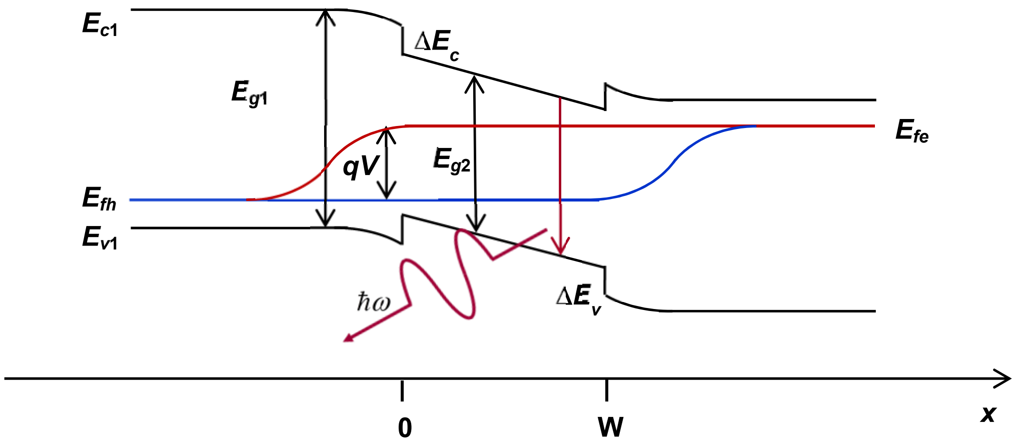
Chapter 7

Semiconductor Light Emitting Diodes and Solid State Lighting

7.1 Introduction

Semiconductor light emitting diodes are forward biased pn junction diodes in which electron-hole recombination due to spontaneous emission in the junction region results in light generation. The pin-heterostructure diode is the most basic and practically useful light emitting structure, and its bands in forward bias are shown in the Figure below.



Under forward bias, electrons from the n-side and holes from the p-side are injected into the smaller bandgap intrinsic region. In a homojunction pn diode most of the injected electrons would have made it to the p-side and their subsequent dynamics on the p-side would be described in terms of diffusion and recombination. Similarly, in a homojunction pn diode most of the holes would have made it to the n-side and their transport on the n-side would be explained in terms of diffusion and recombination. The conduction band (valence band) offset that the electrons (holes) see while in the intrinsic region presents a bottleneck for transport and therefore the electrons (holes) injected from the n-side (p-side) get trapped in the intrinsic smaller bandgap material till they recombine via both radiative and non-radiative mechanisms. However, a small fraction of the electrons (holes) makes it to the p-side (n-side) via thermionic emission and recombines there.

One can write the diode current as,

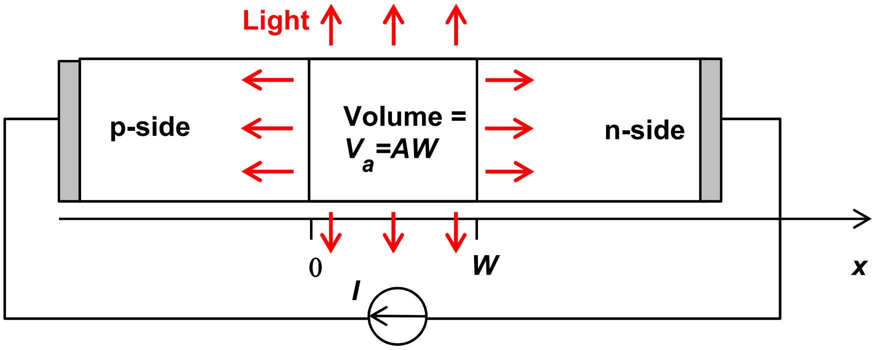
$$\begin{aligned} J_T &= J_o + J_{rec} \\ &= J_o + q\int_0^W \left[R_e(x) - G_e(x)\right] dx \\ &= J_o + q\int_0^W \left[R_h(x) - G_h(x)\right] dx \end{aligned}$$

where J_o is the component due to drift-diffusion-recombination in the quasi-neutral n and p regions and J_{rec} is due to electron-hole recombination in the intrinsic region. In a well-designed pin heterostructure diode J_o is a small fraction of J_{rec}. We can write qualitatively,

$$J_{rec} = \eta_i \, J_T$$
$$J_o = (1-\eta_i) J_T$$

where η_i is the fraction of the total current that is due to recombination in the intrinsic region. Typically, η_i has a value between 0.75 and 0.95. The intrinsic is called the active region as this region is optically active.

7.2 Modeling Radiative and Non-Radiative Recombination Rates in LEDs



7.2.1 Rate Equations for the Active Region:

Let the volume of the active region be V_a,

$$V_a = Aw$$

The electron and hold density everywhere in the intrinsic region is approximately equal because charge neutrality. Let the carrier densities be uniform in space inside the active region (not a good assumption – but it will do for now). Let $n(=p)$ be the average electron and holes density inside the active region. We can write a simple rate equation for the carrier density as follows,

$$\frac{dn}{dt} = \frac{\eta_i I}{qV_a} - (R_{nr} - G_{nr}) - (R_r - G_r)$$

where I is the total current in the external circuit in forward bias, and,

$R_{nr} - G_{nr} =$ Net non-radiative recombination rate (units: per cm^3 per sec).

$R_r - G_r =$ Net radiative recombination rate (units: per cm^3 per sec)

7.2.2 Radiative Recombination Rates

In light emitting diodes (LEDs), R_r is just R_{Tsp} (spontaneous emission rate per unit volume of the material per sec into all radiation modes). From Chapter 3,

$$R_{Tsp} = \int_0^\infty R_{sp}(\omega) V_p \, g_p(\omega) \, d\omega = \int_0^\infty v_g \, \alpha(\omega) \frac{g_p(\omega)}{e^{(\hbar\omega - qV)/KT} - 1} \, d\omega$$

Where,

$$R_{sp}(\omega) = \left(\frac{e}{m}\right)^2 \left(\frac{\pi}{\omega \, n n_g^M \varepsilon_o}\right) \left(\frac{1}{V_p}\right) \left\langle \left| \hat{\vec{p}}_{cv} \cdot \hat{n} \right|^2 \right\rangle 2 \times \int_{FBZ} \frac{d^3\vec{k}}{(2\pi)^3} \, f_c(\vec{k}) \left[1 - f_v(\vec{k})\right] \delta\left(E_c(\vec{k}) - E_v(\vec{k}) - \hbar\omega\right)$$

$$g_p(\omega) = \left(\frac{\omega n}{\pi c}\right)^2 \frac{1}{v_g^M}$$

The complete integral for R_{Tsp} is rather complicated and approximations are desirable, as discussed below.

Spontaneous Emission Factor: One can also write the R_{Tsp} as,

$$\begin{aligned} R_{Tsp} &= \int_0^\infty R_{sp}(\omega) V_p \, g_p(\omega) \, d\omega = \int_0^\infty v_g \, \alpha(\omega) \frac{g_p(\omega)}{e^{(\hbar\omega - qV)/KT} - 1} d\omega \\ &= \int_0^\infty \left[v_g^M \, g(\omega) \, n_{sp}(\omega) \right] \; g_p(\omega) \, d\omega \end{aligned}$$

where the spontaneous emission factor $n_{sp}(\omega)$ is defined as,

$$n_{sp}(\omega) = \frac{1}{1 - e^{(\hbar\omega - qV)/KT}}$$

The net stimulated emission rate (difference between stimulated emission and stimulated absorption rates) into all radiation modes due to thermal photons can be written as,

$$R_{T\downarrow}(\omega) - R_{T\uparrow}(\omega) = \int_0^\infty \left[v_g^M \, g(\omega) \, n_{th}(\omega) \right] \; g_p(\omega) \, d\omega$$

where $n_{th}(\omega)$ is the Bose-Einstein factor,

$$n_{th}(\omega) = \frac{1}{e^{\hbar\omega/KT} - 1}$$

If one includes recombination and generation from spontaneous emission into all radiation modes and also from stimulated emission and stimulated absorption of thermal photons into all radiation modes then one may write the radiative recombination-generation rate as,

$$\begin{aligned} R_r - G_r &= R_{T\downarrow}(\omega) + R_{Tsp}(\omega) - R_{T\uparrow}(\omega) = \int_0^\infty v_g^M \, g(\omega) \left[n_{sp}(\omega) + n_{th}(\omega) \right] \; g_p(\omega) \, d\omega \\ &\approx B\left(n^2 - n_i^2\right) \end{aligned}$$

The expression in the second line is again an approximation. For most III-V semiconductors, B is approximately equal to 10^{-10} cm^3/sec.

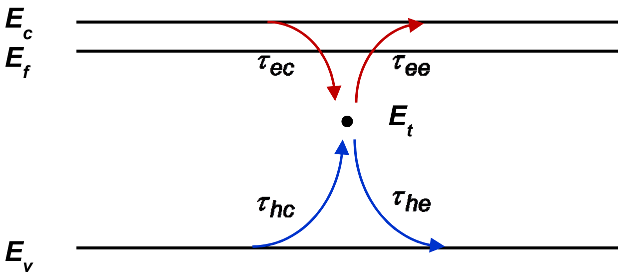
7.2.3 Non-Radiative Transitions:

The most important non-radiative recombination-generation mechanisms are:

i) Defect assisted recombination-generation (Shockley-Read-Hall mechanism)
ii) Surface recombination-generation
iii) Recombination via Auger scattering and generation via impact ionization

7.2.4 Defect Assisted Bulk Recombination-Generation (Shockley-Read-Hall Mechanism)

Crystal defects that result in energy levels inside the bandgap can contribute to electron-hole recombination and generation by trapping electrons and holes. Consider a trap state at energy E_t, as shown in the Figure below.



Suppose the rates at which electrons are captured and emitted by the trap are, $1/\tau_{ec}$ and $1/\tau_{ee}$, respectively, and the rates at which holes are captured and emitted by the trap are, $1/\tau_{hc}$ and $1/\tau_{he}$, respectively. If the trap density is n_t, the probability that a trap level is occupied by an electron is f_t, then one can write the following simple rate equations,

$$n_t \frac{df_t}{dt} = \frac{n(1-f_t)}{\tau_{ec}} - \frac{n_t f_t}{\tau_{ee}} - \frac{p f_t}{\tau_{hc}} + \frac{n_t (1-f_t)}{\tau_{he}}$$

$$\frac{dn}{dt} = -\frac{n(1-f_t)}{\tau_{ec}} + \frac{n_t f_t}{\tau_{ee}}$$

$$\frac{dp}{dt} = \frac{p f_t}{\tau_{hc}} - \frac{n_t (1-f_t)}{\tau_{he}}$$

Since in thermal equilibrium,

$$\frac{dn}{dt} = \frac{dp}{dt} = 0$$

and the electron and hole distributions and the probability f_t are given as,

$$n = N_c e^{(E_f - E_c)/KT}$$

$$p = N_v e^{(E_v - E_f)/KT}$$

$$f_t = \frac{1}{1 + e^{(E_t - E_f)/KT}}$$

one can obtain the emission times in terms of the capture times for both electrons and holes,

$$\frac{\tau_{ee}}{\tau_{ec}} = \frac{n_t}{n} \frac{f_t}{(1-f_t)} = \frac{n_t}{N_c e^{(E_t - E_c)/KT}} = \frac{n_t}{n_t^*}$$

$$\frac{\tau_{he}}{\tau_{hc}} = \frac{n_t}{p} \frac{(1-f_t)}{f_t} = \frac{n_t}{N_v e^{(E_v - E_t)/KT}} = \frac{n_t}{p_t^*}$$

The capture times depend on the trap density since larger the trap density larger the likelihood of an electron getting captured in a tarp. The exact relationship is,

$$\frac{1}{\tau_{ec}} = \sigma_{ec} \langle v_e \rangle n_t$$

$$\frac{1}{\tau_{hc}} = \sigma_{hc} \langle v_h \rangle n_t$$

Here, σ_{ec} and σ_{hc} are the trap capture cross-sections. Capture cross-sections correspond to the effective areas of a trap as they appear to an electron or a hole travelling with an average velocity of $\langle v_e \rangle$ or $\langle v_h \rangle$, respectively.

We assume that the trap state is always in quasi-equilibrium even in non-equilibrium situations so that $df_t/dt \approx 0$. This allows us to solve for f_t and obtain the following expression for the electron-hole recombination and generation rate,

$$\frac{dn}{dt}=\frac{dp}{dt}=-\frac{\left(np-n_i^2\right)}{\left(n+n_t^*\right)\tau_{hc}+\left(p+p_t^*\right)\tau_{ec}}=-\left(R_e-G_e\right)=-\left(R_h-G_h\right)$$

Note that if, for example, we have a p-doped material such that $p_o >> \left\{n_o, n_t^*, p_t^*, n_i\right\}$ then the minority carrier recombination-generation rate (assuming, $n = n_o + \Delta n$) is given as,

$$R_e - G_e \approx \frac{\Delta n\, p_o}{p_o\, \tau_{ec}} = \frac{n-n_o}{\tau_{ec}}$$

We see that for defect assisted recombination-generation, the minority carrier lifetime is just the minority carrier trap capture time. If the material has equal number of electrons and holes and $n = p >> \left\{n_t^*, p_t^*, n_i\right\}$, as in the intrinsic region of an LED, then,

$$R_e - G_e \approx \frac{np-n_i^2}{n\tau_{ec}+p\tau_{hc}} \approx \frac{n-n_i}{\tau_{ec}+\tau_{hc}}$$

The net recombination rate goes linearly with the carrier density.

7.2.4 Defect Assisted Surface Recombination-Generation

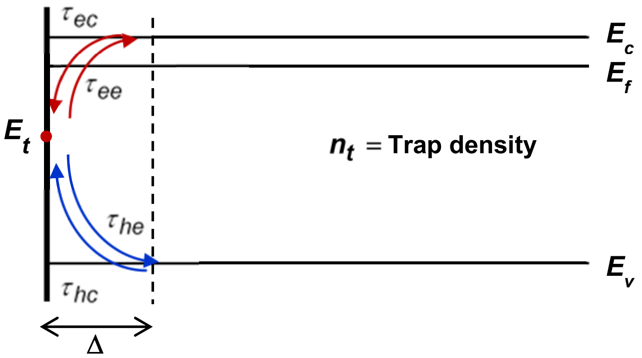
Crystal surfaces have enormous defects from dangling bonds as well as form impurity atoms. These defects can also behave as bulk defects and contribute to electron-hole recombination and generation. The surface recombination-generation rate has the form,

$$R_{es} - G_{es} = R_{hs} - G_{hs} = \frac{\left(np-n_i^2\right)}{\left(n+n_t^*\right)\frac{1}{v_{hc}}+\left(p+p_t^*\right)\frac{1}{v_{ec}}}$$

The units of $R_{es} - G_{es} = R_{hs} - G_{hs}$ are per unit surface area per sec (or per cm^2 per sec). One can see that the above expression has almost the same form as the bulk defect assisted recombination except that the electron and hole capture times are replaced by the electron and hole surface capture velocities, v_{ec} and v_{hc}, respectively. The carrier densities, n_t^* and p_t^*, are defined as before as,

$$n_t^* = N_c e^{\left(E_t - E_c\right)/KT}$$

$$p_t^* = N_v e^{\left(E_v - E_t\right)/KT}$$



A trap located at the surface will only trap carriers within a layer of thickness, say Δ, near the surface. The electron and hole surface capture velocities are then,

$$v_{ec} = \frac{\Delta}{\tau_{ec}} \qquad\qquad v_{hc} = \frac{\Delta}{\tau_{hc}}$$

It is always important to keep the electrons and holes away from semiconductor surfaces if one does not want them to recombine via defects at the surfaces. If the material has equal number of electrons and holes and $n = p >> \left\{n_t^*, p_t^*, n_i\right\}$, as in the intrinsic region of an LED, then,

$$R_{es}-G_{es}\approx\frac{np-n_i^2}{n/v_{ec}+p/v_{hc}}\approx\left(n-n_i\right)v_s \qquad \left\{\frac{1}{v_s}=\frac{1}{v_{ec}}+\frac{1}{v_{hc}}\right.$$

Here v_s is the surface recombination velocity. For GaAs based devices $v_s \le 5\times10^5$ cm/s and for InP/InGaAsP devices, $v_s \le 5\times10^3$ cm/s. Surfaces are routinely passivated with suitable coatings in order to tie up the dangling bonds and protect the surface from impurities.

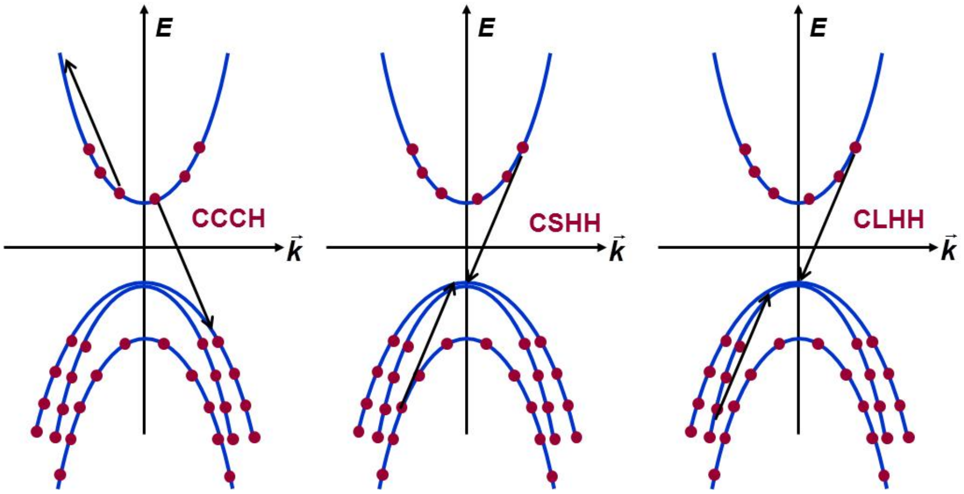
In LEDS, rates for both surface and bulk defect assisted recombination are generally combined into a single expression of the form,

$$R_e-G_e\approx\frac{n-n_i}{\tau_{ec}+\tau_{hc}}+\left(n-n_i\right)v_s\left\{\frac{\text{surface area}}{V_a}\right\}=A\left(n-n_i\right)$$

Values of A are between 10^8 1/sec and 10^9 1/sec for most III-V semiconductors and between 10^4 1/sec and 10^7 1/sec for Silicon.

7.2.5 Recombination by Auger Scattering and Generation by Impact Ionization:

At large carrier densities Auger scattering (or electron-electron scattering) is the dominant mechanism for carrier recombination. The three most important Auger scattering mechanisms are depicted in the Figure below. Note that Auger scattering is the reverse of impact ionization. Auger scattering is responsible for recombination whereas impact ionization is responsible for generation. In each Auger process shown below, an electron from the conduction band ends up in the valence band.



In Auger processes, initial and final energies and momenta must be equal. For this reason, Auger recombination rates tend to increase with the decrease in the bandgap of the material. In general, the expressions for the recombination and generation rates due to Auger scattering and impact ionization are difficult. However, the approximate carrier density dependence of the recombination rates can be figured out as follows. In the CCCH process, two electrons in the conduction band scatter, one ends up at a high energy in the conduction band and the other takes the place of a hole in the heavy hole valence band. The rate is proportional to n^2p since the process involves two electrons and one hole. Similar arguments will show that the rates of the other two processes are proportional to np^2. The total recombination-generation rate can then be written as,

$$R_e-G_e=C_{\text{CCCH}}\,n\left(np-n_i^2\right)+C_{\text{CSHH}}\,p\left(np-n_i^2\right)+C_{\text{CLHH}}\,p\left(np-n_i^2\right)$$

If the material has equal number of electrons and holes and $n=p$, as in the intrinsic region of an LED, then to a very good approximation one can write,

$$R_e-G_e\approx C\,n\left(n^2-n_i^2\right)$$

For GaAs based devices (bandgap: 1.43 eV), $C \approx 5 \times 10^{-30}$ cm^6/s, and for InGaAsP devices (bandgap: 0.8 eV), $C \approx 5 \times 10^{-29}$ cm^6/s. Note that Auger recombination rates go as the cube of the carrier density.

7.2.6 Radiative Efficiency:

The recombination rates can be written as,

$$R_{nr}(n) - G_{nr}(n) = A(n - n_i) + Cn\left(n^2 - n_i^2\right)$$

$$R_r(n) - G_r(n) = B\left(n^2 - n_i^2\right)$$

The rate equation for the carrier density becomes,

$$\frac{dn}{dt} = \frac{\eta_i I}{qV_a} - (R_{nr} - G_{nr}) - (R_r - G_r)$$

In steady state,

$$\frac{dn}{dt} = 0$$

We define radiative efficiency as,

$$\eta_r(n) = \frac{R_r(n)}{[R_{nr}(n) - G_{nr}(n)] + [R_r(n) - G_r(n)]} \approx \frac{Bn^2}{A(n - n_i) + B\left(n^2 - n_i^2\right) + Cn\left(n^2 - n_i^2\right)}$$

In steady state,

$$R_r(n) = \eta_r(n)\eta_i \frac{I}{qV_a}$$

To find the steady state carrier density, one must first solve the equation,

$$\begin{aligned}\frac{dn}{dt} &= \frac{\eta_i I}{qV_a} - [R_{nr}(n) - G_{nr}(n)] - [R_r(n) - G_r(n)] \\ &= \frac{\eta_i I}{qV_a} - \left[A(n - n_i) + B\left(n^2 - n_i^2\right) + Cn\left(n^2 - n_i^2\right)\right]\end{aligned}$$

and find the steady state carrier density n. One can then calculate the radiative efficiency $\eta_r(n)$, and from it obtain the photon emission rate $R_r(n)$ using,

$$R_r(n) = \eta_r(n)\,\eta_i \frac{I}{qV_a}$$

The total photon emission rate (number of photons emitted per second),

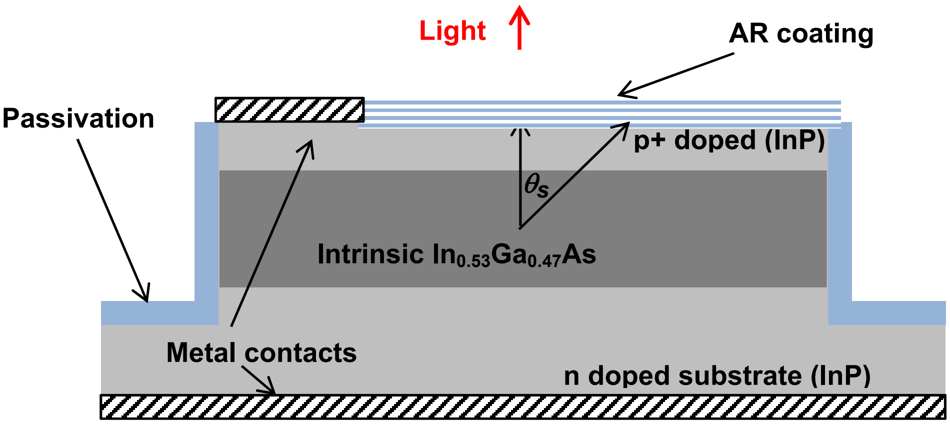
$$R_r(n)\,V_a$$

7.2.7 Figures of Merit for LEDs:

The internal quantum efficiency of a LED is defined as:

$$\begin{aligned}\eta_{\text{int}} &= \frac{\text{Number of photons emitted per second}}{\text{Number of charges flowing into the device per second}} = \frac{R_r(n)V_a}{I/q} \\ &= \eta_r(n)\eta_i\end{aligned}$$

Consider the following structure of an IR-LED.



Not all the photons emitted from the active region of an LED make it out of the device. Some are reabsorbed, some go in the wrong direction, some are reflected back (we will discuss this more below). The **light extraction efficiency** of a LED is,

$$\eta_{\text{extraction}} = \frac{\text{Number of photons that come out of the LED per second in the correct direction}}{\text{Number of photons emitted from the active region of the LED per second}}$$

The **external quantum efficiency** η_{ext} of a LED is,

$$\eta_{\text{ext}} = \frac{\text{Number of photons that come out of the LED per second in the correct direction}}{\text{Number of charges flowing into the device per second}}$$

$$= \eta_{\text{extraction}}\ \eta_{\text{int}} = \eta_{\text{extraction}}\ \eta_{\text{r}}(n)\eta_i$$

7.2.8 Photon Extraction Problems in LEDs:

A simple light emitting device of the form shown above does not work very well. Most of the photons emitted from the active region are total internally reflected back from the top interface. Suppose, the refractive index of the semiconductor is n_s and that of the outside material is n_a. Photons emitted from the active region only come out of the LED if,

$$\theta_s < \theta_c = \text{critical angle} = \sin^{-1}\left(\frac{n_a}{n_s}\right)$$

if $\theta_s > \theta_c$, light is totally internally reflected. Consequently, only the photons emitted in the active region within a solid angle $2\pi\,(1-\cos\theta_c)$ are able to come out of the device from the top surface. Rest are reflected back and get absorbed in the substrate or in the back metal contact. The extraction efficiency is therefore,

$$\eta_{\text{extraction}} = \frac{2\pi\,(1-\cos\theta_c)}{4\pi} = \frac{1}{2}(1-\cos\theta_c) \approx \frac{1}{4}\frac{n_a^2}{n_s^2}$$

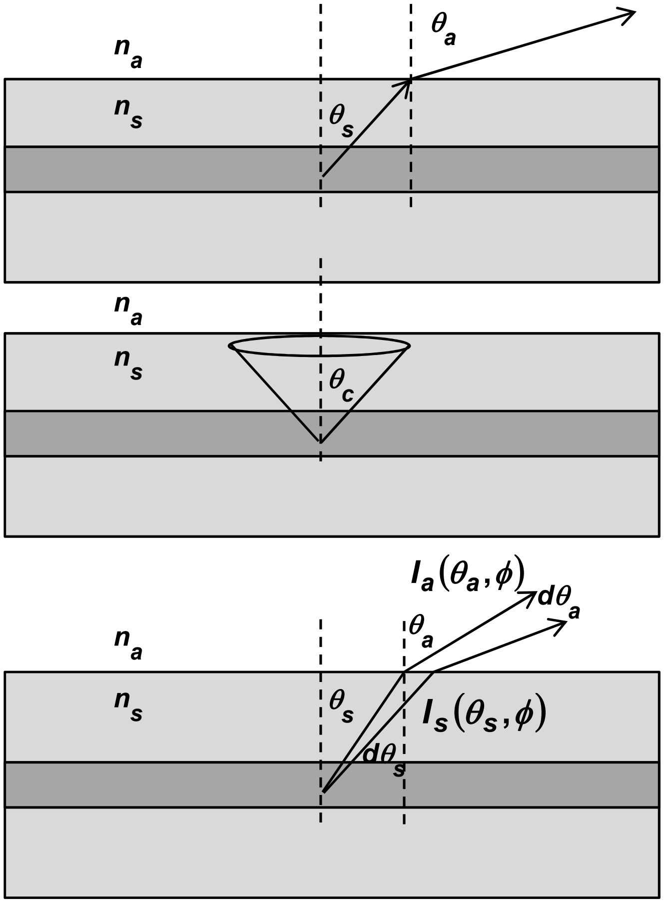
For air and GaAs,

$$n_a = 1,\ n_s \sim 3.6 \quad \Rightarrow \quad \theta_c = 16^\circ \quad \Rightarrow \quad \eta_{\text{extraction}} = 0.02 = 2\%$$

An extraction efficiency of 2% is very small to be useful. It is also interesting to compute the angular dependence of the light power coming out of the LED shown above. Inside the semiconductor, the power of spontaneous emission radiation is isotropic. If $I_s(\theta_s,\phi)$ is the power emitted per unit solid angle inside the semiconductor then,

$$I_s(\theta_s,\phi) = \frac{P}{4\pi}$$

where $P = R_{Tsp}V_a$ is the total energy per second (or power) emitted by the active region.



If $I_a(\theta_a,\phi)$ is the power emitted per unit solid angle in the air then energy conservation requires,

$$I_s(\theta_s,\phi) 2\pi \sin\theta_s \, d\theta_s = I_a(\theta_a,\phi) 2\pi \sin\theta_a \, d\theta_a$$

We have,

$$n_s \sin\theta_s = n_a \sin\theta_a$$

$$\Rightarrow n_s \cos\theta_s \, d\theta_s = n_a \cos\theta_a \, d\theta_a$$

$$\Rightarrow I_s(\theta_s,\phi)\left(\frac{n_a}{n_s}\right)^2 \sin\theta_a \frac{\cos\theta_a}{\cos\theta_s} d\theta_a = I_a(\theta_a,\phi) \sin\theta_a \, d\theta_a$$

$$\Rightarrow I_a(\theta_a,\phi) = I_s(\theta_s,\phi)\left(\frac{n_a}{n_s}\right)^2 \frac{\cos\theta_a}{\cos\theta_s} I_s(\theta_s,\phi)$$

$$\approx \frac{P}{4\pi}\left(\frac{n_a}{n_s}\right)^2 \cos\theta_a \qquad \left\{ \text{assuming } n_s^2 >> n_a^2 \right.$$

The above result shows that for high index semiconductor materials, the radiation power coming out of the device has an angular dependence going as the cosine of the angle from the normal. Such an emission profile is called Lambertian.

7.2.9 Power Efficiency of LEDs:

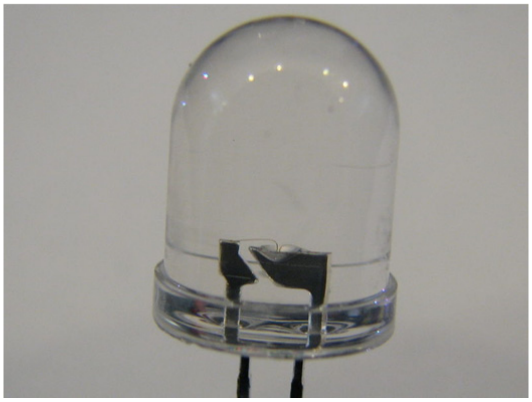
The electrical-to-optical power conversion efficiency of LED is defined as,

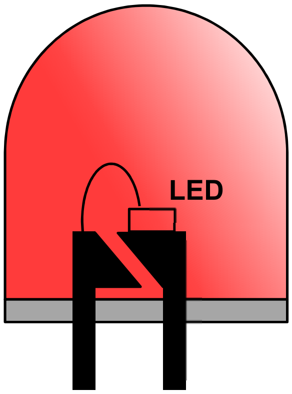
$$\eta_P = \frac{(\text{Number of photons that come out of the LED per second})\,\hbar\omega}{IV}$$

where V is voltage drop across the LED when biased with a current I. This is an important figure of merit for the use of LEDs as sources of lighting.

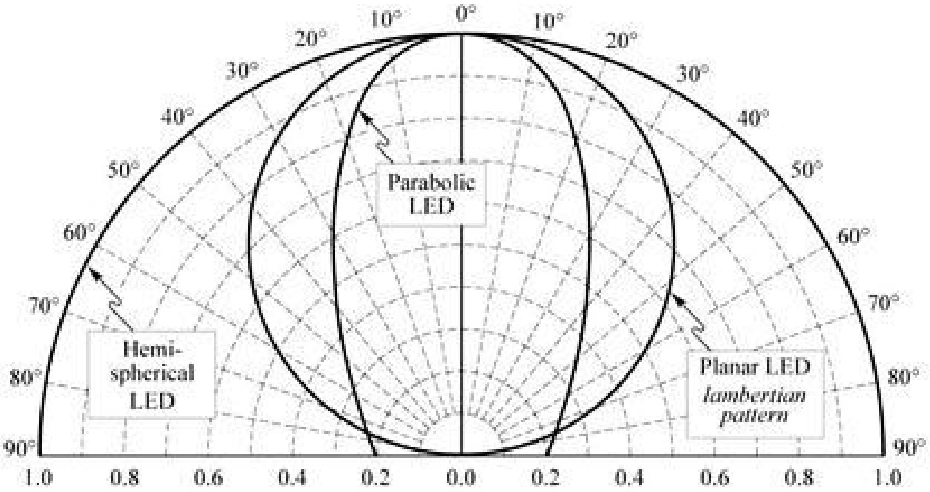
7.2.10 Some Common Methods to Improve Extraction Efficiencies in LEDs:

Plastic Encapsulation: One way to improve the extraction efficiency is to encapsulate the LEDs in a plastic dome as shown below.



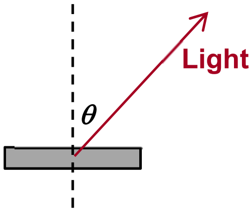


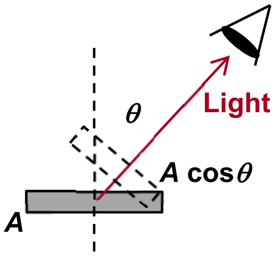
The index of the dome is chosen to be as close to the semiconductor as possible to increase the value of θ_c. The index values of the dome range from 1.5 to 2.5. Photons reach the dome-air interface at an almost normal angle of incidence and so do not suffer from total internal reflection. The radiation patterns for a planar LED, a LED encapsulated with a hemispherical dome, and a LED encapsulated with a parabolic dome are shown below.



Packaged High Power LEDS with Lambertian Back Reflectors:

A Lambertian light emitter is one for which the emitted power per unit solid angle falls off as the cosine of the angle from the normal to the surface of the emitter.

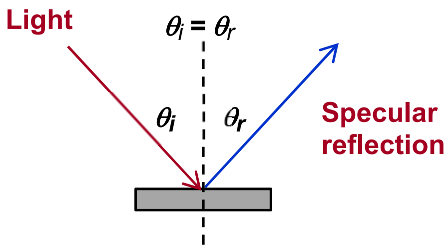


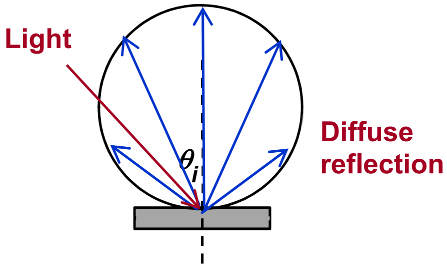


If $I(\theta,\phi)$ is the power emitted per unit solid angle then,

$$I(\theta,\phi) \propto \cos\theta$$

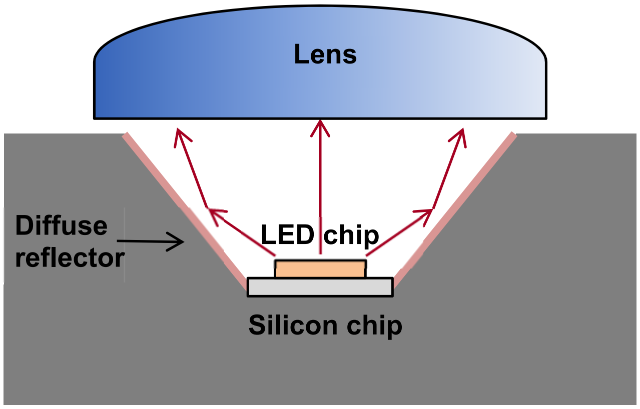
A Lambertian emitter has the interesting property that the light emitted per unit area of the emitter as seen by an observer is the same irrespective of the angular location of the observer. A Lambertian reflector is one for which the reflected light power per unit solid angle falls off as the cosine of the angle from the normal to the surface of the reflector irrespective of the angle of the incident light. Light reflection from rough surface, also called diffuse reflection, has approximately a Lambertian pattern. The difference between specular reflection and diffuse reflection is shown in the Figure below.

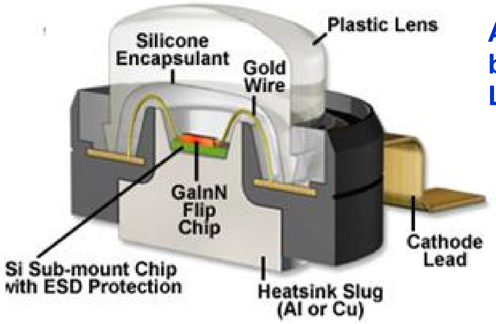




A typical packaging of a high power LED is shown in the Figure below. The LED employs a transparent substrate whose back surface has been roughened to avoid total internal reflection. The LED is positioned inside a reflector dish (typically coated with silver for high reflectivity in the visible) whose surface provides diffuse reflection in order to avoid trapping of light in the whispering gallery modes of the reflector.

A packaged high power LED



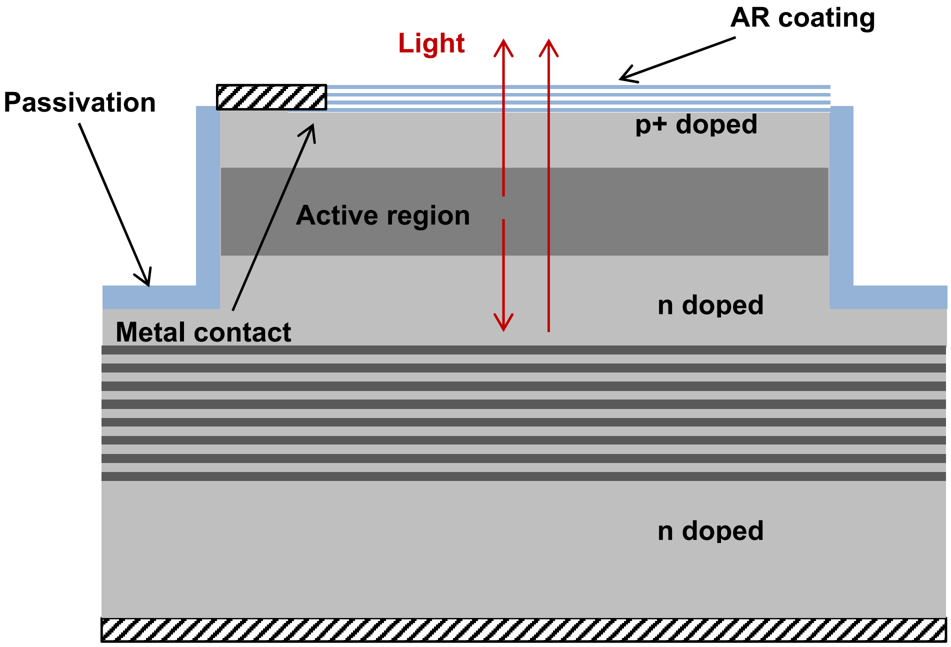


A 5 Watt InGaN/GaN blue LED from Lumileds

Integrated Bragg Back Reflectors:

The idea of coherent back reflection from periodic structures can be used in optics to realize very high reflectivity Bragg reflectors by using a stack of alternate high index and low index dielectric layers, where each layer is quarter wavelength thick. Details of such reflectors will be covered in later part of the course. Such reflectors have been used in LEDs to make all the light come out from one side of the device, as shown below. There are many problems associated with such Bragg reflectors:

i) Many material systems do not have adequate lattice-matched materials that can be used to make high quality Bragg reflectors
ii) Bragg reflectors can have poor conductivities and can contribute to parasitic device series resistance
iii) Bragg reflectors tend to have high reflection only in a narrow frequency band (called the stop band or the bandgap) unless the index contrast between the Bragg layers is very high
iv) They can increase the overall cost of the device significantly



7.2.11 Temperature Performance of LEDs:

The light output of LEDs decreases with temperature. This is because the internal efficiency defined as $\eta_{\text{int}} = \eta_r(n)\,\eta_i$ decreases with the increase in temperature. $\eta_r(n)$ decreases because the rate of non-radiative recombination processes increase rapidly with the increase in temperature. η_i also decreases with temperature because carrier leakage from the intrinsic region due to thermionic emission increases with the temperature. The change is the light power coming out of a LED with temperature empirically given by the formula,

$$P(T) = P_o\, e^{-T/T_1}$$

where T_1 is called the characteristic temperature. The above empirical equation is usually valid only near room temperature. The quantity T_1 should ideally be as large as possible. Large T_1 implies reduced temperature sensitivity of the output light power to variations in the device temperature.

7.3 Visible LEDs and Solid State Lighting

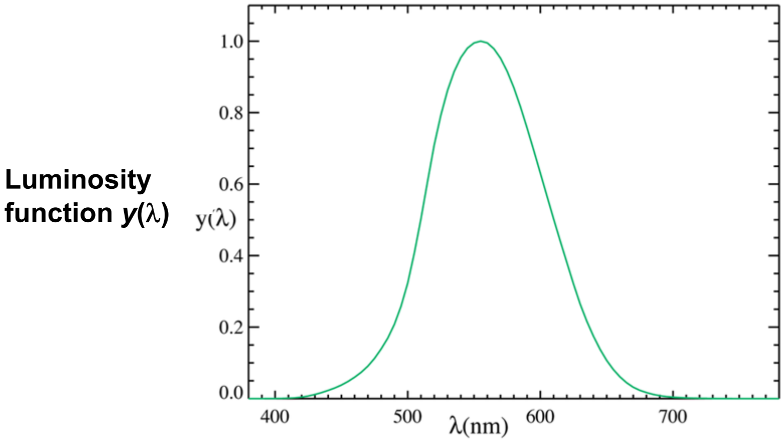
7.3.1 Introduction:

Dramatic changes are unfolding in lighting technology. Semiconductor based solid state lighting (SSL), until recently associated mainly with simple indicator lamps in electronics and toys, has become as bright and efficient as incandescent bulbs at nearly all visible wavelengths. It has already begun to displace incandescent bulbs in many applications, particularly those requiring durability, compactness, cool operation, and/or directionality (e.g., traffic, automotive, display, and architectural and directed-area lighting).

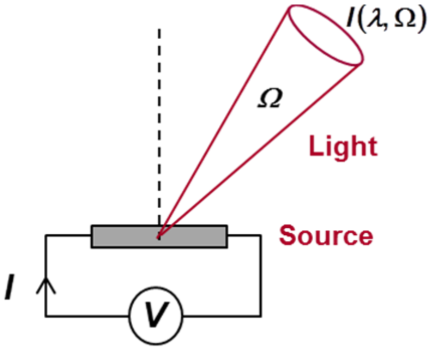
Further major improvements in this technology are believed to be achievable. External electrical-to-optical energy conversion efficiencies exceeding 50% have been achieved in infrared and deep-red light-emitting devices. If similar efficiencies are achieved across the visible spectrum, the result would be the holy grail of lighting: a 150–200 lm/W white-light source two times more efficient than fluorescent lamps and ten times more efficient than incandescent lamps. This new white-light source would change the way we live and the way we consume. The human visual experience would be enhanced through lights whose intensity and color temperature are independently tunable while maintaining high efficiency. Worldwide electricity consumption for lighting would decrease by more than 50%, and total electricity consumption would decrease by more than 10%.

7.3.2 Fundamentals of Lighting:

The human eye is more sensitive to certain colors than to others. This sensitivity is captured by the luminosity function, shown below. The human eye is the most sensitive to green light of wavelength ~555 nm.



Given the frequency (or wavelength) dependence of the human eye, it is not enough to just compare light intensities from two different light sources as a measure of their brightness. One has to weigh the light intensities by the luminosity function shown above.



$$P_{opt} = \int d\Omega \int_0^\infty d\lambda \; I(\lambda,\Omega)$$

$$P_{elec} = IV$$

Luminous Intensity: The luminous intensity $L_I(\Omega)$ of a light source in the direction of the solid angle Ω is the intensity spectrum $I(\lambda,\Omega)$ of the light source (units: Watts per solid angle per wavelength) in the same direction weighted by the luminosity function as,

$$L_I(\Omega) = 683 \int_0^\infty d\lambda \; y(\lambda)\, I(\lambda,\Omega)$$

The SI unit of luminous intensity is Candela (cd).

Luminous Flux: The luminous intensity $L_I(\Omega)$ of a light source integrated over all solid angles gives the total luminous flux L_F of the light source,

$$L_F = \int d\Omega \, L_I(\Omega)$$

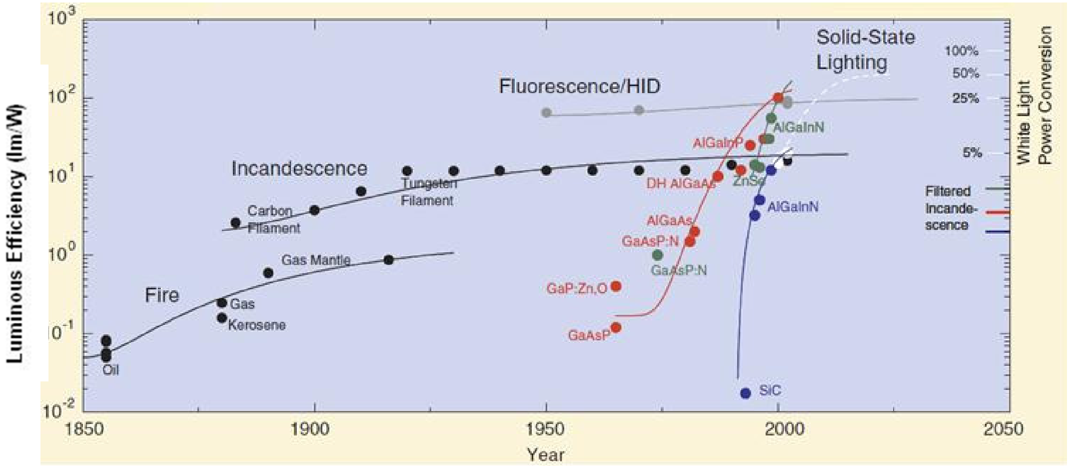
The SI unit of luminous flux is Lumen (lm).

Luminous Efficacy: A light source may put out a lot of optical power but might not put out a lot of luminous flux if its wavelength is located near the tails of the luminosity function. The luminous efficacy of a light source is defined as the ratio of the luminous flux to the optical power produced by the light source, L_F / P_{opt}, and is a measure of the efficacy with which a light source produces optical power of high luminous flux.

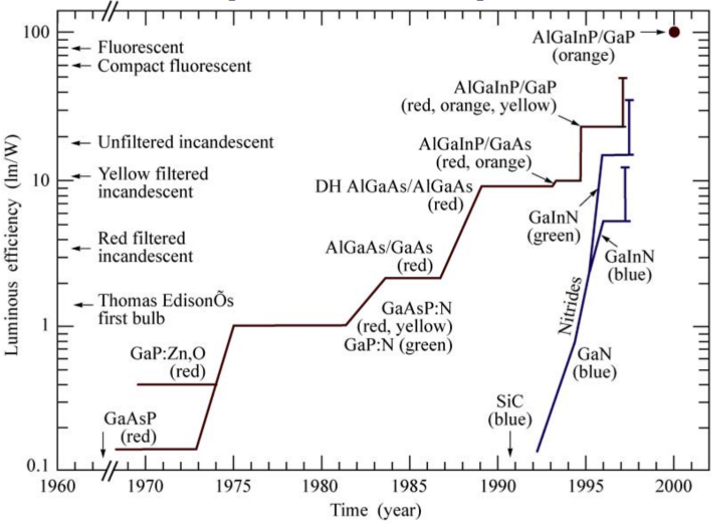
Luminous Efficiency: The luminous efficiency of a light source is defined as the ratio of the luminous flux to the total power (typically electrical) consumed by the light source, L_F / P_{elec}, and is a measure of the overall efficiency with which a light source converts energy into useful light.

7.3.3 Solid State Lighting - State of the Art:

The Figure below shows the evolution of the light sources over the years.

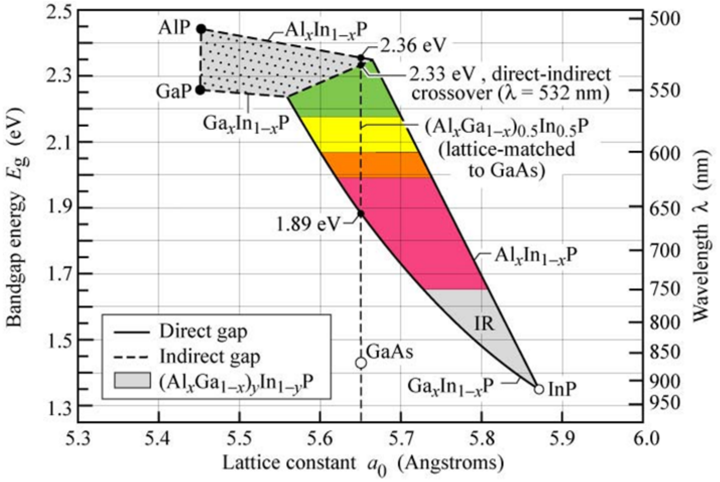


Incandescent sources (light bulbs) typically produce 10-20 lm/Watt. Fluorescent sources produce 60-90 lm/Watt. The goal for solid state lighting is to be able to produce white light with luminous efficiency greater than 100 lm/Watt and power conversion efficiency greater than 50%. The luminous efficiency of various LED technologies is shown in the Figure below.

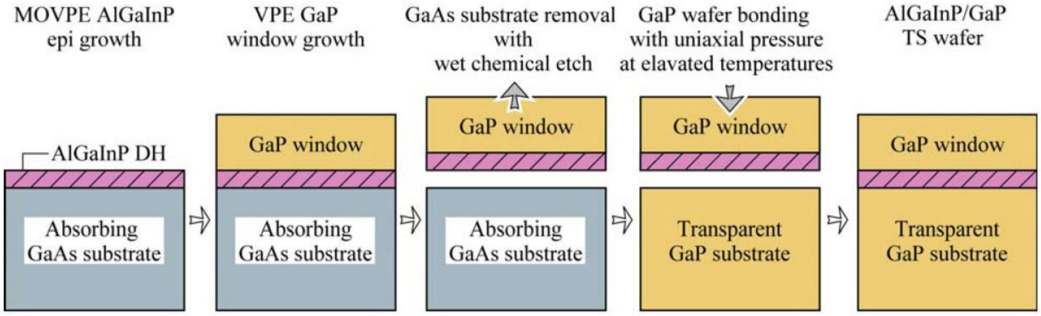


Adopted from Craford, 1997, 1999, 2000.

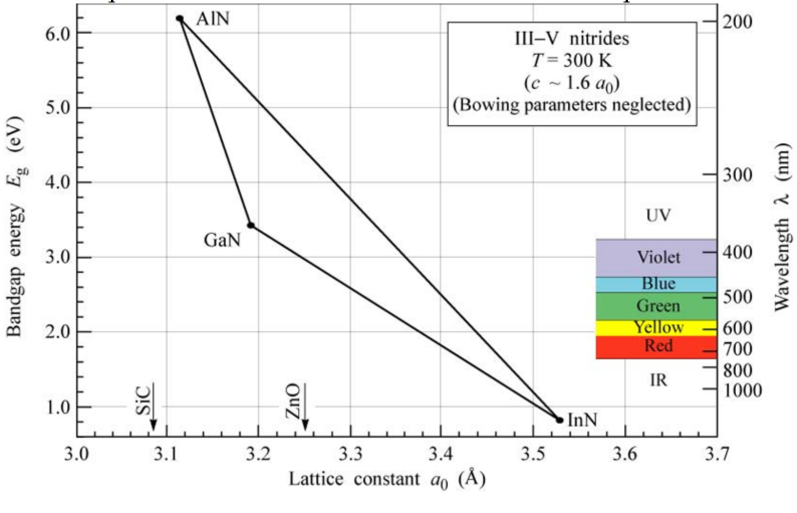
The GaAs/AlGaInP system has been the most successful for the red/amber LEDS. In these LEDS, the absorptive GaAs substrate is usually replaced with the wider bandgap GaP to get better light extraction efficiencies, as shown below.

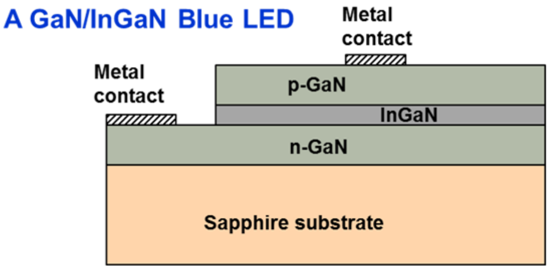


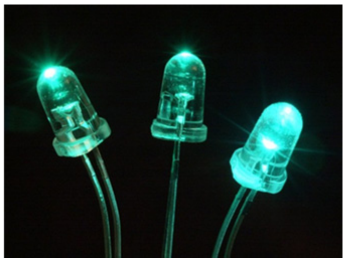
Adopted from Chen, 1997.

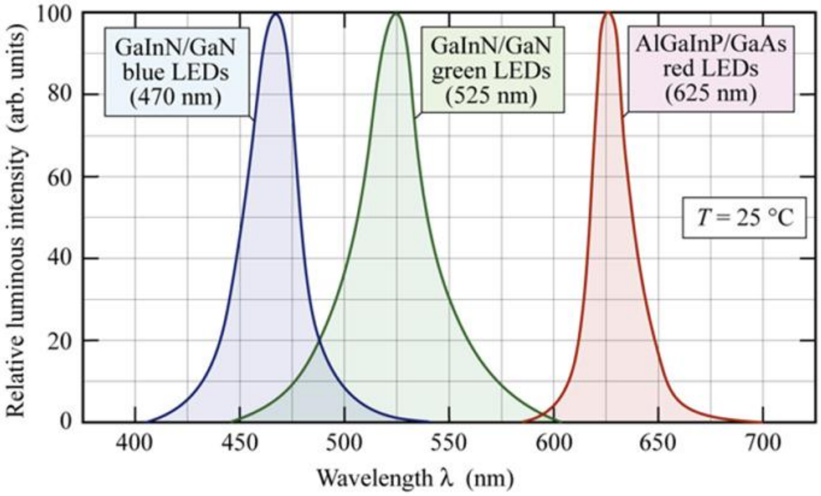


The GaN/InGaN system is in comparison a new material system and this technology is still being developed. It offers the promise of LEDs that cover the entire visible spectrum.





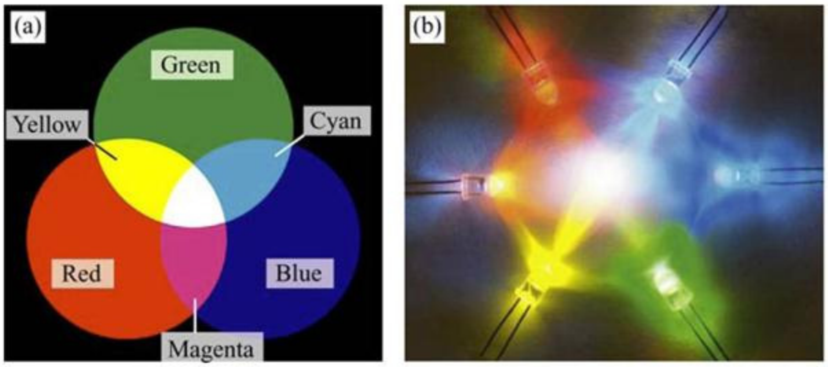




Spontaneous emission spectra of some important active materials used in LEDs. From Toyoda Gosei Corp, 2000.

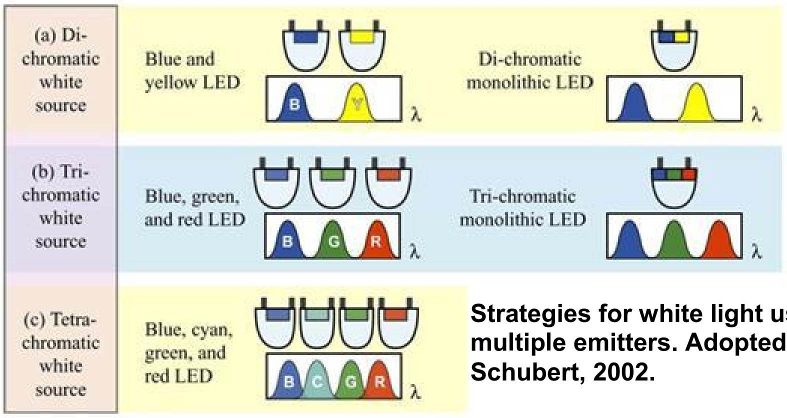
7.3.4 LEDs for White Light:

For solid state lighting to be used widely, it must be able to produce white light with high efficiency. The human eye has receptors for red, green, and blue light and signals from these are combined to give the sensation of white light, as depicted below.

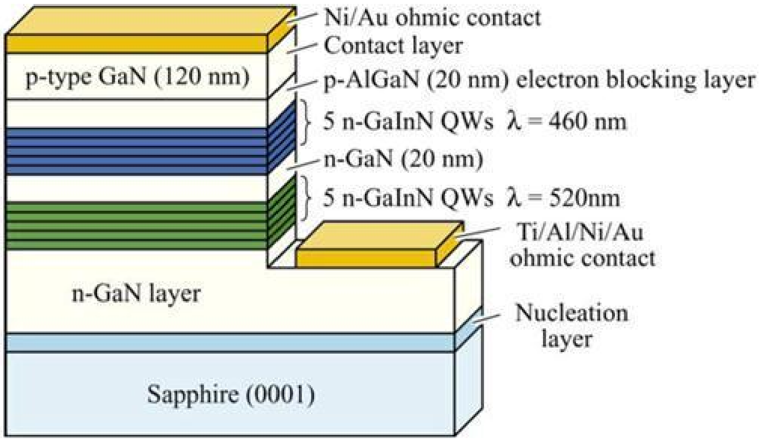


(a) Additive color mixing (b) Demonstration using LEDs

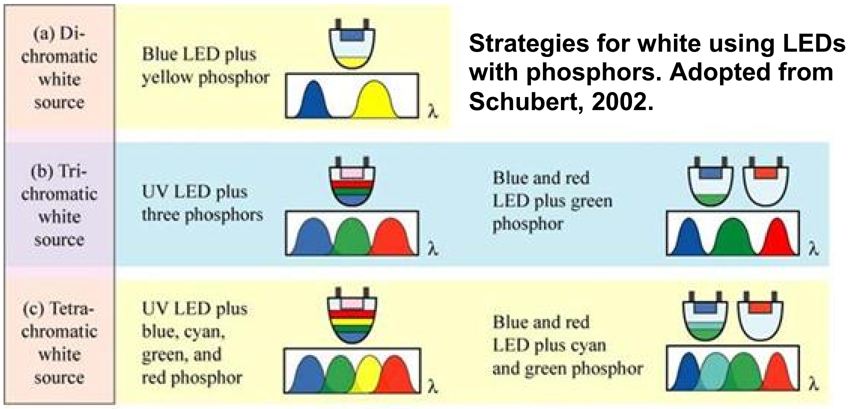
There are two commonly used strategies for generating white light: i) Use LEDs of different colors in the light source, ii) Use a high energy LED, for example an ultraviolet (UV) LED, along with phosphors to down convert the light into red, green, and blue light. These strategies are depicted in the Figures below.



Strategies for white light using multiple emitters. Adopted from Schubert, 2002.

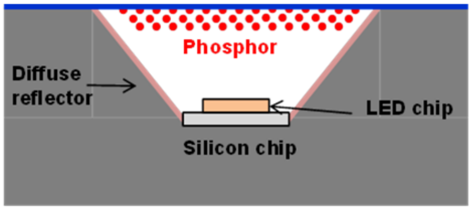


A monolithic dichromatic nitride LED with integrated active regions for blue and green emission. Light comes out from the Sapphire substrate. Adopted from Li, 2003.

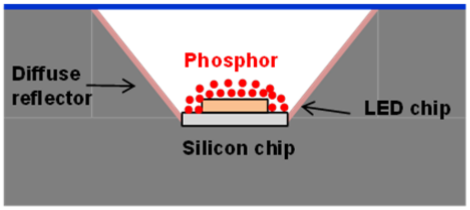


Strategies for white using LEDs with phosphors. Adopted from Schubert, 2002.

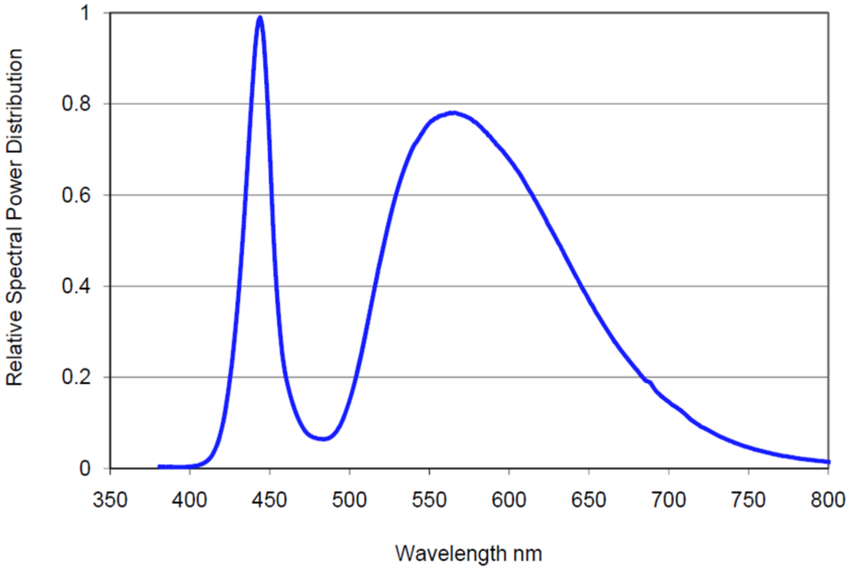
Integrating red, blue, and green LEDs on the same chip has proven to be difficult and expensive. The use of phosphors has been more successful. Different packaging structures to bring phosphors close to the LEDs are shown below.



Remote distribution of phosphor. Adopted from Schubert, 2006.



Proximity distribution of phosphor. Adopted from Schubert, 2006.



Emission spectrum of phosphor coated blue LED for white light (From Luxeon Inc.)

Some places where one find LED lighting today are shown on the next page.


IN A 8400