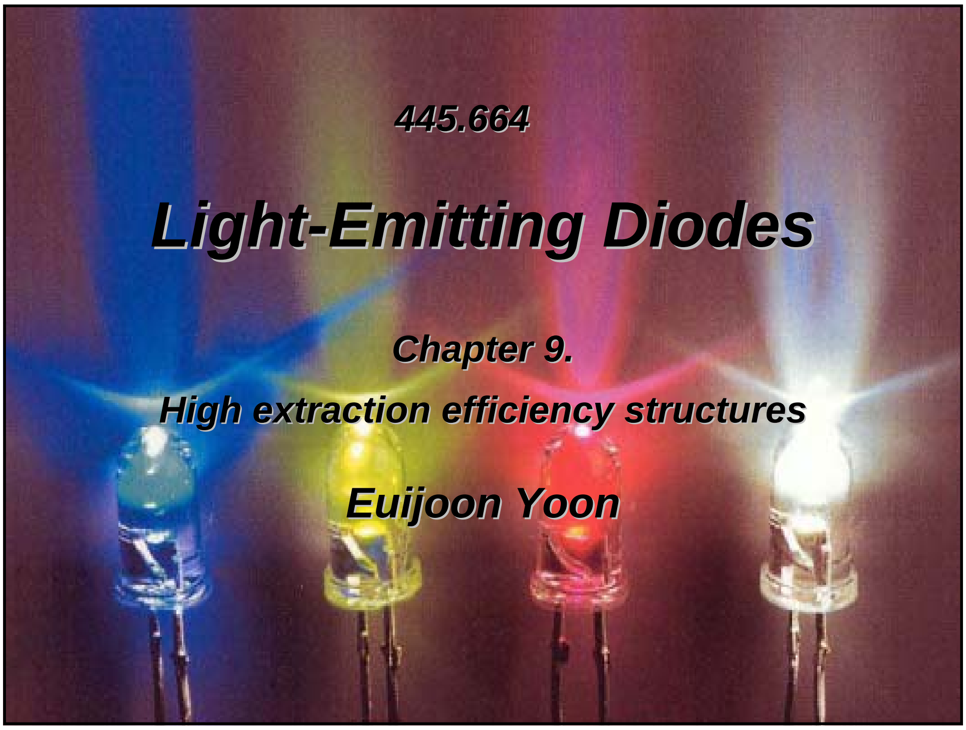

## 445.664

# Light-Emitting Diodes

## Chapter 9.
## High extraction efficiency structures

### Euijoon Yoon

## Absorption of below-bandgap light in semiconductors

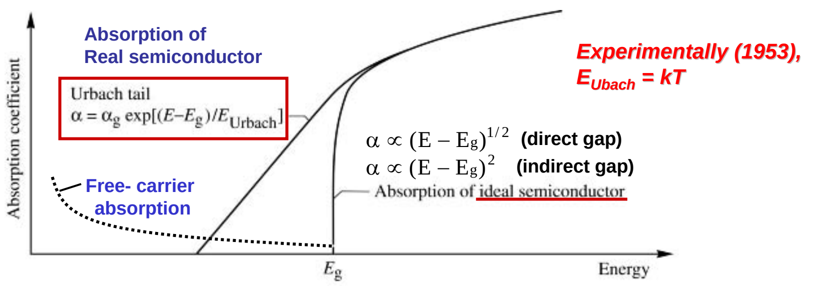


Fig. 6.1. Absorption of light below the bandgap of a semiconductor. No light is absorbed in an ideal semiconductor for photon energies below the bandgap. The absorption of light in a real semiconductor can be described by the "Urbach tail".

- ***Semiconductors do absorb below-bandgap light, although with a much lower absorption coefficient.***

  → ***Urbach tail** : caused by phonon-assisted transition, potential fluctuation such as random dopant distribution, or chemical composition of a ternary or quaternary alloy semiconductor.*

- ***For energies sufficiently lower than the $E_g$, free-carrier absorption becomes the dominant absorption mechanism. Transparent substrate.***

## Double heterostructures

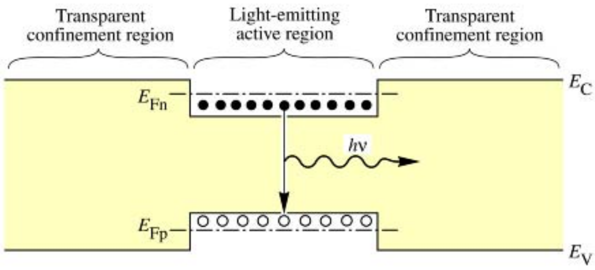


Fig. 6.2. Double heterostructure (DH) with light-emitting active region and optically transparent confinement regions. Reabsorption in the active region is unlikely due to the high carrier concentration in the active region and the resultiung Burstein-Moss shift of the absorption edge.

- ***Double heterostructures (DHs) are optically transparent.***
  - ***The active region is, under normal injection conditions, injected with high current densities so that the electron and hole quasi-Fermi levels rise into the bands.***

- ***All efficient LED designs use DH structures.***



## Shaping of LED dies

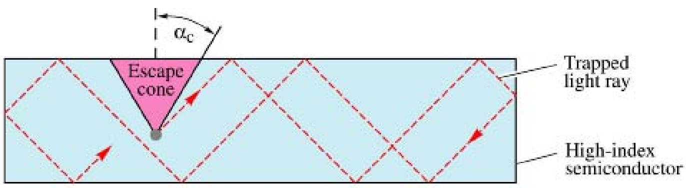


Fig. 6.3. Illustration of "trapped light" that cannot escape from a cube-shaped semiconductor for emission angles larger than $\alpha_c$ due to total internal reflection.

- ***Light rattles around and cannot escape.***
- ***Die shaping promises advantages.***
- ***However, die shaping can be expensive.***

## Shaping of LED dies

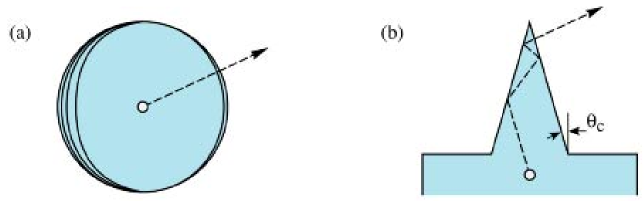


Fig. 6.4. Schematic illustration of different geometric shapes for LEDs with perfect extraction efficiency. (a) Spherical LED with point-like light-emitting region in the center of the sphere. (b) Cone-shaped LED.

- ***The optimum LED would be spherical in shape with a point-like light-emitting region. Total internal reflection does not occur. However, the light is still subject to Fresnel reflection at the interface unless the sphere is coated with an anti-reflection coating.***
- ***Are these structures practical ?? High cost!***



## The most common LED structure

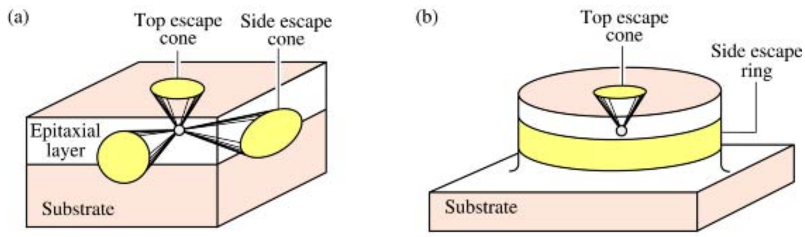


Fig. 6.5. Illustration of different geometric shapes of LEDs. (a) Rectangular parallelepipedal LED dice with a total of six escape cones. (b) Cylindrical LED with top escape cone and side escape ring.

- ***Cylindrical shape advantageous over parallelepipedal shape***
  - ***An escape ring replaces the four in-plane escape cones of the rectangular LED, which results in a substantial improvement of the extraction efficiency.***
- ***Additional cost of cylindrical shape***
  - ***due to one more processing step (etching step)***

# Truncated inverted pyramid (TIP) LED

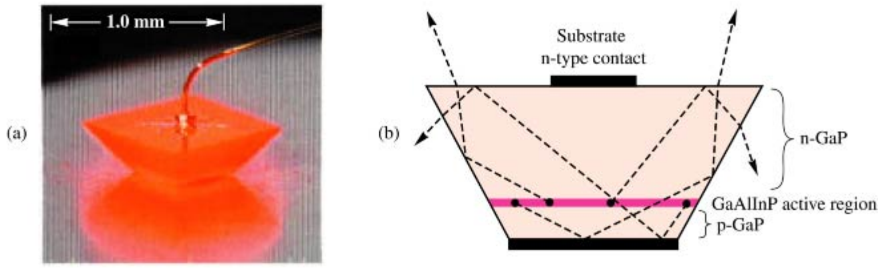


Fig. 6.6. Truncated inverted pyramid (TIP) AlInGaP/GaP LED. (a) LED driven by an electrical injection current. (b) Schematic diagram of the LED illustrating the enhanced light extraction efficiency (after Krames *et al*., 1999).

- ***The TIP geometry reduces the mean photon path-length within the crystal, and thus reduces the effect of internal loss mechanisms.***
- ***Additional cost of die shaping***



# Truncated inverted pyramid (TIP) LED

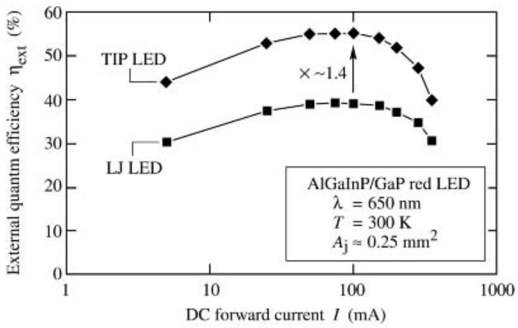


Fig. 6.7. External quantum efficiency versus forward current for red-emitting ($\lambda \approx 650$ nm) truncated-inverted-pyramid (TIP) LEDs and conventional large-junction (LJ) LEDs in power lamp packages. The TIP LED exhibits an approximately 1.4 times improvement in extraction efficiency as compared to the conventional device, resulting in a peak external quantum efficiency of 55 % at 100 mA DC (after Krames *et al*., 1999).

- ***One of the efficient LED designs***

# Textured semiconductor surfaces

- ***Increase of the light extraction efficiency using roughened or textured semiconductor surfaces***

***The interference fringes, observed for the GaN device having the smooth surface, completely vanish for the surface-textured film***

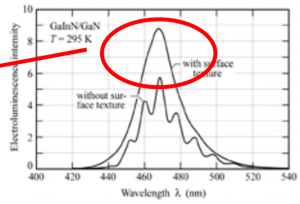


Fig. 9.9. Emission spectrum of GaInN blue LED with and without surface texture. The spectrum exhibits Fabry-Perot interference fringes for the device with a smooth surface (after Haerle, 2004).

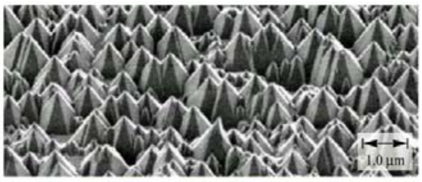


Fig. 9.8. Scanning electron micrograph of strongly textured GaN surface (after Haerle, 2004).

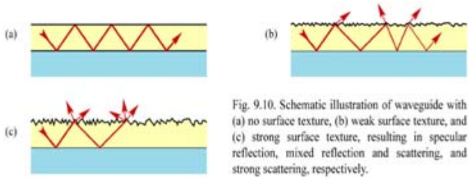


Fig. 9.10. Schematic illustration of waveguide with (a) no surface texture, (b) weak surface texture, and (c) strong surface texture, resulting in specular reflection, mixed reflection and scattering, and strong scattering, respectively.



# *Cross-shaped contacts and other contact geometries*

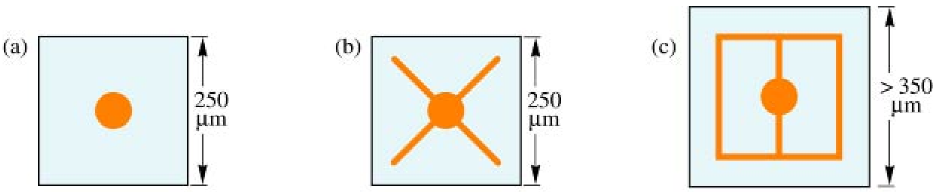


Fig. 6.13. Top view on LED dice with (a) a circular contact also serving as bond pad and (b) a cross-shaped contact with circular bond pad. (c) Typical contact geometry used for larger LED dies.

- ***Circular top contact suited for small LEDs.***
- ***Large-die LEDs require different contact geometry for uniform current distribution.***

## Transparent substrate (TS) technology

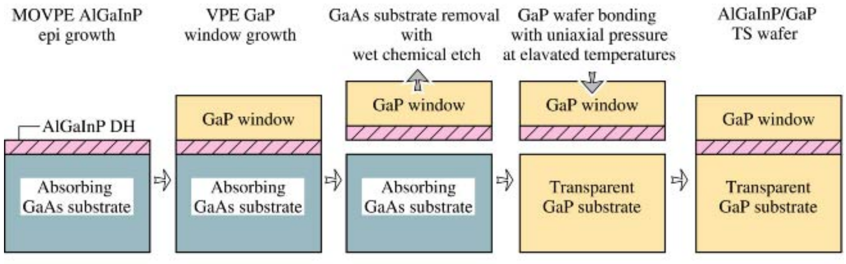


Fig. 6.14. Schematic diagram of the fabrication process for wafer-bonded tarnsparent substrate (TS) AlGaInP/GaP LEDs. After the selective removal of the original GaAs substrate, elevated temperature and uniaxial pressure are applied to the GaP substrate and the AlGaInP/GaP epitaxial film, resulting in the formation of a single TS LED wafer (adopted from Kish *et al.* 1994).

- ***Regular AlGaInP LEDs ( $\lambda$~ 560-660 nm) are grown on GaAs substrates.***
- ***GaAs ( $\lambda_g$ = 870 nm) is absorbing (absorbing substrate = AS)***
  ***→ Transparent substrate (TS) technology***



## Small forward-voltage penalty for TS technology

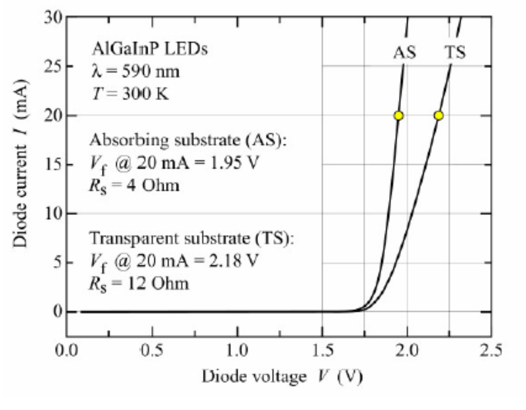


Fig. 7.18. Current-voltage characteristic, forward voltage, and series resistance of absorbing-substrate (GaAs) and transparent-substrate (GaP) LEDs with AlGaInP active regions.

- ***Wafer-bonded hetero-interface produces additional voltage drops.***
- ***Doping needs to be kept low to reduce free carrier absorption.***

## AS versus TS technology

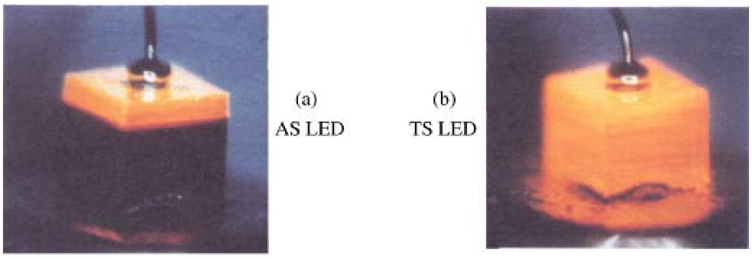


Fig. 6.15. (a) Amber GaP/AlGaInP/GaAs LED with GaP window layer and absorbing GaAs substrate (AS). (b) Amber GaP/AlGaInP/GaP LED with GaP window layer and transparent GaP substarte (TS) fabricated by a wafer bonding technique. Conductive Ag-loaded die-attach epoxy can be seen at the bottom of the TS LED (after Kish and Fletcher, 1997).

- ***TS AlGaInP/GaP LEDs have a factor of 1.5~ 3.0 higher external efficiency compared with AS AlGaInP/GaAs LEDs.***



## Anti-reflection (AR) optical coatings

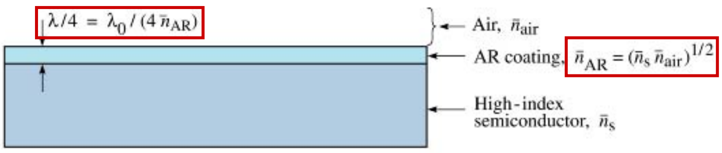


Fig. 6.16. Illustration of optimum thickness and refractive index of an antireflection (AR) coating.

$$R = \frac{(\overline{n}_s - \overline{n}_{air})^2}{(\overline{n}_s + \overline{n}_{air})^2}$$

***Table:***
***Refractive index and transparency range of common dielectrics suitable as AR coatings***

| *Dielectric material* | *Refractive index* | *Transparency range* |
|---|---|---|
| $SiO_2$ (Silica) | 1.45 | > 0.15 μm |
| $Al_2O_3$ (Alumina) | 1.76 | > 0.15 μm |
| $TiO_2$ (Titania) | 2.50 | > 0.35 μm |
| $Si_3N_4$ | 2.00 | > 0.25 μm |
| ZnS | 2.29 | > 0.34 μm |
| $CaF_2$ | 1.43 | > 0.12 μm |