

Chapter 4

Optical Properties of Materials

Classification of optical materials - Carrier generation and recombination processes - Absorption, emission and scattering of light in metals, Insulators and Semiconductors (concepts only) - Photo current in a P - N diode - Solar cell - Photo detectors - LED - Organic LED - Laser diodes - excitons - Quantum confined stark effect - Quantum dot laser.

4.1 Introduction

By "optical property" we mean a material's response to exposure to electromagnetic radiation and, in particular, to visible light. First let us discuss some of the basic principles and concepts relating to the nature of electromagnetic radiation and its possible interactions with solid materials. Then let us study the optical behaviors of metallic and nonmetallic materials in terms of their absorption, reflection, and transmission characteristics. Finally let study few applications of these optical materials and the practical utilization of few optical phenomena.

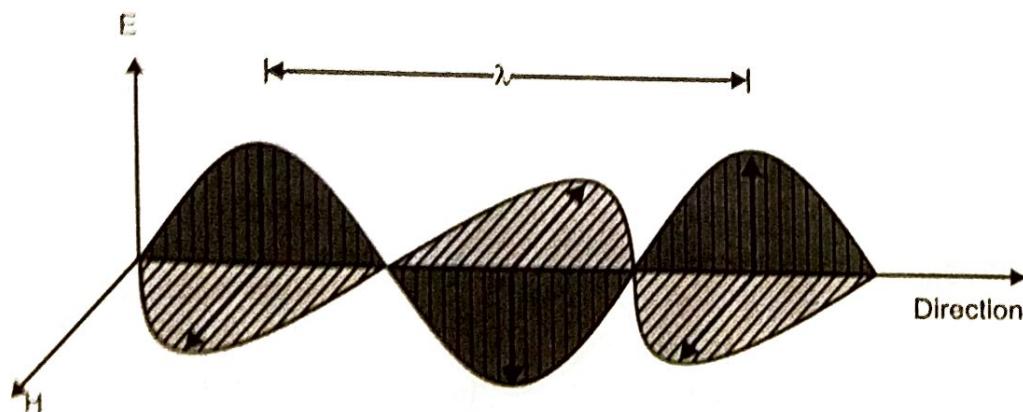


Figure 1 An electromagnetic wave showing electric field E and magnetic field H components, and the wavelength λ .

4.2 Electromagnetic Radiation

Electromagnetic radiation is electromagnetic wave consisting of electric and magnetic field components that are perpendicular to each other and also to the direction of propagation.

The electromagnetic spectrum of radiation has the wide range from gamma rays (emitted by radioactive materials) having wavelengths in the order of 10^{-12} m and spanning through x-rays, ultraviolet, visible, infrared, and finally radio waves with wavelengths as long as 10^5 m. This spectrum, on a logarithmic scale, shown in Figure 2.

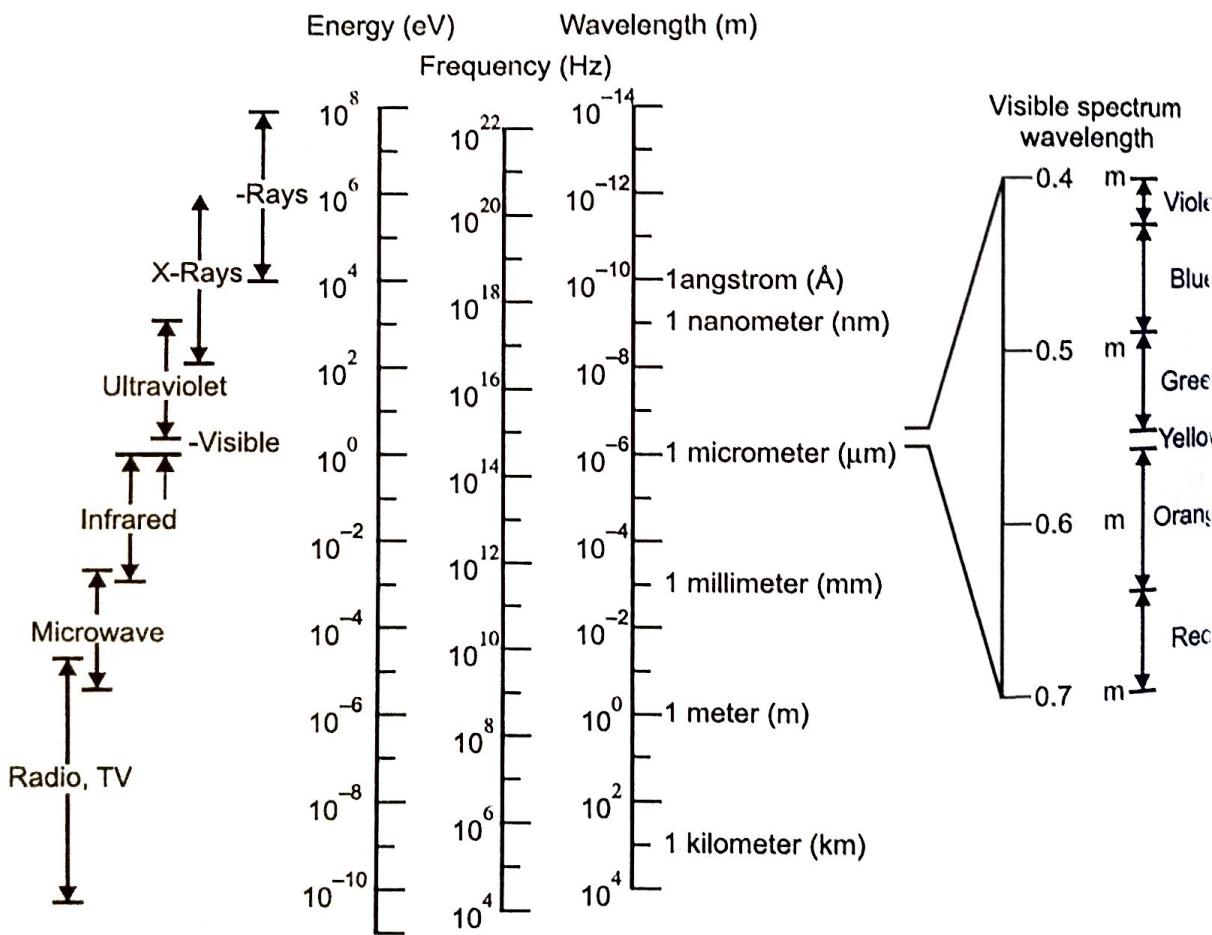


Figure 2 The spectrum of electromagnetic radiation, including wavelength ranges for the various colors in the visible spectrum.

Visible light lies within a very narrow region of the spectrum, with wavelengths ranging between about 400 nm (violet) and 700 nm (red).

All electromagnetic radiation traverses a vacuum at the velocity 3×10^8 m/s. This velocity, c , is related to the electric permittivity of a vacuum ϵ_0 and the magnetic permeability of a vacuum μ_0 .

$$c = \frac{1}{\sqrt{\mu_0 \epsilon_0}} \quad (1)$$

We know that the frequency ν and the wavelength of the electromagnetic radiation λ are a function of velocity c .

$$c = \nu \lambda \quad (2)$$

When describing optical phenomena involving the interactions between radiation and matter, often light is treated in terms of photons. The energy E of a photon is quantized i.e., it can have only specific values as given below

$$E = h\nu = \frac{hc}{\lambda} \quad (3)$$

where h is Planck's constant.

4.3 Light Interactions with Solids

When light proceeds from one medium into another (e.g., from air into a solid substance), several things happen. Some of the light radiation will be reflected at the interface between the two media, some may be transmitted through the medium and some will be absorbed. The intensity of the beam incident to the surface of the solid medium (I_0) is equal the sum of the intensities of the reflected (I_R) transmitted (I_T) and absorbed (I_A) beams respectively.

$$\text{i.e. } I_0 = I_R + I_T + I_A \quad (4)$$

Here

$$\text{Reflectivity (R)} = \frac{I_R}{I_0}$$

$$\text{Transmissivity (T)} = \frac{I_T}{I_0} \text{ and}$$

$$\text{Absorptivity (A)} = \frac{I_A}{I_0}$$

Hence equation (4) can be also written as

$$R + T + A = 1$$

4.3.1 Classification of optical materials

Materials are classified on the basis of their interaction with visible light into three categories.

- (i) Materials that are capable of transmitting light with relatively little absorption and reflection are ***transparent*** - one can see through them.
- (ii) ***Translucent*** materials are those through which light is transmitted diffusely; that is, light is scattered within the interior that objects are not clearly viewed through a specimen of the material.
- (iii) Those materials that do not transmit visible light are termed ***opaque***.
 - Bulk metals are opaque throughout the entire visible spectrum; that is, all light radiation is either absorbed or reflected.
 - On the other hand, electrically insulating materials can be made to be transparent.
 - Furthermore, some semiconducting materials are transparent whereas others are opaque.

4.4 Atomic and Electronic Interactions

Interactions of the electromagnetic radiation with the atoms, ions, and/or electrons result in two most important electronic phenomena called ***electronic polarization*** and ***electron energy transitions***.

i) Electronic Polarization

When an atom is placed inside an electric field, the electron cloud shifts relative to the nucleus of the atom (Figure 3) resulting in creation of electric dipole and this phenomenon is called ***electronic polarization***.

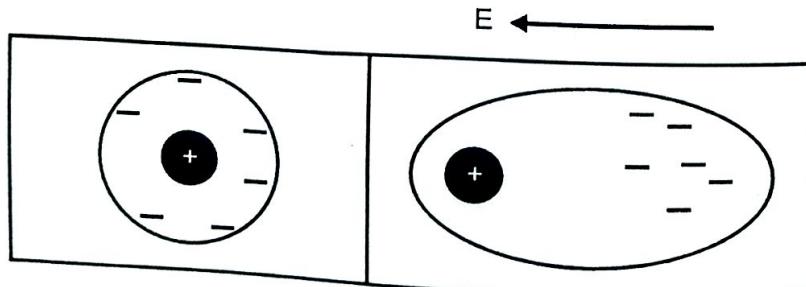


Figure 3 Electronic polarization - electron cloud shifts relative to the nucleus of the atom along the applied field direction.

For the visible range of frequencies, the oscillating electric field of e.m.wave interacting with the atoms change the direction of electric field component

resulting in oscillating dipole. Two consequences of this polarization are: (1) some of the radiation energy may be absorbed, and (2) light waves are retarded in velocity as they pass through the medium. The second consequence is manifested as refraction.

ii) Electron Energy Transitions

The absorption and emission of electromagnetic radiation may involve electron transitions from one energy state to another. Now for sake of simplicity let us consider an isolated atom whose electron energy diagram is given in Figure 4. An electron may be excited from an occupied state at energy E_2 to a vacant and higher-lying one, denoted E_4 , by the **absorption of a photon** of energy $h\nu$. For this to happen the energy of the photon ($h\nu_{42}$) must be exactly equal to the difference in energy between the two states ($E_4 - E_2$).

$$\text{i.e., } h\nu_{42} = E_4 - E_2 \quad (5)$$

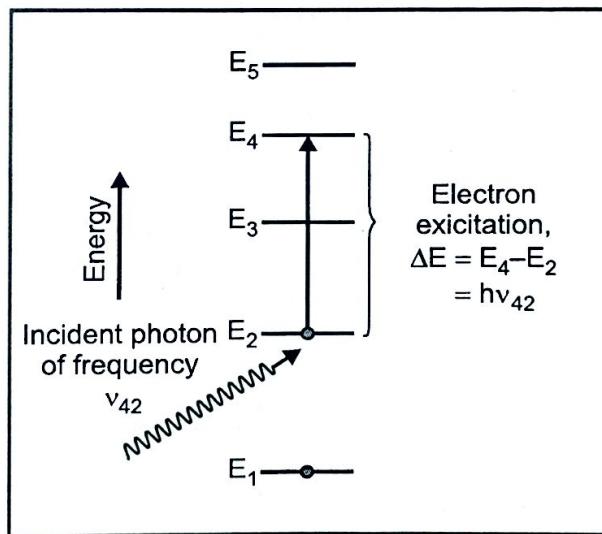


Figure 4 Photon absorption in an isolated atom by the excitation of an electron from one energy state to another.

Thus the change in energy experienced by the electron, ΔE , depends on the radiation frequency.

$$\boxed{\Delta E = h\nu} \quad (6)$$

Since the energy states for the atom are discrete, only specific ΔE values exist between the energy levels; thus, only photons of energies equal to these ΔE energy values for the atom can be absorbed by electron transitions. In each excitation event energy of one photon is fully absorbed.

A second important concept is that a stimulated electron cannot remain in an excited state indefinitely. After a short time (called its life time), it falls or decays

back into its ground state, or unexcited lower level. This results in *reemission of photon*. Several decay paths are possible but there must be a conservation of energy for absorption and emission during electron transitions.

4.5 Optical Properties of Metals

- Metals consist of partially filled high-energy conduction bands.
- When photons are directed at metals, their energy is used to excite electrons into unoccupied states. Thus metals are opaque to the visible light.
- Metals are, however, transparent to high end frequencies i.e. x -rays and γ -rays.
- Absorption of takes place in very thin outer layer. Thus, metallic films thinner than $0.1 \mu\text{m}$ can transmit the light.
- The absorbed radiation is emitted from the metallic surface in the form of visible light of the same wavelength as reflected light. The reflectivity of metals is about 0.95, while the rest of impinged energy is dissipated as heat.
- The amount of energy absorbed by metals depends on the electronic structure of each particular metal.

For example: with copper and gold there is greater absorption of the short wavelength colors such as green and blue and a greater reflection of yellow, orange and red wavelengths.

4.6 Optical Properties of Non-Metals

Non-metallic materials consist of various energy band structures. Thus, all four optical phenomena such as *absorption*, *reflection*, *transmission* and *refraction* are important for these materials.

4.6.1 Refraction

- When light passes through a transparent material they cause polarization of electrons and in term, its velocity decreases and as a result, it is bent towards the normal at the interface; this phenomenon is termed *refraction*.
- The index of refraction n of a material is defined as the ratio of the velocity in a vacuum c to the velocity in the medium v , or

$$n = \frac{c}{v}$$

(7)

The magnitude of n depends on the wavelength of the light.

This effect results in **dispersion** or separation of a beam of white light into its component colors by a glass prism. Since each color is deflected by a different amount as it passes through glass it results in the separation of the colors. Thus the angle of refraction depends on the refractive index of the material which in turn depends on the wavelength of light.

If the angle of incidence from a normal to the surface is θ_i , and angle of refraction is θ_r , the refractive index of the medium n is given by

$$n = \frac{\sin \theta_i}{\sin \theta_r} \quad (8)$$

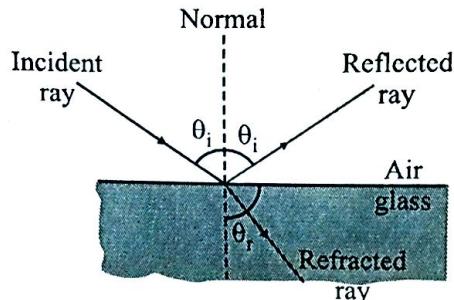


Figure 5 Refraction of light

Velocity of light in a medium is given by

$$v = \frac{1}{\sqrt{\mu \epsilon}} \quad (9)$$

where μ and ϵ are permeability and permittivity of the particular substance respectively.

Now equation 7 can be written as

$$\begin{aligned} n &= \frac{c}{v} \\ n &= \frac{c}{v} = \frac{\sqrt{\mu \epsilon}}{\sqrt{\mu_0 \epsilon_0}} \\ \text{or } n &= \sqrt{\mu_r \epsilon_r} \end{aligned} \quad (10)$$

where μ_r and ϵ_r are relative permeability and relative permittivity (dielectric constant) of the particular substance respectively. Since most materials are only slightly magnetic ($\mu_r \approx 1$),

$$n \approx \sqrt{\epsilon_r} \quad (11)$$

Thus, for transparent materials, there is a relation between the index of refraction and the dielectric constant.

- Larger an atom or ion, greater will be the electronic polarization and slower the velocity of light and hence greater the index of refraction.

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The index of refraction for a typical soda-lime glass is approximately 1.5. Addition of large barium and lead ions (as BaO and PbO) to a glass increases n significantly. For example glasses containing 90 wt% PbO have an index of refraction of approximately 2.1.

For crystalline ceramics that have cubic crystal structures, and for glasses(i.e., for isotropic materials), the index of refraction is independent of crystallographic direction. For non cubic crystals (i.e., for anisotropic materials), the index is greatest along the directions that have the highest density of ions.

Table 1 gives refractive indices for some transparent materials.

Table 1 Refractive Indices for Some Transparent Materials

• Air	1.0
• Water	1.33
• Magnesium fluoride	1.38
• Fused silica (SiO_2)	1.46
• Sapphire (Al_2O_3)	1.8
• Lithium niobate ($LiNbO_3$)	2.25
• Indium phosphide (InP)	3.21
• Gallium arsenide ($GaAs$)	3.35
• Silicon (Si)	3.48
• Indium gallium arsenide phosphide ($InGaAsP$)	3.51
• Aluminium gallium arsenide ($AlGaAs$)	3.6
• Germanium (Ge)	4.0

(The index varies with a number of parameters, such as wavelength and temperature).

4.6.2 Reflection

- When light radiation passes from one medium into another having a different index of refraction, some of the light is scattered at the interface between the two media even if both are transparent.
- Fraction of the incident light which is reflected at the interface is given by reflectivity

$$R = \frac{I_R}{I_0}$$

(12)

where I_0 and I_R are the intensities of the incident and reflected beams, respectively.

- If the light is perpendicular to the interface (i.e., normal), then

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (13)$$

where n_1 and n_2 are the indices of refraction of the two media. If the incident light is not normal to the interface, R will depend on the angle of incidence.

- When light is transmitted from a vacuum or air (for which the index of refraction is very nearly unity) into a solid of index of refraction n_s , then

$$R = \left(\frac{n_s - 1}{n_s + 1} \right)^2 \quad (14)$$

Thus, the higher the index of refraction of the solid, the greater is the reflectivity. For typical silicate glasses, the reflectivity is approximately 0.05.

- Just as the index of refraction of a solid depends on the wavelength of the incident light, so also the reflectivity varies with wavelength.

Reflection losses for lenses and other optical instruments are minimized significantly by coating the reflecting surface with very thin layers of dielectric materials of lower refractive index such as magnesium fluoride (MgF_2).

6.3 Absorption

- When a light beam impinges on a material surface, portion of the incident beam that is not reflected by the material is either absorbed or transmitted through the material.
- Light radiation is absorbed in nonmetallic materials by two basic mechanisms viz. electronic polarization and electron energy transitions explained in section 4.4.
- Absorption by electronic polarization is important only at light frequencies in the vicinity of the relaxation frequency of the constituent atoms. The other mechanism involves valence band conduction band electron transitions, which depend on the electron energy band structure of the material;
- The main difference between a semiconductor and an insulator is that in semiconductors band gap is less than 3.5 eV whereas insulators have much higher band gap. In semiconductors absorption of a photon results in generation of an electron-hole pair due to breaking of covalent bond of the atom. Electron moves to conduction band whereas the hole remains in the valence band. In insulators when an electron moves to conduction band the atoms released the electron remains positively ionised as shown in Figure 6.

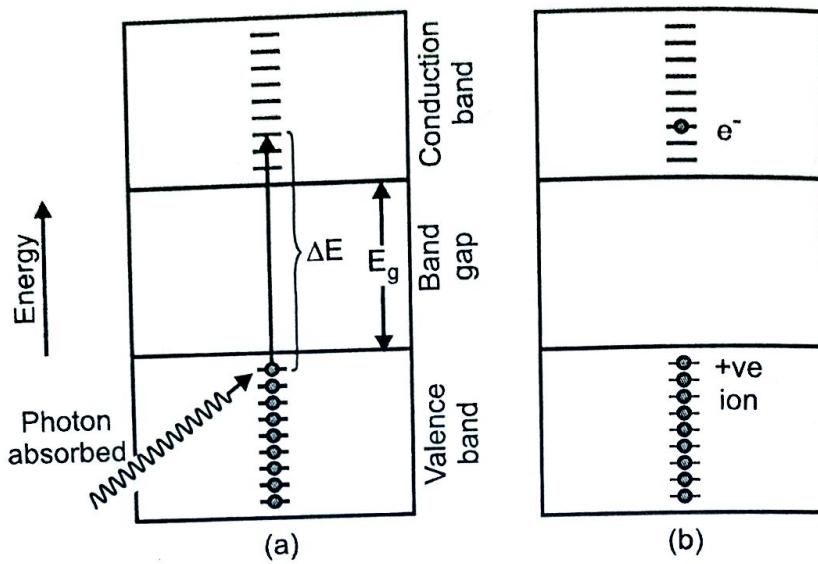


Figure 6 (a) Photon absorption via a valence band-conduction band electron excitation (b) Free electron in the conduction band leaves positively ionised atom in the valence band

- These excitations with the accompanying absorption can take place only if the photon energy is greater than that of the band gap E_g .

$$h\nu > E_g \quad (15)$$

or in terms of wavelength

$$h\frac{c}{\lambda} > E_g \quad (16)$$

in which an electron is excited across the band gap, leaving a positively ionised atom in the valence band.

Other absorption mechanisms

Other types of absorptions arise due to the following phenomena:

- **Rayleigh scattering:** where photon interacts with the electrons orbiting an atom and is deflected without any change in photon energy. This is significant for high atomic number atoms and low photon energies. Ex.: Blue color in the sunlight gets scattered more than other colors in the visible spectrum and thus making sky look blue.
 - **Compton scattering:** interacting photon knocks out an electron losing some of its energy during the process. This is also significant for high atomic number atoms and low photon energies.
- Tyndall effect and photoelectric effect also contribute towards absorption.
- **Tyndall effect:** is where scattering occurs from particles much larger than the wavelength of light. Ex.: Clouds look white.

- **Photoelectric effect:** occurs when photon energy is consumed to release an electron from atom nucleus. This effect arises from the fact that the potential energy barrier for electrons is finite at the surface of the metal.
Ex.: Solar cells.

(These scatterings are different from scattering due to inhomogeneity dealt in section 4.6.5 Scattering).

Bouguer's law: The fraction of beam that is absorbed is related to the thickness of the materials and the manner in which the photons interact with the material's structure.

$$I_T = I_0 \exp(-\alpha x) \quad (17)$$

where I_T - intensity of the beam coming out of the material,

I_0 - intensity of the incident beam,

x - distance through which the photons move, and

α - linear absorption coefficient, which is characteristic of a particular material.

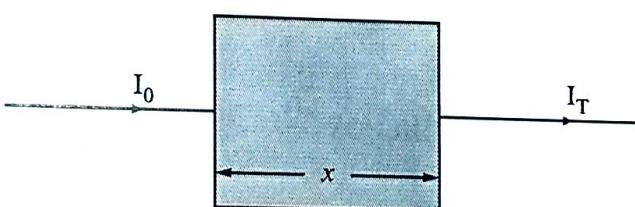


Figure 7 Absorption of light - Bouguer's law

4.6.4 Transmission

The phenomena of absorption, reflection, and transmission of light through a transparent solid can be represented as shown in Figure 8. Let I_0 be the intensity of incident beam that impinges on the front surface of a specimen of thickness l and absorption coefficient α .

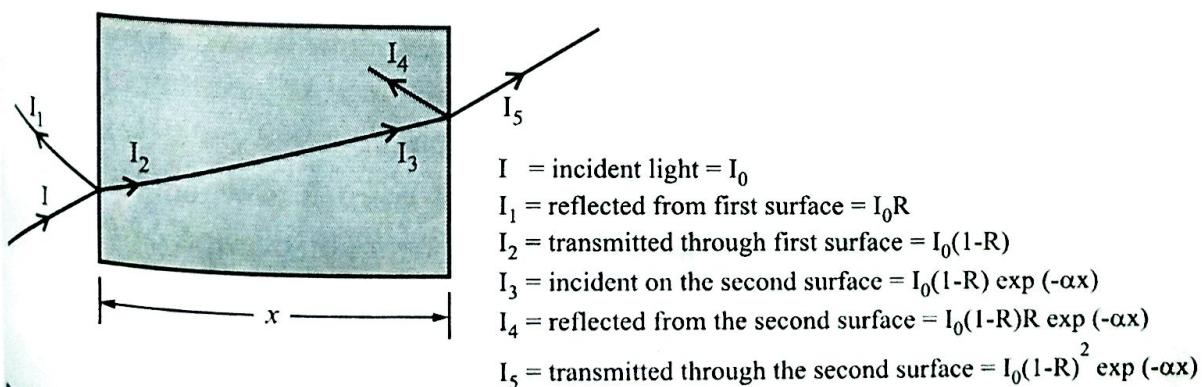


Figure 8 The transmission of light through a transparent medium for which there is reflection at front and back faces, as well as absorption within the medium.

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If R is the reflectance of the material, the intensity of the beam reflected from the front surface of the material is given by

$$I_1 = I_0 R$$

and what enters inside the surface is given by

$$I_2 = I_0(1 - R)$$

What reaches the second surface after absorbed by the material on traveling the length x is given by

$$I_3 = I_0(1 - R) \exp(-\alpha x)$$

Intensity of the beam reflected from the second surface of the material is given by

$$I_4 = I_0(1 - R)R \exp(-\alpha x)$$

Finally the intensity of the beam that is transmitted through the second surface of the material is given by $I_5 = I_T$

$$I_T = I_0(1 - R)^2 \exp(-\alpha x) \quad (18)$$

Thus, the fraction of incident light that is transmitted through a transparent material depends on the losses that are incurred by absorption and reflection.

4.6.5 Scattering

Many dielectric materials that are intrinsically transparent may be made translucent or even opaque introducing interior scattering centres. A transmitted light beam can be made to appear diffuse as a result of multiple scattering. Opacity results when the scattering is so extensive that virtually no light is transmitted to the back surface. This internal scattering may be due to different sources.

- (i) Polycrystalline specimens in which the index of refraction is *anisotropic* normally appear translucent. Both reflection and refraction occur at grain boundaries. This causes a diversion in the incident beam. This is due to a slight difference in index of refraction n between adjacent grains that do not have the same crystallographic orientation.
- (ii) Scattering of light also occurs in *two-phase materials* in which one phase is finely dispersed within the other. Again, the beam dispersion occurs across phase boundaries when there is a difference in the refractive index for the two phases; the greater this difference, the more efficient is the scattering.
- (iii) As a consequence of fabrication or processing, many ceramic pieces contain some *residual porosity* in the form of finely dispersed pores. These pores also effectively scatter light radiation.

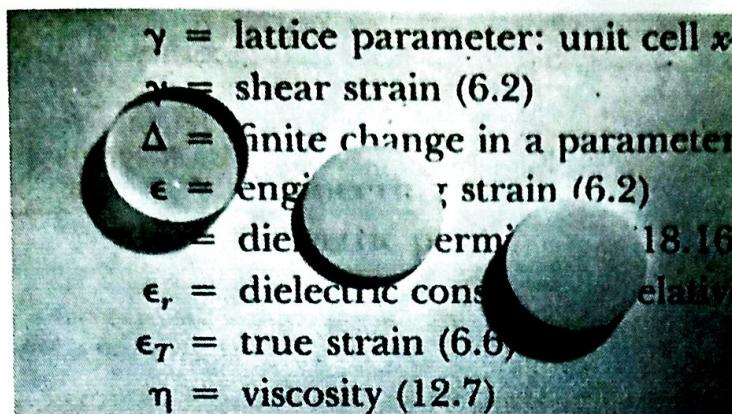


Figure 9 Single crystal that is totally transparent (left), polycrystalline that is translucent (middle) and porous (right) aluminum oxide specimens.

Photograph in figure 9 demonstrates the difference in optical transmission characteristics of single-crystal, fully dense polycrystalline, and porous (5% porosity) aluminum oxide specimens. Whereas the single crystal is totally transparent, polycrystalline and porous materials are, respectively, translucent and opaque.

For intrinsic polymers (without additives and impurities), the degree of translucency is influenced primarily by the extent of crystallinity. Some scattering of visible light occurs at the boundaries between crystalline and amorphous regions, again as a result of different indices of refraction. For highly crystalline specimens, this degree of scattering is extensive, which leads to translucency, and in some instances, even opacity. Highly amorphous polymers are completely transparent.

4.7 Optical Properties of Semiconductors

Like other solids, semiconductor materials have an electronic band structure determined by the crystal properties of the material. In semiconductors, the Fermi level lies in the middle of a forbidden band or band gap between the valence band and the conduction band. The valence band, immediately below the forbidden band, is very nearly completely occupied. The conduction band, above the Fermi level, is nearly completely empty. Because the valence band is so nearly full, its electrons are not mobile, and cannot flow as electric current.

However, if an electron in the valence band acquires enough energy to reach the conduction band, it can flow freely among the nearly empty conduction band

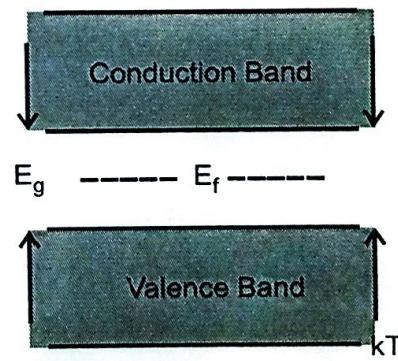


Figure 10 Band structure of semiconductor

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energy states. Also it leaves behind a hole that can flow as current exactly like a positively charged electron.

Carrier generation describes processes by which electrons gain energy and move from the valence band to the conduction band, producing two mobile carriers namely free electrons and holes.

Recombination describes processes by which a conduction band electron loses energy and re-occupies the energy state of a hole in the valence band.

In a semiconductor at thermal equilibrium generation and recombination are balanced, so that the net charge carrier density remains constant.

4.7.1 Generation and recombination processes

Carrier generation and recombination are always happening in semiconductors, both optically and thermally, and their rates are in balance at equilibrium. The product of the electron and hole densities (n and p) is a constant ($n_0 p_0 = n_i^2$) at equilibrium, maintained by recombination and generation occurring at equal rates.

Carrier generation and recombination occur when an electron makes transition from the valence band to conduction band in a semiconductor. These processes must conserve both quantized energy and momentum. This as a result of interaction of transition electron with other electrons, holes, photons, or the vibrating crystal lattice (phonons). The following models are used to describe generation and recombination, depending on which particles are involved in the process.

- photon transition or optical generation/recombination,
- phonon transition or Shockley-Read-Hall generation/recombination,
- Auger generation/recombination or three particle transitions, and
- impact ionization

i) Photon Transition

The photon transition is a direct, band-to-band, generation/recombination process. The generation of an electron-hole pair, is triggered by a sufficiently energetic photon which transfers its energy to a valence band electron which is excited to the conduction band leaving a hole behind Figure (11a). The photon energy for this process has to be at least of the magnitude of the band-gap energy E_g ($h\nu \geq E_g$). In the reverse process, an electron from the conduction band falls back to the valence-band and releases its energy in the form of a photon (light) as shown in Figure.(11b).

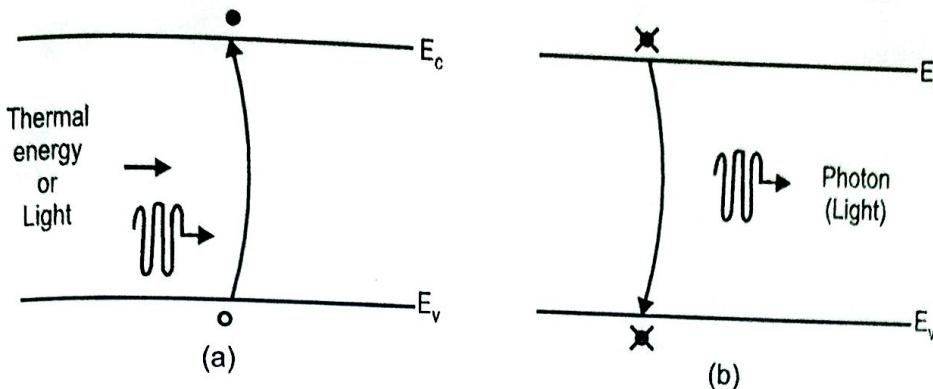


Figure 11 Photon transition (a) generation (b) recombination

For this type of transition to occur the energy and the momentum have to be conserved. The energy is emitted or absorbed via a photon with the energy $E = h\nu$. However, as the momentum of a photon is very small no momentum transfer is possible. Therefore, only direct band-to-band transitions are possible, where no change in momentum is necessary. In direct band gap semiconductors like *GaAs*, this effect is very important. Silicon and germanium are indirect semiconductors having their valence band maximum and their conduction band minimum on different positions in momentum space. Hence this type of direct transitions are not possible for those materials as studied in chapter 2.

ii) Phonon Transition

This process is trap-assisted utilizing a lattice defect at the energy level E_T within the semiconductor band-gap. Since the theory describing this effect was given by Shockley, Read, and Hall this transition is named after them as Shockley-Read-Hall (SRH) generation/recombination.

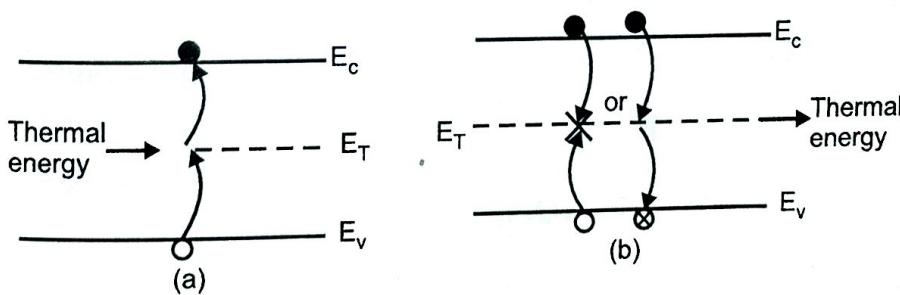


Figure 12 Phonon transition (a) generation (b) recombination

Both, the recombination and the generation processes are two-step processes. For the SRH generation of an electron-hole pair external energy has to be supplied from the lattice (Figure 12(a)). During recombination of an electron-hole pair, the excess energy of approximately the band-gap energy is transferred to the crystal lattice via lattice vibrations, (phonons) as shown in Figure 12(b).

iii) Auger generation/recombination

In the direct band-to-band Auger mechanism, three particles are involved. During generation, an electron hole pair is generated consuming the energy of a highly energetic electron from conduction band or hole from valence band as shown in Figure 13(a). In the opposite process, when an electron hole pair recombines, the excess energy is transferred to a third particle either electron in conduction band or hole in valence band as shown in Figure 13(b).

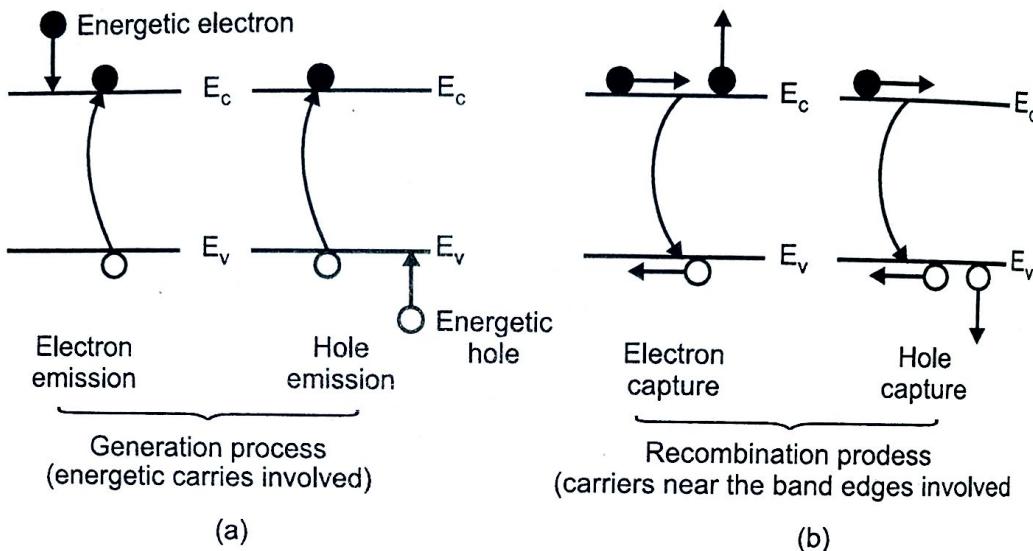


Figure 13 Auger generation (a) and recombination (b)

iv) Impact Ionization

Impact ionization is a pure generation process. It is exactly the same mechanism as the generation part of the Auger process: a highly energetic carrier moves to the conduction or valence band, depending on the carrier type, and the excess energy is used to excite an electron from the valence band to the conduction band generating another electron hole pair.

4.8 Optical Applications

Carrier generation and recombination processes are fundamental to the operation of many optoelectronic semiconductor devices, such as p-n junction diodes, photodiodes, LEDs and laser diodes. Now let us study about few of such devices which find applications in our day-to-day life.

4.9 Photo Diode

A **photo diode** is a light sensitive PN junction capable of converting incident light into a voltage or current signal. It works on the principle of photo generation.

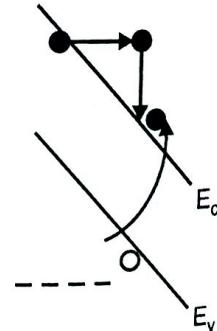


Figure 14 Impact ionization

Photodiodes can be used to detect the presence of minute quantities of light and can be calibrated for extremely accurate measurements from intensities below 1 pW/cm² to intensities above 100 mW/cm².

4.9.1 Symbol of photo diode

The symbol of photo diode is shown in Figure.15

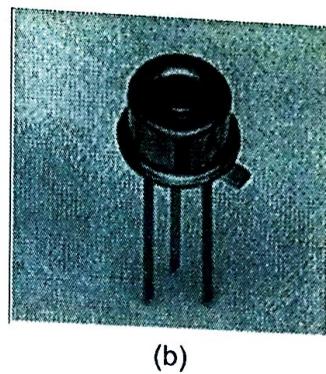
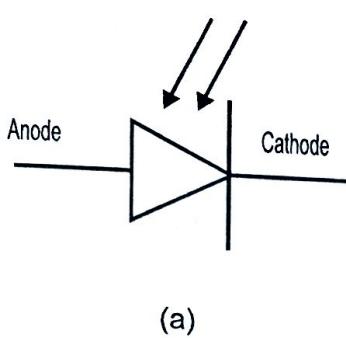


Figure 15 (a) Photo diode symbol (b) Photodiode

Photo diode has two terminals anode and cathode with the arrows indicating that the light rays falling on photo diode.

4.9.2 Types of photo diodes

There are mainly three types of photo diodes

- PN junction photo diode
- PIN photo diode
- Avalanche photo diode

Normal PN junction photo diode is used in low frequency and low sensitive applications. When high frequency of operation and high sensitivity are needed PIN photo diodes or avalanche photo diodes are used.

4.9.3 Photodiode construction

A normal PN junction photo diode is made by sandwiching a P type semiconductor into N type semiconductor. Let us now study the construction of Planar diffused silicon photodiodes. They are simply P-N junction diodes.

A P-N junction can be formed by diffusing either a P-type impurity (anode) such as boron into a N-type bulk silicon wafer, or a N-type impurity such as phosphorous into a P-type bulk silicon wafer. The diffused area defines the photodiode active area.

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The contact pads are deposited on the front active area on defined areas, and on the backside, completely covering the device. The active area is then passivated with an antireflection coating to reduce the reflection of the light for a specific predefined wavelength. The non-active area on the top is covered with a thick layer of silicon oxide.

By controlling the thickness of bulk substrate, the speed and responsivity of the photodiode can be controlled. All the sides of PN junction diode are enclosed in metallic case or painted black except for one side on which radiation is allowed to fall. The photodiodes must be operated in the reverse bias mode, i.e. a negative voltage applied to anode and positive voltage to cathode.

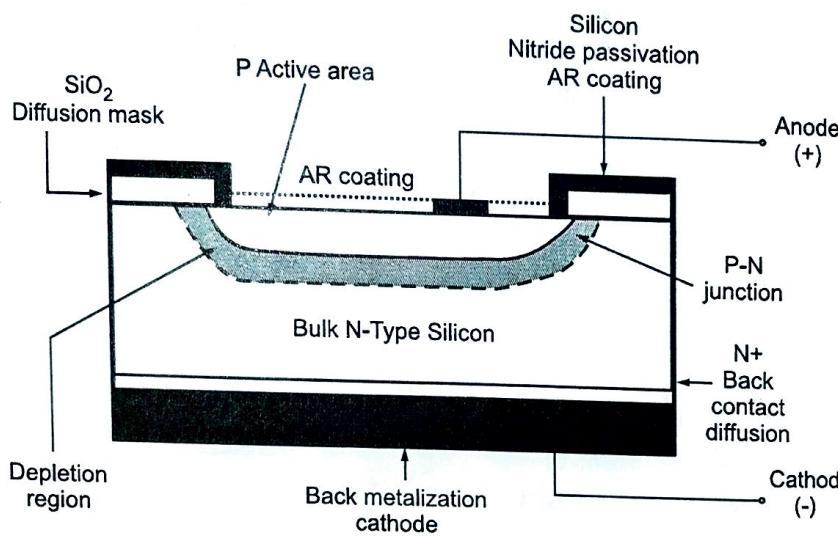


Figure 16 Structure of a photodiode

4.9.4 Current-voltage characteristics of a photodiode (Photo current in photo diodes)

The current-voltage characteristic of a photodiode with no incident light is similar to a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as:

$$I_D = I_{SAT} \left(e^{\frac{qV_A}{k_B T}} - 1 \right) \quad (19)$$

where I_D is the photodiode dark current, I_{SAT} is the reverse saturation current, q is the electron charge, V_A is the applied bias voltage, $k_B = 1.38 \times 10^{-23} J/K$, is the Boltzmann constant and T is the absolute temperature.

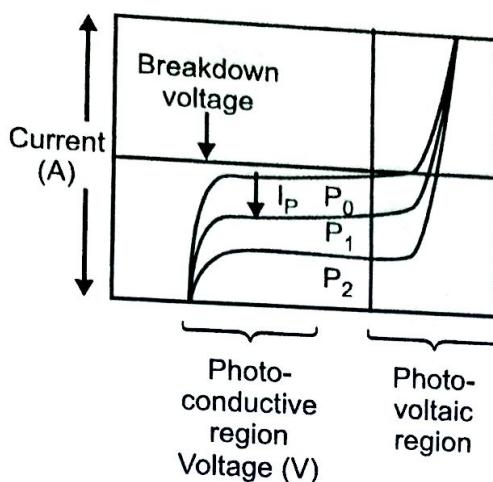


Figure 17 Characteristic I-V Curves of a typical photodiode for Photoconductive and Photovoltaic modes of operation. $P_0 - P_2$ represent different light intensities.

This relationship is shown in Figure 17. From equation 19, three various states can be defined:

- (a) $V_A = 0$, in this state, the dark current $I_P = 0$.
- (b) $V_A = +V$, in this state the current increases exponentially. This state is also known as forward bias mode.
- (c) $V_A = -V$, when a very large reverse bias is applied to the photodiode, the dark current becomes the reverse saturation current, I_{Sat} .

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent (I_P). Thus:

$$I_{\text{TOTAL}} = I_{\text{SAT}} \left(e^{\frac{qV_A}{k_B T}} - 1 \right) - I_P \quad (20)$$

where I_P is defined as the photocurrent given by $I_p = R_\lambda P_I$ where R_λ is the responsivity and P_I is incident light intensity.

A photo diode is always operated in reverse bias mode (Figure 18). As the applied reverse bias increases, there is a sharp increase in the photodiode current. The applied reverse bias at this point is referred to as breakdown voltage (Figure 17). This is the maximum applied reverse bias, below which, the photodiode should be operated (also known as maximum reverse voltage) so that we get a linear I-V characteristic curve as shown in Figure 19.

From the photo diode characteristics (Figure 19) it is seen clearly that the photo current is almost independent of applied reverse bias voltage. For zero luminance the photo current is almost zero except for small dark current. It is of the order of nano amperes. As optical power increases the photo current also

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increases linearly. The maximum photo current is limited by the power dissipation of the photo diode.

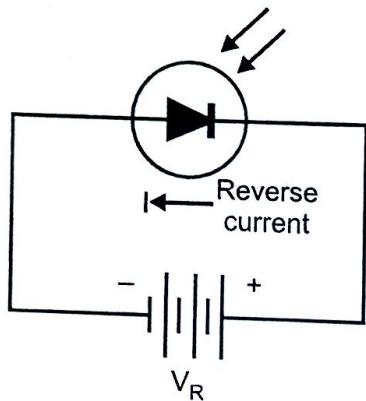


Figure.18 Photodiode under reverse bias

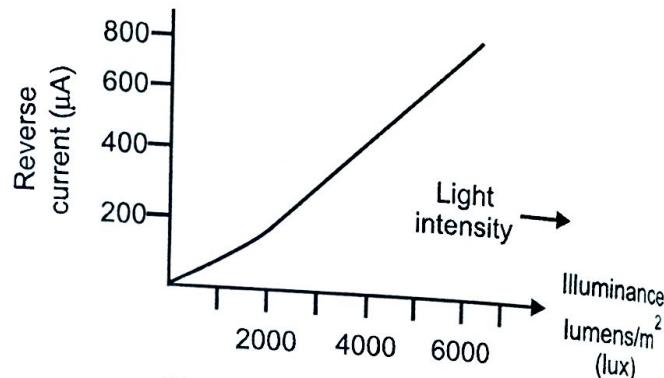


Figure.19 Photo diode characteristics

4.9.5 Modes of operation of photo diode

A photo sensitive diode can be operated mainly in two modes

- Photo conductive mode
- Photo voltaic mode

The photo detectors are operated in photo conductive mode. The photo diodes used as photo detectors are optimized (in the physical construction of the device itself) to have fast response times.

Solar cells are operated in Photo voltaic mode. Photo diodes used in such electrical energy generation are optimized to have high efficiency of energy conversion.

Disadvantage of normal PN junction photo diodes

- Normal PN junction photo diodes exhibit slow response i.e., they have very high response times.
- They have very low sensitivity.
- Quantum efficiency is low at longer wavelengths.
- Reverse current breakdown.

Applications of photo diodes

Photodiodes are utilized in such diverse applications as spectroscopy, photography, analytical instrumentation, optical position sensors, beam alignment, surface characterization, laser range finders, optical communications and medical imaging instruments.

4.10 Photo Detectors

A photo detector is a device which absorbs light and converts the optical energy into measurable electric signal (current or voltage). The photo diodes used as photo detectors are operated in photo conductive mode and optimized to have fast response times and higher quantum efficiency.

Semiconductor photodiodes are the most commonly used detectors. Semiconductor photodiodes are made of *Si*, *Ge*, *GaAs*, *InGaAs*, etc.

Working of a photodiode as photo detector

The following illustration in Figure 20, shows how a photo detector work. The detector is electrically reverse-biased.

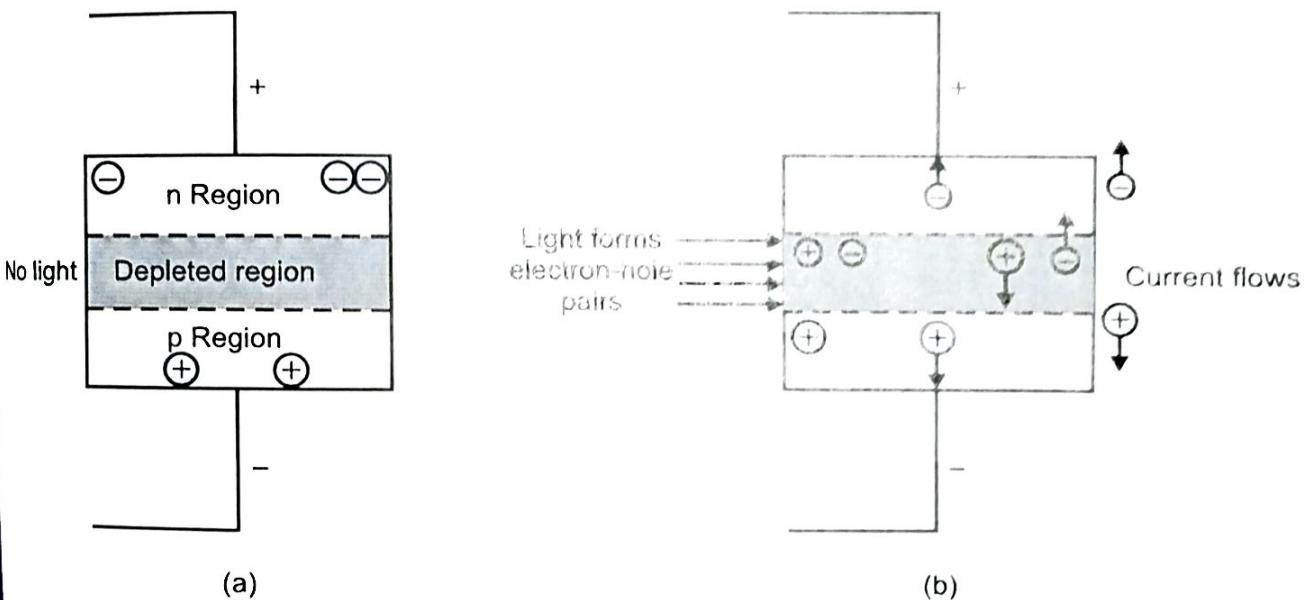


Figure 20 (a) Photo diode when no light falls on it; (b) Photo diode when light falls on it

With no light:

In Figure 20(a), when there is no light, the reverse bias draws current-carrying electrons and holes out of the p-n junction region, creating a depleted region. Hence there is no current through the diode.

With light:

In Figure 20(b), when light falls on the detector, photons with the proper energy (wavelength) create electron-hole pairs in this region by raising an electron from the valence band to the conduction band, leaving a hole behind. The bias voltage causes these current carriers to drift quickly away from the junction region,

so a current flows proportional to the intensity of light falling on the detector. The wavelengths at which the detector responds to light depend on the detector's material composition.

4.11 PIN-Diode as Detector

The most common photodiode detector is the Silicon PIN photodiode. The Silicon PIN photodiode is capable of delivering high-speed response when operated with an applied reverse voltage.

The PIN diode has three layers such as

- P-type layer
- Intrinsic layer
- N-type layer

This is shown schematically in Figure 21.

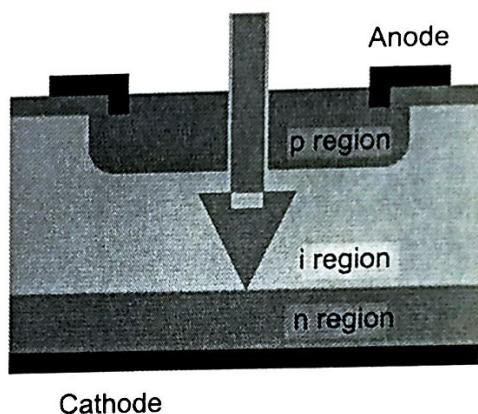


Figure 21 Cross section of the silicon PIN photodiode, showing the intrinsic region between the p-type and n-type regions.

The PIN photodiode is operating in the photoconductive mode where a reverse bias is applied. This intrinsic region serves to increase the width of the junction by having a huge amount of charge carriers from the p-type and n-type regions. This in turn provides for more efficient conversion of photons to charge carriers and increased responsivity.

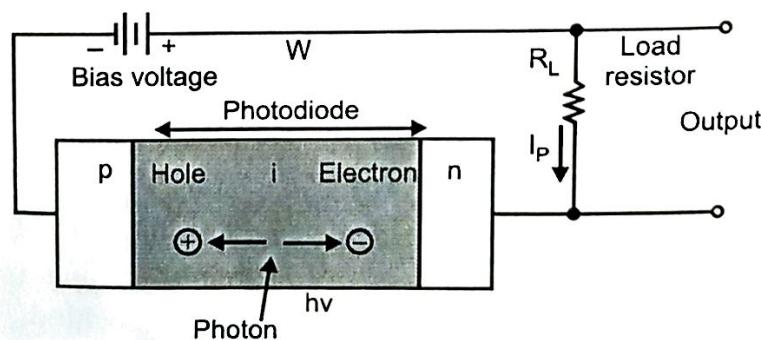


Figure 22 PIN Photo diode when light falls on it

4.11.1 Charge carrier generation

When photons of energy greater than the band gap of silicon (approximately 1.1 eV) fall on the photodiode, they are absorbed and electron-hole pairs, which are charge carriers, are created. The separated electron and hole are then attracted by the positive and negative terminals respectively. As the two sides are electrically connected, a generated external current flows through the external circuit, and this current is known as the **photocurrent**.

4.11.2 Reverse bias

In the reverse-biased state, a voltage is applied across the device such that it adds to the built-in voltage and enhances the flow of charge carriers, resulting in a wider depletion region. The higher electric field in the depletion region decreases the probability that charge carriers can diffuse from one side of the junction to the other, hence the diffusion current decreases.

4.11.3 Photocurrent

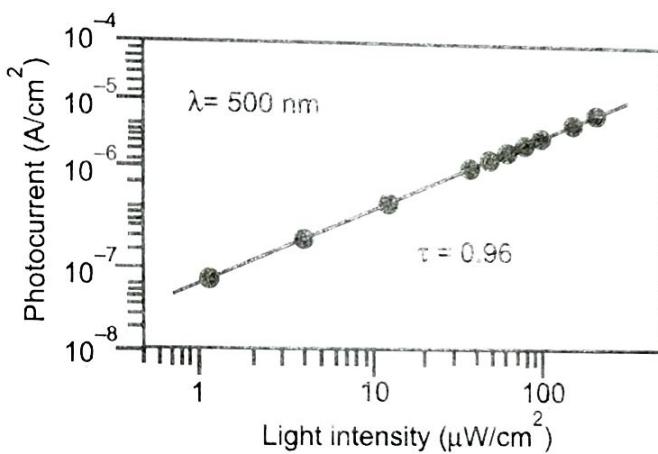


Figure 23 Incident optical power Vs generated photocurrent

The amount of photocurrent (I_p) generated is dependent on the amount of incident optical power (P). It follows that as more photons are incident on the active area of a photodiode, more charge carriers are created. The high electric field present in the depletion region causes photo-generated carriers to separate and be collected across the reverse-biased junction and thus a higher photocurrent is generated. This relationship can be written as

$$I_p = R_\lambda P_I$$

where, R_λ = Responsivity of the photodiode and P_I is the incident light intensity

4.11.4 Saturation effect

However, at high intensity, it is expected that the incident light power and generated photocurrent do not exhibit a linear relationship, and the photodiode is

saturated. This is possibly due to the depletion of available electron-hole pairs, thus excess photons are not absorbed.

4.12 Avalanche photodiode

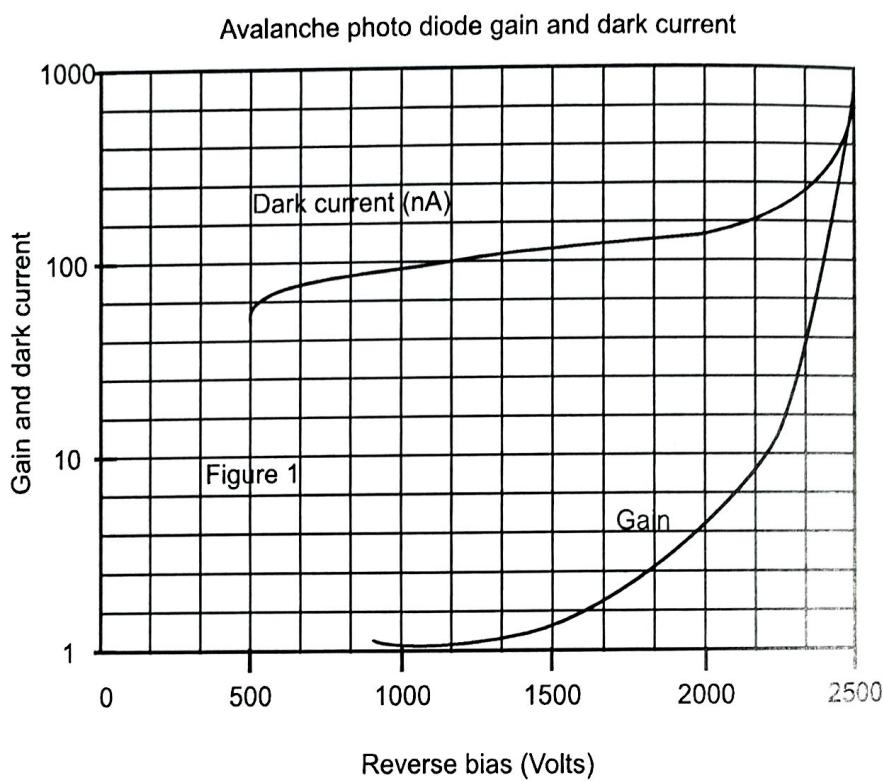


Figure 24 Avalanche photodiode gain and dark current

The avalanche photodiode possesses a similar structure to that of PN photodiode. Avalanche photodiode is operated at high reverse bias close to the breakdown, which causes photo excited charge carriers to accelerate in the depletion region and produce additional carriers by avalanching.

The avalanche action enables the gain of the diode to be increased many times (Figure 24), providing a much greater level of sensitivity.

Advantages of avalanche photodiode

- High level of sensitivity as a result of avalanche gain

Disadvantages of avalanche photodiode

- Much higher operating voltage may be required.
- Avalanche photodiode produces a much higher level of noise than a PN photodiode.
- Avalanche process means that the output is not linear.

4.13 Optical Characteristics - Detector Performance Parameters

Quantum Efficiency (QE): Quantum efficiency is defined as fraction of incident photons contributing to photo current. It is unit less as it is a fraction.

$$QE = \frac{N_E}{N_{\text{Photons}}}$$

where N_E is the number of generated carriers/unit time

N_{Photons} is the number of incident photons/unit time

$$\text{Also } QE = \frac{R_{\lambda \text{observed}}}{R_{\lambda \text{ideal}}} = R_\lambda \frac{hc}{\lambda q} = 1240 \frac{R_\lambda}{\lambda}$$

where $h = 6.63 \times 10^{-34} J - s$, is the Planck constant, $c = 3 \times 10^8 \text{ m/s}$, is the speed of light, $q = 1.6 \times 10^{-19} \text{ C}$, is the electron charge, R_λ is the responsivity in A/W and λ is the wavelength in nm.

Responsivity (R_λ): The ratio of photocurrent to a corresponding level of incident light is called responsivity of the detector. Responsivity varies with wavelength.

Spectral Responsivity: Responsivity plotted as a function of wavelength gives Spectral Responsivity of the detector.

Rise Time (T_r): The time required for the photodetector output level to change from 10% to 90% of the peak output level.

Fall Time (T_f): The time required for the photodetector output level to change from 90% to 10% of the peak output level.

Frequency Response: The electrical output response to a sinewave modulated light input. This is typically measured in dB vs. Hertz.

Cut Off Frequency: The frequency at which the detector output power decreases by 3 dB from the output at 100 kHz.

Bandwidth: The difference between the high and low cutoff frequencies, measured in Hertz. The bandwidth of the photodetector is approximately related to the rise time (T_r) by:

$$\text{Bandwidth (Hz)} \approx 0.35/T_r$$

Dark Current: The small current which flows when a reverse voltage is applied to a photodiode and no optical input is present.

Junction Capacitance: An effective capacitor is formed at the P-N junction of a photodiode. The junction capacitance is the major factor in determining the speed of a photodiode.

Reverse Breakdown Voltage: The level of reverse voltage which can cause breakdown and deterioration of the detector.

Noise Equivalent Power (NEP): The amount of incident photon energy equivalent to the intrinsic noise level of the device, providing a signal-to-noise ratio of 1.

4.13.1 Applications of photo detectors

Photo detectors are used in various applications such as radiation detection, smoke detection, flame detection and to switch on/off relays for street lighting.

4.14 Solar Cell

A **solar cell** (also called a **photovoltaic cell**) is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect. It is a form of **photo-electric cell** which, when exposed to light, can generate and support an electric current without being attached to any external voltage source.



Figure 25 Solar cell

Solar cells generate electricity from sunlight. Cells can be described as photovoltaic even when the light source is not necessarily sunlight (lamp light, artificial light, etc.,).

The solar cell works in three steps:

1. Photons in sunlight fall on the solar panel and are absorbed by semiconducting materials, such as silicon.
2. Electrons (negatively charged) are knocked loose from their atoms, causing an electric potential difference. Current starts flowing through the material to cancel the potential and this electricity is captured. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.
3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

4.14.1 I-V Characteristics of a solar cell

Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module. They show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell. It gives a detailed description of its solar energy conversion ability and efficiency.

Solar cells produce direct current (DC) electricity. Since power equals current times voltage we represent the current versus the voltage for a solar cell (photovoltaic device). The intensity of the solar radiation (irradiance) that hits the cell controls the current (I), while the increase in the temperature of the solar cell reduces its voltage (V).

I-V curves provide the information required to operate the system as close to its optimal peak power point (MPP) as possible at the existing conditions of irradiance and temperature.

Solar cell I-V characteristic curve

The Figure 26 shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions.

- The power delivered by a solar cell is the product of current and voltage ($I \times V$). Multiplication is done, point by point, for all voltages from short-circuit to open-circuit conditions and the power curve is obtained for a given radiation level.
- When the solar cell is open-circuited (i.e., not connected to any load) the current is at its minimum (zero) and the voltage across the cell is at its maximum, known as ***open circuit voltage***, or V_{oc} .
- At the other extreme, when the solar cell is short circuited (i.e., connected to a load) the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as ***short circuit current***, or I_{sc} . In other words, the maximum voltage available from a cell is at open circuit, and the maximum current at closed circuit.
- However, there is one particular combination of current and voltage for which the power reaches its maximum value, at I_{mp} and V_{mp} . This point at which the cell generates maximum electrical power shown at the top right area of the inner rectangle is called the “***Maximum Power Point***” or MPP. Therefore the ideal operation of a photovoltaic cell (or panel) is defined to be at the maximum power point. The maximum power point (MPP) of a solar cell is positioned near the bend in the I-V characteristics curve.
- Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature.

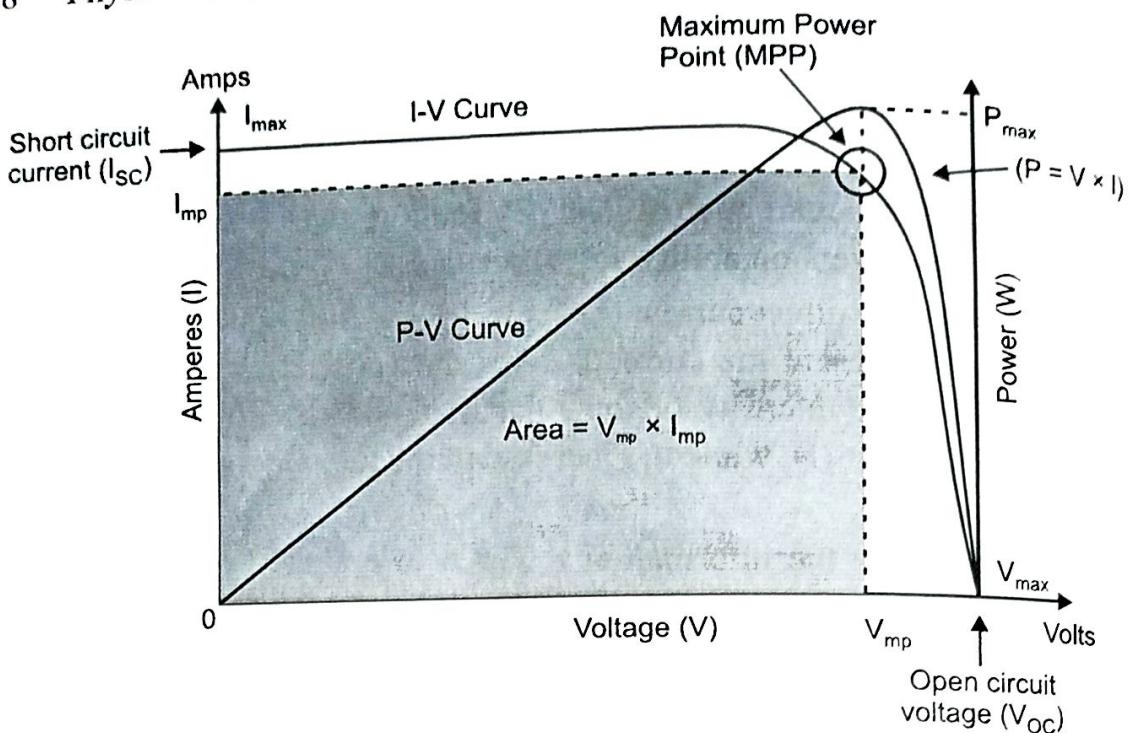


Figure 26 Solar cell I-V characteristic curve

Thus Solar Cell I-V Characteristic Curves are graphs of output voltage versus current for different levels of intensity of light and temperature and tell us about a PV cell or panel's ability to convert sunlight into electricity.

4.14.2 Efficiency of solar cells

The efficiency of a solar cell may be divided into reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency and conductive efficiency. The overall efficiency is the product of each of these individual efficiencies.

4.14.3 Solar cell materials

By far, the most prevalent bulk material for solar cells is crystalline silicon (abbreviated as a group as $c-Si$), also known as "solar grade silicon". Bulk silicon is separated into multiple categories according to crystallinity and crystal size such as ingot, ribbon, or wafer.

Thin-film technologies reduce the amount of material required in creating the active material of solar cell. Most thin film solar cells are sandwiched between two panes of glass to make a module. Cadmium telluride ($CdTe$), copper indium gallium selenide ($CIGS$) and amorphous silicon ($A-Si$) are three thin-film technologies often used as outdoor photovoltaic solar power production. $CdTe$ technology is most cost competitive among them.

4.14.4 Advantages of solar power

The first commercial use of photovoltaic cells nearly 50 years ago was powering communications satellites in near-earth orbit. Today, the declining cost and

increasing efficiency of solar energy technology has given rise to practical applications on earth - from powering personal electronic devices, homes and factories to generating utility-scale power.

1. Solar energy provides a huge advantage for satellites because they can be launched into orbit without the added weight of a fuel supply.
2. The advantages of solar energy on earth are even greater: Solar-generated energy provides abundant and pollution-free energy.
3. Solar power generation provides energy when and where we need it, and is highly scalable to match our electrical demand.
4. Since solar energy cells have no moving parts, they are reliable and easy to maintain.

4.15 Light Emitting Diodes (LED)

Emission of radiation from a solid when it is supplied with some form of energy is known as luminescence.

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

$$\frac{hc}{\lambda} = E_2 - E_1 = E_g$$

i.e.
$$\boxed{\lambda = \frac{hc}{E_g}} \quad (21)$$

Usually E_1 and E_2 are two groups of energy levels and hence instead of a single wavelength emission, a band of wavelength is emitted.

PN junction diode operated under forward bias gives rise to injection luminescence. Under forward bias, majority carriers from both sides of the junction cross the internal potential barrier and enter the other side of the junction where they are minority carriers. This process is called **minority carrier injection**. These excess minority carriers while diffusing away from the junction undergo radiative recombination with majority carriers as illustrated in Figure.27, emitting photons. In reverse bias, no carrier injection takes place and consequently no light is emitted.

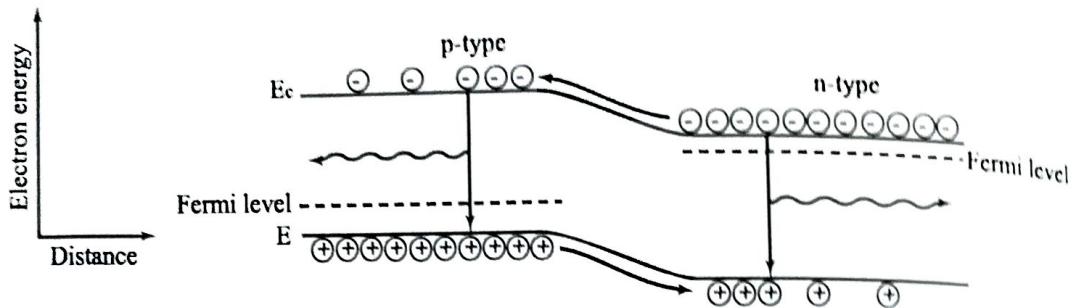


Figure 27 Injection of minority carriers and subsequent radiative recombination with the majority carriers in a forward biased p-n junction.

The number of radiative recombinations is proportional to the carrier injection rate and hence to the total current flowing.

The current voltage ($I - V$) relationship for a diode can be written as

$$I = I_0 \left[\exp \left(\frac{eV}{\beta kT} \right) - 1 \right] \quad (22)$$

where I_0 is the saturation current and β varies between 1 and 2 depending on the semiconductor and the temperature.

Actually, all semiconductor diodes produce radiation when electrons from the conduction band recombine with the holes in the valence band and the emitted radiation is absorbed by the surrounding semiconductor material. In an LED, the semiconductor has a high energy gap and the junction is constructed such that radiation from the junction can escape.

Solved Problem 4.1 Calculate the wavelength of radiation emitted by a LED made up of GaAs with band gap energy 1.43 eV.

Solution

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

With $h = 6.62 \times 10^{-34}$ joule sec

$$c = 3 \times 10^8 \text{ m/sec}$$

$$E_g = 1.43 \text{ eV} = 1.43 \times 1.6 \times 10^{-19} \text{ joule}$$

$$\lambda = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{1.43 \times 1.6 \times 10^{-19}} \\ = \frac{19.86}{2.288} \times 10^{-7} = 0.868 \mu\text{m}$$

(Answer)

4.15.1 LED Materials

The main requirements for a suitable LED material are

- 1) It must have an energy gap of appropriate width (The energy gaps greater than or equal to about 2 eV are required to obtain visible radiation).
- 2) Both *p* and *n* types must exist with low resistivities.
- 3) Efficient radiative pathways must be present.

Silicon carbide (*SiC*) can be doped as both *n* and *p* type. Doping with *B*, *Al*, *Sc* and *Be* gives rise to yellow, blue, green and red emission respectively. But since *SiC* is an indirect band gap material radiative transition efficiency is low.

Ga, *As*, *GaP* and the ternary alloy $\text{GaAs}_{1-x}\text{P}_x$ are most important III-V compounds used.

Gallium arsenide (*GaAs*)

This is a direct bandgap semiconductor with $E_g = 1.443 \text{ eV}$ ($\lambda_g = 860 \text{ nm}$); *p-n* junctions are readily formed. When *GaAs* is doped with silicon, based on growing condition, either silicon can replace *Ga* or *As*. On replacing *Ga* it acts as a donor and on *As* replacement it acts as an acceptor. In silicon doped diodes, the emission lies between 910 and 1020 nm. This has high quantum efficiency. These diodes have become standard near-IR emitting devices.

Gallium phosphide (*GaP*)

This is an indirect bandgap semiconductor with $E_g = 2.26 \text{ eV}$ ($\lambda_g = 549 \text{ nm}$). Group V elements, such as *N* and *Bi*, are commonly used as dopants. Since they have the same valency as the atoms which they replace (*P*), they do not form normal donor or acceptor states. As the impurity atom differs considerably from the atom it replaces both in its size and its tendency to acquire negative charge, it acts as a trapping centre called *isoelectronic traps*. Once a carrier is trapped, the resulting potential attracts a carrier of the opposite charge and emits radiation. The nitrogen isoelectronic traps result in peak emission at about 565 nm, i.e. green radiation. At high nitrogen concentrations the room temperature emission shifts to 590 nm (i.e. yellow). Using *Zn*, *O* for double doping, emission at 690 nm (i.e. red) is also possible from *GaP*.

Gallium arsenide phosphide ($\text{GaAs}_{1-x}\text{P}_x$)

This material changes from being a direct bandgap material (when $x < 0.45$) to being an indirect bandgap material (when $x > 0.45$). At changeover point, the

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$E_g \simeq 2.1$ eV. From $GaAs_{0.6}P_{0.4}$, red emission is obtained. From $GaAs_{0.35}P_{0.65}$: N and $GaAs_{0.15}P_{0.85}$: N, orange and yellow emissions are obtained respectively.

Gallium aluminium arsenide ($Ga_xAl_{1-x}As$)

In heterojunction formed between *n*-type $Ga_{0.3}Al_{0.7}As$ and *p*-type $Ga_{0.6}Al_{0.4}As$ (with Zn as dopant) radiative recombination takes place and emission with higher efficiency occurs at 650 nm. When Si is used as dopant to form both donor and acceptor states, by varying Al concentration, bandgap can be varied and emission between 870 and 890 nm can be obtained.

Table 2 summarizes the characteristics of the most commonly used LED materials.

Table 2 Characteristics of LED materials

Material	Dopant	Peak emission (typical values) (nm)	Colour	External quantum efficiencies (commercial diodes) (%)
$GaAs$	Si	910 → 1020	Infrared	10
GaP	N	570	Green	0.1
GaP	N, N	590	Yellow	0.1
GaP	Zn, O	700	Red	4
$GaAs_{0.6}P_{0.4}$		650	Red	0.2
$GaAs_{0.35}P_{0.65}$	N	632	Orange	0.2
$GaAs_{0.15}P_{0.85}$	N	589	Yellow	0.05
$Ga_{0.6}Al_{0.4}As$	Zn	650	Red	3
$Ga_xAl_{1-x}As (1 < x < 0.7)$	Si	870 → 890	Infrared	15

4.15.2 Construction of LED

The typical construction of an LED is shown in Figure 28. LED has to be designed and constructed in such a way that most of the radiative recombinations take place from the side of the junction nearest to the surface so that loss due to reabsorption is minimized. For this, *p-n* junction layer has to be parallel and closer to the surface layer.

- The LED is constructed on a GaP *n*-doped substrate. A thin epitaxial *p*-doped GaP layer is grown on the top of this substrate.
- Electrical contacts are made leaving as much of the upper surface of the *p*-material uncovered.
- The recombination takes place and radiation is generated between *p* and *n* layers i.e. *p-n* junction. Since GaP layer is transparent, the radiation escapes through the top layer. To the bottom electrode a reflective layer is added to improve the efficiency.

Although the internal quantum efficiencies of some LED materials can approach 100 %, the external efficiencies are much lower. The main reason is that most of the emitted radiation strikes the material interface at angles greater than critical angle and so lost due to total internal reflection. Since the III-V materials have high refractive indices, the critical angles are small. For example in GaP and air interface, since the critical angle is 17° , the rays incident at an angle greater than this are lost.

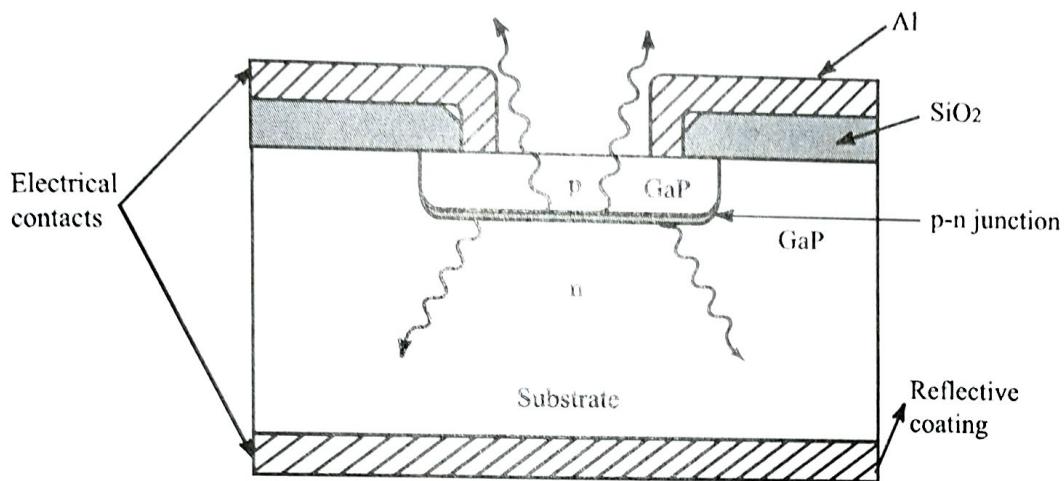


Figure 28 Construction of a typical LED.

There are two ways of improving the situation; the first is to ensure that most rays strike the surface at angles less than critical angle. This is achieved by shaping the semiconductor/air interface into a hemisphere, as shown in Figure 29(a). In this the *p* material is made into a hemispherical dome. More radiation then strikes the semiconductor/air interface at less than the critical angle and hence are not lost. This technique is too difficult and more expensive.

The second technique is to encapsulate the junction in a transparent plastic medium of high refractive index. Moulding the plastic into an approximately hemispherical shape, loss at the plastic/air interface is minimized (Figure 29(b)).

Intensity of the emission is an important optical parameter of an LED.

- The relative intensity increases with LED current.
- LED output is not monochromatic but contains considerable bandwidth (≈ 30 to 40 nm) around the central wavelength.
- Output intensity is temperature dependant. If the temperature increases by $25^\circ C$, the intensity decreases by 25 %.

Another very important characteristic of an LED is its fast response time, typically 90 ns for yellow and red and 500 ns for green. This short response time makes LEDs suitable as a source in communication links.

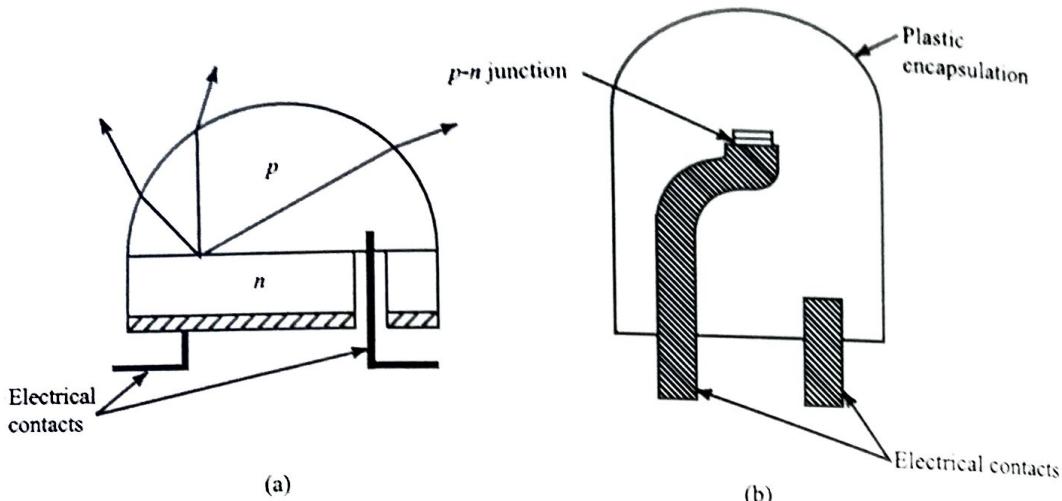


Figure 29 Two methods used to reduce reflection losses in LEDs (a) hemispherical dome made of **p** material and (b) plastic mould in hemispherical shape.

Advantages of LEDs in electronic display

1. Output is bright and the intensity can be controlled easily by varying current
2. They can be operated over a wide range of temperatures 0 to 70°C
3. Very fast response time in the order of ns and hence very useful as source for optical communication
4. Available in different colours
5. Very small in size and hence can be closely packed for high density display
6. Has long life (about 10^5 hours) and a high degree of reliability
7. The viewing angle is not limited
8. Very rugged and hence suitable for any environment.

Disadvantages of LEDs in electronic display

1. Consume more energy (i.e. high power) when compared to LCDs
2. Relatively costlier.

4.16 Organic Light Emitting Diode (OLED)

An **organic light-emitting diode (OLED)** is a light-emitting diode (LED) in which the photo emissive electroluminescent layer is a film of organic compound. This layer of organic semiconductor is situated between two electrodes; it emits light in response to an electric current.

OLEDs are used to create digital displays in devices such as television screens, computer monitors, portable systems such as mobile phones etc. A major area of research is the development of white OLED devices for use in solid-state lighting applications.

An OLED display works without a backlight; thus, it can display deep black levels and can be thinner and lighter than a liquid crystal display (LCD). In low ambient light conditions (such as a dark room), an OLED screen can achieve a higher contrast ratio than an LCD.

4.16.1 Construction

- A typical OLED is composed of a layer of organic materials situated between two electrodes, the anode and cathode deposited on substrates.
- The organic molecules are electrically conductive. Since these materials have conductivity levels ranging from insulators to conductors, they are therefore considered as organic semiconductors.
- The highest occupied molecular orbitals (HOMO) and lowest unoccupied molecular orbitals (LUMO) of organic semiconductors are analogous to the valence and conduction bands of inorganic semiconductors.

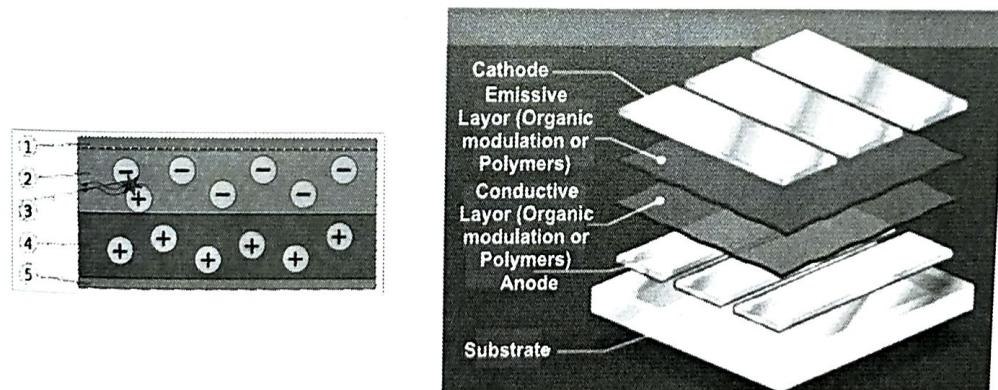


Figure 30 Schematic of a bilayer OLED: 1. Cathode (−), 2. Emissive Layer, 3. Emission of radiation, 4. Conductive Layer, 5. Anode (+)

Originally, the most basic polymer OLEDs consisted of a single organic layer. Multilayer OLEDs can be fabricated with two or more layers in order to improve device efficiency. Many modern OLEDs incorporate a simple bilayer structure, consisting of a conductive layer and an emissive layer.

Indium tin oxide (*ITO*) which is transparent to visible light is commonly used as the anode material. It has a high work function and promotes injection of holes into the HOMO level of the organic layer.

A typical conductive layer may consist of PEDOT:PSS(poly(3,4-ethylene dioxythiophene) polystyrene sulfonate is a polymer mixture of two ionomers. One component sulfonated polystyrene carry a negative charge. The other component poly(3,4-ethylene-dioxythiophene) carries positive charges).

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The HOMO level of this material generally lies between the work function of ITO and the HOMO of other commonly used polymers, reducing the energy barriers for hole injection.

Metals such as barium and calcium are often used for the cathode as they have low work functions which promote injection of electrons into the LUMO of the organic layer. Such metals are reactive, so they require a capping layer of aluminium to avoid degradation.

4.16.2 Working

- During operation, a voltage is applied across the OLED such that the anode is positive with respect to the cathode.
- A current of electrons flows from cathode to anode, as electrons are injected into the LUMO of the organic layer at the cathode and withdrawn from the HOMO at the anode. This latter process may also be described as the injection of electron holes into the HOMO.
- Electrostatic forces bring the electrons and the holes towards each other and they recombine forming an exciton (a bound state of the electron and hole). This happens closer to the emissive layer, because in organic semiconductors holes are generally more mobile than electrons.
- The decay of this excited state results in a relaxation of the energy levels of the electron. This results in the emission of radiation whose frequency is in the visible region.
- The frequency of this radiation depends on the difference in energy between the HOMO and LUMO.

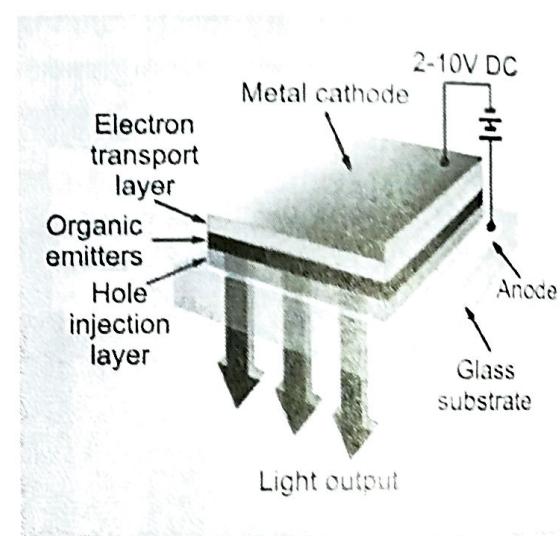


Figure 31 Working of OLED

An OLED display can be driven with a passive-matrix (PMOLED) or active-matrix (AMOLED) control scheme. In the PMOLED scheme, each row (and line) in the display is controlled sequentially, one by one. AMOLED control uses a thin-film transistor backplane to directly access and switch each individual pixel on or off, allowing for higher resolution and larger display sizes.

4.16.3 Fabrication

Transfer-printing, the technology used for the fabrication of ICs, is used to assemble large numbers of parallel OLED devices efficiently. It takes advantage of standard metal deposition, photolithography, and etching to create alignment marks commonly on glass or other device substrates.

- Thin polymer adhesive layers are applied to enhance resistance to particles and surface defects.
- Micro-scale ICs are transfer-printed onto the adhesive surface and then baked to fully cure adhesive layers.
- An additional photosensitive polymer layer is applied to the substrate to account for the topography caused by the printed ICs, reintroducing a flat surface.
- Photolithography and etching removes some polymer layers to uncover conductive pads on the ICs.
- Afterwards, the anode layer is applied to the device backplane to form bottom electrode.
- OLED layers are applied to the anode layer with conventional vapor deposition, and covered with a conductive metal electrode layer.

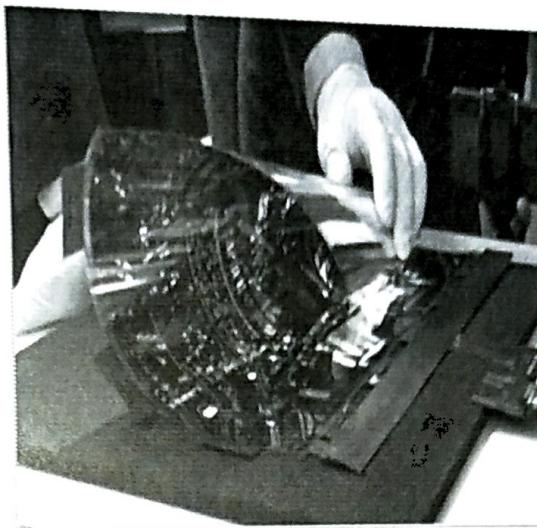


Figure 32 Flexible plastic substrate of an OLED

4.16.4 Advantages and Disadvantages

Advantages

- Lower cost in the future
- Lightweight and flexible plastic substrates
- Better picture quality
- Better power efficiency
- Faster response time

Disadvantages

- Present cost
- Lifespan (five years at 8 hours a day)
- Color balance issues



- Efficiency of OLEDs less than 10%
- Water damage may limit the longevity
- Poor outdoor performance
- More Power consumption lead to reduced battery life in mobile devices

4.17 Laser Diodes

i) Homojunction lasers

Semiconductor lasers are not very different in principle from the light emitting diodes. A $p-n$ junction provides the active medium.

- To obtain laser action we have to create population inversion and provide optical feedback.
- To obtain stimulated emission, there must be a region in the device where there are many excited electrons and holes present together. This is achieved by forming a homojunction from very heavily doped n and p materials. In such $n+$ type material, the Fermi level lies within the conduction band. Similarly, for the $p+$ type material Fermi level lies in the valence band. Figure 33 shows the heavily doped $p-n$ junction a) in equilibrium and b) with forward bias condition.

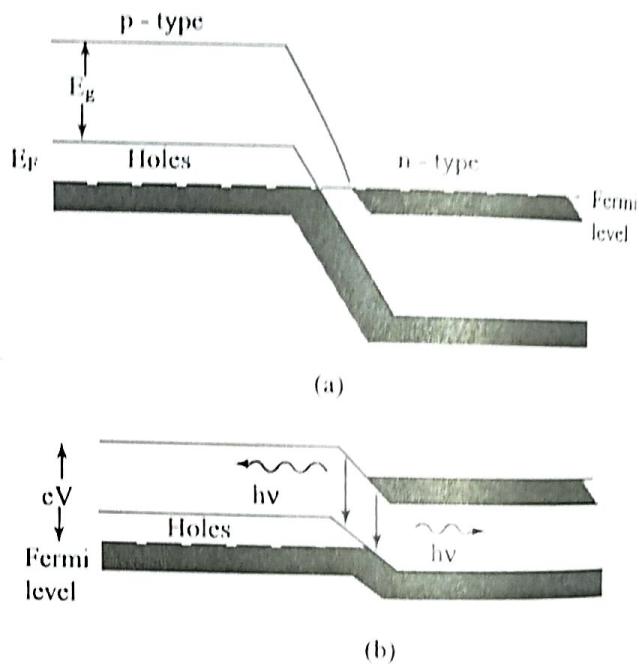


Figure 33 Heavily doped $p-n$ junction: (a) in equilibrium and (b) with forward bias (the broken lines represent the Fermi level in equilibrium (a) and with forward bias (b))

- When the junction is forward biased with a voltage that is nearly equal to the energy gap voltage (E_g/e), the electrons and holes are injected across the junction in sufficient numbers to create a population inversion in a narrow zone called the active region (Figure 34).
- If doping level of n region is higher than that of p region, then the junction current is carried mainly by electrons. If L_e is the diffusion length of elec-

trons injected into the *p* region, the thickness *t* of the active region can be approximated to L_e .

- For heavily doped *GaAs* at room temperature L_e is $1 - 3\mu\text{m}$. Since *GaAs* has direct bandgap, the electrons and holes have a higher probability of radiative recombination.
- The photons thus produced may either interact with valence band electrons and be absorbed (stimulated absorption), or interact with the conduction band electrons thereby stimulating radiative recombination (stimulated emission) producing further photons of the same energy ($E_g = h\nu$).
- If the injected carrier concentration is large, the stimulated emission can exceed the absorption so that optical amplification is achieved in the active region.
- To provide feedback, there is no need to use external mirrors in the case of diode lasers. The diode is cleaved along natural crystal plane normal to the plane of the junction so that the end faces are perfectly parallel. For *GaAs*, the junction plane is (100) and the cleaved faces are (110) planes. The high refractive index (≤ 3.6) of *GaAs* ensures sufficiently high reflection at the material/air interface so that there is no need for separate external mirrors to provide optical feedback. Laser oscillations occur when the round trip gain exceeds the total losses.

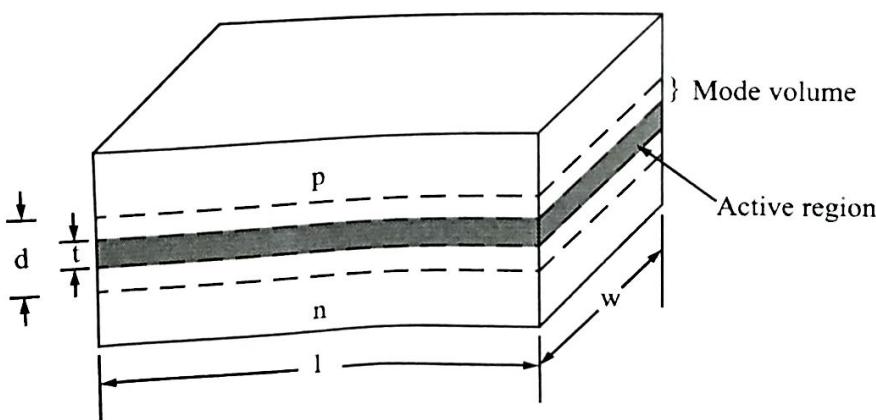


Figure 34 Diagram showing the active region and mode volume of a semiconducting laser

In semiconductors, the major losses are due to scattering at optical inhomogeneities in the semiconductor material and free carrier absorption.

In the active region additional charge carriers present increases its refractive index above that of the surrounding material, thereby forming a dielectric waveguide. Since the difference in refractive index between the centre waveguiding layer and the surrounding regions is very less (about 0.02 only), the waveguiding effect is not very efficient. Therefore the radiation generated in the active region

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extends to some extent beyond the active region, thereby forming the *mode volume*.

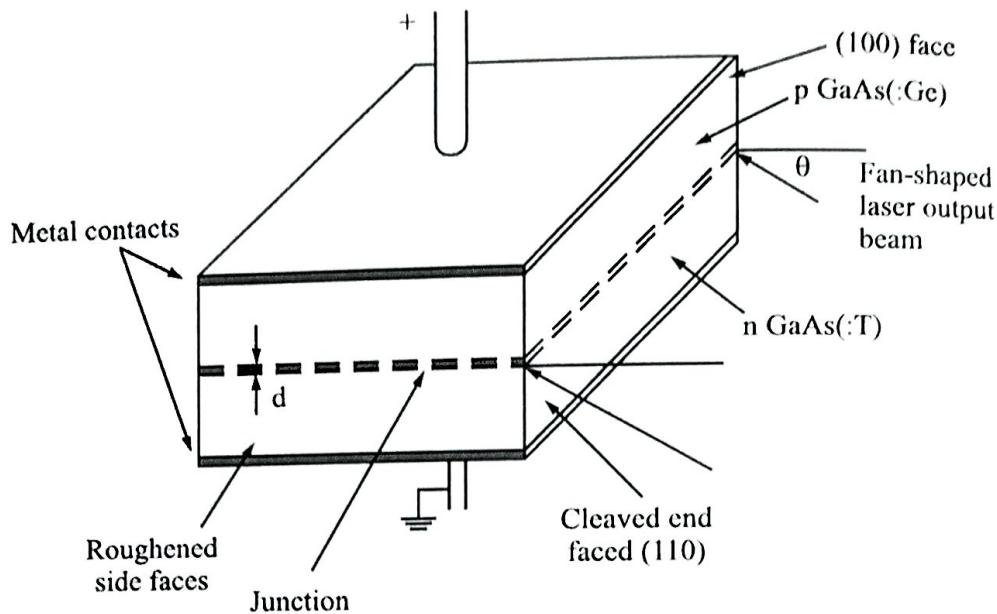


Figure 35 Schematic construction of a GaAs homojunction semiconductor diode laser having side lengths $200 - 400\mu\text{m}$. The emission is confined to the junction region

The waveguiding effect achieved in simple homojunction laser diodes of the form shown in Figure 35 just allows the laser action on vigorous pumping. They can be operated only in the pulsed mode at room temperature because of very high threshold pumping current density (typically of the order of 400 A mm^{-2}). The onset of laser action at the threshold current density is indicated by a sudden increase of light output intensity at the emitting region as shown in Figure 36.

Below threshold, spontaneous emission takes place and output emission is observed to be spectrally wide. Above threshold there is a marked decrease in spectral width and abrupt increase in intensity of the output, as illustrated in Figure 37.

The GaAs laser emits light at 900 nm (infrared) while a GaAsP laser radiates at 650 nm (visible red region). Unlike other lasers, for diode lasers divergence is high since the active region emitting radiation acts as a narrow single slit diffracting the output. Along the direction parallel to the layer, divergence is around 10° while in the direction normal to the active layer it is around 40° .

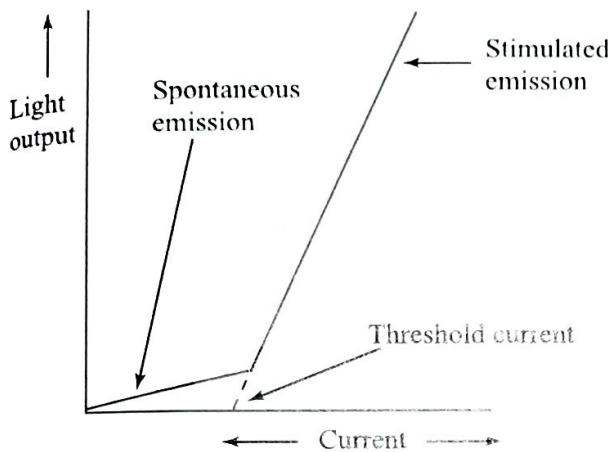


Figure 36 Light output - current characteristic of an ideal semiconductor laser.

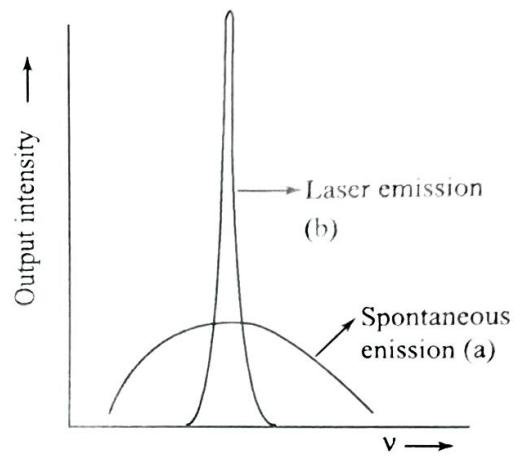


Figure 37 Radiant output as a function of frequency for a *p-n* junction laser: (a) below threshold (spontaneous emission); (b) with the dominant laser mode above threshold.

ii) Heterojunction lasers

We have seen that the threshold current density for homojunction lasers is very large due to poor optical and carrier confinement.

Heterojunction lasers have high efficiency even at room temperatures. Threshold current density reduces to 10 A mm^{-2} and CW operation is possible. Using multilayers in the laser structure, carriers are confined to a narrow region so that population is built up at lower current levels. With operating currents of less than 50 mA, output powers of about 10 mW can be produced.

Lasers with lifetimes in excess of 40,000 hours are now available corresponding to continuous operation over a five-year period.

In optical fibre communications, it is desirable to have a laser emitting at wavelengths in the region 1.1 to $1.6\mu\text{m}$, where present optical fibers have minimum attenuation and dispersion. From lasers fabricated with quaternary compounds such as $\text{Ga}_x\text{In}_{1-x}\text{As}_{1-y}\text{P}_y$, wavelengths in this range can be obtained.

Semiconductor laser applications

- Semiconductor lasers are the cheapest and smallest lasers available. They are mass produced and easily fabricated into arrays using the same techniques developed for transistors.
- The laser output can be easily modulated by modulating the current through the laser diode.
- Also they are small in size and highly efficient.

These properties have made these lasers well suited as light sources for fibre optic communication system.

4.18 Exciton

In an ideal pure semiconductor, the primary electronic excitation results in a free electron-hole pair generation. The energy required for its creation is equal to the bandgap value E_g . This energy may be supplied by the interacting photon. Once excited, both electron and hole become free charge carriers and represent two independent quasi-particles.

An exciton may be visualized as a couple consisting of an electron and the associated hole, attracted to each other via Coulomb forces.

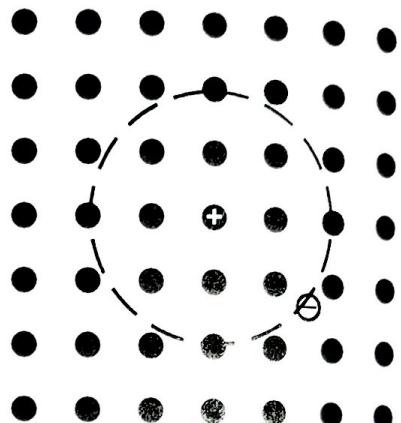


Figure 38 Exciton

Therefore, such a bound electron-hole pair no longer represents two independent quasi-particles and its internal energy is lower than E_g . The exciton is thus a quasi-particle representing the lowest electronic excitation in a semiconductor.

Thus exciton is the combination of an electron and a positive hole, which is free to move through a nonmetallic crystal as a unit. Because the electron and the positive hole have equal but opposite electrical charges, the exciton as a whole has no net electrical charge. This makes excitons difficult to detect, but detection is possible by indirect means.

- The annihilation of an exciton is accompanied by a characteristic luminescence due to radiative recombination of the electron with the hole. Exciton line shapes reflect differences in atomic dopant species.

4.19 Quantum Well

A quantum well is a very thin atomic layer of width less than 30 nm which can confine (quasi-)particles (typically electrons or holes) in the dimension perpendicular to the layer surface. The movement in the other dimensions is not restricted.

The confinement is a quantum effect. It has profound effects on the density of states for the confined particles. For a quantum well with a rectangular profile, the density of states is constant within certain energy intervals.