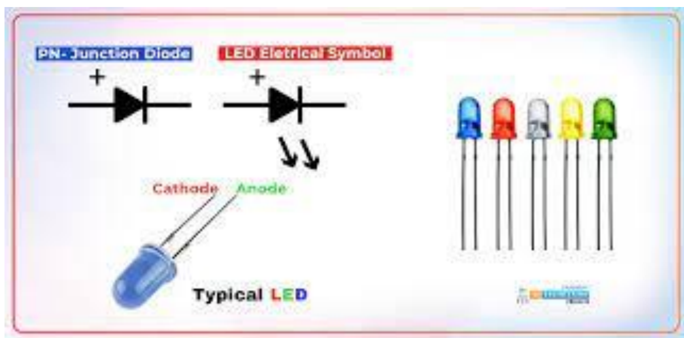
The Light Emitting Diode



- The basic LED is a p-n junction that is forward biased to inject electrons and holes into the p- and n-sides, respectively.
- The injected minority charge recombines with the majority charge in the depletion region or the neutral region.

Important applications: Display and optical communication

LED Wavelength (color):	LED Applications:
410nm - 420nm (violet)	Skin Therapy
430nm - 470nm (blue)	Dental Curing Instruments
470nm (blue)	White LED's using Phosphor, blue for RGB white lights
520nm - 530nm (green)	Green Traffic Signal Lights, green for RGB white
580nm - 590nm (amber)	Amber Traffic Signal Lights, amber for RGBA white lights
630nm - 640nm (red)	Red Signal Lights, red for RGB white lights
660nm (deep red)	Blood Oximetry
680nm (deep red)	Skin Therapy
800nm - 850nm (near IR)	Night Vision Illuminators and Beacons for use with Night Vision Goggles or CCD's
850nm - 940nm (near IR)	Photo Electric Controls
940nm (near IR)	Covert Illumination CCD based Systems

Light Emitting diode:

The light emitting diode (LED) is one of the simplest optoelectronic devices which has found important applications as a display device as well as an optical signal generator for optical communication. Compared to the laser diode, the fabrication of the LED is very simple since it does not require any special optical cavity for its operation. However, one pays the price in terms of low optical output, broad and incoherent spectra, and slow device response. In this chapter we will explore the physics behind the operation of the LED .

The simplicity of the light emitting diode (LED) makes it a very attractive device for display and communication applications. It gives way to the laser diode in applications where modulation speeds above $\sim$ 5 GHz are needed or where spectrally pure optical output is needed. The spectral width of the optical output of an LED is of the order of $k_B T$ which translates into a wavelength spread of 300-400 Å at room temperature. Although this is a large value, the LED produces a single color to the human eye. Thus the LEDs can be used very effectively in color displays. An important recent application of LEDs is in providing tail lights in automobiles, an application that could make LEDs very important commercial devices.

kT ~ 26 meV, equivalent to $\Delta\lambda$ ~ 300-400 Å

The basic LED is a p-n junction which is forward biased to inject electrons and holes into the p- and n-sides respectively. The injected minority charge recombines with the majority charge in the depletion region or the neutral region. *In direct band semiconductors, this recombination leads to light emission since radiative recombination dominates in high quality materials. In indirect gap materials, the light emission efficiency is quite poor and most of the recombination paths are non-radiative which generate heat rather than light.* We will now examine the important issues which govern the material systems that are used for LEDs.

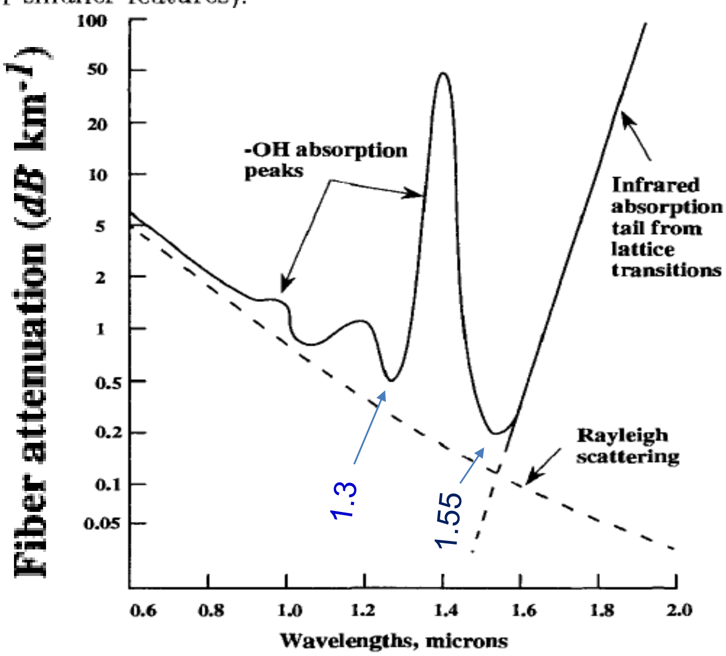
Choice of Materials

Emission Energy:

The **light emitted from the device is very close to the semiconductor bandgap**. One has to choose an alloy since there is greater flexibility in the band gap range available. As can be seen from **Fig. 6.1**, the loss is less at 1.55 μm and 1.3 μm. **If optical communication sources are desired, one must choose materials which can emit at that wavelengths**.

Important semiconductor materials exploited in optoelectronics are the alloy $Ga_xAl_{1-x}As$ which is lattice matched very well to GaAs substrates; $In_{0.53}Ga_{0.47}As$ and $In_{0.52}Al_{0.48}As$ which are lattice matched to InP; InGaAsP which is a quaternary material whose composition can be tailored to match with InP and can emit at 1.55 μm

GaAsP which has a wide range of bandgaps available. Recently there has been a considerable interest in large bandgap materials such as ZnSe, ZnS, SiC, and GaN to produce devices that emit blue or green light. The motivation is for superior display technology and for high density optical memory applications (a shorter wavelength allows reading of smaller features).



1.55μm loss ~ 0.2 dB/km
1.3μm loss ~ 0.5 dB/km

Fig. 6.1: The Optical **attenuation vs. wavelength** for an optical fiber. Primary loss mechanisms are identified as absorption and scattering.

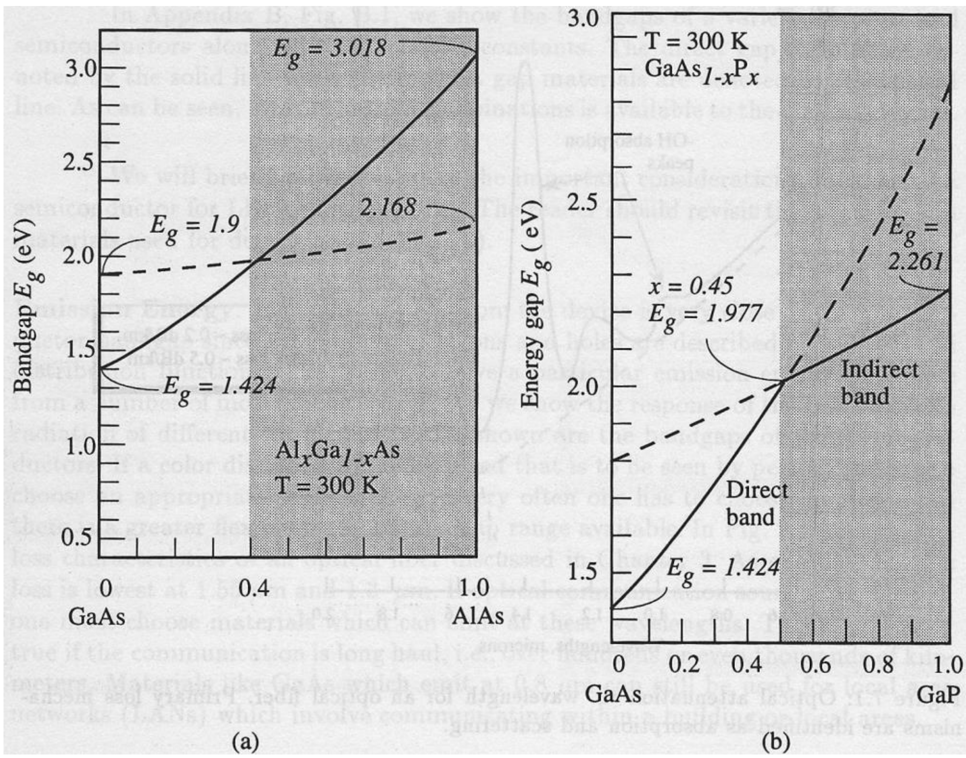
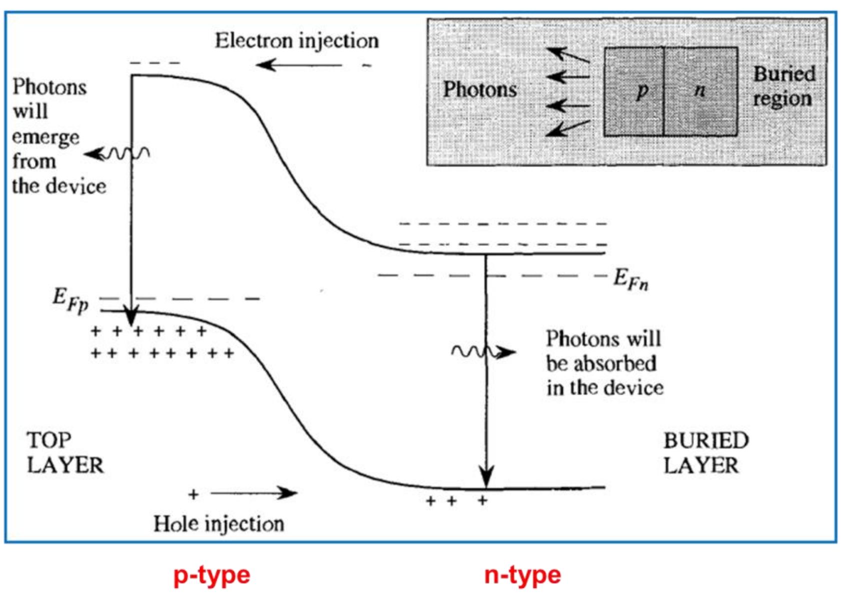


Fig. 6.2: Bandgap of $Al_xGa_{1-x}As$ and (b) $GaAs_{1-x}P_x$ as a function of alloy composition. Note that **the bandgap changes from direct to indirect as shown**.

Operation of LED:

The LED is a forward biased p-n diode in which electrons and holes are injected into a region where they recombine. In general, the electron-hole recombination process can occur by radiative and nonradiative channels. Under the condition of minority carrier recombination or high injection recombination



Operation of LED:

If τ_r and τ_{nr} are the radiative and non-radiative lifetimes, the total recombination time is

$$\boxed{\frac{1}{\tau_n} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

The internal quantum efficiency for the radiative processes is then defined as

$$\boxed{\eta_{Qr} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}}}$$

In high quality direct gap semiconductors, the internal efficiency is usually close to unity. In indirect materials the efficiency is of the order of 10^{-2} to 10^{-3}.

Carrier Injection and Spontaneous Emission

The LED is essentially a forward biased p-n diode as shown in Fig.

In the forward
bias conditions the electrons are injected from the n-side to the p-side while holes are injected from the p-side to the n-side. As discussed earlier , the forward bias current is dominated by the minority charge diffusion current across the junction. The diffusion current, in general, consists of three components: i) minority carrier electron diffusion current, ii) minority carrier hole diffusion current; and iii) trap assisted recombination current in the depletion region of width W. These current densities have the following forms respectively

$$\boxed{\begin{aligned} J_n &= \frac{eD_n n_p}{L_n}\left[exp\left(\frac{eV}{k_BT}\right)-1\right] \\ J_p &= \frac{eD_p p_n}{L_p}\left[exp\left(\frac{eV}{k_BT}\right)-1\right] \\ J_{GR} &= \frac{en_iW}{2\tau}\left[exp\left(\frac{eV}{2k_BT}\right)-1\right] \end{aligned}}$$

Electron diffusion current density

where τ is the recombination time in the depletion region and depends upon the trap density. *The LED is designed so that the photons are emitted close to the top layer and not in the buried layer as shown in Fig. 9.4. The reason for this choice is that photons emitted deep in the device have a high probability of being reabsorbed. Thus one prefers to have only one kind of carrier injection for the diode current.* Usually the top layer of the LED is p-type, and for photons to be emitted in this layer one must require the diode current to be dominated by the electron current (i.e., $J_n >> J_p$). The ratio of the electron current density to the total diode current density is called the injection efficiency γ_{inj}. Thus we have

$$\boxed{\gamma_{inj} = \frac{J_n}{J_n + J_p + J_{GR}}}$$

Photon energy and the electron and hole energies are related by

$$\boxed{\hbar\omega - E_g = \frac{\hbar^2 k^2}{2}\left[\frac{1}{m_e^*} + \frac{1}{m_h^*}\right] = \frac{\hbar^2 k^2}{2m_r^*}}$$

where m_r^* is the reduced mass for the e-h system. The electron and hole energies are related to the photon energy by the relations

$$\boxed{\begin{aligned} E^e &= E_c + \frac{\hbar^2 k^2}{2m_e^*} = E_c + \frac{m_r^*}{m_e^*}(\hbar\omega - E_g) \\ E^h &= E_v - \frac{\hbar^2 k^2}{2m_h^*} = E_v - \frac{m_r^*}{m_h^*}(\hbar\omega - E_g) \end{aligned}}$$

If an electron is available in a state k, and a hole is also available in the state k (i.e., the Fermi functions for the electrons and holes satisfy $f^e(k) = f^h(k) = 1$), the radiative recombination rate is given by

$$\boxed{W_{em} = \frac{1}{\tau_o} = \frac{e^2 n_r \hbar\omega}{3\pi\epsilon_o m_o^2 c^3 \hbar^2} \left|p_{cv}\right|^2}$$

where n_r is the refractive index of the semiconductor, m_0 the free electron mass, and p_{cv} the momentum matrix elements between the conduction and valence bands. It turns out that p_{cv} does not vary too much between semiconductors and has a value given by the equation

$$\frac{2p_{cv}^2}{m_0} \cong 22\ eV$$

Thus the emission rate turns out to be

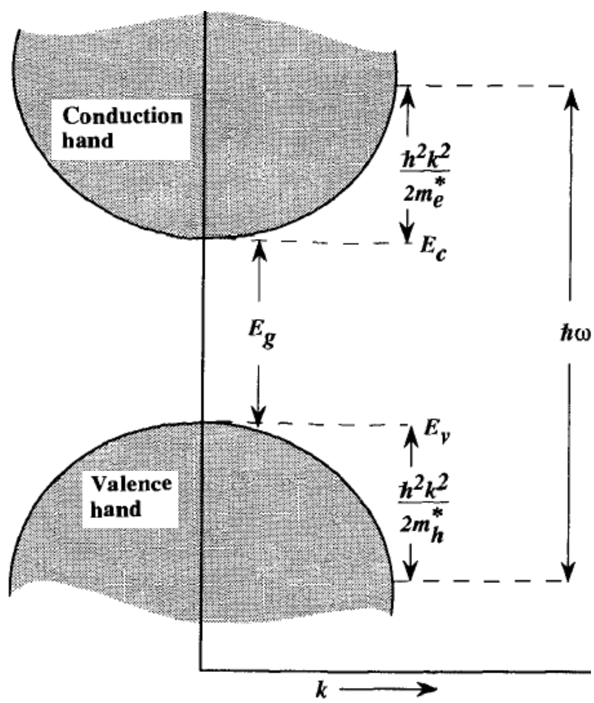
$$W_{em} \sim 1.14 \times 10^9 \hbar\omega(eV) \qquad s^{-1}$$

and the recombination time becomes ($\hbar\omega$ is expressed in electron volts)

$$\tau_o = \frac{0.88}{\hbar\omega(eV)} \qquad ns$$

The recombination time discussed above is the shortest possible spontaneous emission time since we have assumed that the electron has a unit probability of finding a hole with the same k-value.

When carriers are injected into the semiconductors the occupation probabilities for the electron and hole states are given by the appropriate quasi-Fermi levels. *The e-h recombination process is determined by the spontaneous emission which implies that the photon density of the emission is quite low so that stimulated emission is not significant.* The emitted photons leave the device volume so that the photon density never becomes high in the *e-h* recombination region. In a laser diode the situation is different, as we shall see later. The photon emission rate is given by integrating the emission rate W_{em} over all the electron-hole pairs after introducing the appropriate Fermi functions.



A schematic of the E-k diagram for the conduction and valence bands.

In the case where the electron and hole densities n and p are small (non-degenerate case), the Fermi functions have a Boltzmann form ($exp(-E/k_BT)$). The recombination rate then becomes

$$R_{spon} = \frac{1}{2\tau_o}\left(\frac{2\pi\hbar^2 m_r^*}{k_BTm_e^*m_h^*}\right)^{3/2} n\ p$$

The rate of photon emission depends upon the product of the electron and hole densities. If we were to define the lifetime of a single electron injected into a lightly doped ($p = N_a \le 10^{17}\mathrm{cm}^{-3}$) p-type region with hole density p

$$\boxed{\frac{R_{spon}}{n} = \frac{1}{\tau_r} = \frac{1}{2\tau_o}\left(\frac{2\pi\hbar^2 m_r^*}{k_BTm_e^*m_h^*}\right)^{3/2} p}$$

The time τ_r in this regime is very long (hundreds of nanoseconds), as shown in Fig. and becomes smaller as p increases.

In the case where electrons are injected into a heavily doped p-region (or holes are injected into a heavily doped n-region), the function $f^h(f^e)$ can be assumed to be unity. The spontaneous emission rate is then

$$R_{spon} \sim \frac{1}{\tau_o}\left(\frac{m_r^*}{m_h^*}\right)^{3/2} n$$

for electron concentration n injected into a heavily doped p-type region and

$$R_{spon} \sim \frac{1}{\tau_o}\left(\frac{m_r^*}{m_e^*}\right)^{3/2} p$$

for hole injection into a heavily doped n-type region.

EXTERNAL QUANTUM EFFICIENCY

There are three main loss mechanisms for the emitted photons: i) the emitted photons can be reabsorbed in the semiconductor by creating an electron-hole pair; ii) a certain fraction of photons will be reflected back at the semiconductor-air interface; and iii) some photons impinge upon the surface with angles greater than the critical angle thus suffering total internal reflection.

To minimize the absorption of the 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. This criterion was considered in our discussion of the injection efficiency γ_{inj} in the previous subsection. Note that for direct gap materials, a photon can only travel a micron or so before getting absorbed. *It must be noted, however, that the active emission volume cannot be placed too close to the surface, otherwise non-radiative recombination processes mediated by surface defects will reduce the device efficiency.*

Photons that are able to make it to the semiconductor-air surface have to suffer reflection from the surface. Those that are reflected are lost. If n_{r2} is the refractive index of the semiconductor and n_{r1} the index of air, the reflection coefficient is (for vertical incident light),

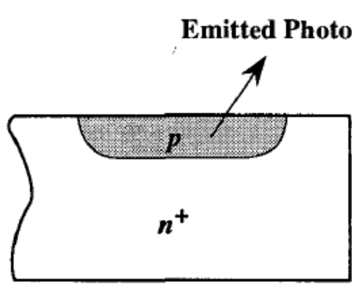
$$R = \left(\frac{n_{r2} - n_{r1}}{n_{r2} + n_{r1}} \right)^2$$

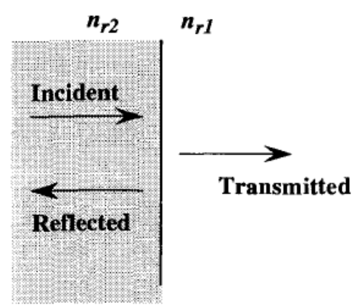
This loss is called the Fresnel loss. For a GaAs LED, if we choose $n_{r2} = 3.66$, $n_{r1} = 1.0$, we get a loss of 0.33, i.e., 33% of the photons cannot get through.

Finally, one has the loss of photons due to total internal reflection. If light impinges at a surface from a region of high refractive index ($n_{r2} > n_{r1}$), it is totally reflected back if the angle of incidence is greater than a critical angle θ_C where

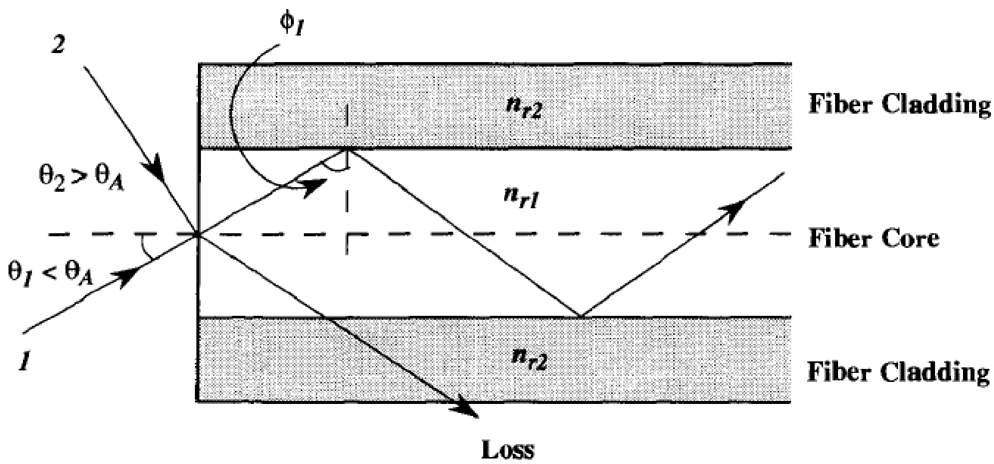
$$\theta_C = sin^{-1}\left(\frac{n_{r1}}{n_{r2}}\right)$$

For the GaAs-air surface, the critical angle is 15.9°.





$$R = \left(\frac{n_{r2} - n_{r1}}{n_{r2} + n_{r1}}\right)^2$$



θ_A = Maximum Acceptance Angle

$\phi = \phi_C$ = Critical Angle for Total Internal Reflection

An optical fiber is made up of a core region of index n_{r1} and an outer cladding region of index n_{r2} ($n_{r1} > n_{r2}$). If the light is incident at an angle $\theta_1 < \theta_A$ so that the light suffers total internal reflection in the fiber, the light is coupled successfully into the fiber. Optical waves coming at an angle greater than θ_A are not able to propagate in the fiber.

the maximum angle of acceptance, θ_A,

$$\theta_A = sin^{-1}\left(n_{r1}^2 - n_{r2}^2\right)^{1/2} = sin^{-1}(A_n)$$

where A_n is called the numerical aperture of the fiber.

The photons emerging from the LED have an angular distribution between $\theta = 0$ and $\theta = \pi/2$. Let us assume that the distribution has a form

$$I_{ph}(\theta) = I_0 cos\theta$$

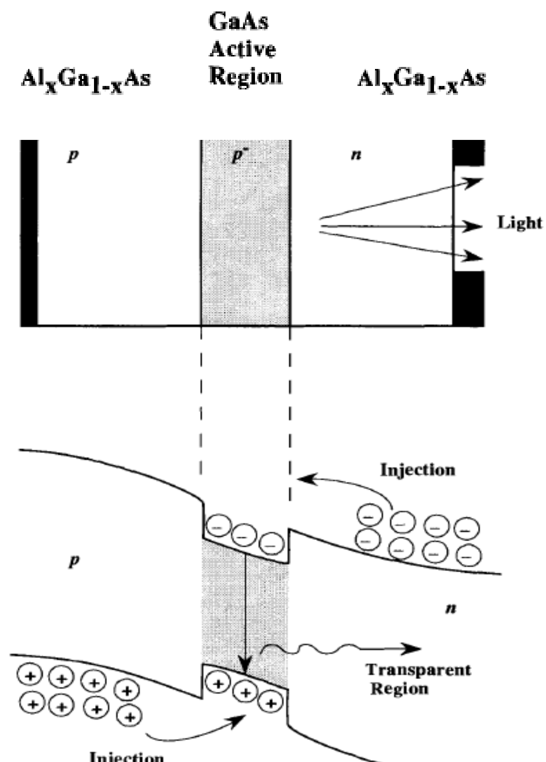
The fraction of the light coupled into the fiber is then

$$\eta_{fiber} = \frac{\int_0^{\theta_A} I_{ph}(\theta) sin\theta d\theta}{\int_0^{\pi/2} I_{ph}(\theta) sin\theta d\theta} = sin^2\theta_A$$

Heterojunction LED:

If the LED is made from a single semiconductor, there are a number of problems that reduce the device efficiency. An important problem is that in a homojunction LED (i.e., a device based on a single semiconductor), the photon emission volume must be close to the surface so that the emitted photons are not reabsorbed.

The heterojunction LED resolves these problems by injecting charge from a larger bandgap material in a narrow gap active region. Fig. gives a schematic of the LED. Electrons and holes are injected from the wide gap n- and p-regions into the narrow gap active region. The electrons cannot enter the wide gap p-region below the active region and thus do not suffer from poor surface conditions. *The photons emitted are also not absorbed in the top or bottom region since the photon energy is smaller than the bandgap of the n- or p-region.*

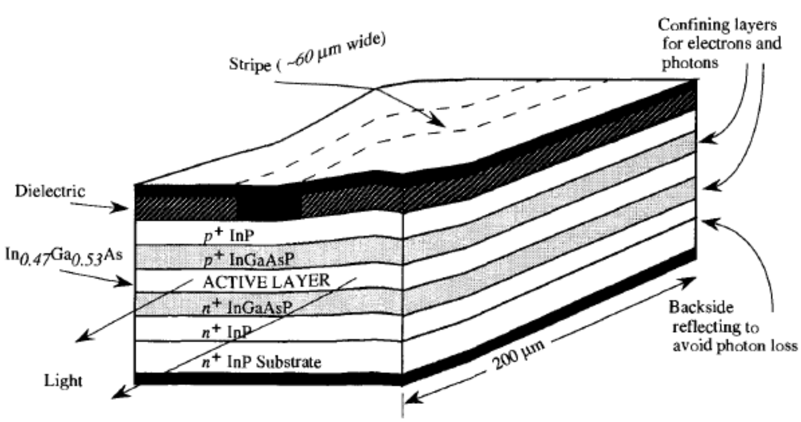


A heterojunction LED uses a narrow gap semiconductor for the active region.

Edge emitting diode

An important ingredient of the edge emitting LED is the wide gap cladding layers which confine not only the electrons and holes to the active layer, but also cause the emitted photons to travel along the LED axis and emerge from the edge of the device. This optical cavity will be discussed in more detail when we discuss the laser diode.

Due to the superior collimation of the edge emitting LED (~30° width perpendicular to the layer and ~ 120° parallel to the layer) the coupling efficiency to a fiber is greatly improved.

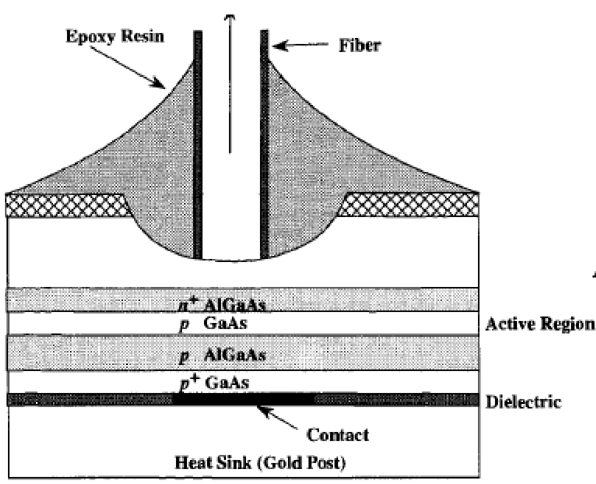


Schematic of edge emitting diode.

Surface emitting diode:

An important class of LEDs is the surface emitting LED first realized by Burrus and Dawson in 1970. A schematic of this LED is shown in Fig. 9.11. An optical fiber is butt coupled to the LED by etching a hole in the LED and attaching the fiber by epoxy resin. The LED itself is a heterostructure LED with a thin active region of low bandgap surrounded by wide gap regions.

The photons emitted are directly coupled to the optical fiber. In various advanced structures a microlens is placed on the LED to improve the coupling efficiency.

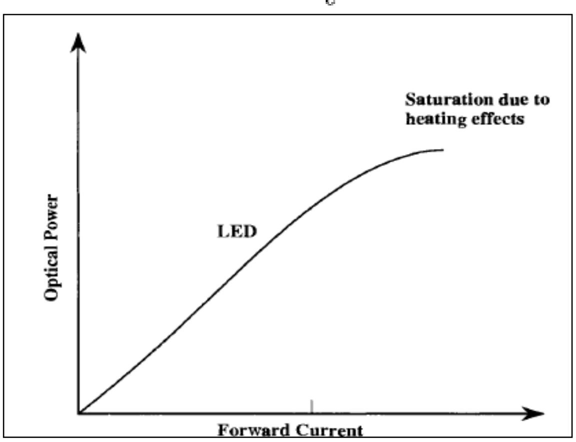


A schematic of a surface emitting LED.

Light Current characteristics:

When a current I is passing through the forward bias diode, a certain fraction of the current is converted to light. If η_{Tot} represents the total efficiency of this conversion, the photon current that emerges from the diode is

$$\begin{aligned} I_{ph} &= \text{Number of photons per second} \\ &= \eta_{Tot} \cdot \frac{I}{e} \end{aligned}$$



The output power of an LED is essentially linear with the injected currents.

Spectral Purity of LEDs.

The spectral purity or the linewidth of the emitted radiation is an important characteristic of optical devices. The importance of the spectral purity of the emitted light depends upon applications. If the LED is to be used in a display device, the spectral purity is not an issue. However, in optical communication applications the spectral purity is a critical issue. Light pulses of different wavelengths travels through an optical fiber at different speeds.

the emission spectrum is essentially determined by the product $(\hbar\omega - E_g)^{1/2}\ f^e(E^e) f^h(E^h)$. This is the convoluted product of the electron and hole occupation probabilities. At low injection, this width is of the order of $k_B T$. At high injection the width is (n is the total charge density)

$$\Delta E \sim \frac{n}{N_c}\ k_B T$$

where N_c is the effective bandedge density of states

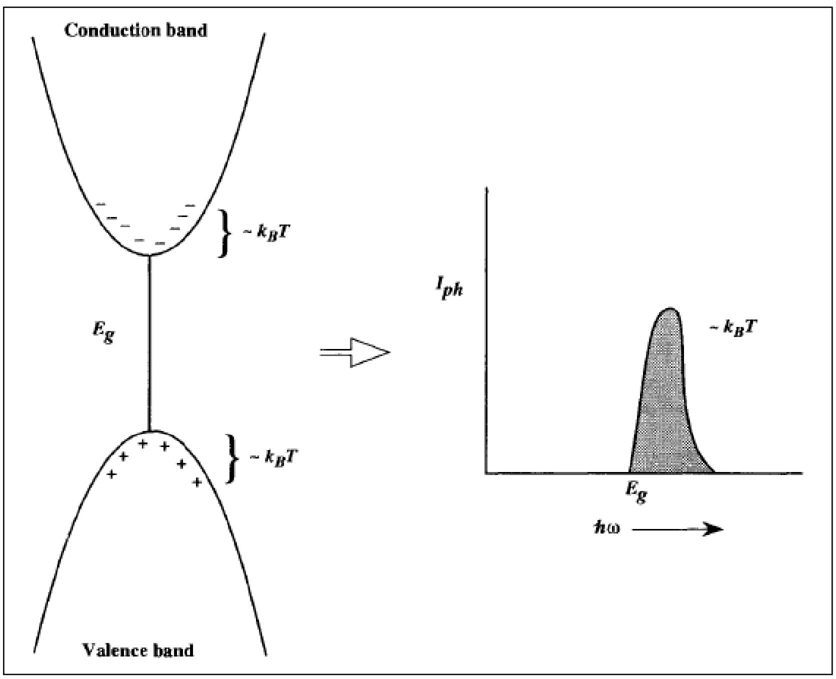
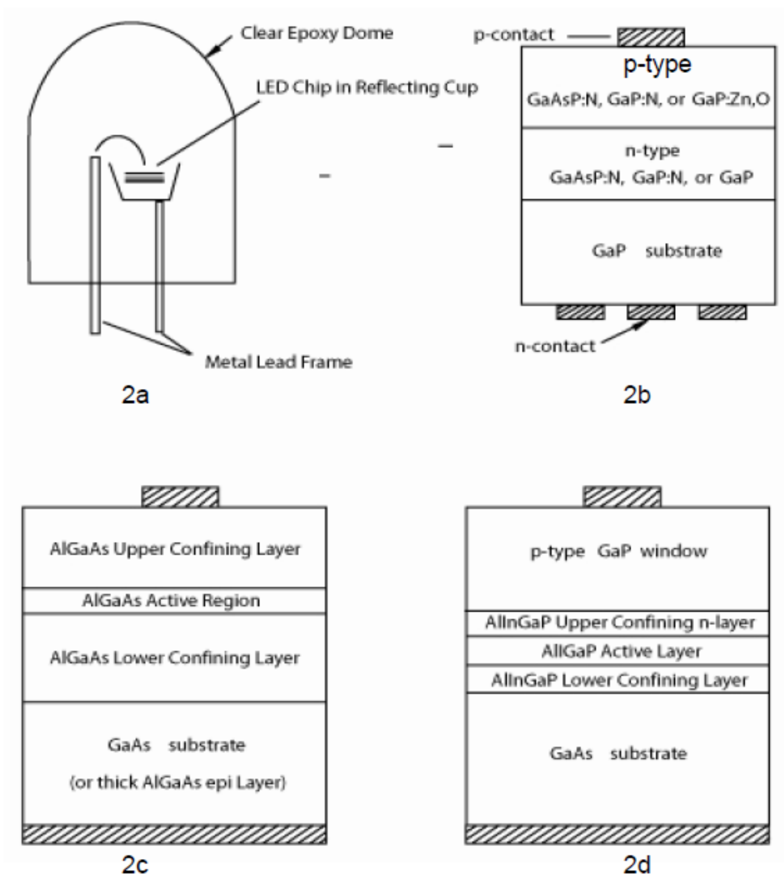


Figure : In an LED, the electrons and holes are distributed over an energy width of $\sim k_BT$. Since all the e-h pairs contribute to the optical output, the LED output is quite broad with a width roughly equal to k_BT. The shape of the output depends upon the carrier occupation function and the density of states function.

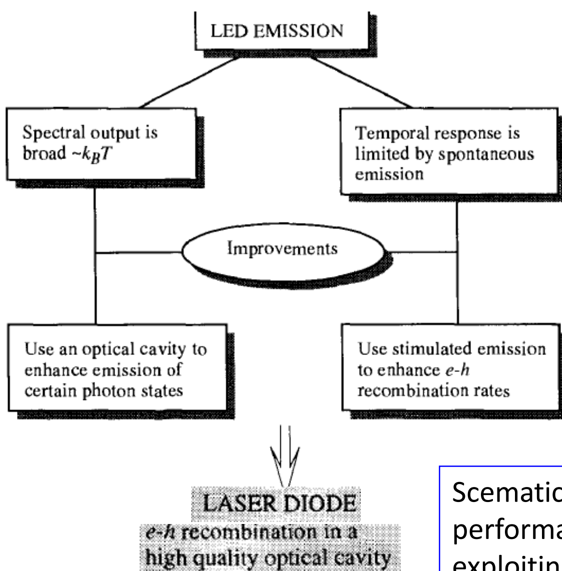
Typical LED device and chip configurations



The Laser Diode

The Laser Diode:

The key drawbacks of the LED are the broad spectrum of the emitted light and the difficulty in pushing the modulation bandwidths above a gigahertz. The laser diode is able to overcome these limitations. The semiconductor laser diode provides an extremely sharp emission line with linewidth up to orders of magnitude narrower than that of an LED. The modulation bandwidth of laser diode approaches 50GHz. And also for its superior spatial coherence the laser beam des not spread as much as beam from other sources.



Scematic diagram of how the LED performance can be improved by exploiting an optical cavity

The semiconductor laser diode operates as a forward bias p-n junction just as the LED studied in the previous sections. *However, while the structure appears similar to the LED as far as the electron and holes are concerned, it is quite different from the point of view of the photons.*

As in the case of the LED, electrons and holes are injected into an active region by forward biasing the laser diode. At low injection, these electrons and holes recombine radiatively via the spontaneous emission process to emit photons. However, the laser structure is so designed that at higher injections the emission process occurs by stimulated emission. Previously we have discussed the difference between spontaneous and stimulated emission. The stimulated emission process provides spectral purity to the photon output, provides coherent photons, and offers high speed performance. *Thus the key difference between the LED and the laser diode arises from the difference between spontaneous and stimulated emission.*

In the case of Fig. 7.1 we show the electron-hole pair along with photons of energy $\hbar\omega$ equal to the electron-hole energy difference. In this case, in addition to the spontaneous emission rate, one has an additional emission rate called the stimulated emission process. The stimulated emission process is proportional to the photon density (of photons with the correct photon energy to cause the e-h transition). *The photons that are emitted are in phase (i.e., same energy and wave vector) with the incident photons.*

the rate for stimulated emission is $W_{em}^{st}(\hbar\omega) = W_{em}(\hbar\omega) \cdot n_{ph}(\hbar\omega)$

where $n_{ph}(\hbar\omega)$ is the photon occupation number and W_{em} is the spontaneous emission rate discussed earlier. In the LED, when photons are emitted by spontaneous emission, they are lost either by reabsorption or simply leave the structure. Thus $n_{ph}(\hbar\omega)$ remains extremely small and stimulated emission cannot get started.

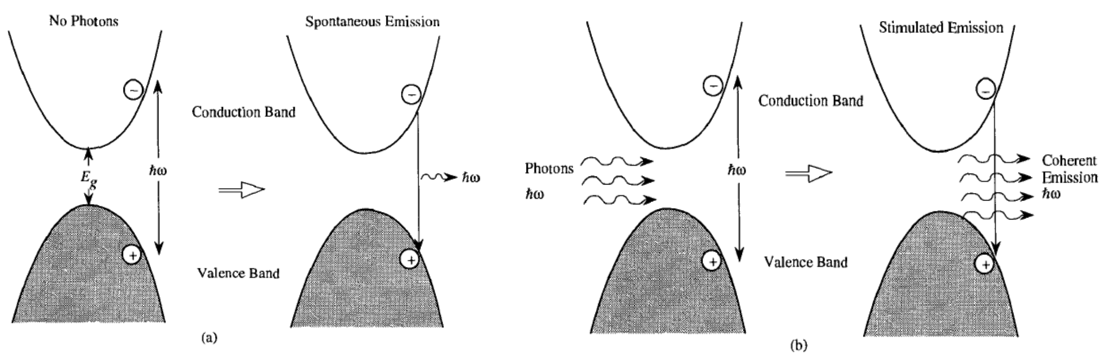


Figure 7.1: (a) In spontaneous emission, the e-h pair recombines in the absence of any photons present to emit a photon. (b) In simulated emission, an e-h pair recombines in the presence of photons of the correct energy $\hbar\omega$ to emit coherent photons. In coherent emission the phase of the photons emitted is the same as the phase of the photons causing the emission.

OPTICAL CAVITY:

While both the LED and the laser diode use a forward biased p-n junction to inject electrons and holes to generate light, the laser structure is designed to create an "optical cavity" which can "guide" the photons generated. The optical cavity is

essentially a resonant cavity in which the photons have multiple reflections. Thus, when photons are emitted, only a small fraction is allowed to leave the cavity. As a result, the photon density starts to build up in the cavity. A number of important cavities are used for solid state lasers. These are the Fabry-Perot cavity, cavities for distributed feedback lasers containing periodic gratings, surface emitting laser cavities containing specially designed reflectors, etc.. For semiconductor lasers, the most widely used cavity is the Fabry-Perot cavity shown in Fig. 7.2 . The important ingredient of the cavity is a polished mirror surface which assures that resonant modes are produced in the cavity as shown in Fig. 7.2 . These resonant modes are those for which the wavelengths of the photon satisfy the relation

$$L = q\lambda/2$$

where q is an integer, L is the cavity length, and λ is the light wavelength in the material and is related to the free space wavelength by

$$\lambda = \frac{\lambda_o}{n_r}$$

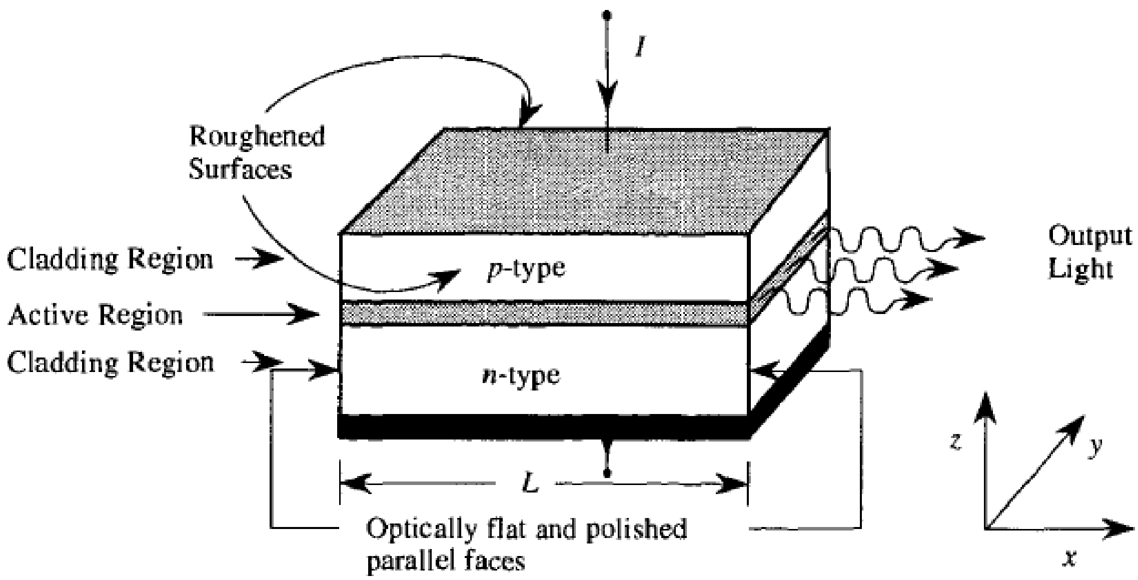


Fig. 7.2: A typical laser structure showing cavity and the mirrors used to confine the photons.

where n_r is the refractive index of the cavity. The spacing between the stationary mode: is given by

$$\Delta k = \frac{\pi}{L}$$

While the optical cavity can confine the photons with certain characteristics, it must be noted that the active region of the laser in which electron-hole pairs are recombining may only occupy a small fraction of the optical cavity. *It is important that a large fraction of the optical waveform overlap with the active region since only this fraction will be responsible for stimulated emission. As a result, it is important to design the laser structure so that the optical wave has a high probability of being in the region where e-h pairs are recombining.*

An important parameter of the laser cavity is the optical confinement factor Γ, which gives the fraction of the optical wave in the active region,

$$\Gamma = \frac{\int_{\text{active region}} |F(z)|^2 dz}{\int |F(z)|^2 dz}$$

Optical aborption loss and gain:

The photon current associated with an electromagnetic wave traveling through a semiconductor is described by

$$I_{ph} = I_{ph}^{0}\ exp\,(-\alpha x)$$

where α (the absorption coefficient) is usually positive, and I_{ph}^{0} is the incident photon current at $x = 0$. The optical intensity which is the photon current multiplied by the photon energy $\hbar\omega$ falls as the wave travels if α is positive. However, if electrons are pumped in the conduction band and holes in the valence band, the electron-hole recombination process (photon emission) can be stronger than the reverse process of electron-hole generation (photon absorption). In general, as discussed in Section 4.7, the gain coefficient is defined by gain = emission coefficient−absorption coefficient. If $f^{e}(E^{e})$ and $f^{h}(E^{h})$ denote the electron and hole occupation, the emission coefficient depends upon the product of $f^{e}(E^{e})$ and $f^{h}(E^{h})$ while the absorption coefficient depends upon the product of $(1-f^{e}(E^{e}))$ and $(1-f^{h}(E^{h}))$. Here the energies E^{e} and E^{h} are related to the photon energy by the condition of vertical k-transitions.

$$\begin{aligned} E^{e} &= E_{c} + \frac{m_r^*}{m_e^*}(\hbar\omega - E_g) \\ E^{h} &= E_{v} - \frac{m_r^*}{m_h^*}(\hbar\omega - E_g) \end{aligned}$$

The occupation probabilities f^e and f^h are determined by the quasi-Fermi levels for electrons and holes

The gain which is the difference of the emission and absorption coefficient is now proportional to

$$g(\hbar\omega) \sim f^e(E^e) \cdot f^h(E^h) - \{1 - f^e(E^e)\}\{1 - f^h(E^h)\} = \{f^e(E^e) + f^h(E^h)\} - 1$$

The optical wave has a general spatial intensity dependence

$$I_{ph} = I_{ph}^0 \ exp\ (g(\hbar\omega)x)$$

and *if g is positive, the intensity grows because additional photons are added by emission to the intensity.* The condition for positive gain requires "inversion" of the semiconductor system

$$f^e(E^e) + f^h(E^h) > 1$$

The quasi-Fermi levels must penetrate their respective bands for this condition to be satisfied.

$$g(\hbar\omega) = \frac{\pi e^2 \hbar}{m_0^2 c n_r \epsilon_0} \frac{1}{\hbar\omega} |a \cdot p_{cv}|^2 N_{cv}(\hbar\omega)[f^e(E^e) + f^h(E^h) - 1]$$

Note that if $f^e = 0 = f^h$, the gain is just $-\alpha(\hbar\omega)$, the negative of the absorption coefficient.

$$g(\hbar\omega) \cong 5.6 \times 10^4 \frac{(\hbar\omega - E_g)^{1/2}}{\hbar\omega} \left[f^e(E^e) + f^h(E^h) - 1\right] \ cm^{-1}$$

For a given injection density n(=p) the position of quassi fermi level is given by

$$
\begin{aligned}
E_{Fn} &= E_c + k_BT\left[\ell n\frac{n}{N_c} + \frac{1}{\sqrt{8}}\frac{n}{N_c}\right] \\
E_{Fp} &= E_v - k_BT\left[\ell n\frac{p}{N_v} + \frac{1}{\sqrt{8}}\frac{p}{N_v}\right]
\end{aligned}
$$

With these expressions the gain can be calculated as a function of photon energy for various levels of injection densities $n(=p)$. At low injections, f^e and f^h are quite small and the gain is negative. However, as injection is increased, for electrons and holes near the bandedges, f^e and f^h increase and gain can be positive. However, even at high injections, for $\hbar\omega >> E_g$, the gain is negative. The general form of the gain-energy curves for different injection levels is shown in Fig. 7.3

The gain discussed above is called the material gain and comes only from the active region where the recombination is occurring. Often this active region is of very small dimensions. In this case, one needs to define the cavity gain which is given by

$$
\text{Cavity gain} = g(\hbar\omega)\Gamma
$$

To study the photon losses by reflection and transmission from the cavity, let us consider a Fabry-Perot cavity whose reflection coefficient and transmission coefficient is shown in Fig. 7.4 . Let us consider a wave with field F_0 incident on one edge of the cavity as shown in Fig. and let us follow this wave as it moves through the cavity.

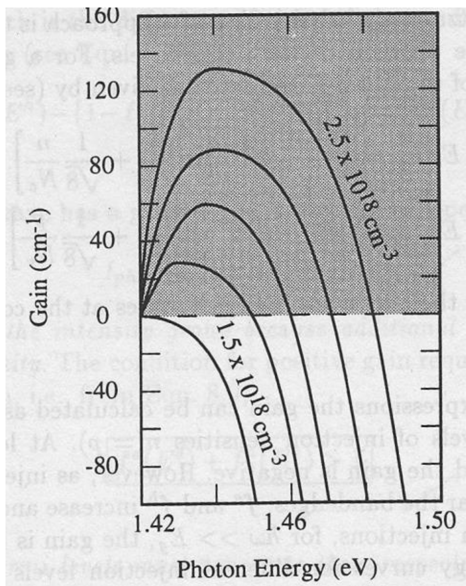


Fig. 7.3: Gain vs. photon energy curves for a variety of carrier injections for GaAs at 300K. The electron and hole injections are the same. The injected carrier densities are increased in steps of 0.25×10^{18} cm^{-3} from the lowest value.

It is straightforward to show that the transmitted and the reflected fields are given by

$$F_{\text{trans}} = F_4 + F_{10} + \ldots = \frac{t_1 t_2 A}{1 - A^2 r_1^2} F_0$$

$$F_{\text{ref}} = F_2 + F_7 + \ldots = \left(r_2 + \frac{r_1 t_1 t_2 A^2}{1 - A^2 r_1^2} \right) F_0$$

The gain of the wave when it moves a distance L is given by

$$A = exp \left[\left(\frac{g_{tot}}{2} + ik \right) L \right]$$

where g_{tot} consists of gain in the cavity and any loss term $\alpha_{\text{loss}}(g_{tot} = \Gamma g - \alpha_{\text{loss}})$.

Laser action occurs when non-zero F_{trans} and F_{ref} exist when F_0 is zero, i.e., photon generation in the cavity is sufficient to create photons outside the cavity. This requires a certain value of $g_{tot} = \Gamma g_{th}$. For lasings to start, we must have

$$A^2 r_1^2 = 1$$

The real part of this condition gives

$$g_{tot}(th) = \Gamma g_{th} - \alpha_{\text{loss}} = \frac{1}{L} \ell n r_1^{-2}$$

or $(R = r_1^2)$

$$\Gamma g_{th} = \alpha_{\text{loss}} - \frac{1}{L} \ell n R$$

The phase part of the lasing condition requires that $k = \frac{m\pi}{L}$

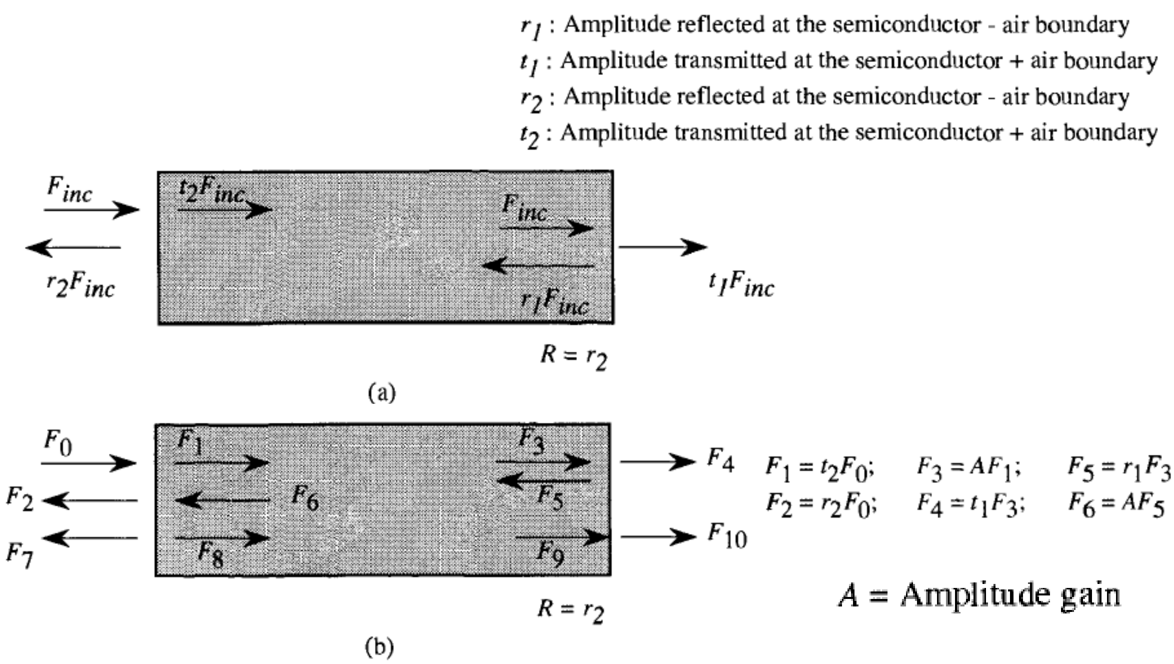


Figure 7.4 (a) A schematic of the Fabry-Perot cavity showing the reflectance and transmittance of waves. (b) The path of a light wave as it moves through the cavity.

The Laser below and above threshold:

The light output from a laser diode displays a rather abrupt change in behaviour below the thresold condition and above this condition. The thresold condition is usually defined as the condition where the cavity loss for any photon energy when,

$$\Gamma g(\hbar\omega) = \alpha_{\text{loss}} - \frac{\ell n R}{L} > 0$$

Another useful definition in the laser is the condition of transparency when the light suffers no absorption or gain, i.e.,

$$\Gamma g(\hbar\omega) = 0$$

When the p-n diode making up the semiconductor laser is forward biased, electrons and holes are injected into the active region of the laser. These electrons and holes recombine to emit photons. It is important to identify two distinct regions of operation of the laser. Referring to Fig. 7.5 when the forward bias current is small, the number of electrons and holes injected are small. As a result, the gain in the device is too small to overcome the cavity loss. The photons that are emitted are either absorbed in the cavity or lost to the outside. Thus, in this regime there is no buildup of photons in the cavity. However, as the forward bias increases, more carriers are injected into the device until eventually the threshold condition is satisfied for some photon energy. As a result, the photon number starts to build up in the cavity. As the device is further biased beyond threshold, stimulated emission starts to occur and dominates the spontaneous emission. The light output in the photon mode for which the threshold condition is satisfied becomes very strong.

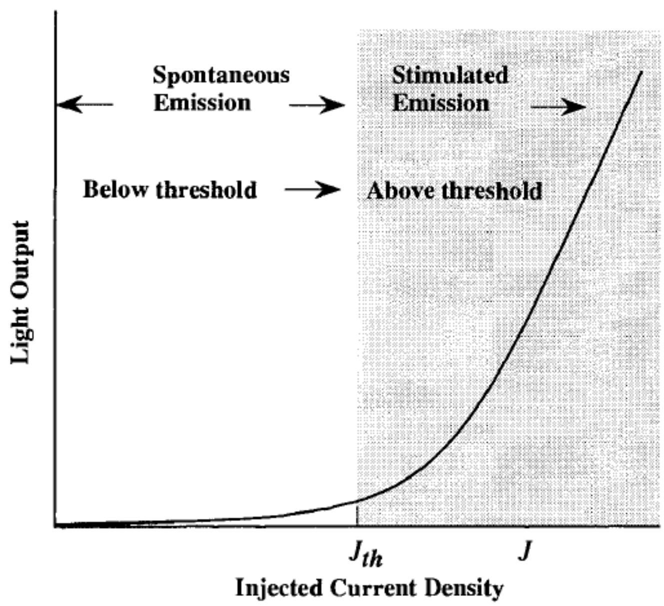


Figure 7.5 : The light output as a function of current injection in a semiconductor laser. Above threshold, the presence of a high photon density causes stimulated emission to dominate.

Below the threshold the device essentially operates as an LED except that there is a higher cavity loss in the laser diode since photons cannot escape from the device due to the mirrors. Let β_{loss} be the fraction of photons that cannot escape from the device. The photon current output is given by

$$\begin{aligned} I_{ph} &= (1 - \text{loss})\,(\text{total } e{-}h \text{ recombination per second}) \\ &= (1 - \text{loss})\,(\text{electron particle current}) \end{aligned}$$

$$I_{ph} = (1 - \beta_{\text{loss}})\,(R_{\text{spon}} A d_{las}) = (1 - \beta_{\text{loss}})\frac{I}{e}$$

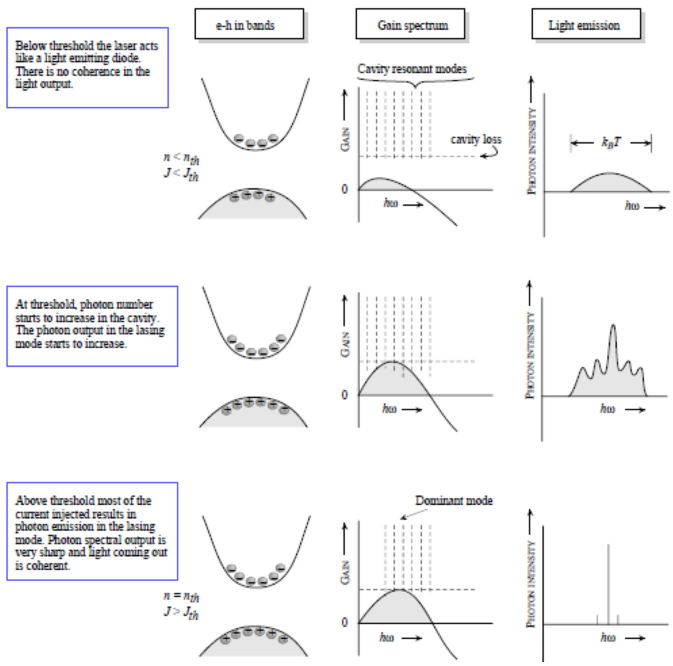


Figure 7.6 : (a) The laser below threshold. The gain is less than the cavity loss and the light emission is broad as in an LED. (b) The laser at threshold. A few modes start to dominate the emission spectrum. (c) The laser above threshold. The gain spectrum does not change but, due to the stimulated emission, a dominant mode takes over the light emission.

The carrier density in the active region increases initially as the laser is pumped from the zero current, but as the carrier density is simply

$$n_{2D} = \frac{J_{rad}\tau_r}{e}$$

The current density is

$$J_{th} = \frac{e \cdot n_{th} \cdot d_{las}}{\tau_r}$$

Quantum Well Lasers:

In quantum well lasers, the active region where e-h recombination takes place is only about a hundred Angstroms. A typical quantum well laser structure is shown in Fig. . A narrow bandgap region is surrounded by a wider gap region to form the quantum well. Surrounding the quantum well is the wide gap bandgap cladding layer. Often the quantum well is surrounded by a region which "funnels" the electrons and holes into the well. Such structures are called graded index separate (GRIN) confinement structures.

Quantum well lasers have gained wide acceptance as high speed low threshold lasers. Their advantage in low threshold applications comes from the special density of states that quasi-2D systems have.

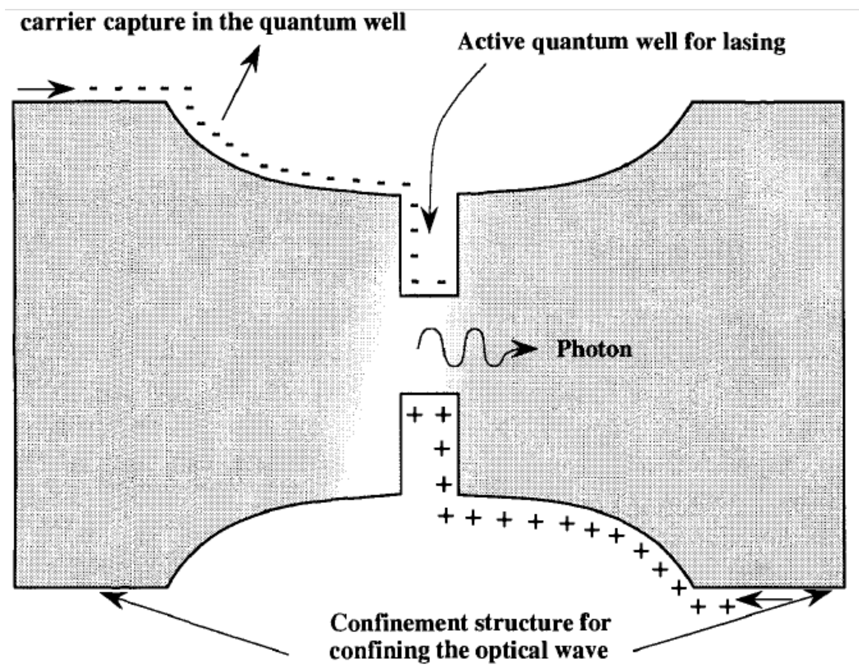


Figure : A typical quantum well laser structure for low threshold lasers.

Index Guided Cavities

Index guided cavities rely on a step in the index profile in the lateral direction. An example is shown in Fig. . Such a device is also called a buried heterostructure laser. The device fabrication is much more complex. To produce a lateral index step, one requires to first grow an epitaxial layer with a structure similar to the normal laser. The structure is then etched down leaving a few micron regions. Regrowth is then carried out to surround the active region by a large bandgap material.

The buried heterostructure laser, if fabricated correctly, does not suffer from kinks in the light-current curve. The output is single mode and the threshold current is very small. Of course, to take full advantage of the electronic properties, the active region must contain quantum well structures.

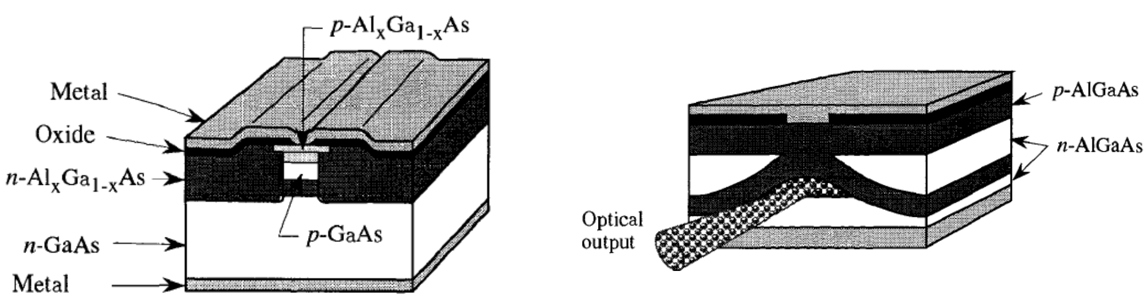


Figure : Index guided laser cavities. Etching and regrowth techniques are employed to produce buried active regions.