Roadblocks to High Efficiency Solid-State Lighting: Bridging the “Green-Yellow Gap”

M. H. Crawford, D. D. Koleske, S. R. Lee, J. Y. Tsao, A. M. Armstrong, G. T. Wang, A. J. Fischer, J. J. Wierer, M. E. Coltrin, and L. E. Shea-Rohwer

Sandia National Laboratories, Albuquerque, NM

Acknowledgements: DOE Office of Basic Energy Sciences
Laboratory Directed Research and Development Program
National Institute of Nanoengineering

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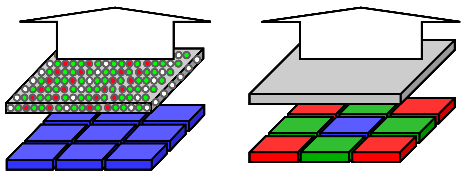
OUTLINE

Roadblocks to Ultra-high Efficiency Solid-State Lighting: the "Green-Yellow Gap"



I. Introduction

A. Solid-State White lighting Approaches

B. Present performance limitations and predicted future performance

C. InGaN materials challenges at long wavelengths

II. Research Strategies for Overcoming the Gap

A. Polarization mitigation strategies

B. Strain management approaches

C. Nanostructured materials and devices

III. Conclusions

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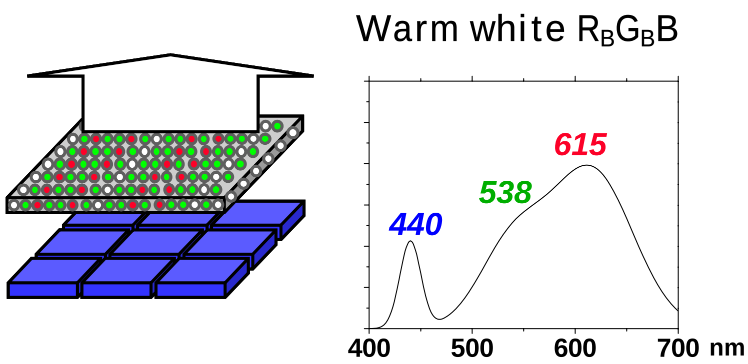
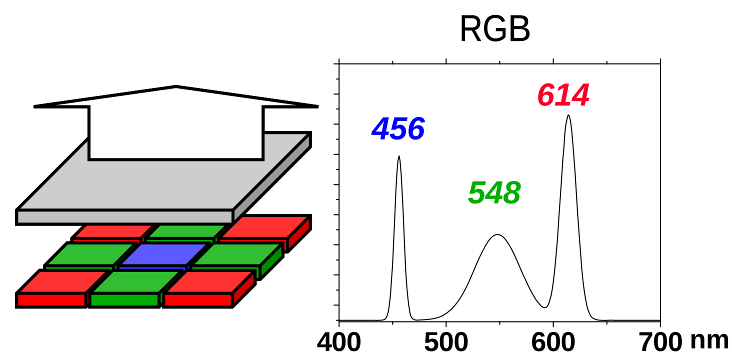
Solid-State White Lighting Approaches

<u>Approaches:</u>

Phosphor-converted



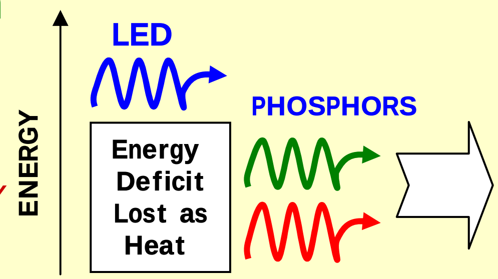
Multi-chip (all LED)



<u>Advantages/limitations:</u>

Phosphor-converted

- Requires high performance LED only in blue region
- Simpler operation
- Inherent losses *(pump absorption, phosphor efficiency Stokes' loss)*
- Requires high performance green and red phosphors (suitable for blue pump)



Multi-chip (all LED)

- Direct light emission from LEDs → <u>highest efficiencies</u>
- Greater automation and color control possibilities ***("smart lighting")***
- Requires high performance from LEDs <u>across the spectrum</u>
- More complex operation (drive circuitry, disparate LED degradation)

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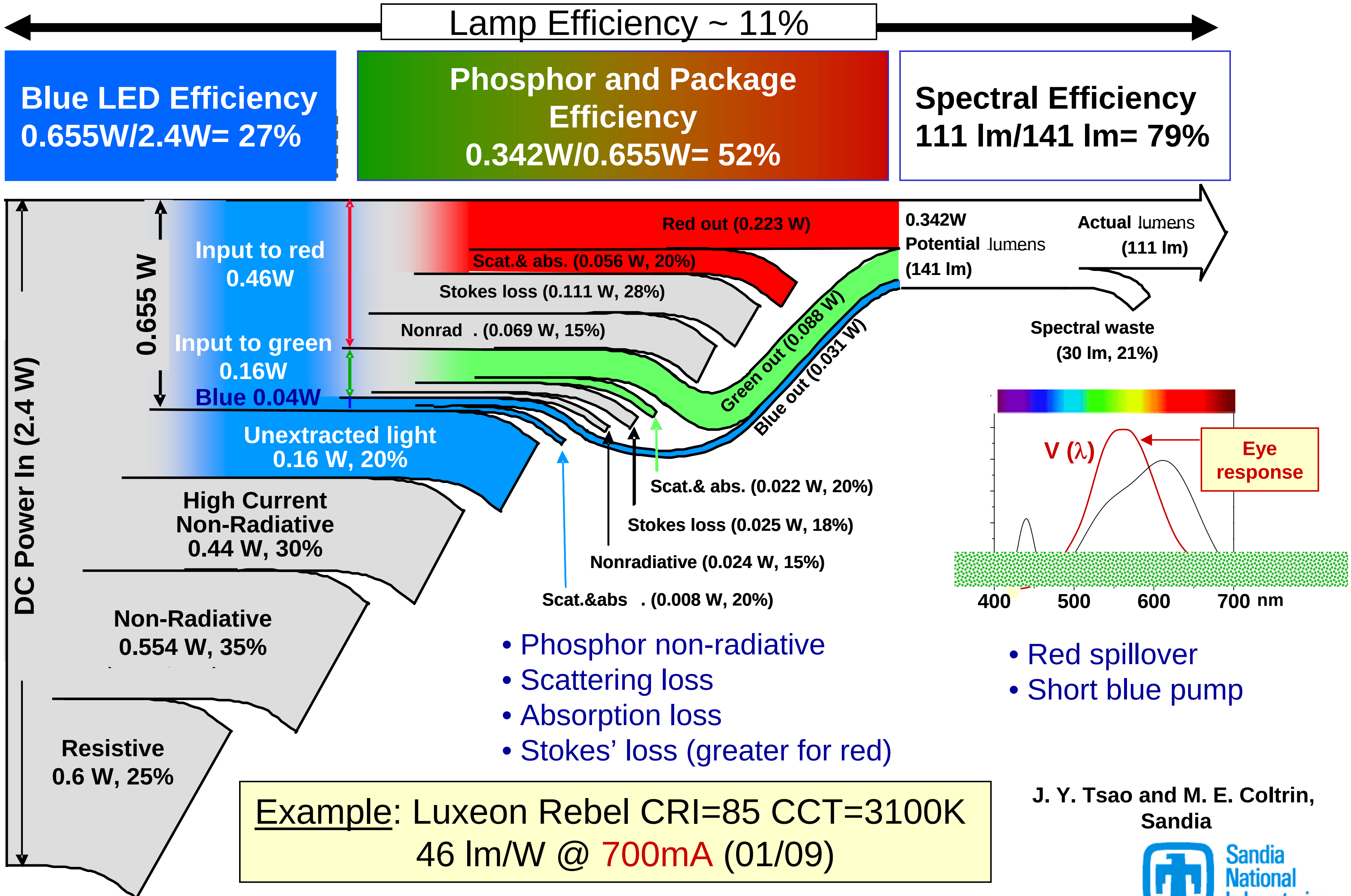
Phosphor-converted Warm White LED Power Flow



- Phosphor non-radiative
- Scattering loss
- Absorption loss
- Stokes' loss (greater for red)

- Red spillover
- Short blue pump

Example: Luxeon Rebel CRI=85 CCT=3100K
46 lm/W @ 700mA (01/09)

J. Y. Tsao and M. E. Coltrin,
Sandia

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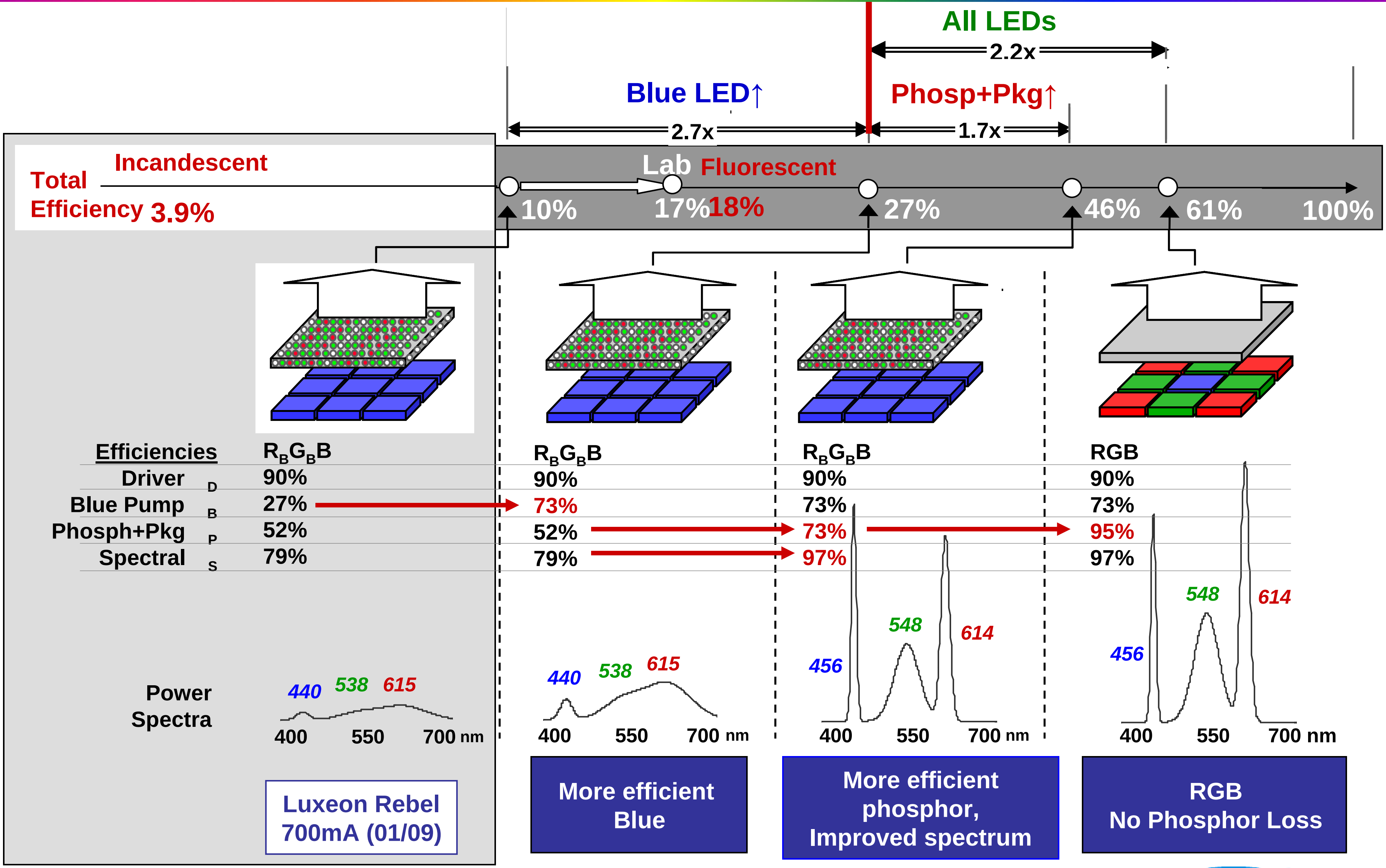
Future White Lighting Performance



J. Y. Tsao, Sandia

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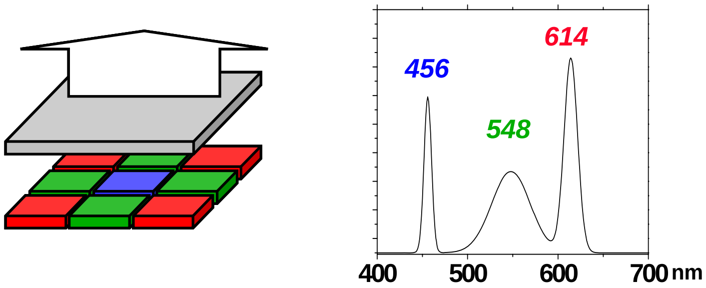
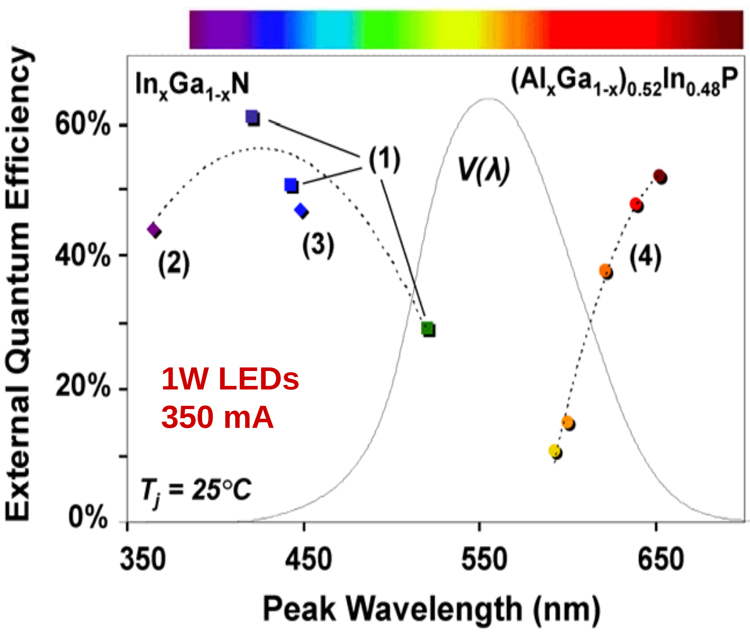
RGB LED performance limitations

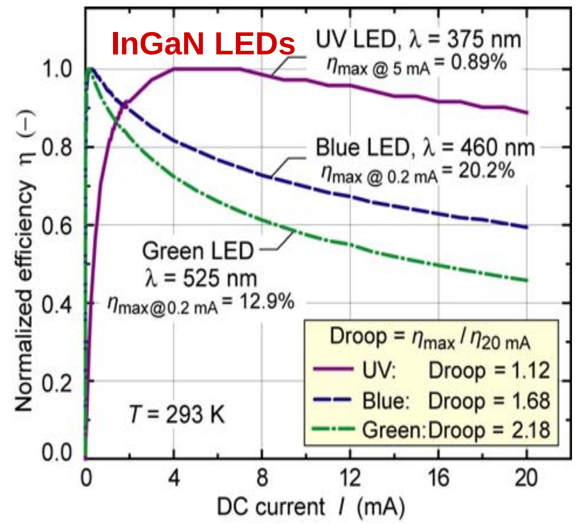
Efficiency vs. Wavelength





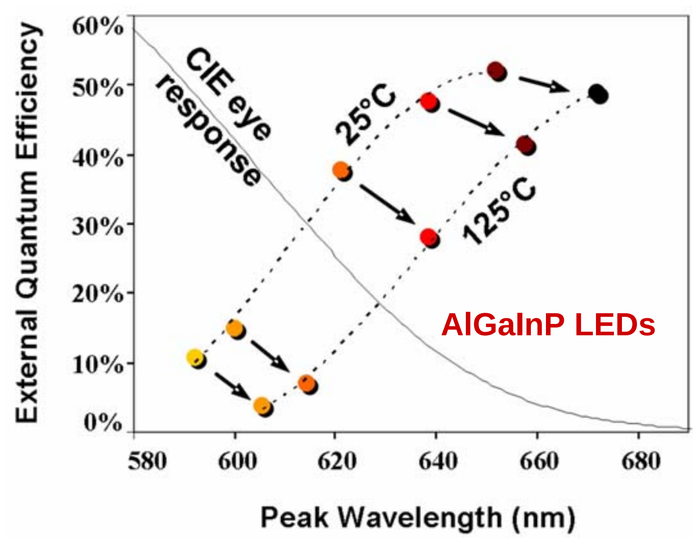
Krames et al., Philips Lumileds

Blue/Green limitations→ IQE and Efficiency Droop



Small area devices
E. F. Schubert

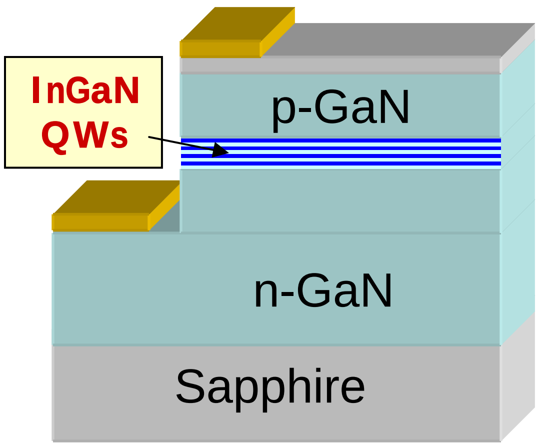
AlGaInP short red limitations→ Temperature



Philips Lumileds

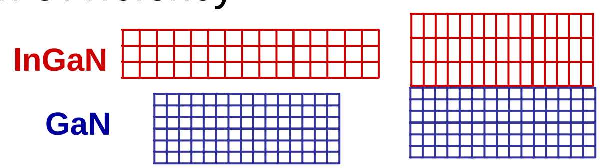
Materials Challenges of InGaN LEDs

The green-yellow efficiency loss is inextricably linked with the evolution of InGaN materials properties with increasing indium composition of the alloy

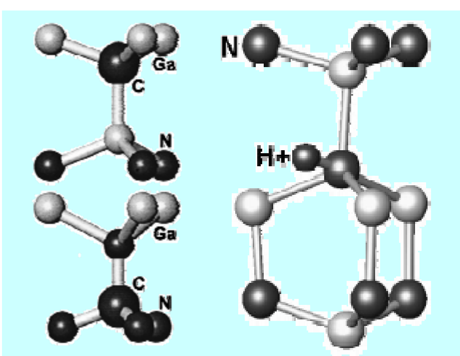


Major materials issues related to high indium alloys:

- Thermal instability→ require lower growth temperatures
  → potential for increased impurities,defects, 3D growth
- Lattice-mismatch strain when grown on GaN epilayers
  → reduced indium incorporation efficiency
  → compositional instabilities
  → enhanced defect formation
  → piezoelectric polarization

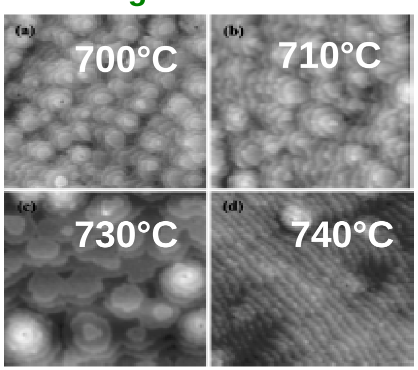


Impurities and point defects



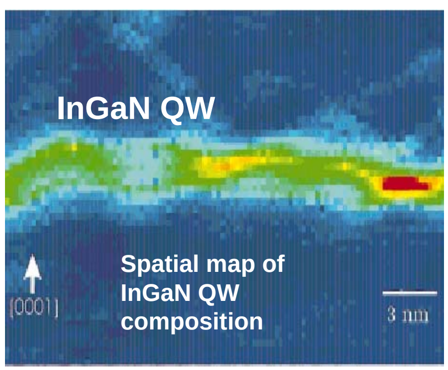
Wright et al., JAP 2002

3D growth modes



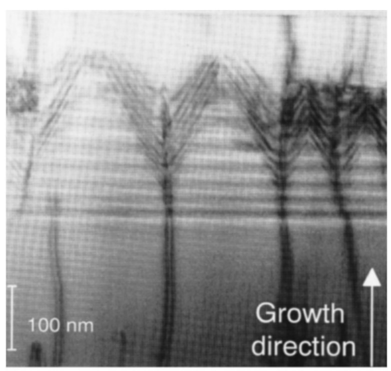
Oliver et al., JAP 2005

Compositional instabilities



Gerthsen, et al., Phys. Stat. Sol. A (2000)

"V- defects"



Scholz et al. Mat Sci & Eng B (1997)

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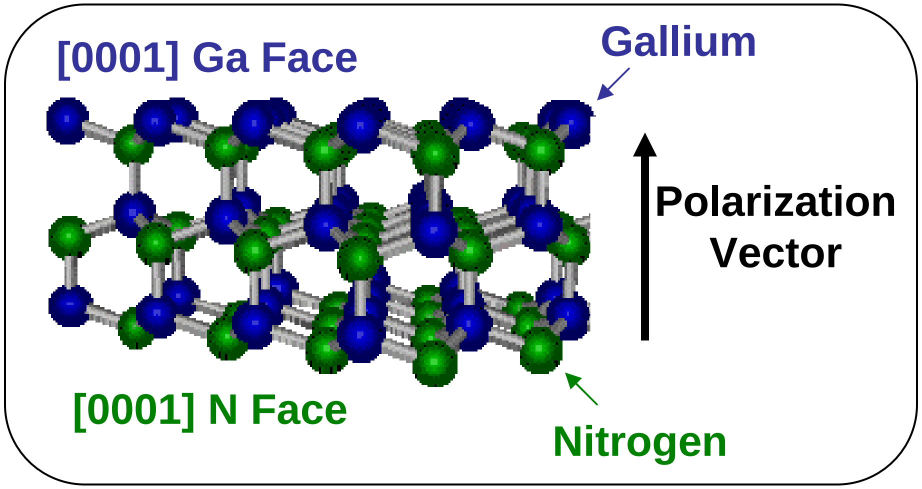
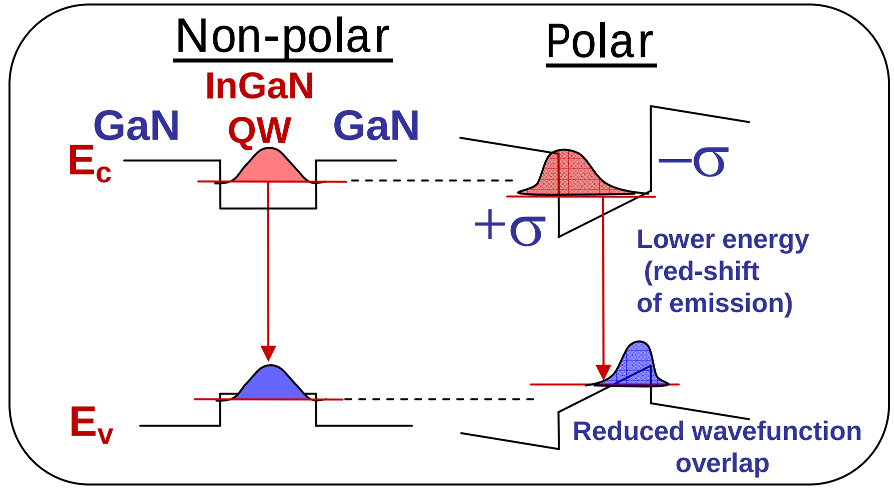
Polarization effects in InGaN LEDs

Hexagonal (Wurzite) GaN crystal structure



Effect on InGaN quantum well



- **Dominated by piezoelectric (strain-driven) polarization for InGaN QWs on GaN**
- **Internal E-fields cause reduced electron-hole overlap → reduced radiative efficiency**
- **E-fields shift emission to <u>longer wavelengths</u>; → blue-shifts with current**
- **Significant band-bending creates barriers to carrier flow and/or reduced carrier confinement**

Role in the "green-yellow gap"?

Full LED structure

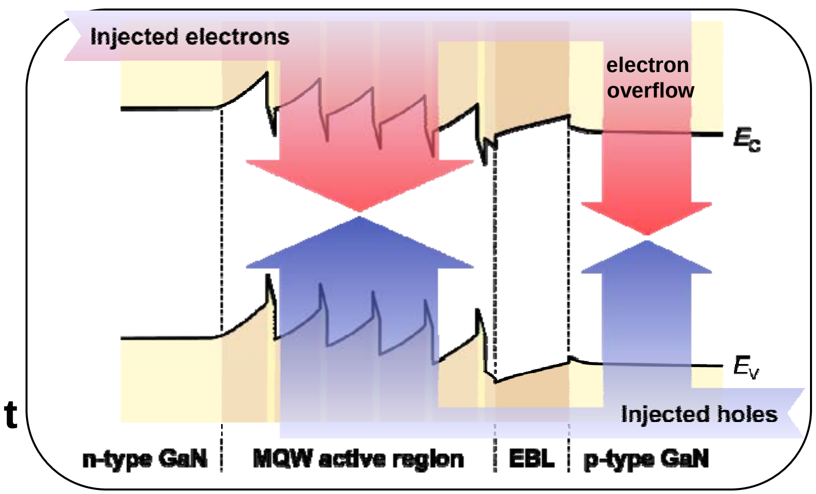


Figure: E. F. Schubert (RPI)

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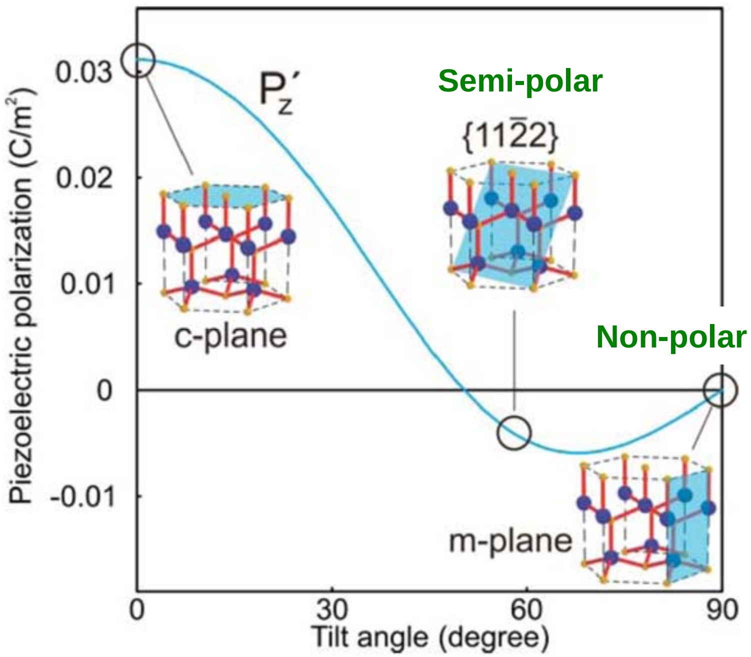
Non-polar and Semi-polar Nitrides

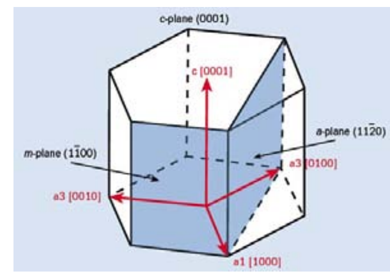
Piezoelectric polarization vs. crystal orientation



Challenges and recent advances:

- **Poor material quality**: high stacking fault densities in non-polar (e.g., *a*-plane GaN on *r*-plane sapphire)

→**Breakthrough:**
high quality HVPE
c-plane GaN substrates;
Sectioned into alternative
orientations



- **Indium incorporation:** higher compositions needed than for c-plane (no red-shift); evidence of 2-3X lower incorporation on non-polar planes

→ **Semipolar:** (11-22), indium incorporation efficiency may be similar to c-plane

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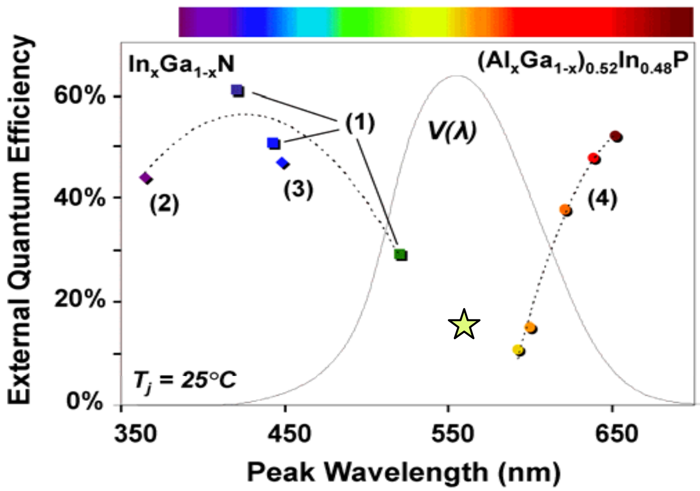
Non-Polar / Semi-polar LEDs and the Green-Yellow Gap

Highlights of nonpolar / semipolar LEDs:

- **Near-UV (402 nm) *m*-plane LED EQE~45%** (comparable to c-plane); blue (468 nm) EQE ~16.8%@ 20 mA
  Kim et al., PSS RRL, 2007 (UCSB)

- **Yellow (563 nm) Semipolar (11-22) LED**; 5.9mW@ 20 mA → reportedly most efficient LED at this λ (**EQE~13%**)
  Sato et al., Appl. Phys. Lett, 2008 (UCSB)



m-plane (non-polar) LED output vs. λ

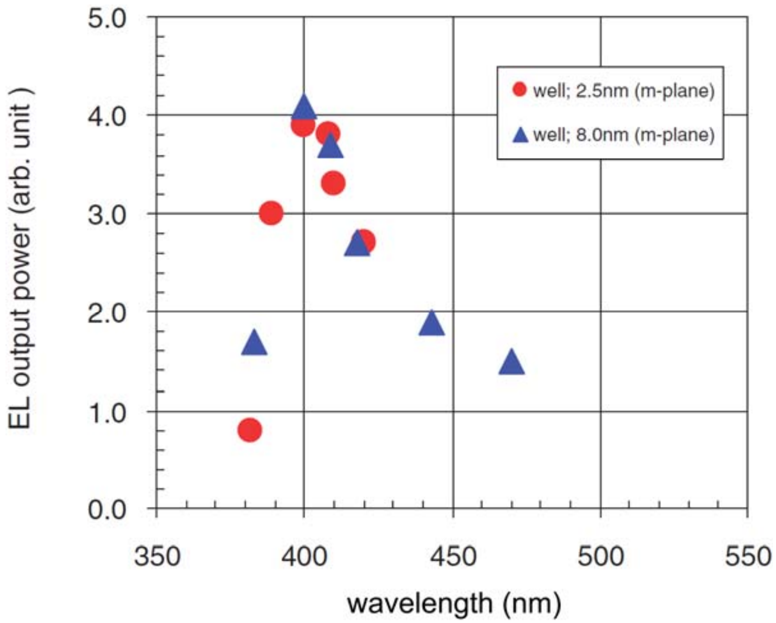


Figure: Yamada et al., Appl. Phys. Express, 2008

- **Study of *m*-plane LEDs as a function of emission wavelength**
- **Similar to *c*-plane LEDs, peak efficiency in near-UV / Violet; dropping at longer λ**

Efficiency loss toward green seen even in the *absence* of polarization

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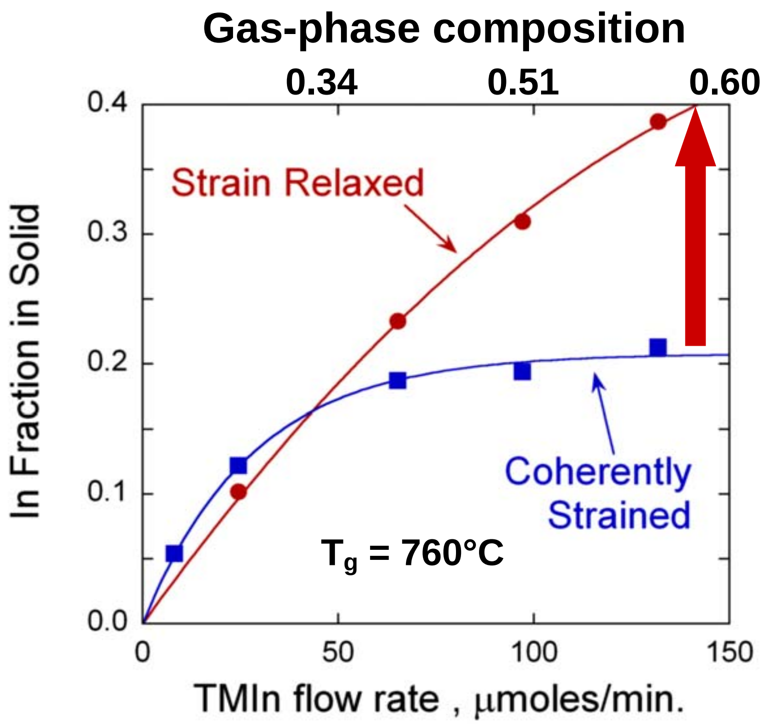
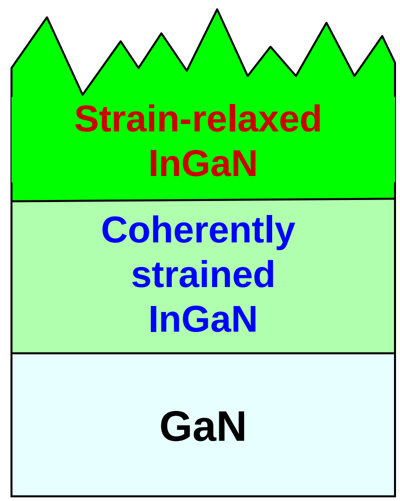
Additional Strain Effects in InGaN LEDs

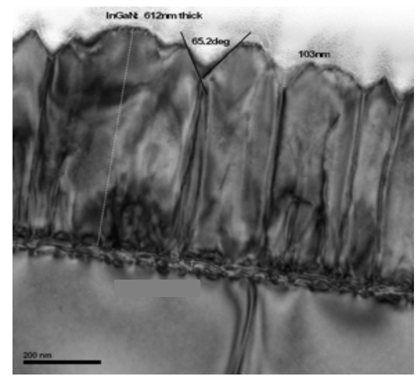
→ Strain limits indium incorporation, important for longer wavelengths



~100-nm-thick InGaN on GaN



TEM of partially-relaxed InGaN



→ unsuitable for devices

- Elimination of strain enables higher indium incorporation at a given growth condition
- Reduced strain may help to avoid lower growth temperatures and related detrimental effects (impurity/defect incorporation, 3D growth modes)

To enable long wavelength InGaN QW LEDs with reduced strain:

Possible to develop a *strain-relaxed InGaN substrate* with high crystalline quality and a smooth surface?

S. R. Lee and D. D. Koleske, Sandia

Related observations: Z. Liliental-Weber, et al., J. Electron. Mat. 30 (2001) 439. S. Pereira, et al., APL 80 (2002) 3913,; Shimizu, et al., JJAP 36 (1997) 3381.

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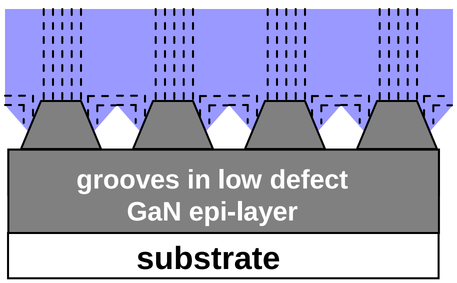
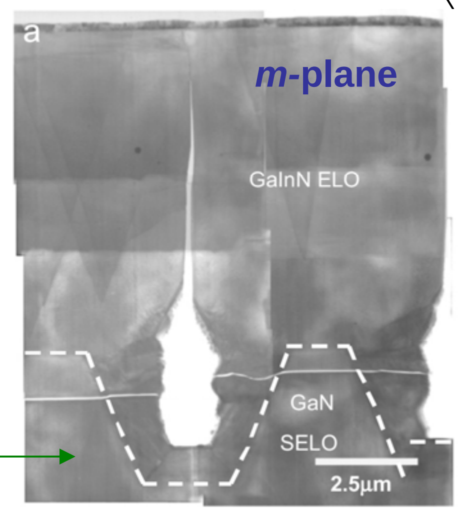
Emerging InGaN Template/Substrate Solutions

Strain-relaxed InGaN-on-GaN

InGaN overgrowth on Grooved GaN



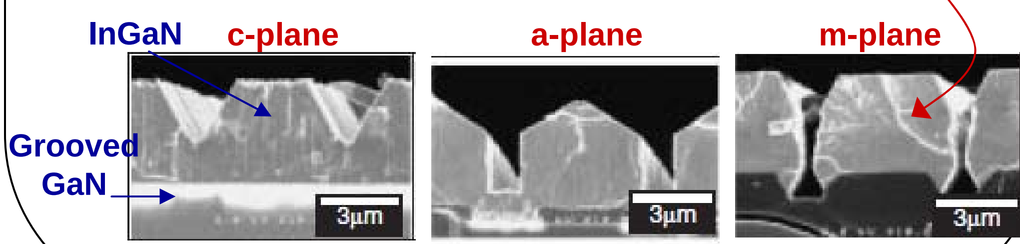


Starting template
m-plane GaN with grooves
etched along <0001>

→ strain-relaxed 7 µm thick $In_{0.07}Ga_{0.93}N$

→ < $1x10^{8}$ cm^{-2} threading dislocation density

→ Growth on *m*-plane key to planar InGaN



Alternative Approaches

InGaN growth on ZnO substrates

- Lattice match for $In_{0.18}Ga_{0.82}N$
- Challenge: ZnO requires lower growth temperatures (< 650°C); leads to inferior InGaN crystalline quality
- Progress: Non-polar ZnO, pulsed laser deposition

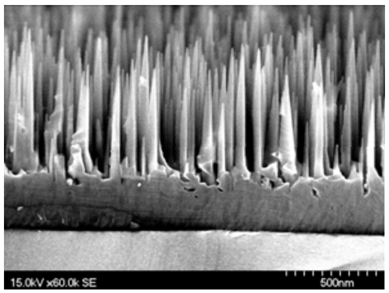
InGaN HVPE Substrates and LEDs

- High growth rate, low cost technique; yields high quality GaN templates
- InGaN significantly more challenging
- On-going development by TDI, Inc.
  → Next presentation (A. Syrkin)

Figures: Meijo University, Iwaya et al., J Crystal Growth, 2008; Senda et al., Japan. J. Appl. Phys, 2007

Nanostructured InGaN Materials

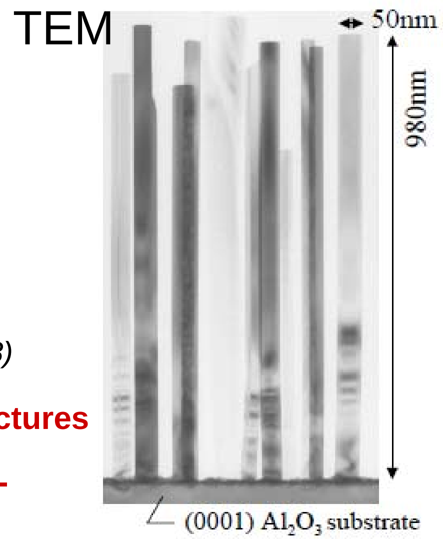
GaN nanowires (nanorods)



Li et al., Appl. Phys. Lett. (2008)

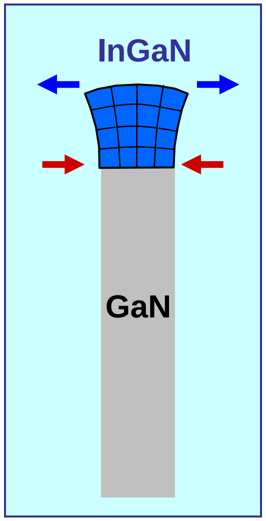
- **highly aligned " 1D" structures**
- **Self-assembly or directed-assembly approaches**

No threading defects

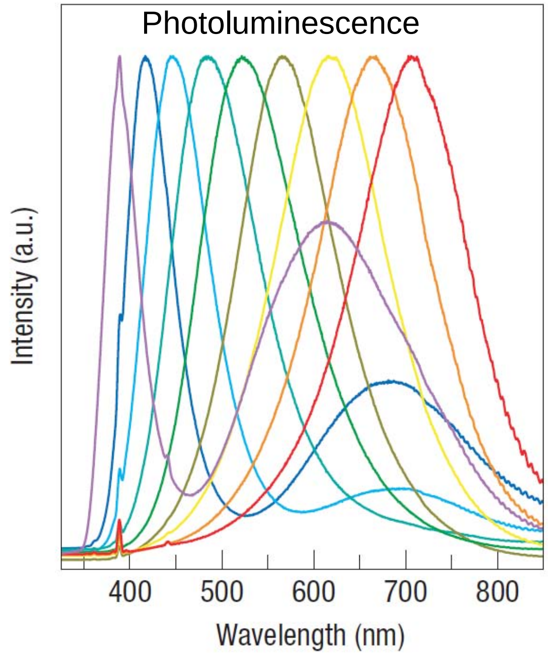


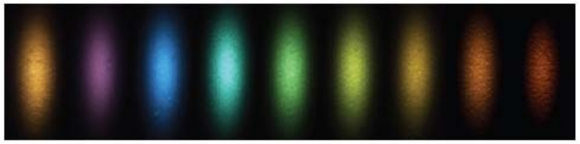
Kishino et al., Proc. SPIE 2007

Strain Accomodation



Broad range of emission λ





Growth by Halide Chemical Vapor Deposition

Kuykendall et al., Nat Mat. 2007

- Compatible with a wide range of substrates (including Si)
  → lower cost, integration possibilities
- Can be grown with no threading defects
  → higher radiative efficiency
- Lateral structure allows strain accommodation
  → greater indium composition/color range possible
- 1D geometry may provide light extraction benefits
  → higher external quantum efficiency

☆ Potential for solving red problem also?

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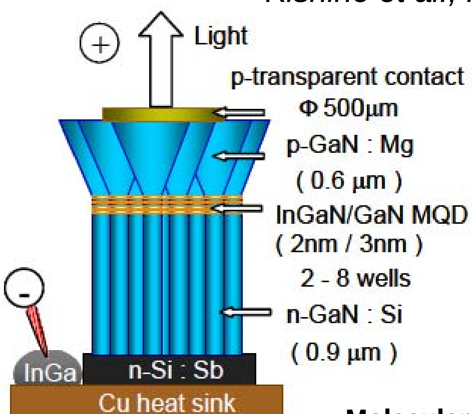
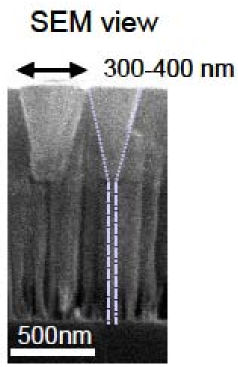
Nanostructured InGaN LEDs

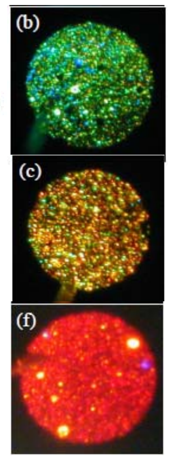
Axial LED Geometries

Self-assembled Nanorods, p- GaN Planarization

Kishino et al., Proc. SPIE 2007







Molecular Beam Epitaxy

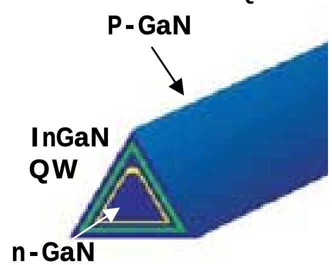
→Indium composition variations between nanorods; leads to broad spectra

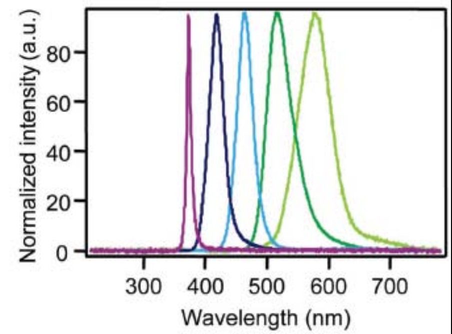
Also, Spin-on-glass planarization *Kim et al., Nanolett. 2004*

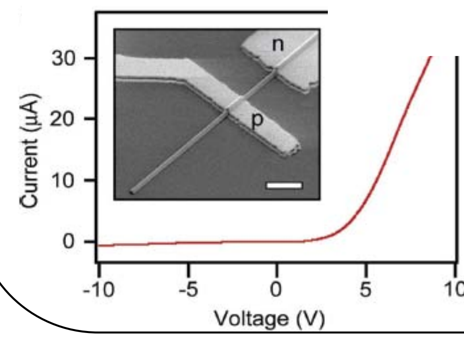
Radial (Core-Shell) LED Geometries

n-GaN/InGaN/p-GaN core/shell Nanowires

Qian et al., Nat Mat. 2005





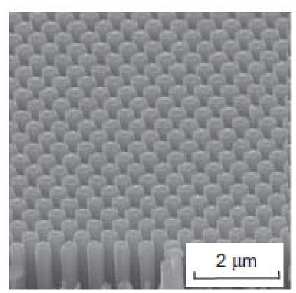


Single NW: EQE= 3.9% @ 540 nm

Outstanding Issues:

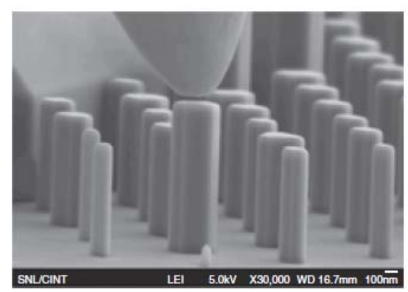
- NW uniformity for InGaN composition and color control
  - → Selective area growth
- Device architectures

RF MBE



Kishino et al., JCG 2009

MOCVD



Hersee et al., Electron. Lett. 2009

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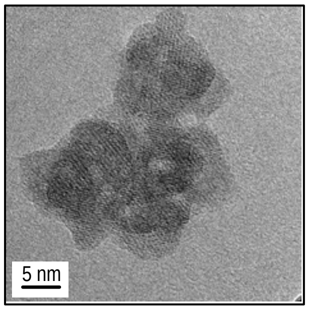
Avenues for Green Phosphor Advances

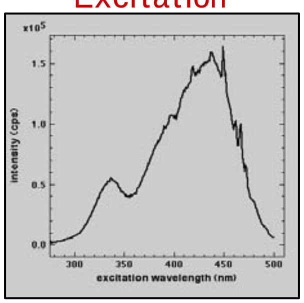
Nanostructured YAG:Ce

→ Reduced scattering losses

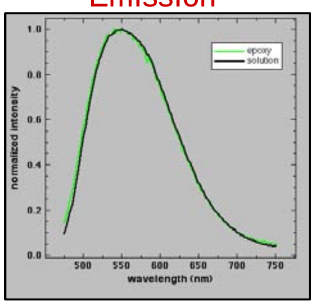


Dispersed nanoparticles facilitates encapsulation

Excitation



Emission

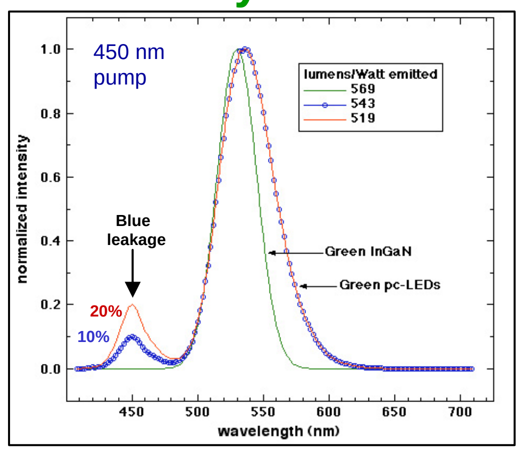


- **Bulk optical properties preserved**
- **Quantum Yield ~45%→ promising**

Alternatives to YAG:Ce Phosphor

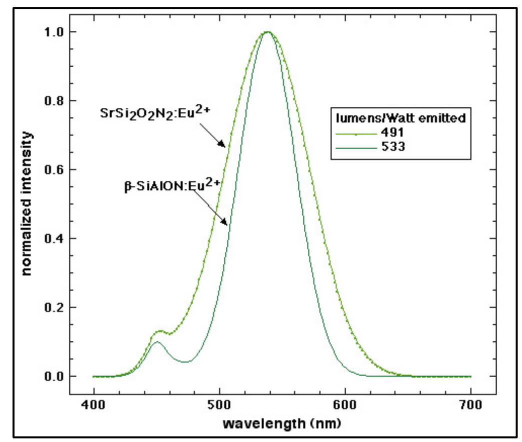
LED or Phosphor	Luminous Efficiency of Radiation
Green LED: FWHM 35 nm, λ_{pk}=535 nm	**569 lm/W_{em}**
Commercial YAG:Ce	**394 lm/W_{em}**
$SrGa_2S_4:Eu^{2+}$	**564 lm/W_{em}**
$SrSi_2O_2N_2:Eu^{2+}$, FWHM 78 nm, λ_{pk}=538 nm	**506 lm/W_{em}**
β-SiAlON:Eu^{2+}, FWHM 55 nm, λ_{pk}=538 nm	**556 lm/W_{em}**

Ternary Sulfides



- **PC-LEDs using $SrGa_2S_4:Eu^{2+}$**
  - **→ QY~ 80%**
  - **→ Moisture sensitivity**
  - **→ Strong thermal quenching**

Covalent Nitrides



- **PC-LEDs using nitride phosphors**
  - **→QY~90%, small Stokes' shift**
  - **→Good stability**
  - **→ Manufacturing challenges**

M. Nyman, Chemistry of Materials, (2009) (Sandia)

strontium thiogallate pc-LED:
R. Mueller-Mach et al., IEEE JSTQE 2002

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Conclusions

- Focus on blue LED efficiency improvements is yielding impressive performance advances for phosphor-converted white LEDs

- Multi-chip white LEDs hold tremendous promise for achieving ultra-efficient solid-state white lighting, but must overcome the green-yellow gap in LED efficiency

- Emerging approaches for InGaN LEDs in the green-yellow gap:

Semipolar LEDs (up to 563 nm yellow)

→ reduced polarization and sufficient indium incorporation

Strain relaxed InGaN templates

→ extension of lateral overgrowth approaches to non-polar InGaN for strain relief in concert with defect reduction and planar surfaces

Nanostructured LEDs

→ Advantages in strain accommodation and defect reduction, axial and radial LED geometries for green, yellow and red being explored