Chapter 11
Light Emitting Diodes

In this chapter we discuss theory and implementations of light emitting diodes (LEDs). LEDs are the basis for the development of lasers. In a junction LED photons of near bandgap energy are generated by the process of spontaneous emission, in which a large population of electrons, injected into a normally empty conduction band by a small forward bias, recombine with the holes in the valence band. Spontaneous emission is different from stimulated emission that is used in junction lasers. Spontaneous emission occurs at low forward bias voltages as opposed to the stimulated emission that occurs at much higher forward bias and much higher current densities.

LEDs do not require an optical cavity and mirror facets to provide feedback of photons. The emitted photons have random phases, and therefore an LED is an incoherent light source. The linewidth of the spontaneous emission is approximately equal to the photoluminescence linewidth which is a few kT (typically 30-50nm at room temperature). Thus many optical modes are supported, thus LED is a multimode optical source suitable for use with multimode fibers.

Advantages of LEDs as a light source are simpler fabrication process, lower cost, higher lifetime and reliability and simple drive circuitry when compared to laser diodes. Ideally, the LED exhibits a linear output light – current characteristics thus is suitable for analog modulations. The light –current characteristics is less sensitive to temperature than that in a laser diode. Main disadvantages of LEDs compared to laser diodes are lower output light power (makes them only suitable for short distance telecommunications), smaller modulation bandwidth (less data capacity), and harmonic distortion due to multimodal output. Superradiant LEDs have output light power comparable to that of lasers.

Basic Principles of LEDs:

In a forward biased PN junction of a direct bandgap material which has high doping concentration on both P and N side, excess minority carriers (electrons in the P-side and holes in

the N-side) recombine with the majority carriers through a radiative recombination process. The resulting photons emitted through the radiative recombination process has an energy of about the direct bandgap of the material

$$h\nu = E_g \tag{11.1}$$

Transitions of band to band, impurity level to band, donor to acceptor and excitonic transitions all contribute to the spontaneous emission. The rate of the radiative recombination is normally proportional to the forward bias injection rate, and hence to the diode current given by

$$I = qA\left(\frac{D_p p_{n0}}{L_h} + \frac{D_n n_{p0}}{L_e}\right)\left(e^{\frac{qV_{Forward}}{kT}} - 1\right) \tag{11.2}$$

where A is the area of the LED junction, p_{n0} and n_{p0} are, respectively, the concentration of the minority carriers at the edge of the depletion region in N-type and P-type materials, and L_h and L_e are the Debye length of holes and electrons as the minority carriers.

The internal quantum efficiency of the device is defined as the rate of emission of photons divided by the rate of supply of electrons. Note that not all the electrons recombine with holes through radiative recombination, therefore an internal quantum efficiency of less than 100% is expected. The peak in the density distribution of electrons in the conduction band occurs at an energy kT/2 above the band edge. Therefore the band to band transition energy is slightly higher than the bandgap, resulting in the re-absorption of some of the emitted photons. Due to the involvement of phonons, this self absorption does not exist in indirect semiconductors which also emit spontaneously. Despite the lack of re-absorption in the indirect bandgap semiconductors the quantum efficiency is very low again due to the low rate of radiative recombination compared to other recombination processes.

The spontaneous emission rate can be calculated in the case of weak injection in an LED such that the quasi-Fermi levels are still several kT away from the band edges and are within the bandgap. Under these conditions, the spontaneous emission rate $r_{SP}(E)$ can be written as

$$r_{SP}(E) = \frac{\left(\frac{2m_e^* m_h^*}{m_e^* + m_h^*}\right)^{3/2}}{2\pi^2 \hbar^3 \tau_r}\left(E - E_g\right)^{1/2} e^{\frac{E_{Fn} - E_{Fp} - E_g}{kT}} e^{-\frac{E - E_g}{kT}} \tag{11.3}$$

where τr is the radiative recombination lifetime. For GaAs, τr can be calculated to be ~0.6nSec. The spectral distribution of the spontaneous emission is shown in Fig. 11.1. The total photon flux Φ_o(in sec^{-1}) can be found by integrating of Eq. 11.3 over the active region volume V.

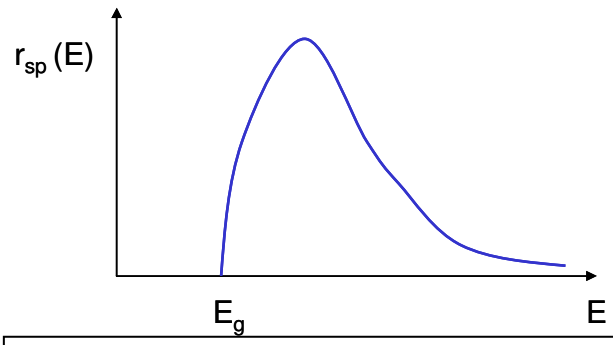

Fig. 11.1: Spectral distribution of the rate of spontaneous emission.

$$\Phi_o = V\int_0^\infty r_{SP}(E)dE = \frac{V}{\sqrt{2}\hbar^3\tau_r}\left(\frac{m_e^* m_h^*}{\pi(m_e^* + m_h^*)}\right)^{3/2}(kT)^{3/2}\, e^{\frac{E_{Fn}-E_{Fp}-E_g}{kT}} \tag{11.4}$$

When the injection level is increased, the quasi-fermi levels move into the bands and the probability function increases resulting in the increase of output light. The responsivity of an LED, *R* is defined as the ratio of the emitted optical power $P_o = \Phi_o h\nu$ to the injection current *I*.

$$R = \frac{\Phi_o h\nu}{I} = \eta_o \frac{h\nu}{q} = \frac{1.24\eta_o}{\lambda(\mu m)} \quad (W/A) \tag{11.5}$$

where η_o is the overall efficiency of the LED. According to Eq.11.5, the output light power is proportional to drive current. This means a constant responsivity. As the injection current is increased, saturation effects take over, resulting in a decrease in the responsivity.

The overall efficiency is a product of injection efficiency η_{in}, radiative recombination efficiency η_r and light extraction efficiency η_e, therefore $\eta_o = \eta_{in}\eta_r\eta_e$. In GaAs, values of injection efficiency η_{in} higher than 0.8 can be easily achieved. Radiative recombination efficiency η_r which is basically the internal quantum efficiency of the LED material is the ratio of the number of photons generated divided by the number of electrons injected. The main non-radiative processes that can reduce η_r are Shockley-Read-Hall recombination, band to band and trap assisted Auger recombination and surface recombination processes. Extraction efficiency depends on several factors such as the absorption of the semiconductor at the emission wavelength (re-absorption) and the depth of the junction from the surface. In direct bandgap

materials where re-absorption is dominant, light-emitting junction is placed very close to surface to circumvent re-absorption and obtain high light extraction efficiency η_e. An encapsulated LED with a dome shaped high dielectric transparent material as shown in Fig. 11.2 is often used to increase the light transmission thus increasing the light extraction efficiency η_e.

Fig. 11.2: Dome LED for enhancing the light extraction efficiency

LED Materials

The choice of LED material depends on the wavelength of the light emission required. An equally important factor is the ability to heavily dope these materials n- and p-type and thereby fabricate the junction diode. Lower bandgap materials are required for infrared and far-infrared applications and larger bandgap materials are needed for a light source in the visible part of the spectrum (around 2eV). High bandgap materials have higher resistivity and cannot be easily doped to high levels as may be desired for LED fabrication.

GaAs, GaP and their ternary derivative $GaAs_{1-x}P_x$ are the most important III-V compounds for LEDs. GaAs has a direct bandgap of 1.43eV (λ=860nm), therefore emits near infrared. Band to band recombination is the dominant radiative recombination process in Si doped GaAs LEDs. Si doped GaAs LEDs emit at around 940nm and have a small re-absorption. Typical external quantum efficiencies of ~10% are achieved.

GaP has an indirect bandgap of 2.26eV (λ=549nm) and therefore impurity levels in the bandgap are needed for it to be used as an efficient light emitter. GaP is typically used for red, yellow and green emission. Nitrogen doping is used as donor-like dopant to help GaP emit at a near bandgap wavelength (550nm) which is green. The quantum efficiency of this band to donor transition is less than 1%. Higher N doping results in the formation of N-N complex and emission at 590nm (yellow). If GaP is simultaneously doped with Zn and O, red emission at 690nm is obtained.

The ternary $GaAs_{1-x}P_x$ changes from direct to indirect bandgap material for x=0.45 at which composition E_g=2.1eV. Thus direct bandgap and indirect bandgap with N-doping can be used for the fabrication of diodes to emit red ($GaAs_{0.6}P_{0.4}$), orange ($GaAs_{0.35}P_{0.65}$: N), and yellow ($GaAs_{0.15}P_{0.85}$: N) light.

For longer wavelength in the near infrared region of the spectrum, InP based compounds such as the ternary $In_{0.53}Ga_{0.47}As$ and the quarternary $In_xGa_{1-x}P_yAs_{1-y}$ are important. LEDs made of these materials operate in the 1.1-1.6µm range, which overlaps with the spectral region of low loss and minimum dispersion of optical fibers. For far infrared region of the spectrum, GaSb, InSb and their alloys are important materials that are currently under investigation.

GaN and InGaN compositions are used to generate orange, green, blue and white LEDs. Typical structures consist of multiple quantum wells of $In_{0.15}Ga_{0.85}N$ /GaN. The wavelength emission can be tuned from blue to orange by increasing the QW thickness. White (blue + yellow) dual color LEDs can be fabricated using this technology.

LED Structures

Heterojunction LED

In homojunction LEDs, the light emitting junction has to be close to the surface otherwise re-absorption is enhanced. Therefore, surface recombination which is a nonradiative recombination limits the internal quantum efficiency. Additionally, the minority carriers injected to the either side of the junction can diffuse away from the edges of the depletion region, therefore increasing the light interaction volume. Higher volume of light generation translates into larger non-radiative recombination. The heterostructure LED addresses these problem of low internal quantum efficiency of homojunction LEDs. Fig. 11.3 shows the

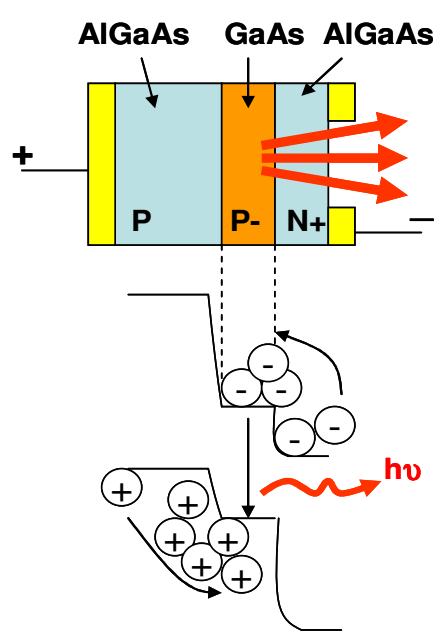

Fig. 11.3: Device Structure and band diagram of forward biased double heterostructure LED.

device structure and band diagram of a forward biased double heterostructure LED in AlGaAs/GaAs material system. Note that the junction does not have to be close to the surface as AlGaAs because of its larger bandgap is transparent to the light generated in the GaAs interaction region. Additionally injected carriers in lower bandgap GaAs are restricted from diffusing out by larger bandgap AlGaAs layers.

Surface Emitting LED

Surface emitting LEDs are used to couple light to an optical fiber. The structure is shown in Fig. 11.4. The backside of the wafer is etched using wet etching. The structure provides high radiance and efficient coupling of light to optical fibers.

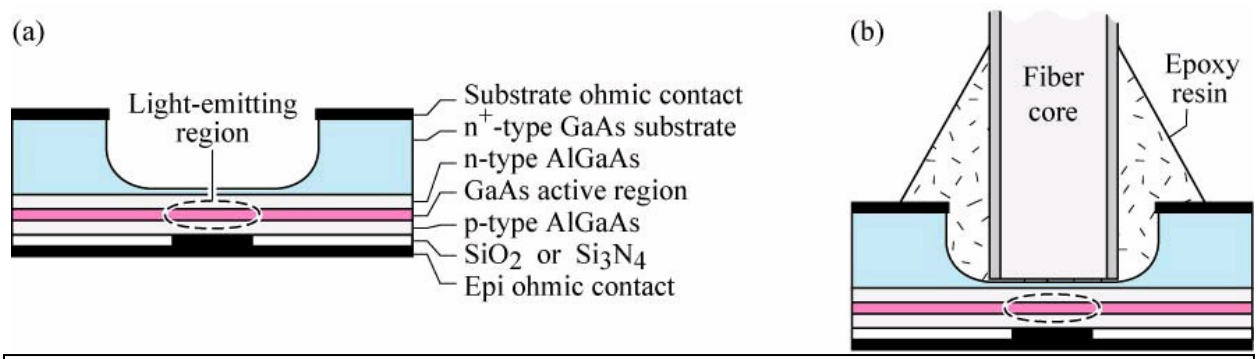

Fig. 11.4: The structure for an AlGaAs/GaAs double heterostructure surface emitting LED (a) made by etching a well in the backside and (b) connecting the optical fiber.

Edge-Emitting LED

Guided-wave or edge emitting LEDs are used for optical communication systems where tight coupling of the emitted light to fiber or waveguide is required. The stripe geometry allows higher carrier injection density for the same drive current. Therefore, the power conversion efficiency is improved. This technique is often used

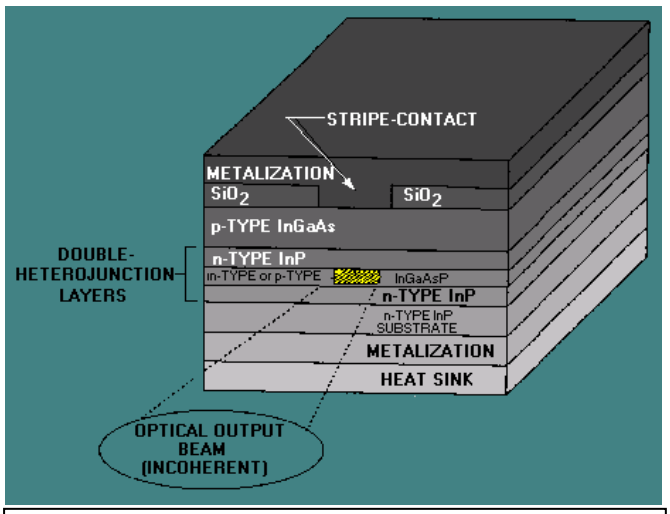

Fig. 11.5: Edge-Emitting LED

for laser fabrication as optical confinement in the transverse direction can be created by selective etching and regrowth of the higher bandgap material.

Edge emitting LEDs with thin undoped active region promise the best high frequency response. Therefore their modulation bandwidth is higher than other types of LEDs. The modulation bandwidth depends on that radiative recombination lifetime. Note that in LEDs, photons are generated by spontaneous emission. Therefore the radiative lifetime is longer than that under stimulated emission as in a laser. Therefore, lasers have higher modulation bandwidth than LEDs.