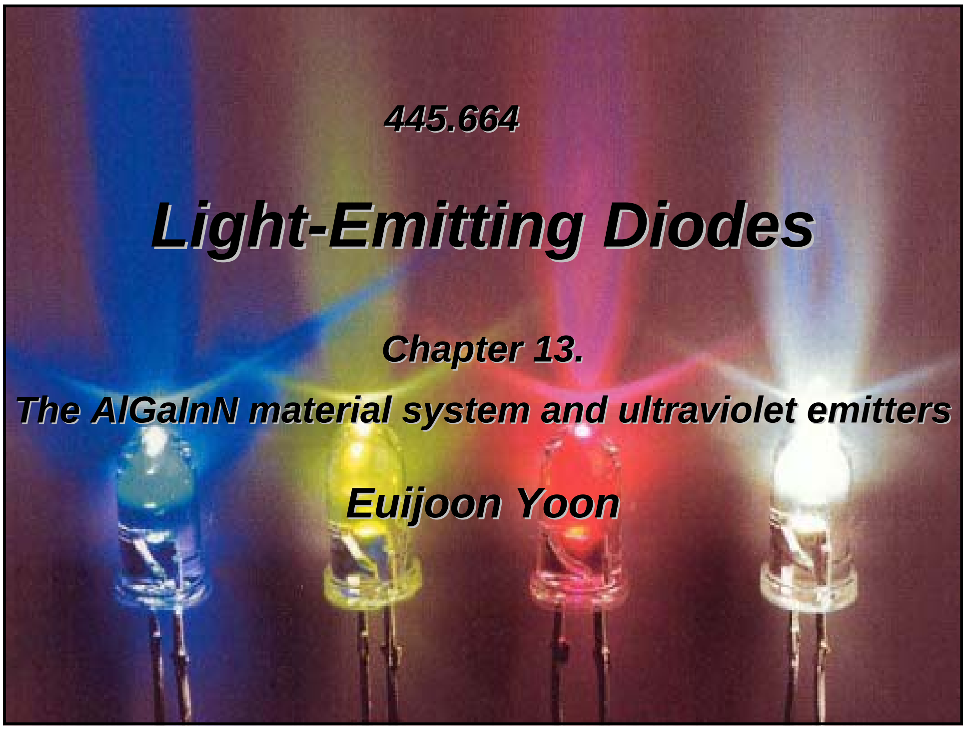

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Light-Emitting Diodes

Chapter 13.

The AlGaInN material system and ultraviolet emitters

Euijoon Yoon

The UV spectral range

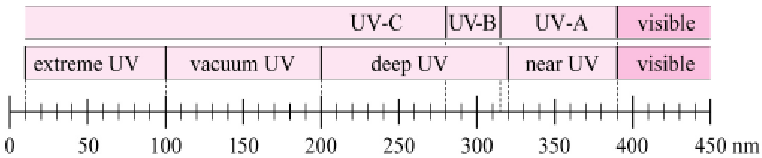

Fig. 13.1. Nomenclature of UV radiation versus wavelength (after International, 1932).

- Two classifications of UV spectrum

1.

UV-A	315-390 nm	Penetration of atmosphere, damage to deeper skin and eye (cataracts)	
UV-B	280-315 nm	Partially absorbed by ozone layer	Serious damage to skin and eye
UV-C	< 280 nm	Mostly absorbed by ozone layer	

2. Extreme UV (10-100 nm)
   Vacuum UV (100-200 nm)
   Deep UV (200-320 nm)
   Near UV (320-390 nm)

The AlGaInN bandgap

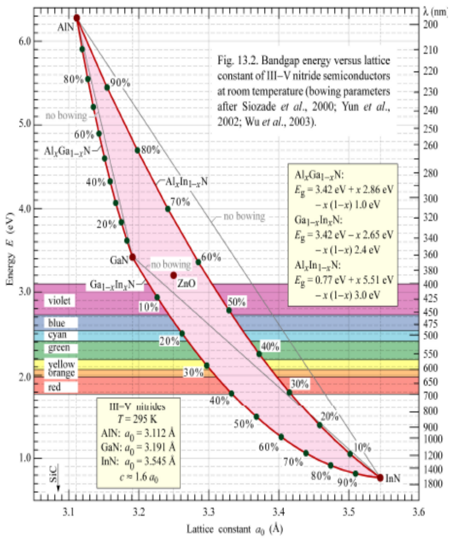

Fig. 13.2. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature (bowing parameters after Siozade *et al.*, 2000; Yun *et al.*, 2002; Wu *et al.*, 2003).

- **AlGaInN material system spans a very wide range of wavelength covering the deep UV, near UV, visible and near infrared.**
- **It has been difficult to synthesize Al-rich AlGaN alloys and In-rich GaInN alloys with high IQE.**
- **Controversy with respect to the bandgap energy of InN**
  - **1.9 eV -> ~0.7 eV**
- **Bowing parameter, E_b**

$$E_g^{AB} = E_g^A + (E_g^B - E_g^A)x + x(1-x)E_b$$

Polarization effects in III-V nitrides

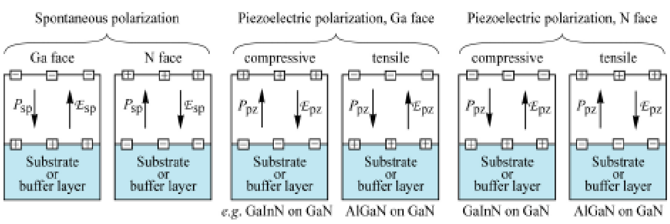

Fig. 13.3. Surface charges and direction of electric field and polarization field for spontaneous and piezoelectric polarization in III–V nitrides for Ga and N face orientation.

- **Most common epitaxial growth direction of III-V nitrides**
  - **c-plane of the hexagonal wurtzite structure**
  - **Polarization charges located at each of the two surfaces of a layer**
  - **Internal electric fields occur in III-V nitrides**
    - **Significant effect on the optical and electrical properties**
  - **The direction of the internal electric field depends on**
    - **Strain**
    - **Growth orientation (Ga face or N face)**

Piezoelectric polarization charges

- The strain in the epitaxial layer
  - Compressive-strain : epi-layer is laterally compressed
    - Ex.) GaInN is compressively strained when grown on a thick relaxed GaN buffer layer.
  - Tensile-strain : epi-layer is expanded along the lateral direction
    - Ex.) AlGaN is under tensile strain when grown on a thick relaxed GaN buffer layer.

- Calculated magnitude of the electric field for common III-V nitride alloys grown on relaxed GaN

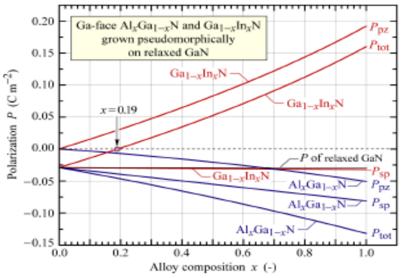

Fig. 13.4. Magnitude and direction of spontaneous and piezoelectric polarization in GaInN and AlGaN grown pseudomorphically on relaxed GaN. Relaxed GaN has a spontaeous polarization, but no piezoelectric polarization (after Gessmann *et al.*, 2002).

Consequence of the polarization fields

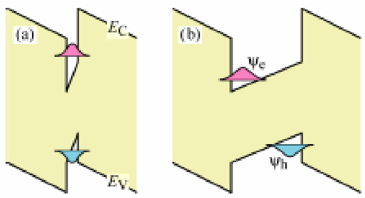

Fig. 13.5. Schematic band diagram of (a) thin and (b) thick AlGaN/GaN active region with poalization fields for Ga-face growth (substrate on right-hand side).

- Quantum well layers have an internal electric field
  - Spatially separated electrons and holes thereby preventing efficient radiative recombination
  - Particularly true for thick quantum wells, e.g. > 100Å
    - To avoid this deleterious effect, it is imperative that the quantum well layers are kept very thin. (20~30 Å)
- Screen of large electric field caused by polarization effects
  1. high doping of the active region
  2. high injection current

  : screening of the internal electric field

  ⇨ blue-shift of emission as the injection current is increased

Doping activation in III-V nitrides

- Low doping activation : problem in III-V nitrides
  - 2 origins
    1. Chemical deactivation of acceptors by hydrogen atoms bonding to acceptors.
       - The missing electron that acceptors strive to capture is provided by a hydrogen atom.
    2. Acceptors in III-V nitrides have a high thermal activation energy (>> kT at 300K)
       - Only a small percentage of acceptors are ionized at RT.
- Amano et al. (1989)

  : 'Acceptor dopants can be activated by low-energy electron-beam irradiation (LEEBI)'
- Nakamura et al. (1991)

  : 'Acceptors can be activated by thermal annealing'
  - During thermal annealing, the relatively weak acceptor-hydrogen bond is broken and hydrogen atoms are driven out of the epi-layer.

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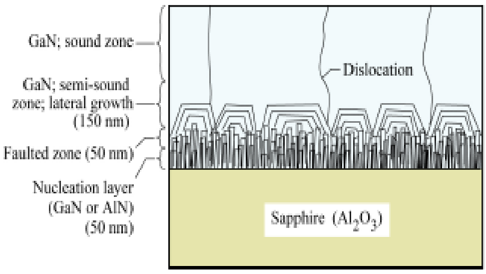
Dislocations in III-V nitrides

- Sapphire
  - most common substrate for GaN growth
  - very stable substrate
  - corundum structure (III-V nitrides : wurzite structure)
  - different lattice constants to GaN

  ⇒ Misfit dislocations (threading and edge dislocations) in GaN epi-layer (10^8 ~ 10^9 cm^{-2})



- Initial layer (faulted layer)
  - grown at low temperatures(~500 °C) and subsequently annealed
- (Semi-)sound zone
  - dislocations undergo self-annihilation during anneal
  - much lower dislocation densities

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Charged dislocation

- **Generally, dislocation lines are electrically charged**
  - **The region surrounding a dislocation line is either *coulombically attractive or repulsive to a free carrier.***
  - **The nature of the coulombic interaction depends on the polarity of the dislocation line and the carrier.**

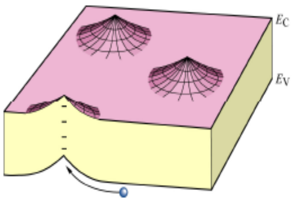


Fig. 13.8. Bandgap diagram of semiconductor having negatively charged dislocations. Holes are attracted to disclocation lines where they must ultimately recombine with electrons.

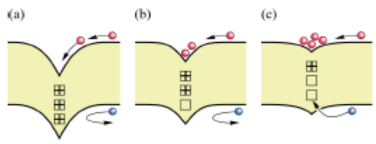


Fig. 13.9. Recombination in a positively charged dislocation. (a)–(c) Sequence shows electrons accumulating in the potential minimum thereby screening the dislocation potential and allowing holes to recombine.

- ***Positively charged dislocation line***
- ***Initially, electrons are attracted but holes are repelled.***
- ***Continued collection of electrons will screen the dislocation potential***
  - ***Reduction of the repulsive barrier for holes***
- ***Electrons and holes will recombine non-radiatively via electron states of the dislocation line.***

High radiative recombination efficiency in III-V nitrides

- **Why the radiative recombination efficiency in III-V nitrides is so high despite the high density of dislocations?**
  - **Several possible explanations**
    1. **Electronic states of the dislocation line lie outside the forbidden gap (within the allowed band)**

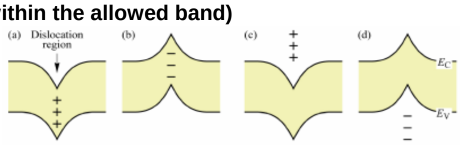


Fig. 13.10. Band diagram of dislocation: (a) donor states in gap, (b) acceptor states in gap, (c) donor states in conduction band, and (d) acceptor states in valence band. Whereas (a) and (b) lead to non-radiative recombination, (c) and (d) no not.

2. **Compositional alloy fluctuation**
   - **variation of the bandgap energy and local potential minima**
   - **The potential minima attract and confine carriers and prevent them from diffusing towards the dislocation lines.**

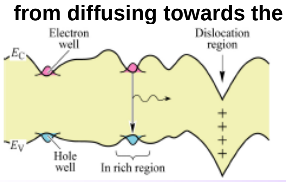


Fig. 13.11. Band diagram of GaInN having clusters of In rich regions which spatially localize carriers and pevent them from diffusing to dislocations.

High tolerance towards dislocation in III-V nitrides

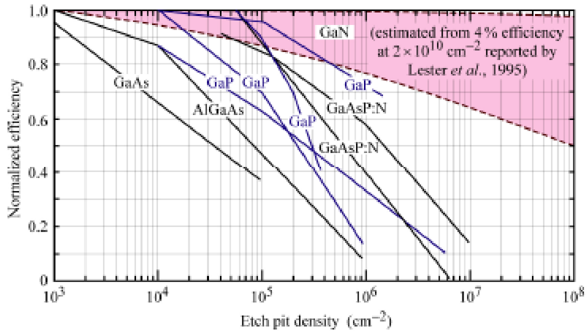


Fig. 13.12. Dependence of radiative efficiency on etch pit density (III–V arsenide and phosphide data adopted from Lester *et al.*, 1995; III–V nitride data estimated by the author of this book).

- **Direct detection of indium-composition fluctuations in GaInN by TEM was shown to be difficult and even ambiguous due to high-energy electron beam damage.**
- **The magnitude of the indium fluctuation in GaInN is still under discussion.**
- **Generally accepted explanation has not yet been established.**
- **III-V nitrides have a much higher tolerance towards dislocations as compared to III-V arsenides and phosphides.**

UV devices emitting at wavelength > 360 nm

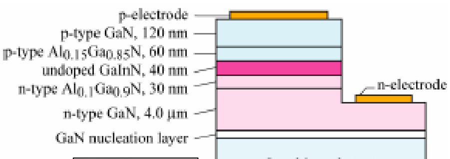


Fig. 13.13. Layer structure of GaInN UV LED grown on saphire substrate emitting at 370 nm (after Mukai *et al.*, 1998).

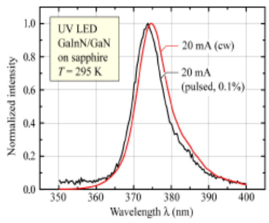
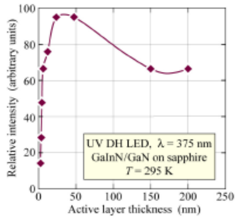
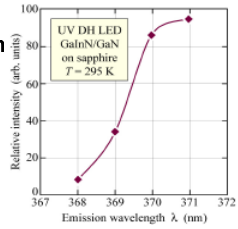


Fig. 13.14. Room temperature emission spectrum of commercial 375 nm UV LED (Nichia Corp.) under cw and pulsed condition.

- **Generally GaN of GaInN active layer**
- **Small red-shift of the peak wavelength when going from pulsed to CW current injection**
  - **Caused by junction heating**



- **optimum output power at 30-50 nm active layer**
- **Active region is heavily doped to screen the PZ fields.**



- **As the emission wavelength decreases, a pronounced drop in the emission intensity**
- **very positive influence of In corporation on the IQE**

UV devices emitting at wavelength < 360 nm

- **AlGaN active region or $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ MQW active region**
- **Low power efficiency, less than 1%**

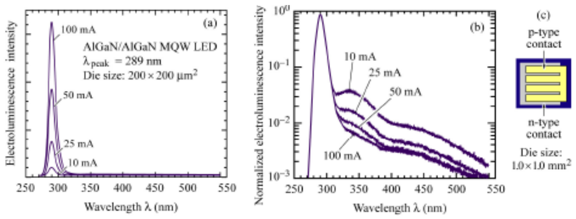


Fig. 13.17. Emission spectrum of deep-UV AlGaN/AlGaN multiple quantum well LED for different injection-currents on (a) linear and (b) logarithmic scale. An interdigitated contact geometry, as shown in (c), was used for large-area dies (after Fischer *et al.*, 2004).

- **Active region composed of three $Al_{0.36}Ga_{0.64}N$ QW with $Al_{0.48}Ga_{0.52}N$ barriers for emission at 290 nm**
- **Some sub-bandgap emission near 330nm becomes apparent when plotting the spectrum on log scale.**

Issues for AlGaN/AlGaN UV LED

- **Affinity of Al to oxygen**
  - **Al has a very high affinity to O_2 making the incorporation of O into AlGaN increasingly likely as the Al content increases.**
- **Conductivity of AlGaN**
  - **Conductivity of AlGaN decreases as the Al mol fraction increases for Al>30%**
  - **Higher resistivity in the confinement layer and higher series resistance**
- **Lateral conductivity**
  - **As the resistivity of Si-doped n-type AlGaN increases with the Al content, devices generally become more resistive.**
- **Contact resistance**
  - **Due to the high bandgap of AlGaN, contact-barrier heights are generally high.**
- **Diffusion of acceptors**
  - **During the epitaxial growth of the top cladding layer, Mg acceptors may diffuse back into the active region**
  - **lowering of radiative efficiency**
  - **limit on the maximum thickness of the p-type cladding layer**

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Issues for AlGaN/AlGaN UV LED

- **Heterojunction barriers**
  - **Due to the larger bandgap energy, band discontinuity of heterojunctions are generally larger than for smaller bandgap semiconductors.**
  - **Compositional grading at the heterojunction reduces the junction barrier resistance**
- **Light extraction**
  - **To reduce reabsorption effects**
  - **All device layers should have an Al content sufficiently high to be transparent to the emitted light**
- **Cracking**
  - **AlGaN films on relaxed GaN : tensile strain**
  - **For sufficiently thick films : crack**
  - **Cracking can be strongly reduced or even eliminated by using Al-rich strain-compensating superlattices**

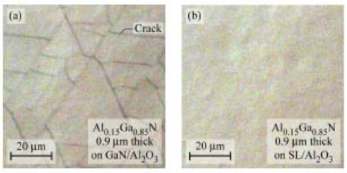

Fig. 13.18. Optical micrograph of $Al_{0.15}Ga_{0.85}N$ layer grown (a) without and (b) with a strain-compensating $AlN/Al_{0.45}Ga_{0.55}N$ superlattice (SL). The SL has 10 periods and equal well and barrier thickness of 10 nm. Angles between crack lines frequently are 60° or 120°.