

$$\frac{J}{q\,d} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\,\phi_s = 0 \qquad \text{...... (7)}$$

where ϕ_s is the ***steady – state photon flux density.***

Steady State Photon Density (ϕ_s)

Adding equation (6) and (7), we will obtain

$$Cn_{th}\,\phi_s + R_{sp} - \frac{\phi_s}{\tau_{ph}} + \frac{J}{q\,d} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\,\phi_s = 0 \qquad \text{...... (8)}$$

$$\frac{\phi_s}{\tau_{ph}} = R_{sp} + \frac{J}{q\,d} - \frac{J_{th}}{q\,d}$$

$$\boxed{\phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph}\,R_{sp}} \qquad \text{...... (9)}$$

$$\phi_s = \begin{Bmatrix}\text{Number of photons} \\ \text{resulting from} \\ \text{stimulated emission}\end{Bmatrix} + \begin{Bmatrix}\text{Spontaneously} \\ \text{generated} \\ \text{photons}\end{Bmatrix}$$

- Since ϕ_s cannot be ***negative,*** therefore, in the steady state the current must exceed the threshold value, that is,

$$J > J_{th} \qquad \text{...... (10)}$$

- The variation of an optical power output of an injection laser diode with the applied drive current is shown in Fig 5.20.

- From Fig 5.20, it is clear that ***below*** the threshold current (I_{th}) where only ***spontaneous emission occurs,*** and there is a small increase in ***optical output power*** with ***drive current.***

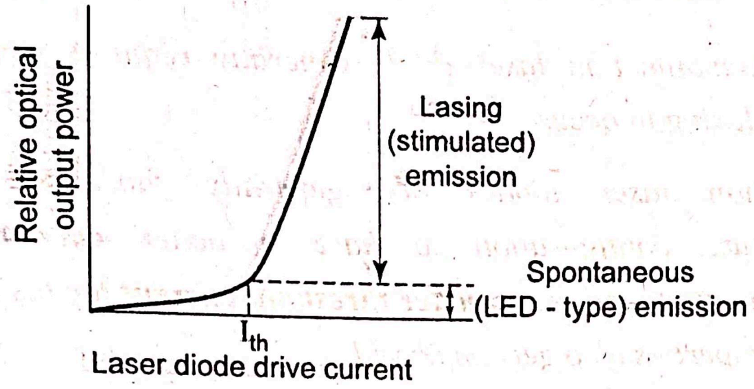

Fig 5.20 Relationship between optical output power and laser diode drive current

- At this threshold when lasing conditions are satisfied, the optical power ***increases sharply*** after the lasing threshold because of ***stimulated emission.*** At high power outputs, the slope of the curve ***decreases*** because of ***junction heating.***

- The lasing threshold optical gain (g_{th}) is related to the ***threshold current density*** (J_{th}) for stimulated emission and this expression is given as,

$$g_{th} = \beta J_{th} \quad \text{...... (11)}$$

where, β is a ***constant*** that depends on the ***specific device construction.***

- The ***threshold current density*** (J_{th}) is given by,

$$J_{th} = \frac{1}{\beta}\left[\bar{\alpha} + \frac{1}{2L} \ln \frac{1}{R_1 R_2}\right] \quad \text{...... (12)}$$

5.4 HETEROJUNCTIONS

Homojunction:

A single p-n junction fabricated from a single-crystal semiconductor material. This is known as a homojunction.

☒ Drawback of Homojunction Laser:

- *A simple homojunction laser diode generally requires a* ***high threshold current*** *for lasing to occur.*
- *The injection laser diodes are generally fabricated with double heterostructure configuration to have a* ***better carrier and optical confinements*** *that lead to a* ***smaller threshold current*** *for lasing and thus the radiation properties also gets improved.*

Definition: Heterojunction Structure

- *Heterojunctions is an interface between two adjoining single crystal semiconductors with different bandgap energies. Devices which are fabricated with heterojunctions are said to have* ***heterostructure****.*
- *Heterojunction are also known as Double Hetero (DH) structure device because of two different alloy layers on each side of an active region.*

♣ The layer structure and an energy band diagram for a DH injection laser are illustrated in Figure 5.21. A heterojunction is shown either side of the active layer for laser oscillation.

♣ The forward bias is supplied by connecting a ***positive electrode*** of a supply to the ***p-side*** of the structure and a *negative electrode* to the ***n-side***. When a voltage which corresponds to the band gap energy of the active layer is applied then a large number of electrons (or holes) are injected into the active layer and laser oscillation commences.

♣ These carriers are confined to the active layer by the energy barriers provided by the hetero junctions which are placed within the diffusion length of the injected carriers.

♣ A refractive index step *(usually a difference of 5 to 10%)* at the heterojunctions provides radiation containment to the active layer. In effect the active layer forms the center of a dielectric waveguide which strongly confines the electroluminescence within this region, as illustrated in Figure 5.20 (c).

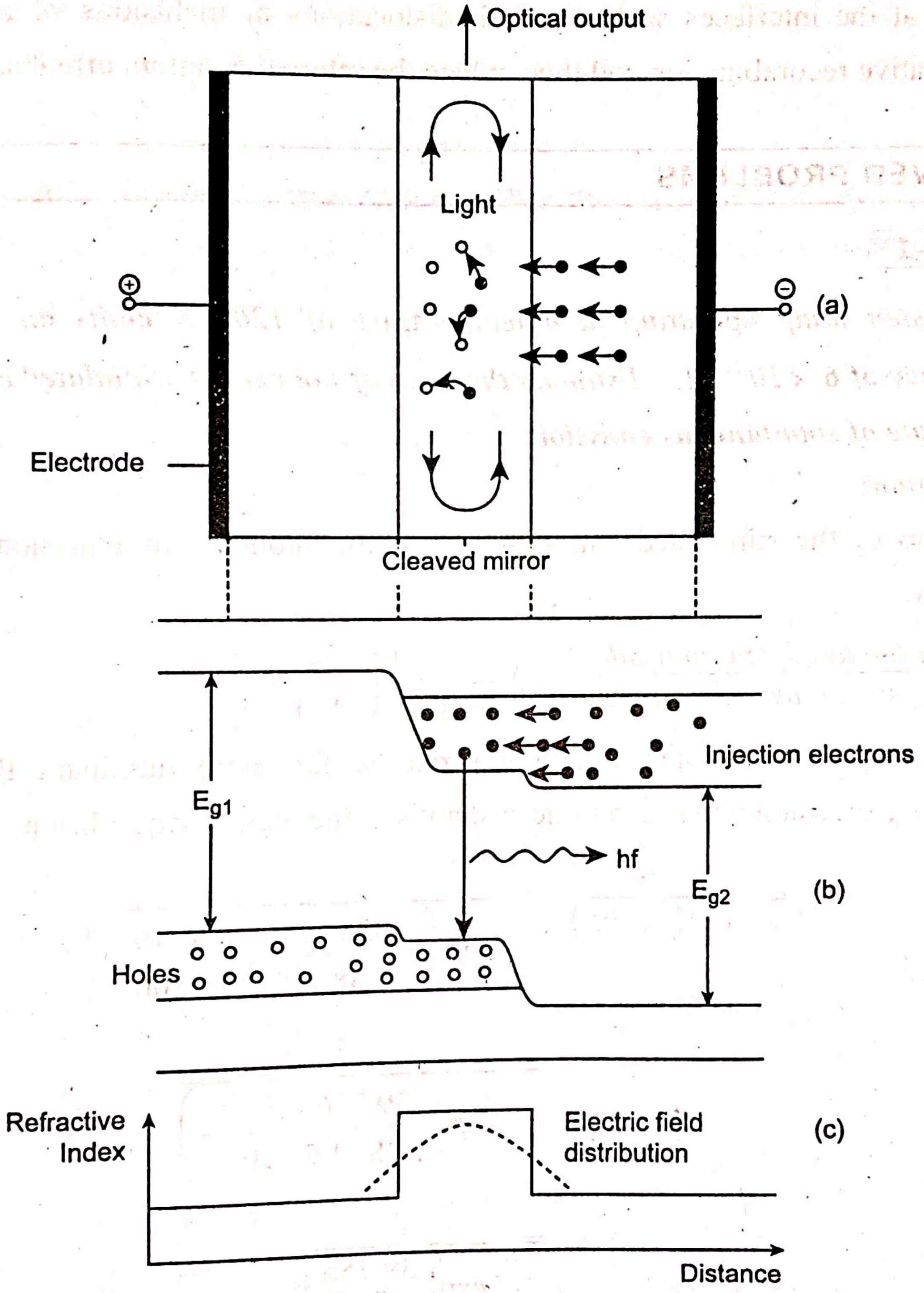

***Fig 5.21** The DH junction laser (a) The layer structure, shown with an applied forward bias (b) Energy band diagram indicating a p – p heterojunction on the left and a p – n heterojunction on the right (c) The corresponding refractive index diagram and electric field distribution.*

LIGHT EMITTING DIODES (LEDs)

6.1 INTRODUCTION

- LEDs are used in optical communication systems that requirement of power is not more than a ***few tens of microwatt*** and the desired ***bit rate*** is in the range of approximately *100 – 200 Mb/s*.
- It is mostly coupled with the multimode optical fiber and the structure of an LED largely depends on the desired application.
- The radiation from an LED is ***incoherent*** and it is emitted over a ***wide range*** of angles. It covers a ***broad spectrum*** of wavelengths and the emitted power is proportional to the diode current.
- *LEDs require **less complex drive circuitry** than the laser diodes since **no thermal or optical stabilization circuits are needed.***

Emission of Light from LED

*Normally, an empty conduction band of the semiconductor is populated by electrons injected into it by the **forward current** through the junction and light is generated when these electrons recombine with holes in the valence band to emit a photon. This is the **mechanism** by which light is emitted from an LED.*

☑ Advantages of LED

LED has a number of distinct advantages which have given it a prominent place in optical fiber communications.

(i) Simpler fabrication.

(ii) ***Low Cost:*** *The simpler construction of the LED leads to much reduced cost.*

(iii) Reliability.

(iv) Generally less temperature dependence.

(v) ***Simpler Drive Circuitry:*** This is due to the normally lower drive currents and reduced temperature dependence which makes temperature compensation circuits unnecessary.

(vi) ***Linearity:*** Ideally, the LED has a linear light output against current characteristic.

Drawbacks:

The drawbacks of LED when compared to Lasers are,

(i) Generally lower optical power coupled into a fiber (microwatts),

(ii) Usually supports lower modulation bandwidth, and

(iii) Harmonic distortion.

6.1.1 Principle of Operation

- LED can be used in fiber transmission applications. LED's must have,

  (i) High radiance output (or) brightness,

  (ii) Fast emission response time, and

  (iii) High quantum efficiency.

(1) Radiance (Brightness)

Definition:

*It is a measure of **optical power radiated into a unit solid angle per unit area** of an emitting surface. The unit for radiance or power is **Watts**.*

- High radiances are required to ***couple sufficiently*** high optical power levels into a fiber.

(2) Emission Response Time

Definition:

It is a time delay between an application of a current pulse and a respective optical emission.

- This time delay is the factor ***limiting the bandwidth*** with which the source ***(light)*** can be modulated ***(intensity modulation)*** directly by varying the ***injected current.***

(3) Quantum Efficiency

It is related to the fraction of an electron-hole pairs that recombine radiatively.

6.2 LED POWER AND EFFICIENCY

6.2.1 Introduction

- An excess of electrons and holes in *p*- and *n*-type material, respectively ***(referred to as minority carriers)*** are created in a ***semiconductor light source*** by the injection of carrier at the device contacts. The excess carriers can recombine either ***radiatively*** or ***non- radiatively.***

- When there is a ***constant current*** flow into an LED, an ***equilibrium condition*** is established. That is, an excess density of electrons *n* and holes *p* are equal, then the recombination of injected carriers is in accordance with the requirement of ***charge neutrality*** 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 - *Current density in A/cm^2,*

  q - *Electron charge,* and

  d - *Thickness of the recombination region.*

- The thermal generation rate is given by n/τ.

  where, n - *Excess carrier density,* and

  τ - *Carrier life time.*

- The ***rate equation*** for carrier recombination in an LED is given as,

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau} \quad \text{...... (1)}$$

At equilibrium condition, $\frac{dn}{dt} = 0$. Then equation (1) becomes,

$$\boxed{n = \frac{J\tau}{qd}} \quad \text{...... (2)}$$

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

6.2.2 Internal Quantum Efficiency (η_{int})

Definition:

- *The internal quantum efficiency in an* ***active region*** *is the* ***fraction*** *of the* ***electron – hole pairs*** *that* ***recombine radiatively.***
- *The internal quantum efficiency (η_{int}) is defined as, "the* ***ratio of radiative recombination rate to the total recombination rate".***

$$\eta_{int} = \frac{R_r}{R_r + R_{nr}} \quad \text{...... (3)}$$

where, R_r – ***Radiative recombination*** rate, and

R_{nr} – ***Non-radiative*** *recombination rate.*

- The ***radiative recombination life time (τ_r)*** is expressed as,

$$\tau_r = \frac{n}{R_r} \quad \text{...... (4)}$$

- The ***non-radiative recombination life time (τ_{nr})*** is expressed as,

$$\tau_{nr} = \frac{n}{R_{nr}} \quad \text{...... (5)}$$

Equation (3) can be rewritten as,

$$\eta_{int} = \frac{1}{1+\frac{R_{nr}}{R_r}} \quad \text{...... (6)}$$

♣ The ***bulk recombination life time* 'τ'** is expressed as,

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} = \frac{\tau_{nr}+\tau_r}{\tau_{nr}\tau_r} \quad \text{...... (7)}$$

From equation (7),

$$\tau = \frac{\tau_{nr}\tau_r}{\tau_{nr}+\tau_r} \Rightarrow \frac{\tau}{\tau_r} = \frac{1}{1+\frac{\tau_r}{\tau_{nr}}} \quad \text{...... (8)}$$

♣ By substituting equations (4) and (5) in equation (6) and using equation (8), we get

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

$$\eta_{int} = \frac{1}{1+\frac{\tau_r}{\tau_{nr}}} = \frac{\tau}{\tau_r} \quad \text{...... (9)}$$

♣ If the current injected into the LED is *I*, then the ***total number of recombinations per second*** is

$$R_r + R_{nr} = \frac{I}{q} \quad \text{...... (10)}$$

By substituting equation (10) in equation (3), we get

$$\boxed{\eta_{int} = \frac{R_r}{I/q}} \quad \text{...... (11)}$$

$$\boxed{R_r = \frac{\eta_{int} I}{q}} \quad \text{...... (12)}$$

6.2.3 Internal Optical Power (P_{int}):

- R_r is the ***total number of photons generated per second*** and that each photon has an energy '*hf*', then an ***optical power*** generated ***internally in LED*** and it is given as,

$$P_{int} = \eta_{int} \frac{I}{q} hf \qquad \text{...... (13a)}$$

$$P_{int} = \eta_{int} \frac{h c I}{q \lambda} \qquad (f = c/\lambda) \qquad \text{...... (13b)}$$

- The internal quantum efficiency is about ***50%*** for ***simple homo junction*** LEDs. However, LEDs having ***double – hetero junction*** structures can have quantum efficiencies of ***60 – 80%.***

6.2.4 External Power Efficiency (η_{ep})

Definition:

The external power efficiency of the device (η_{ep}) is defined as, " the ratio of the optical power emitted externally P_e to the electric power provided to the device P".

$$\eta_{ep} = \frac{P_e}{P} \times 100\ \% \qquad \text{...... (14)}$$

- The optical power emitted P_e into a medium of low refractive index *n* from the face of a planar LED fabricated from a material of refractive index n_x is given approximately by

$$P_e = \frac{P_{int} F n^2}{4 n_x^2} \qquad \text{...... (15)}$$

where P_{int} -Power generated internally, and

F - Transmission factor of the semi-conductor external interface.

6.3 LED STRUCTURES

6.3.1 Introduction

- LED's should provide a ***high radiance*** and a ***high quantum efficiency***, it must achieve a ***carrier and an optical confinement.***
- ***Carrier confinement*** *is used to* ***achieve a high level of radiative recombination*** *in the active region of the device, which yields a high quantum efficiency.*
- ***Optical confinement*** *is used for* ***preventing absorption*** *of an emitted radiation by the material surrounding the* ***pn*** *junction.*

6.3.2 Homojunction LED

- *An LED in the simplest form is essentially a pn-junction formed by using one of the suitable direct bandgap semiconductors that ensures emission in the desired wavelength. Such a LED which uses the same material (say, GaAs) on both sides with different conductivity is called as* ***homojunction LED.***
- But homojunction LEDs are ***not useful*** for an application in fiber optic communication system because of their ***poor radiance*** and ***low quantum efficiency.***

6.3.3 Heterojunction LED: Double Hetero (DH) Structure LED: n-Heterostructure LED

Definition of Heterojunction Structure

Heterojunction structures are used to ***achieve carrier and optical confinement*** *in the central active layer. It consists of two adjoining semiconductor materials with different band – gap energies. Heterojunction are also known as* ***Double Hetero(DH) structure device*** *because of two different alloy layers on each side of an active region.*

- The band gap energy differences between the adjacent layers confine the ***charge carriers (carrier confinement)*** and refractive indices difference between the adjoining layers which ***confine an optical field (optical confinement)*** to the ***central active layer.*** So, ***high efficiency*** and ***high radiance*** of the LED is obtained due to this dual confinement. The electron – hole recombination occurs only in an active layer.

☑ **Advantages:**

The advantages of heterostructure LED are,

⇒ *A heterostructure LED generally consists of a combination of multiple heterojunctions that secure the carriers and subsequently the emitted photon in such a way that an overall quantum efficiency and radiance of the LED is increased.*

⇒ *Other parameters that influencing the device performance are optical absorption in the active region (self-absorption), carrier recombination at the heterostructure interfaces, doping concentration of the active layer, injection carrier density, and active-layer thickness.*

∴ A Double Hetero junction (DH) structure will confine both holes and electrons to a narrow active layer. *Under forward bias,* there will be a large number of carriers injected into an active region where they are efficiently confined.

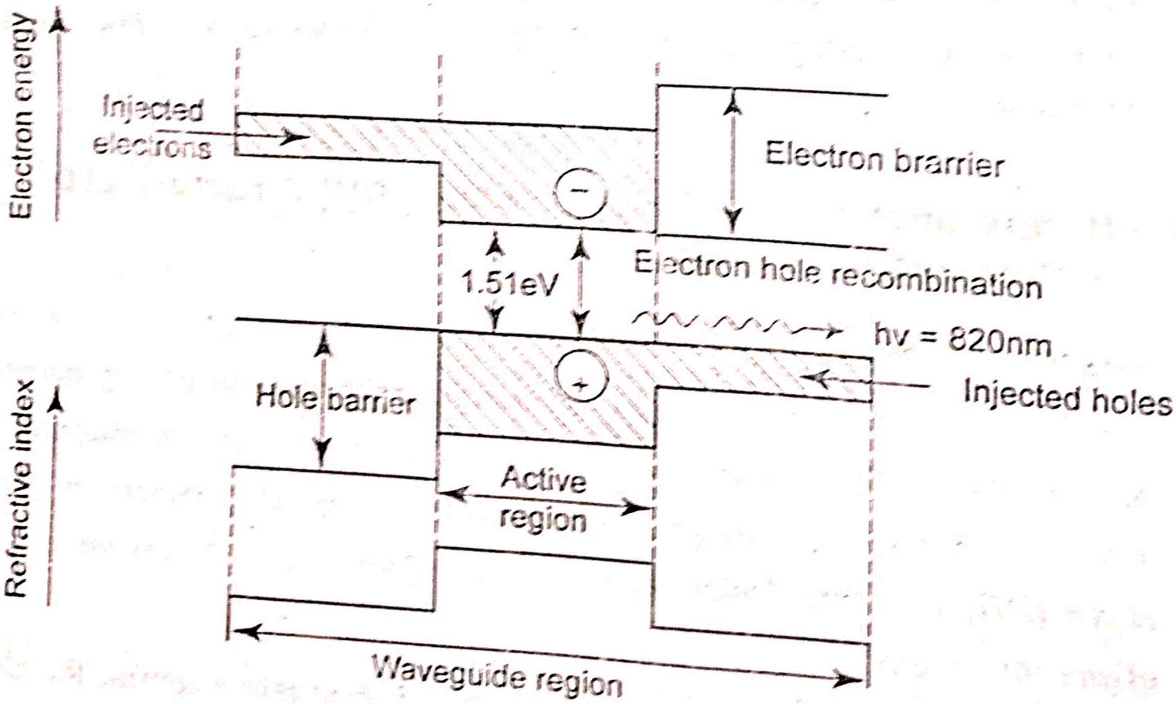

Fig 6.1 GaAlAs double – hetero structure light emitter

- A variety of LED structures ranging from *simple planar LED, Dome LED to more complex double heterostructure Surface Emitting LED (SELED), double heterostructure Edge Emitting LED (ELED) and more advanced Super Luminescent Diode (SLD).*

6.3.4 Planar LED

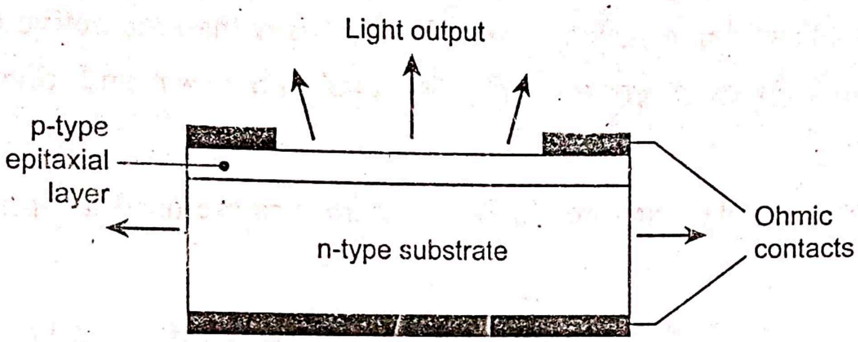

Fig 6.2 Structure of a planar LED

- A planar LED is the simplest one which can be easily fabricated by ***Liquid Phase Epitaxy (LPE)*** or ***Vapour Phase Epitaxy (VPE)*** processes over the whole surface of a GaAs substrate.
- Diffusion of *p*-type impurity on an *n*-type substrate can produce a planar LED as illustrated in Fig 6.2.
- Forward current flow through the junction gives ***Lambertian spontaneous emission*** and the device ***emits light from all surface*** and only a limited amount of light escapes the structure due to total internal ***reflection***.

6.3.5 Dome LED

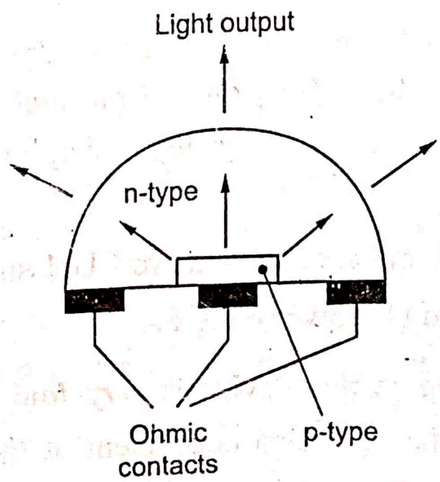

Fig 6.3 Structure of a dome LED

♣ The structure of a typical dome LED is shown in Fig 6.3. A hemisphere of *n* type GaAs is formed around a diffused *p* type region. The 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.

♣ This device has a ***higher external power efficiency*** than the planar LED. The geometry of the dome structure must be far larger than the active recombination area, which gives a ***greater effective emission area*** and thus reduces the radiance.

♣ The two basic DH structure LED configurations are used in optical fiber links are,

(i) Surface emitting LEDs (Burrus or front emitters), and

(ii) Edge emitting LEDs.

6.3.6 Surface Emitting LED(SLEDs): Burrus Emitting LEDs

♣ Surface emitting LEDs are needed where ***data rates*** excess of ***100Mbps*** are required.

Definition:

*In surface emitting LEDs, the plane of active **light-emitting region will be always perpendicular to the fiber axis.***

Double Hetero junction (DH) Structure

*DH structures giving increased efficiency from electrical and optical confinement as well as **less absorption** of the emitted radiation.* This type of surface emitter LED is now widely employed within optical fiber communications.

♣ The structure of a high radiance etched well DH surface emitter for the 0.8 to 0.9 μm wavelength band is shown in Fig 6.4.

♣ The ***internal absorption*** in this device is ***very low*** due to the larger band gap confining layers, and the reflection coefficient at the back crystal face is high giving ***good forward radiance.***

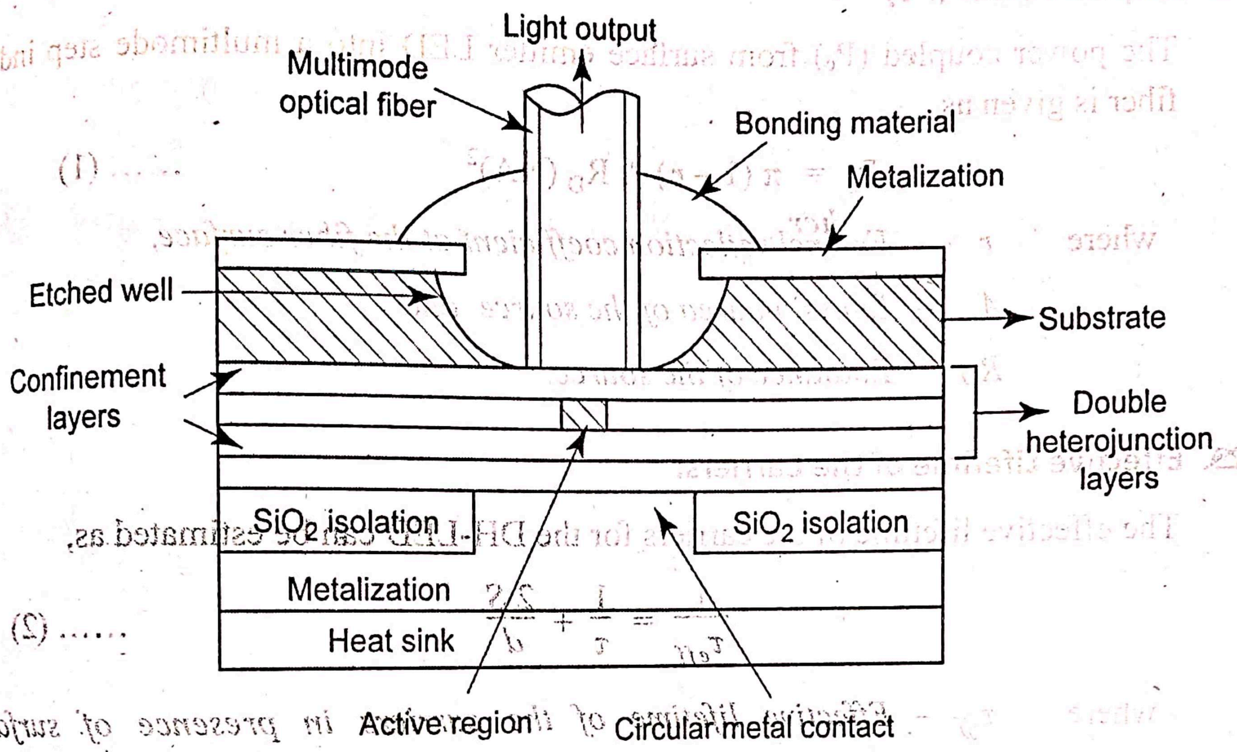

Fig 6.4 Surface emitting LED

- In this configuration, a well is etched in a substrate (GaAs) of the device, in order to avoid the ***heavy absorption*** of the ***emitted radiation,*** and the fiber is then connected to accept the emitted light.
- The circular active area in practical surface emitters is nominally ***50μm*** in diameter and upto ***2.5μm thick.*** The emission pattern is isotropic with a ***120° half power beam width.***

Lambertian Pattern

Isotropic pattern from a surface emitter LED is called lambertian pattern. *In this pattern, the source is equally bright when viewed from any direction. This radiation pattern decides the coupling efficiency of LED.*

- In this pattern, the source is equally bright when viewed from any direction but the power diminishes as ***cos θ***, where θ is an angle between ***viewing direction*** and the ***normal to the surface.*** Power is exactly 50% down at its peak when θ = 60°. So that the total half power beam width is ***120°.***

Coupled Power (PC)

The power coupled (P_c) from surface emitter LED into a multimode step index fiber is given as,

$$P_c = \pi(1-r)\,A\,R_D\,(NA)^2 \qquad \text{...... (1)}$$

where r – *Fresnel reflection coefficient at the fiber surface,*

A – *Emission area of the source, and*

R_D – *Radiance of the source.*

Effective Lifetime of the Carriers:

The effective lifetime of the carriers for the DH-LED can be estimated as,

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau} + \frac{2S}{d} \qquad \text{...... (2)}$$

where τ_{eff} – *Effective lifetime of the carriers in presence of surface recombination,*

τ – *Bulk carrier lifetime,*

S – *Surface recombination velocity at the interface, and*

d – *Thickness of the active layer.*

Drawbacks:

The drawbacks of SLED are,

(i) SLEDs generally suffer from the problem of ***lateral current spreading*** when the contact area is less than 25 µm. In such cases, the effective emission area is much less than the contact area which results in ***coupling loss.***

⇒ *The lateral current spreading can be reduced by making use of a mesa structure SLED.*

⇒ *The coupling can be increased by making use of a multimode fiber with a relatively large value of numerical aperture.*

⇒ *The coupling efficiency can also be improved by making use of micro-lensing arrangement.*

(ii) This lambertian pattern allows ***more power to be coupled*** into an optical fiber, but they are also ***more difficult*** and ***expensive*** to the ***manufacture.***

(iii) Lens coupling may give increased levels of optical power coupled into the fiber but it will also leads to ***additional complexity.***

6.3.7 Edge Emitting LED (ELEDs)

Definition:

- *Edge emitting LEDs emit a* ***more directional*** *light pattern than the surface emitting LEDs.*
- *In order to* ***reduce the losses*** *caused by an absorption in an active layer and to make the beam* ***more directional,*** *the light is collected from the edge of the LED. Such a device is known as* ***edge emitting*** *LED or ELED.*

- The edge emitting LED has ***two transparent guiding layers*** with very thin active layer of about ***50 to 100μm*** in order that the light produced in the active layer spreads into the transparent guiding layers, thereby reducing ***self absorption*** in the active layer.
- The guiding layers have ***refractive indices which is lower than*** the active region but ***higher than*** the outer surrounding material. This structure forms a waveguide channel that directs the optical radiation toward the fiber core.
- To match the typical fiber – core diameters (50 - 100μm), the contact stripes for the edge emitter are ***50 - 70μm*** wide.
- When the plane ***parallel*** to the junction, where there is ***no waveguide effect,*** an emitted beam is ***lambertian*** *(varying as cos θ)* with a half – power width of θ_{11} = 120°(Horizontal), as illustrated in Fig 6.5.
- When the plane highly directional ***perpendicular to*** the junction, then the half power beam width $\theta_{\perp}$ is ranging from 25^{0} to 35° by a proper choice of ***waveguide thickness.***

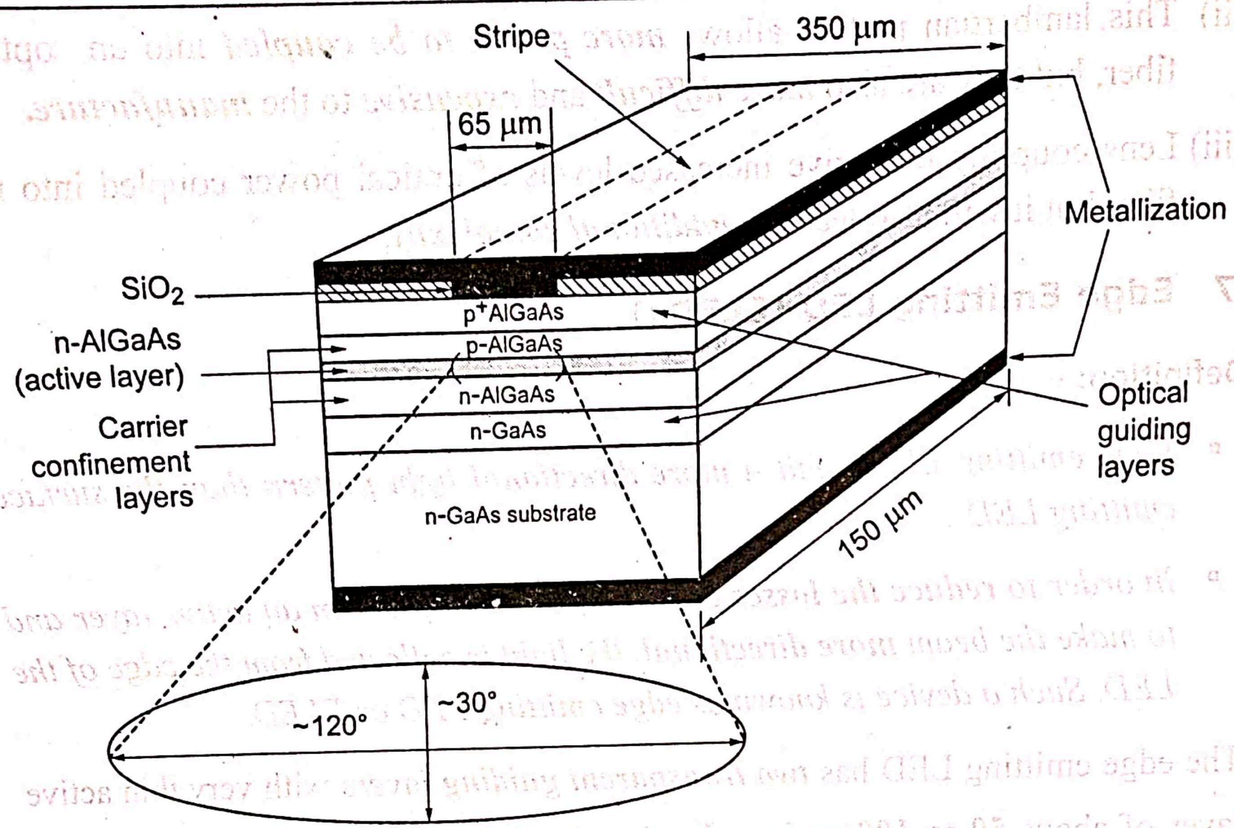

Fig 6.5 Edge – emitting double – hetero junction AlGaAs LED

☑ **Advantages**

Advantages of Edge emitter LEDs when compared to surface LEDs are,

(i) *Edge emitters have a substantially better* ***modulation bandwidth*** *of the order of* ***hundreds of megahertz*** *than comparable surface – emitting structures with the same drive level.*

(ii) *The* ***coupling losses*** *with surface emitters are greater, and they have* ***narrow bandwidths.***

(iii) *An edge emitter couples 7.5 times more power into the low NA fiber than a comparable surface emitter.*

6.4 LED CHARACTERISTICS

6.4.1 Optical Output Power

♣ The ideal light output power against current characteristics for an LED is shown in Fig 6.6. It is linear corresponding to the linear part of the injection laser optical power output characteristics before lasing occurs.

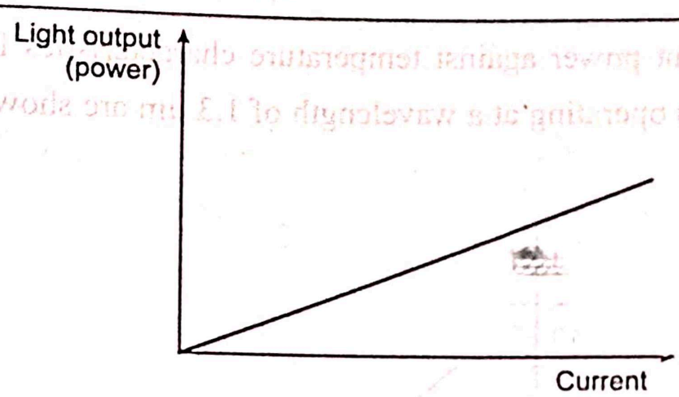

Fig 6.6 An ideal light output against current characteristic for an LED

- The LED is a very linear device as compared to with the majority of injection lasers and hence it tends to be more suitable for *analog transmission*.

- In practical, LEDs do exhibit significant nonlinearities which depend upon the configuration utilized. Therefore, it often use some form of linearizing circuit technique in order to ensure the linear performance of the device to allow its use in ***high-quality analog transmission*** systems.

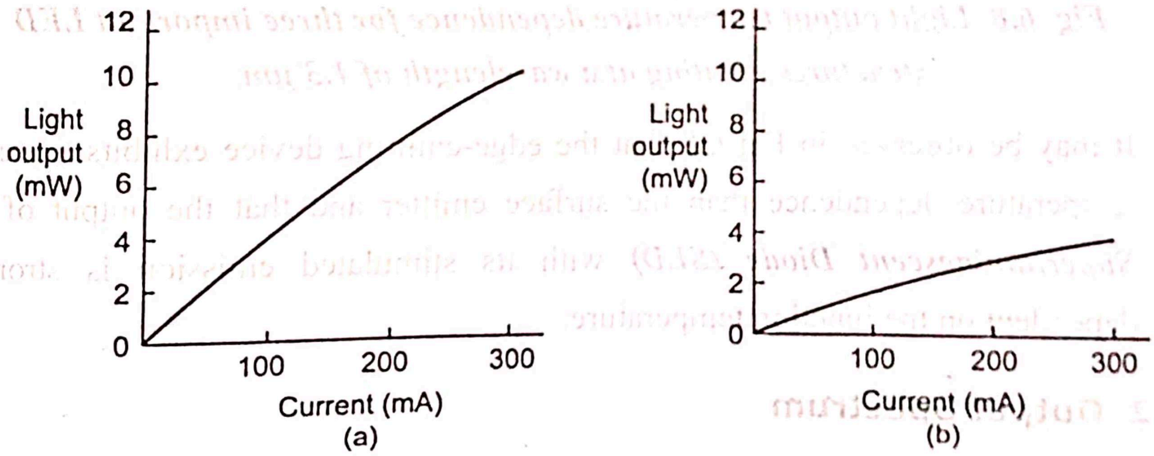

Fig 6.7 Light output (power) against d.c. drive current for typically good LEDs
(a) An AlGaAs surface emitter (b) An AlGaAs edge emitter

- Figure 6.7 (a) and (b) show the light output against current characteristics for typically good surface and edge emitters respectively. The surface emitter radiates significantly ***more optical power*** into air than the edge emitter, and that both devices are reasonably linear at moderate drive currents.

- The internal quantum efficiency of LEDs ***decreases exponentially*** with ***increasing temperature***. Hence the light emitted from these devices decreases as the p–n junction temperature increases.

- The light output power against temperature characteristics for three important LED structures operating at a wavelength of 1.3 μm are shown, for comparison, in Fig 6.8.

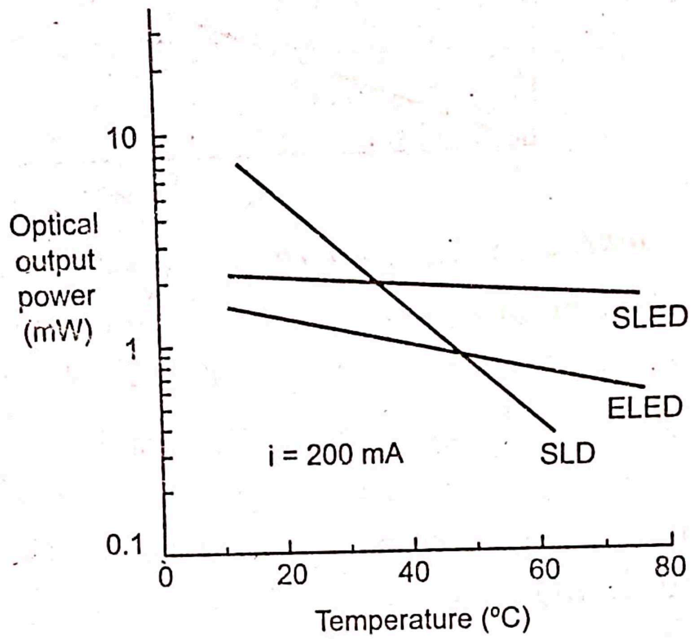

Fig 6.8 Light output temperature dependence for three important LED structures emitting at a wavelength of 1.3 μm

- It may be observed in Fig 6.8 that the edge-emitting device exhibits a greater temperature dependence than the surface emitter and that the output of the ***Superluminescent Diode (SLD)*** with its stimulated emission is strongly dependent on the junction temperature.

6.4.2 Output Spectrum

- The principal material used for making optical sources operating in ***800 – to – 900nm*** is based on $Ga_{1-x}Al_xAs$. The ratio x of ***aluminum arsenide*** to ***gallium arsenide*** determines the band gap of the alloy and correspondingly, the ***wavelength*** of the ***peak emitted radiation.***

- The value of x for an active-area material is usually chosen to give an emission wavelength of about 800-850 nm.

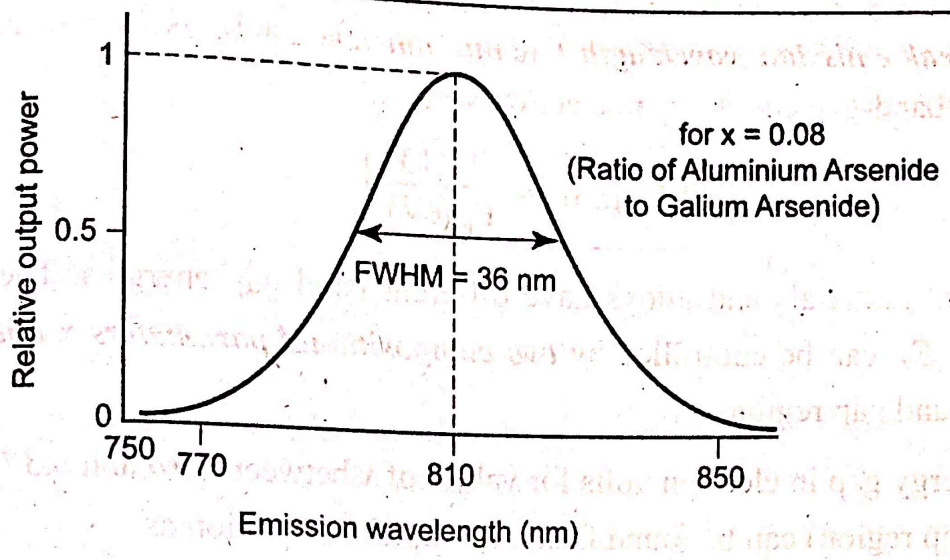

Fig 6.9 Spectral emission of $Ga_{1-x}Al_xAs$ LED

- In the above Fig 6.9, $x = 0.08$. The width of the spectral pattern at its ***half-power point*** is ***36 nm*** and the ***peak output power*** is obtained at ***810 nm.***

Full – Width Half – Maximum (FWHM)

The width of the spectral pattern at its half-power point is known as the ***Full-Width Half-Maximum (FWHM) spectral width***. For the given LED, FWHM is 36 *nm*.

- At longer wavelengths, the quaternary alloy $In_{1-x}\ Ga_x\ As_y\ P_{1-y}$ is one of the primary material candidates. By varying the mole fractions *x* and *y* in the active area, LEDs with peak output powers at any wavelength between 1.0 and 1.7 μm can be constructed.

- Using the fundamental ***quantum-mechanical*** relationship between energy *E* and frequency *v*. The relation between E and *v* is expressed as,

$$E = hf \qquad \text{...... (1)}$$

$$= h\frac{c}{\lambda} \qquad \text{where } c = f\lambda;$$

$$\boxed{\lambda = \frac{hc}{E}} \qquad \text{...... (2)}$$

where, energy (*E*) is in ***joules*** and wavelength (λ) is in ***meters***.

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

$$\lambda\ (\mu m) = \frac{1.240}{E_g\ (eV)} \qquad \text{...... (3)}$$

- Different materials and alloys have different band gap energies. The band gap energy (E_g) can be controlled by ***two compositional parameters x and y***, within direct band gap region.
- The energy gap in electron volts for values of x between ***zero*** and ***0.37*** (the direct band-gap region) can be found from the empirical equation as,

$$E_g = 1.424 + 1.266\,x + 0.266\,x^2 \qquad \text{...... (4)}$$

- For the given value of E_g in electron volts, the peak emission wavelength in micrometers can be found from equation (3). The compositional parameters x and y follows the relationship $y \approx 2.20x$ with $0 \leq x \leq 0.47$.
- For $In_{1-x}\,Ga_x\,As_y\,P_{1-y}$ compositions that are ***lattice matched*** to InP, the band gap in eV varies as,

$$E_g = 1.35 - 0.72\,y + 0.12\,y^2 \qquad \text{...... (5)}$$

- Band – gap wavelengths from ***0.92 to 1.65μm*** are covered by this material system.

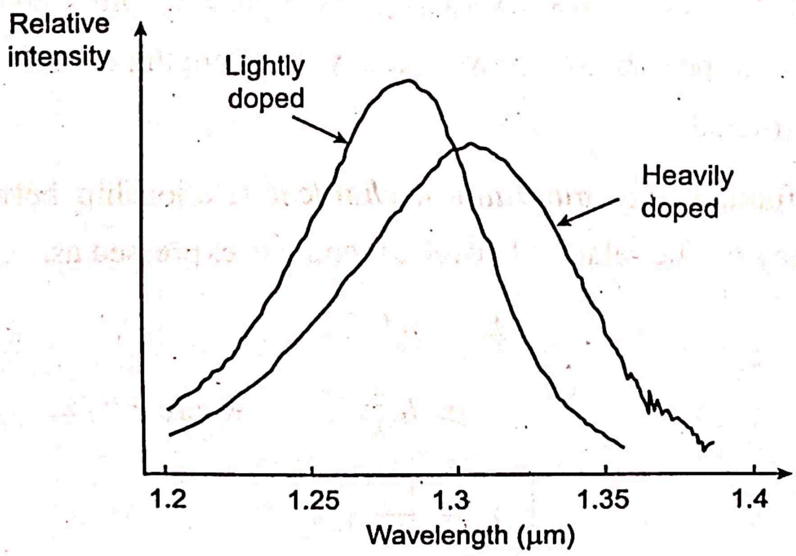

Fig 6.10 LED output spectra for an InGaAsP surface emitter

- From the Fig 6.10, it is observed that the increases in linewidth due to ***increased doping levels*** and the formation of bandtail states. This becomes apparent in the differences in the output spectra between surface and edge-emitting LEDs where the devices have generally ***heavily doped*** and ***lightly doped (or undoped)*** active layers respectively.

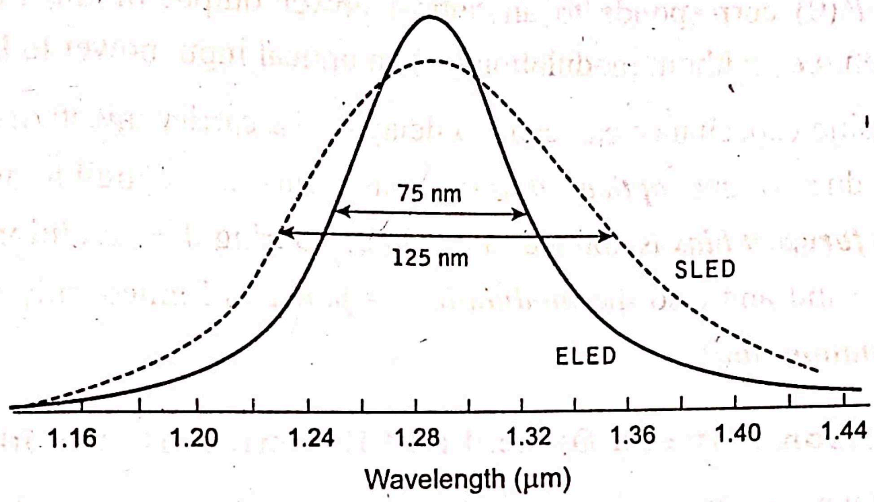

Fig 6.11 Typical spectral output characteristics for InGaAsP surface- and edge-emitting LEDs operating in the 1.3 μm wavelength region

- The differences in the output spectra between InGaAsP SLEDs and ELEDs caused by self-absorption along the active layer of the de vices are displayed in Fig 6.11. It may be observed that the FWHP points are around 1.6 times smaller for the ELED than the SLED.

- In addition, the spectra of the ELED may be further narrowed by the ***superluminescent operation*** due to the onset of stimulated gain and the line width can be far smaller (e.g. 30 nm) than that obtained with the SLED

6.4.3 Modulation Bandwidth

(1) Introduction

- The following three factors are used to determine the ***frequency response*** of a LED.

  (i) Doping level in the active region,

  (ii) The injected carrier radiation life time τ in the recombination region, and

  (iii) Parasitic capacitance of the LED.

- The optical output power $P(\omega)$ of a LED biased by a drive current modulated at an angular frequency ω can be expressed as,

$$P(\omega) = \frac{P(0)}{\sqrt{1+(\tau\omega)^2}} \quad \text{......(1)}$$

where, $P(0)$ corresponds to an optical power output of the LED under DC condition. *i.e.,* without modulation (or) an optical input power to LED.

- The parasitic capacitance can cause a delay of the carrier injection into the active junction due to this ***optical output.*** This delay is negligible when a small, ***constant forward bias*** is applied to the diode. During this condition, equation (1) becomes valid and also the ***modulation response*** is limited only by the ***carrier recombination time.***

(2) Comparison between Optical and Electrical Bandwidth

- The modulation bandwidth of a LED can be defined in either ***electrical or optical*** terms as shown in Fig 6.12.

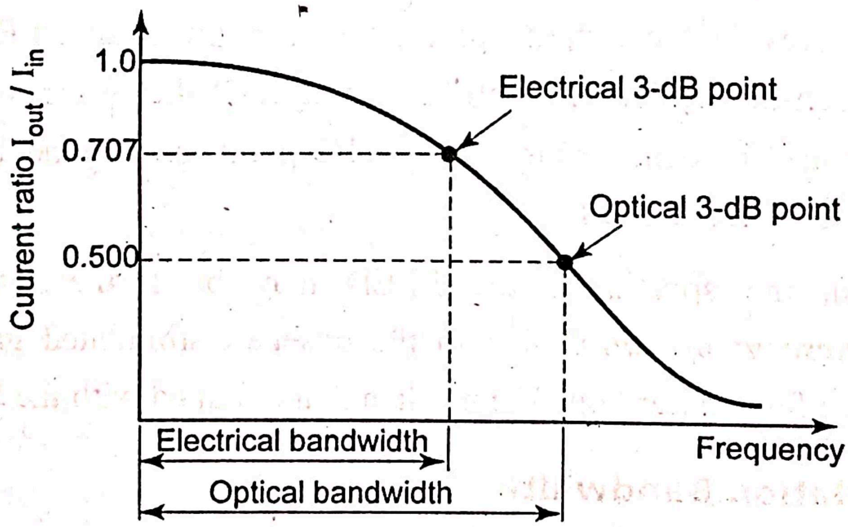

Fig 6.12 Frequency response of an optical source showing the electrical and optical 3-dB bandwidth point

(i) Electrical Bandwidth

- ***Modulation bandwidth*** of a LED is defined in terms of electrical as, *the point where the electrical signal power has dropped to half of its constant value*

resulting from the modulated portion of an optical signal. This gives as the electrical 3-dB point.

- The electrical 3-dB point is nothing but, the frequency at which an ***output electrical power*** is reduced by ***3dB*** with respect to an ***input electrical power***, as illustrated in Fig 6.12.

- An electrical bandwidth (EB_{dB}) is defined as, *"the ratio of an electrical output power to an electrical input power in decibels"* and it is given by,

$$EB_{dB} = 10 \log_{10} \frac{\text{Electrical power out (at the detector)}}{\text{Electrical power in (at the source)}}$$

(or)

$$EB_{dB} = 10 \log_{10} \frac{\text{Output electrical power at frequency } (\omega)}{\text{Electrical power at zero modulation}}$$

$$= 10 \log_{10} \left[\frac{P(\omega)}{P(0)}\right]$$

$$= 10 \log_{10} \frac{\dfrac{I^2(\omega)}{R_{out}}}{\dfrac{I^2(\omega)}{R_{in}}} \quad \text{...... (2)}$$

- Consider that an input resistance and output resistance are equal, that is, $R_{in} = R_{out} = R$

$$= 10 \log_{10} \left(\frac{I(\omega)}{I(0)}\right)^2$$

- The ***electrical 3dB points*** occur when,

$$\left(\frac{I(\omega)}{I(0)}\right)^2 = \frac{1}{2}$$

$$\boxed{\frac{I(\omega)}{I(0)} = \frac{1}{\sqrt{2}} = 0.707} \quad \text{...... (3)}$$

- Thus, the electrical bandwidth may be defined as ***the frequency*** when an ***output current*** has dropped to $\frac{1}{\sqrt{2}}$ *or 0.707* of an ***input current*** to the system.
- Then, a 3-dB electrical bandwidth is simply expressed as,

$$f_{3dB-el} = \frac{1}{2\pi\tau} \qquad \ldots\ldots (4)$$

where, τ is the ***carrier recombination life-time.***

(ii) Optical Bandwidth

Definition:

The optical 3-dB bandwidth is defined as, *"the ratio of the optical power at frequency ω to an unmodulated value of an optical power".*

- Here, the detected current is directly proportional to an optical power and this ratio is given as,

$$Ratio_{optical} = 10\log\left[\frac{P(\omega)}{P(0)}\right] = 10\log\left[\frac{I(\omega)}{I(0)}\right] \qquad \ldots\ldots (5)$$

- The variation of an optical power output of a LED modulated by the drive current at frequency ω normalized with respect to an output of the LED in absence of modulation with the modulation frequency is shown in Fig 6.13.

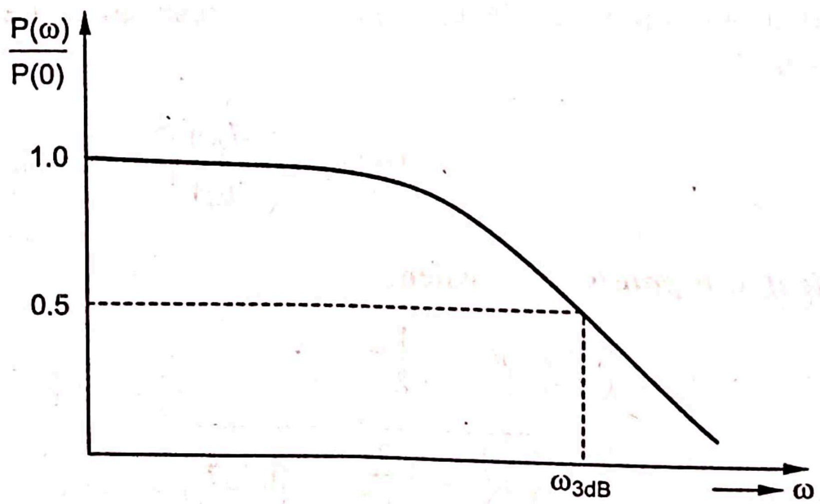

Fig 6.13 Frequency response of an optical source showing the 3-dB bandwidth

- From equation (1) it is clear that an *optical output power of the LED decreases with increase in the value of the angular frequency of the modulating signal.*
- The half-power point which corresponds to a drop of power by 3-dB from its constant value can be obtained by locating the point on the normalized frequency response curve corresponding to $P(\omega)/P(0) = 0.5$.
- The frequency corresponding to this point is the 3-dB bandwidth of the LED *(in terms of angular frequency)* as shown in Fig 6.12. From equation (1), the ***half-power (3dB) point*** is expressed as,

$$\frac{P(\omega)}{P(0)} = \frac{1}{2} \text{ when } (\omega\tau)^2 = 3 \qquad \text{...... (6)}$$

- Designating *the* corresponding value of ω *by* ω_{3dB} we may write as,

$$\omega_{3dB} = \frac{\sqrt{3}}{\tau} \qquad \text{...... (6a)}$$

- Alternatively, *the* 3–dB optical bandwidth can be expressed as,

$$f_{3dB-op} = \frac{\sqrt{3}}{2\pi\tau} \qquad \text{...... (7)}$$

- The *bandwidth* calculated by the above method by considering the optical power directly gives the bandwidth of the LED in the optical domain. Therefore, this value of bandwidth is often referred to as the ***optical bandwidth*** of the source.
- Based on equations (4) and (7) the relation between electrical and optical 3-dB bandwidth is *expressed* as,

$$f_{3dB-op} = \sqrt{3}\, f_{3dB-el} \qquad \text{...... (8)}$$

6.4.4 Reliability

- LEDs are not generally affected by the ***catastrophic degradation mechanisms*** which can severely affect injection lasers. Early or infant failures do, however, occur as a result of random and not always preventable ***fabricational defects.*** Such failures can usually be removed from the LED batch population over an initial burn-in operational period.
- In addition, LEDs do exhibit gradual degradation which may take the form of a rapid degradation mode or a slow degradation mode.

- Rapid degradation in LEDs is similar to the injection lasers, and is due to both the growth of dislocations and precipitate-type defects in the active region giving rise to ***Dark Line Defects (DLDs)*** and ***Dark Spot Defects (DSDs)***, respectively, under device aging.
- LEDs may be fabricated largely free from these defects but subject to a slower long-term degradation process. This homogeneous degradation is due to recombination enhanced point defect generation *(i.e. vacancies and interstitials)*, or the migration of impurities into the active region.
- The optical output power $P_e(t)$ may be expressed as a function of the operating time t, and is expressed as,

$$P_e(t) = P_{out} \exp(-\beta_r t) \qquad \ldots\ldots (9)$$

where, P_{out} - Iinitial output power, and

β_r - Degradation rate.

- The degradation rate is characterized by the activation energy of homogeneous degradation E_a and is a function of temperature.

$$\beta_r = \beta_0 \exp(-E_a/KT) \qquad \ldots\ldots (10)$$

where β_0 - Proportionality constant,

K - Boltzmann's constant, and

T - Absolute temperature of the emitting region.

- The activation energy E_a is a variable which is dependent on the material system and the structure of the device. The value of E_a is in the range 0.56 to 0.65 eV, and 0.9 to 1.0 eV for surface-emitting GaAs/AlGaAs and InGaAsP/InP LEDs respectively.

OPTICAL DETECTOR

7.1 INTRODUCTION

- The detector is an essential component of an optical fiber communication system and it is one of the ***crucial elements*** which decide the ***overall system performance.***

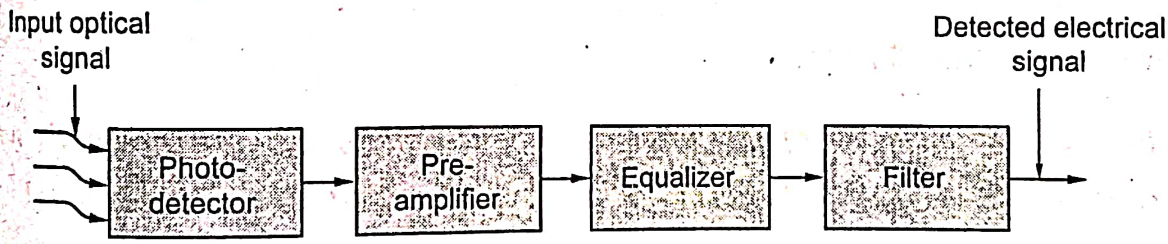

Fig 7.1 Block diagram of a digital optical receiver

Photodetector:

- *The photodetector is basically a transducer that converts the **variation in optical power** into a corresponding variation in an **electric current**. This process is known as **Optical-to-Electrical (O/E) conversion**.*
- *Its function is simply to convert the received optical signal into an electrical signal, which is then amplified before it is used for further processing.*

7.1.1 Characteristics of a General Photodetector: Requirements

The photodetectors which are used in optical fiber communication should have the following performance standards:

(i) Size Compatibility: Small Size

The size of the detector must be compatible with the size of the fiber which is carrying the light. i.e. radius of the core so that the optical power carried by the fiber can be efficiently coupled to the photodetector.

(ii) High Conversion Efficiency:

The photodetector must be able to produce a maximum electrical signal for a given amount of received optical signal.

(iii) High Sensitivity at Operating Wavelength:

The photodetectors based on suitable semiconductor materials are required in the various operating wavelengths so as to provide a significant electrical output for a small input optical power at a room temperature.

(iv) High Response Speed:

The detector must be capable of converting fast-changing optical signals which carries millions of bits of information to the corresponding electrical signal.

(v) Minimum Noise:

The photodetectors must have extremely low noise.

(vi) High Reliability:

The detector must be capable of continuous stable operation at a room temperature for so many years.

(vii) High Fidelity: .

To reproduce the received signal waveform with fidelity, for analogy transmission the response of the photodetector must be linear with regard to the optical signal over a wide range.

(viii) Large Electrical Response to the Received Optical Signal:

The photodetector should produce a maximum electrical signal for a given amount of optical power; that is the ***quantum efficiency*** *should be* ***high.***

(ix) Stability of Performance Characteristics:

Ideally, the performance characteristics of the detector should be independent of changes in ambient conditions. The detector has characteristics such as sensitivity, noise and internal gain which vary with temperature. So, the compensation for temperature effects is often necessary.

(x) Low Bias Voltages:

Ideally the detector should not require excessive bias voltages or currents.

- The design of an optical receiver is much ***more complicated*** than that of an optical transmitter because the receiver must first ***detect weak, distorted signals*** and then make decisions on ***what type of data*** was sent based on an amplified version of this distorted signal.
- The two types of photodiodes used are the ***pin photo-detector*** and an ***Avalanche PhotoDiode (APD).*** The photodetector works on the principle of ***optical absorption.***

7.2 OPTICAL DETECTION PRINCIPLES

- The basic detection process in an ***intrinsic absorber*** is illustrated in Fig 7.1 which shows a ***p – n photodiode.*** This device is ***reverse biased*** and the electric field developed across the *p – n* junction sweeps mobile carriers ***(holes and electrons)*** to their respective majority sides *(p – and n – type material).*
- A ***depletion region or layer*** is therefore created on either side of the junction. This ***barrier*** has the effect of stopping the majority carriers crossing the junction in the opposite direction to the field.

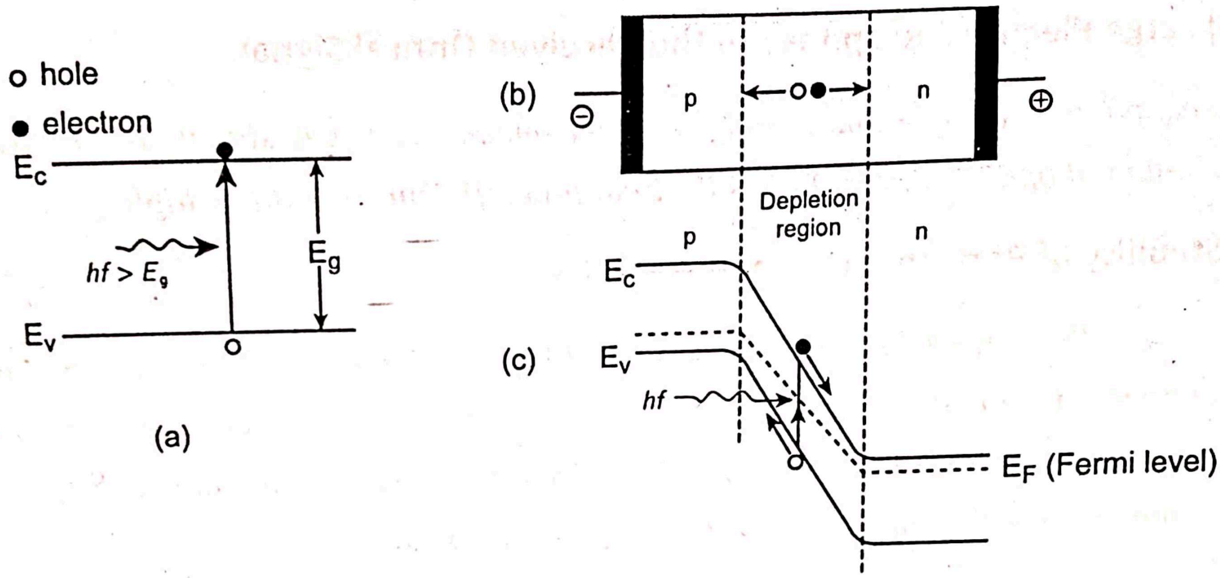

Fig 7.2 Operation of the p-n photodiode (a) Photo generation of an electron-hole pair in an intrinsic semiconductor (b) Structure of the reverse – biased p – n junction (c) Corresponding the energy band diagram

- The field accelerates minority carriers from both side of the junction and forming the reverse leakage current of the diode. Thus intrinsic conditions are created in the depletion region.
- A photon incident in or near the depletion region of this device which has an energy greater than or equal to the bandgap energy E_g of the fabricationg material (i.e. $hf \geq E_g$) will excite an electron from the valence band into the conduction band.
- This process leaves an empty hole in the valence band and is known as the ***photogeneration of an electron – hole*** (carrier) pair, as shown in Fig 7.2 (a).
- Carrier pairs so generated near the junction are separated and ***swept (drift)*** under the influence of the electric field to produce a displacement by current in the external circuit in excess of any reverse leakage current which is shown in Fig 7.2 (b).
- Photogeneration and the separation of a carrier pair in the depletion region of this reverse – biased *p – n* junction is illustrated in Fig 7.2 (c).

- The depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed in order to achieve ***maximum carrier pair generation.***

7.3 CHARACTERISTICS OF A PHOTODETETCOR

- Two important characteristics of a photodetector are:

  (i) Quantum efficiency, and

  (ii) Responsivity.

- These parameters depend on the ***material band gap***, the ***operating wavelength*** and the ***doping thickness*** of the *p, i,* and *n* regions of the device.

7.3.1 Quantum Efficiency (η)

The quantum efficiency 'η' is defined as, " *the fraction of incident photons which are absorbed by the photodetector and generate electrons which are collected at the detector terminals*".

$$\eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}} \quad \ldots (1)$$

$$\eta = \frac{r_e}{r_p} \quad \ldots (2)$$

where r_p is the ***incident photon rate (photons per second)*** and r_e is the corresponding ***electron rate (electrons per second).***

7.3.2 Responsivity (R)

- The responsivity is an useful parameter as it gives the ***transfer characteristic*** of the detector that is, photocurrent per unit incident optical power.

- It is defined as *"ratio of photo output current in amperes to an **incident optical power in Watts**".*

$$= \frac{\textit{Photo output current}}{\textit{Incident optical power}}$$

$$R = \frac{I_p}{P_0}\left(AW^{-1}\right) \qquad \text{...... (3)}$$

where I_p is the ***output photocurrent*** in ***amperes*** and P_0 is the ***incident optical power (output optical power from the fiber)*** in Watts.

- The incident photon rate r_p may be written in terms of ***incident optical power*** and the ***photon energy*** as,

$$r_p = \frac{P_0}{hf} \qquad \text{... (4)}$$

Energy of a photon, $E = hf$

From equation (2), the ***electron rate*** is given by

$$r_e = \eta r_p \qquad \text{... (5)}$$

By substituting equation (4) in equation (5), we get

$$r_e = \frac{\eta P_0}{hf} \qquad \text{... (6)}$$

where, P_0 is the ***optical power incident on the photo detector*** and r_e is also expressed as,

$$r_e = \frac{I_p}{e} \qquad \text{... (7)}$$

From equation (7), the ***output photo current*** as,

$$I_p = r_e e \qquad \text{... (8)}$$

By substituting equation (6) in equation (8),

$$\boxed{I_p = \frac{\eta P_0 e}{hf}} \qquad \text{... (9)}$$

where 'e' is the ***charge on an electron*** and from equation (1),

$$\eta = \frac{r_e}{r_p} = \frac{\frac{I_p}{e}}{\frac{P_0}{hf}}$$

$$\eta = \frac{I_p}{e} \cdot \frac{hf}{P_0}$$

$$\frac{I_p}{P_0} = \frac{\eta e}{hf}$$

$$R = \frac{\eta e}{hf} \quad \text{... (10)}$$

- Equation (10) is a useful relationship for responsivity which may be developed a stage further to include the wavelength of the incident light.
- The frequency 'f' of the incident photons is related to their wavelength 'λ' and the velocity of light in air 'c' as,

$$f = \frac{c}{\lambda} \quad \text{... (11)}$$

By substituting equation (11) in equation (10), we get

$$\boxed{R = \frac{\eta e \lambda}{hc}} \quad \text{... (12)}$$

- The ***responsivity*** is ***directly proportional*** to the ***quantum efficiency*** at a ***particular wave length***. The ideal responsivity against wavelength characteristic for a silicon photodiode with unit quantum efficiency is illustrated in Fig 7.3.

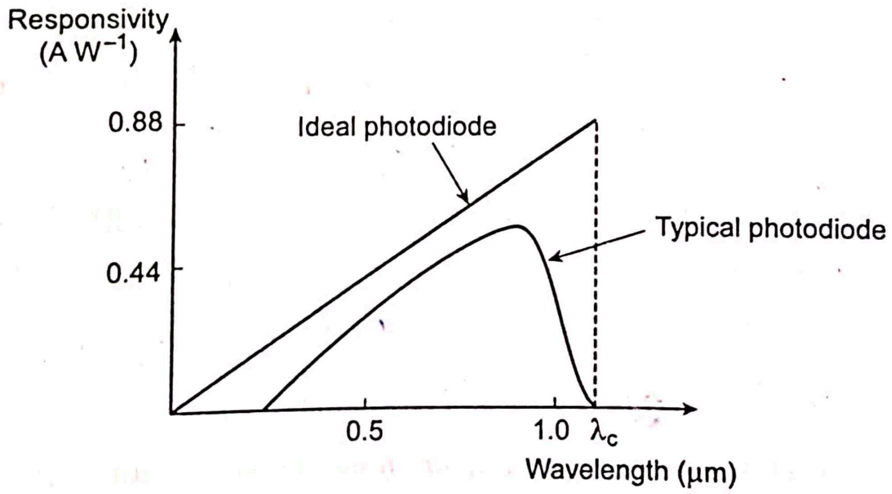

Fig 7.3 Responsivity against wavelength characteristics of an ideal silicon photodiode

7.4 P-N PHOTODIODE

- Fig 7.4 shows a reverse-biased p–n photodiode with both the depletion and diffusion regions.

♣ The depletion region is formed by ***immobile positively charged donor atoms*** in the ***n-type semiconductor material*** and ***immobile negatively charged acceptor atoms*** in the ***p-type material***, when the mobile carriers are swept to their majority sides under the influence of the electric field.

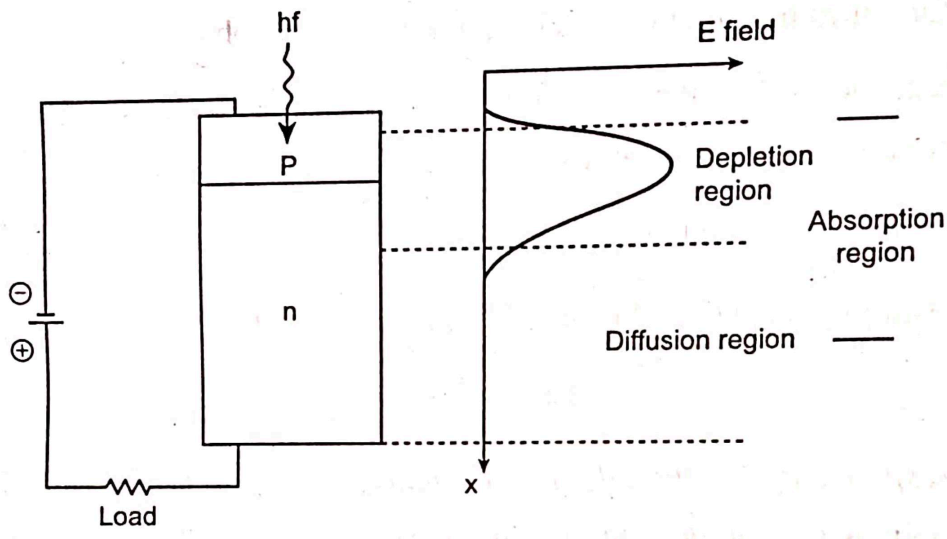

Fig 7.4 The p-n photodiode showing depletion and diffusion regions

♣ The width of the depletion region is dependent upon the doping concentrations for a given applied reverse bias .i.e. *lower the doping results wider the depletion region.*

♣ Photons may be absorbed in both the depletion and diffusion regions, as indicated by the absorption region in Fig 7.4. The absorption region's position and width depend upon the energy of the incident photons and on the material from which the photodiode is fabricated.

♣ In the case of the ***weak absorption of photons***, the absorption region may extend completely throughout the device. Electron–hole pairs are therefore generated in both the depletion and diffusion regions.

♣ In the depletion region the carrier pairs separate and drift under the influence of the electric field, whereas outside this region the hole diffuses towards the depletion region in order to be collected.

- The photons are absorbed in the depletion region. Thus it is made as long as possible by decreasing the doping in the *n*-type material. The depletion region width in a *p–n* photodiode is normally 1 to 3 μm and is optimized for the efficient detection of light at a given wavelength.
- Typical output characteristics for the reverse-biased *p–n* photodiode are illustrated in Fig 7.5. The different operating conditions are moving from no light input to a high light level.

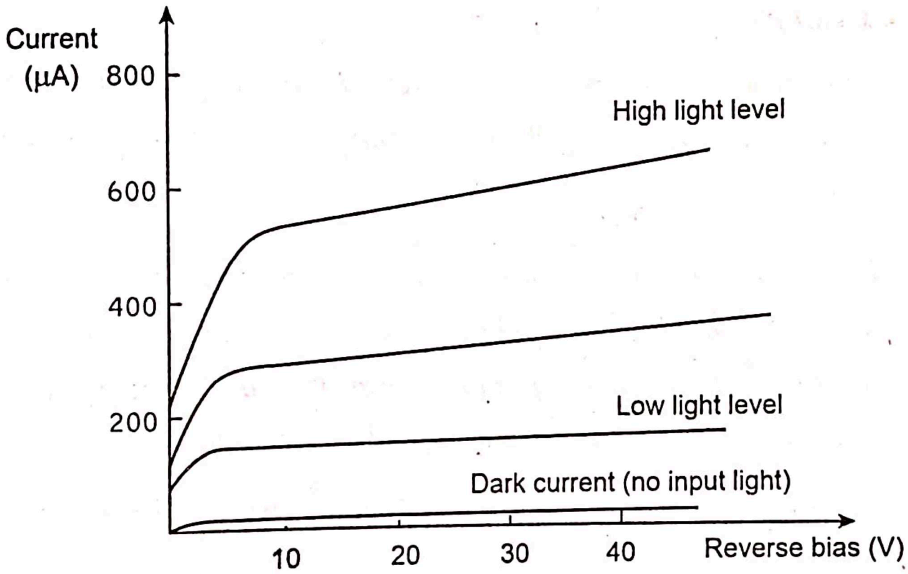

Fig 7.5 Typical p–n photodiode output characteristics

7.5 P-I-N(PIN) PHOTODIODE

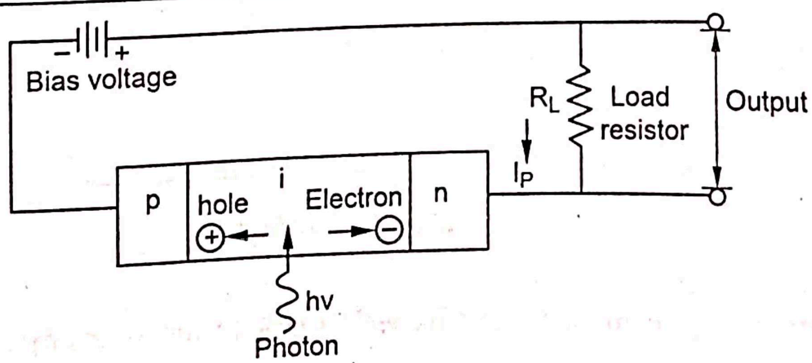

Fig 7.6 Schematic representation of a pin photodiode circuit with an applied reverse bias

7.5.1 Working Operation

- The pin photodetector structure consists of ***p and n regions*** which is separated by a very lightly ***n – doped intrinsic (i)*** region.
- *When the photodiode is reverse biased, the intrinsic region of diode is fully depleted of carriers. That is, the intrinsic n and p carrier concentrations are negligibly small in comparison with the impurity concentration in this region.*

Photocarriers:

- *A photon incident near or in the depletion region of this device which has an energy greater than or equal to the band gap energy (E_g) of the fabricating material ($h\nu \geq E_g$).*
- *The photon can give up its energy and can excite an electron from the valance band to the conduction band. This process leaves an empty hole in the valance band and it is known as the **photon-generation of a free electron-hole pairs,** which are known as **photocarriers,** mainly due to the absorption of photon.*

- This photocarriers are generated in the depleted intrinsic region where most of an incident light photons are absorbed.

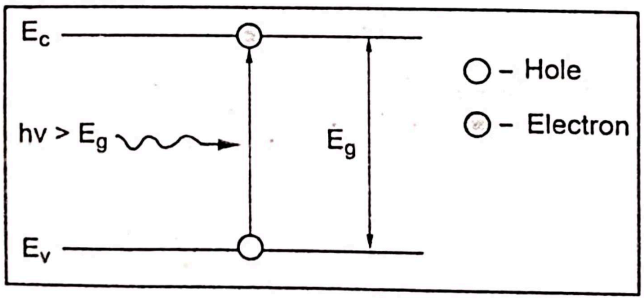

Fig 7.7 Electron – hole pair

- The depletion region must be ***sufficiently thick*** to allow a large fraction of an incident light (photon) to be absorbed in order to achieve ***maximum carrier – pair generation.***

Photocurrent

The high electric field present in the depletion region causes the carriers to separate and be collected across the reverse–biased junction. This gives rise to a current flow in an external circuit.

This current flow is known as the ***photocurrent.*** *One electron flows for every carrier pair generated.*

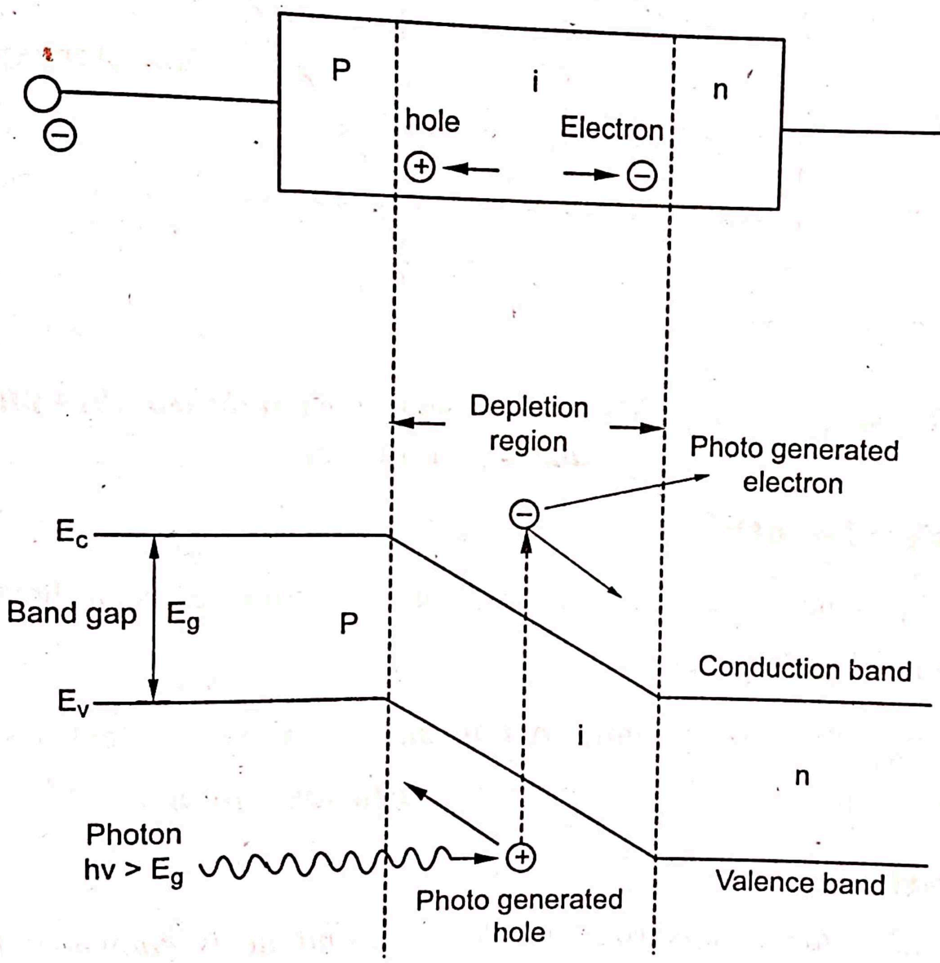

Fig 7.8 Simple energy-band diagram for a pin photodiode

- Because of the large built-in electric field, electrons and holes generated inside the depletion region accelerate in opposite directions and drifts to the *n*-and *p*-sides respectively. The resulting flow of ***current*** is ***proportional*** to the ***incident optical power.***

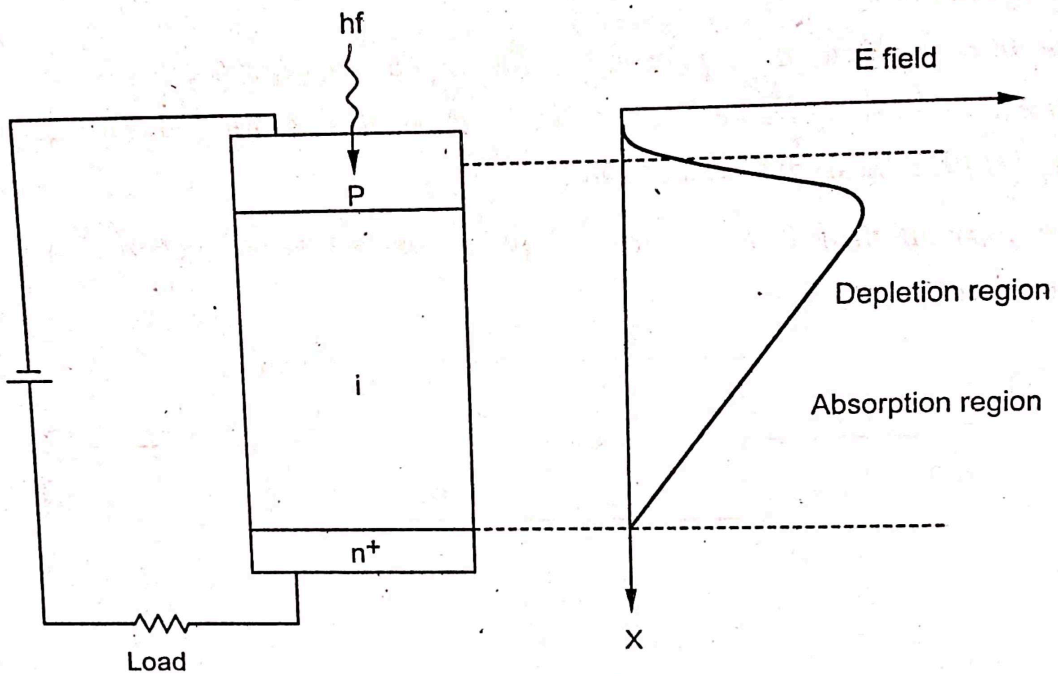

Fig 7.9 The p – i – n photodiode showing the combined absorption and depletion region

7.5.2 Diffusion Length

- As the charge carriers flow through the material, some electron-hole pairs will recombine and hence disappear.
- On an average, the ***carriers move to a distance*** L_n or L_p for electrons and holes, respectively. This distance is known as the ***diffusion length***.

Carrier Lifetime:

The time taken for an electron or hole to recombine is known as the ***carrier lifetime*** *and it is denoted by* τ_n *and* τ_p. The lifetimes and the diffusion lengths are related by the expressions:

$$L_n = (D_n \tau_n)^{1/2} \quad \text{...... (1)}$$

and

$$L_p = (D_p \tau_p)^{1/2} \quad \text{...... (2)}$$

where D_n and D_p are the ***electron*** and ***hole diffusion coefficient*** (or constants), respectively and their unit is ***cm²/second.***

7.5.3 Optical Power Absorbed

- The absorption of photons in a photodiode to produce the carrier pairs and thus a photo current is dependent on the absorption co-efficient 'α'.
- If ***P(x) is an optical power absorbed at a distance 'x'*** in the semiconductor material according to the exponential law as,

$$P(x) = P_0\left(1-e^{-\alpha_s(\lambda)x}\right) \qquad \ldots\ldots (3)$$

where P_0 – Incident optical power level, and

$\alpha_s(\lambda)$ – ***Absorption co-efficient*** at a wavelength λ.

- 'α_s' depends on the ***wavelength,*** a particular semiconductor material can be used only over a limited wavelength range.

7.5.4 Cut-off Wavelength

- The cut-off wavelength is determined by band-gap energy E_g of material. If E_g is expressed in ***electron volts (eV),*** then λ_c is given in ***micrometers*** (μm) by

$$\lambda_c(\mu m) = \frac{hc}{E_g} = \frac{1.24}{E_g(eV)} \qquad \ldots\ldots (4)$$

- Typical value of λ_c for ***silicon*** is ***1.06 μm*** and for ***germanium*** it is ***1.6 μm.***

7.5.5 Depletion Region Width

If the depletion region has a width *w*, then, from equation (3) the total power absorbed in the distance *w* is given as,

$$P(w) = P_0\left(1-e^{-\alpha_s w}\right) \qquad \ldots\ldots (5)$$

7.6 AVALANCE PHOTODIODE (APD)

7.6.1 Introduction

- Avalanche Photodiodes (APDs) internally ***multiplies the primary signal*** photo current before it enters an input circuitry of the following amplifier. It has an internal gain and its ***responsivity*** is better than the *p-i-n* photodiode.

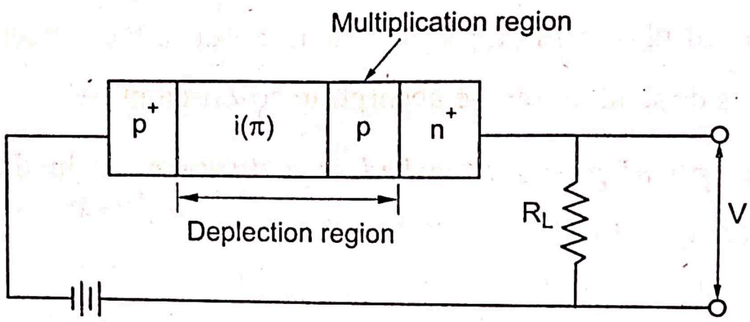

Fig 7.10 Avalanche photodiode

- The photocurrent is multiplied to increase the ***receiver sensitivity.*** Extremely high electric field region is created. Most of the photons are absorbed in the depletion region and the primary electron-hole pairs are generated.

Impact Ionization

*The photo-generated carriers traverse a region where a very high electric field is present. A photo-generated electron or hole can gain enough energy in this high electric field and excite new electron-hole pairs. This carrier multiplication mechanism is known as **impact ionization.***

Avalanche Effect

*Due to an **ionization effect** new carriers also generated. The newly created carriers also accelerated by the high electric field and gain enough energy to cause further impact ionization. This phenomenon is known as **avalanche effect.***

- ***Finite numbers*** of carriers are created ***below the break down*** voltage and above the breakdown voltage ***infinite numbers*** of carriers are generated. These carriers are ***multiplied internally.***

7.6.2 Reach Through Avalanche Photo-Diode (RAPD)

- A commonly used structure for achieving ***carrier multiplication*** with very little excess noise is the ***reach-through construction*** shown in Fig 7.11.

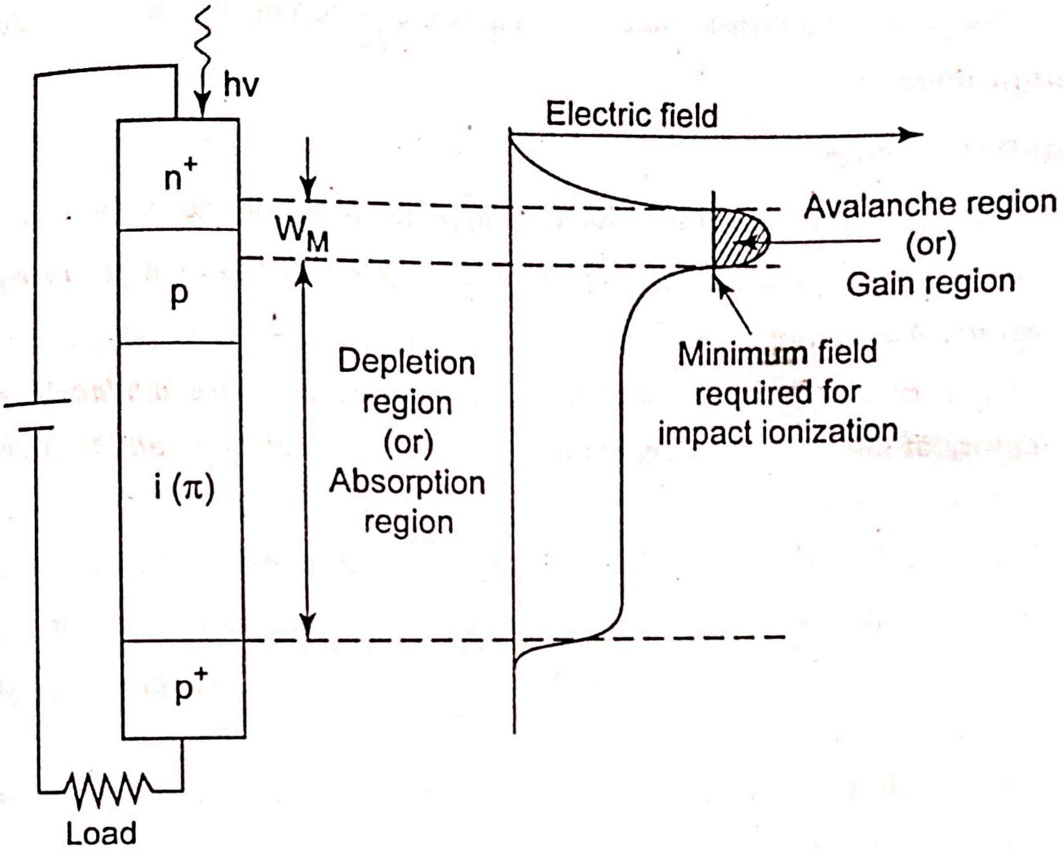

Fig 7.11 Avalanche photodiode showing high electric field (gain) region

- RAPD is composed of a high-resistivity $p-$type material deposited as an epitaxial layer on p^+ *(heavy 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 $p^+\pi\, pn^+$ ***reach through structure.***

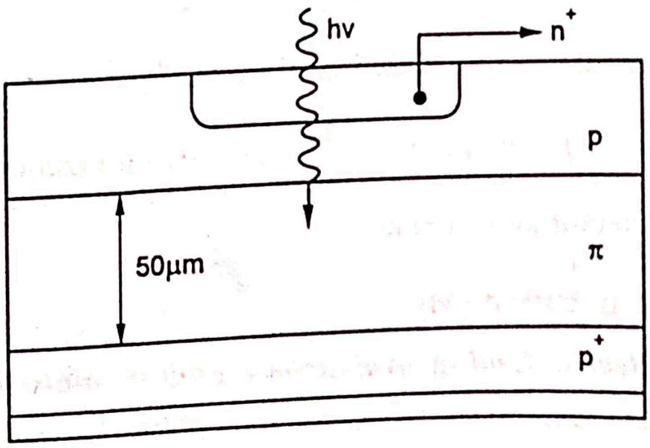

Fig 7.12 Structure of a Silicon RAPD

- The π-layer is an intrinsic layer but has some p doping because of ***imperfect purification.***

(1) RAPD Operation

- When a low reverse-bias voltage is applied, most of the potential drop is across the pn^+ junction. The depletion layer gets ***increases*** with an ***increasing reverse bias voltage.***
- At a particular voltage lesser than that needed to cause ***avalanche break down,*** at this point, the depletion layer just ***"reaches through"*** to the nearly intrinsic π region.
- Normally, RAPD is operated in the ***fully depleted mode.*** When light (photons) enters the device through the p^+ region and its absorbed in the "π" region. This "π" region acts as a ***collection of region for the photo generated carriers.***
- The absorbed photon gives up its energy and electron – hole pairs are created which are then separated by an electric field in the π region.
- The photogenerated electrons drift through the π region in the pn^+ junction, where a high electric field exists. The carrier multiplication takes place in this high electric field region.

Ionization Rate (k)

- *"The average number of electron-hole pairs created by a carrier per unit distance traveled"* is called the ***ionization rate.*"**
- Different materials exhibit different ***electron ionization rates (α)*** and ***hole ionization rate (β)***. The ratio $k = \frac{\beta}{\alpha}$ of the two ionization rates of a measure of the photodetector performance.

Avalanche Multiplication (M)

- In the ***high electric field*** or ***avalanche region*** or ***multiplication region,*** the charge carrier multiplication can takes place by ***impact ionization*** or ***avalanche effect.***

$$\text{Avalanche multiplication } (M) = \frac{I_m}{I_p}$$

where, I_m – *Average value of the total multiplied output current. i.e. where **carrier multiplication occurs.***

I_p – *Primary or initial un-multiplied photocurrent. i.e. **before carrier multiplication occurs.***

Responsivity (R)

The responsivity of APD is given as,

$$R_{APD} = \frac{\eta q}{h\nu} M = R_0 M$$

where R_0 is the ***unity gain responsivity.***

7.6.3 Benefits and Drawbacks with APD

☑ Benefits

(i) These diodes are having excellent linearity over optic power levels ranging from a fraction of a ***nanoWatts*** to several ***microWatts.***

(ii) The $p-i-n$ photodiode receiver has ***10 to 12 dB less sensitive*** than the APD.

☒ Drawbacks

(i) If power received at the receiver is more than one microwatts, then APD is not used, because the pin diodes at this power level provide ***sufficient responsivity*** and ***sufficiently large SNR.***

(ii) The internal gain of an APD depends on the temperature. The ***gain*** normally ***decreases*** as the ***temperature rises.***

(iii) Fabrication difficulties due to their ***more complex structure*** and hence ***increased cost.***

(iv) The random nature of the gain mechanism which gives an ***additional noise contribution.***