Light Emitting Diode (LED) 发光二极管

01 Generation of light （光产生）
02 Internal quantum efficiency （内量子效率）
03 External quantum efficiency （外量子效率）
04 LED devices
LED applications

Display & Lighting
Generation of light

Photoluminescence
High energy light excitation
determined by the material

Electroluminescence
Electrical injection
determined by both active and
transporting layers
These excess minority carriers diffuse into the neutral semiconductor regions where they recombine with majority carriers.

- When a voltage is applied across a pn junction, electrons and holes are injected across the space charge region where they become excess minority carriers.

- If this recombination process is a direct band-to-band process, photons are emitted.
The internal quantum efficiency of an LED is the fraction of diode current that produces luminescence.

The internal quantum efficiency is a function of the injection efficiency, and it is also a function of the percentage of radiative recombination events compared with the total number of recombination events.

\[ \eta_i = \frac{R_{rad}}{R_{nrad} + R_{rad}} \]
The three current components in a forward-biased diode are the minority carrier electron diffusion current, the minority carrier hole diffusion current, and the space charge recombination current.

\[ J_n = \frac{eD_n n_p}{L_n} \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] \]

\[ J_p = \frac{eD_p p_n}{L_p} \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] \]

\[ J_R = \frac{en_i W}{2\tau_0} \left[ \exp \left( \frac{eV}{2kT} \right) - 1 \right] \]

Injection efficiency is the fraction of electron current to total current.

\[ \gamma = \frac{J_n}{J_n + J_p + J_R} \]
The radiative efficiency is defined as the fraction of recombination that are radiative.

\[ R = R_r + R_{nr} = \frac{\delta n}{\tau} = \frac{\delta n}{\tau_r} + \frac{\delta n}{\tau_{nr}} \]

\[ \eta = \frac{R_r}{R_r + R_{nr}} = \frac{1}{\tau_r} \left( \frac{1}{\tau_r} + \frac{1}{\tau_{nr}} \right) = \frac{\tau}{\tau_r} \]

The nonradiative recombination rate is proportional to \( N_t \), which is the density of nonradiative trapping sites within the forbidden bandgap. Obviously, the radiative efficiency increases as \( N_t \) is reduced.

\[ \eta_i = \gamma \eta \]

The radiative recombination rate is proportional to the p-type doping.
The external quantum efficiency of an LED is the fraction of generated photons that are actually emitted from the semiconductor.

The external quantum efficiency is normally a much smaller number than the internal quantum efficiency.

Once a photon has been produced in the semiconductor, there are three loss mechanisms the photon may encounter: photon absorption within the semiconductor, Fresnel loss, and critical angle loss.
Photons must be emitted from the semiconductor into air; thus, the photons must be transmitted across a dielectric interface.

Figure 14.26 shows the incident, reflected, and transmitted waves. The parameter $n_2$ is the index of refraction for the semiconductor and $n_1$ is the index of refraction for air. The reflection coefficient is

$$\Gamma = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$
GaAs$_{1-x}$P$_x$ red LED

- GaAs$_{1-x}$P$_x$ is a direct bandgap material for 0 $\leq x \leq$ 0.45. At $x=0.40$, the bandgap is 1.9 eV, producing an optical output in the red range.

- When the mole fraction $x$ is greater than 0.45, the material changes to an indirect bandgap semiconductor so that the quantum efficiency is greatly reduced.

![Graph showing brightness vs. wavelength for GaAsP diodes](Image)

**Figure 14.29** Brightness of GaAsP diodes versus wavelength (or versus bandgap energy).
- Wavelength is 880 nm due to its narrow bandgap of 1.4 eV.
- Electrons are injected from the wide-bandgap N-GaAl$_{0.7}$As$_{0.3}$ into the narrow-bandgap p-GaAl$_{0.6}$As$_{0.4}$.
- The minority carrier electrons in the p material can recombine radiatively.
- Since $E_{gp} < E_{gN}$, the photons are emitted through the wide-bandgap N material with essentially no absorption. The wide bandgap N material acts as an optical window.
Perovskite LED and OLED

Device structure and energy band diagram