

Module 6 : Light Emitting Diode

Lecture : Light Emitting Diode

part - I

Objectives

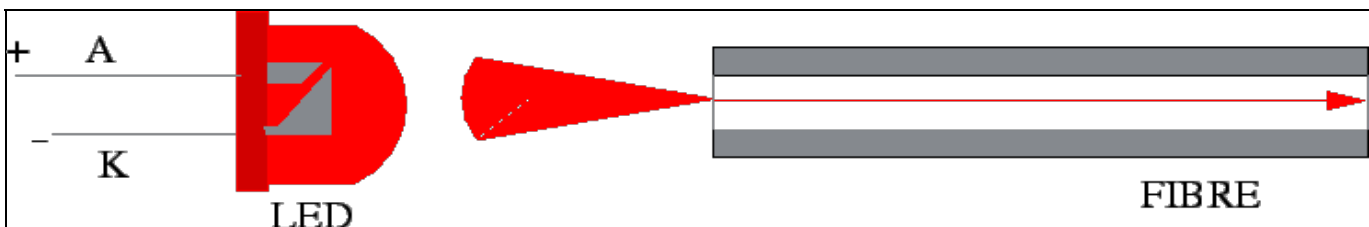
In this lecture you will learn the following

- Introduction to Light Emitting Diode (LED)
- **Principle of LED - p-n Homojunction**
- **Double Heterojunctions**
- LED Materials - Direct and Indirect Band Gaps
- LED Circuit

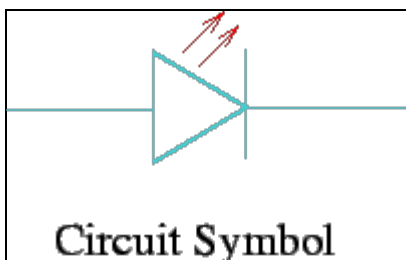
1.1 Introduction

A light emitting diode (LED) is a device which converts electrical energy to light energy. LEDs are preferred light sources for short distance (local area) optical fiber network because they:

- are inexpensive, robust and have long life (the long life of an LED is primarily due to its being a cold device, i.e. its operating temperature being much lower than that of, say, an incandescent lamp),
- can be modulated (i.e. switched on and off) at high speeds (this property of an LED is also due to its being a cold device as it does not have to overcome thermal inertia),
- couple enough output power over a small area to couple to fibers (though the output spectrum is wider than other sources such as laser diodes).

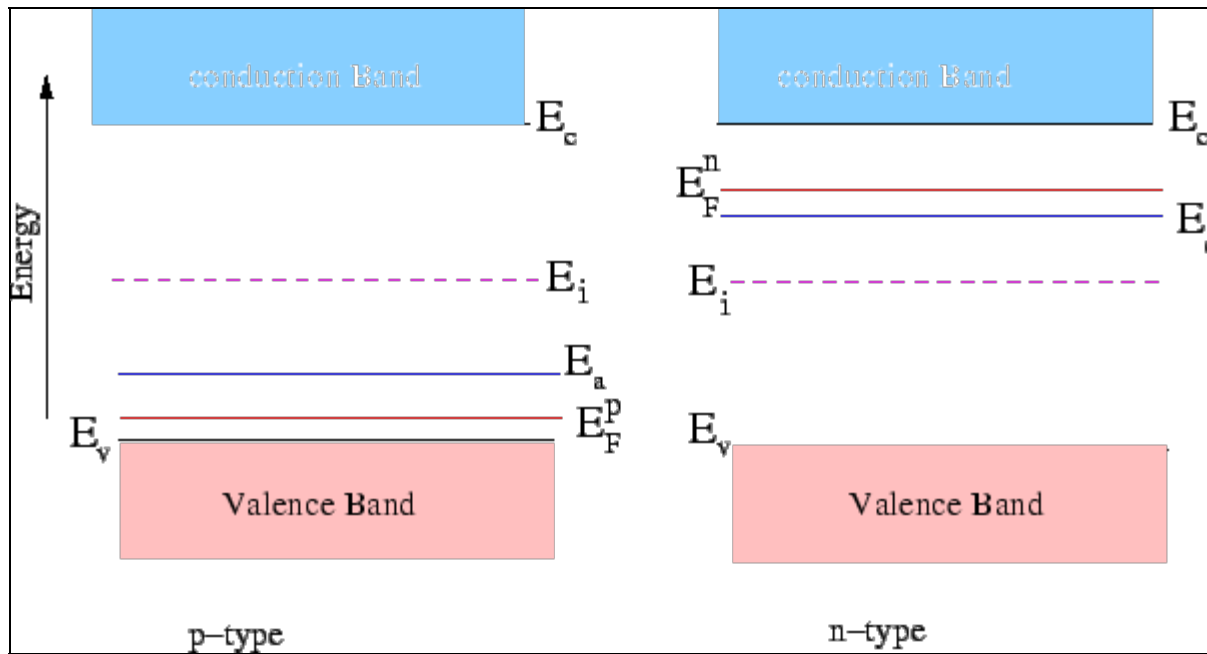


The circuit symbol of an LED is shown alongside. There are two leads, a short one, cathode, labelled — or k and a long one, anode, labelled a or +.



1.2 Principle of LED - p-n Homojunction

An LED is essentially a p-n junction diode. It may be recalled that a p-type semiconductor is made by doping an intrinsic semiconductor with acceptor impurities while an n-type is made by doping with donor impurities. Ionization of carriers from the localized levels near the bottom of the conduction band provides electron carriers in the conduction band. Similarly, excitation of electrons from near the top of valence band leave holes in the valence band.

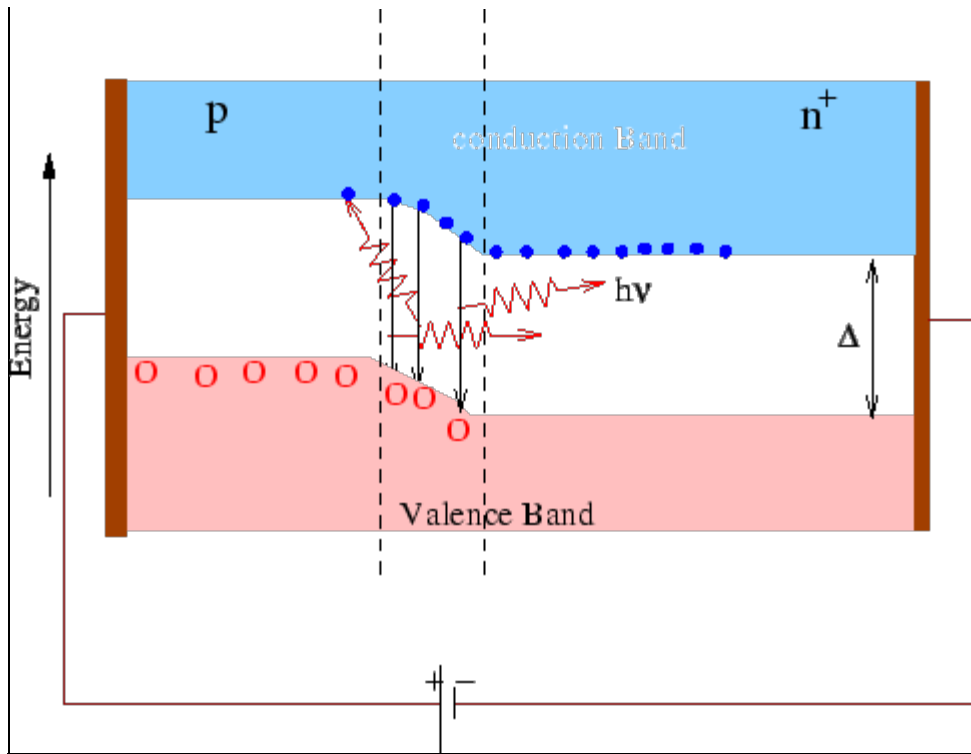


As the concentration of holes is higher on the p-side, holes diffuse towards right and enter the n-side combining with the majority carriers, viz. electrons. The n-side gets depleted of electrons and develop net positive charge. In a like manner, electrons diffusing to the left create negative charges. Thus the region near junction develop an electric field which stop further diffusion of charges. This region, which is free of carriers, is called **depletion region or space charge layer**.

In the band picture, the Fermi level E_F^p for the p-type lies closer to the top of the valence band than the acceptor level and the Fermi level E_F^n for the n-type lies closer to the

bottom of the conduction band than the donor level. It may be recalled that if the effective masses of the electrons and holes are taken to be equal, the intrinsic Fermi level lies in the middle of the gap.

When a junction is made of a p-type and an n-type material, the Fermi level on the two sides are not aligned. Since the Fermi level for a system in equilibrium must be uniform, **band bending** takes place. In the absence of a bias, the bottom of the conduction band on the n-side lies lower than that on the p-side. This prevents net diffusion as the electrons have to overcome a potential barrier $q\phi$.



Recombination of electrons and holes also takes place non-radiatively, which reduce output of the device. The fraction of the electrons that are injected into the depletion layer which results in photons getting produced is called the **internal quantum efficiency** of the LED, usually denoted by η . If N is the number of electrons injected into the depletion layer every second, the power output of the device is given by

$$P = \eta N h \nu = \eta I h \nu / e$$

where I is the forward current and e the electronic charge. If the energy of the photon is measured in electron volts, the current in milli-amperes, the above expression for power output becomes

$$P \text{ (in mW)} = \eta E_{\gamma} I$$

Example 1 :

A GaAs LED radiates at 900 nm. If the forward current in the LED is 20 mA, calculate the power output, assuming an internal quantum efficiency of 2%.

Solution :

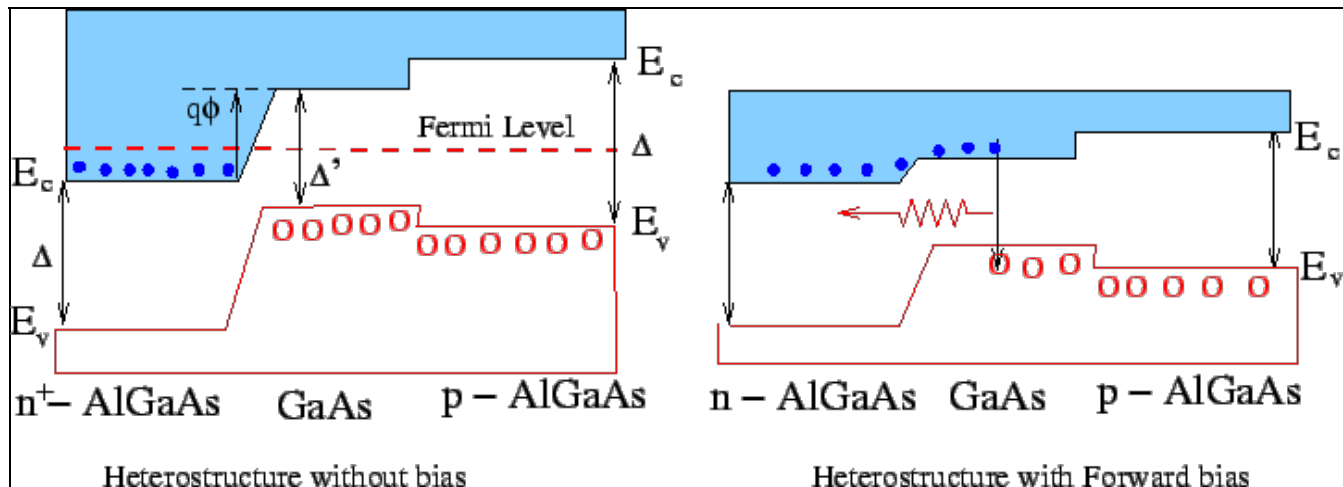
The energy of the photon (in eV) is

$$\frac{hc}{e\lambda} = \frac{6.62 \times 10^{-34} \times 3 \times 10^8}{1.6 \times 10^{-19} \times 9 \times 10^{-7}} = 1.38$$

Thus the power output is $P = 0.02 \times 1.38 \times 20 = 0.55\text{mW}$.

1.2.1 Double Heterojunctions :

One of the ways in which light output in LEDs is increased is to use **heterojunction** rather than homojunction described above. A heterojunction is a junction of two materials of different band gaps.



In the double heterostructure shown above a layer of p - type GaAs is sandwiched between a heavily doped n-type AlGaAs and a lightly doped p-type AlGaAs. The band gap of AlGaAs is 1.92 eV while that of GaAs is 1.42 eV. Thus electrons to the left of the GaAs layer find a potential barrier. In the absence of a bias, the Fermi energy is uniform. When a forward bias is applied, the height of the barrier is reduced at both the junctions. The electrons from the left can climb up the reduced barrier and enter the GaAs layer. However, they remain confined to this layer as in going over to the layer on the right they find a further potential barrier. The electrons and holes (which are already existing in the **confining layer**) combine and emit radiation. The emitted photon is not reabsorbed by the material as the band gap on either side of the confining layer is large. They escape to the surface.

1.3 LED Materials - Direct and Indirect Band Gaps :

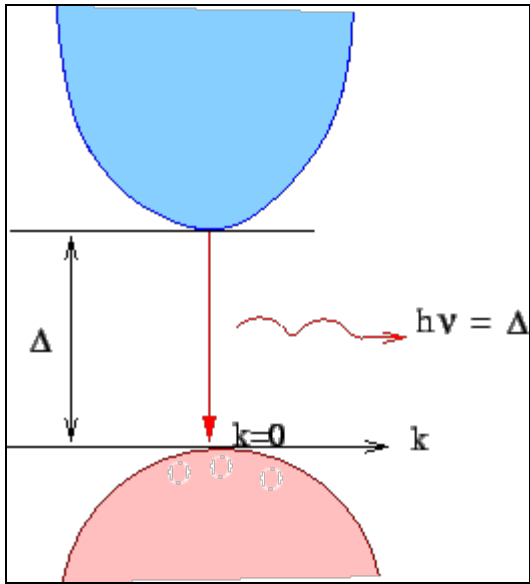
Various dopants are added to a p-n junction of GaAs to get emission over a wide range of colours. GaAs is preferred over semiconductors like Si and Ge as GaAs is a **direct bandgap** material.

In a direct bandgap material, the bottom of the conduction band lies directly above the top of the valence band. The energy of electrons in the conduction band (with the zero of energy being at the top of the valence band) is

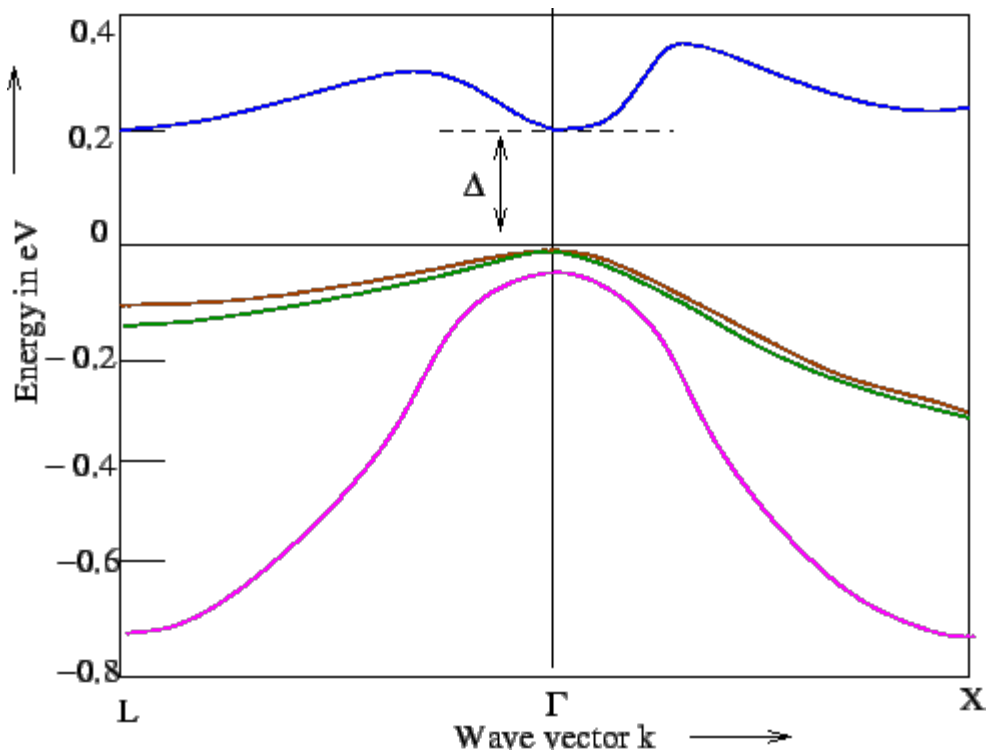
$$E_n = \Delta + \frac{p_n^2}{2m} = \Delta + \frac{\hbar^2 k^2}{2m_n^*}$$

where $k = 2\pi/\lambda$ is the wave vector. The energy of holes in the valence band is given by

$$E_p = \frac{\hbar^2 k^2}{2m_h^*}$$



GaAs is a direct band gap material with $\Delta = 1.42\text{eV}$. The band structure of GaAs is shown in the figure. Other direct band gap materials are InP, InSb, ZnS, ZnSe etc.



When electrons from the conduction band drops to a hole in the valence band, the transition is vertical in the $E - k$ diagram as there is no change in the momentum. The electron hole pair combines to give energy in the form of heat (called **non-radiative transition**) or light (**radiative transition**) depending on the band-gap energy. The wavelength of the emitted photon is given by $\lambda = hc/E_g$. If the energy is measured in eV,

$$\lambda = hc/E$$

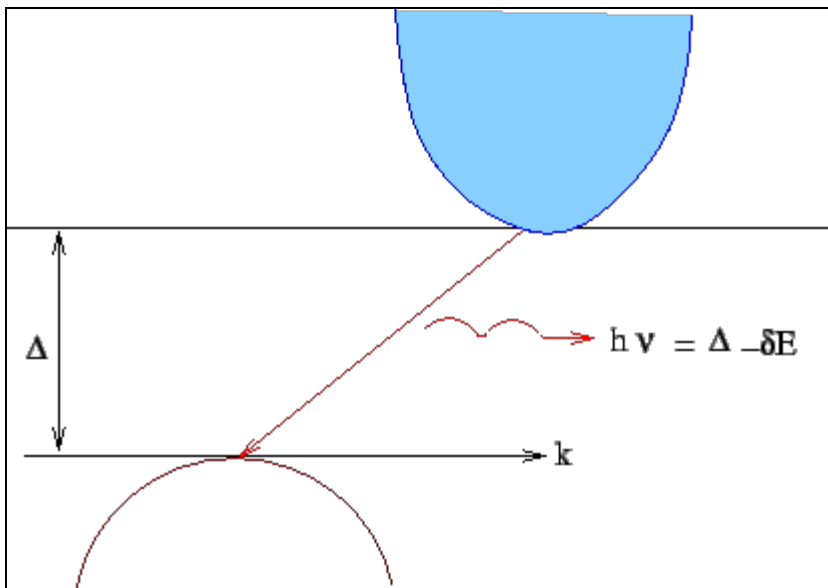
the wavelength is approximately given by the formula

$$\lambda \text{ (in nm)} = \frac{1242}{E \text{ (in eV)}}$$

Semiconductors like Ge and Si are **indirect bandgap** material in the sense that the bottom of the conduction band is shifted from $k = 0$ to $k = k_0$, so that the energy is given by

$$E_n = \Delta + \frac{\hbar^2(k - k_0)^2}{2m_n^*}$$

As both energy and momentum must be conserved in the process of transition, when an electron recombines with a hole in the valence band, the difference in the momentum must be transferred to a third entity, e.g., the lattice.



As $\hbar k$ is momentum, conservation of momentum implies conservation of wave vector k . Photon carries very little momentum. For instance, the value of k for a photon with

$\lambda = 600 \text{ nm}$ is 10^7 m^{-1} . The wavevector of electron in a lattice is in the range $-\pi/a$ to

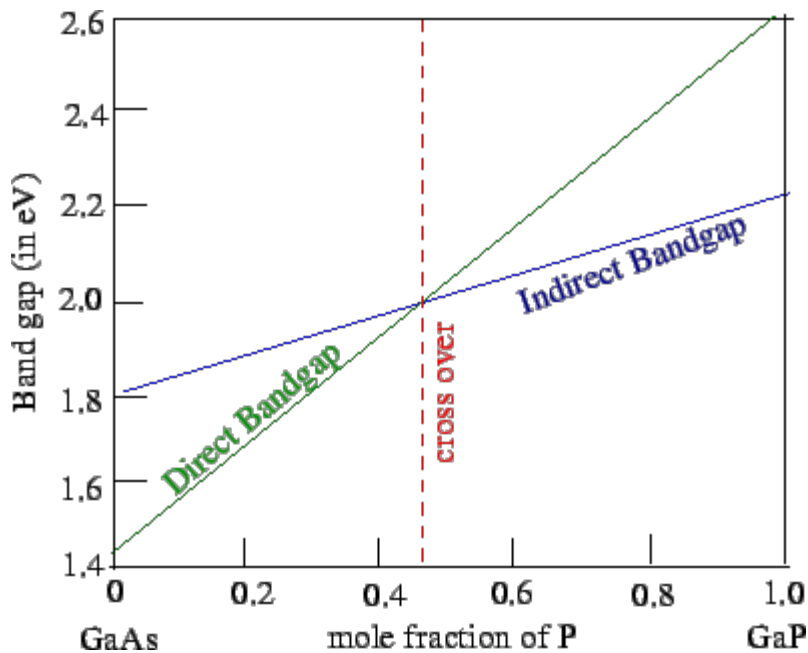
$+\pi/a$. Taking the lattice spacing to be 5 \AA , the k value for the electron is

$\approx 10^{10} \text{ m}^{-1}$. Thus while photon takes most of the energy in a radiative transition, it carries negligible momentum. Thus recombination in indirect gap semiconductors is essentially a three body process. A three body process is much less probable to occur than a two body process.

GaAs, direct bandgap material emits in infrared (870-900 nm). GaP has an indirect band gap of 2.2 eV. Both As and P belong to Group III of the periodic table. It is possible to make

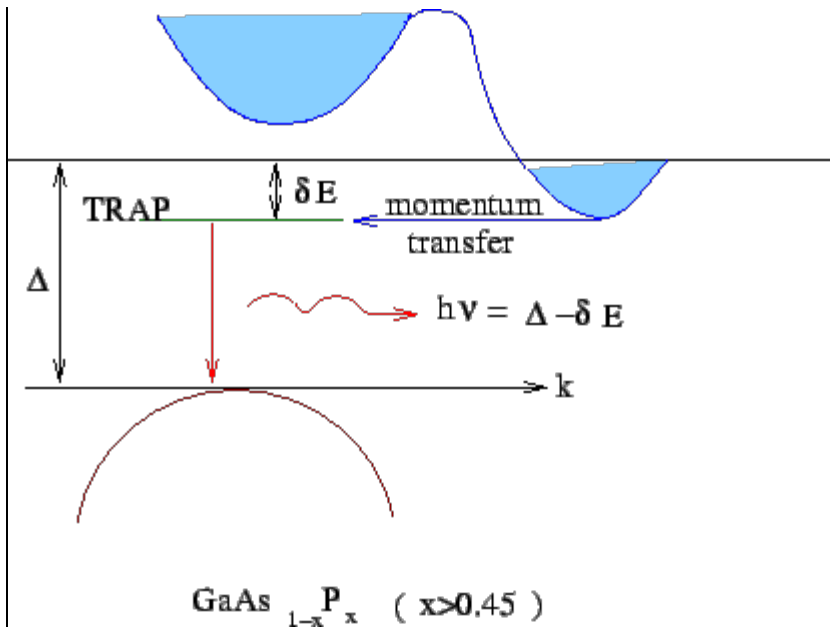
alloys having composition $\text{GaAs}_{1-x}\text{P}_x$ in which phosphorus atoms occupy As sites substitutionally as the lattice constants of GaAs and GaP are nearly equal.

For $x < 0.45$, the alloy remains a direct bandgap material with radiative transitions in red and infrared (630 nm to 870 nm). For $x > 0.45$, the alloy becomes an indirect bandgap material with emission in red, orange and yellow (560 to 700 nm) with pure GaP emitting in red at 700 nm. Another direct bandgap alloy is $\text{In}_{0.49}\text{Al}_x\text{Ga}_{0.51-x}\text{P}$ which emits at 590 to 630 nm corresponding to green and red.



Indirect band gap material are generally inefficient as light emitting devices. It is, however, possible to circumvent the three body process by a two stage two body processes.

If one adds nitrogen impurities to GaAs_{1-x} , nitrogen being isoelectronic with phosphorus, occupy the sites of P. Nitrogen sites act as trapping levels for electrons in the conduction band. Electrons in the conduction band first make a transition to trapping centre. This result in a transfer of momentum but the energy remains the same. A final vertical transition to the valence band is now made with emission of radiation. The emission is in green, yellow and orange.



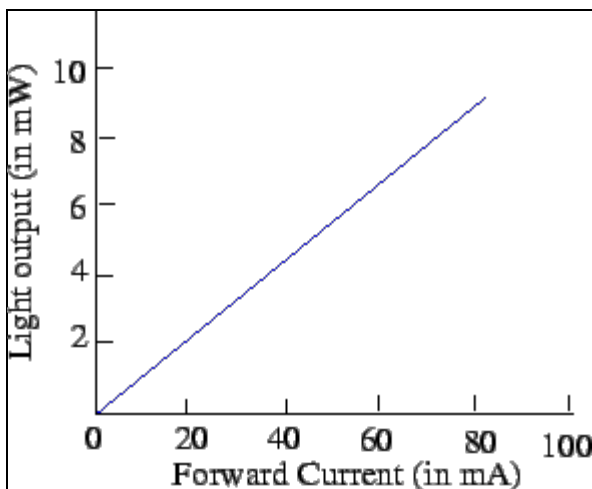
GaP with nitrogen traps also emit in green. Traps are undesirable as they contribute to non-radiative recombination and also reduce carrier life time before recombination.

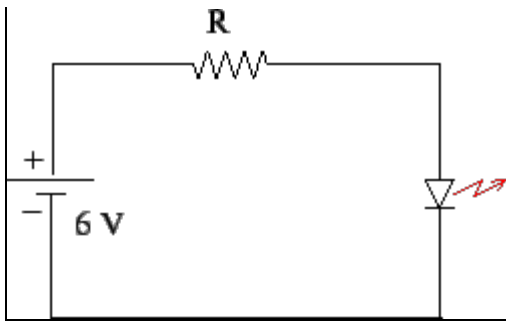
To cover the entire visible spectrum, the need for LEDs which emit blue light has been felt. SiC which has an indirect band gap in the range 2.2 to 3 eV and it emits in blue. However, it makes an extremely inefficient device. Compound II-VI semiconductors like ZnSe also emit in blue - green. GaN with a band gap of 3.4 eV is a direct bandgap material. An alloy of GaN, viz., InGaN has a smaller direct bandgap and it emits in blue (430 - 460 nm).

1.4 LED Circuit :

LED is operated in forward bias. The variation of light power is linear with the applied forward voltage. This linearity is useful in modulating signal that is being sent through a fiber. The power output of an LED is in milli watts while the current through the device is in milli amperes.

LEDs have much larger voltage drop than a rectifying diode. Typical voltage drop across an LED is between 1.5 to 2 volts. The current through the LED is a few tens of milli-amperes. It is necessary to connect appropriate resistance to account for this drop.





Example 2 :

In the circuit shown, the forward biased LED has a voltage drop of 1.5 volts. If the battery voltage is 6 V, calculate the resistance to be connected to the circuit, if the current through the LED is 15 mA. How much power is dissipated in the resistor ?

Solution :

If r is the internal resistance of the LED the current through the resistors is

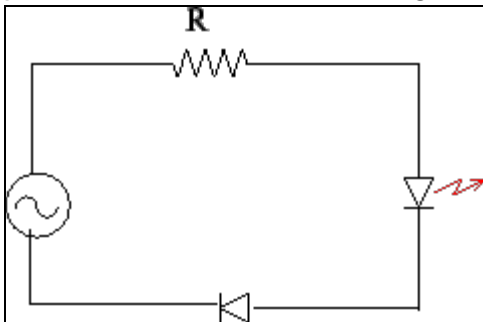
$V/(R + r) = 0.015$ which gives $R + r = 6/0.015 = 400 \Omega$. As the drop across LED is

1.6 V, the internal resistance r is $1.5/0.015 = 100 \Omega$. The external resistance to be

connected is $R = 400 - 100 = 300 \Omega$. The power rating of the resistor should at least be

$$RI^2 = 300 \times 2.25 \times 10^{-4} = 77.5\text{mW}.$$

The peak inverse voltage of an LED is rather low. This requires care to be taken when operating an LED with an alternating supply. A rectifying diode is added to the circuit to protect the diode from damage every other half cycle.



Exercise :

The working voltage of an LED is 1.8 volts. If the desired current flow is 15 mA, how much power is dissipated in a resistor that must be connected to an LED circuit operated on a d.c. voltage of 12 V. (Ans. 0.153 W)

Recap

In this lecture you have learnt the following

- Introduction to Light Emitting Diode (LED)
- Principle of LED - p-n Homojunction

- **Double Heterojunctions**
- LED Materials - Direct and Indirect Band Gaps
- LED Circuit

Part - II

Objectives

In this lecture you will learn the following

- Quantum Efficiency
- Radiation Pattern
- Emission Spectrum
- Coupling of LED output to optical fiber
- Fiber Coupling Efficiency

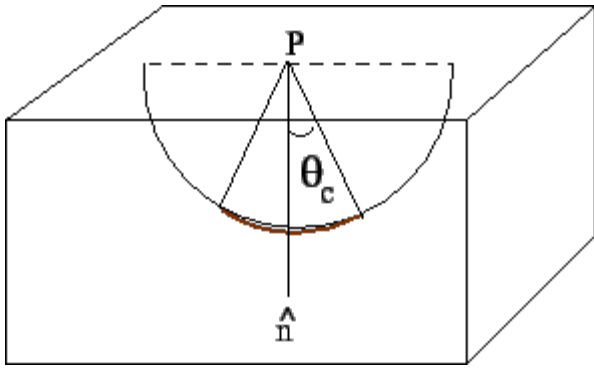
1.5 Quantum Efficiency

Efficiency of an LED refers to the percentage of power output in relation to input. There are three different efficiencies defined to measure the efficiency of conversion to light energy. We have already defined the **internal quantum efficiency** as a fraction of the electron hole pairs injected into the depletion layer which recombine to generate light. We define **external quantum efficiency** as the fraction of the number of photons which are generated within the semiconductor which are emitted outside. External quantum efficiency is important because in view of the high refractive indices of semiconductors ($n \simeq 3.5$), the critical angle for total internal reflection is rather small. As a consequence thereof, only those photons which strike the internal surface of the semiconductor at near normal incidence can go out of the material.

Let θ_c be the critical angle for total internal reflection at the semiconductor - air interface.

Photons which arrive at a particular point P on the interface are those which were travelling along a radial direction from the surface of hemispheres of different radii with P as their centres.

However, only those which were on the surface of a hemisphere within a cone of semi-angle can escape the semiconductor. The area of such a surface can be shown to be $\pi r^2 \sin^2 \theta_c$. The fraction of photons which will emerge out of the surface is therefore $\sin^2 \theta_c$. If one considers all the photons which were on such a surface, on an average, only half travel towards the interface and half away from it. Thus the fraction is reduced by a further factor of 2 and is $\frac{1}{2} \sin^2 \theta_c$.



As θ_c is small for semiconductors, one can approximate the fraction by using $\sin \theta_c \simeq \theta_c$ and $\cos \theta_c \simeq 1 - \theta_c^2/2$. Using the definition of critical angle, $\sin \theta_c = 1/n$ where n is the relative refractive index of the semiconductor with respect to air. Thus the fraction of photons which emerge out is

$$\frac{1 - \cos \theta_c}{2} = \frac{\theta_c^2}{4} = \frac{1}{4n^2}$$

There is a further reduction that we need to consider. Whenever light falls at an interface between two media a fraction of the intensity is reflected back into the incident medium and a fraction transmitted. This is known as **Fresnel reflection**. For normal incidence, the fraction transmitted is given by $4n/(1+n)^2$. Thus an approximate expression for

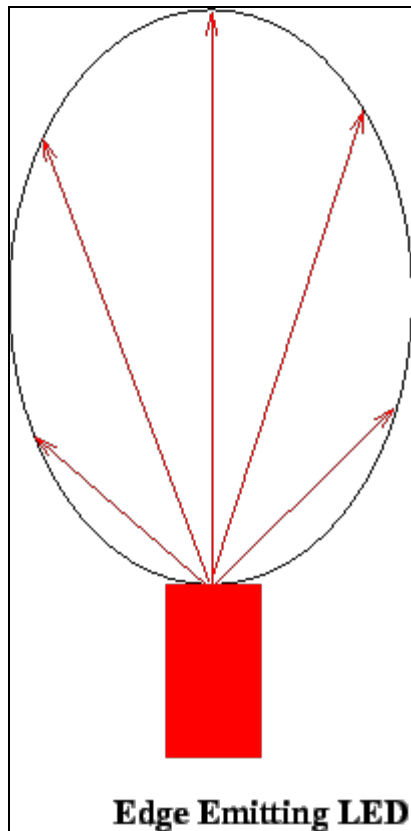
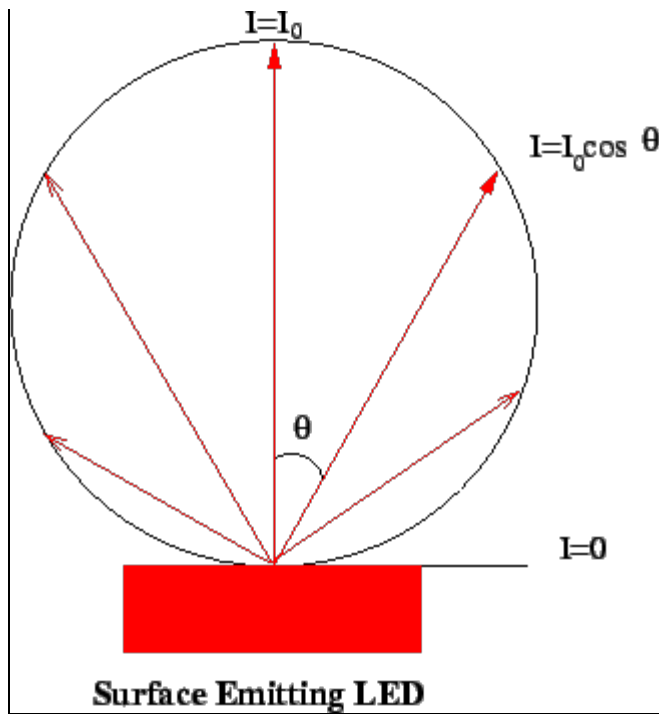
external quantum efficiency is

$$\eta_e = \frac{1}{4n^2} \frac{4n}{(n+1)^2} = \frac{1}{n(n+1)^2}$$

. For GaAs, with $n = 3.5$, the external quantum efficiency calculated by above formula is 1.4%. In practice, external quantum efficiency can be somewhat increased by coating the surface with a material of index of refraction which lies between that of the semiconductor and air.

1.6 Radiation Pattern :

LEDs come in two forms, viz., (i) surface emitting and (ii) edge emitting. Surface emitting LEDs radiate light at a wide angle the the source is nearly **Lambertian**. They are not suitable as sources for coupling to an optical fiber because the radiation is highly incoherent. Such LEDs are usually used as signalling devices and as indicators in panels and instruments.



Edge emitting LEDs radiate at a relatively narrow angle. The emitting area is smaller as a result of which the coupling to the end of a fiber is more efficient. These LEDs are generally temperature sensitive and must be maintained under environmental control.

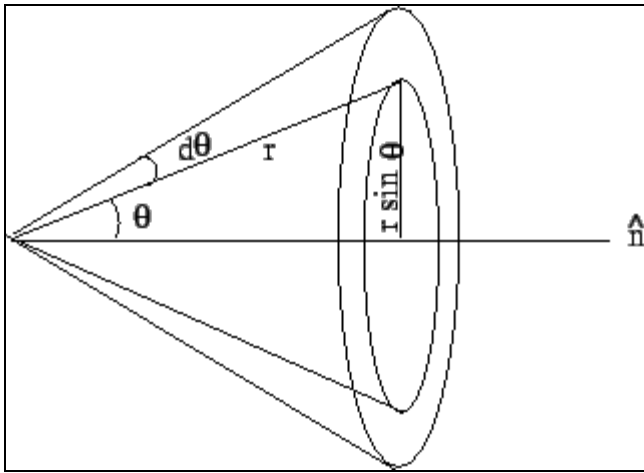
A **lambertian source** is one for which the power output is proportional to the cosine of the angle between the direction of observation and normal to the emitting surface. The **luminance** L of a source is defined as the flux (power) per unit area of the emitting

surface per unit solid angle. The luminance of a lambertian source is constant. Consider the flux $d\Phi$ emitted by a surface of unit area into a solid angle $d\Omega$ whose axis makes an angle θ with the normal to the emitting surface.

The flux $d\varphi$ emitted into a solid angle $d\Omega$ is

$$d\Phi = L \cos \theta d\Omega$$

where $d\Omega$ is the solid angle subtended between two right circular cones whose semi-angles with the axis \hat{n} are θ and $\theta + d\theta$.



The solid angle subtended at O is

$$\Omega = \frac{\text{area}}{(\text{distance})^2} = \frac{\pi (r \sin \theta)^2}{r^2} = \pi \sin^2 \theta$$

so that $d\Omega = 2\pi \sin \theta d\theta$. Substituting this in the expression for the flux element $d\Phi = 2\pi L \sin \theta \cos \theta d\theta$. The total flux radiated to all space is obtained by integrating over θ from 0 to $\pi/2$.

$$\begin{aligned} \Phi &= \int d\varphi = 2\pi L \int_0^{\pi/2} \sin \theta \cos \theta d\theta \\ &= 2\pi L [\sin^2 \theta]_0^{\pi/2} = \pi L \end{aligned}$$

Example 3 :

Show that half the total emitted power of a lambertian source is contained in a cone of angle $2\pi/3$ around the normal \hat{n} .

Solution :

In polar coordinates, the element of a surface element on the hemisphere is $r^2 \sin \theta d\theta d\phi$,

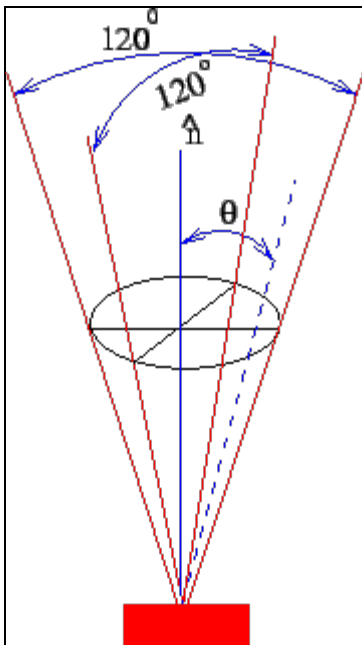
where ϕ is the azimuthal angle. The solid angle subtended by the surface element at O is

$d\Omega = \sin \theta d\theta d\phi$. Integrating the flux emitted in the cone of semi-angle $\pi/3$, for a lambertian source, we get

$$\Phi = L \int \cos \theta d\Omega = L \int_{-\pi/3}^{\pi/3} d\phi \int_{-\pi/3}^{\pi/3} \sin \theta \cos \theta d\theta$$

$$= L \frac{2\pi \sin^2 \theta}{2} \Big|_{-\pi/3}^{\pi/3}$$

$$= L \frac{\pi}{2} = \frac{1}{2} \Phi_{\text{hemisphere}}$$

**Exercise :**

An LED of 1 mm^2 active area emits $100 \mu\text{W}$ of radiation in a lambertian profile. Estimate the power received by a surface of area 50 mm^2 normal to the direction of emission at a

distance of 200 mm. (ASns. $0.2\mu W$)

1.7 Emission Spectrum :

As the electrons in the conduction band and the holes in the valence band have energy distribution around the bottom of the conduction band and the top of the valence band respectively, the energy of photons released by recombination of electron - hole pairs is also distributed in energy. The intensity of emitted radiation depends on the carrier concentration of both the carriers. The intensity, therefore, depends on

- the density of states of electrons and holes, and,
- the temperature T through the Fermi distribution function $f(E)$ which gives the probability of finding an electron with

an energy E .

The minimum energy of emitted photon is the band gap energy Δ . The theoretical emission spectrum is shown.

The qualitative feature of the emission spectrum may be obtained by a simple model. According to Boltzman statistics, the electrons and holes have average kinetic energy of kT , which is much smaller than the band gap. As the average carrier momentum is given by $\sqrt{2m^*kT}$ while the photon momentum is Δ/c , the carrier momentum is much larger

than the photon momentum. As a result, the transitions in the momentum space are nearly vertical. Conservation of energy requires.

$$h\nu = \left[E_c + \frac{\hbar^2 k^2}{2m_e^*} \right] - \left[E_v - \frac{\hbar^2 k^2}{2m_h^*} \right]$$

$$= \Delta + \frac{\hbar^2 k^2}{2m_r^*}$$

where m_r^* is the reduced mass of the electrons and holes given by

$$\frac{1}{m_r^*} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$$

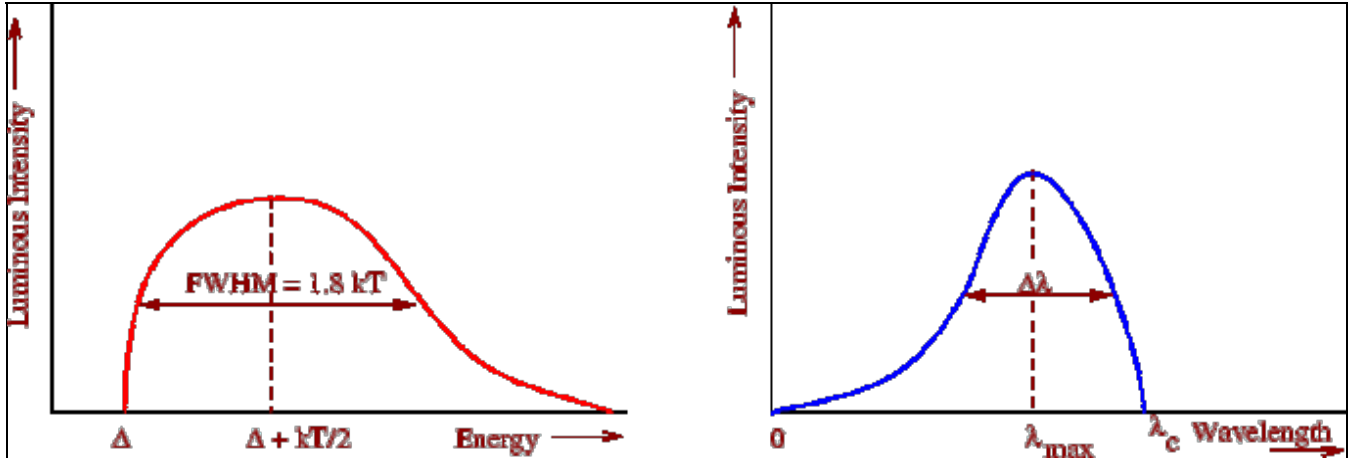
Thus instead of considering the motion of electrons and holes separately, we can describe the transition in terms of the excitation of a free particle of reduced mass. The emission intensity is then given by the occupation probability of such a particle having an energy E and the density of state. In the free electron approximation, the density of state is

proportional to _____ and the occupation probability is given by Boltzmann factor as

$$\sqrt{E - \Delta}$$

$\exp(-E/kT)$. Thus the emission intensity $I(E)$ is proportional to product of these two factors

$$I(E) \propto \sqrt{E - \Delta} e^{-E/kT}$$



spectrum has a peak in intensity at $\Delta + kT/2$ and the full width at half maximum (FWHM) is $1.8kT$. The corresponding distribution of emitted wavelength is shown alongside.

Example 4 :

For the theoretical spectrum shown, calculate the linewidth $\Delta\lambda$ at half the maximum intensity for $\lambda = 870$ nm at room temperature.

Solution :

As $\lambda = hc/E$, on differentiating, we get

$$\Delta\lambda = \frac{hc}{E^2} \Delta E = \frac{\lambda^2}{hc} \times 1.8kT$$

Substituting $\lambda = 870$ nm and $T = 300$ K, $\Delta\lambda = 28.4$ nm.

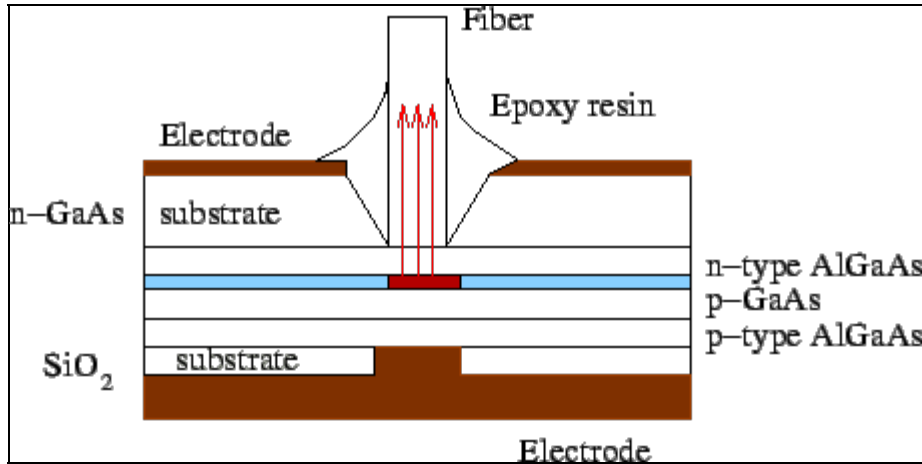
Exercise :

The change in the emitted wavelength of a GaAs LED is 3 nm when the temperature is changed from 300 K to 310 K. Assuming a linear variation with temperature, find the change in the band gap energy of GaAs, if the gap at 300 K is 1.420 eV. (Ans. 5 meV)

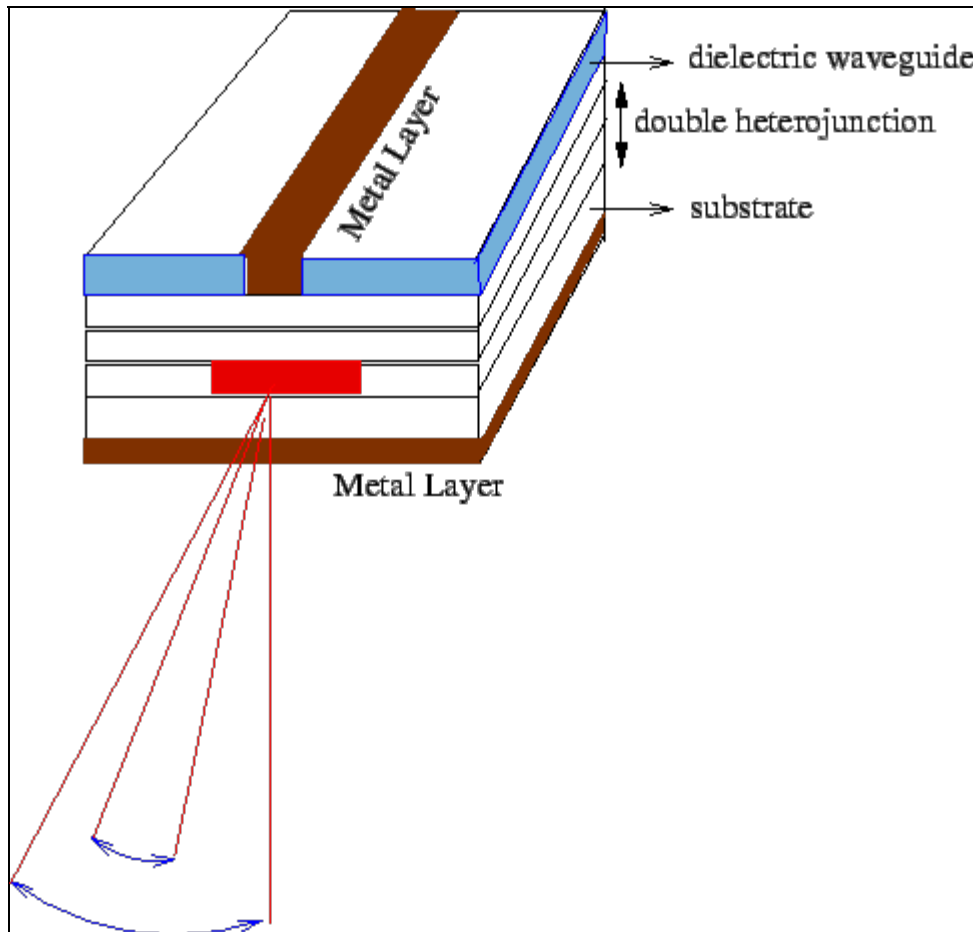
1.8 Coupling of LED output to optical fiber :

A surface emitting LED can be coupled to a fiber by etching a well in a planar LED structure and bring the end of the fiber as close to the active layer as possible.

This type of coupling is known as **Burrus** device after its developer C. A. Burrus. The fiber is bonded to the well by an epoxy resin which provides better refractive index matching so that the fiber may capture as much light as possible.



In the case of edge emitter, the light is more directional. In this case the double heterostructure is surrounded by a semiconductor having a larger band gap than that of the active layer. This makes the process of recombination to be confined to the active layer. The surrounding layer acts as a dielectric waveguide. The light coming out of the waveguide is coupled to the optical fiber by a lens system.



1.8.1 Fiber Coupling Efficiency

The most basic method of coupling the optical output of a source into an optical fiber is known as **butt coupling**. This consists of placing the cleaved end of a fiber as close as possible to the output aperture of the source. The coupling is also known as **end-fire** coupling.

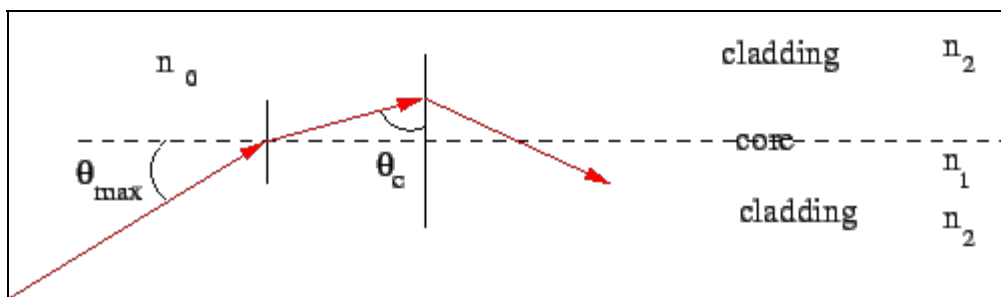
An optical fiber is characterized by a **numerical aperture**. Numerical aperture is defined in terms of the maximum angle of incidence (**the acceptance angle**) that a ray may have at the end face of a fiber so that the ray will travel along the core being totally reflected at the core - cladding boundary.

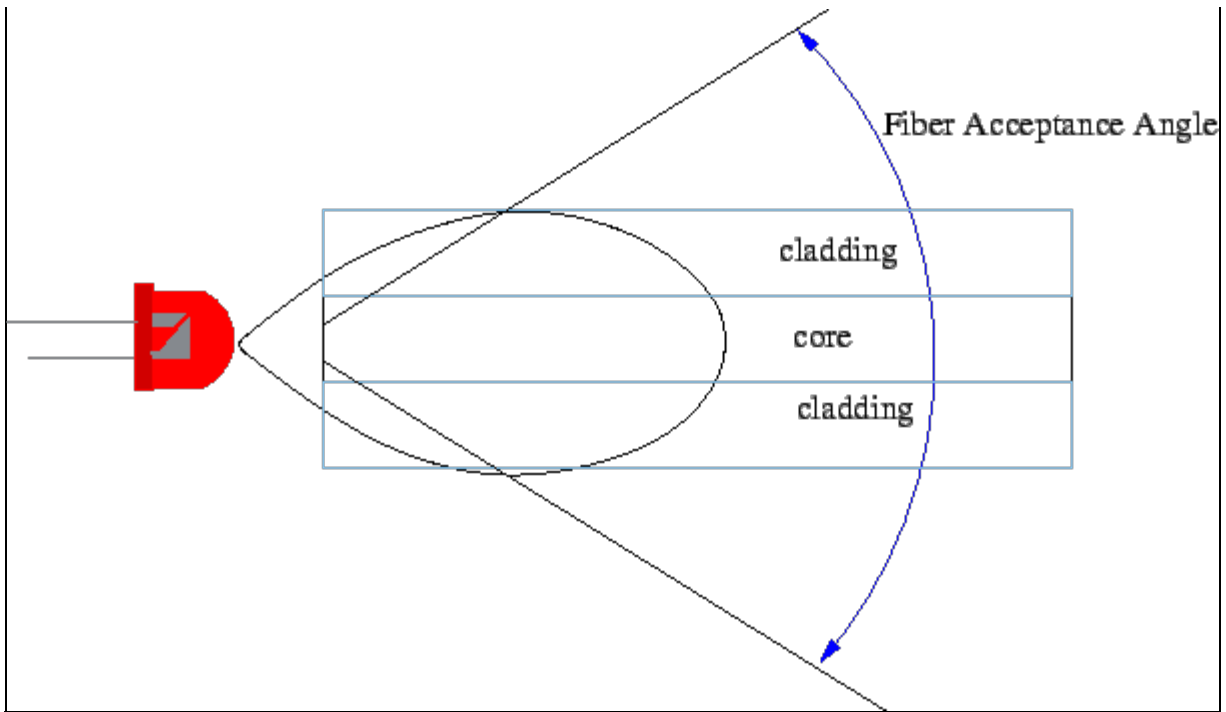
If the acceptance angle is θ_{\max} , then the numerical aperture is given by

$$\text{N.A.} = \sin \theta_{\max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$\approx \sqrt{n_1^2 - n_2^2}$$

where the refractive index of air $n_0 \approx 1$.





If the reflection losses at the end face is neglected, all the output power of the LED that lies within the acceptance angle (and are within the physical dimensions of the fiber) will be coupled to the fiber. The coupled power is given by

$$P = \int_f dS_f \int P(\theta, \phi) d\Omega$$

where the integration over S_f is over the cross section of the end face of the core, or over the output face of the source, whichever is of smaller area. Assuming each of these areas to be of circular cross section (taking core radius r_c to be smaller than the source radius r_s), for a lambertian source, the output power coupled is given as follows.

$$P = \int_f dS_f \int \left(2\pi L \int_0^{\theta_{\max}} \cos \theta \sin \theta d\theta \right)$$

$$= \pi L \sin^2 \theta_{\max} \int_f dS_f$$

$$= \pi^2 L r_c^2 \sin^2 \theta_{\max}$$

The fiber-coupling efficiency is the ratio of P to the total power emitted by the source which is $P_0 = \pi^2 L r_s^2$. Thus the fiber-coupling efficiency for $r_c < r_s$ is

$$\eta = \left(\frac{r_c}{r_s} \right)^2 (\text{N.A.})^2$$

If $r_s < r_c$, the efficiency is given by

$$\eta = (\text{N.A.})^2$$

Exercise :

A surface emitting LED of large surface area is coupled to a step index fiber of core radius $25 \mu\text{m}$. If the luminance of the LED is $10^4 \text{W/m}^2\text{-sr}$, how much power is coupled to a fiber of numerical aperture 0.2 ? (Ans. $2.4 \mu\text{W}$)

Recap

In this lecture you have learnt the following

- Quantum Efficiency
- Radiation Pattern
- Emission Spectrum
- Coupling of LED output to optical fiber
- Fiber Coupling Efficiency

Congratulations, you have finished Module 6. To view the next lecture select it from the left hand side menu of the page