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Pathways to Ultra-Efficient Solid-State Lighting

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Acknowledgements: ***J. Y. Tsao, D. D. Koleske, J. J. Wierer, Jr., A. J. Fischer, W. W. Chow, G. T. Wang, A. M. Armstrong, S. R. Lee, M. E. Coltrin, Sandia National Labs***

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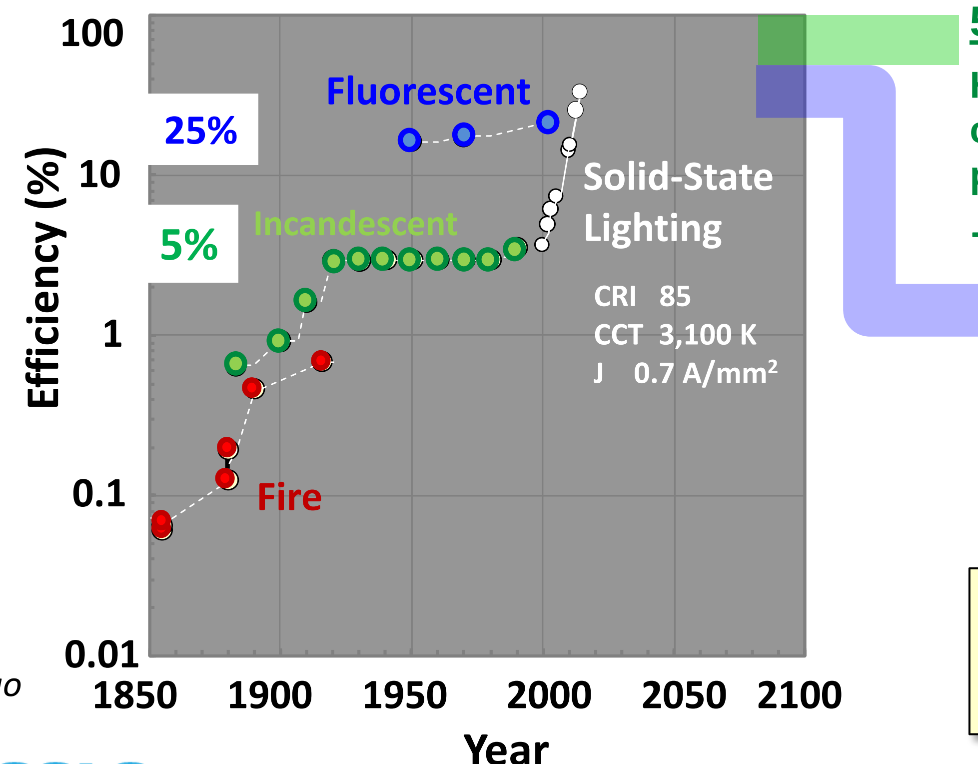
Motivation for "Ultra-Efficient" SSL

- ~18% of electricity consumption is for general illumination
- Achieving 50% efficient lighting would have tremendous global impact:
  - ➤decrease electricity consumed by lighting by > 50%
  - ➤decrease total electricity consumption by 10%



J. Y. Tsao

50-100% ("ultra-efficient")

Highest savings in energy consumption and gains in human productivity

→ Not obvious how to achieve

25-50%

Enables penetration of traditional lighting

→ Up to 50% might be achieved with existing LED architectures

Target For DOE EERE Luminaire ~ 200 lm/W (~50%) LED Package ~ 250 lm/W

Outline

I. Introduction to Solid-State Lighting
   A. Intro to LEDs
   B. White LED Architectures and Performance
   C. Three "Grand Challenges" for ultra-efficient SSL (focus on the LED chip level)

II. LED efficiency droop at high currents
   A. Proposed mechanisms
   B. Benefits of tunnel-junctions
   C. Benefits of lasers for SSL

III. Bridging the "green-yellow gap" in LED efficiency
   A. Materials challenges
   B. Nanostructured LED solutions

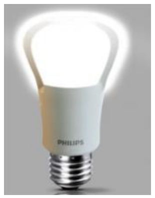
IV. The search for a narrow-band red emitter
   A. Limitations of present technology
   B. Direct-emitter challenges and potential solutions

V. Conclusions

LED Chip

Packaged LED

LED bulbs



LED Luminaires

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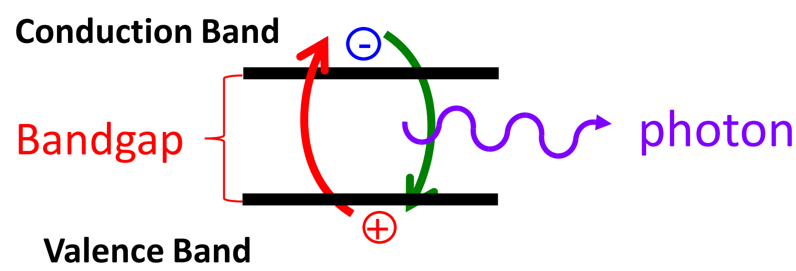
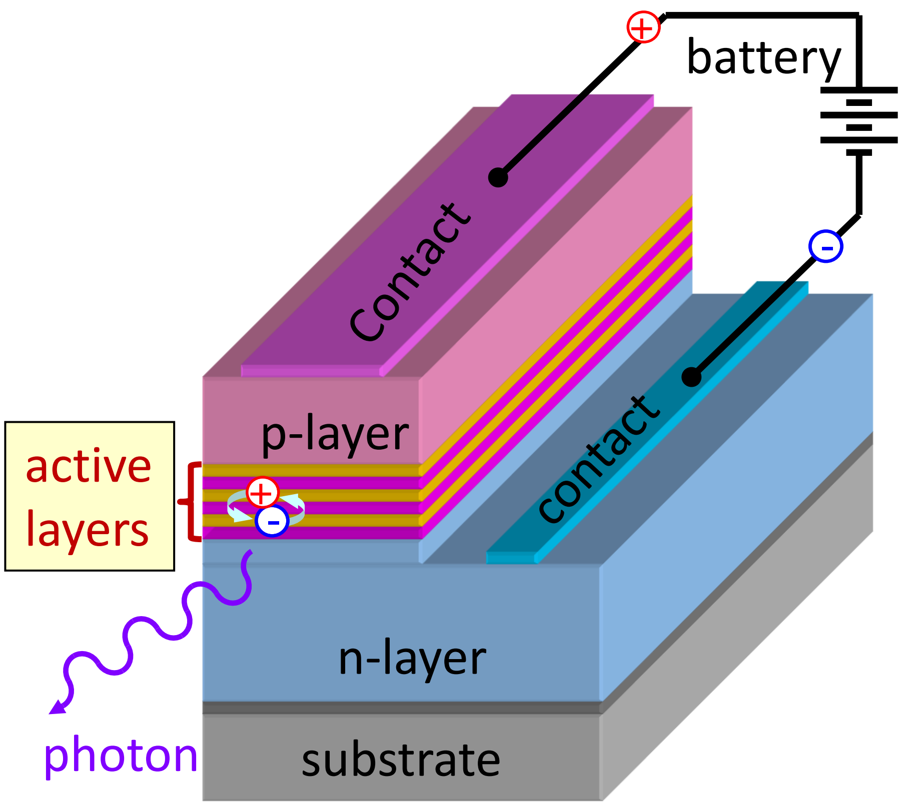
What is needed to make an efficient LED?

Total efficiency=
joule efficiency x injection efficiency x
radiative efficiency x light extraction efficiency





1. Effective p-type and n-type doping
   → inject charge carriers
2. Carrier confinement in active layers
   → keep charge in light emitting layers
3. Ultra-low defect densities
   → avoid non-radiative processes
4. Efficient light extraction
   → surface texturing, chip shaping

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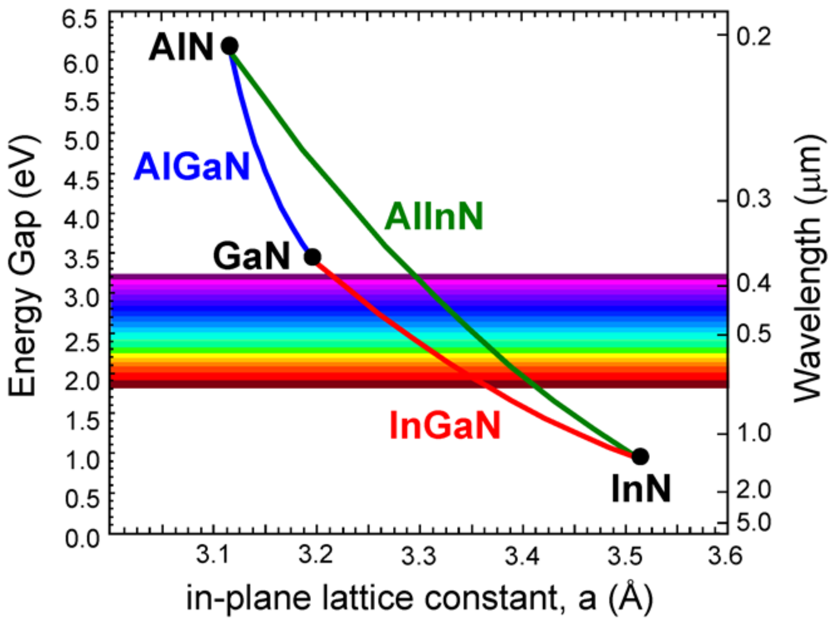
Materials: Alloys and Heterostructures

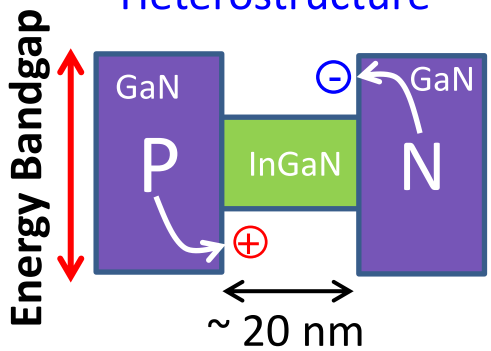
Alloys enable tunable properties and enhanced carrier confinement

Bandgap vs. Lattice Constant

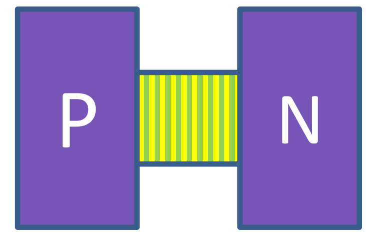


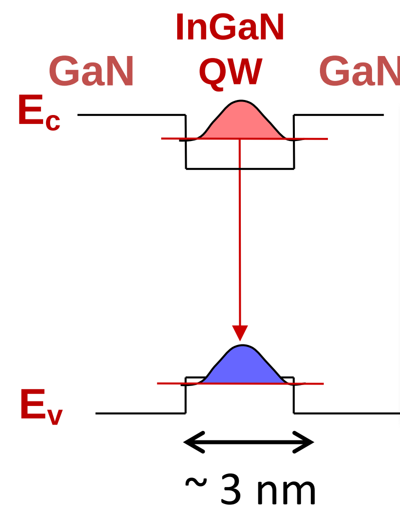
$In_xGa_{1-x}N$: potential for tuning emission through the entire visible spectrum!

Double Heterostructure



Multiple Quantum Well





Quantum Wells: Strong spatial overlap of electron and "hole" wavefunctions

→ Efficient light emission

Efficiency breakdown for Phosphor Converted White LEDs

Fluorescent:	**18-25%**
Incandescent:	**~3-5%**

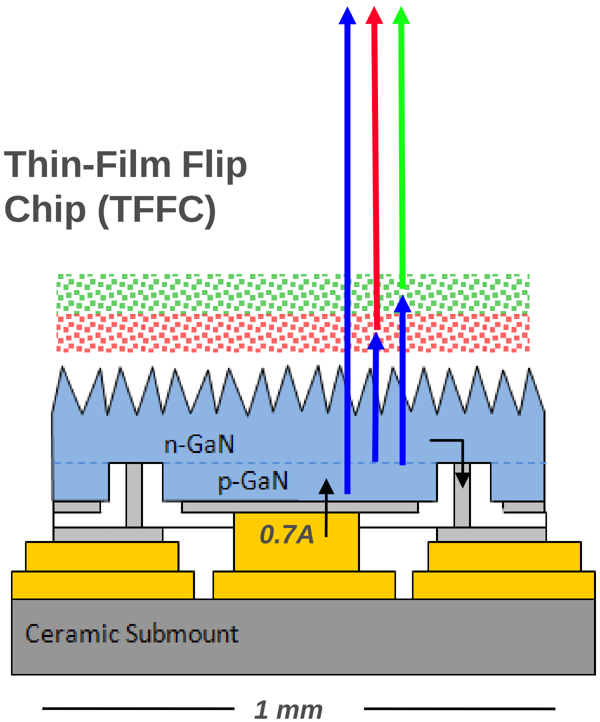
Performance Characteristics of 2014 Commercial LED (DOE)*

	η	123 lm/W
	CRI	85
	CCT	3000K
	I	0.35A
	T	25 °C

CONCLUSION:

Primary Roadblocks:
1) Blue LED Efficiency Droop
2) Inherent Stokes Loss
3) Broad phosphor linewidths

Thin-Film Flip Chip (TFFC)

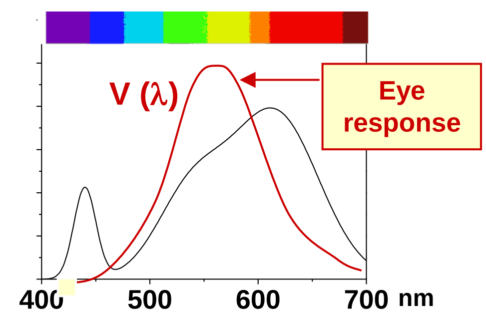


Blue LED @ 35 A/cm2	***55%***
Joule	*92%*
*IQE at low power**	*88%*
**Droop at 100A/cm2*	*80%*
Light extraction	*85%*
Package efficiency	*80%*

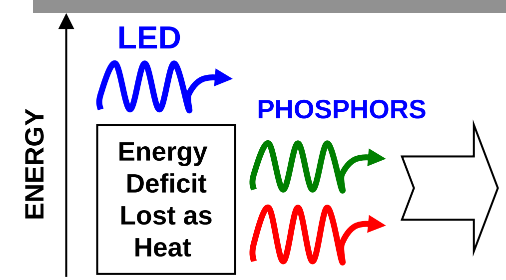
Overall Efficiency	***~32%***

(Color weighted)

Spectral Efficiency	***81%***



Phosphor/Package	***54%***
Green QE	*95%*
Green Stokes deficit	*84%*
Red QE	*90%*
Red Stokes deficit	*74%*

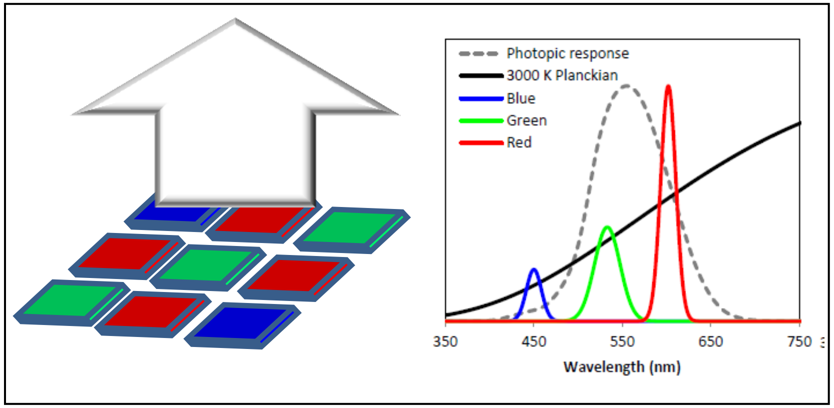


*derived from DOE Multi-Year Program Plan 2014 (DOE/EE-1089)

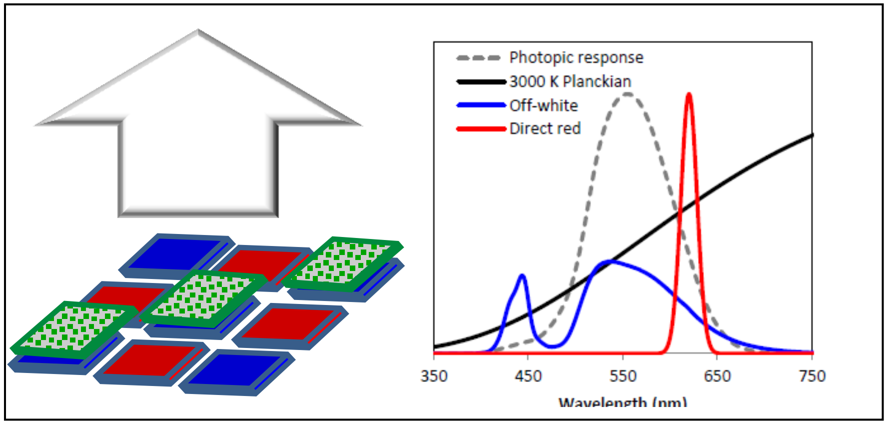
schematic courtesy of Jon Wierer

Alternate Architectures for LED Lighting

Multi-chip (all LED)



Hybrid Approach



Advantages/limitations:

- Direct light emission from LEDs
  → **highest efficiencies**
- Greater automation and color control possibilities
  (*"**smart lighting**"*)
- Narrow Linewidths (high spectral efficiency)
- Requires high performance from LEDs across the spectrum
- More complex/costly (drive circuitry, disparate LED degradation and thermal performance)

- Avoids broad red phosphor problem
- Automation and color control possibilities
  (*"**smart lighting**", Philips "Hue"*)
- Inherent losses for green phosphor
  (pump absorption, phosphor efficiency, Stokes' loss)
- More complex/costly (drive circuitry, disparate LED degradation and thermal performance)

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* Spectral curves from Soer et al. Philips 2014

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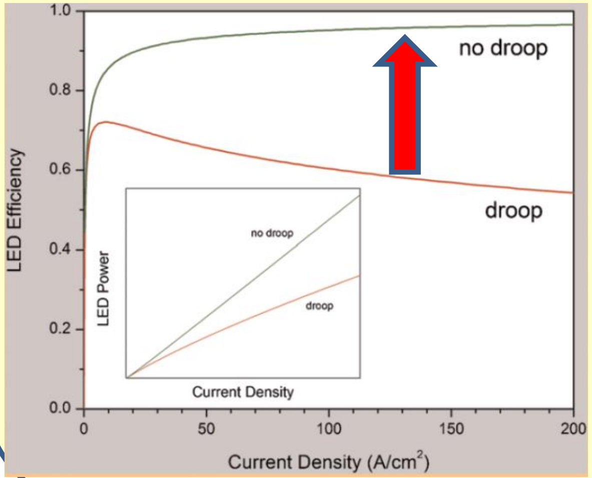
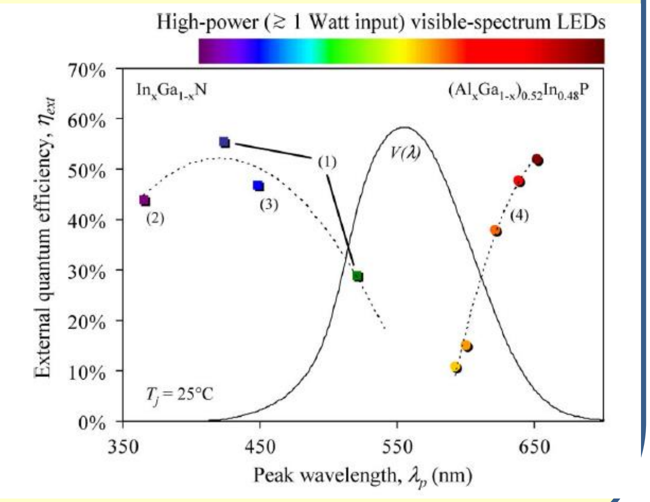
Technology "Grand Challenges" for ultra-efficient SSL

① *Eliminate blue LED efficiency droop at high currents**



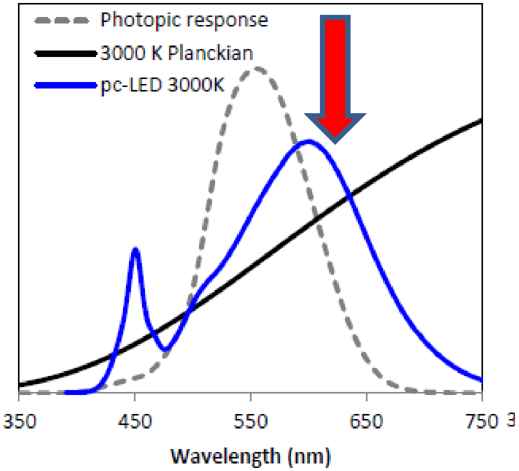
Piprek, PSSA, 2010

② *Fill in the green-yellow gap in LED efficiency*



Krames, et al., IEEE J. Displ. Tech. 2007.

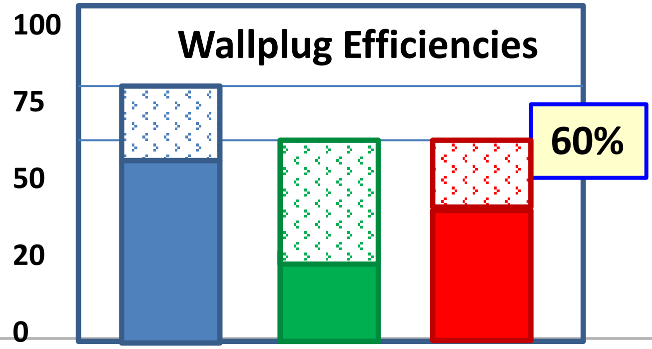
③ *Develop a shallow-red emitter with narrow linewidth*



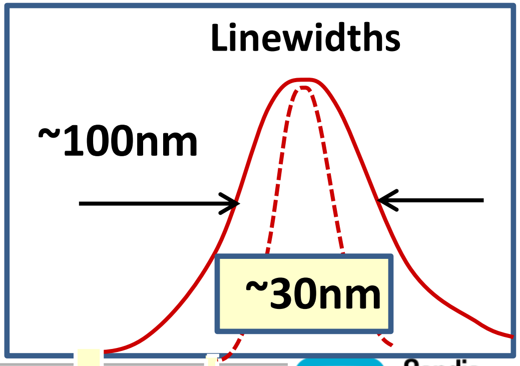
Soer Philips 2014

***high current operation needed for cost competitiveness (maximize light per chip)**

To approach 250 lm/W



WP= optical power out/electrical power in



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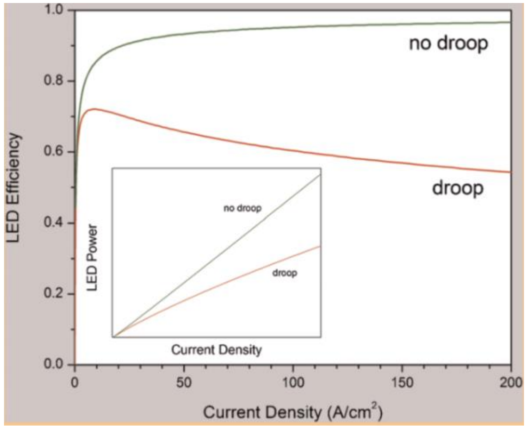
First Grand Challenge:
Overcoming Efficiency Droop



Piprek, PSSA, 2010

Recombination model:

$$\varepsilon_{IQE} = \varepsilon_{INJ} \cdot \frac{Bn^2}{An + Bn^2 + \underbrace{Cn^3 + Dn^m}_{\text{Auger and higher order processes}} + \ldots}$$

Carrier Injection efficiency

Shockley-Read-Hall (nonrad at defects)

Radiative

Auger and higher order processes

Phonon-assisted Auger recombination

Kioupakis et al., APL 2011

Pasenow, 2009

Carrier capture / leakage

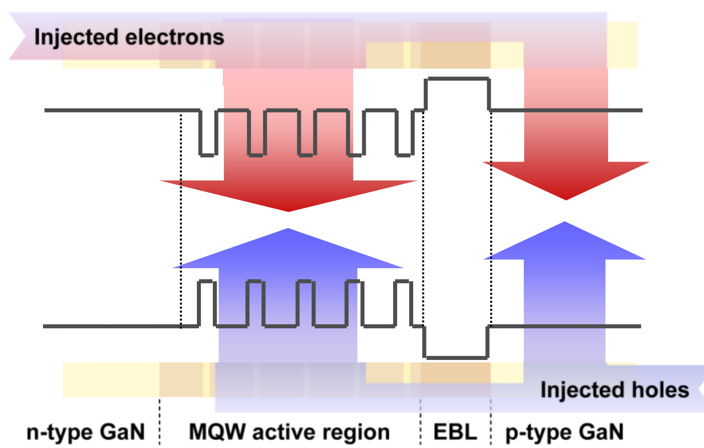
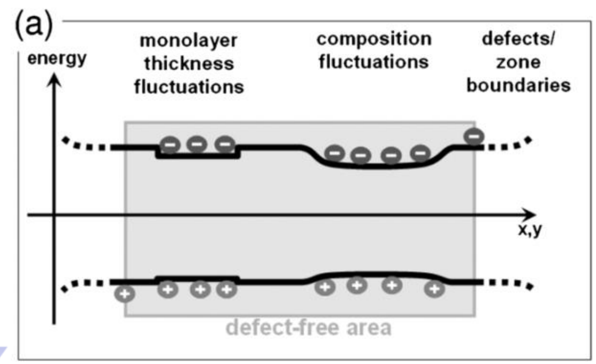


Figure: E. F. Schubert

Carrier delocalization/ defect recombination



Hader et al, APL 2010

(Iveland et al., PRL 2013; APL 2014)

Approaches to Reducing Droop

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)

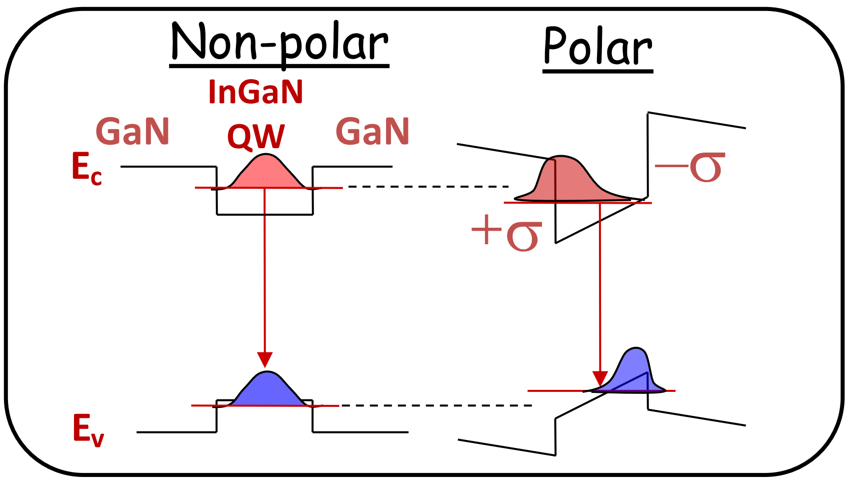
Radiative

Auger and higher order processes*

- **Specific**: Engineering of recombination rates, especially *Auger*
- **Generic:** Designs to achieve high output powers at *lower carrier densities*

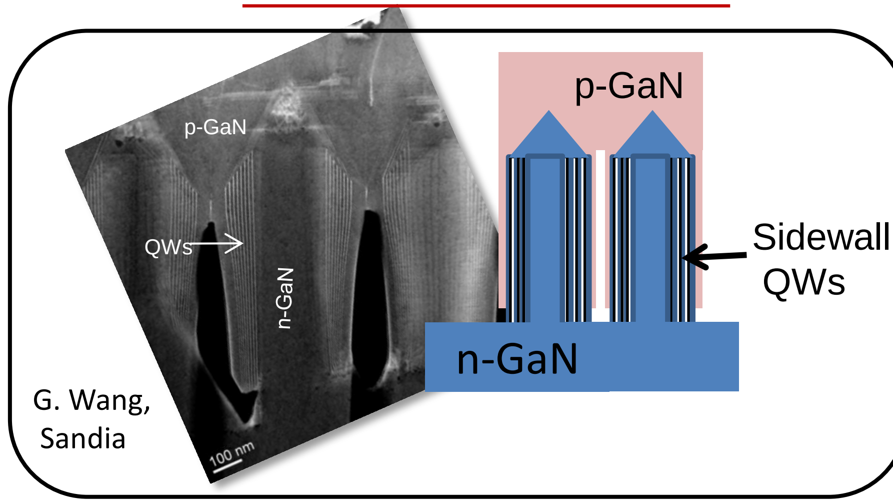
"Volumetric" Approaches to reduced carrier densities

Wider Active Layers (QWs)



- Non-polar tolerant of wider QWs (no QCSE)

Core-shell Nanorod LEDs



- Potential for ~10x active volume for a given substrate surface area

OSRAM: Kolper PSSA 2012

Tsao et al, Adv Opt. Mat. 2014

Benefits of Tunnel Junctions for LED Efficiency

Original TJ paper by Esaki (1958)

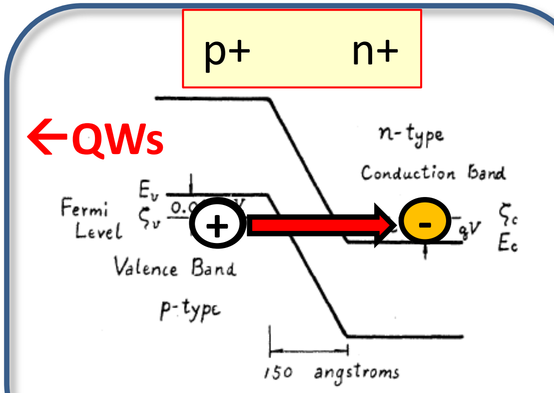
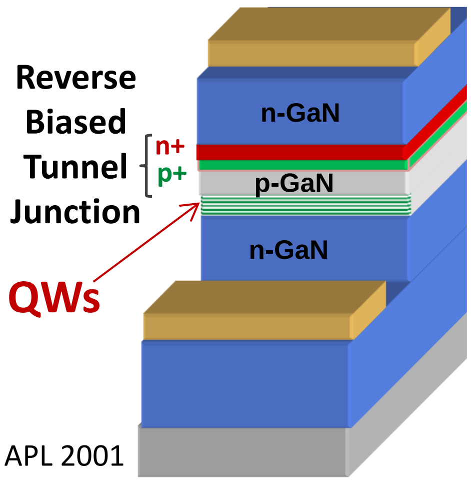


FIG. 2. Energy diagram of the p-n junction at 300°K and no bias voltage.

LED with single TJ



Jeon et al. APL 2001
Takeuchi et al. SPIE 2002

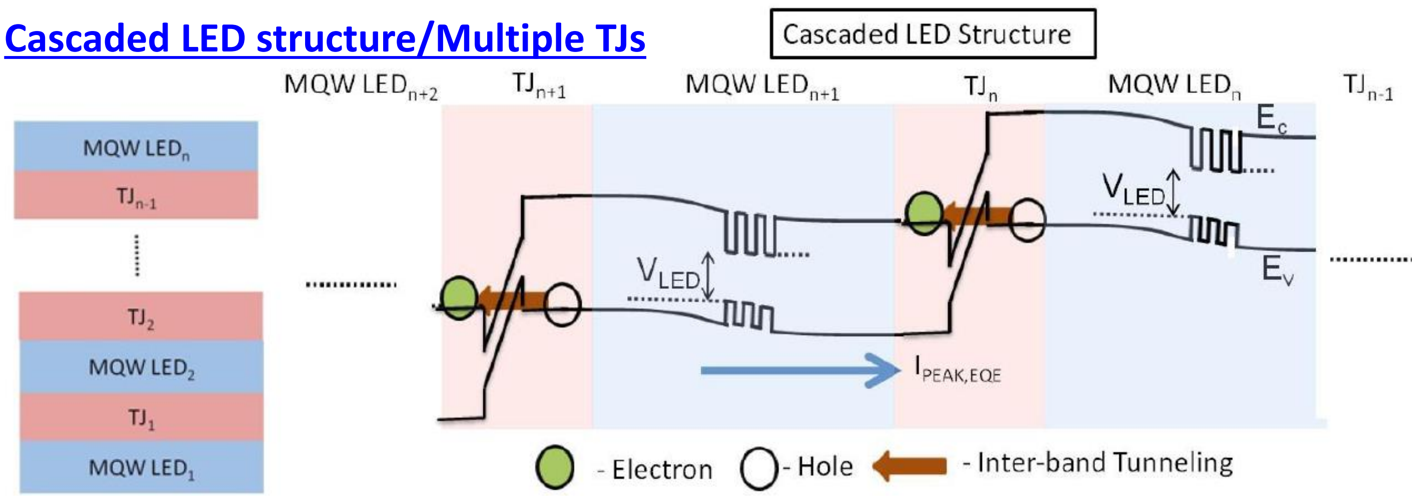
Single TJ:

- Avoids thick resistive p-layers and p-contacts

Multiple TJs / Cascaded Active Regions:

- Increases active volume
- Enables carrier recycling
  (> 100% quantum efficiency possible)
- High voltage/low current (carrier density) operation

Cascaded LED structure/Multiple TJs

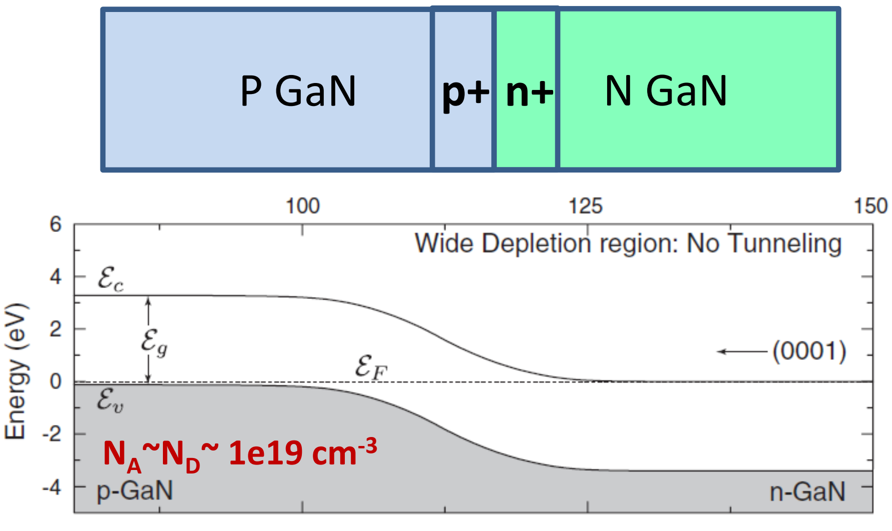


LED Input power
I x V

Krishnamoorthy et al. SPIE 2014

Challenges and Solutions to TJs in III-N Semiconductors

TJs via degenerate doping



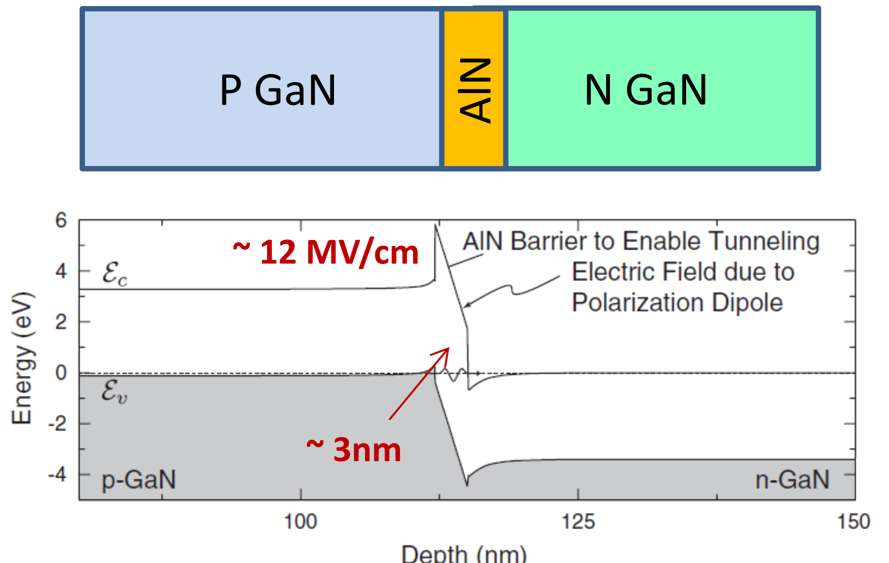
Simon PRL 2009

- **Challenging for WBG materials**
- **Large tunnel barriers due to high bandgaps and difficulties in achieving high doping levels**

Early Reports : InGaN LEDs

Jeon et al. APL 2001
Takeuchi et al. SPIE 2002 } $V_{TJ} > 0.5$ V

Polarization Engineered TJs for polar III-Ns



Simon PRL 2009

- **Band-bending is achieved through polarization induced fields**
- **Potential for low resistance tunnel junction**

Refs:

Grundmann et al. PSSC 2007,
Simon et al. PRL 2009,
Schubert PRB 2010

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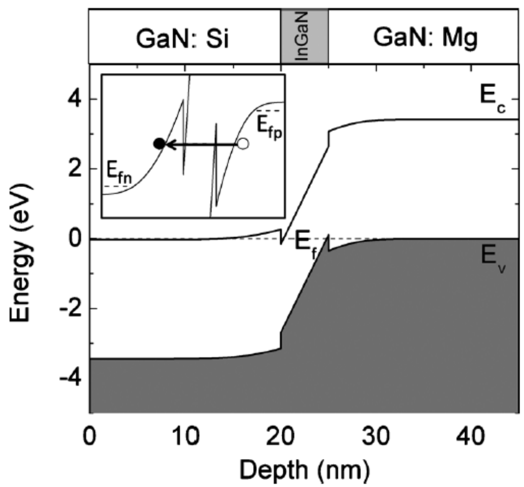
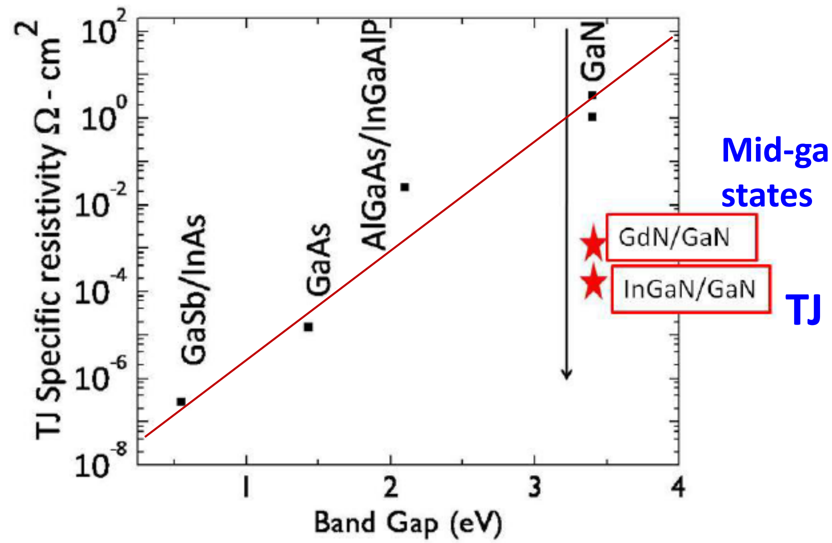
Recent III-N Tunnel Junction Advances

S. Rajan,
Ohio State

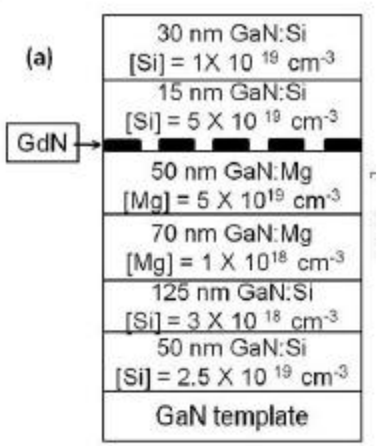
n-GaN/ InGaN /p-GaN TJ



TJ Specific Resistivity



GdN nanoisland (mid-gap states)



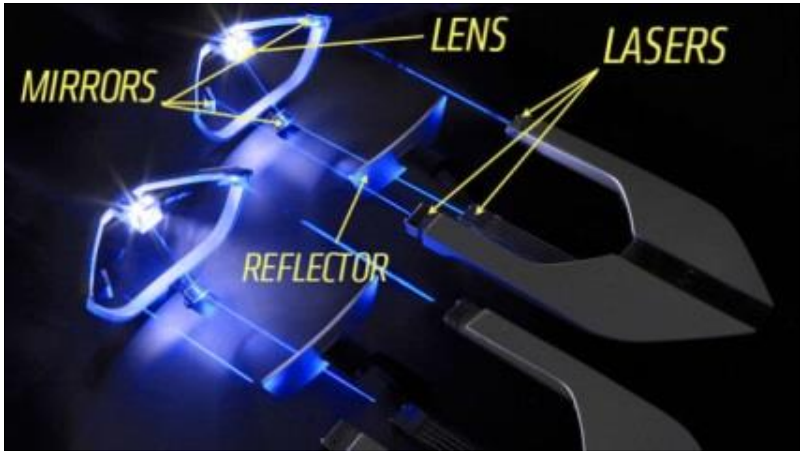
GaN/InGaN/GaN TJ:

- Current densities up to 9.2 kA/cm^2

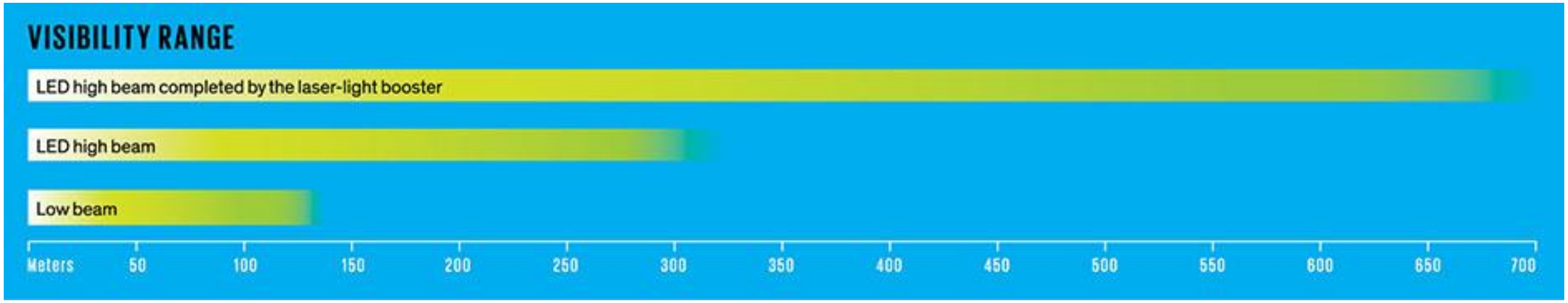
GdN Nanoislands:

- Viable for both Ga-polar and N-polar

Lasers for Solid-State Lighting: Blue lasers pumping phosphors



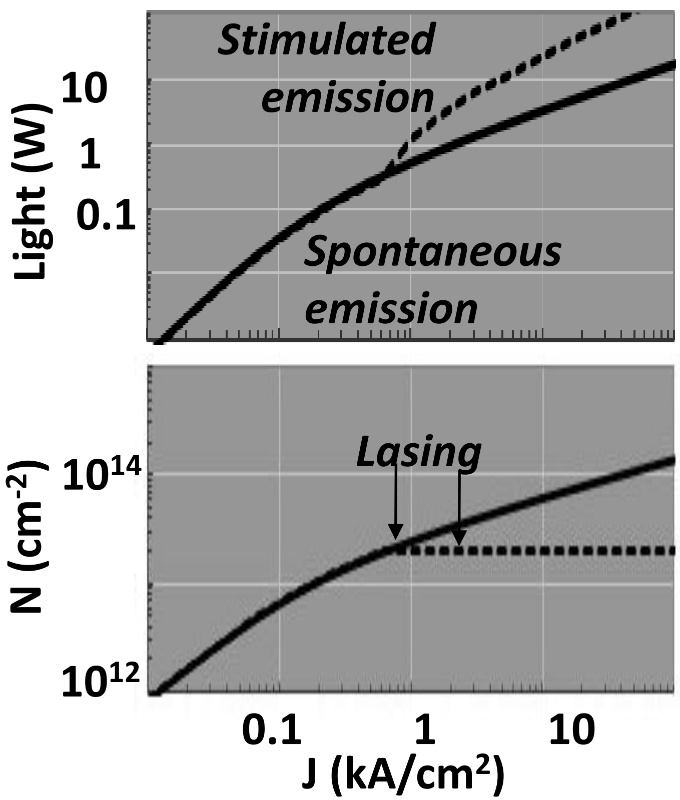
- Potential to be more powerful, more efficient and more compact than LED or traditional headlights
- BMW proposed features: pedestrian illumination, auto-dimming, steerable/adaptive headlights



http://spectrum.ieee.org/transportation/advanced-cars/bmw-laser-headlights-slice-through-the-dark

Lasers for SSL : Implications for Efficiency Droop

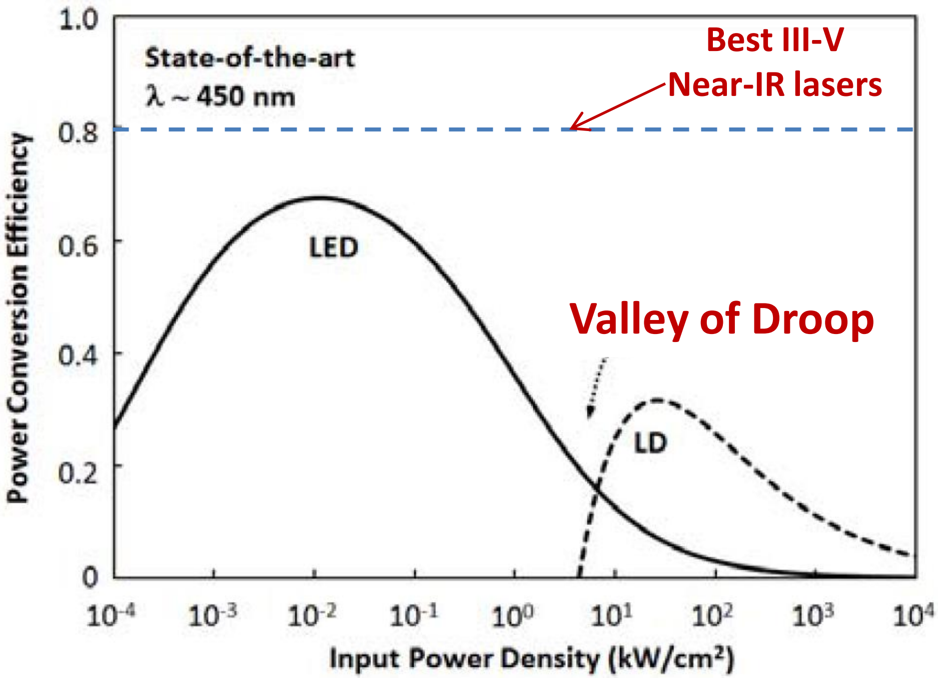
Carrier density clamping



Wierer et al. Laser Photon Rev 2013

Tsao et al., Adv Opt. Mat 2014

Efficiency comparison: LEDs vs. LD



Challenges for Nitride Lasers:

1) Greatly reduce threshold current densities
   (e.g., Quantum Dot Lasers with higher modal gain)
2) Improve overall efficiency
3) Reduce resistive losses

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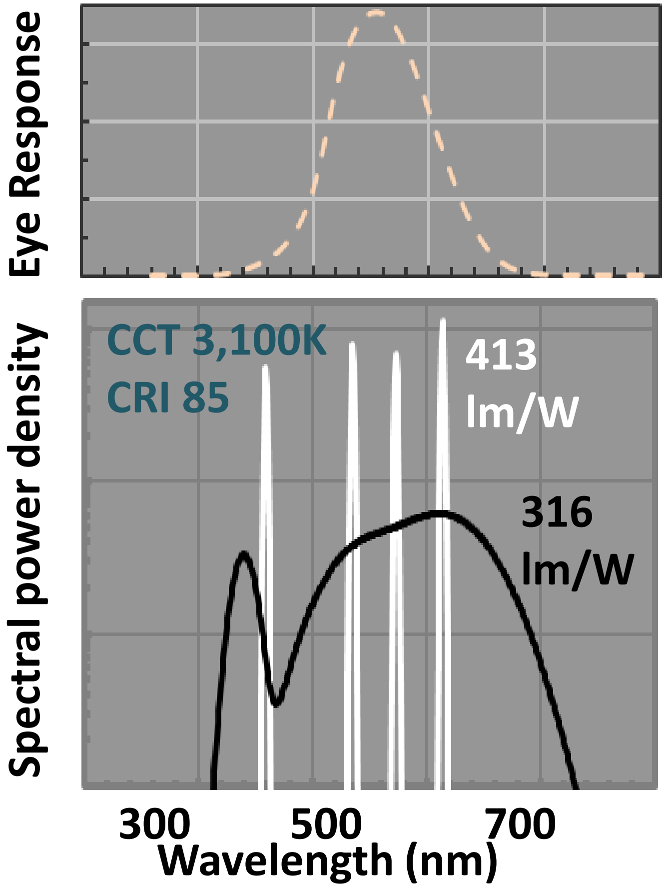
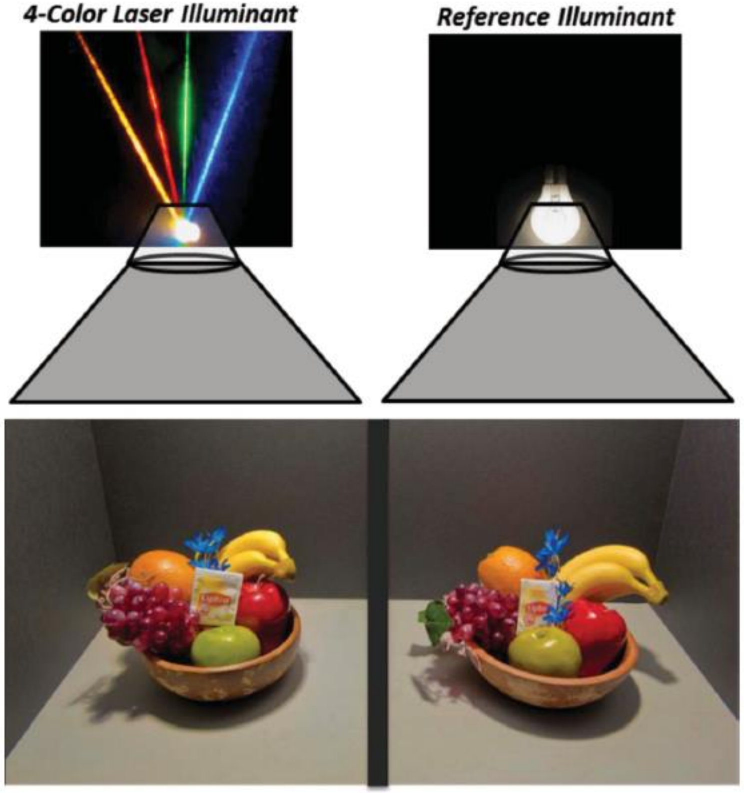
Lasers for SSL: Can direct laser emission render colors properly?

Narrow Spectra
High Luminous efficacy



Neumann et al., Optics Express 2011

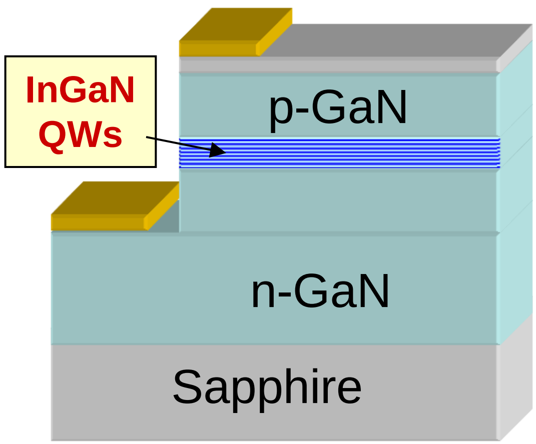
Potential for high Color Rendering Index (CRI)



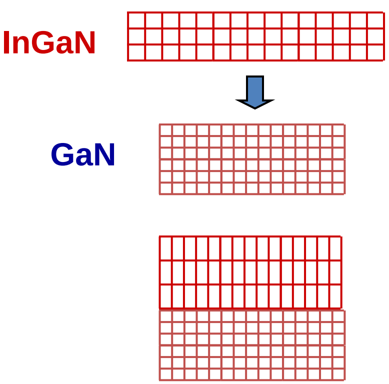
A four-color laser white illuminant was shown experimentally to be virtually indistinguishable from high quality state-of-the-art white reference illuminants

Second Grand Challenge:
Filling the Green-Yellow Gap

Issues related to ***high-indium-composition*** InGaN alloys:

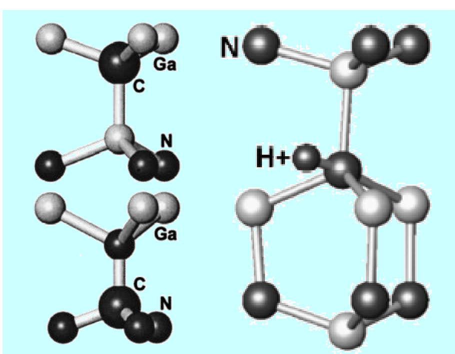


- Thermal instability→ require lower growth temperatures
  → potential for increased impurities, defects
- Lattice-mismatch strain when grown on GaN epilayers
  → reduced indium incorporation efficiency
  → enhanced defect formation
  → piezoelectric polarization



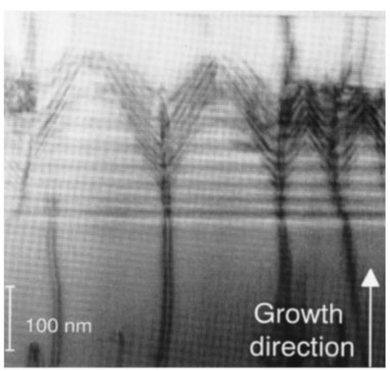
Compressively strained InGaN on GaN

Impurities and point defects



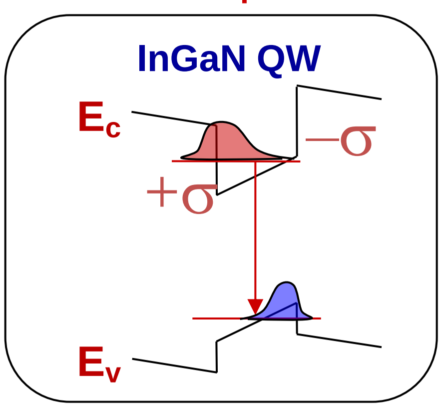
Wright et al., JAP 2002

"V- defects"



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

Piezoelectric polarization



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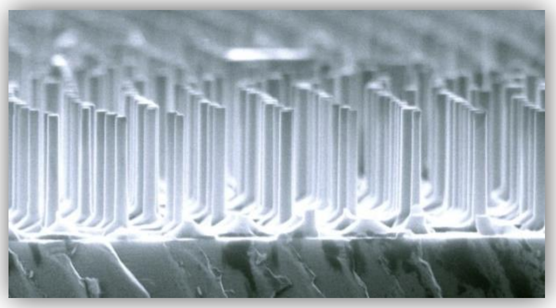
Nanostructured InGaN Materials

GaN nanowires

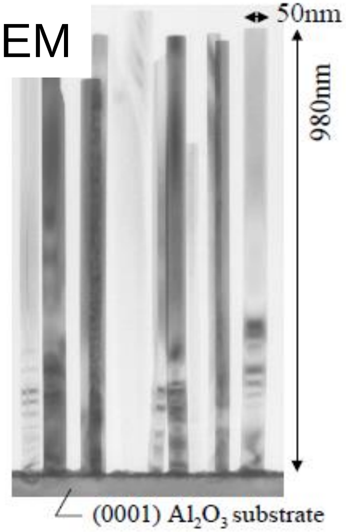


SANDIA: G. Wang, Q. Li

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

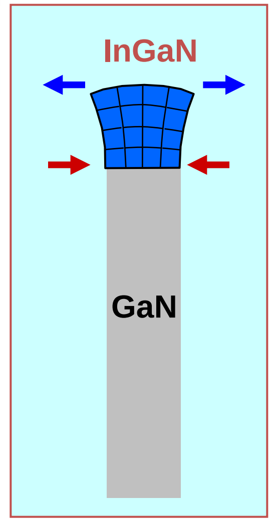
No threading defects

TEM

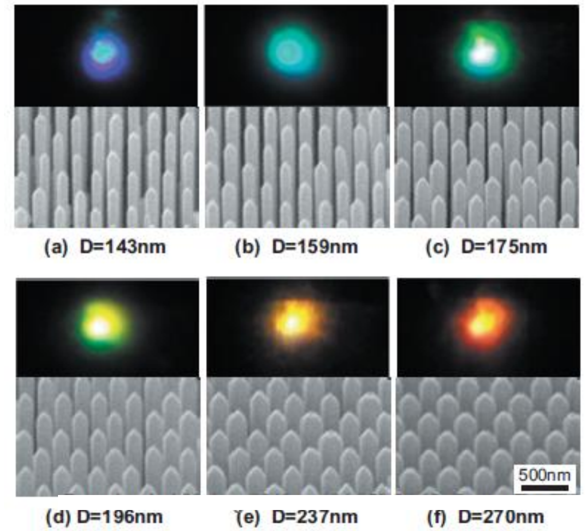


Kishino et al.,
Proc. SPIE 2007

Strain Accomodation



Broad range of emission wavelengths

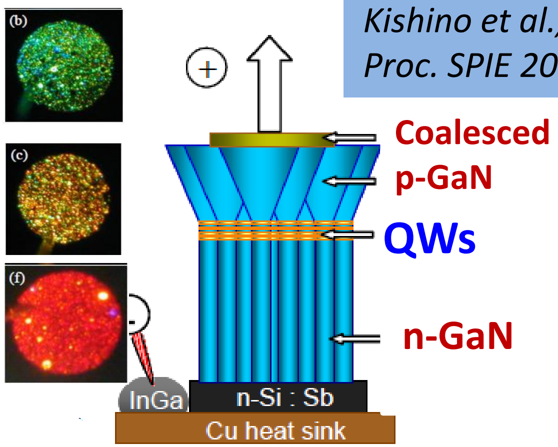


Color control by diameter

***Photoluminescence**: Sekiguchi et al APL 2010*

- Compatible with a wide range of substrates (including low-cost Si)
- Can be grown with virtually no threading defects
- Lateral structure allows strain accommodation
  - → reduced QCSE
  - → Increased indium incorporation (allows higher growth temps)

InGaN/GaN Nanowire Heterostructures:
Axial LED Geometries



Kishino et al., Proc. SPIE 2007

Outstanding Issues:

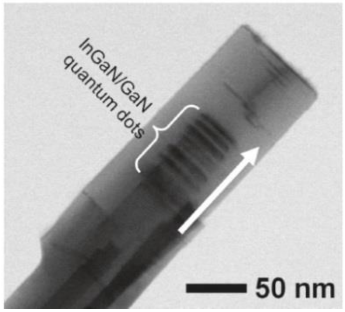
- Output powers/efficiencies
- Reduced active volume
- Emission Color Control
- Broad Linewidths (lm/W)
- Optimized device architectures

(thermal, light extraction, etc.)

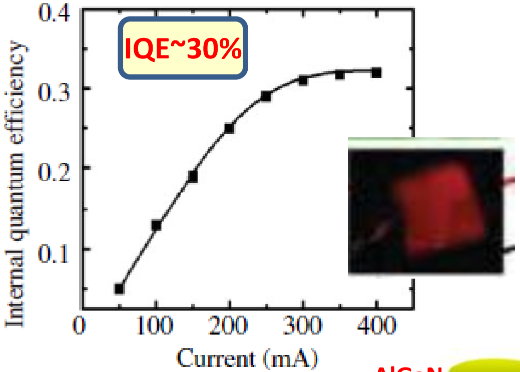
Advances: "Dot-in-a-Wire" Structures

(McGill Univ, Univ Michigan et al.)

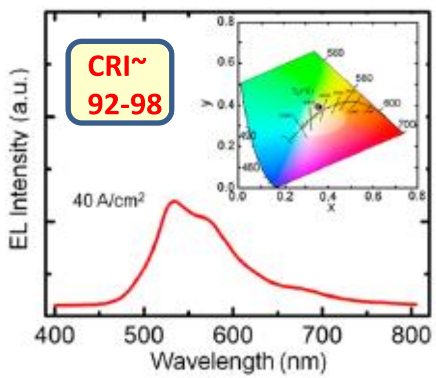
Self-Aligned dot formation



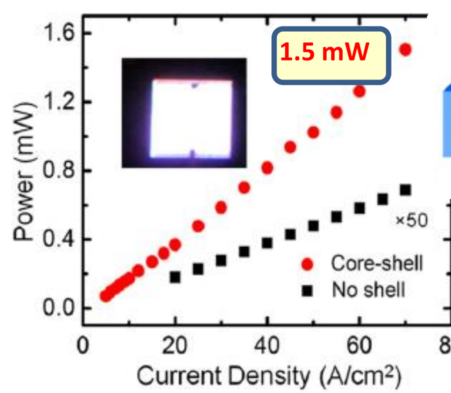
Improving IQEs into red region

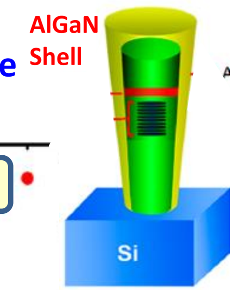


White Emission/ High CRI



Reduced surface Recombination



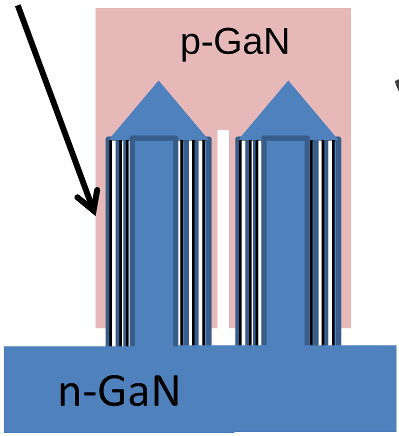


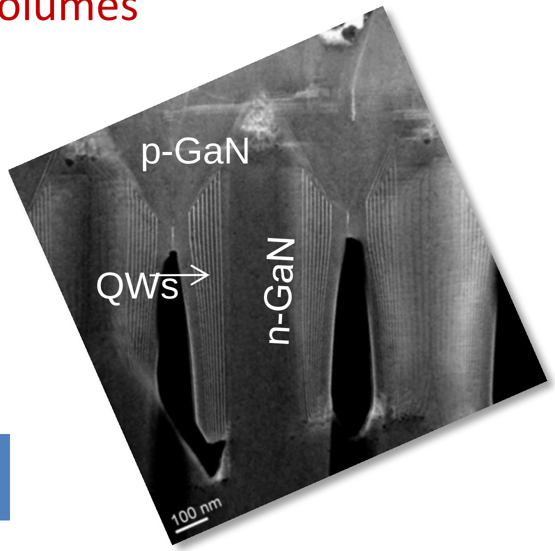
Nguyen et al Nanolett 2011 Nguyen et al IEEE PLT 2011

Nguyen et al Nanolett 2013

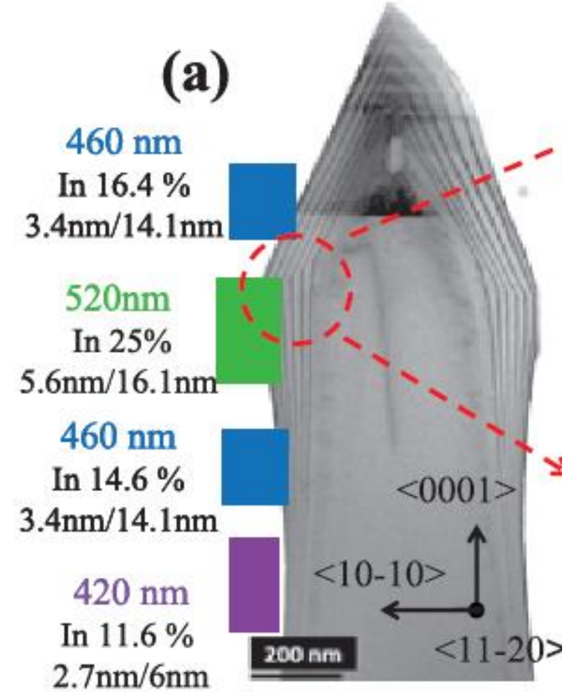
InGaN/GaN Nanowire Heterostructures:
Radial (core-shell) LED Geometries

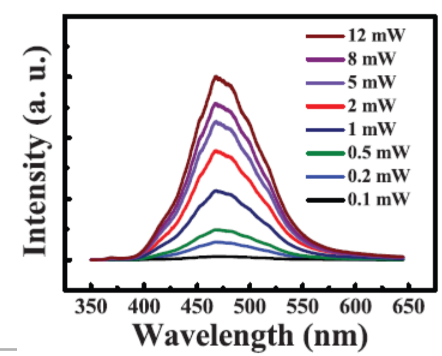
High Active Volumes





Composition/thickness variations





Outstanding Issues:

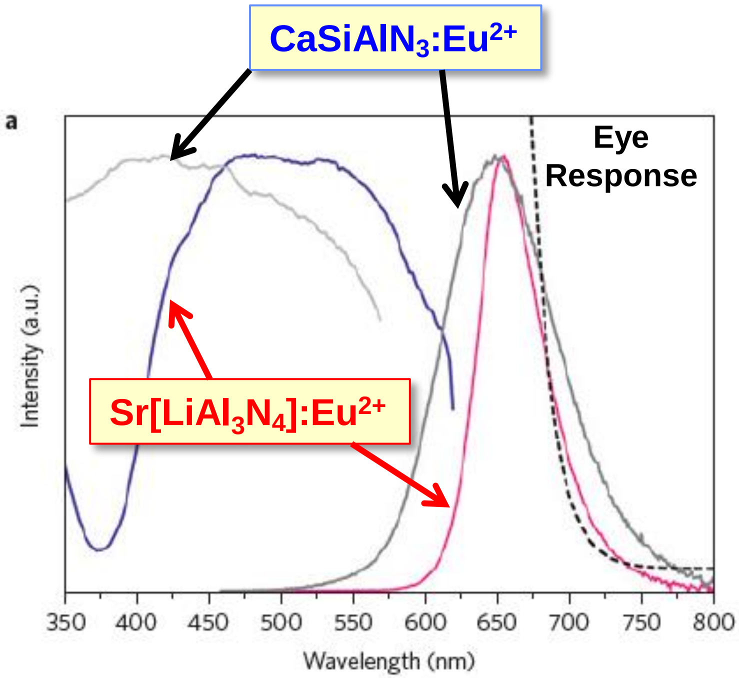
- Output powers/efficiencies
- Current injection/resistive p-GaN → ITO on sidewalls
- Color control/Large composition and thickness variations
- Broad linewidths, difficult to control for high quality white
- Optimized device architectures
  (e.g., photon recycling (m-plane QWs)/high IQE needed)

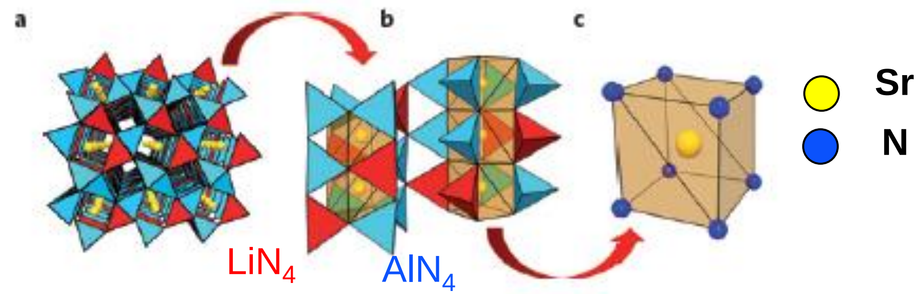
Chang et al. APL 2012
Riley et al. Nanolett 2013

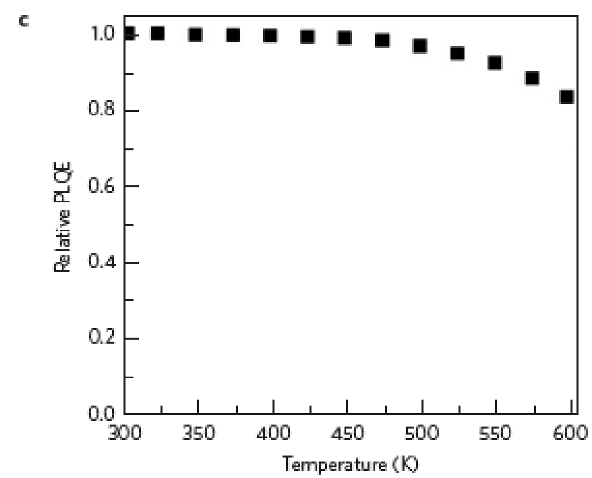
Third Grand Challenge:
Narrow-band Red Emitter

Recent Phosphor Advances: $Sr[LiAl_3N_4]:Eu^{2+}$:

Univ. Munich
Philips







- ~50 nm linewidth centered at ~650 nm
- Low thermal quenching (> 95% at 200C)
- IQE=76%, EQE = 52% (powder) for 440 nm excitation

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Pust Nat Mat. 2014

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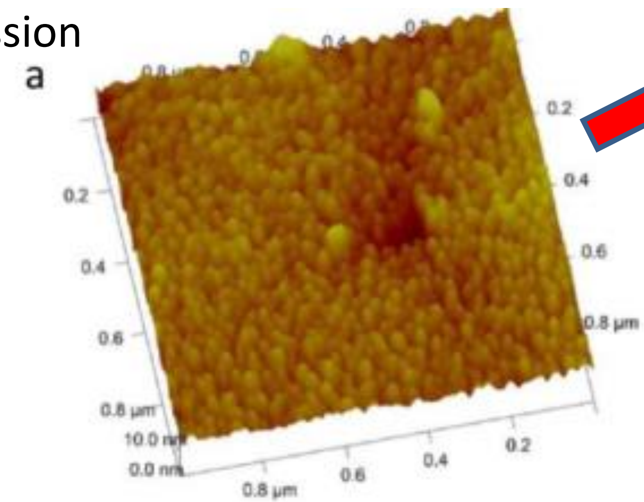
Narrow-band Red Emitter: Quantum Dot Laser

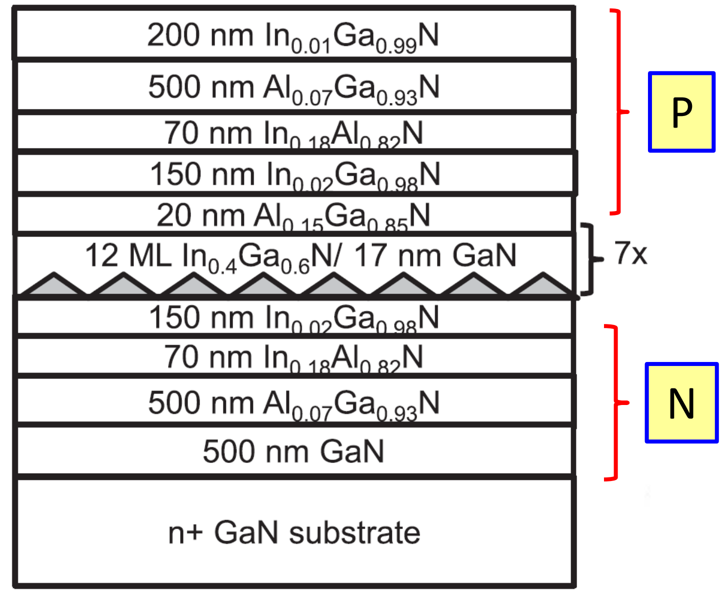
What is a Quantum Dot?

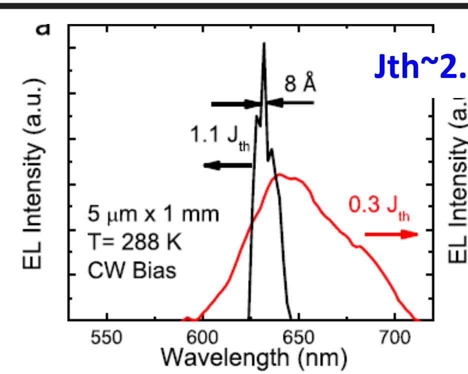
- Semiconductor particle or region small enough to exhibit quantum properties
- Often only 2-5 nm in diameter, ~50 atoms
- Emission wavelength tunable by size
- 3D confinement of carriers for potentially high efficiency emission



InGaN QD lasers

→ emission into the red region!





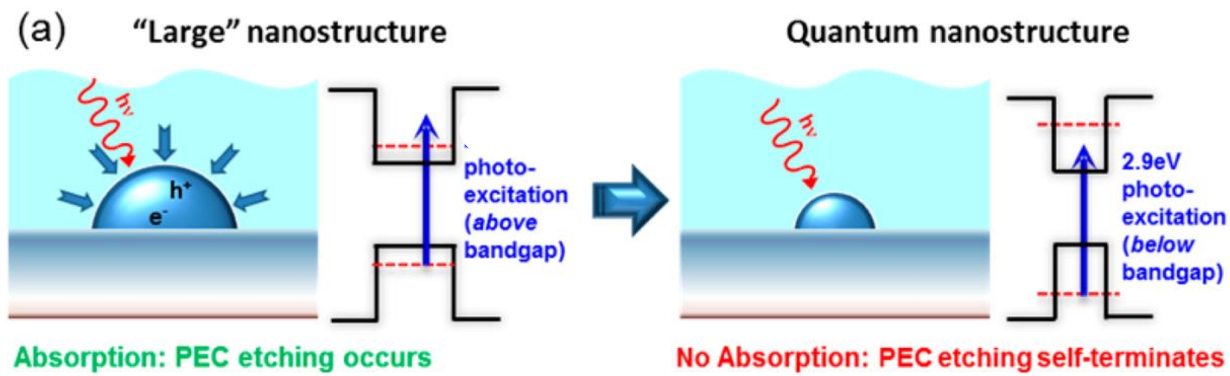
Jth~2.5 kA/cm²

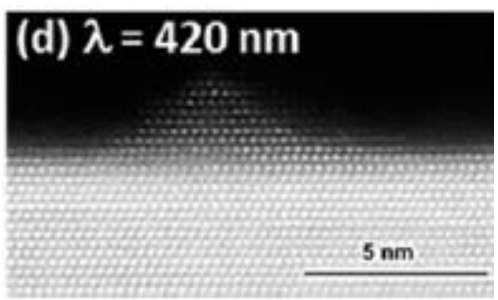
- Molecular Beam Epitaxial growth
- Self-organized QDs formed by strain relaxation
- Challenge of large size distribution, reduced peak gain

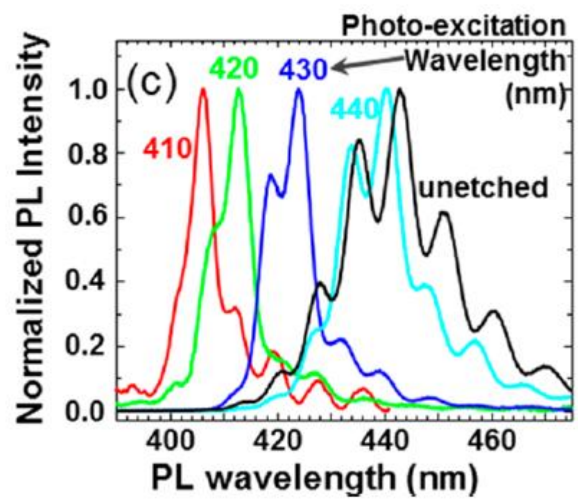
Frost et al. IEEE JQE 2013

Narrow-band Red Emitter: Quantum Dot LED or Laser

Epitaxial Semiconductor QDs: Quantum-Size Controlled Etching







1 um x 1 um area

- PEC etching of InGaN epilayer
- Sizes in quantum regime (< 5 nm)
- Notably narrower PL linewidths

Xiao et al., Nanolett 2014 (Sandia)

Conclusions

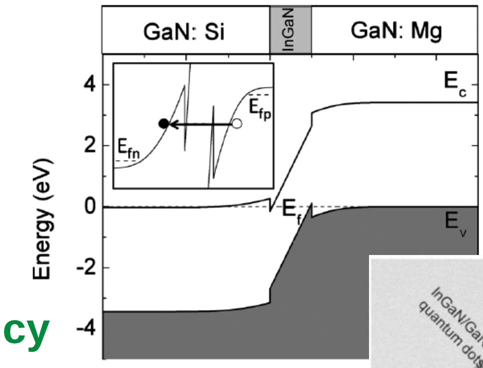
SSL has the potential to move significantly beyond traditional lighting, providing greater efficiencies and functionality

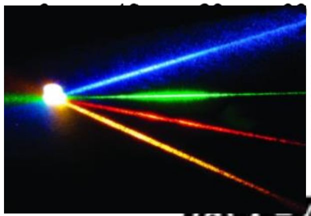
Breakdown of white LED component efficiencies identifies critical technical roadblocks to 50% and higher system efficiency and possible solutions:

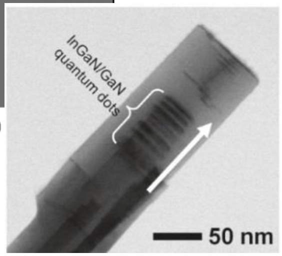
LED Efficiency droop:
- Volumetric approaches
- Tunnel junctions/cascaded LEDs
- Lasers for lighting /nanolasers

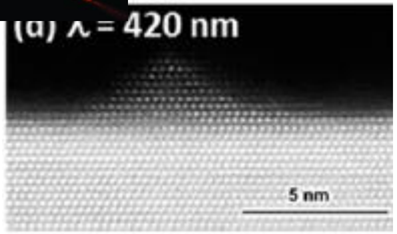
Bridging the green-yellow gap in LED efficiency
- Enabler for "smart lighting" concepts
- Nanostructured emitters

Narrow-band red emitter
- QD emitters
- Processes for narrow-linewidth nanostructured emitters





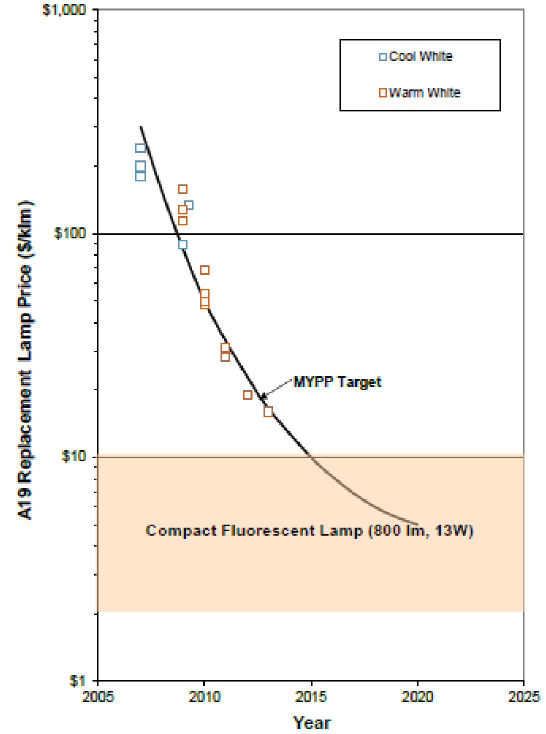




Back up slides

Summary of LED Lighting Performance, Cost, and Roadmap Targets

Lighting Source	Price ($/klm)
Halogen Lamp (A19 43W; 750 lumens)	$2.5
CFL (13W; 800 lumens)	$2
CFL (13W; 800 lumens, dimmable)	$10
Fluorescent Lamp and Ballast System (F32T8)	$4
LED Lamp (A19 12W; 800 lumens, dimmable)	$16
CFL 6" Downlight (13W; T4; ~500 lumens)	$10
LED 6" Downlight (11.5W; 625 lumens)	$43
OLED Panel	$500
OLED Luminaire	$1,400



Metric	2013	2015	2017	2020	Goal
Cool-White Efficacy (lm/W)	166	192	211	231	250
Cool-White Price ($/klm)	4	2	1.3	0.7	0.5
Warm-White Efficacy (lm/W)	135	169	197	225	250
Warm-White Price ($/klm)	5.1	2.3	1.4	0.7	0.5

*derived from DOE Multi-Year Program Plan 2014 (DOE/EE-1089)

DOE Roadmap Predictions for Evolution of LED Efficacy

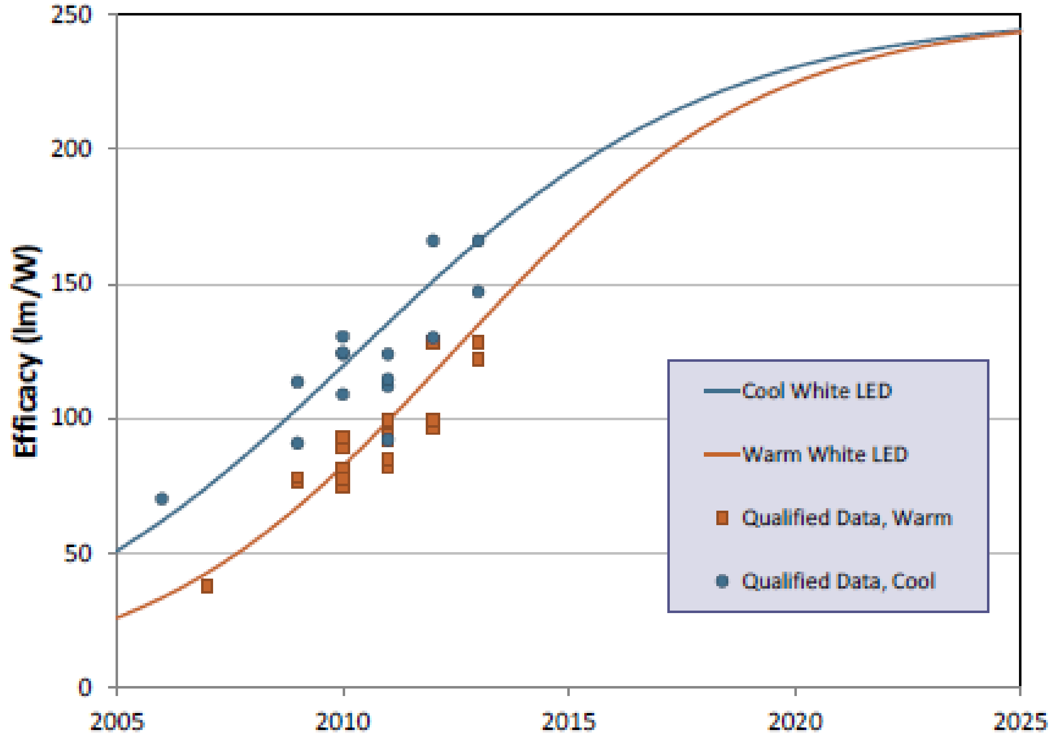


FIGURE 4.1 WHITE-LIGHT PC-LED PACKAGE EFFICACY PROJECTIONS FOR COMMERCIAL PRODUCT

All products produced to date use phosphor-converted or hybrid architectures. Hybrid LEDs will meet the asymptote more quickly than pc-LEDs due to the ready availability of narrow line-width red LED sources. Pc-LEDs will gradually approach the goal as narrower phosphors are developed (less than 50 nm). Cm-LEDs offer the prospect of even higher efficacies, provided green and amber LED sources can be developed with power conversion efficiencies in excess of 60 percent.

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*derived from DOE Multi-Year Program Plan 2014 (DOE/EE-1089)

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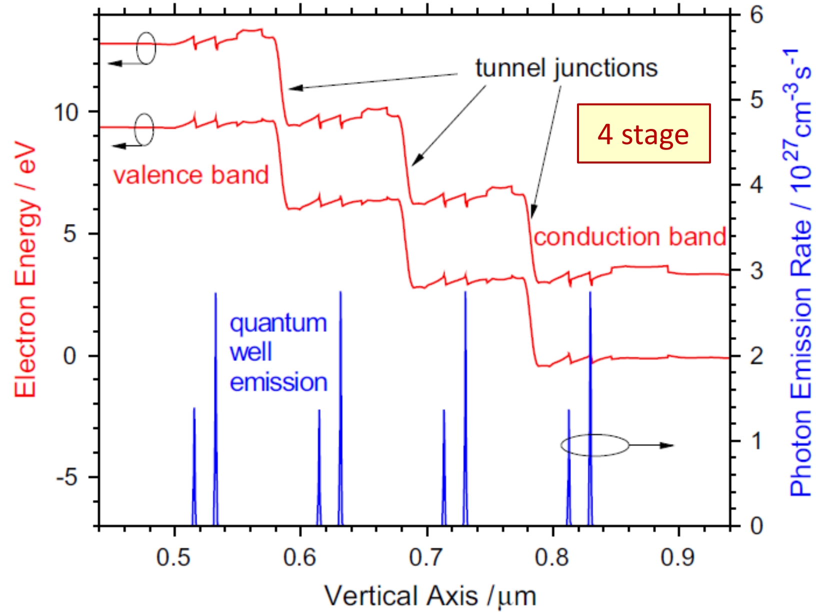
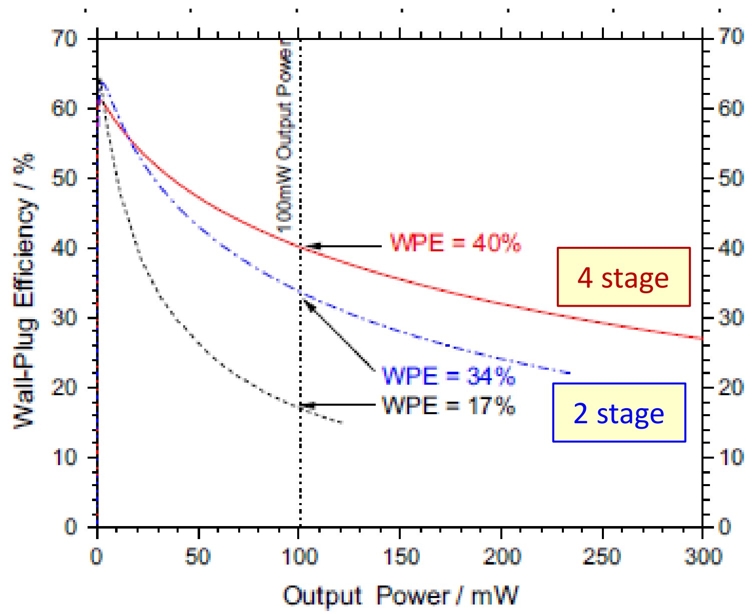
Recent III-N Tunnel Junction Modeling Results

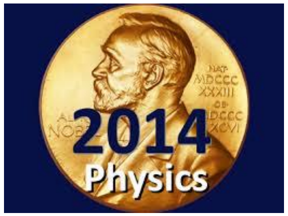
J. Piprek, NUSOD

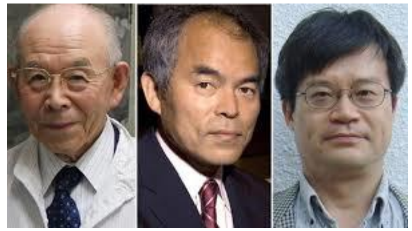




- Decisive efficiency benefits even without increasing number of QWs
- Combined benefits of uniform carrier distributions and carrier recycling
- Potential for > 100% quantum efficiency, improved WP efficiency, at relatively high output powers

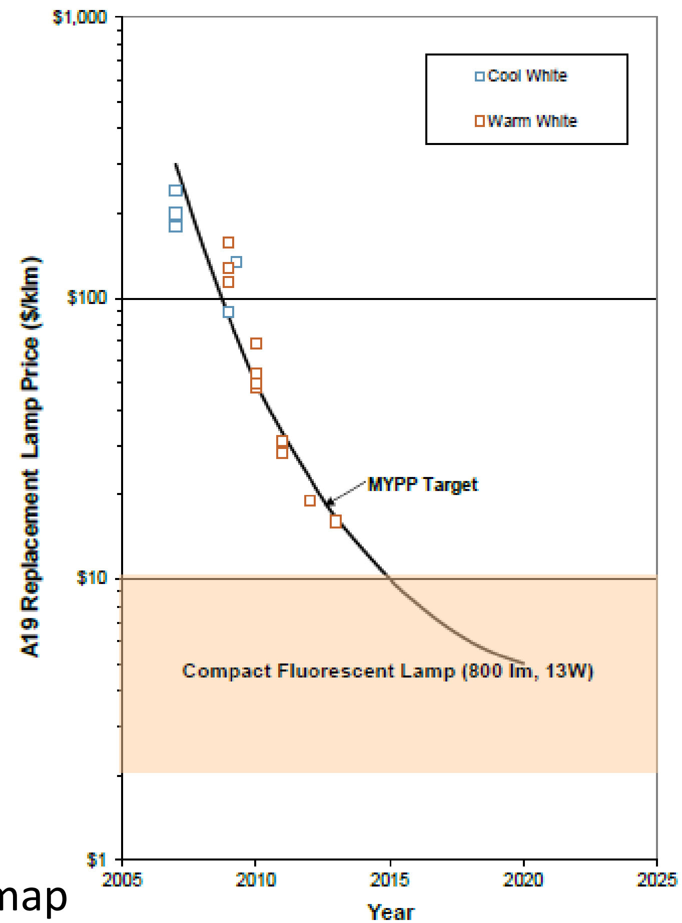
Next-Generation Lighting: Are we there yet?





Product Type	Luminous Efficacy (lm/W)	Wall Plug Efficiency (%)
LED A19 lamp (warm white)	**94**	**32**
Compact fluorescent lamp	73	25
Halogen	20	7
Incandescent	15	5

Evolution of A19 LED cost



LED-based White Lighting is:

- Surpassing traditional lighting in efficiency
- Cost effective over lifetime
- Declining in up-front costs, trending with DOE roadmap

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Numbers are representative examples,
data, plot from DOE Multi-Year Program Plan 2014 (DOE/EE-1089)

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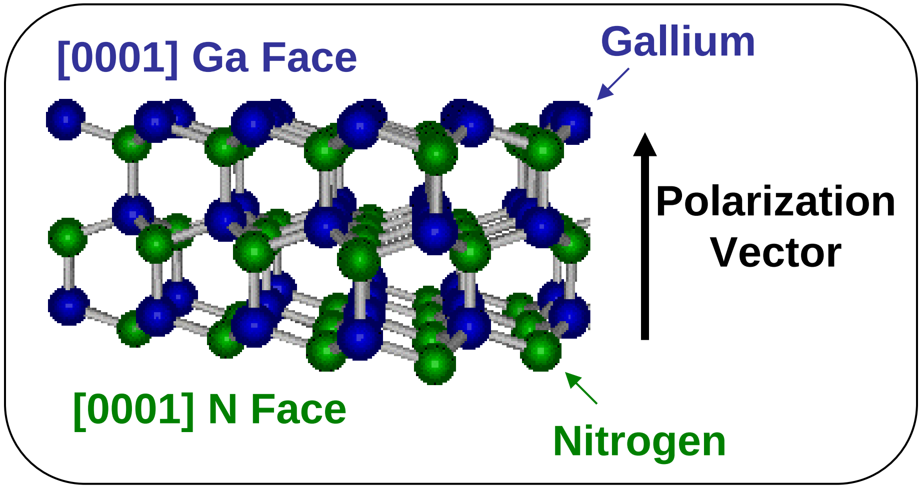
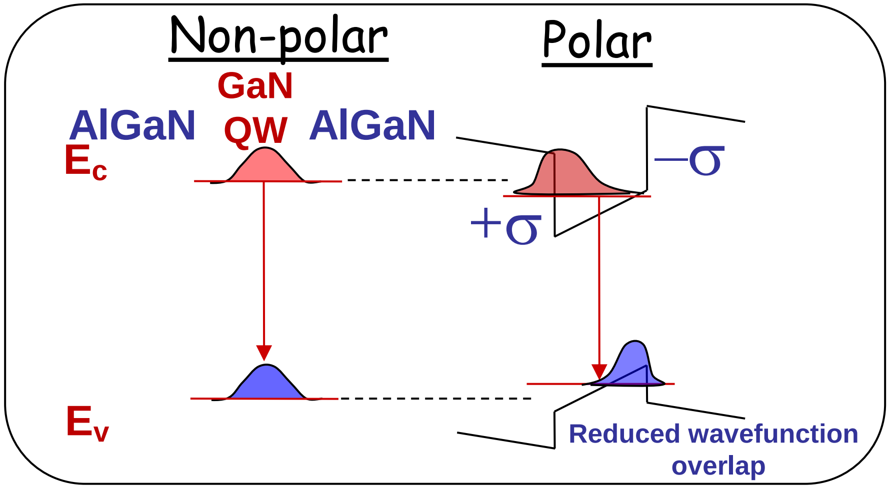
Property of GaN/InGaN: Spontaneous and Piezoelectric Polarization

Wurzite GaN crystal structure



Polarization effect on GaN quantum well



- Creates very large internal fields (~MV/cm) in InGaN QWs
- Quantum Confined Stark Effect
  → reduced electron hole overlap, can reduce radiative efficiency
  → wavelength shift with injection current as fields are screened
- Also positive effects e.g, enables tunnel junctions