LED Science and Technology Advancements

DOE SSL R&D Workshop
January 29-31, Nashville, Tennessee

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1/29/2018

LUMILEDS

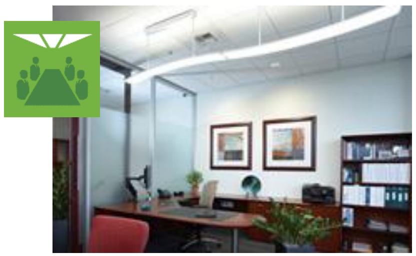
Outline

- Introduction
  - LED applications
  - Dominant LED architectures
  - Key LED metrics and progress
  - Remaining technology challenges
- Update on technology advancements
  - Droop in InGaN based LEDs
  - Green gap
  - Amber and red LEDs
  - Quantum Dots
- Technology impact on LED products (examples)
  - 90 CRI LEDs with QDs
  - High Luminance LEDs
  - Integrated, compact spot module
- Conclusions

Application Focus

Breadth of SSL applications requires a range of LED capabilities

High Efficacy — **High Luminance** | **Colors**



Indoor Area Lighting
- Mid/Low Power

Outdoor/Stadium
- High Power
- CSP

Spotlights
- HD CoB
- High Power
- CSP

Architectural
- Color
- High Power

Downlights
- COB
- Mid Power

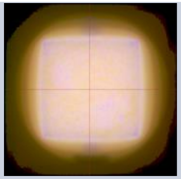
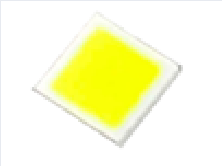
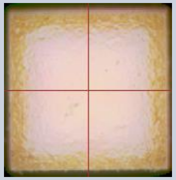
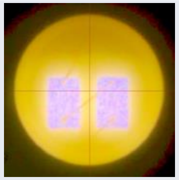
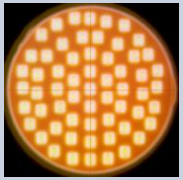
High Bay & Low Bay
- High Power
- MP

Specialty
- High Power
- CSP

Horticulture
- Color
- MP Color
- High Power

Relevant LED Architectures

Fundamental LED architectures and key characteristics

Emitter Type	Emitter image	Luminance	Efficacy	Directionality	Luminance	Source Size	Luminance Uniformity	Color over Angle	Color over Source
Domed High Power			++	++	++	++	++	++	++
Directional CSP			+	+++	+++	+++	+++	+++	+++
Non-directional CSP			++	+	+	++	++	++	++
Mid Power Low Power			+++	+++	+	++	+	+++	+
Chip on Board			++	+++	+	+	+	+++	+

LED Metrics

Critical LED metrics: Luminous efficacy and Luminance

Luminous efficacy: η_L (lm/W)

η_L = WPE x CE

The efficiency of a "white" LED converting electrical power to light perceptible by the human eye (lm/W)

WPE = IQE x EXE_n x ELE

- IQE : Internal Quantum Efficiency
- EXE_n : Extraction Efficiency
- ELE : Electrical Efficiency

Power conversion efficiency of blue LED (W_{opt}/W)

CE = LE x QED x QD x PE

- LE : Lumen Equivalent
- QED : Quantum Efficiency in Down Conversion
- QD : Quantum Deficit
- PE : Package Efficiency

Phosphor conversion efficiency (lm/W_{opt})

Luminance: L_V (cd/m² = nit)

$$L_V = d^2\,\Phi_V / (dS \times d\Omega \times \cos\Theta)$$

The luminous power per unit solid angle per unit projected area (cd/m²)

Increasing Luminance

- Higher drive current: Reduction of IQE and QED
- Smaller source size: Reduction of PE

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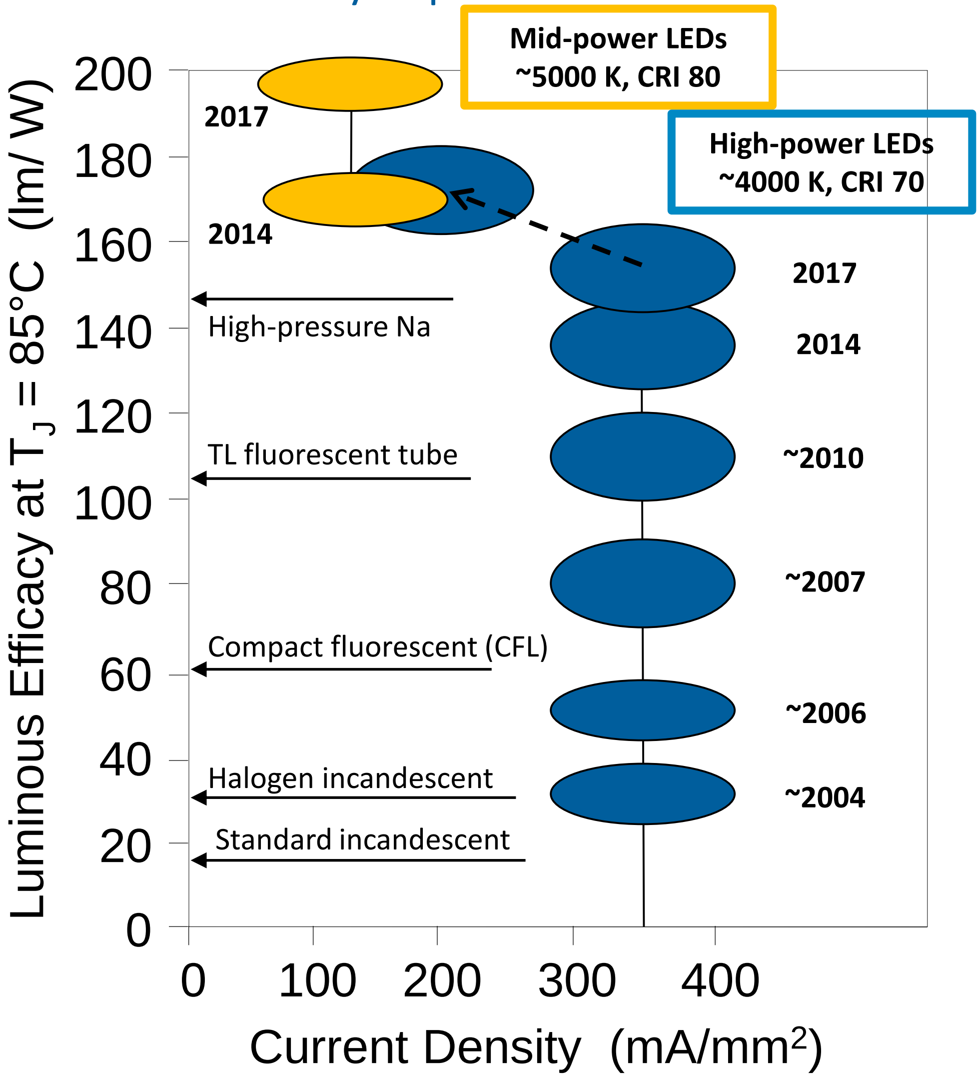
LED Progress

Substantial efficacy improvements



In addition, improvements in:

- "Quality of light"
  - High CRI available
  - Uniform CoS and CoA
  - Controlled radiation patterns
  - Glare control
- Lumen maintenance
- Color stability
- Cost reduction ($/lm)

Key Focus Areas for LED Technology Development

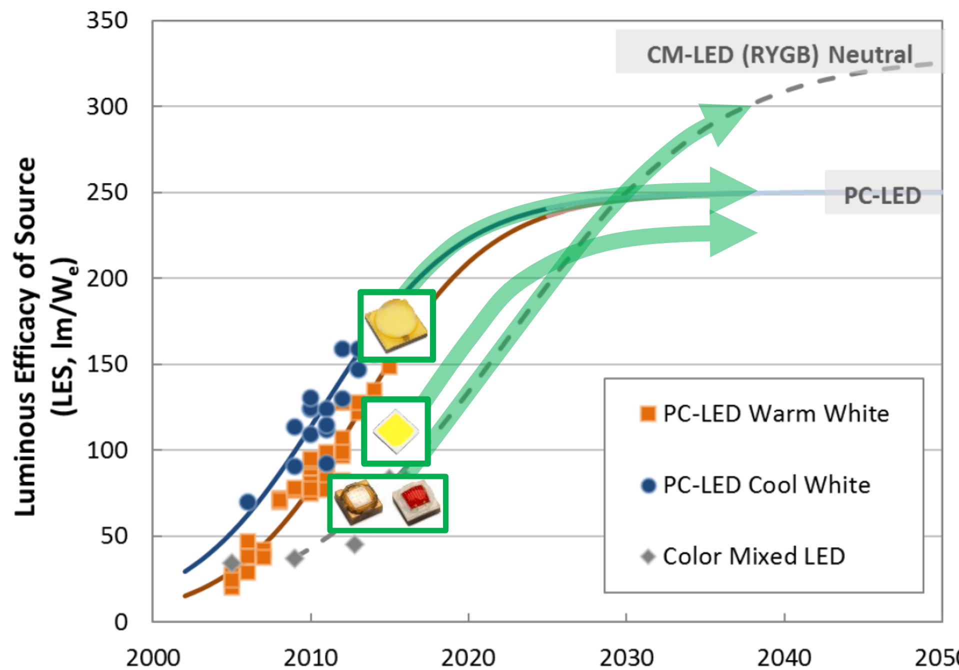
There is still a lot to do…

Further efficacy improvement

- Epi and die development
- Narrow band phosphors and QDs

Efficacy at high drive current for high luminance applications

- Droop reduction
- Converter saturation
- Efficient packages with small source size



From 2017 DOE SSL R&D Plan

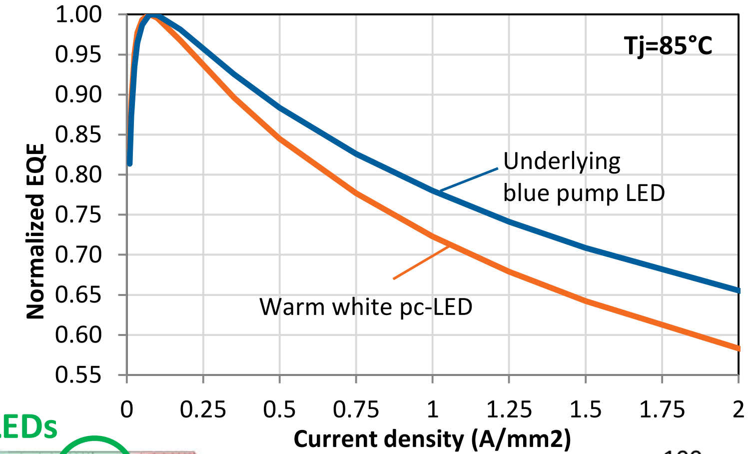
Efficacy across the visible spectrum

- Improve InGaN green and AlInGaP amber and red

Droop

"Droop" in InGaN based LEDs

Decrease in LED efficacy with increasing drive current



η_L = WPE x CE — *The efficiency of a "white" LED converting electrical power to light perceptible by the human eye (lm/W)*

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- IQE : Internal Quantum Efficiency
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- ELE : Electrical Efficiency

CE = LE x QED x QD x PE — *Phosphor conversion efficiency (lm/W_{opt})*

- LE : Lumen Equivalent
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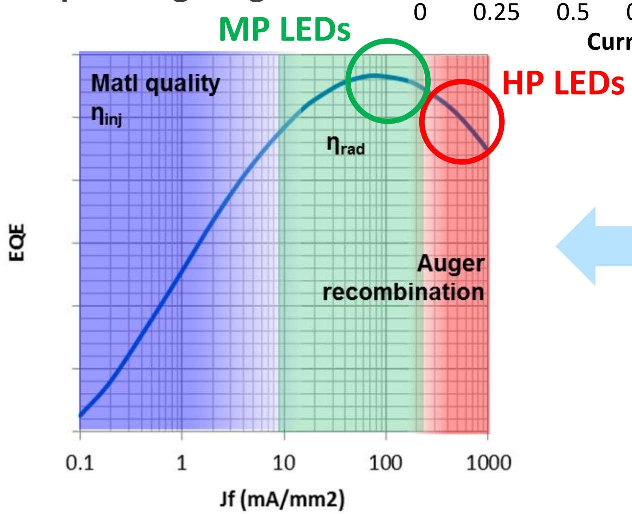
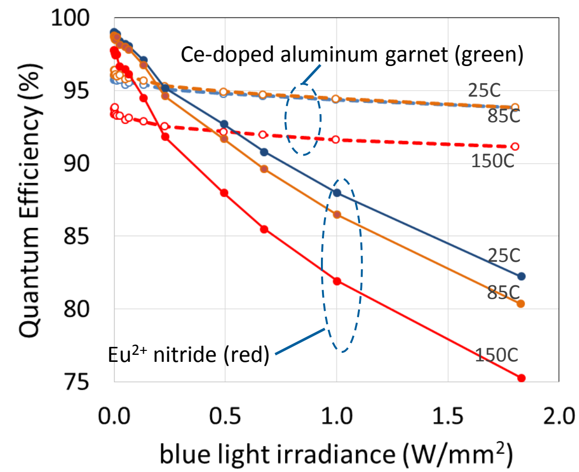
Typical operating range:





Epi droop: non-radiative recombination in active layers at high current density

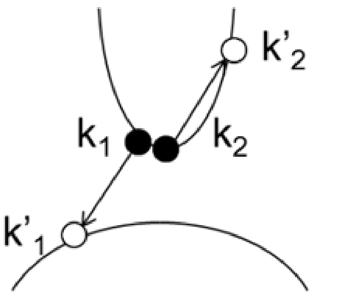
Phosphor droop: photothermal saturation of quantum efficiency of phosphor materials (esp. red)

 | February 5, 2018

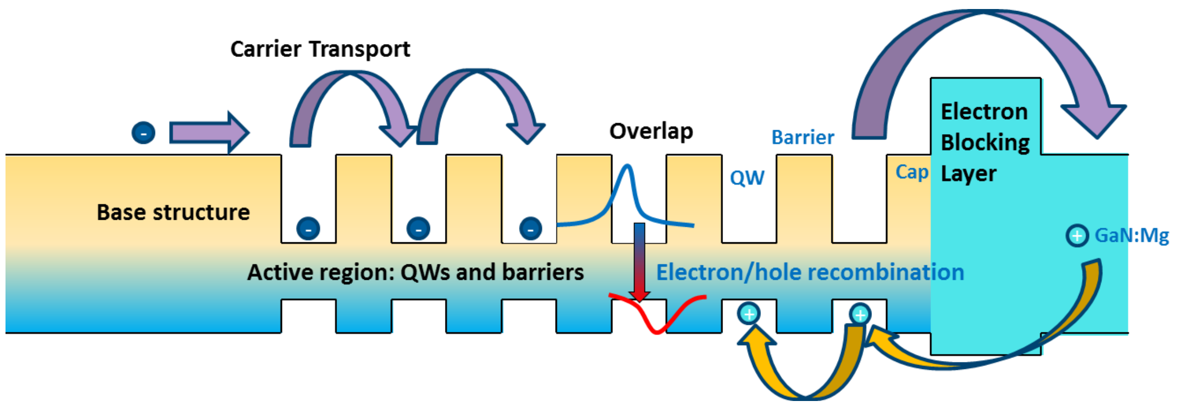
Origin of “Epi Droop”

Dominant mechanism: Auger recombination

n^2p Auger recombination



Schematic band diagram



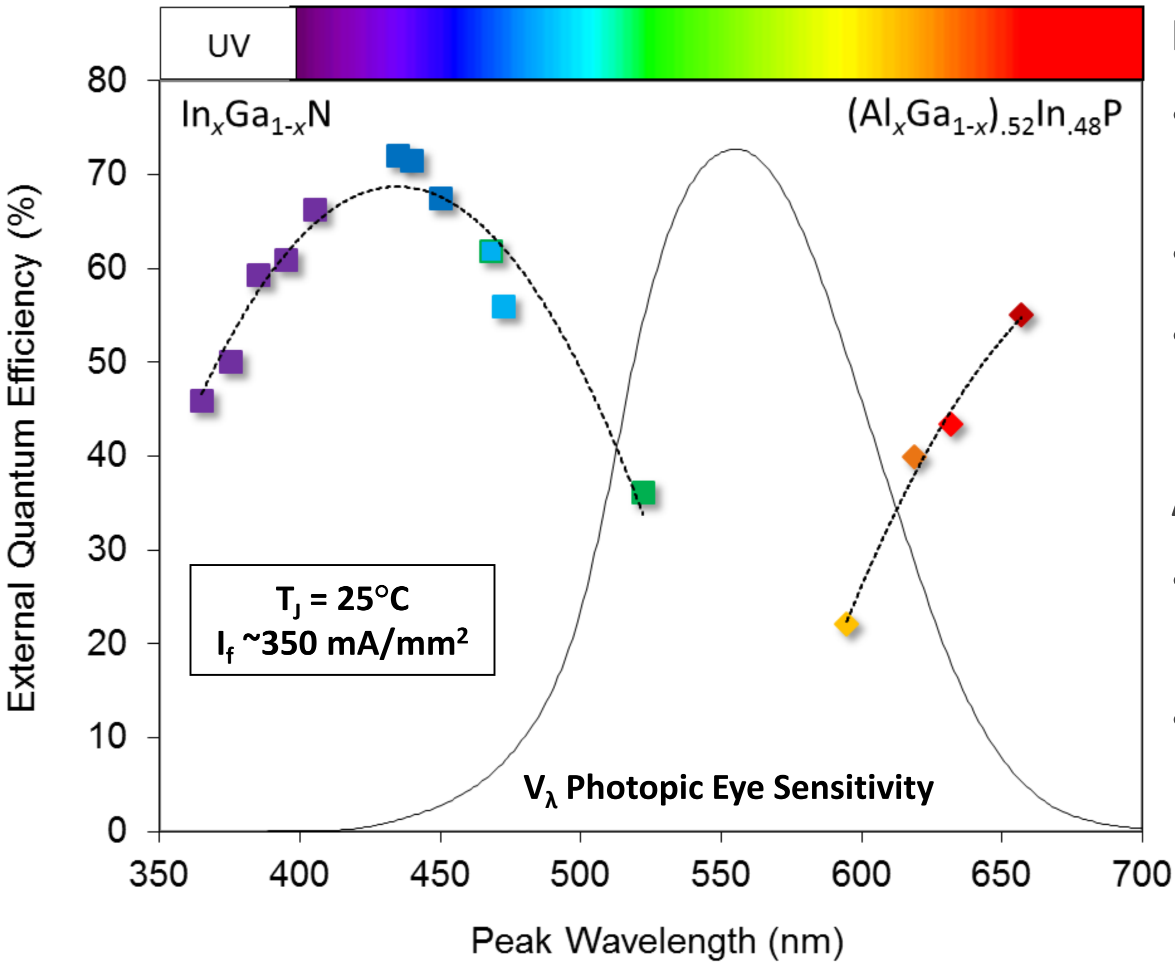
Key processes to consider:

- Carrier density in the QWs
  - Auger recombination increases with increasing carrier density
  - ➢ Reduce carrier density by improving electron and hole transport to spread carriers more evenly
- Radiative vs Auger recombination in QWs
  - Auger recombination increases as QW width decreases
  - ➢ Design of active region structure to improve radiative recombination rate
- Materials quality
  - The number and type of defects in the material has significant impact on performance (peak efficiency)
  - ➢ If thick QWs can be growth with good materials quality, the onset of efficiency droop can be pushed out

Green Gap

Green Gap

InGaN LED efficiency drops approaching green WL



Data from various manufacturers included

InGaN

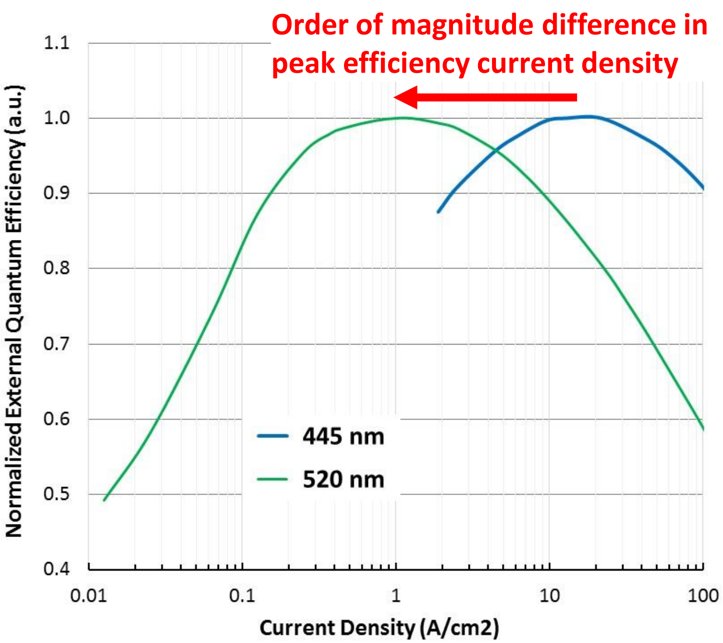
- EQE vs WL peaks at 425 nm (>70%)
- Royal blue (440nm) >65%
- EQE ~2x lower for green

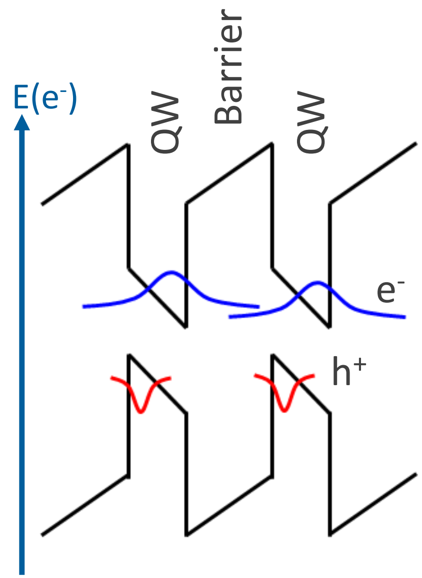
AlInGaP

- Band structure fundamentally limits EQE at shorter WL
- Inherent temperature dependency worse than InGaN

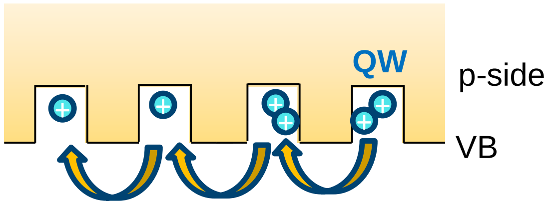
Efficacy of Direct Green Emitting LEDs

Green LEDs in “droop” regime at lower current densities

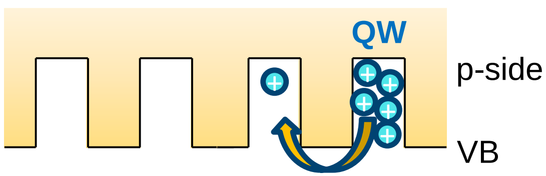




Active region with QWs emitting at Blue WL



Active region with QWs emitting at Green WL



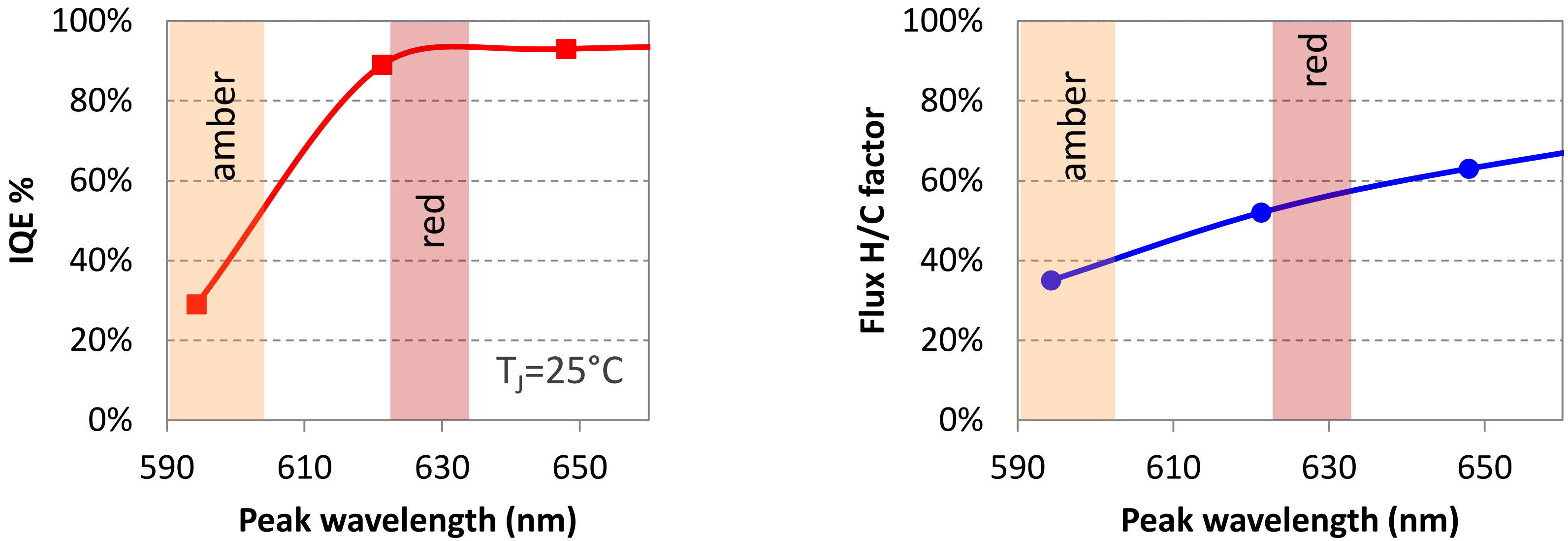
Contributing factors for lower efficiency in “Green Gap”:

- Lower IQE (or peak EQE):
  - Worse carrier overlap (larger polarization induced electric fields, which increase with increasing bias in c-plane)
  - Material quality challenges with higher indium in QW (lattice mismatch, miscibility gap, etc….)
- Worse efficiency Droop:
  - Greater energy barriers to carrier transport, which increases carrier density on p-side QWs → higher Auger
  - Worse electron-hole overlap reduces radiative rate, which increases carrier density in QWs → higher Auger

Amber and red AlInGaP LEDs

Efficiency of Direct Emitting AlInGaP LEDs

Reduced efficiency for amber LEDs and limited hot/cold factor



IQE is flux limiting for amber

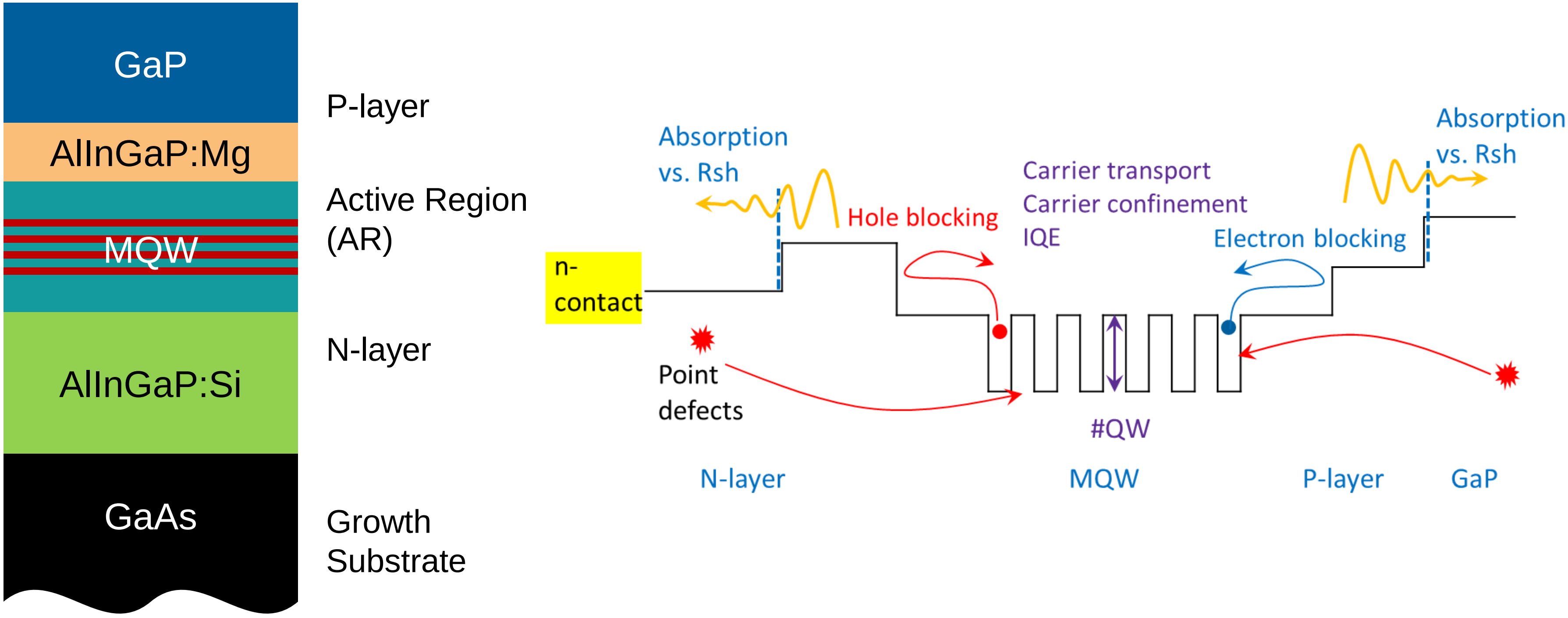
- IQE drops steeply when the Al% approaches 53%, because the bandgap transitions from direct to indirect
- IQE and H/C factor is ~ 30%

Light extraction is flux limiting for red

- IQE is ~80-90%, thus the light extraction efficiency is the limiting factor for flux
- Phosphide refractive index is high, resulting in light trapping inside the LED die

AlInGaP Epi Structure

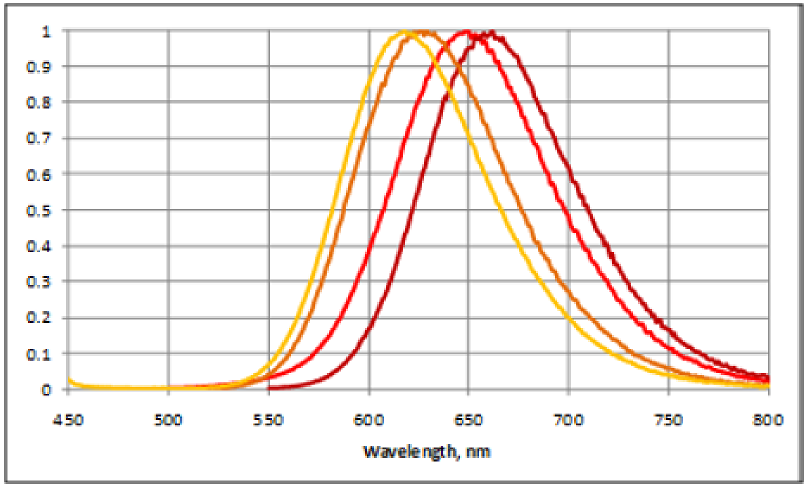
Key issues facing AlInGaP Technology

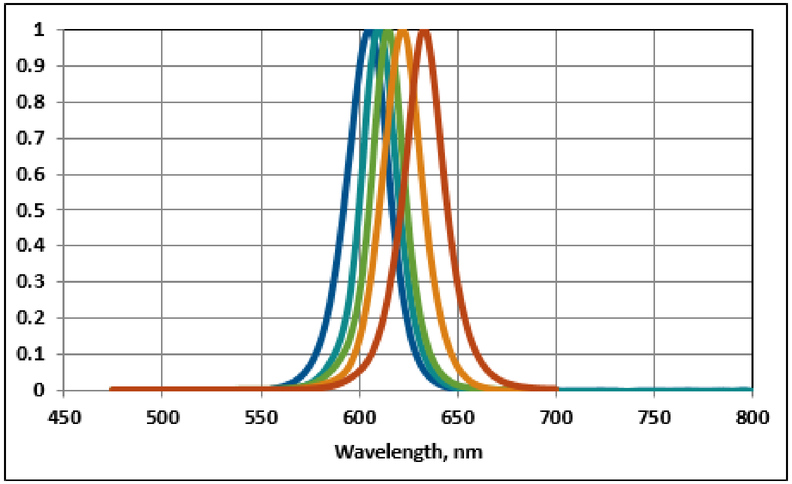


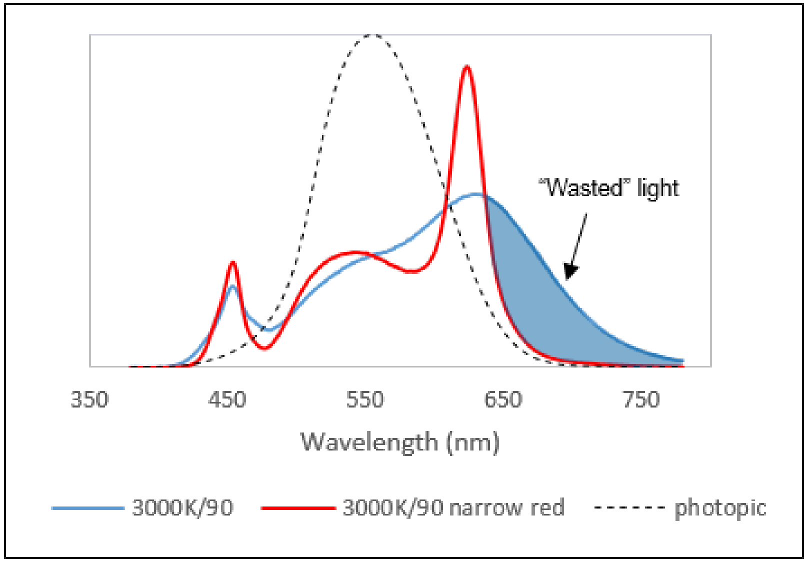
- Point defects originating from the growth substrate degrade active region
- Small Band offsets
- Carrier overflow significant for short WL devices
- Indirect band gap nature when wavelength gets close to amber

Quantum Dots

Quantifying the Benefits of Narrow Band Phosphors







Simulated FWHM Dependence for LE at 3000K and 90CRI

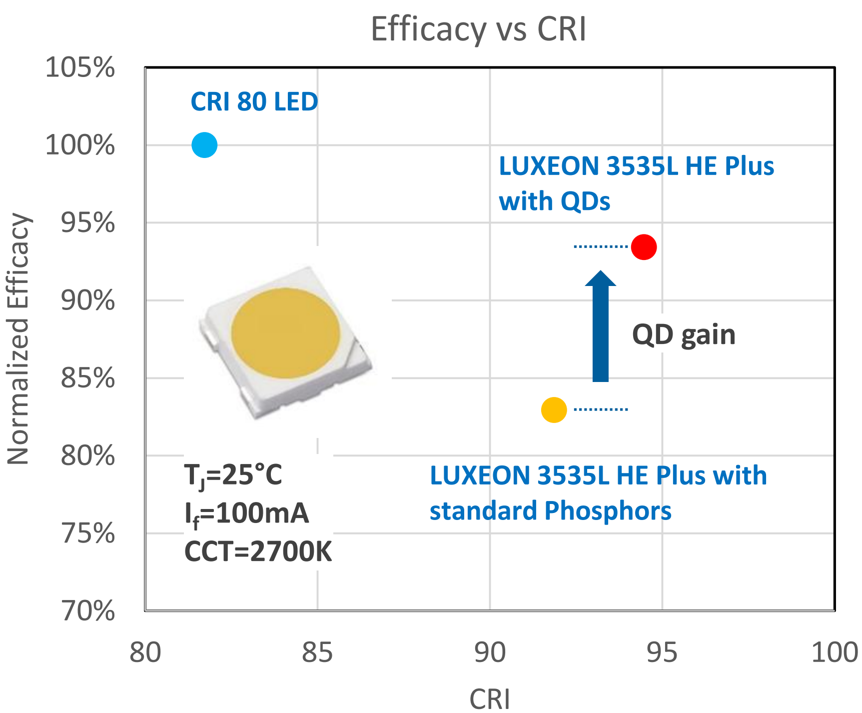
		Gaussian Green FWHM (nm)				
		30	50	70	90	110
Gaussian Red FWHM (nm)	30		117%	118%	116%	113%
	50		114%	113%	111%	109%
	70	110%	109%	107%	106%	105%
	90	105%	104%	102%	101%	100%

LE gains normalized to 90nm Red and 110nm Green FWHM

Technology impact on LED products (examples)

QD LEDs

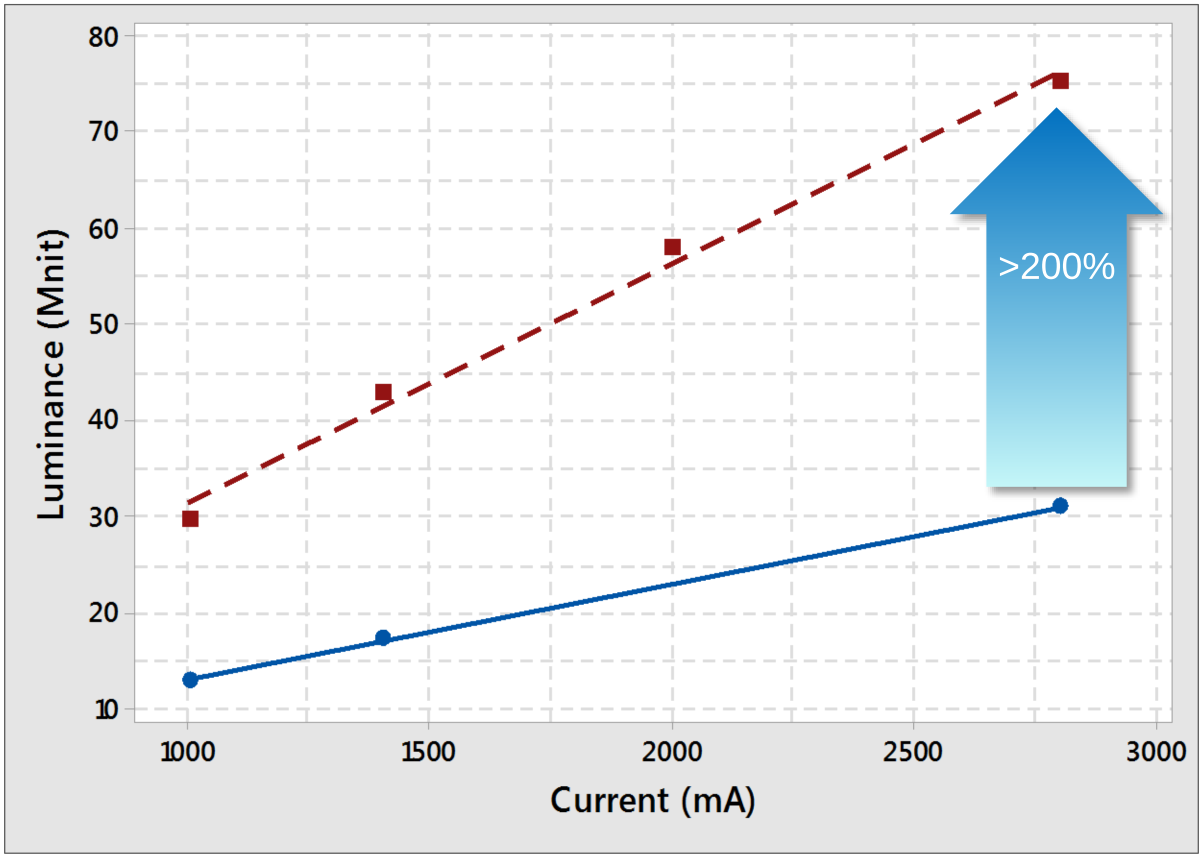
CRI 90 MP LEDs with QDs narrow gap to CRI 80

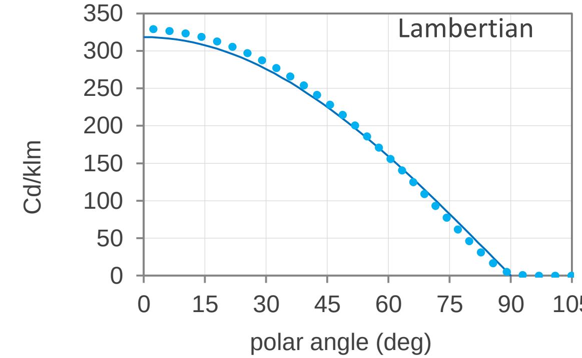


- Efficacy gap to comparable CRI 80 LED reduced to ~7% (2700K, CRI 80)
- Red QDs in on-chip configuration released in LUXEON 3535L HE Plus mid-power LED
- LED meets required reliability criteria

High-Luminance LEDs

High-drive CSP technology enables “bright” sources for highly directional applications





Metric	Typical value
Viewing angle	118°
Total included angle	140°
Forward emission	99.9%

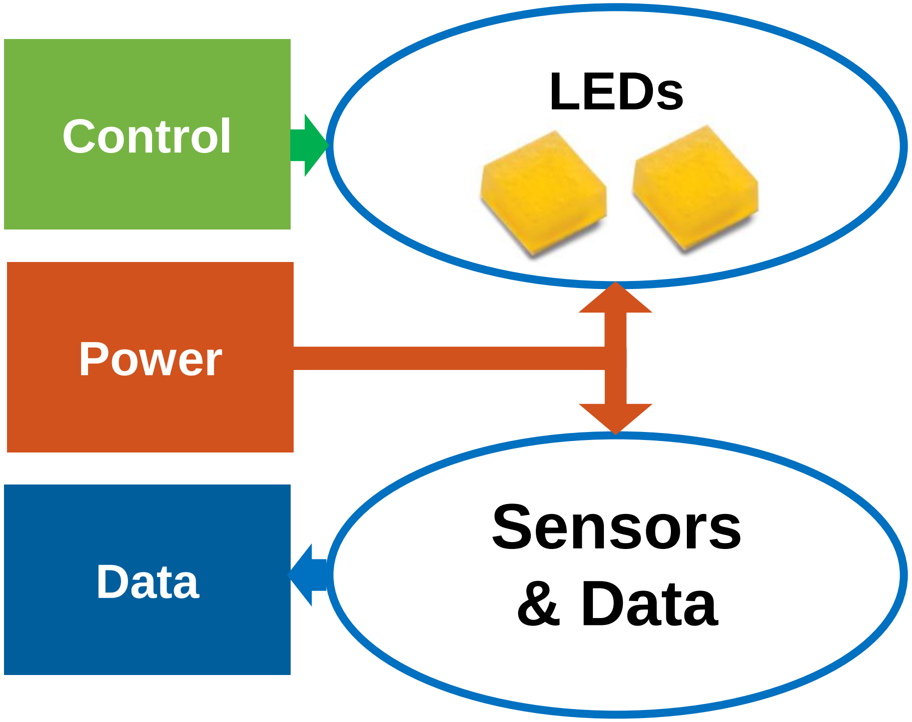
- Luminance of >75 Mnit from compact, Lambertian light source
- Enable small form factor luminaires with narrow beam angle and high punch
- Precise delivery of light where it is needed to drive energy savings

Compact Modular Light engine

High luminance LEDs enable small form-factor light engine

Enable upgrade-ability of light engine by:

- Tightly packing CSPs to allow for flexible high eténdue sources
- Choosing power and control partitioning to allow for standard interfaces
- Placing minimal electronics and intelligence on board with CSP array



Conclusions

LED technology advancements have resulted in substantial improvements

- **LED efficacy:** MP LEDs achieve ~200 lm/W and HP LEDs achieve 150 lm/W at their respective typical operating conditions
- **High drive current density operation:** Compact sources with high luminance are becoming available delivering up to 100Mnits with controlled forward directed beams
- **Quality of light:** Narrow band red phosphors and QDs enable CRI 90+ LEDs with efficacy close to CRI 80 LEDs (~7% gap with QDs)
- **Direct color LEDs:** Quantum efficiency of direct emitting green and amber LEDs continues to improve. Green InGaN LEDs with EQE >35% at operating conditions are now commercially available and have the potential for significant further advancement

Buildings

Retail

Outdoor Spaces

Human-centric

Horticulture

Embedded lighting

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