SSLS EFRC

SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

SAND2010-6326P

Science Challenges for Ultra-Efficient Solid-State Lighting

Mary H. Crawford

Sandia National Laboratories

Acknowledgements: *J. Y. Tsao, L. E. Shea Rohwer, D. D. Koleske, S. R. Lee, W. W. Chow, G. T. Wang, Q. Li, A. M. Armstrong, M. E. Coltrin, J. A. Simmons, Sandia National Labs*
E. F. Schubert, Rensselaer Polytechnic Institute

Funding: *SSLS EFRC, Department of Energy, Office of Basic Energy Sciences*

Sandia is a multiprogram laboratory operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Office of Basic Energy Sciences • Serving the Present, Shaping the Future •

Sandia National Laboratories

Outline

I. Introduction to Solid-State Lighting
   A. Projected benefits of solid-state lighting
   B. Comparison of white lighting technologies
   C. Three "Grand Challenges" for ultra-efficient SSL (focus on the LED chip level)

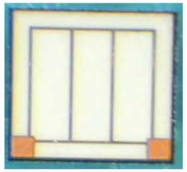
II. LED efficiency droop at high currents
   A. Potential nonradiative mechanisms
   B. Approaches for efficiency droop mitigation

III. The search for an efficient, narrow-band red emitter
   A. Limitations of present technology
   B. Direct-emitter challenges and potential solutions
   C. Novel down-conversion materials

IV. Bridging the "green-yellow gap" in LED efficiency
   A. The potential for "smart lighting"
   B. New directions for long wavelength InGaN emitters

V. Conclusions

LED Chip

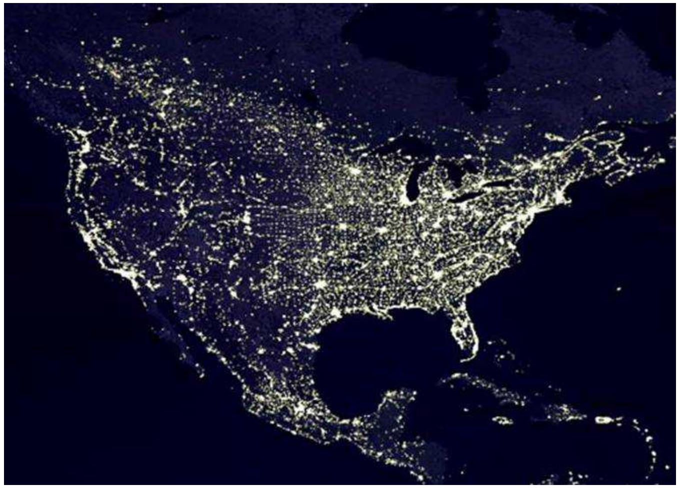


Packaged LED

Luminaires

Figures from DOE EERE SSL MYPP March 2010

Motivation for a lighting revolution



- ~22% of electricity consumption is for general illumination
- Lighting is one of the most ***inefficient*** energy technologies in buildings → opportunity!
- Achieving 50% efficient lighting would have tremendous global impact:
  - ➢ decrease electricity consumed by lighting by > 50%
  - ➢ decrease total electricity consumption by 10%

Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	20-25%
Incandescent:	~3-5%

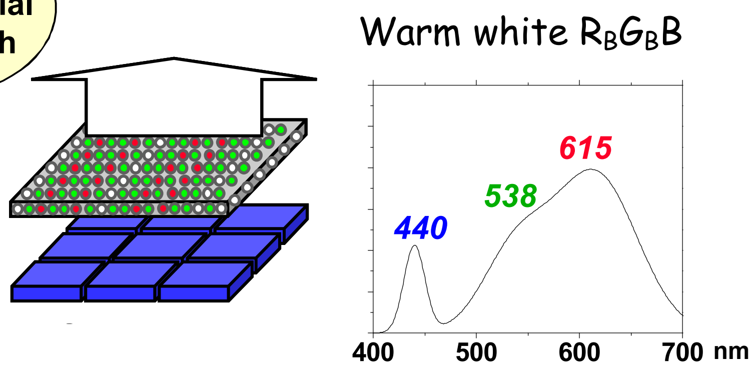
US DOE target: 50%
"Ultra-efficient" SSL: > 50%

Projected Year 2025 Savings	US	World
Electricity used (TW-hr)	620/year	~2,000/year
$ spent on Electricity	42B/year	~150B/year
Electricity generating capacity (GW)	75	~250
Carbon emissions (Mtons/year)	100	~350

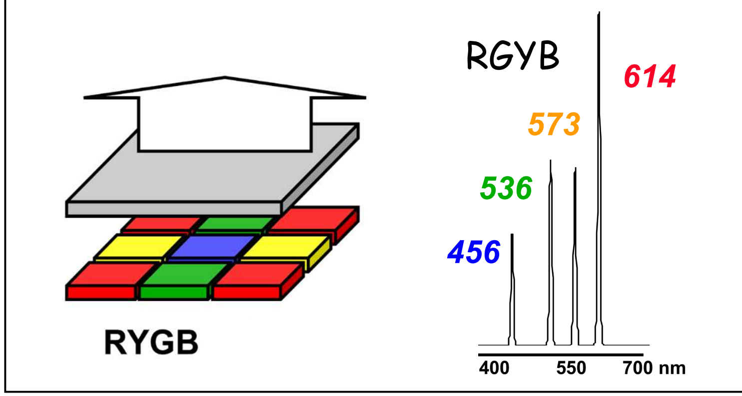
Architectures for LED-based White Lighting

Dominant Commercial Approach

Phosphor-converted

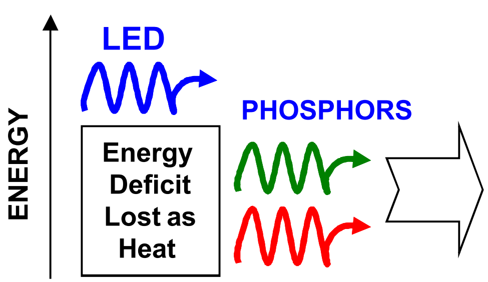


Multi-chip (all LED)



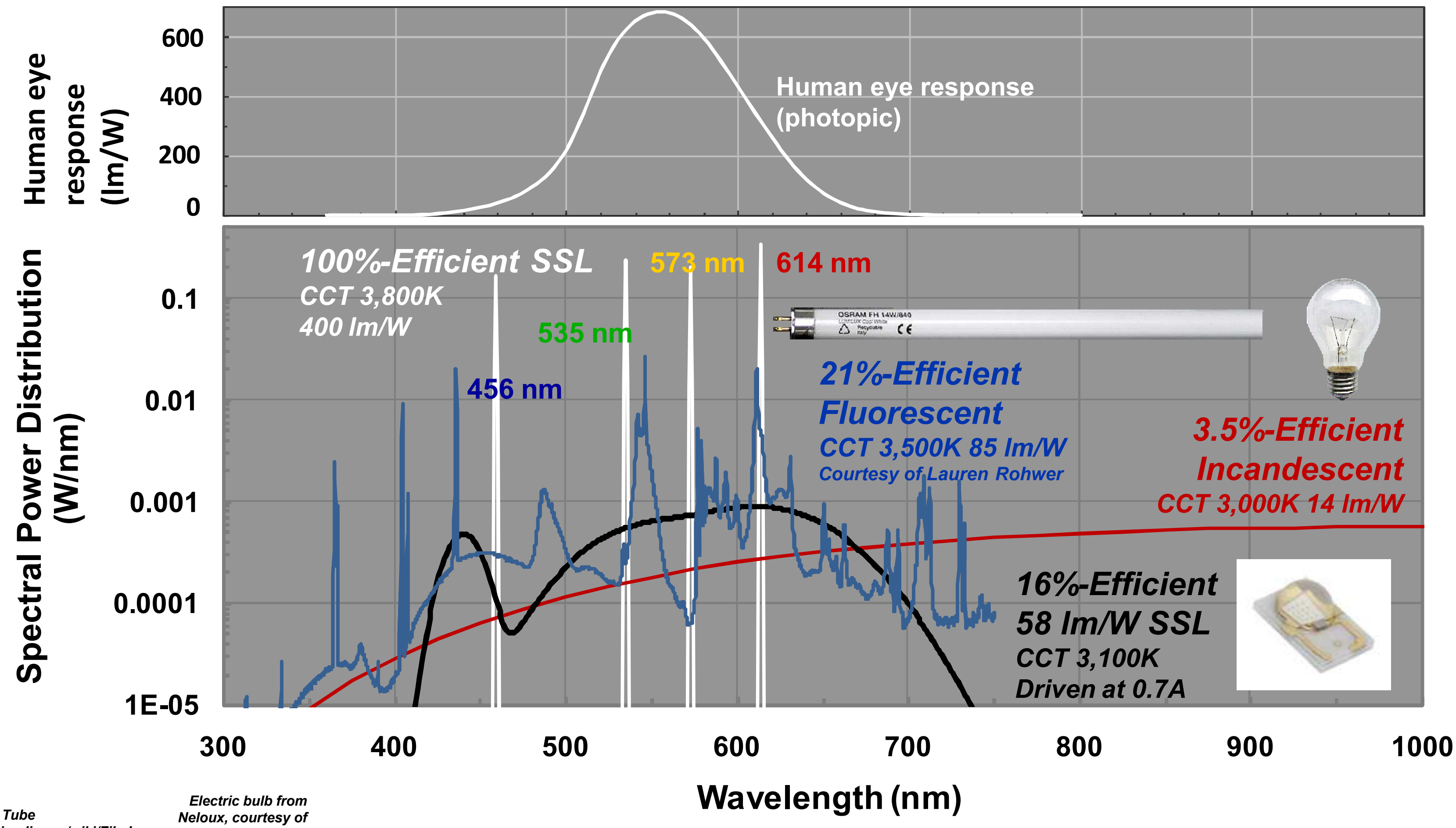
Advantages/limitations:

- 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)



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

Comparison of Lighting Technologies



Fluorescent Tube http://en.wikipedia.org/wiki/File:Leuchtstofflampen-chtaube050409.jpg

Electric bulb from Neloux, courtesy of KMJ. http://commons.wikimedia.org/wiki/File:Gluehlampe_01_KMJ.jpg

100% efficient SSL source: SANDIA et al,: J. Phillips et al., Laser and Photonics Review, 2007

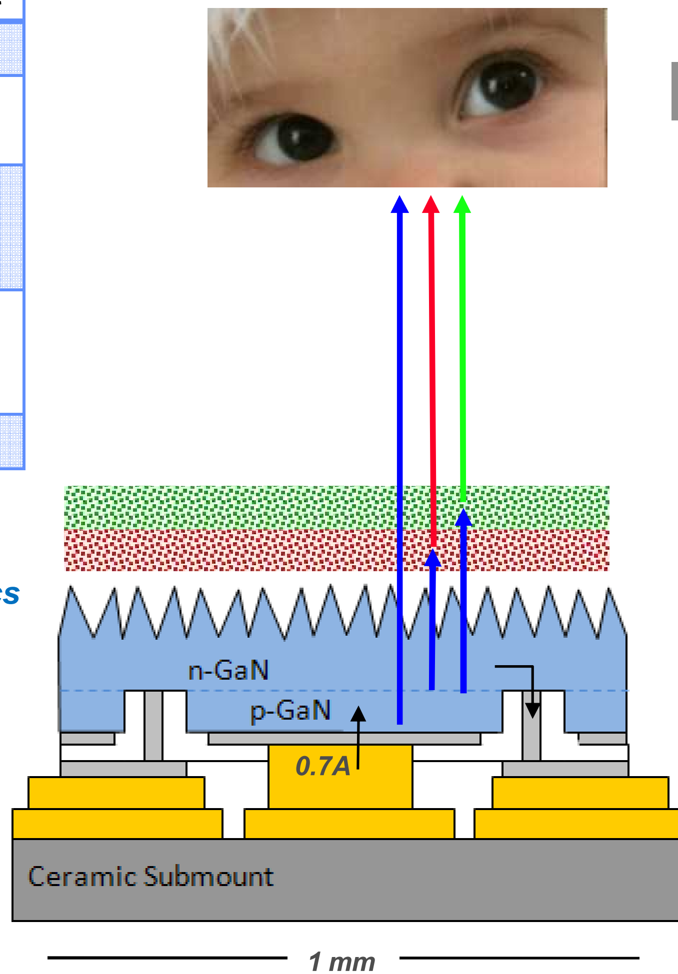
Efficiency breakdown for Warm White LEDs

Performance Characteristics of Early-2010 Commercial State-of-art		
Efficiency	ε	16%
Luminous Efficacy	η	64 lm/W
Color Rendering Index	CRI	85
Correlated Color Temperature	CCT	3,100K
Drive Current	I	0.7A

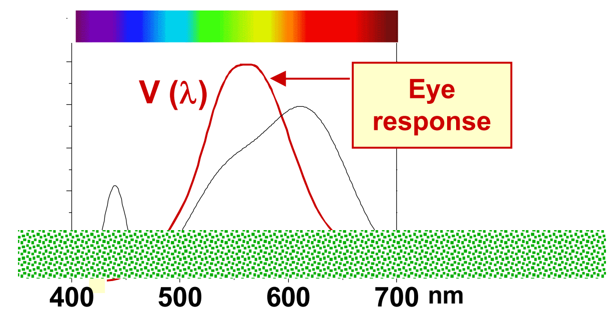
Efficiency and luminous efficacy can be increased by relaxing some performance characteristics

Blue LED	38%
Joule	*90%*
IQE at low power	*75%*
Droop at high power	*70%*
Light extraction	*80%*

http://bobbymercerbooks.com



Spectral Content	78%



Phosphor/Package	54%
Internal quantum eff.	*90%*
Stokes deficit	*76%*
Scattering/absorption	*80%*

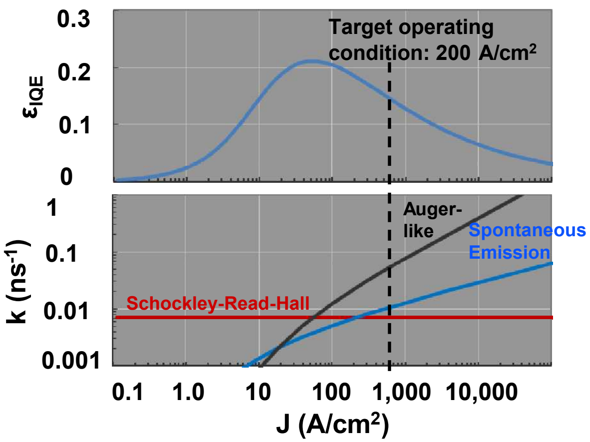
Thin-Film Flip Chip (TFFC)
e.g., Philips-Lumileds Luxeon
schematic courtesy of Jon Wierer

J. Y. Tsao

Technology "Grand Challenges" for ultra-efficient SSL

① *Eliminate blue LED efficiency droop at high currents*

Internal quantum efficiency vs. current



$$\varepsilon_{IQE} = \varepsilon_{INJ} \cdot \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

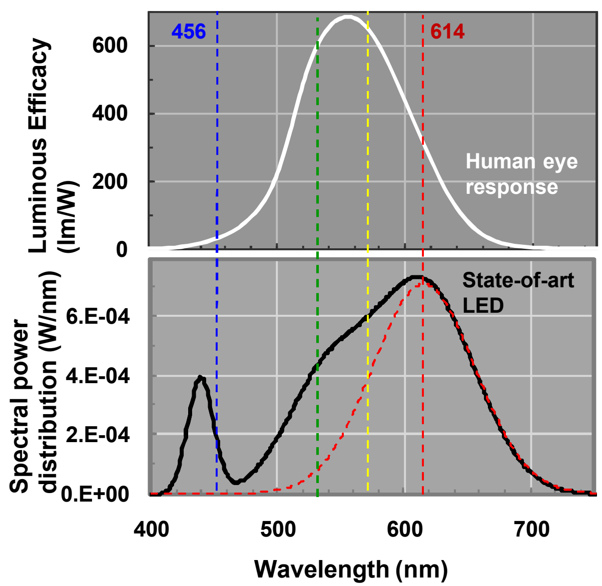
Shockley-Read-Hall

Spontaneous Emission

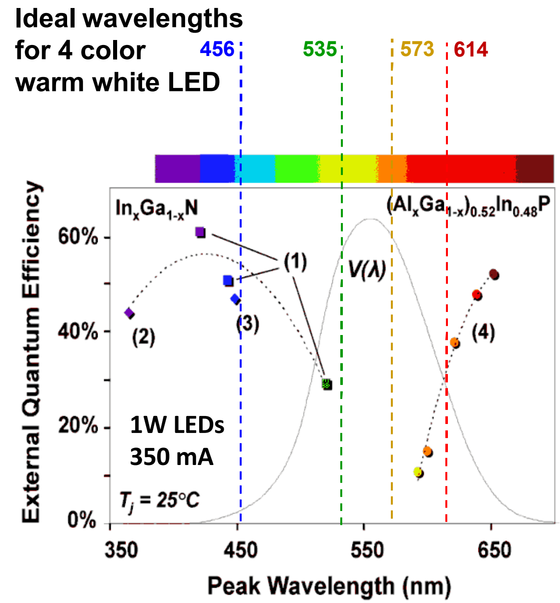
Auger-like

Rate constants for 510nm LED, after UT Schwarz, "Emission of biased green quantum wells in time and wavelength domain," SPIE Proc 7216, 7216U-1 (2009).

② *Narrow-linewidth shallow-red emitter*



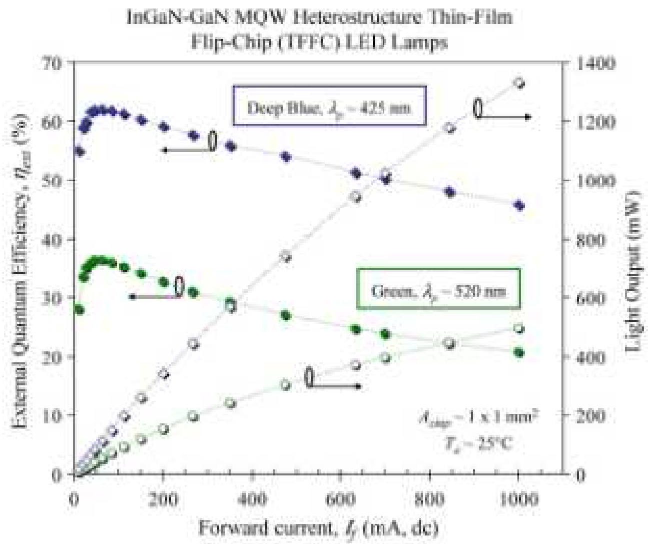
③ *Fill in the green-yellow gap in LED efficiency*



Courtesy of M. Krames, Philips-Lumileds

Blue LED	***38%***
Joule	*90%*
IQE at low power	*75%*
Droop at high power	*70%*
Light extraction	*80%*

First Grand Challenge: Overcoming Efficiency Droop



Krames et al., J. Displ. Technol. (2007)

Distinguishing factors:

- Present under pulsed conditions (non-thermal)
- Onset at rather low current densities (~10-30 A/cm^2)
- More dramatic at longer wavelengths (higher indium InGaN QWs)

Recombination model:

$$\varepsilon_{IQE} = \varepsilon_{INJ} \cdot \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

Carrier Injection efficiency; Shockley-Read-Hall (nonrad at defects); Radiative; Auger and higher order processes

potential non-radiative mechanisms

Carrier capture / leakage

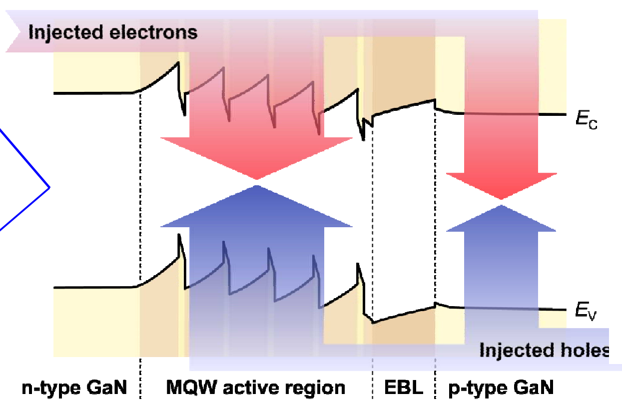
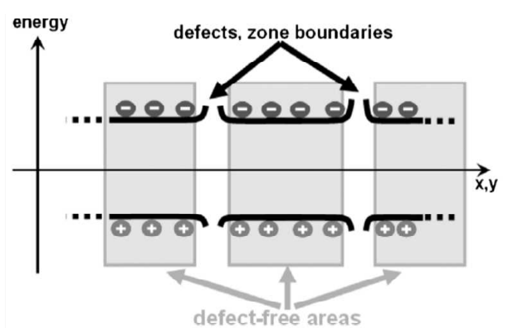
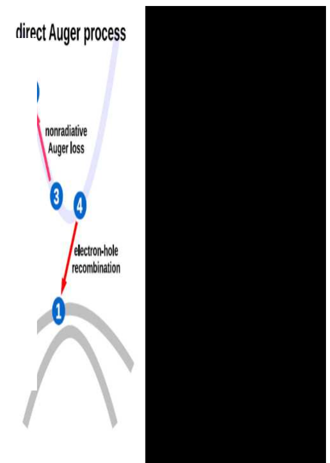


Figure: E. F. Schubert

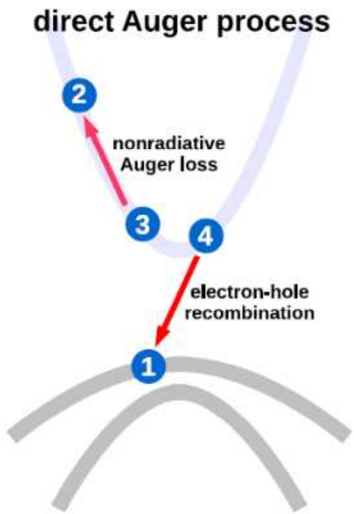
Carrier delocalization/ defect recombination



Auger recombination



The Role of Auger Recombination



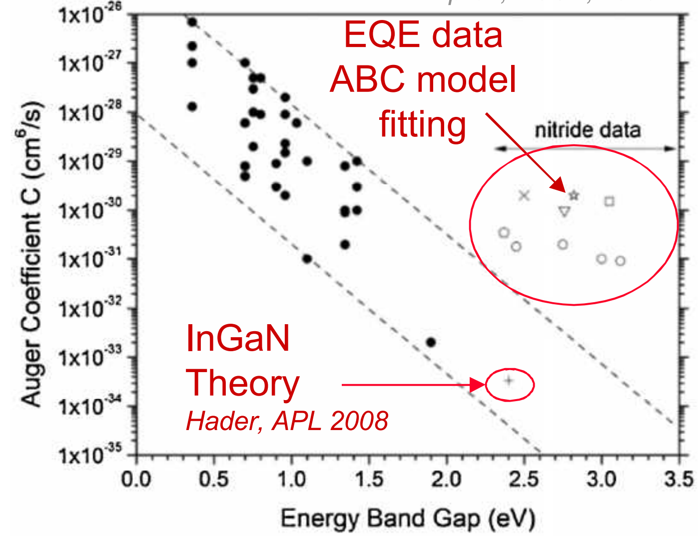
"ABC model"

$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

Shockley-Read-Hall (nonrad at defects) — Radiative — Auger

Major discrepancy between theoretical and experimental predictions of Auger coefficient!

Piprek, PSSA, 2010



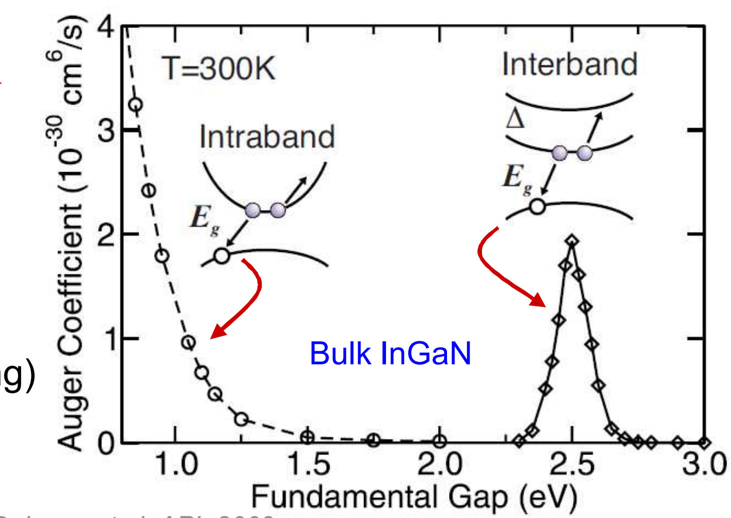
Microscopic theory:

- Lack of consideration of higher order bands (interband)? →
- Consideration of phonon-assisted Auger?

EQE data with ABC model fitting:

- ABC model oversimplified!
- Lack of consideration of alternative n^3 processes
- Carrier injection ignored
- No non-equilibrium effects (hot carrier injection, plasma heating)

→ Need *direct* measurement of Auger coefficient!

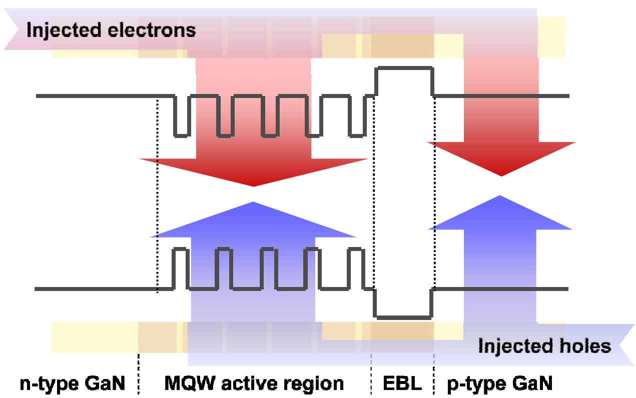


Delaney et al, APL 2009

$$\varepsilon_{IQE} = \varepsilon_{INJ} \cdot \frac{Bn^2}{An + Bn^2 + Cn^3}$$

The Role of Carrier Transport

Non-polar MQW LED



Polar InGaN MQW LED

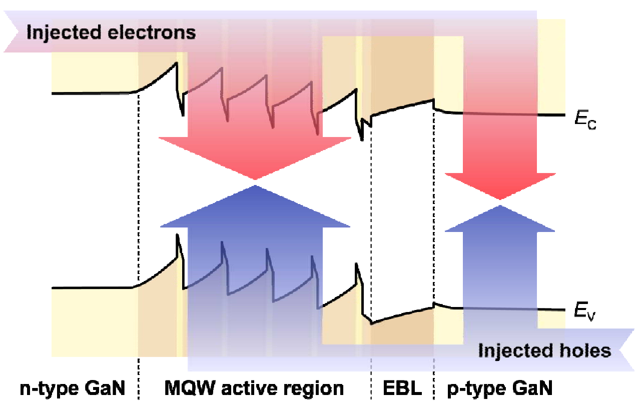
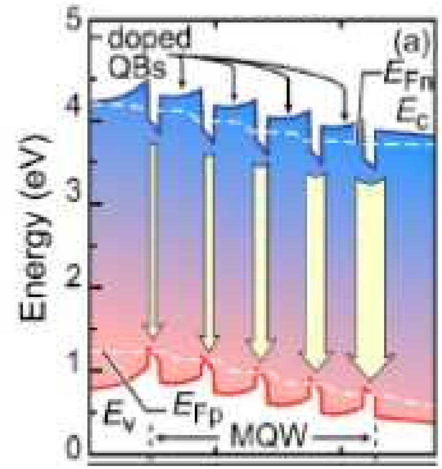
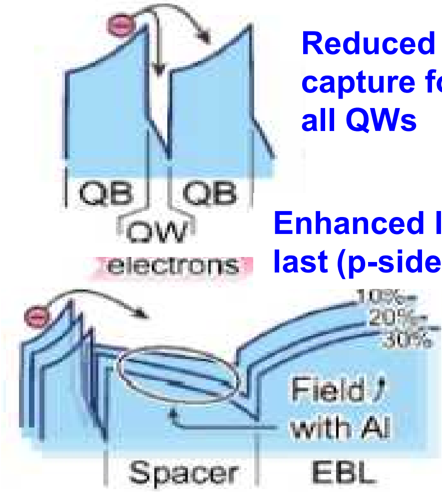


Figure: E. F. Schubert





Reduced e- capture for all QWs

Enhanced leakage for last (p-side) QW!

RPI/Sandia: D. Zhu et al, APL 2010

Polarization effects contribute to:

- Dominant recombination from last (p-side) QW
  - *→ high carrier densities at low currents! (Auger, etc)*
- Reduction of EBL energies, enhanced e^- leakage

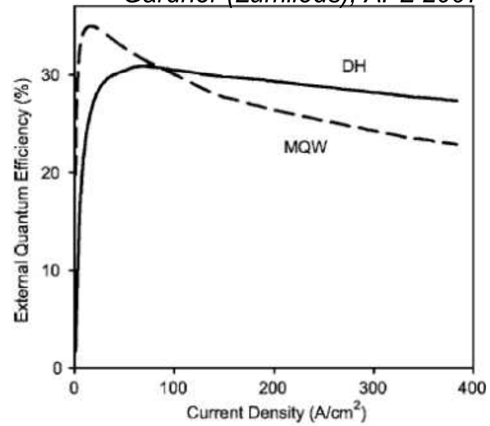
Outstanding issues:

- Droop still reported for some *non-polar* InGaN LEDs
- Injection /leakage not included in many models, ~n^3 dependence is unclear

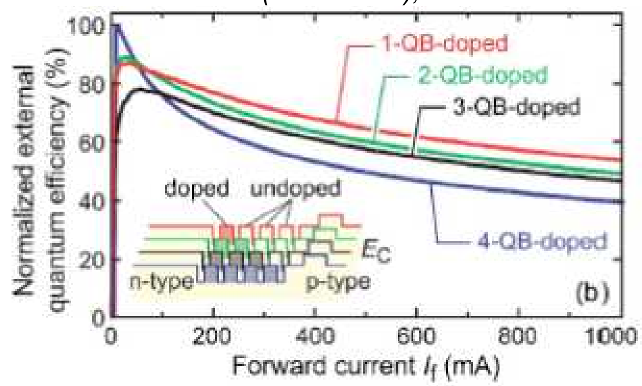
Still…promising approaches are being discovered!

- Double heterostructure
  (reduced carrier densities)
- Active region designs for improved carrier distribution
  (InGaN barriers, Si-doped barriers, polarization-matched AlInGaN barriers)

Gardner (Lumileds), APL 2007

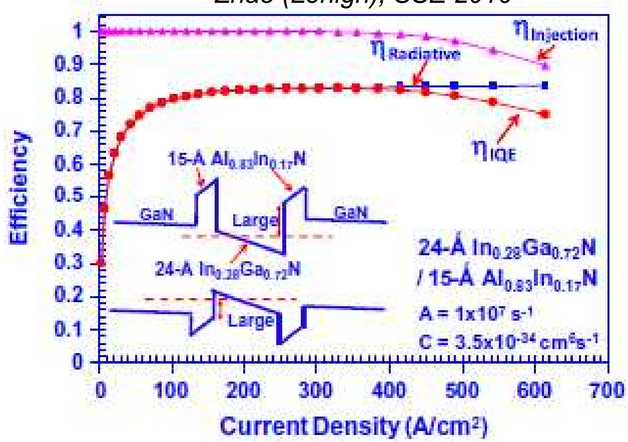


Zhu (RPI/Sandia), APL 2010

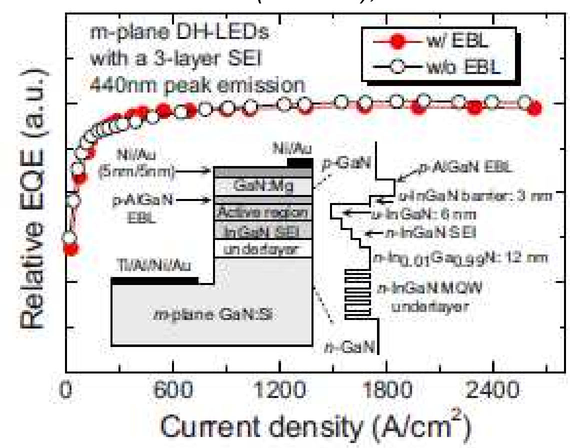


- AlInN electron block layers
- AlInN barrier designs
- P-doped barrier designs
- Staircase electron injector
- m-plane (non-polar) LEDs

Zhao (Lehigh), SSE 2010



Ni (VC Univ), APL 2010



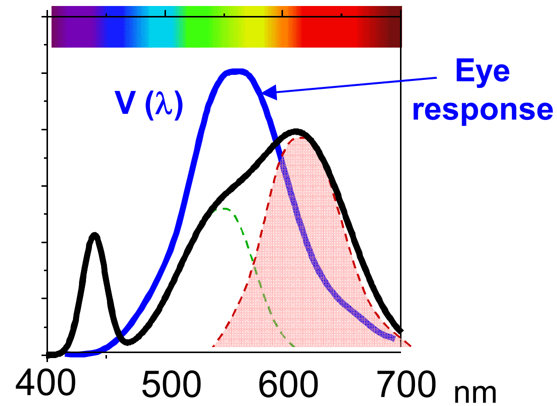
- Need more advanced modeling, incorporating multiple mechanisms, non-equilibrium effects
- R&D solutions must be amenable to high yield, low cost production

Second Grand Challenge:
Narrow-band Red Emitter

Key Requirements for SSL Phosphors:

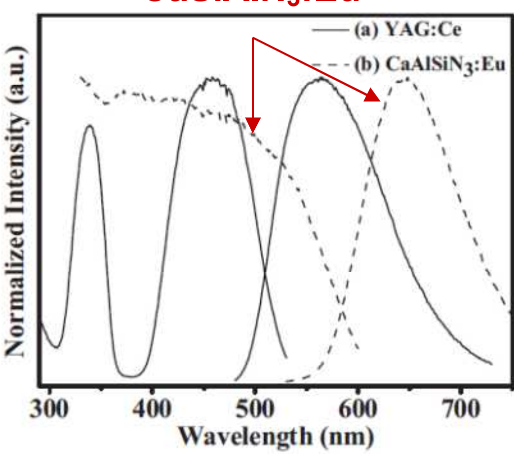
- Good absorption in the blue (~460 nm)
- High QE (> 80%) maintenance at high temperatures, high pump powers *and* upon integration with LED chip
- High luminous efficacy of radiation
  (Red: shorter red (~615nm), narrow-band)
- minimal green-yellow absorption
- High chemical stability
- Ease of manufacture

R_BG_BB Warm White Spectrum



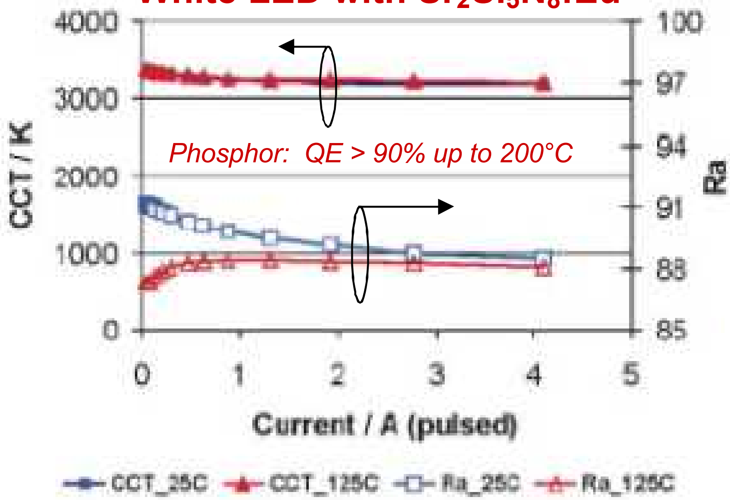
Largely met by Eu^{2+}-doped nitride phosphors: $Sr_2Si_5N_8:Eu^{2+}$, $CaSiAlN_3:Eu^{2+}$

$CaSiAlN_3:Eu^{2+}$



Lin, ECS, 2010

White LED with $Sr_2Si_5N_8:Eu^{2+}$

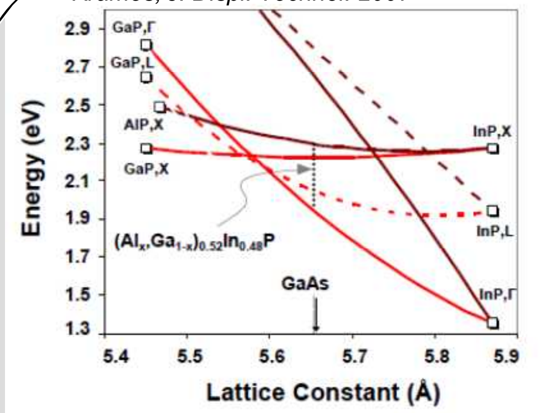


Mueller-Mach PSSA, 2005

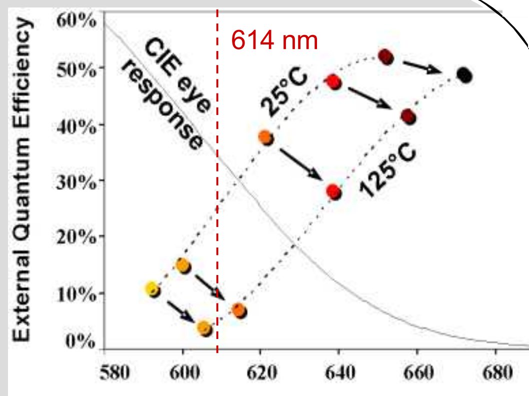
Remaining Deficiencies	
Spectral Content	***78%***
Phosphor/Package	***54%***
Internal quantum eff.	*90%*
Stokes deficit	*76%*
Scattering/absorption	*80%*

Red LED Candidate Materials

AlGaInP



Krames, J. Displ. Technol. 2007



Philips Lumileds

Fundamental problem: Indirect band cross-over at ~553 nm (~55% AlInP)

Reduced carrier confinement, bandgap shift with temperature → low EQE at shorter λ

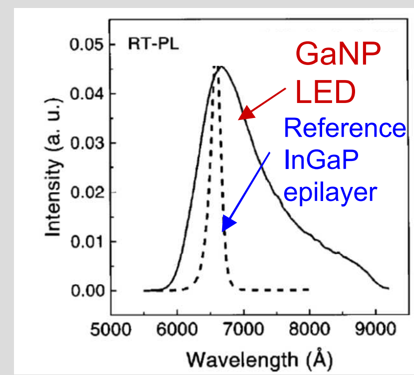
Recent Advance: Osram prototype red LED

(07-2010, LED magazine)

- 615 nm (typical FWHM~18 nm)
- 44% efficiency @ 350 mA (1x1 mm^2)
- claims reduced temperature dependence

(In)GaNP

- > 0.5% N enables direct bandgap, yellow to red emission
- **Potential advantages**
  - larger band offsets
  - weaker temp. dep. of bandgap
  - transparent (GaP) substrates



Xin (UCSD) APL 2000

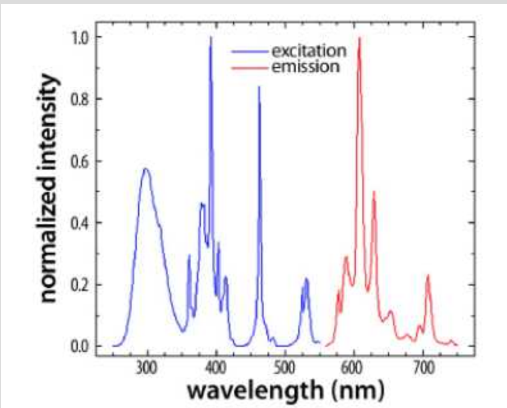
- **Outstanding issues:**
  - efficiency
  - broad linewidths

→ Direct red emitter solution not clear

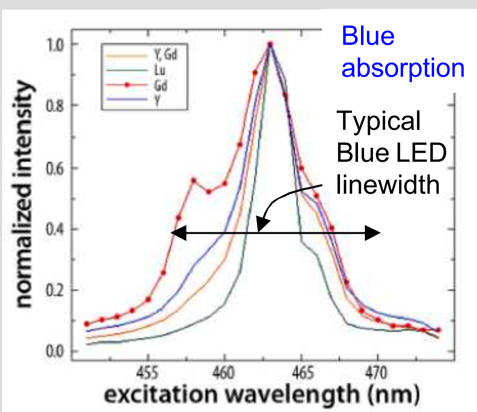
Novel Red Down-conversion Materials

Eu^{3+}-doped tantalate phosphors

SANDIA: M. Nyman et al. J. Am. Chem Soc. 2009



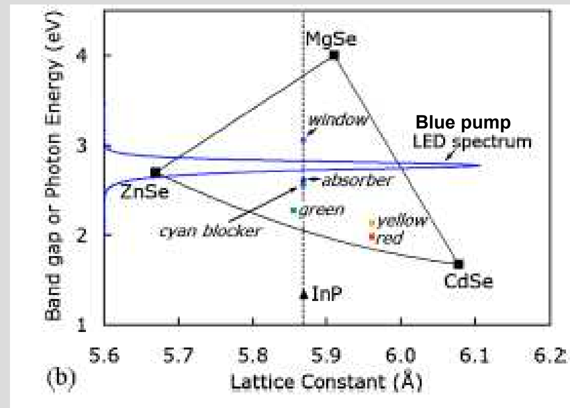
- narrow-band 4f→ 4f transition
- $K(Re)Ta_2O_7$ (Re=Gd, Y. Lu) host, Blue absorption
- QE ~ 80% 610 nm peak
- ~3% thermal quenching @ 130°C
- **Challenge**: broadening blue absorption band



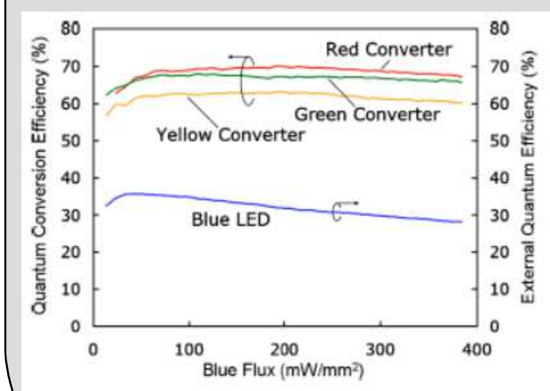
L. E. Shea Rohwer, Sandia

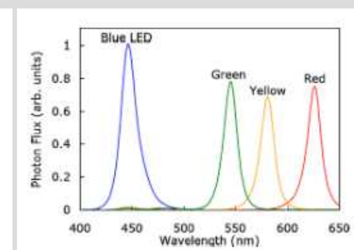
CdZnSe-CdZnMgSe QWs

3M: M. A. Haase et al. APL 96, 231116 (2010)



- II-VI QWs pumped by blue LEDs
- Avoids p-type doping challenges in direct II-VI LEDs
- Green-to-red emission, tunable by alloy composition

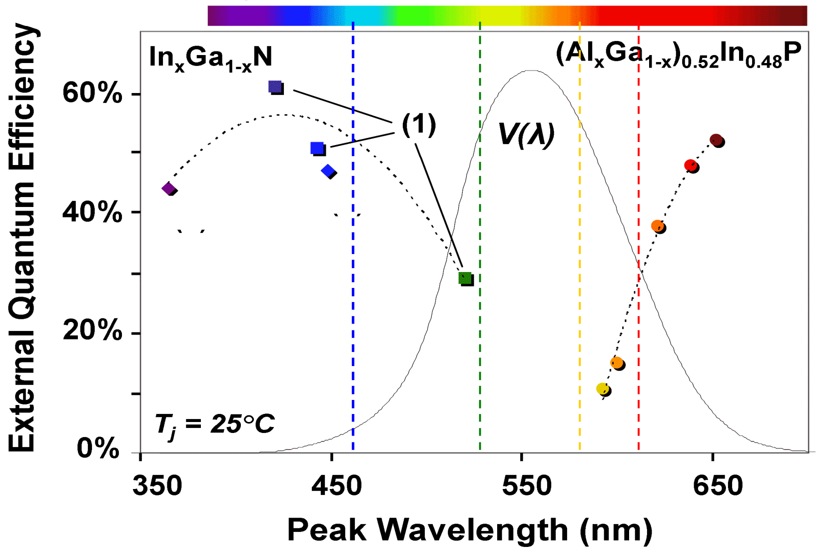


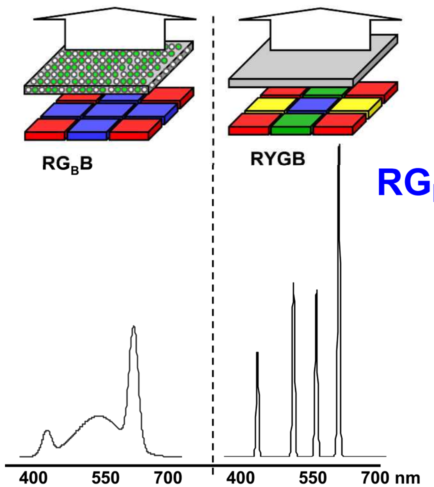


- Quantum Efficiency 60-70%
- Linewidths ~15 nm
- Reliability issues?

Third Grand Challenge:
Filling the “green-yellow gap”

Figure: M. Krames, Philips Lumileds





RG_BB (green phosphor) vs. RYGB (all LED) approach

How critical is an LED solution?

- Broad sources (e.g., phosphors) are better tolerated in green-yellow region
- Stokes loss not as large as for red, but still limiting overall efficiency

  536nm (15%) 573 nm (20%) 614 nm (25%)

- Could enable all-LED white sources and “smart lighting” opportunities…

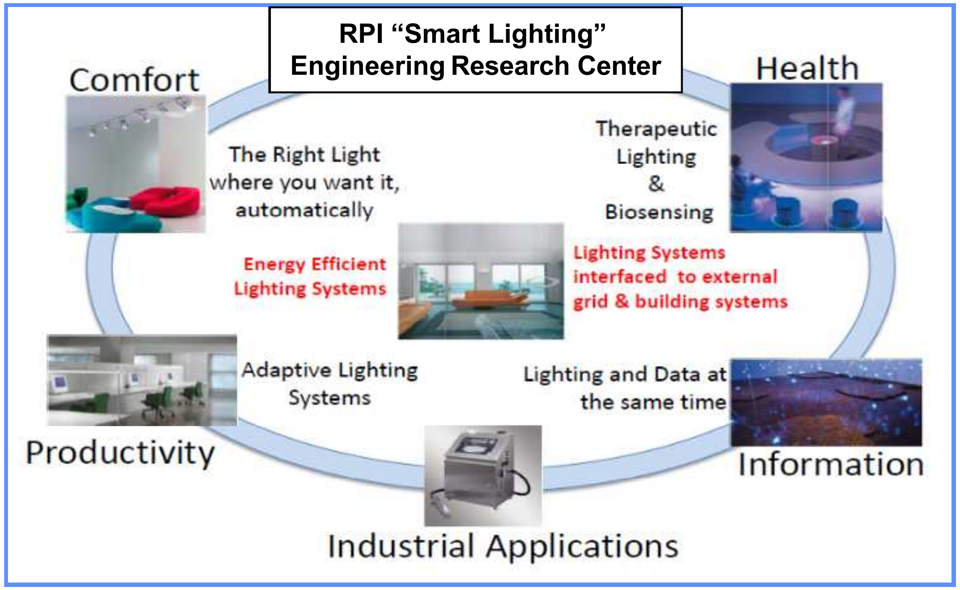
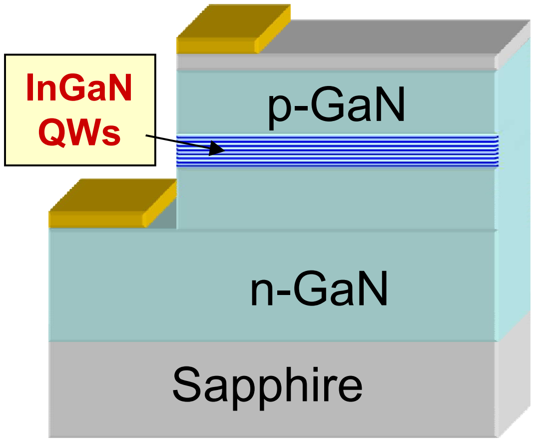


Figure: R. Karlicek, Green Photonics Forum, 2010

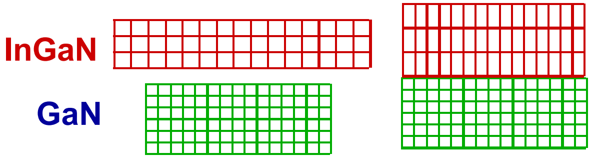
Materials Challenges of Green-Yellow InGaN LEDs

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

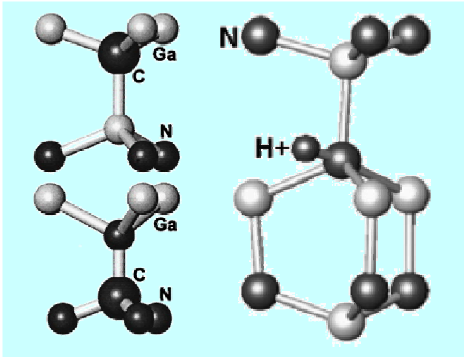


Major materials issues related to high indium alloys:

- 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

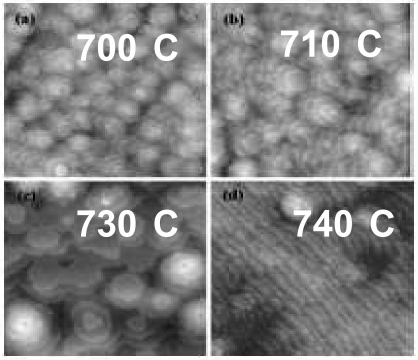


Impurities and point defects



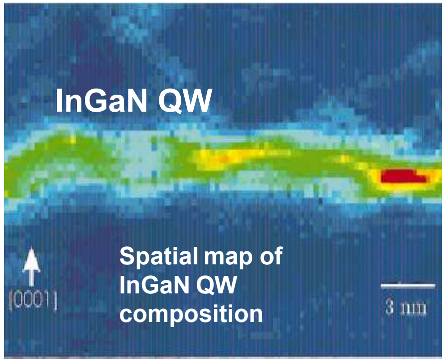
Wright et al., JAP 2002

3D growth modes



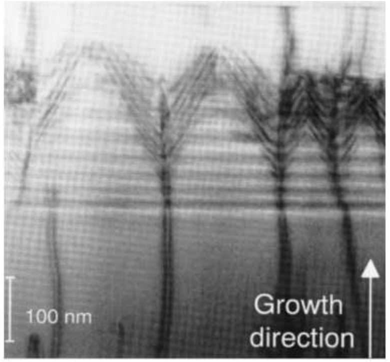
Oliver et al., JAP 2005

Compositional instabilities



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

"V- defects"



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

Non-Polar/Semi-polar LEDs

Piezoelectric polarization vs. crystal orientation

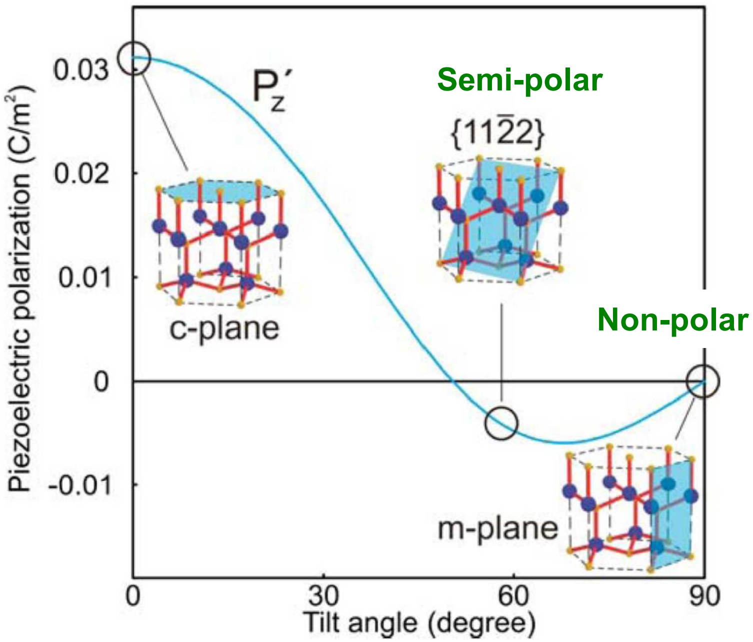


Figure: U. T. Schwarz PSS RRL (2007)

Non-polar/semi-polar LEDs (UCSB)

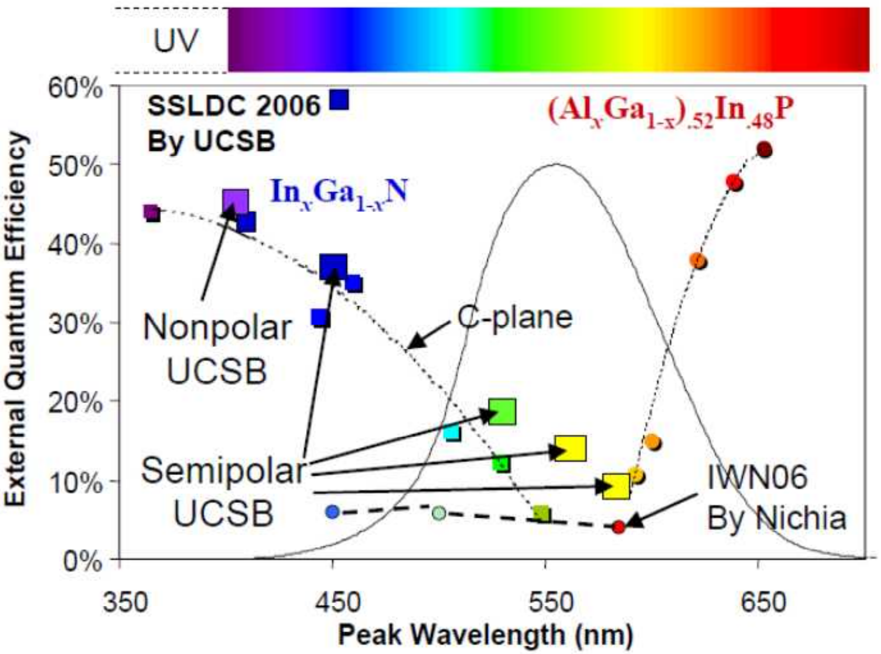
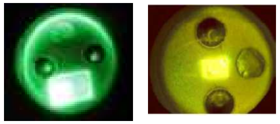


Figure and LED photos: S. Nakamura, Raleigh Workshop, 2010

→**Breakthrough**:
high quality, thick (~1 cm) HVPE *c*-plane GaN substrates; cut into alternative orientations (e.g., Mitsubishi)

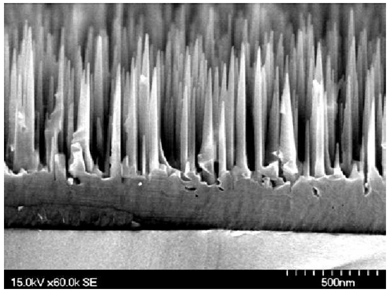
→ **Semipolar:** (11-22), indium incorporation efficiency may be comparable to, or greater than, *c*-plane



Northrup, APL, 2009

Nanostructured InGaN Materials

GaN nanowires (nanorods)

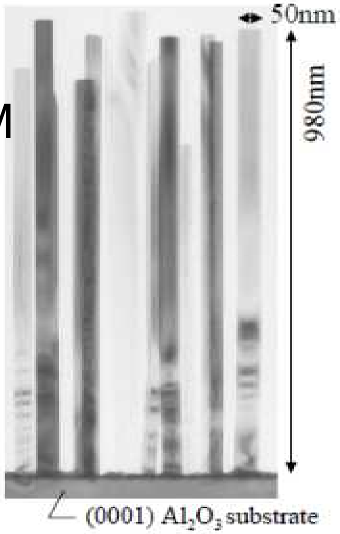


Li et al., Appl. Phys. Lett. (2008) (Sandia)

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

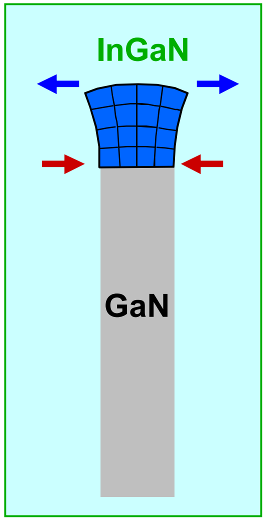
No threading defects

TEM



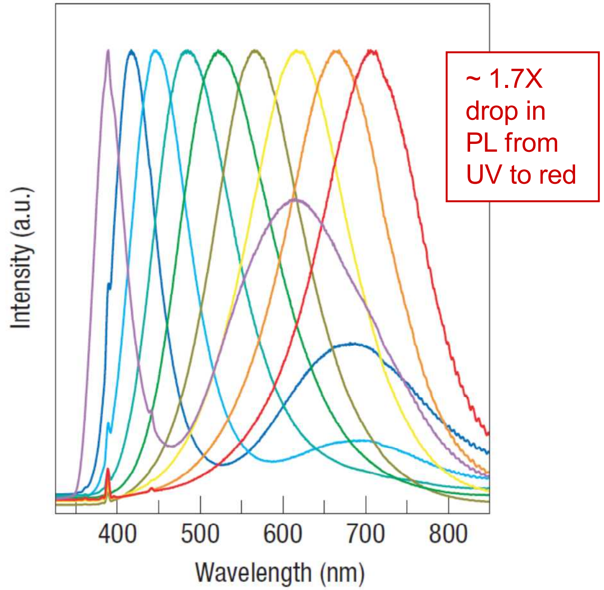
Kishino et al., Proc. SPIE 2007

Strain Accomodation



Broad range of emission l

Normalized Photoluminescence



Growth by Halide Chemical Vapor Deposition

Kuykendall et al., Nat Mat. 2007

- Compatible with a wide range of substrates (including Si)
- Can be grown with no threading defects
- Lateral structure allows strain accommodation
- 1D geometry may provide light extraction benefits

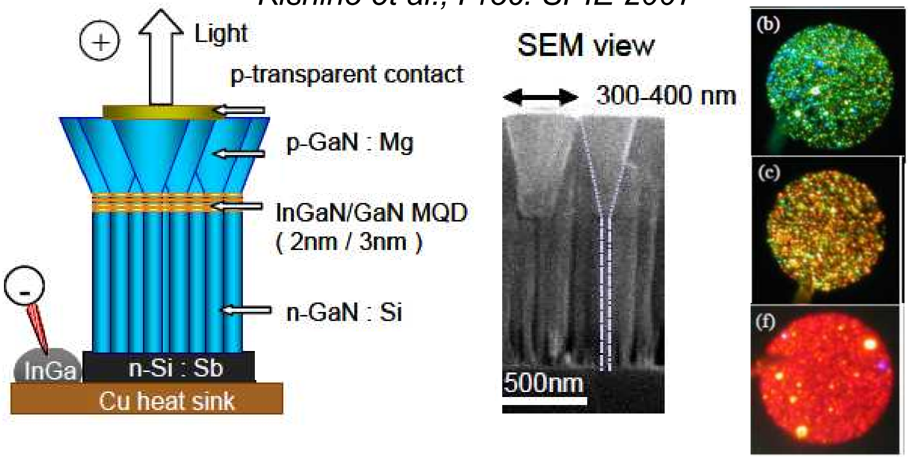
☆ Potential for solving red problem also?

Nanostructured InGaN LEDs

Axial LED Geometries

Self-assembled Nanorods, p-GaN Planarization

Kishino et al., Proc. SPIE 2007



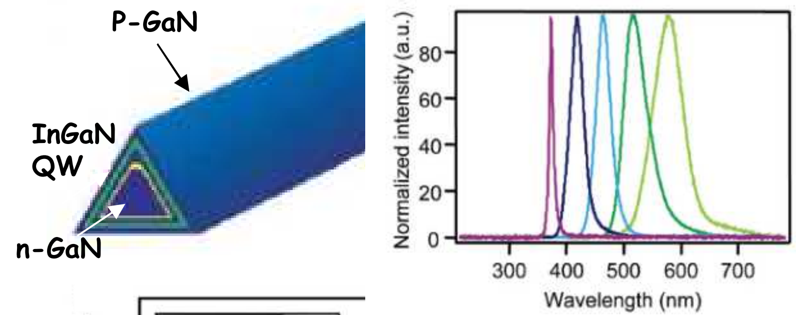
→**Indium composition variations between nanorods; leads to broad spectra**

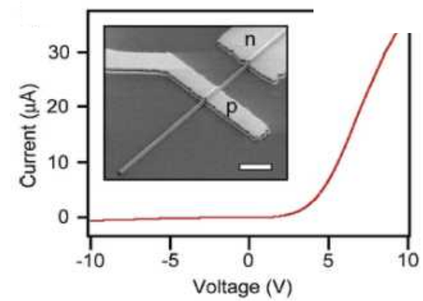
Also, Spin-on-glass planarization *Kim et al., Nanolett. 2004*

Radial (Core-Shell) LED Geometries

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

Qian et al., Nat Mat. 2005



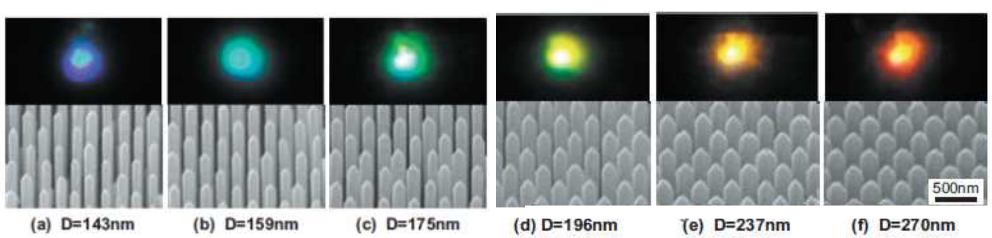


Single NW:
EQE= 3.9%
@ 540 nm

Outstanding Issues:

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

Selective-area GaN/InGaN nanorod growth through patterned Ti mask (PA-MBE)



PL Images

Sekiguchi, APL 2010

Conclusions

SSL has the potential to move significantly beyond traditional lighting, providing greater efficiencies and functionality

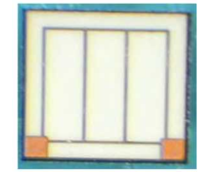
Breakdown of white LED component efficiencies allows an assessment of the most critical technical roadblocks to 50% and higher efficiency SSL:

LED Efficiency droop:
- Designs to reduce carrier density, improve carrier injection efficiency showing promise
- More accurate models needed to elucidate nonradiative mechanisms

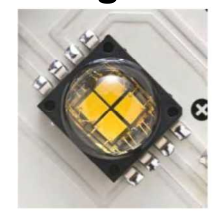
Narrow band red emitter
- Major breakthrough needed in direct red emitters
- Novel down conversion materials (Eu3+ tantalate phoshors, II-VI converters) show promise

Bridging the green-yellow gap in LED efficiency
- Enabler for "smart lighting" concepts
- Examples of emerging approaches: semipolar and nanostructured InGaN

LED Chip



Packaged LED



Luminaires

Exterior hanging light

Exterior porch light

Track light

Interior recessed can

Figures from DOE EERE SSL MYPP March 2010