Photonic devices

Photonic devices can be devided into three groups:

1. devices that convert electrical energy into optical radiation (spontaneous emission): LED (light emitting diodes), LASER (light amplification by stimulated emission of radiation).
2. devices that detect optical signals through electronic processes (photodetectors).
3. devices that convert optical radiation into electrical energy (photovoltaic device or solar cell).

History

1954 Townes and al. invented the Maser (microwave amplification by stimulated emission of radiation) and the subsequent operation of optical maser and laser (light), semiconductors were suggested for use as laser materials.

1961 Theoretical calculations by Bernard and Duraffourg

1962 Dumke showed that laser action was indeed possible in direct bandgap semiconductor

1962 Three groups announced simultaneously that they had achieved lasing in semiconductors (pulsed at LN, forward-biased GaAs p-n junction).

1970 RT operation by use of heterostructure LASER

Text: S.M. Sze, Physics of Semiconductor Devices, J. Wiley &Sons, 1981

J. Singh, Semiconductor devices, Mc-Graw-Holl Intern. Editions

Emission Spectra

There are three processes for interaction between a photon and an electron in a solid. A photon may be adsorbed by the transition of an electron from a filled state in the valence band to an empty state in the conduction band.

In addition to being adsorbed, a photon can stimulate the emission of a similar photon by the transition of an electron from a filled state in the conduction band to an empty state in the valence band.

Also, an electron in the conduction band can spontaneously return to an empty state in the valence band with emission of a photon.

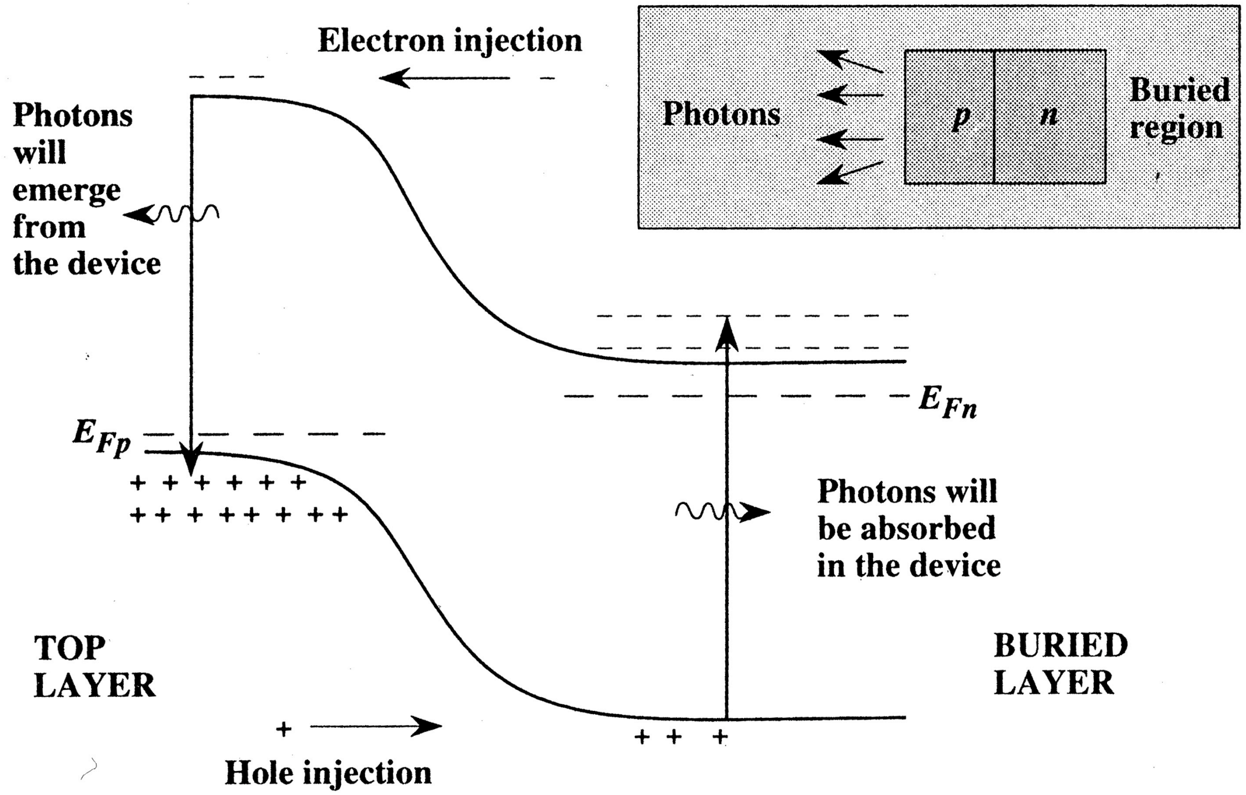
The LED and semiconductor laser belong to luminescence device family. Luminescence is the emission of optical radiation (UV, visible or infrared) as a result of electronic excitation of a material.

Methods of Excitations:

1) Photoluminescence involving excitation by optical radiation
2) Catholuminescence by electron beam
3) Radioluminescence by other fast particles or high-energy radiation
4) Electroluminescence by electric field or current (forward bias applied to a p-n junction, the injection of minority carriers across the junction can give rise to efficient radiative recombination).

p-n Junction

In the forward bias conditions the electrons (holes) are injected from the n-side (p-side) to the p-side (n-side) and they may recombine to produce photons.



'igure 11.3: In a forward biased p-n junction, electrons and holes are injected as shown. In the gure, the holes injected into the buried n region will generate photons which will not emerge om the surface of the LED. The electrons injected will generate photons which are near the ırface and have a high probability to emerge.

Electromagnetic spectrum

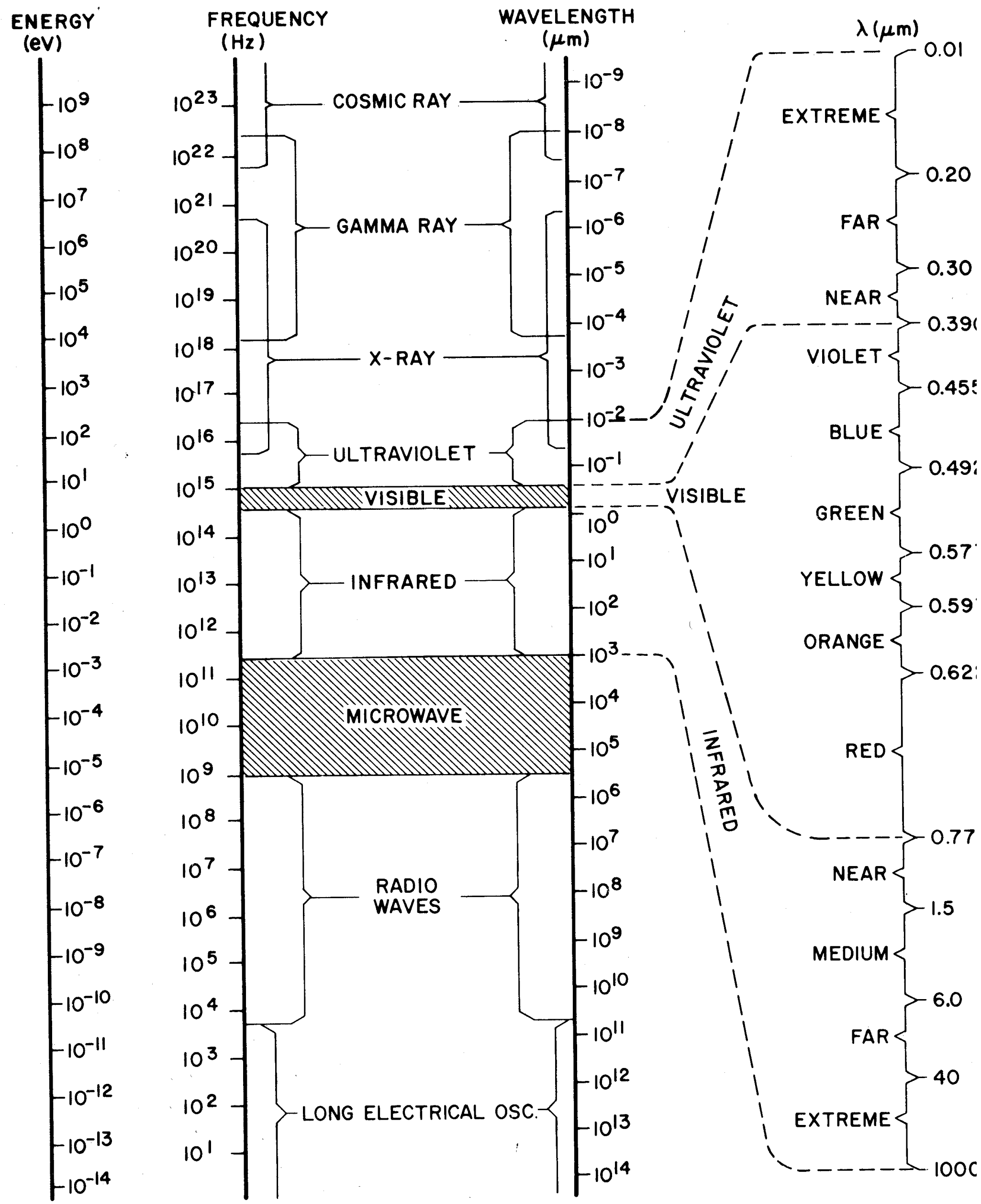


Fig. 1 Chart of electromagnetic spectrum.

Light-emitting Diodes

Light-emitting diodes (LEDs) are semiconductor p-n junctions that under proper forward-biased conditions can emit external spontaneous radiation in UV, visible, and infrared regions of e. m. spectrum.

Visible LEDs present a multitude of applications in the essential information linkage between electronic instruments and their human users (display).
Infrared LEDs are useful as potential light source for optical-fiber communication.

Visible LED
The effectiveness of light for stimulating the human eye is given by the relative eye sensitivity $V(\lambda)$.

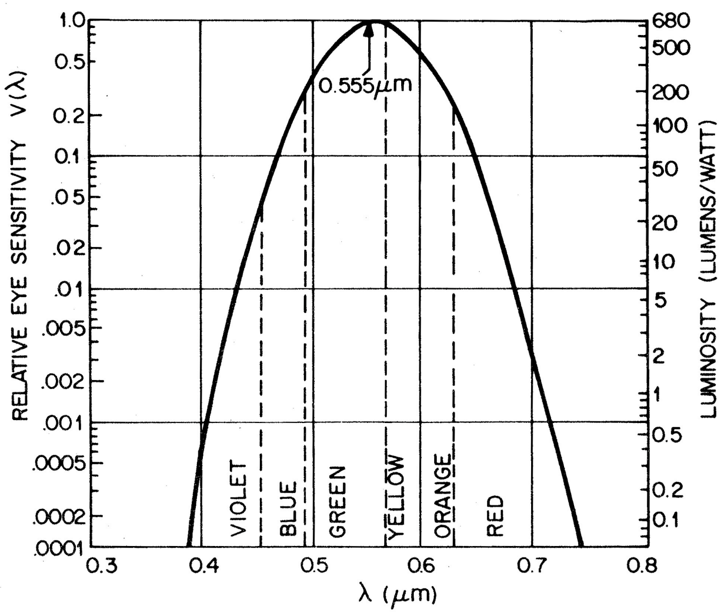


Fig. 6 Relative luminosity function as defined by the CIE for normal photopic vision. Major color bands are also indicated.

Materials for visible LED

Since the eye is only sensitive to light of energy $h\nu > 1.8eV$ the semiconductors of interest must have E_g larger then this limit.

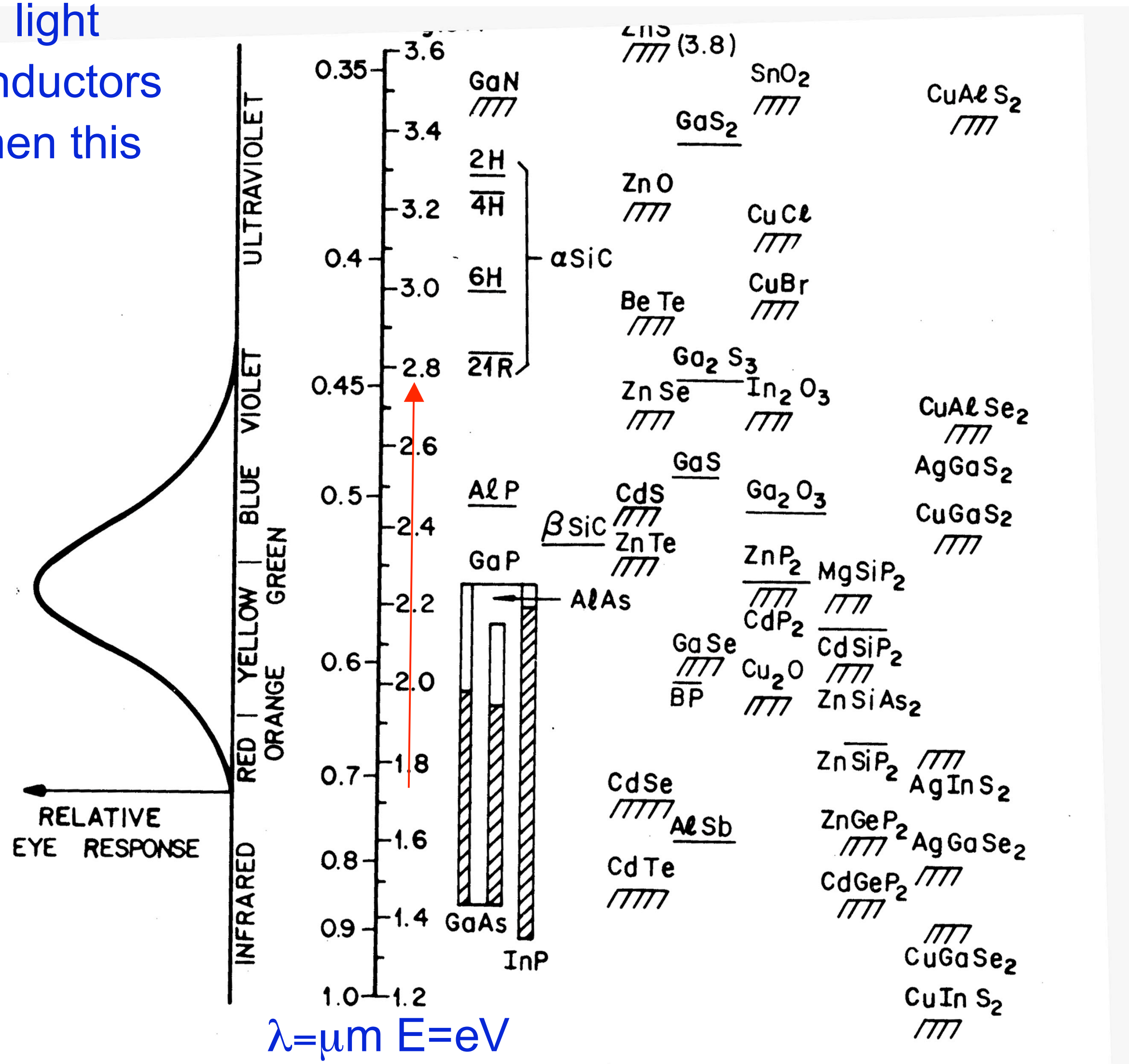


Fig. 7 Semiconductors of interest as visible LEDs, including the relative luminosity function of the human eye. (After Bergh and Dean, Ref. 2.)

Loss Characteristics

If the optical communication sources are desired one must choose materials which can emit at the wavelengths at 0.9µm 1.55µm and 1.3µm. For these wavelengths the loss characteristics of the optical fibers show two minima.

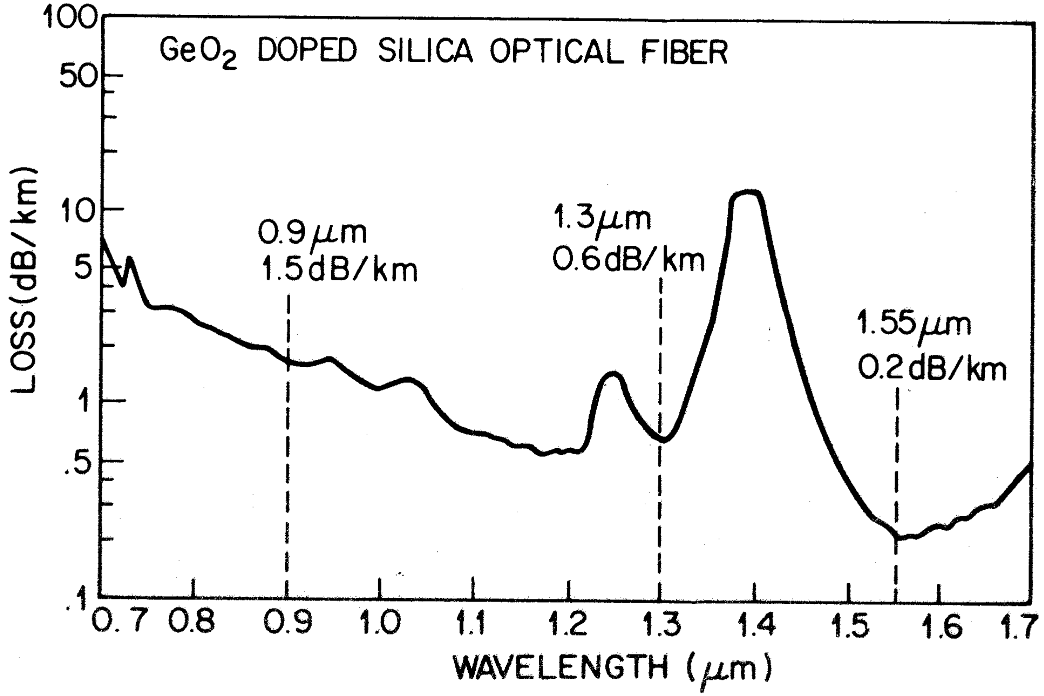


Fig. 22 Loss characteristics of a silica optical fiber. The three wavelengths of intere[st] are also shown. (After Miya et al., Ref. 43.)

Materials like GaAs which emit at 0.8µm can still be used for local are networks but not for comunications over hundreds or even thousands of Km.

Radiative Efficiency: direct vs indirect band-gap

The momentum conservation causes strong radiative transitions to occur only in direct gap semiconductors. Some indirect gap materials can, have a reasonable radiative (LED but not LASER) efficiency if they are doped with certain impurities.

$GaAs_{1-x}P_x$

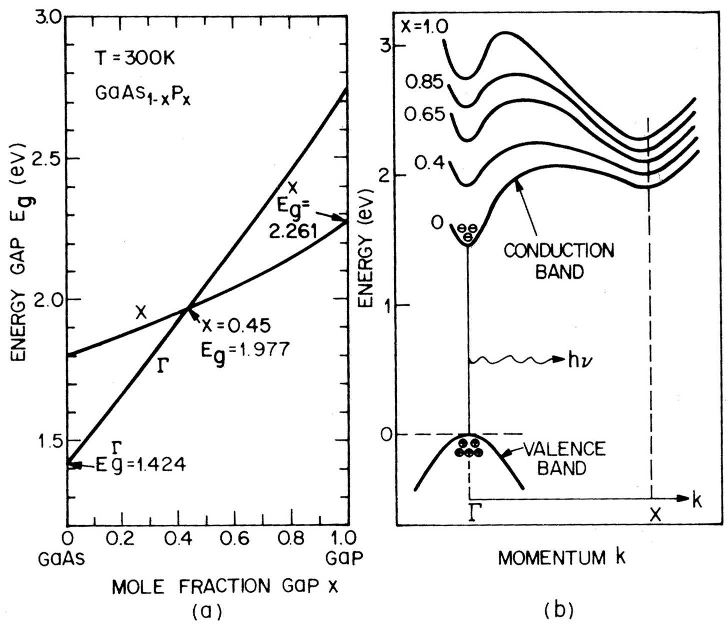
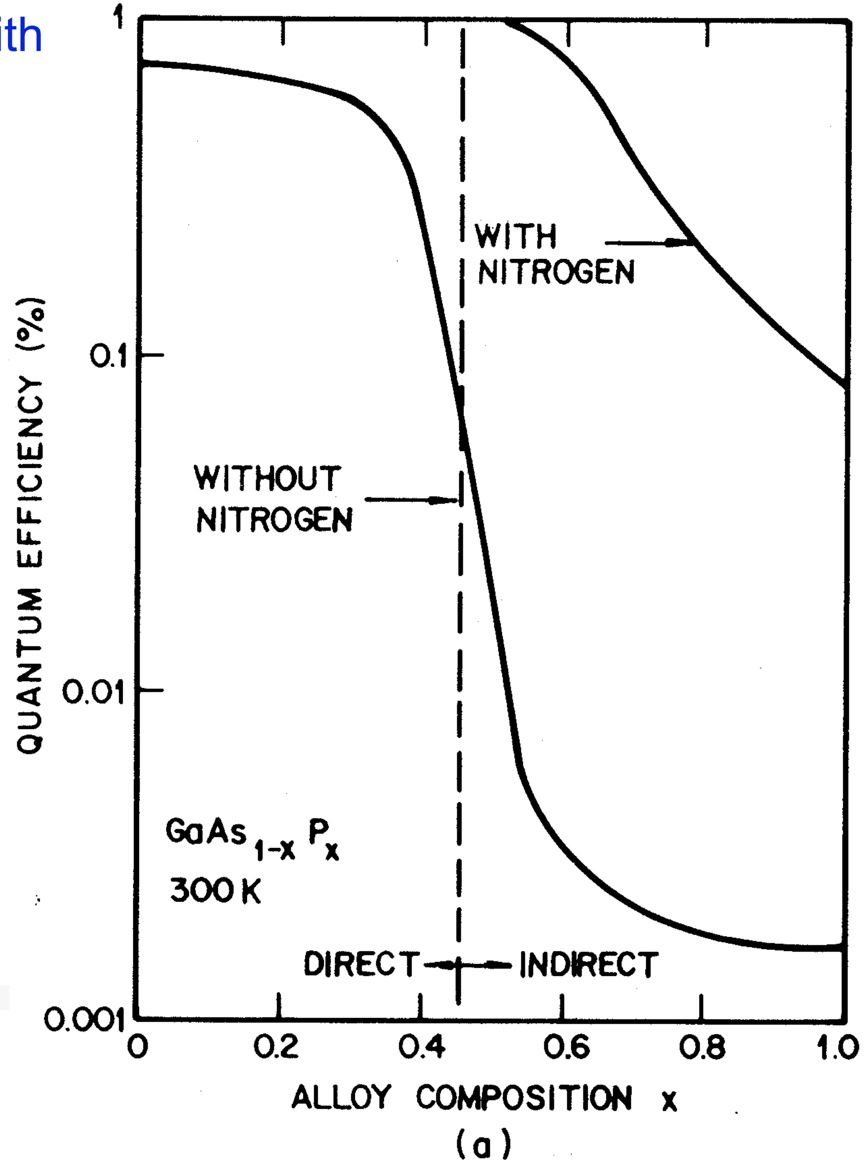


Fig. 8 (a) Compositional dependence of the direct and indirect energy bandgap for $GaAs_{1-x}P_x$. (After Casey and Panish, Ref. 20.) (b) Schematic energy–momentum diagram for $GaAs_{1-x}P_x$. The alloy compositions shown correspond to red ($x = 0.4$), orange (0.65), yellow (0.85), and green light (1.0). (After Craford, Ref. 30.)

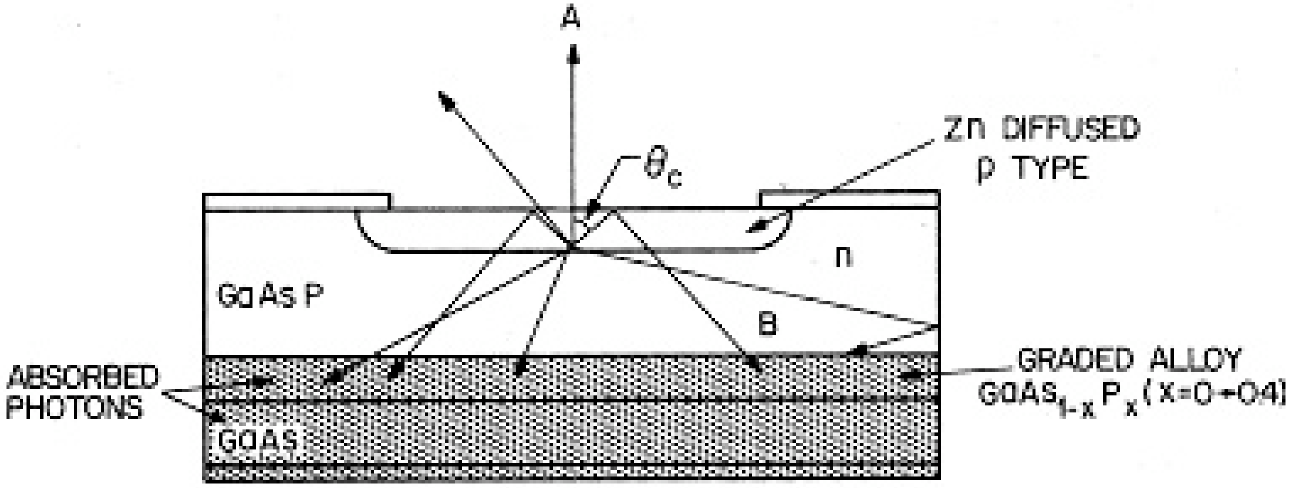


Red x=0.4 orange (direct bandgap) x=0.65, yellow x=0.85, green x=1 (indirect bandgap)

LED Substrates

Generally direct bandgap GaAsP LEDs (red x=0.4) are fabricated on GaAs substrates and indirect bandgap LEDs (x>0.6 orange, yellow, and green) are fabricated on GaP substrates.

When GaAs is used as substrate, a graded-alloy $GaAs_{1-x}P_x$ with x from 0 to 0.4 is epitaxialy grown and then followed by a layer of $GaAs_{1-x}P_x$ with a constant alloy composition.



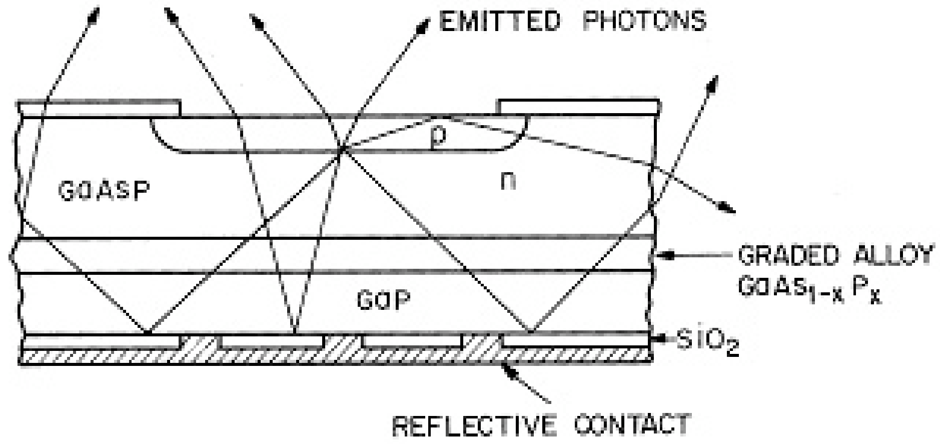
(a)

Loss Mechanisms

The photons generated at the junction are emitted in all directions, but only a fraction of these photons can emerge from the surface to reach the eye of an observer (losses).

There are three main loss mechanisms dot the emitted photons:

1) They can be readsorbed in the semiconductor by creating an electron-hole pair;
2) a certain fraction of photons will be reflected back at the semiconductor-air interface
3) Some photons impinge upon the surface with angles greater than the critical angle ths suffering total internal reflection.



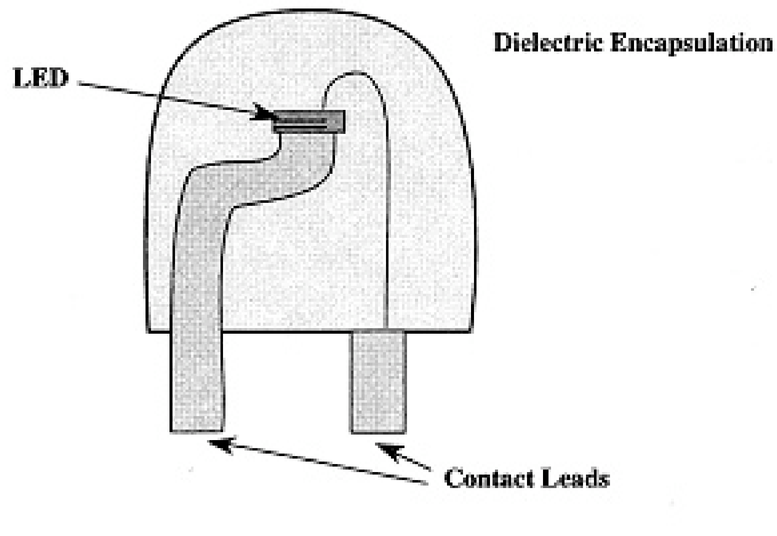
External Quantum Efficiency

To minimize the absorption of photons, it is essential that the photons be emitted near the surface so that a good fraction of the photons do not have to travel long distances to the surface.

Furthermore, photons that are able to make it to the semiconductor-air surface have to suffer reflection from the surface. Those that are reflected they are lost. If n_2 is the refractive index of the semiconductor and n_1 the index of air, the reflection coefficient is (for vertical incident light),

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

This loss is called Fresnel loss. For a GaAs LED, if we choose n_2=3.66 and n_1=1 we get a loss of 0.33, i.e. 33% of the photons cannot get through. To avoid this excessive loss, usually the device is encapsulated in a dielectric dome. The dielectric has $n_1 \approx 1.6$ and this allows a greater fraction of photons to emerge.



(b)

Figure 11.6: (a) The LED structure along with a schematic of the reflection and transmission of light at the semiconductor surface. (b) The dielectric encapsulation used to improve the transmission of photons generated. The presence of the dielectric reduces the reflection losses from the GaAs-air surface.

External Quantum Efficiency

Another loss of photons is due to total internal reflection. If light impinges at a surface from a region of high refractive index ($n_2 > n_1$), it is totally reflected back if the angle of incidence is greater than a critical angle (θ_c) where

$$\theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right)$$

For the GaAs-air surface, the critical angle is 15.9^o. Once again, use of the dome encapsulation suppresses this loss (critical angle increases to 25.9^o).