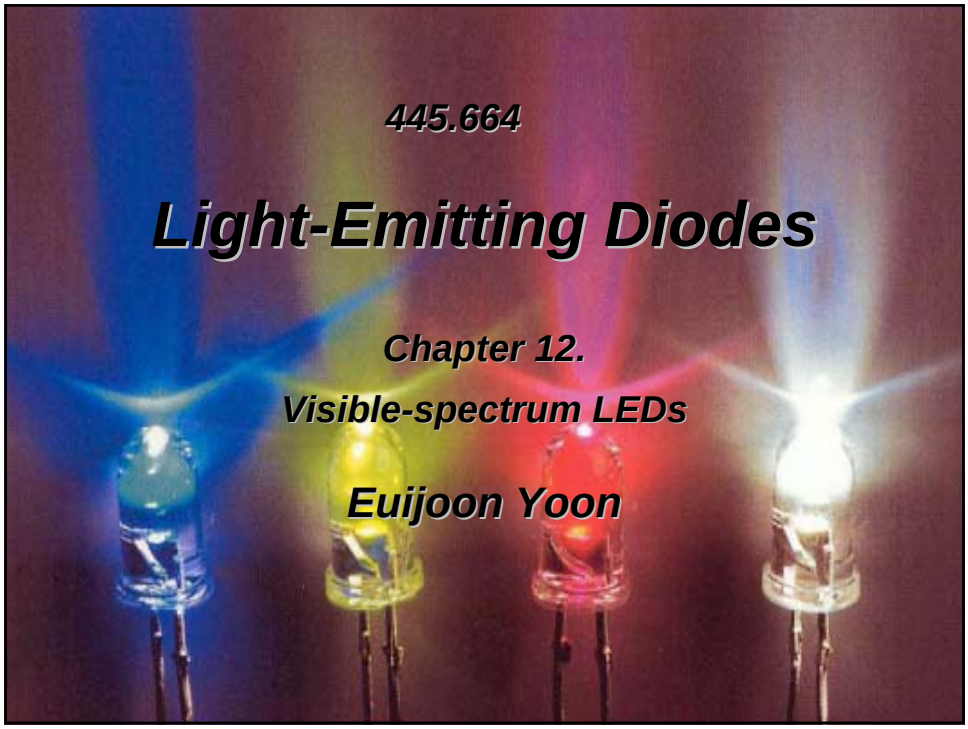

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Light-Emitting Diodes

Chapter 12.

Visible-spectrum LEDs

Euijoon Yoon

The GaAsP, GaP, GaAsP:N, and GaP:N material system

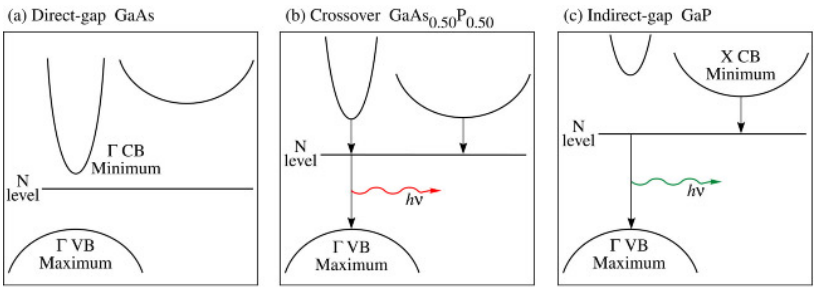


Fig. 7.1. Schematic band structure of GaAs, GaAsP, and GaP. Also shown is the nitrogen level. At a P mole fraction of about 45 - 50 %, the direct-indirect crossover occurs.

(E_g(GaAs): 1.43eV (870nm), E_g(GaP): 2.26eV (550nm))

- ***GaAsP on GaAs is the lattice mismatched system.***
  - ***A lattice mismatch between GaAs and GaP is large, about 3.6%.***
  - → ***low internal quantum efficiency***

- ***GaAsP, GaAsP:N suitable for indicator light***
  - ***The isoelectronic impurities form an optically active level within the forbidden gap of the semiconductor so that carriers recombine radiatively via the N levels.***

GaAsP

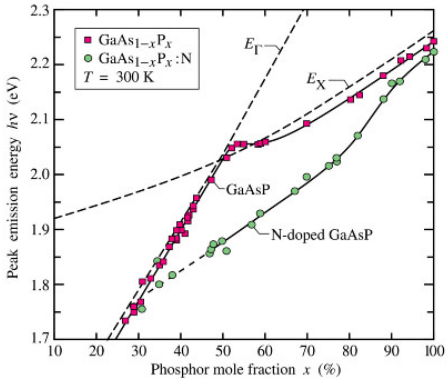


Fig. 7.2. Room - temperature peak emission energy versus alloy composition for undoped and nitrogen - doped GaAsP light - emitting diodes injected with a current density of 5 A / cm^2. Also shown is the energy gap of the direct (E_Γ) and indirect (E_X) transition. The direct-indirect crossover occurs at $x \approx 50$ % (after Craford *et al*. 1972).

- ***Isoelectronic impurities** have an electronic wave function that is strongly localized in position space (small Δx) so that **the wave function is delocalized in momentum space (large Δp).***

- The change in momentum occurring when an electron makes a transition from the indirect X valley of the conduction band to the central Γ valley of the valence band, **the momentum change is absorbed by the isoelectronic impurity atom.

GaAsP

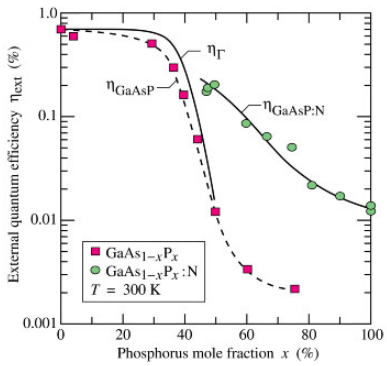


Fig. 7.3. Experimental external quantum efficiency of undoped and N-doped GaAsP versus P mole fraction. Also shown is the calculated direct - gap (Γ) transition efficiency, η_Γ, and the calculated nitrogen (N) related transition efficiency, η_N (solid lines). Note that the nitrogen-related efficiency is higher than the direct-gap efficiency in the indirect bandgap ($x > 50$ %) regime (after Campbell *et al*., 1974).

- ***The efficiency of the N-doped LEDs is strongly enhanced over the entire composition range compared with the GaAsP LEDs without N doping.***

- ***GaAsP LED efficiency decreases by more than 2 orders of magnitude in the composition range x= 40~60% due to the **direct-indirect crossover** occurring in GaAsP and the **increasing dislocation density** occurring at higher P mole fractions. → **Not suitable for high power LEDs***

GaAsP

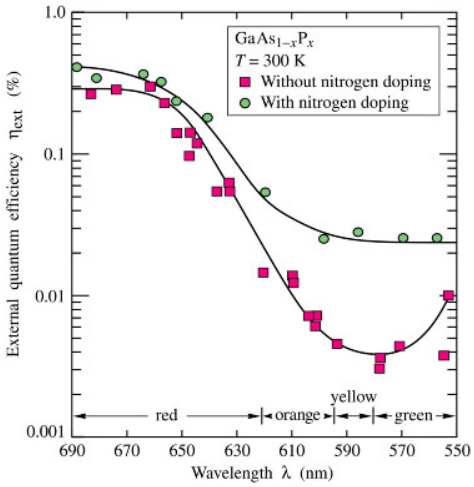


Fig. 7.4. External quantum efficiency versus emission wavelength in undoped and nitrogen-doped $GaAs_{1-x}P_x$ (after Groves *et al.*, 1978a and 1978b).

- ***GaAsP and GaAsP:N is suitable for low-brightness applications.***

GaAsP vs. GaAsP:N

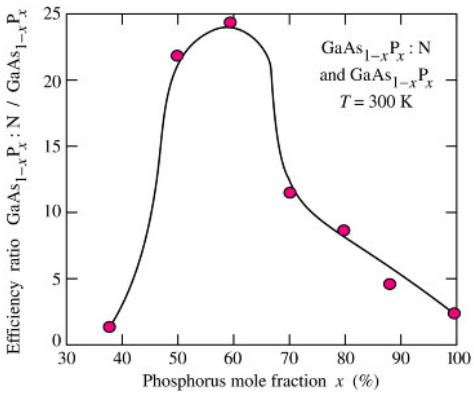


Fig. 7.5. Efficiency ratio between nitrogen-doped and undoped $GaAs_{1-x}P_x$ at 300 K (after Groves *et al.*, 1978a and 1978b).

- ***N-doped GaAsP devices have a higher efficiency over the entire composition range.***
- ***The brightness of LEDs based on isoelectronic impurity transitions is limited by the finite solubility of nitrogen.***

The AlGaAs/GaAs material system

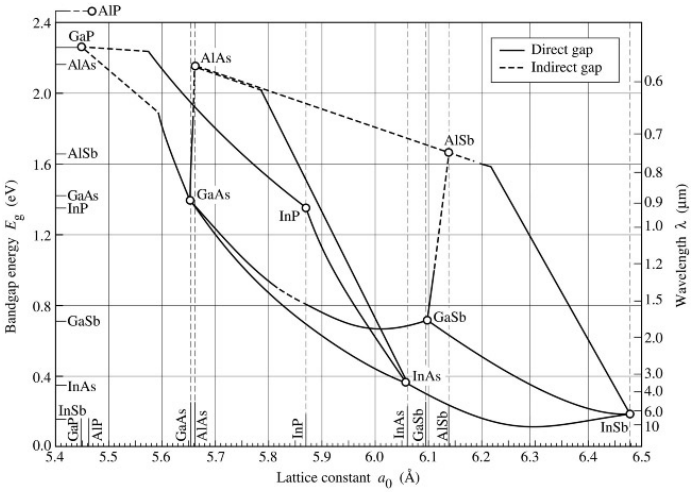


Fig. 7.6. Bandgap energy and lattice constant of various III-V semiconductors at room temperature (adopted from Tien, 1988).

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

AlGaAs/GaAs

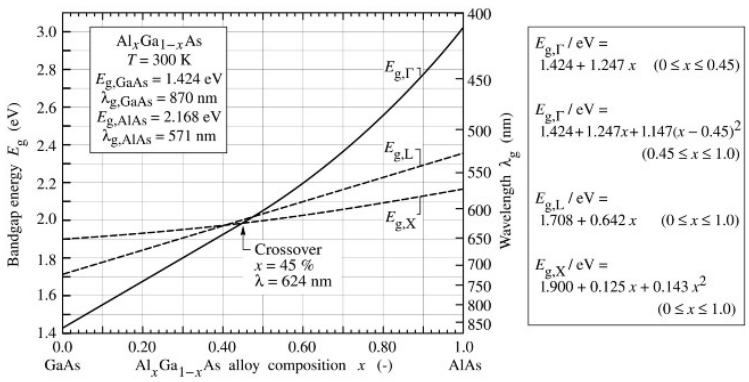


Fig. 7.7. Bandgap energy and emission wavelength of AlGaAs at room temperature. E_Γ denotes the direct gap at the Γ point and E_L and E_X denote the indirect gap at the L and X point of the Brillouin zone, respectively (adopted from Casey and Panish, 1978).

- ***AlGaAs/GaAs has a direct-indirect crossover at a wavelength of 621 nm.***

- ***The AlGaAs material system is suited for high-brightness visible-spectrum LEDs emitting in the red wavelength range.***

AlGaAs/GaAs

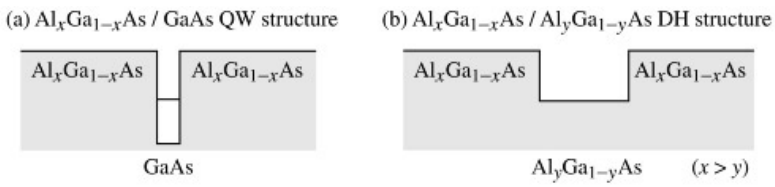


Fig. 7.8. Band diagrams of AlGaAs/GaAs structures suited for light emission in the red part of the visible spectrum. (a) AlGaAs/GaAs quantum well (QW) structure with thin GaAs well. (b) AlGaAs/AlGaAs double heterostructure (DH) with AlGaAs active region.

- ***The AlGaAs/GaAs system is suited for IR and red high-power LEDs.***
- ***AlGaAs DH-TS LEDs***
- ***The reliability of AlGaAs devices is lower than that of AlGaInP devices. High-Al-content AlGaAs layers are subjected to oxidation and corrosion, thereby lowering the device lifetime. Hydrolysis.***

The AlGaInP/GaAs material system

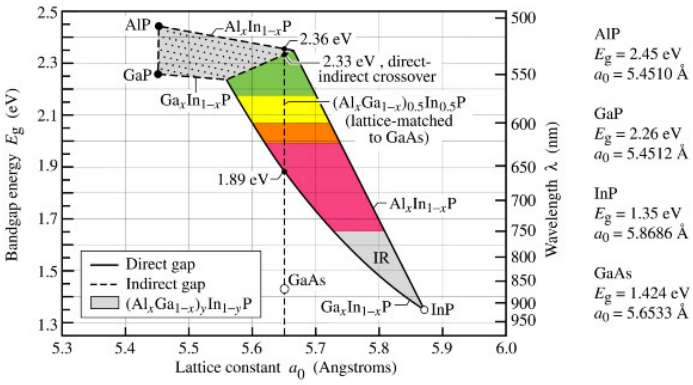


Fig. 7.9. Bandgap energy and corresponding wavelength versus lattice constant of $(Al_xGa_{1-x})_yIn_{1-y}P$ at 300K. The dashed vertical line shows $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ lattice matched to GaAs (adopted from Chen *et al.* 1997).

- ***High-brightness system for red, orange, amber, and yellow LEDs***
- ***Since Al (1.82Å) and Ga (1.81Å) have very similar atomic radii, the material $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is lattice matched to GaAs.***

AlGaInP/GaAs

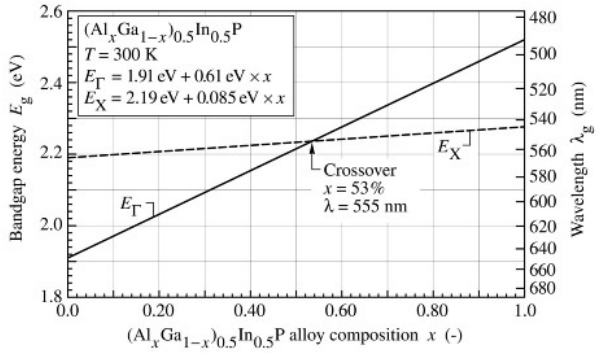


Fig. 7.10. Bandgap energy and emission wavelength of the unordered AlGaInP quaternary semiconductor lattice-matched to GaAs at room temperature. E_Γ denotes the direct gap at the Γ point and E_X denotes the indirect gap at the X point of the Brillouin zone (adopted from Prins *et al.*, 1995 and Kish and Fletcher, 1997).

- ***$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is a direct-gap semiconductor for Al mole fractions $x < 0.53$***
- ***Direct-indirect crossover at a wavelength of 555 nm***

AlGaInP/GaAs

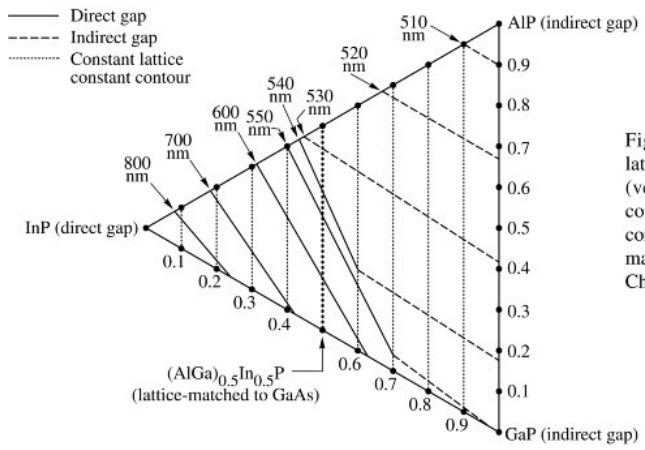
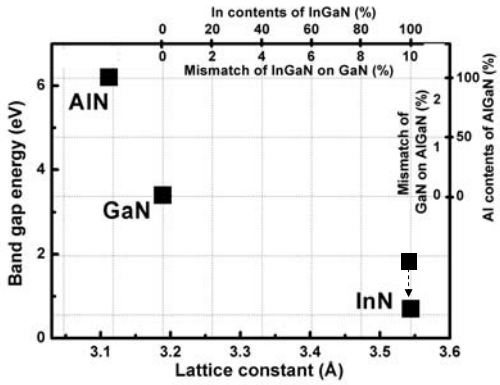


Fig. 7.11. Constant lattice constant conturs (vertical lines) and constant emission line conturs of the AlGaInP materials system (after Chen *et al.*, 1997).

- ***The AlGaInP/GaAs system is suited for red, orange, and amber high-power LEDs. Efficiency decreases for yellow, yellow-green, and green LEDs.***

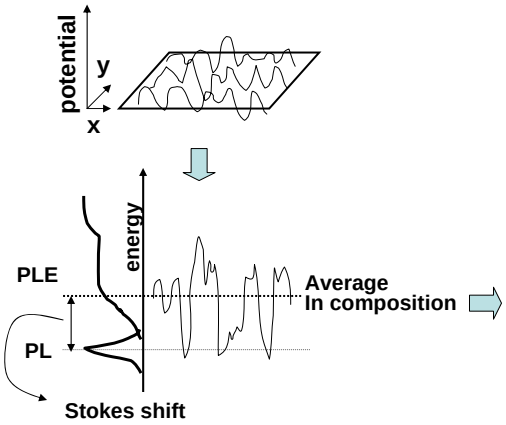
III-V Nitride material system



"Growth of Nitride Quantum Dots"
by H. J. Kim, S. -Y. Kwon, and E. Yoon,
in "Optoelectronic Devices: III Nitride ",
edited by M. Henini and M. Razeghi
(Elsevier), 2004

- ***High radiative efficiency despite the presence of a very high concentration of threading dislocations due to large lattice mismatch in InGaN/GaN epitaxial films.***
- ***The InGaN material system is suited for UV, blue, cyan, and green high-power LEDs. Efficiency decreases in green spectral range.***
- ***In theory, InGaN is suitable for covering from UV to IR ranges.***

InGaN/GaN *(Carrier localization due to potential fluctuations)*



- **In compositional fluctuation**
- **Interface roughness**
- **Structural defects**

⇩

Potential fluctuation

⇩

Localized state

- **Stokes shift between PL peak position and PLE band edge**
- **High thermal activation energy**

- ***Fluctuations of the In content in InGaN causes carriers to be localized in potential minima, thus preventing carriers from reaching dislocations.***
  → High radiative efficiency

Progress in luminous efficiency of LEDs

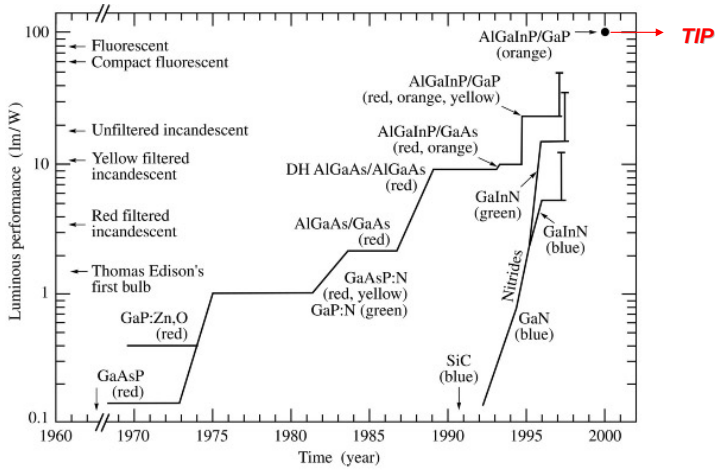


Fig. 7.13. Luminous performance of visible LEDs versus time. Also shown is the luminous performance to other light sources (adopted from Craford, 1997, 1999, updated 2000).

- ***Strong progress over last decades***

Comparison across spectrum

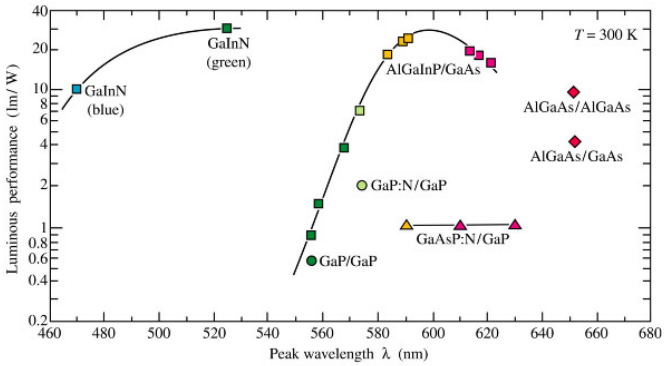


Fig. 7.14. Overview of luminous performance of visible LEDs made from the phosphide, arsenide, and nitride material system (adopted from United Epitaxy Corporation, 1999; updated 2000).

- ***Yellow (590nm) and orange (605nm) AlGaInP and green (525nm) InGaN LEDs are excellent choices for high luminous efficiency devices.***

- ***Lack of LEDs at 550 nm is sometimes referred to as the "green gap".***
  - Maximum eye sensitivity occurs in the green at 555 nm.

Comparison: Light bulb vs. LED

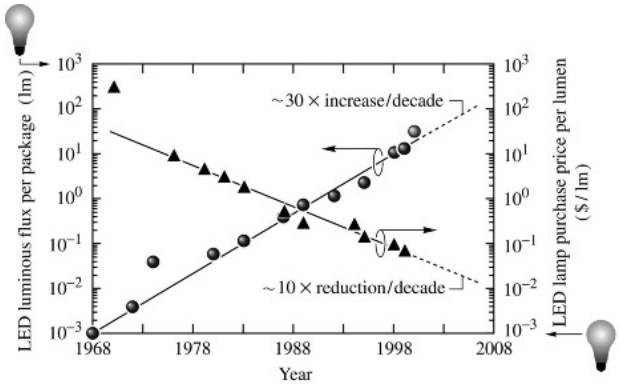


Fig. 7.15. LED luminous flux per package and LED lamp purchase price per lumen versus year. Also shown are the values for a 60 W incandescent tungsten-filament light bulb with a luminous performance of about 17 lm/W and a luminous flux of 1000 lm with an approximate price of US $ 1.00 (after Krames *et al.*, 2000).

- ***The luminous flux per LED package has increased by about four orders of magnitude over a period of 30 years.***
- ***cost of ownership: less electrical power consumption over time***

Optical characteristics of high-brightness LEDs

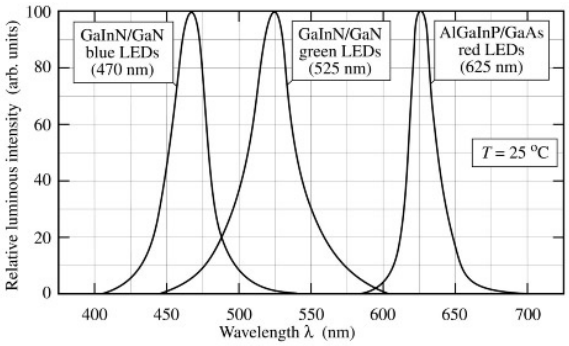


Fig. 7.16. Typical emission spectrum of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LEDs at room temperature (after Toyoda Gosei Corp., 2000).

- ***Note that green emitters shows broadest emission line.***
  - ***alloy broadening: random fluctuation of the chemical composition***
  - ***broadening greater than 1.8 kT***
- ***Green emitters need further development.***

Light output power vs. current

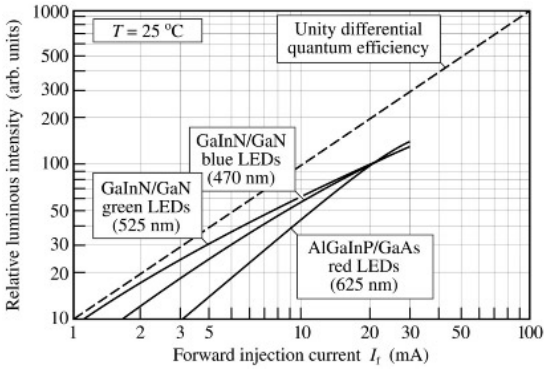


Fig. 7.17. Typical light output power versus injection current of GaInN / GaN blue, GaInN / GaN green, and AlGaInP / GaAs red LEDs at room temperature (adopted from Toyoda Gosei Corp., 2000).

- ***AlGaInP is more mature than InGaN.***

- ***The green LED has a large deviation from the unit differential quantum efficiency slope due to the lower maturity of the InGaN material system, especially with high concentration of In.***

Temperature dependence

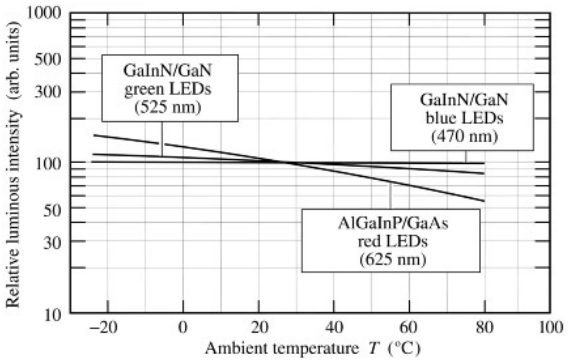


Fig. 7.18. Typical light output intensity of GaInN / GaN blue, GaInN / GaN green, and AlGaInP / GaAs red LEDs versus ambient temperature (after Toyoda Gosei Corp., 2000).

- ***III-V nitride diodes have a much weaker temperature dependence than the AlGaInP LED due to***

1) The active-to-confinement barriers are higher in III-V nitride system.
2) Carrier localization in InGaN
3) AlGaInP has a direct-indirect transition of the bandgap at about 555nm.
- Increasing population of the indirect valleys at elevated temperature

Electrical characteristics of high-brightness LEDs

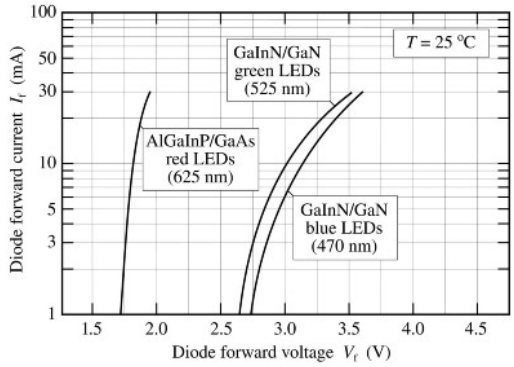


Fig. 7.19. Typical forward current - voltage (I-V) characteristic of GaInN / GaN blue, GaInN / GaN green, and AlGaInP / GaAs red LEDs at room temperature (after Toyoda Gosei Corporation, 2000).

- ***AlGaInP is more mature than InGaN.***

- ***The larger resistance in InGaN LEDs due to,***
  1) Lateral resistance in the n-type buffer layer grown on sapphire substrate
  2) Strong polarization effects in nitride system
  3) lower p-type conductivity in the cladding layer
  4) higher p-type contact resistance

Forward voltage vs. temperature

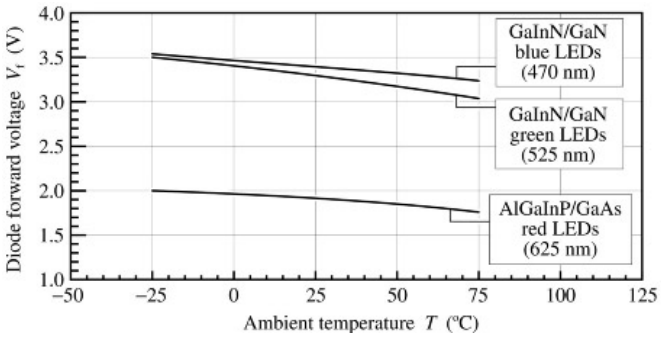


Fig. 7.20. Typical diode forward voltage at a current of 30 mA of GaInN / GaN blue, GaInN / GaN green, and AlGaInP / GaAs red LEDs versus temperature (after Toyoda Gosei Corp., 2000).

- ***Forward voltage decreases with temperature due to the decrease of the bandgap energy.***

- ***In InGaN diodes, the lower forward voltage is due to the decrease in series resistance occurring at high temperatures. This resistance decrease is due to the higher acceptor activation occurring at elevated temperatures and the resulting higher conductivity of the p-type GaN and InGaN layers.***