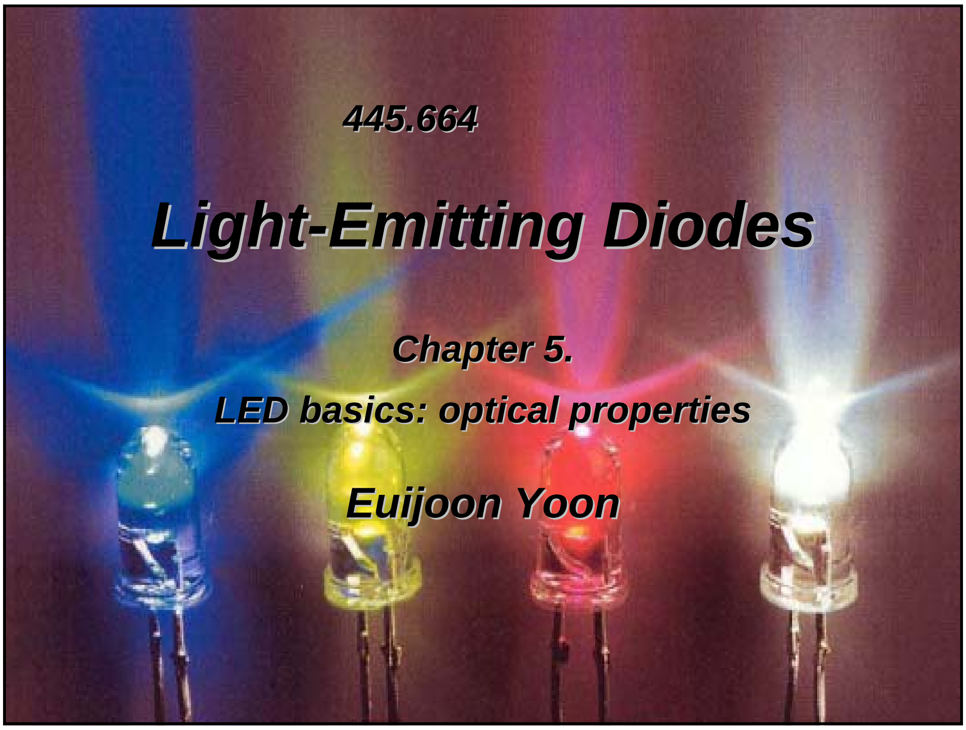


Internal, extraction, external, and power efficiency

The internal quantum efficiency

$$\eta_{int} = \frac{P_{int}/(h\nu)}{I/e} = \frac{\text{\# of photons emitted from active region per second}}{\text{\# of electrons injected into LED per second}}$$

(P_{int} : the optical power emitted from the active region, I : injection current)

The light extraction efficiency

$$\eta_{extraction} = \frac{P/(h\nu)}{P_{int}/(h\nu)} = \frac{\text{\# of photons emitted into free space per second}}{\text{\# of photons emitted from active region per second}}$$

(P : the optical power emitted into free space)

The external quantum efficiency

$$\eta_{ext} = \frac{P/(h\nu)}{I/e} = \eta_{int}\,\eta_{extraction} = \frac{\text{\# of photons emitted into free space per second}}{\text{\# of electrons injected into LED per second}}$$

The power efficiency
wallplug efficiency

$$\eta_{power} = \frac{P}{IV}$$ **(IV : the electrical power provided to LED)**

Emission spectrum

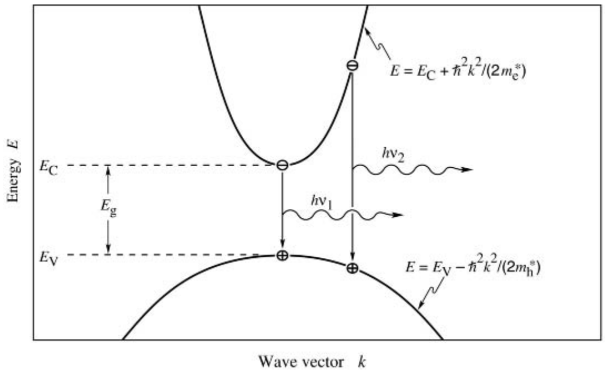


Fig. 4.1. Parabolic electron and hole dispersion relations showing "vertical" electron-hole recombination and photon emission.

- ***Electron and hole momentum must be conserved***
- ***Photon has negligible momentum -> vertical transition***

Emission spectrum

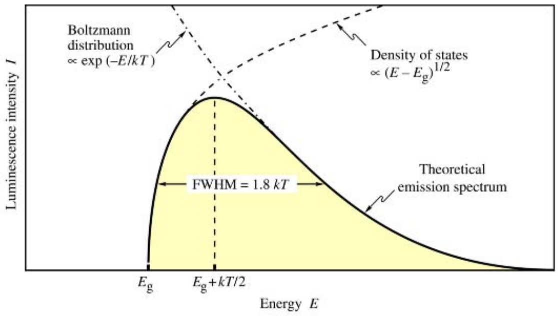


Fig. 4.2. Theoretical emission spectrum of an LED. The full width at half maximum (FWHM) of the emission line is 1.8 kT.

$I(E) \propto \sqrt{E - E_g}\, e^{-E/kT}$	**I(E) : the emission intensity**
$E = E_g + kT/2$	**Energy of Maximum Emission Intensity**
$\Delta E = 1.8kT$	**FWHM of the emission**

For GaAs LED at 870 nm, ΔE=46 meV, $\Delta\lambda$=28 nm

Spectral linewidth of LED emission

(i) The LED emission is even narrower than the spectral width of a single color as perceived by the human eye.

ex) red colors range in wavelength from 625 to 730 nm, which is much wider than the typical emission spectrum of an LED
→ perceived by the human eye as monochromatic

(ii) Optical fibers are dispersive, which leads to a range of propagation velocities for a light pulse consisting of a range of wavelengths. The material dispersion in optical fibers limits the "bit rate x distance product" achievable with LEDs.

ex) the spontaneous lifetime of carriers in LEDs in direct-gap semiconductor is of the order of 1- 100 ns depending on the active region doping concentration (or carrier concentration) and the material quality
→ Modulation speeds up to 1 Gbit/s are attainable with LEDs

CIE Chromaticity Diagram

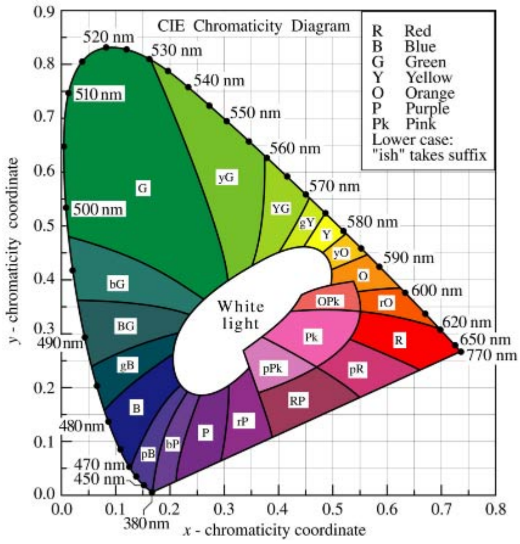


Fig. 10.3. CIE chromaticity diagram. Monochromatic colors are located on the perimeter and white light is located in the center of the diagram (adopted from Gage *et al.*, 1977).

The light escape cone

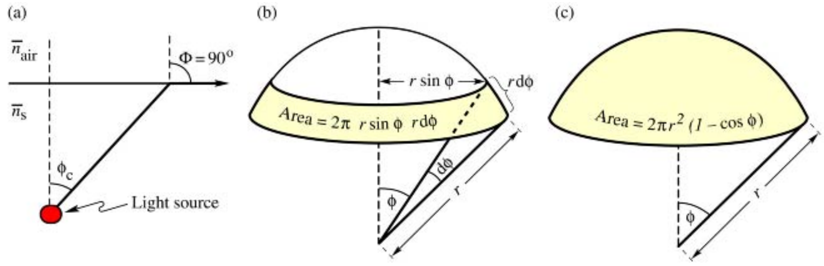


Fig. 4.3. (a) Definition of the escape cone by the critical angle ϕ_c. (b) Area element d*A*.
(c) Area of calotte defined by radius *r* and angle ϕ_c.

- ***Total internal reflection occurs inside LED chip, especially for LEDs consisting of high refractive index materials.***

$$\sin\Phi_c = (\bar{n}_{air} / \bar{n}_s)\sin 90 = \bar{n}_{air} / \bar{n}_s$$ **(the critical angle for total internal reflection)**

- ***Light escape cone defined by critical angle for total internal reflection***

Light escape in planar LEDs

$$\frac{P_{escape}}{P_{source}} = \frac{1}{2}(1-\cos\Phi_c) \approx \frac{1}{2}[1-(1-\frac{\Phi_c{}^2}{2})] = \frac{1}{4}\Phi_c{}^2$$

- Φ_C ***= critical angle of total internal reflection***
- ***Problem : Only small fraction of light can escape from semiconductor***

$$\frac{P_{escape}}{P_{source}} == \frac{1}{4}\frac{\bar{n}_{air}{}^2}{\bar{n}_s{}^2}$$

- ***In most semiconductors, the refractive index is quite high (>2.5) and thus only a few percent of the light generated in the semiconductor can escape from a planar LED.***

- ***Above equation gives < 10% extraction efficiency for typical III-V semiconductors.***

The lambertian emission pattern

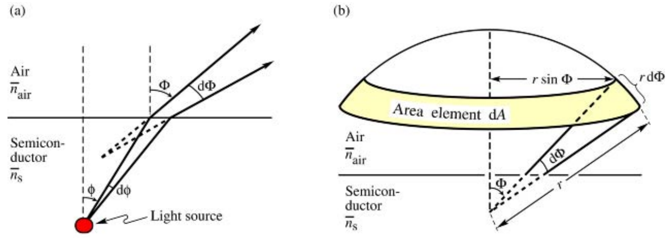


Fig. 4.4. Geometrical model used to derive the Lambertian emission pattern. (a) The light emitted into angle dϕ inside the semiconductor is emitted into the angle dΦ in air. (b) Illustration of area element dA of the calotte.

$$I_{air} = \frac{P_{source}}{4\pi r^2}\frac{\bar{n}_{air}^2}{\bar{n}_s^2}\cos\Phi$$ **(I_{air} : emission intensity in air)**

- ***Lambertian emission pattern has cosine-function dependence.***
- ***The intensity is highest for emission normal to the semiconductor surface and the intensity decreases to half of its maximum at an angle of 60°.***

Far-field patterns

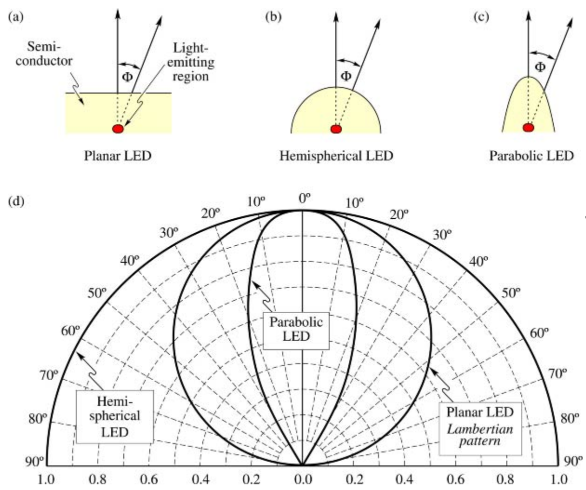


Fig. 4.5. Light-emitting diodes with (a) planar, (b) hemispherical, and (c) parabolic surfaces. (d) Far-field patterns of the different types of LEDs. At an angle of Φ = 60 °, the Lambertian emission pattern decreases to 50 % of its maximum value occuring at Φ = 0 °. The three emission patterns are normalized to unity intensity at Φ = 0 °.

- ***Die shaping can change emission pattern.***
- ***"Natural" LED has a planar surface.***

Effect of epoxy

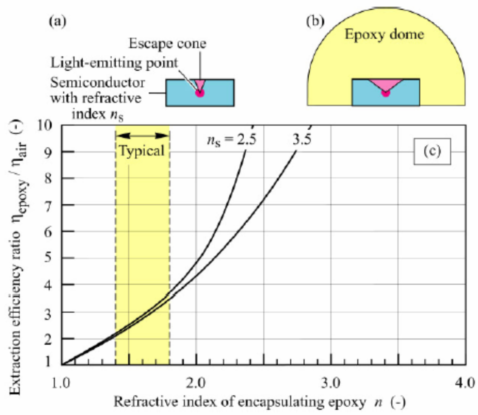
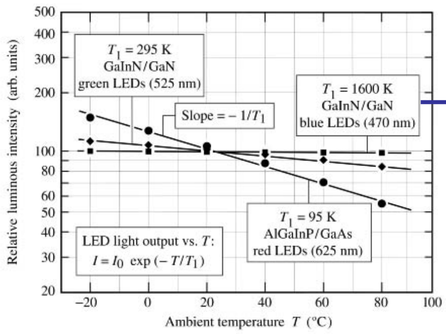


Fig. 5.6. (a) LED without and (b) with dome-shaped epoxy encapsulant. A larger escape angle is obtained for the LED with an epoxy dome. (c) Calculated ratio of light extraction efficiency emitted through the top surface of a planar LED with and without an epoxy dome. The refractive indices of typical epoxies range between 1.4 and 1.8 (adopted from Nuese *et al.*, 1969).

- ***Epoxy increases extraction efficiency .***

Temperature dependence of emission intensity



- ***The blue LED has the deepest wells → Effective confinement***

Fig. 4.6. Characteristic temperature T_1 of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LEDs near room temperature (after data of Toyoda Gosei Corp., 2000).

- ***Temperature dependence is characterized in terms of a characteristic temperature T_1***
- ***$I = I_o \exp(-T/T_1)$: purely phenomenological equation***
- ***High T_1 is desirable for a small temperature dependence***