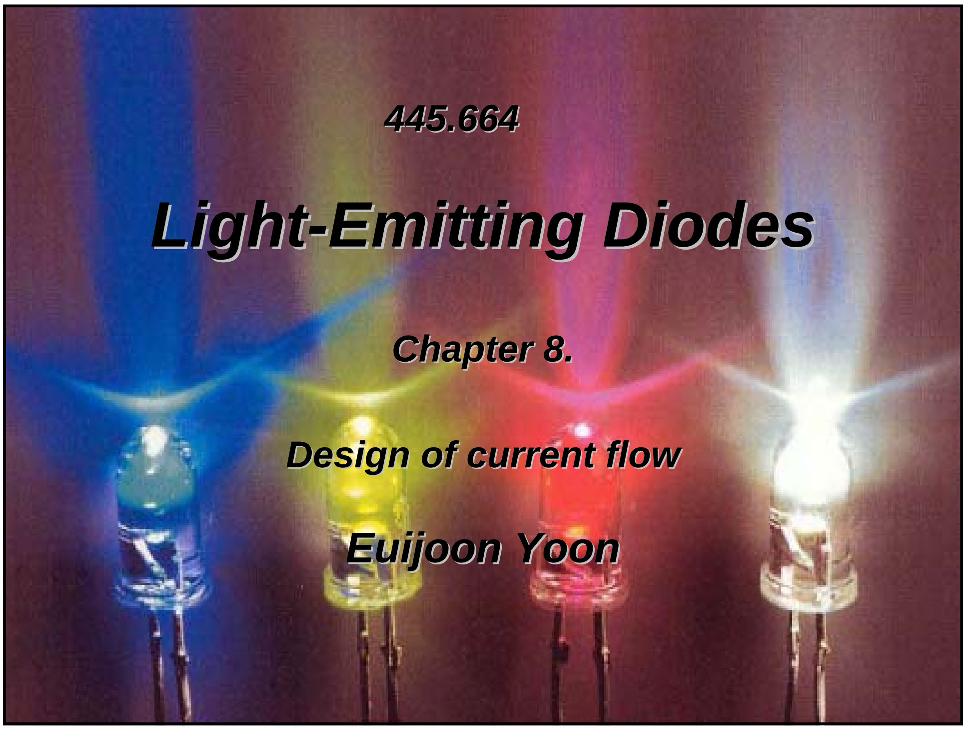

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Light-Emitting Diodes

Chapter 8.

Design of current flow

Euijoon Yoon

Current-spreading layer (Window layer)

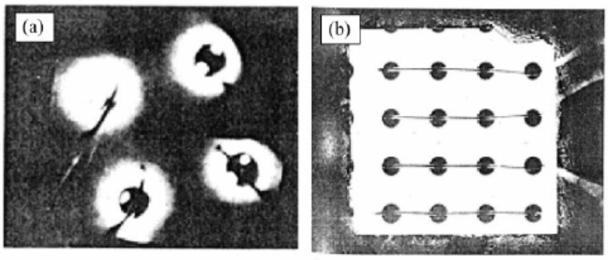


Fig. 7.8. Effect of current spreading layer on LED light output. (a) Top view of LED without current spreading layer. Light emission occurs only near the perimeter of the contact. (b) Top view of LED with current spreading layer (after Nuese *et al.*, 1969).

- ***Light is generated under an opaque metal electrode.***
- ***Current-spreading (window) layer spreads the current under the top electrode to regions not covered by the opaque top electrode.***
- ***The window layer : low resistivity, large thickness for current-spreading, and transparency to minimize absorption losses***

Effect of current-spreading layer

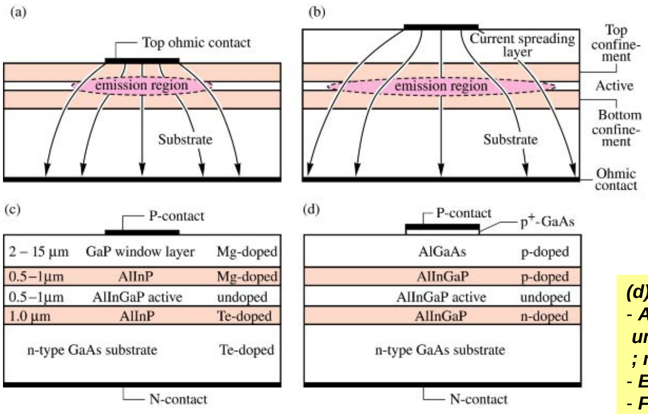


Fig. 6.8. Current spreading structures in high-brightness AlInGaP LEDs. Illustration of the effect of a current spreading layer for LEDs (a) without and (b) with a spreading layer on the light extraction efficiency. (c) GaP current spreading structure (Fletcher *et al.*, 1991). (d) AlGaAs currect spreading structure (Sugawara *et al.*,1992).

(c) GaP window layer

- E_g = 2.26eV
; transparent for red, orange, yellow, and part of green spectrum
- Indirect bandgap
; inherently less absorbing
However,
- lattice mismatched to underlying epitaxial layers
; dislocation propagation to active layer

(d) AlGaAs window layer

- ***AlGaAs is lattice-matched to underlying epitaxial layers ; no misfit dislocation***
- ***E_g(AlAs) = 2.9eV***
- ***For x>0.45, $Al_xGa_{1-x}As$ becomes an indirect semiconductor.***

However,

- ***AlGaAs compositional fluctuation ; larger Urbach energy than GaP***
- ***Difficulty of OMVPE growth using Al-containing compounds***

The AlGaAs/GaAs material system

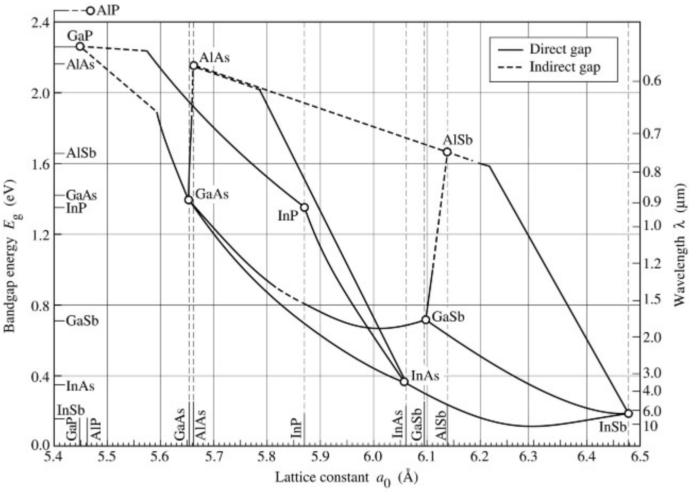


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

- ***AlGaAs is lattice matched to GaAs for all Al mole fractions.***

Effect of current-spreading thickness

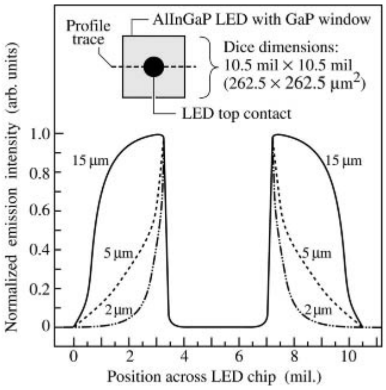


Fig. 6.9. The effect of GaP window thickness on current spreading is illustrated by surface light emission intensity profiles for three different AlInGaP LED chips with window layer thicknesses of 2, 5, and 15 µm. The profile is indicated by the dashed line in the inset. The dip in the middle of the profiles is due to the opaque ohmic contact pad. A microscope fitted with a video camara was used in the measurements (after Fletcher *et al.*, 1991a).

- ***For a window thickness of 2µm, current spreading is limited.***
- ***An even larger thickness (>15µm) of the window layer would spread the current to the edges of the chip.***
- ***A strong current spreading is not desirable due to surface recombination.***

Effect of current-spreading on the efficiency of LED

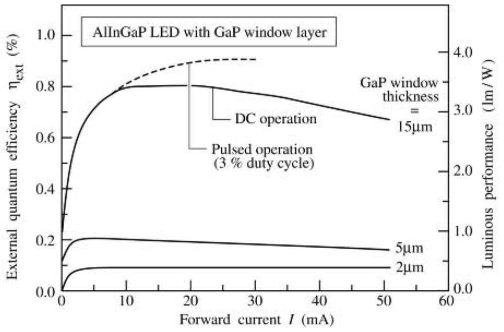


Fig. 6.10. Bare chip external quantum efficiency (photons/electron) and luminous performance (lm/W) versus forward current for AlInGaP LEDs with GaP window layer thicknesses of 2, 5, and 15 µm. Solid curves are under DC conditions. Dashed curve is under pulsed condition using 400 ns pulses and 3 % duty cycle. Heating is essentially eliminated in this case (after Fletcher *et al.*, 1991a).

- ***As the window layer thickness increased, the extraction efficiency increased by a factor of approximately 8.***
- ***The efficiency drop occurring at high currents is caused by heating of the device.***

Optimum current-spreading thickness

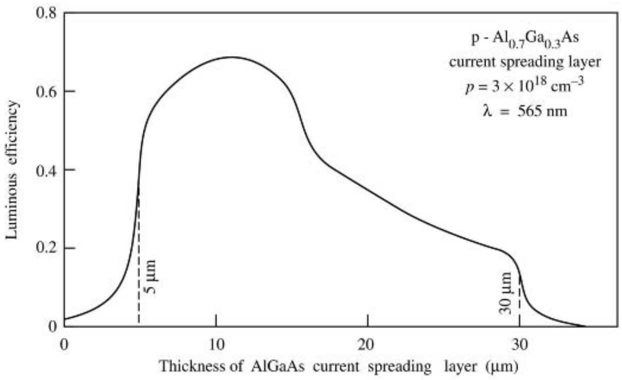


Fig. 6.11. Efficiency of an AlInGaP LED emitting in the red (565 nm) versus the thickness of an $Al_{0.70}Ga_{0.30}As$ current spreading layer (after Sugawara, 1992).

- ***Why is there a lower limit and an upper limit for optimum thickness of the current-spreading layer ?***

Optimum current-spreading thickness

- ***The disadvantage of no or a very thin current-spreading layer***
  - ***Most of the light is generated under the opaque metal contact pad, thereby hindering the escape of light from the LED die.***

- ***The disadvantage of a very thick current-spreading layer***
  - ***Current spreading to the edge of LED dies***
    → ***Surface recombination increases***
  - ***Increase in absorption of below-bandgap light in the window layer***
    → ***Light absorption increases***
  - ***Increase of the ohmic resistance of the device***
    → ***Lowering the overall efficiency***
  - ***Diffusion of dopants from the confinement layers into the active region due to long growth times required for thick window layer***
    → ***Lowering the internal quantum efficiency***

Theory of current spreading

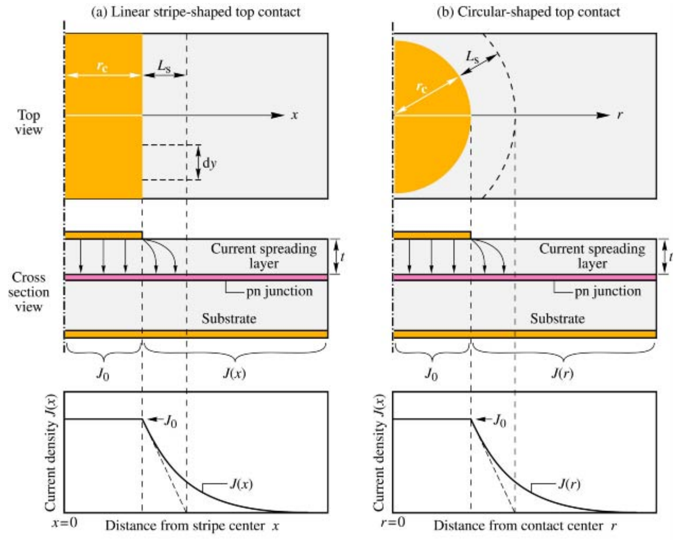


Fig. 6.12. Schematic illustration of current spreading in structures with different top contact geometries. (a) Linear stripe contact geometry. (b) Circular contact geometry.

Theory of current spreading

- ***Current spreading length, L_s***

$$L_s = \sqrt{\frac{t n_{ideal} kT}{\rho J_o e}}$$

t : thickness of current-spreading layer
ρ: the resistivity of the current-spreading layer
n_{ideal} : the diode ideality factor

- ***Thickness of current-spreading layer, t***

$$t = \rho L_s{}^2 J_o \frac{e}{n_{ideal} kT}$$ ***(the linear stripe contact geometry)***

$$t = \rho L_s (r_c + \frac{L_s}{2}) \ln(1 + \frac{L_s}{r_c})(J_o \frac{e}{n_{ideal} kT})$$ ***(the circular contact geometry)***

Current crowding in LEDs on insulating substrates

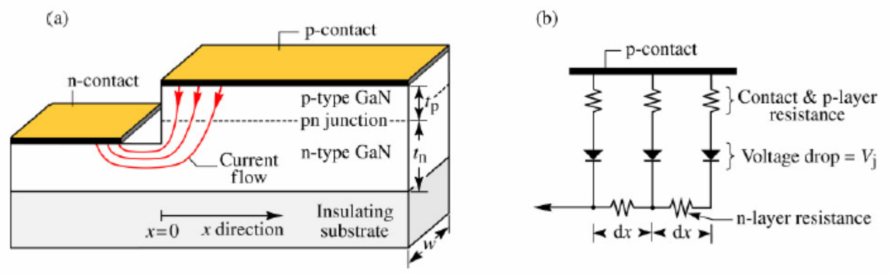


Fig. 7.14. (a) Illustration of current spreading in a mesa-structure GaN-based LED grown on an insulating or semi-insulating substrate. (b) Equivalent circuit consisting of n-type and p-type layer resistances, p-type contact resistance, and ideal diodes representing the pn junction.

- ***Current chooses path of least resistance.***
  - p-n junction current crowds near the edge of the mesa.

- ***How can current crowding be reduced ?***

Theory of current crowding

- ***Current crowding in LEDs on insulating substrates***

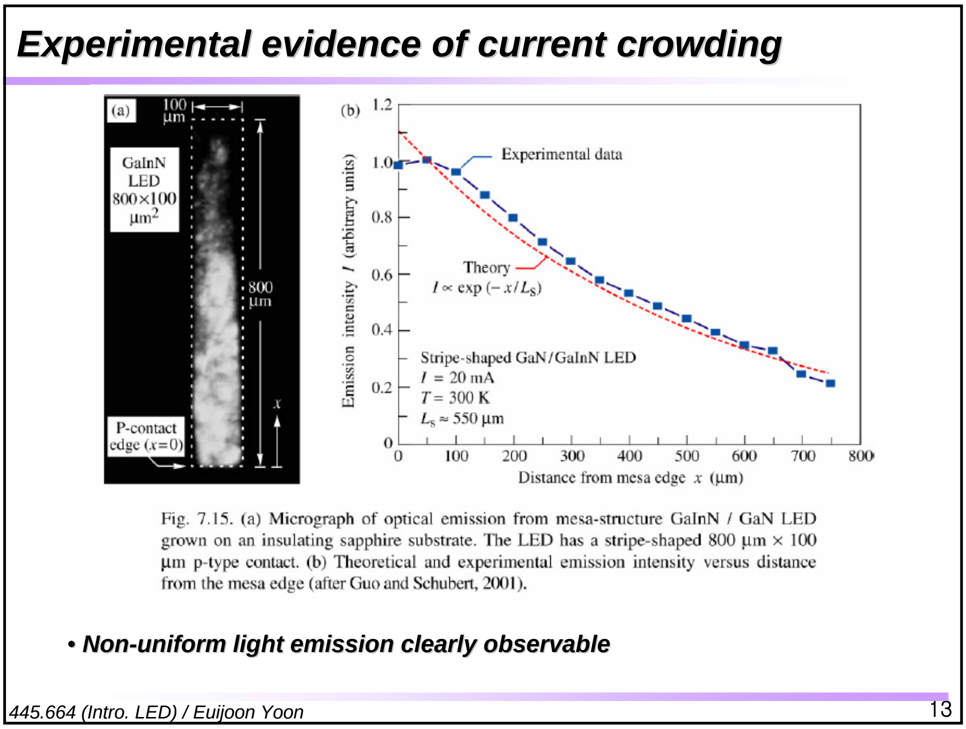
$$J(x) = J(0)\exp(-x/L_s)$$

J(0) : the current density at the p-type mesa edge
L_s : current spreading length

$$L_s = \sqrt{(\rho_c + \rho_p t_p)t_n / \rho_n}$$

ρ_c : the p-type specific contact resistance
ρ_p : the resistivity of the p-type layer

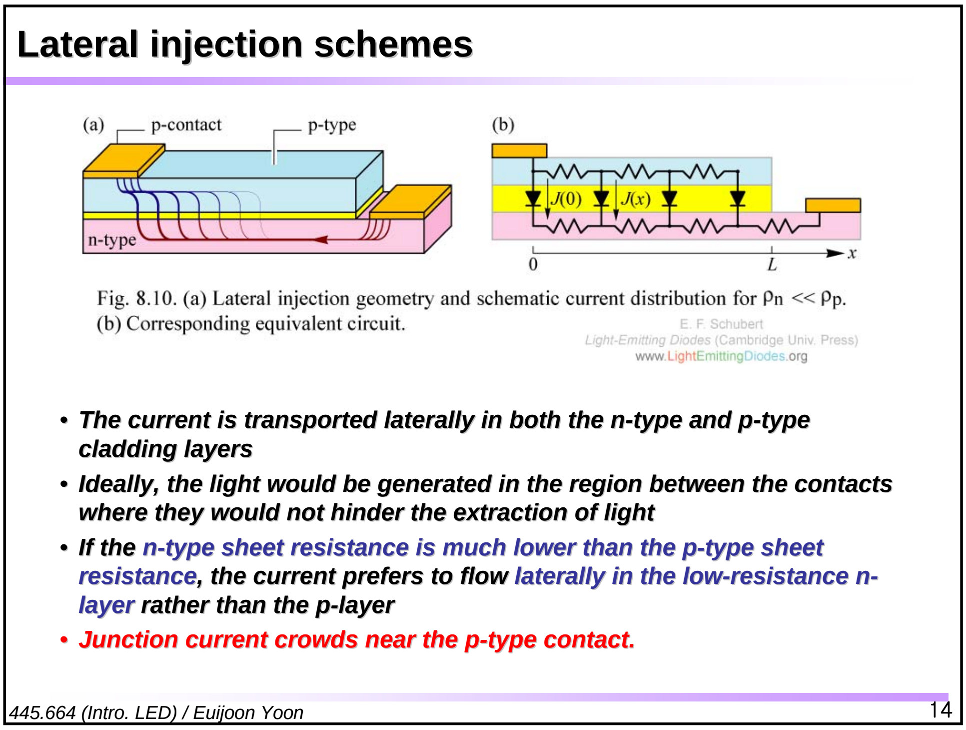
- ***A thick low-resistivity n-type buffer layer is needed to ensure that current crowding is minimized.***
- ***For low p-type specific contact resistance and p-type layer resistivity, strong current crowding results, unless the n-type buffer layer is very conductive so that t_n/ρ_n is very large.***



Experimental evidence of current crowding

Fig. 7.15. (a) Micrograph of optical emission from mesa-structure GaInN / GaN LED grown on an insulating sapphire substrate. The LED has a stripe-shaped 800 μm × 100 μm p-type contact. (b) Theoretical and experimental emission intensity versus distance from the mesa edge (after Guo and Schubert, 2001).

- ***Non-uniform light emission clearly observable***



Lateral injection schemes

Fig. 8.10. (a) Lateral injection geometry and schematic current distribution for $\rho_n \ll \rho_p$.
(b) Corresponding equivalent circuit.

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www.LightEmittingDiodes.org

- ***The current is transported laterally in both the n-type and p-type cladding layers***
- ***Ideally, the light would be generated in the region between the contacts where they would not hinder the extraction of light***
- ***If the n-type sheet resistance is much lower than the p-type sheet resistance, the current prefers to flow laterally in the low-resistance n-layer rather than the p-layer***
- ***Junction current crowds near the p-type contact.***

Current-blocking layers

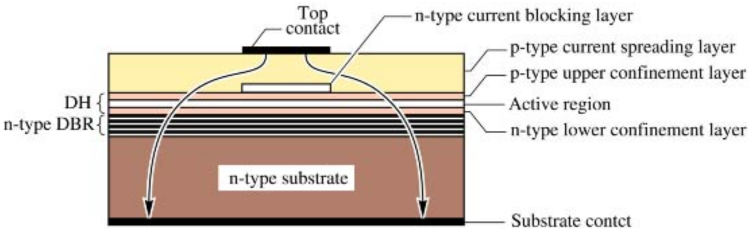

Fig. 6.20. LED with n-type current blocking layer located on top of the upper confinement layer. Light emission occurs in the regions not covered by the opaque top ohmic contact. The LED is fabricated by *epitaxial regrowth*. After the growth of the current-blocking layer, the wafer is taken out of the growth system for patterning (etching). Then the wafer is re-introduced into the epitaxial system for growth of the current spreading layer.

- ***Current-blocking layer blocks the current from entering the active region below the top contact. The current is deflected away from the top contact, thus allowing for much higher extraction efficiency.***

- ***Current-blocking layers require epitaxial regrowth.***