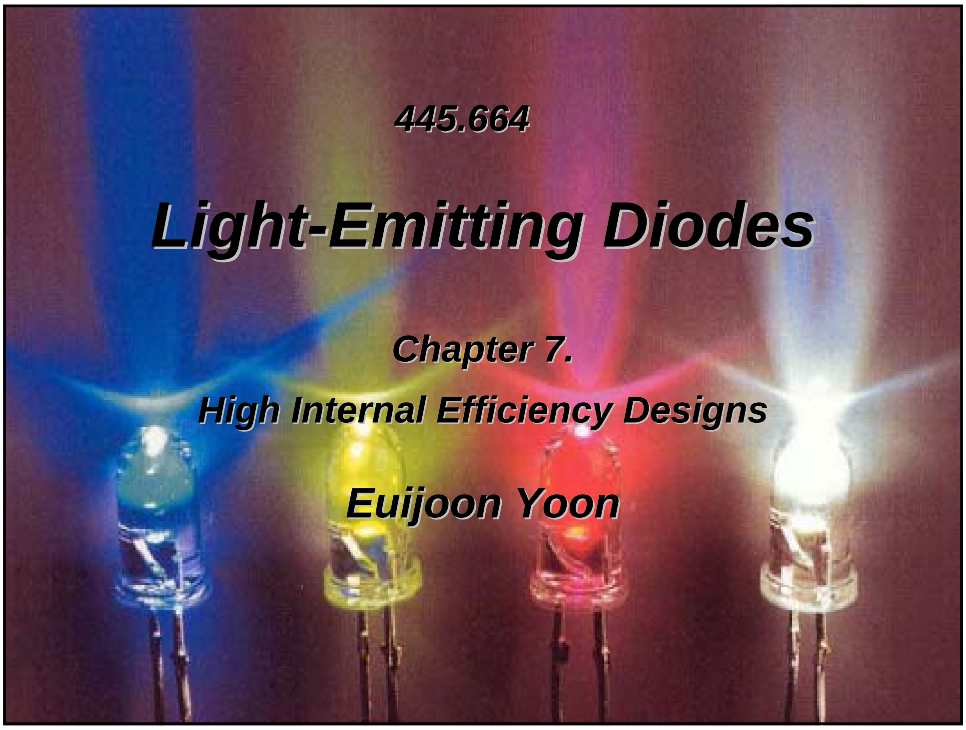


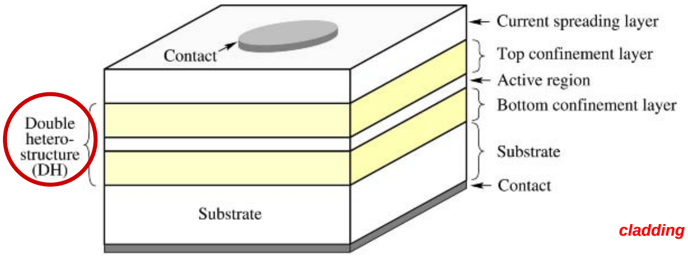
445.664

Light-Emitting Diodes

Chapter 7.
High Internal Efficiency Designs

Euijoon Yoon

Double heterostructures



cladding layer

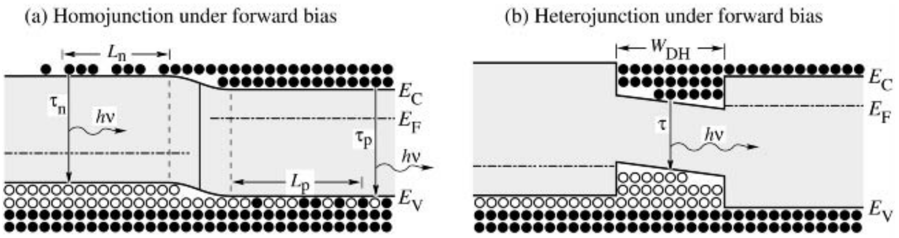
Fig. 5.1. Illustration of a double heterostructure consisting of a bulk or quantum well active region and two confinement layers. The *confinement* layers are frequently called *cladding* layers.

Bimolecular rate equation $$R = -\frac{dn}{dt} = -\frac{dp}{dt} = Bnp$$

→The region in which recombination occurs must have a high carrier concentration.

- ***Confinement of carriers in active region of double heterostructure (DH)***
- ***High carrier concentration in active region of DH***

Homostructures versus double heterostructures


(a) Homojunction under forward bias

(b) Heterojunction under forward bias

Fig. 5.2. Illustration of the free carrier distribution in a (a) homojunction and (b) heterojunction under forward bias conditions. In homojunctions, carriers are distributed over the diffusion length. In heterojunctions, carriers are confined to the well region.

- ***In III-V semiconductors, diffusion lengths can be 10μm or even longer***
  →Low carrier concentration (particularly towards the end of the diffusion tail)

- ***High carrier concentration in active region by introducing DH***

Efficiency versus active layer thickness

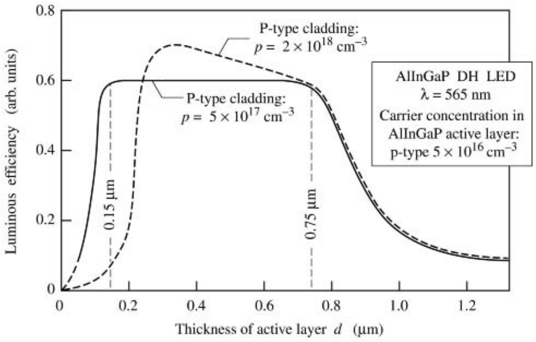


Fig. 5.3. Dependence of the luminous efficiency of an AlInGaP double heterostructure LED emitting at 565 nm on the active layer thickness. The figure reveals an optimum active region thickness of 0.15 – 0.75 μm (after Sugawara *et al*., 1992).

Why is there a lower and upper limit for high efficiency ?

i) Too thick active region (e.g. larger than the diffusion length of carriers)
- Carriers are distributed as they are in homojunctions.
ii) Too thin active region - Overflow at high injection current levels

Doping of active region

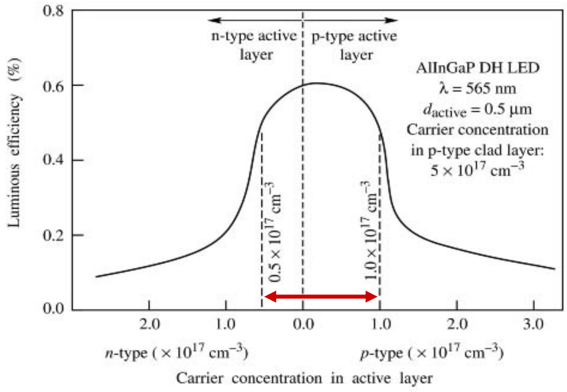


Fig. 5.4. Dependence of the luminous efficiency of an AlInGaP double heterostructure LED emitting at 565 nm on the active layer doping concentration (after Sugawara *et al.*, 1992).

- ***Why is either undoped or doped at a low level active region optimum ?***

Doping of active region

- ***Heavy doping would place the p-n junction effectively at the edge of the DH well region, i.e. at the active/confinement interface, thereby promoting carrier spill-over into one of the confinement regions.***

  → Decrease of the radiative efficiency

- ***P-type doping of the active region is more common than n-type doping of the active region due to the generally longer electron-minority-carrier diffusion length compared with the hole-minority-carrier diffusion length.***

  → More uniform carrier distribution throughout the active region

- ***Intentional doping of the active region***
  - ***In the low-excitation regime, the radiative carrier lifetime decreases with increasing free carrier concentration.***

    → Radiative efficiency increases.
  - ***Dopants may, especially at high concentrations, introduce defects that act as recombination centers. High concentrations of intentional dopants lead to an increased concentration of native defects due to the dependence of the native and non-native defect concentrations on the Fermi level.***

p-n junction displacement

- *Zn, Be: (1) are small atoms, (2) have a strongly concentration dependent diffusion coefficient*

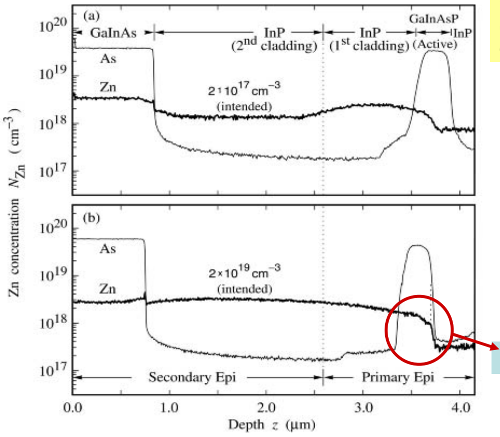


Fig. 5.5. Secondary ion mass spectrometry (SIMS) profile of Zn in a GaInAsP / InP double heterostructure. The structure uses Zn as a p-type dopant. (a) shows no pn junction displacement. (b) shows pn junction displacement caused by high Zn doping of the upper cladding region (after Schubert *et al.* 1995).

p-n junction displacement

- ***The diffusion of dopants can occur during growth and be caused by high growth temperature, a long growth time, or a strongly diffusing dopants.***

- ***If dopant redistribution occurs, the p-n junction can be displaced into one of the confinement layers. -> much lower quantum efficiency***

---

p-n junction displacement in the GaInAsP/InP DH

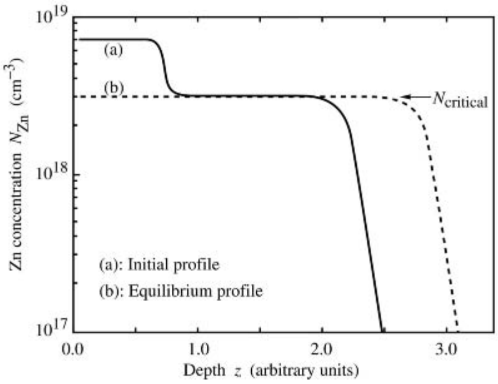


Fig. 5. 6. Schematic illustration of a pn junction displacent process caused by excessive doping of the cladding region. If the acceptor dopnat has a highly concentration-dependent diffusion constant and the diffusion constant increases strongly above a critical concentration, $N_{critical}$, pn junction displacement occurs in the active region (after Schubert *et al.* 1995).

- ***Zn diffusion coefficient increases rapidly above a critical concentration $N_{critical}$.***

- ***Zn will redistribute until the concentration falls below the $N_{critical}$.***
  → Zn can diffuse into and through the active region of the DH.

Doping of confinement regions

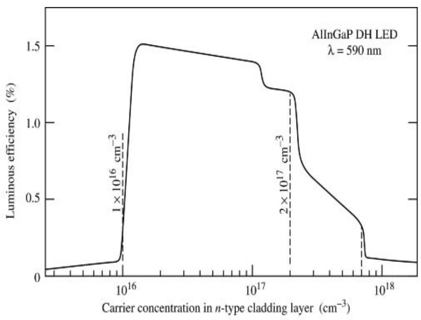


Fig. 5.7. Dependence of the luminous efficiency of an AlInGaP double heterostructure LED emitting at 565 nm on the confinement layer doping concentration (after Sugawara *et al.*, 1992).

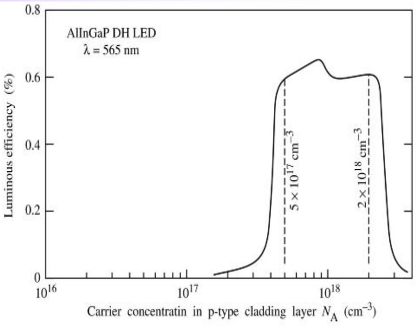


Fig. 5.8. Dependence of the luminous efficiency of an AlInGaP double heterostructure LED emitting at 565 nm on the doping concentration in the p-type confinement layer (after Sugawara *et al.*, 1992).

$N_{D,opt}$: 10^{16} ~2×10^{17} cm^{-3}

$N_{A,opt}$: 5×10^{17} ~2×10^{18} cm^{-3}

- ***For p-type confinement regions, the optimum doping concentration is clearly higher than in the n-type cladding regions due to the larger diffusion lengths of electrons than that of holes.***

- ***A high p-type concentration in the cladding region keeps electrons in the active region and prevents them from diffusing deep into the confinement region.***

Influence of the confinement layer doping concentration on the radiative efficiency

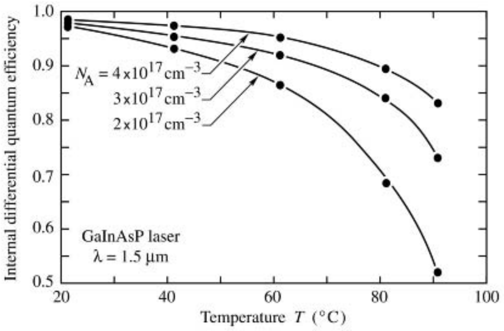


Fig. 5.10. Dependence of internal differential quantum efficiency (emitted photons per injected electron) on temperature for different cladding doping levels (after Kazarinov and Pinto, 1994).

- ***Low doping concentration in the p-type confinement layers facilitates electron escape from the active region, thereby lowering the internal quantum efficiency.***

Nonradiative recombination and lifetime

- ***High crystal quality of active region is needed.***
  - ***Deep levels** caused by point defects, impurities, dislocations, and others must have a very low concentration.*
  - ***Surface recombination** must be kept at the lowest possible levels.*
  - ***Any surface must be “out of reach” of the active region.***

- ***Device reliability affected by surface recombination.***

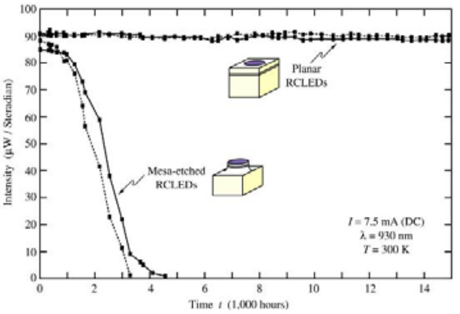


Fig. 5.11. Emission intensity of two mesa-etched LEDs and two planar LEDs versus time (after Schubert and Hunt, 1998)

- *Low IQE*
- *Reduction of lifetime*
- *Formation of dark-line defects*

If one type of carriers are present, i.e., near the top contact of the device, the presence of surface does not reduce the radiative efficiency.

Lattice matching

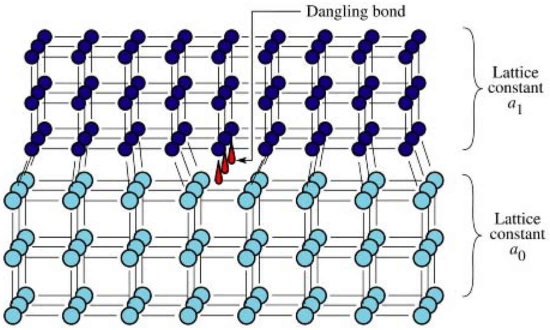


Fig. 5.12. Illustration of two crystals with mismatched lattice constant resulting in dislocations at or near the interface between the two semiconductors.

- ***Lattice matching is crucial for high efficiency.***

- ***Multitude of defects are created in mismatched material system.***

Misfit Dislocation Lines

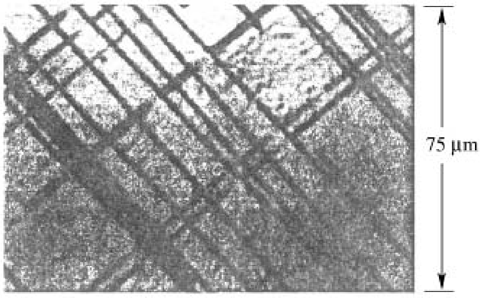


Fig. 5.13. Cathodoluminescence image of a 0.35 μm thick $Ga_{0.95}In_{0.05}As$ layer grown on a GaAs substrate. The dark lines forming a cross-hatch pattern are due to misfit dislocations (after Fitzgerald *et al.*, 1989).

- ***Dark lines due to dislocation lines***
- ***Radiative efficiency low at dislocation lines***

Pseudomorphic layers

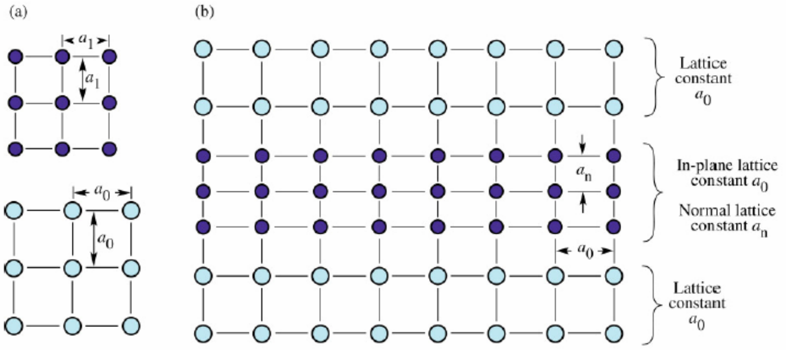


Fig. 6.14. (a) Illustration of two cubic-symmetry crystals with equilibrium lattice constant a_1 and a_0. (b) Illustration of a thin, coherently strained crystal layer with equilibrium lattice constant a_1 sandwiched between two semiconductors with a equilibrium lattice constant a_0. The coherently strained layer assumes an in-plane lattice constant a_0 and a normal lattice constant a_n.

- ***Thin layers can be elastically strained without incurring defects.***
- ***Critical thickness can be calculated by Matthews-Blakeslee law.***

Lattice matching

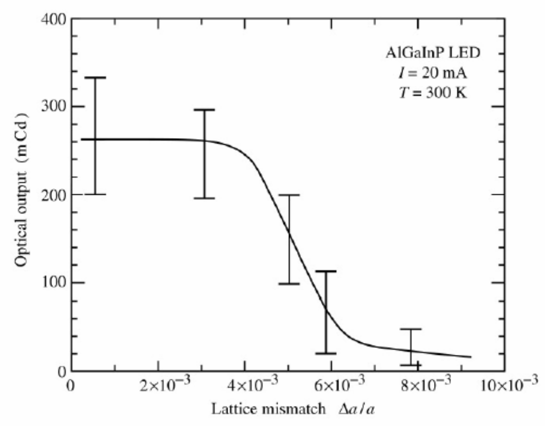


Fig. 6.15. Optical output intensity of an AlGaInP LED driven with an injection current of 20 mA versus lattice mismatch between the AlInGaP active region and the GaAs substrate (after Watanabe and Usui, 1987).

- ***Lattice matching better than 0.2 % required in AlGaInP material system.***
- ***Major challenge : High quality crystal growth on mismatched substrate***

Defect insensitive nitrides

- **Less sensitive to surface recombination and lattice mismatch, compared to GaAs and InP.**
- **Possible Reasons**
  - Lower electrical activity of dislocations
  - Smaller diffusion length of carriers than the mean distance between dislocations, in particular the hole diffusion length
  - Compositional fluctuation of InGaN, leading to carrier localization