Chapter 2

Optical Property of LEDs and Implements

2-1 Internal, extraction, external and power efficiencies

Every electron injected into the active region of an ideal LED can translate into one photon. Each electron quantum-particle generates one photon quantum-particle. Therefore, the quantum efficiency of the ideal active region of a LED is unity. The internal quantum efficiency is defined as below

$$\eta_{\text{int}} = \frac{\text{number of photons emitted from active region per second}}{\text{number of electrons injected into LED per second}}$$

$$= \frac{P_{\text{int}}/(h\upsilon)}{I/e} \qquad (2\text{-}1.1)$$

where P_{int} is the optical power emitted from the active region and I is the injection current.

But the quantum efficiency of a real LED is not unity. For instance, figure 2-1 shows a double hetero-structure LED including MQW, separate confinement hetero-structure (SCH), and cladding layer. Electron and hole particles are confined to the SCH region and recombined in the MQW region to generate photons. Actually, there are many practical problems to consider such as current leakage, nonradiative recombination, and carrier leakage. We can compare the process of a certain steady-state carrier density in the active region to that a reservoir analogy, illustrated in figure 2-2. Rate equation is described as

$$\frac{dn}{dt} = G_{gen} - R_{rec} \qquad (2\text{-}1.2)$$

where n is the carrier density in the active region, G_{gen} is the rate of injected electrons, and R_{rec} is the rate of recombining electrons per unit volume in the active region. We consider efficiency of current injected into the active region,

η_i, included current leakage problem. Then, G_{gen} is $\eta_i I/eV$ electrons per second per unit volume, where V is the volume of the active region.

The recombination process contains spontaneous emission rate, R_{sp}, nonradiative recombination rate, R_{nr}, and carrier leagage rate, R_l, depicted in figure 2-2. Total recombination rate is determined as

$$R_{rec} = R_{sp} + R_{nr} + R_l \quad (2\text{-}1.3)$$

where the three terms on the right refer to the natural carrier decay processes.

Neglecting the photon generation term, the rate equation for carrier decay is, $dn/dt=n/\tau$, where $n/\tau = R_{sp}+R_{nr}+R_l$, by comparison to Eq. (2-1.3) and τ is the carrier lifetime. The carrier rate equation in equivalent be expressed as

$$\frac{dn}{dt} = \frac{\eta_i I}{eV} - \frac{n}{\tau} \quad (2\text{-}1.4)$$

Under steady-state conditions (dn/dt=0), the generation rate equals the recombination rate, i.e.,

$$\frac{\eta_i I}{eV} = \frac{n}{\tau} = R_{sp} + R_{nr} + R_l \quad (2\text{-}1.5)$$

The spontaneously generated optical power, P_{sp}, is obtained by multiplying the number of photons generated per unit time per unit volume, R_{sp}, by the energy per photon, $h\nu$, and the volume of the active region, V. P_{sp} can be expressed as below

$$P_{sp} = h\upsilon V R_{sp} = \eta_i \eta_r \frac{h\upsilon}{e} I \quad (2\text{-}1.6)$$

where the radiative efficiency, , is defined as

$$\eta_r = \frac{R_{sp}}{R_{sp} + R_{nr} + R_l} \quad (2\text{-}1.7)$$

Internal quantum efficiency, η_{int}, equals the product of $\eta_i \eta_r$. Therefore, the real active region of a LED doesn't has a quantum efficiency of unity. It is determined by the factor of η_i and η_r.

Photons emitted by the active region should escape from the LED die. In an ideal LED, all photons emitted by the active region are also radiated into free space. That indicates the extraction efficiency of a LED is unity. Nevertheless, in a real LED, not all the photons emitted from the active region are radiated into free space. Some photons may never leave the LED chip because there are several possible loss mechanisms in the semiconductor die. For instance, photons emitted from the active region can be absorbed in the substrate of the LED, assuming that the substrate material is absorbing at the emission wavelength. Metal also absorbs the light when photons emitted from the active region incident on a metallic contact surface. Furthermore, there is another factor, total internal reflection, to reduce the ability of the photons to escape form the semiconductor. The light extraction efficiency is defined as below

$$\eta_{extraction} = \frac{\text{number of photons emitted into free space per second}}{\text{number of photons emitted from active region per second}} = \frac{P/(h\upsilon)}{P_{\text{int}}/(h\upsilon)} \qquad \text{(2-1.2)}$$

where P is the optical power emitted into free space.

The extraction efficiency can seriously limit the output power of a LED, especially for high-performance LEDs. It is very difficult for the extraction efficiency to enhance beyond 50% without employing to complicated and expensive device processes.

The external quantum efficiency is defined as

$$\eta_{ext} = \frac{\text{number of photons emitted into free space per second}}{\text{number of electrons injected into LED per second}} = \frac{P/(h\upsilon)}{I/e}$$

$$=\eta_{\text{int}}\eta_{extraction} \tag{2-1.3}$$

The external quantum efficiency gives the ratio of the number of useful light particles to the number of injected charge particles.

The power efficiency is defined as

$$\eta_{power}=\frac{P}{IV} \tag{2-1.4}$$

where IV is the electrical power injected into the LED. Commonly, the power efficiency is also called the wall-plug efficiency.

2-2 The light escape cone

One of the most important problems facing high efficiency LEDs is the occurrence of trapped–light within a high-index semiconductor. A light ray emitted by the active layer region will be subjected to TIR, as predicted by Snall's law. If the incidence angle of a light ray is smaller than the critical angle, light can escape from the semiconductor. Nevertheless, total internal reflection occurs for light rays with oblique and grazing-angle incidence. The external efficiency is severely reduced by the total internal reflection, especially for LEDs consisting of high-refractive-index materials.

Assume that θ_1 is the angle of incidence in the semiconductor at the semiconductor-air interface. Therefore, according the Snell's law can determine the angle of incidence of the refracted ray, θ_2.

$$n_s \sin\theta_1 = n_a \sin\theta_2 \tag{2-2.1}$$

where n_s and n_a are the refractive indices of the semiconductor and air, respectively. Assume θ_2=90°. The critical angle for total internal reflection can be obtained, as illustrated in figure 2-3. Using Snell's law, one obtains

$$\sin\theta_c = \frac{n_a}{n_s}\sin 90^\circ = \frac{n_a}{n_s} \tag{2-2.2}$$

$$\theta_c = \sin^{-1}(\frac{n_a}{n_s}) \qquad (2\text{-}2.3)$$

The refractive indices of semiconductors are commonly very high. For instance, GaN has a refractive index of 2.5 The critical angle for GaN is 23.6°.

The light-escape cone is defined by the angle of total internal reflection. Photons emitted into the cone can escape from the semiconductor. On the other hand, photons emitted outside the cone is subject to total internal reflection.

After that, we calculate the surface area of the spherical cone with radius r in order to determine the total fraction of light that is emitted into the light escape cone. The surface area of the calotte-shaped surface is given by the integral

$$Area = \int dA = \int_{\theta=0}^{\theta c} 2\pi r \sin\theta r d\theta = 2\pi r^2 (1-\cos\theta_c) \qquad (2\text{-}2.4)$$

Let us suppose that photons are emitted from a point-like source in the semiconductor with a total power of P_{source}. And the output power of the propagation light escaping from the semiconductor can be expressed as

$$P_{escape} = P_{source} \frac{2\pi r^2 (1-\cos\theta_c)}{4\pi r^2} \qquad (2\text{-}2.5)$$

where $4\pi r^2$ is the entire surface area of the sphere with radius r.

The calculated results indicate that only a fraction of the light emitted inside a semiconductor can escape from the semiconductor. This fraction is described by

$$\frac{P_{escape}}{P_{source}} = \frac{1}{2}(1-\cos\theta_c) \qquad (2\text{-}2.6)$$

Since the critical angle of total internal reflection for high-index materials is relatively small, the cosine term can be expanded into a power series. Ignoring higher-than second-order terms yields

$$\frac{P_{escape}}{P_{source}} = \frac{1}{2}\left[1-(1-\frac{\theta_c^2}{2})\right] = \frac{1}{4}\theta_c^2 \approx \frac{1}{4}\frac{n_a^2}{n_s^2} \quad (2\text{-}2.7)$$

It is a severe problem for light to escape from the semiconductor, especially for high-efficiency LEDs. In the most semiconductors, the refractive index is very high and only a few percent of the photons generated in the active region can escape form a planar LED. For example, the refractive index of GaN is 2.5 and only 4% of the photons can emit into free space. This problem is less significant in semiconductors with a small refractive index, which have refractive indices of the order of 1.5.

2-3 Monte Carlo raytracing

TracePro is a comprehensive, versatile software tool for modeling the propagation of light in imaging and non-imaging opto-mechanical systems, as shown in figure 2-4. TracePro is a Monte Carlo ray tracing program that accounts for flux or light power in your optical system, as well as the irradiance or the distribution of light.

In Monte Carlo raytracing, scattering and diffraction are treated as random processes. Instead of propagating a distribution of light, discrete samples of the distribution, or rays, are propagated with BSDFs (Bidirectional Scattering Distribution Functions) used as probability distributions for determining ray directions. Monte Carlo ray tracing has several advantages over finite element methods. Below list is the characteristic of this software.

- Geometry can be procedural
- No tessellation is necessary
- It is not necessary to pre-compute a representation for the solution
- Geometry can be duplicated using instancing

- Any type of BRDF can be handled
- Specular reflections (on any shape) are easy
- Memory consumption is low
- The accuracy is controlled at the pixel/image level

By using TracePro, we set up a model of our optical system within the program including optical and non-optical surfaces, and trace rays through the model. We can set up a model importing from a lens design program like OSLO, from a CAD program via SAT, STP, or IGS files, or by creating the solid geometry directly in TracePro. The model includes not only the geometric data specifying the surfaces and optical material data, but also the radiometric properties of the surfaces, i.e., the absorptance, reflectance, transmittance, and scattering coefficients. Rays propagate through the model with portions of the flux of each ray allocated for absorption, specular reflection and transmission, and scattering. This forms a "tree" of rays. The flux of a ray is reduced at each ray-surface interaction, with its flux being reduced in value each time. This process continues until the flux of the ray falls below a threshold. We can run TracePro ray-traces in Analysis Mode and view the incident illuminance (or irradiance) on any surface in the model.

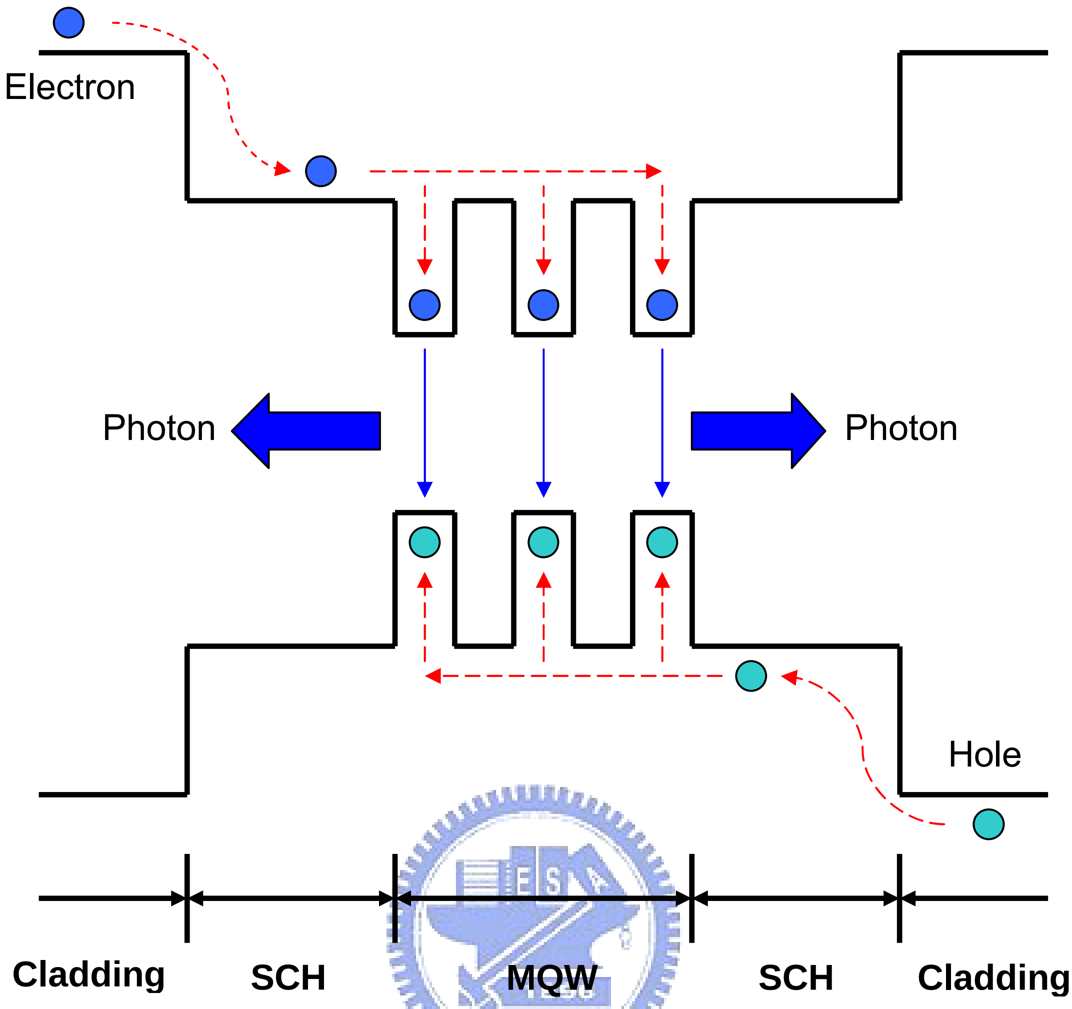

Figure 2-1　Band diagram of active region of LEDs.

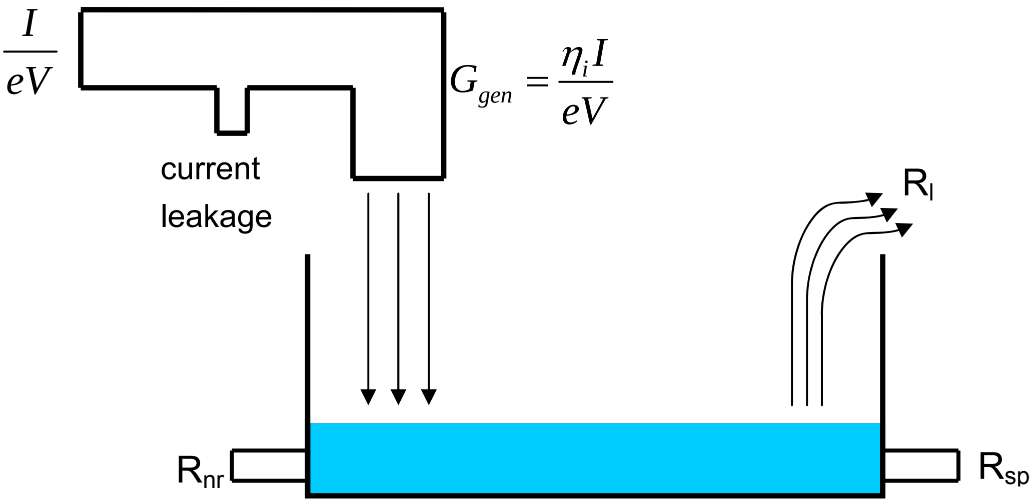

Figure 2-2　Reservoir analogy.

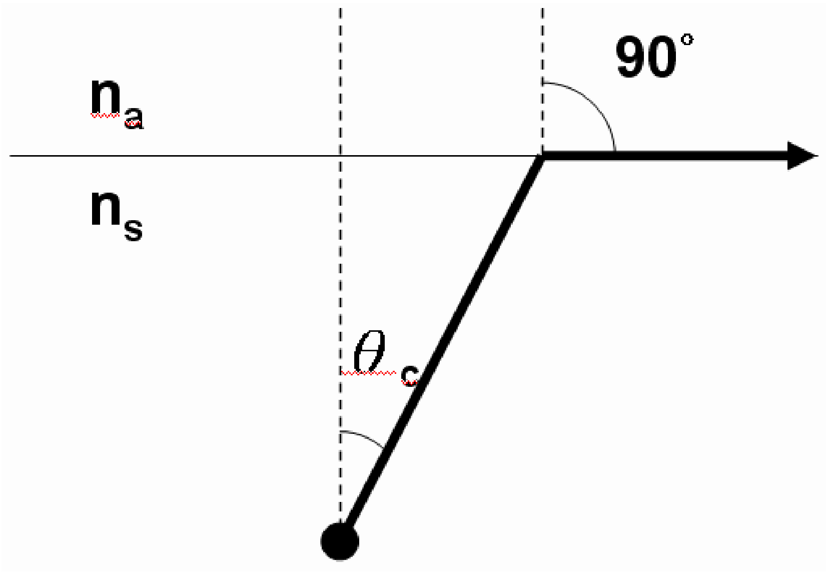

Figure 2-3　Definition of the escape cone by the critical angle θ_c.

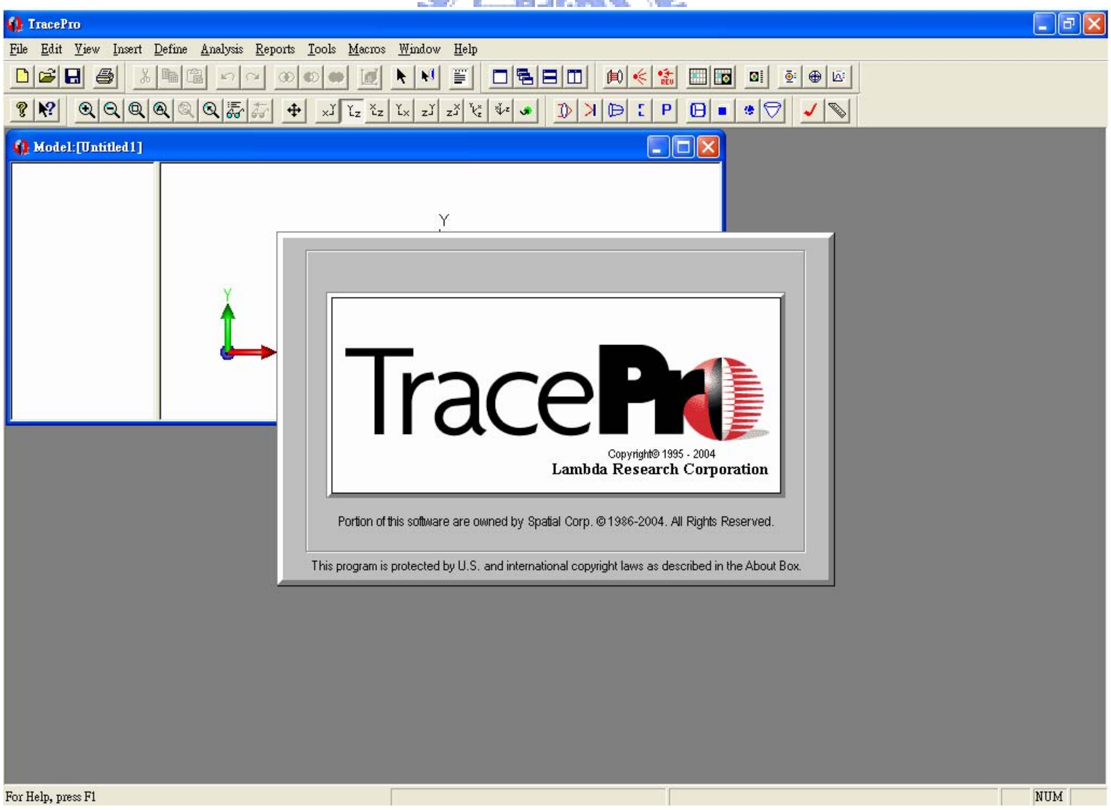

Figure 2-4　Picture of TracePro software.