Progress and outlook for III-nitride blue, green and longer wavelength direct emitters

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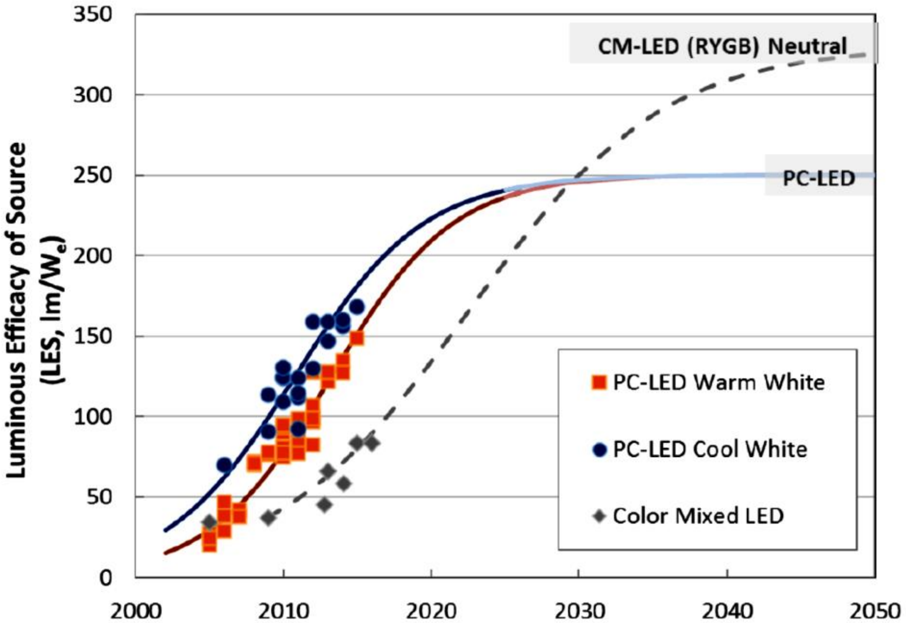
White and Blue performance improvement progress

White LED Luminous Efficacy improvement over time



DOE SSL 2017 Suggested Research Topics Supplement, Fig 4.4

Blue LED WPE improvement over time

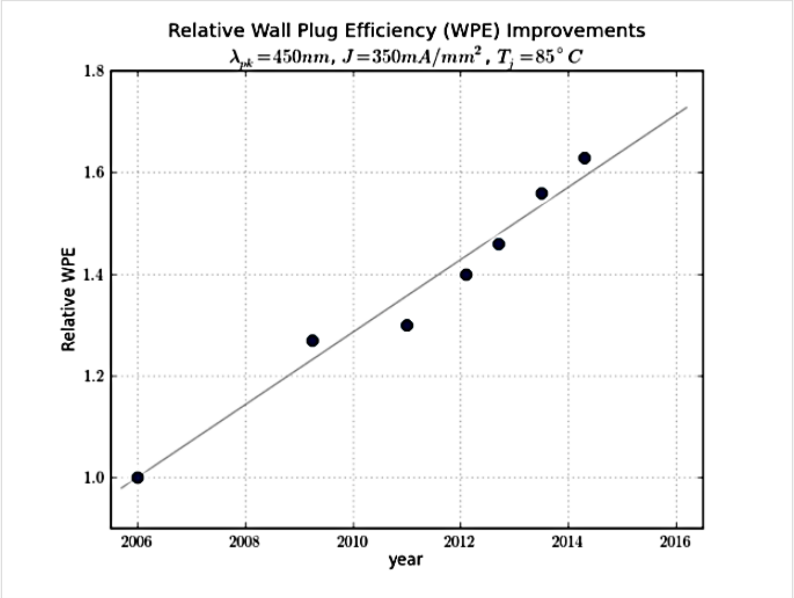


FIGURE 1: RELATIVE WALL PLUG EFFICIENCY IMPROVEMENTS AND CORRESPONDING GENERAL TREND LINE OVER TIME. ALL VALUES ARE NORMALIZED TO THE WPE NUMBER AT THE BEGINNING OF 2006.

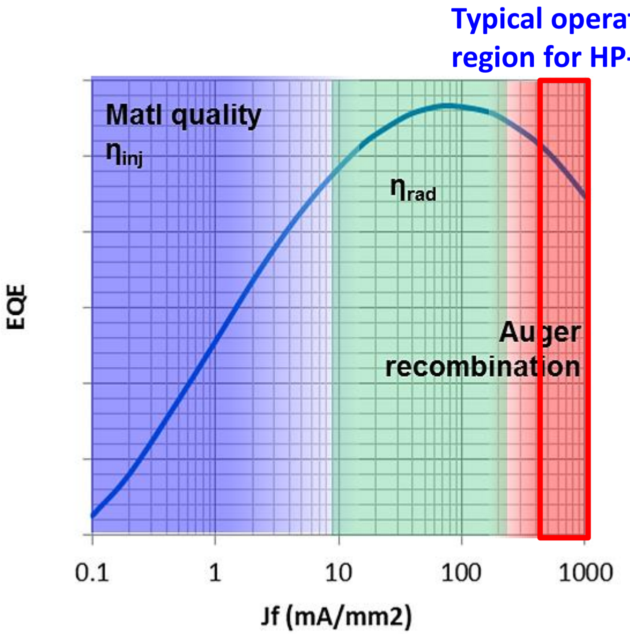
https://www.lumileds.com/technology/luxeon-technology/epi

3x increase in Luminous efficacy over past decade!

- Resulting from improvements in:
  - Phosphor Conversion efficiency
  - Package efficiency
  - Blue LED Wall Plug efficiency (percentages are general current status at 35 A/cm^2, 85C)
    - Internal Quantum efficiency (IQE) = # photons created / # of electrons input to LED: ~80%
    - Extraction efficiency (EXE) = # photons emitted from LED / # of photons created: ~85%
    - Electrical efficiency (ELE) = q x forward voltage / photon energy of emission: ~100%

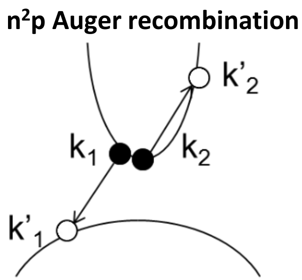
A. Tandon, et. al., Compound Semiconductor Magazine **Vol. 23** Issue 2 March 2017 p.36.

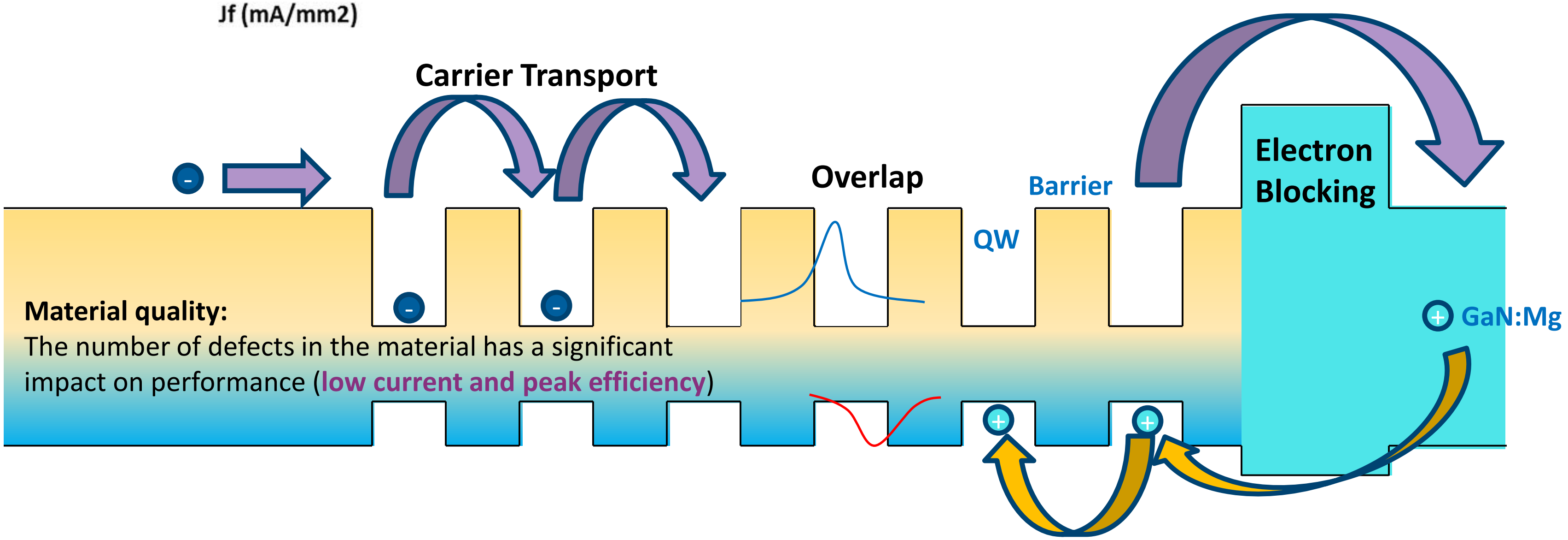
The Basics of LED Efficiency



Different mechanisms control IQE at different carrier densities

- ✓ Low current: SRH = material quality
- ✓ **High current: Auger recombination as the dominant mechanism of high current efficiency droop. Controlled by:**
  - **Auger constant in each QW**
  - **Carrier density in each QW**





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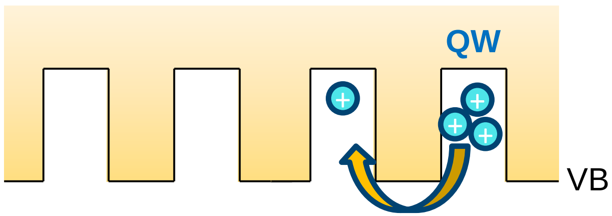
Auger and Carrier Density: Carrier Transport

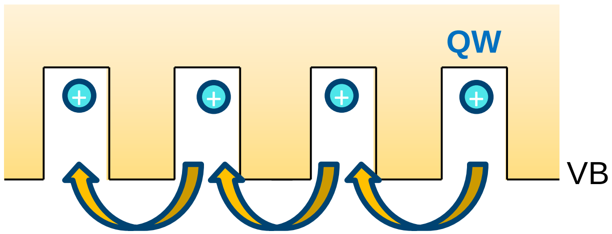
Improving carrier distribution by improving hole transport

Standard Active Region Design



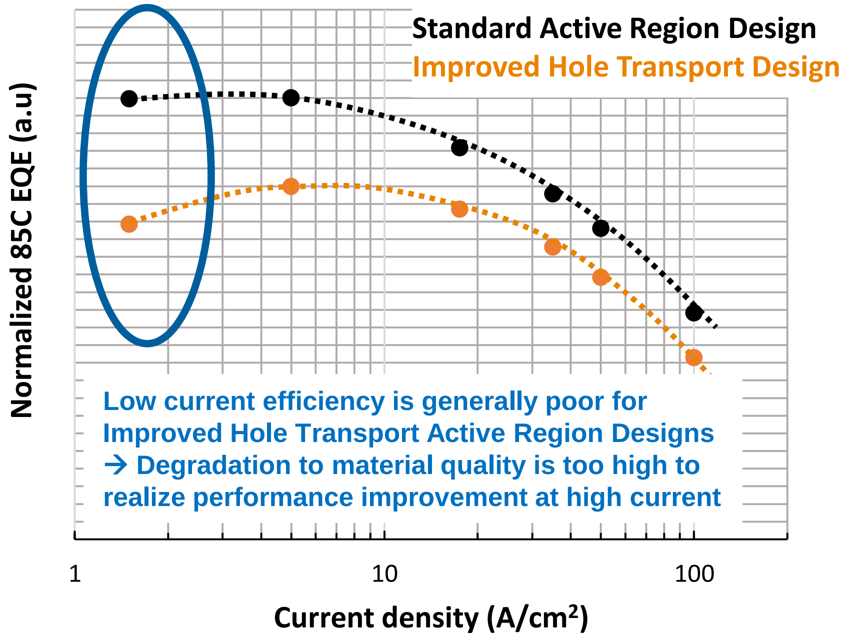
Standard Active Region Designs struggle with poor Hole transport
→ Holes have difficulty spreading past first QW on p-side

Improved Hole Transport Design



Active Region can be designed to improve Hole transport, resulting in emission from more QWs
→ Challenge is resolving material quality issues associated with changes that improve Hole spreading

Material Quality challenges for Improved Hole Transport Design:

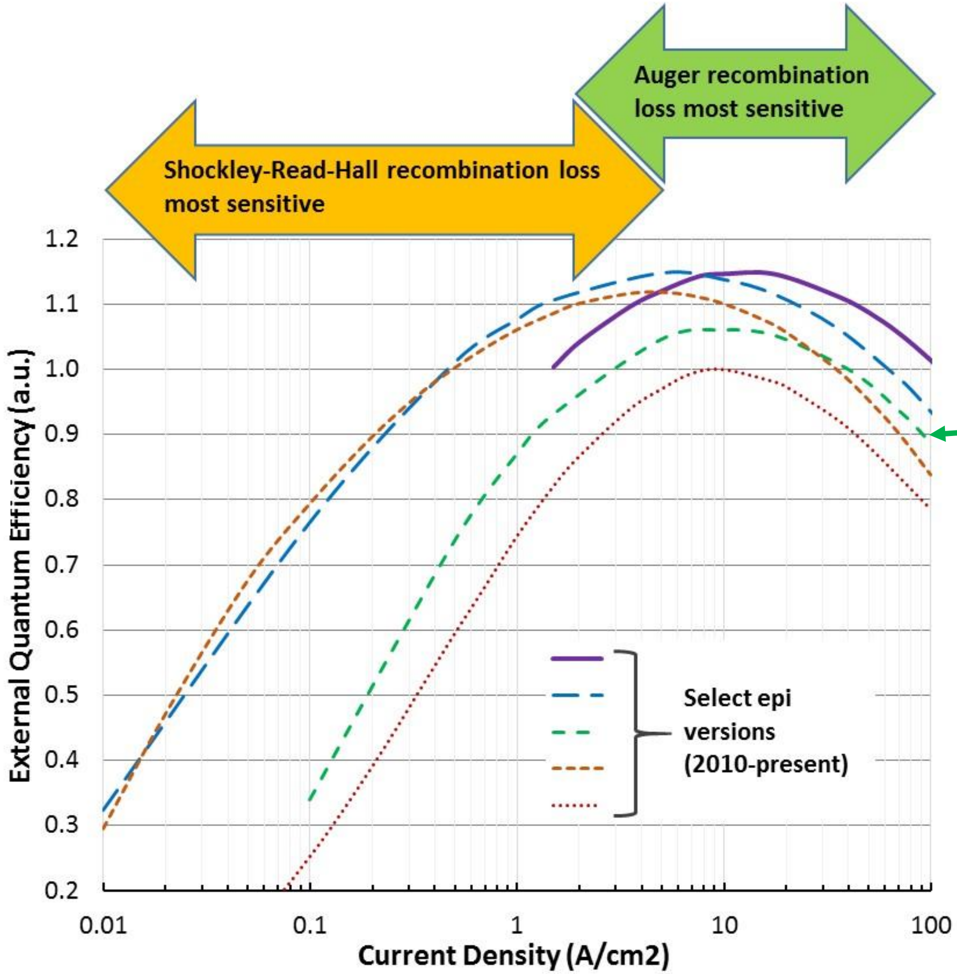


Most LED structure changes that improve carrier transport hurt material quality
→ This is a key development challenge to improve III-nitride LED high current efficiency

Defects related to IQE degradation in low-droop LED designs were studied within a recently completed project "Improved InGaN LED System Efficacy and Cost via Droop Reduction" funded by U.S. DOE EERE Award Number DE-EE0007136

Lumileds Blue High Current EQE Improvement over time

Blue EQE at Tj=85C, 445 nm



Example of compromise in material quality in order to grow an active region design that provides high current gains

Continuous performance improvement enabled by:

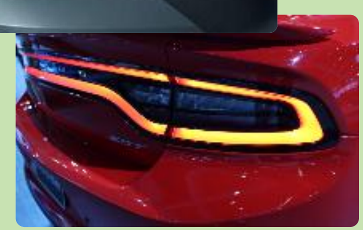
- **Material quality improvement**
- **Carrier overlap**
- **<u>Carrier spreading</u>**

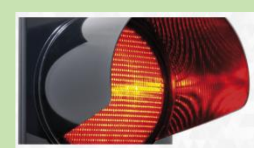
Color applications

Architecture


Horticulture

Entertainment

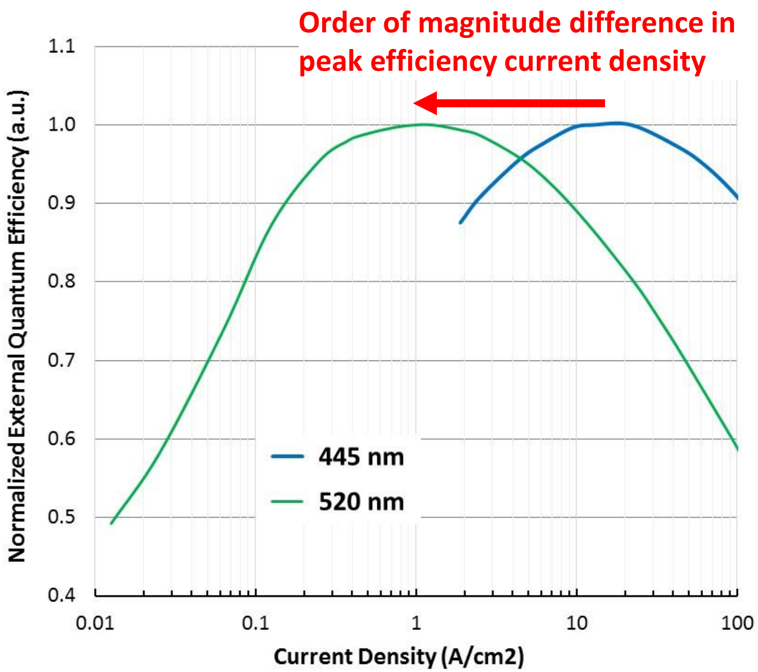



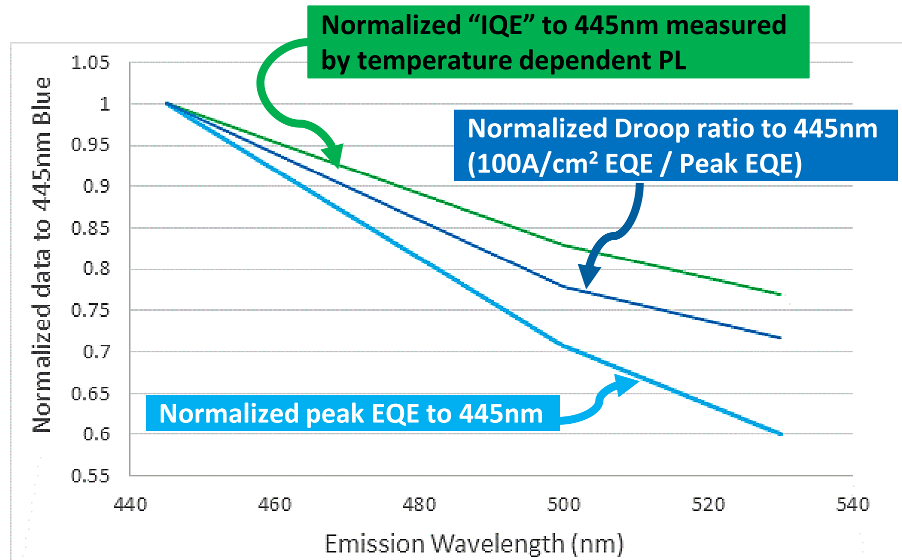


Automotive and transportation

Greater efficiency Droop challenges in Green

Measurements on commercial devices showing relative performance for different wavelength LEDs





- Contributing factors for lower efficiency in "Green Gap" include:
  - Lower IQE (or peak EQE):
    - Worse carrier overlap (larger polarization-induced electric fields on 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 → greater Auger recombination
    - Worse electron-hole overlap reduces radiative rate, which increases carrier density in QWs → greater Auger recombination

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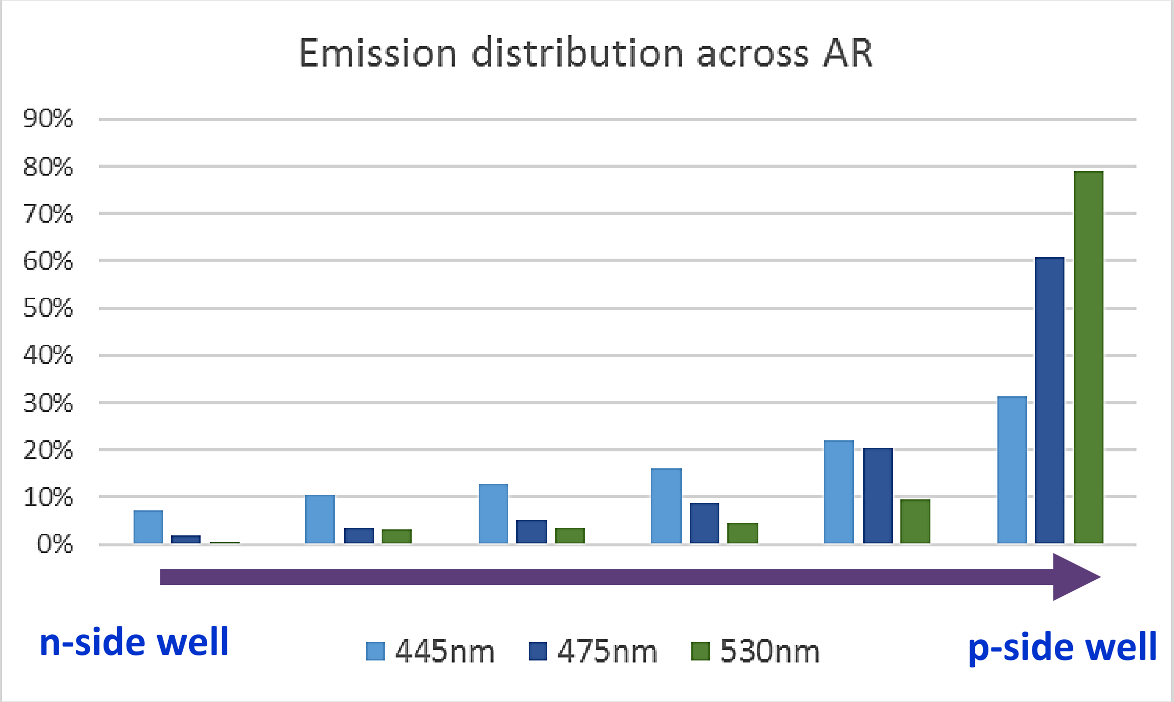
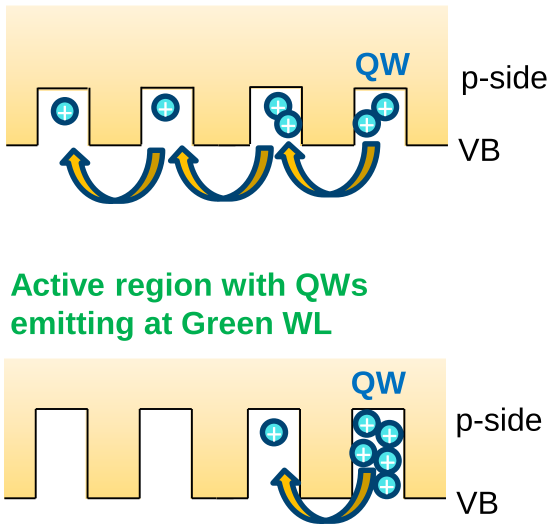
Carrier Distribution Across Active Region from Blue to Green LED

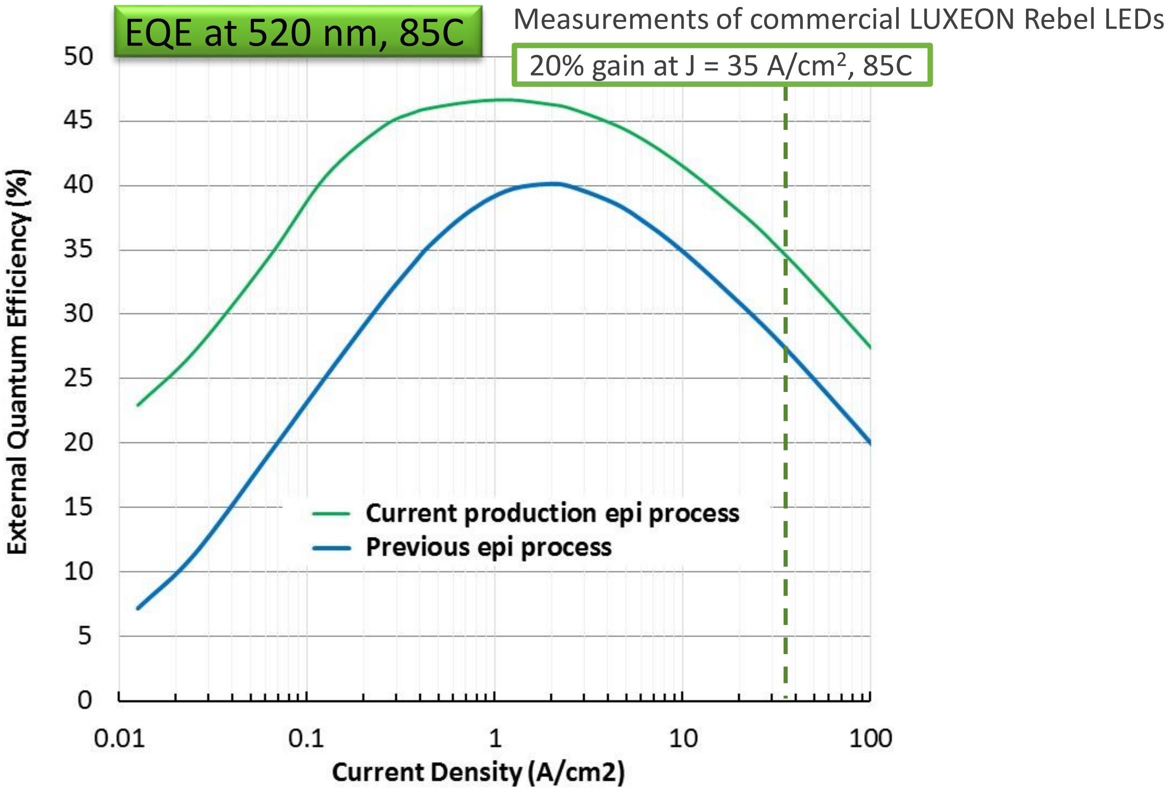
One-dimensional device simulations of emission distribution within an example active region targeted at different wavelengths





- Same active region design structure was evaluated in model with different emission wavelengths
- Much worse carrier distribution observed with increasing WL due to larger energy barriers slowing vertical transport in active region
- Increased barriers to carrier transport in Green LEDs also results in lower electrical efficiency as compared to blue LEDs due to higher Vf relative to its photon energy
- Focusing on improving carrier transport between QWs is even more critical in Green LEDs than in Blue LEDs
  - **However, most LED structure changes that improve carrier transport hurt the material quality even more so in Green LEDs than they do in Blue LEDs → Greater effort is required to maintain material quality in low-droop Green structures**

Improvement of Efficiency Droop in Green LEDs

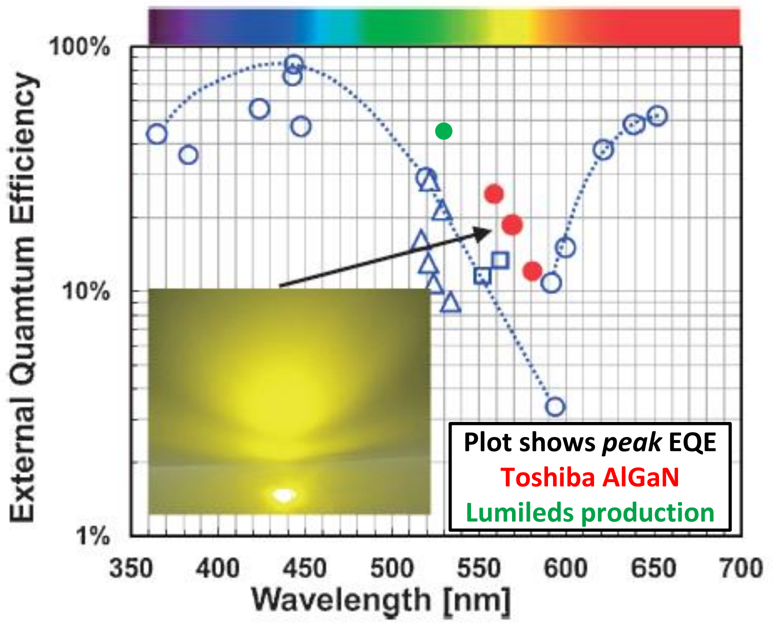


Aside: Recommend that DOE SSL performance goals be set at 85C instead of 25C as this better represents actual operating conditions. *Gains at 25C do not always translate to gains at operating conditions.*

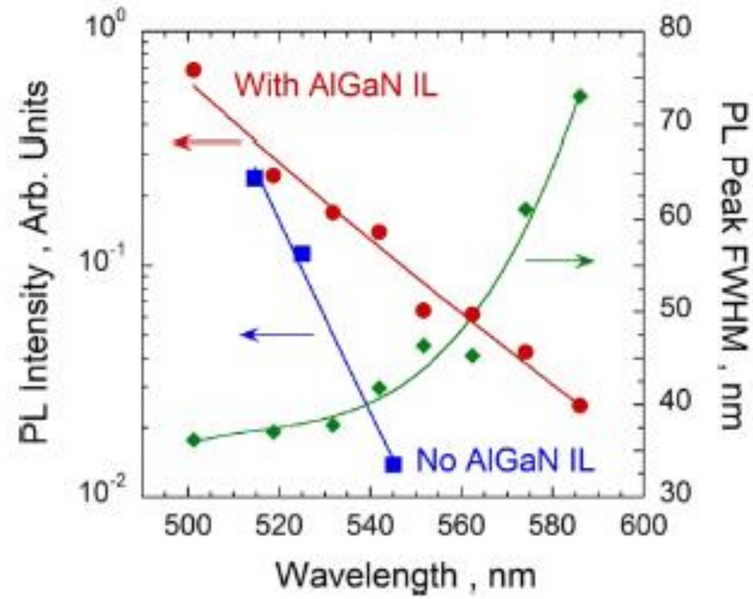
- Droop improvement strategies and learning developed on blue LEDs within DOE SSL EERE Award Number DE-EE0007136 were applied to Lumileds' green epi development
- Gains realized at all current densities due to improved:
  - Material quality by MOCVD process optimization
  - Electron-hole overlap
  - Vertical carrier spreading between QWs by active region design optimization
  - More details on improvement can be found at: https://www.lumileds.com/news/304/50/Market-Leading-Color-Portfolio-Gets-Double-Digit-Performance-Upgrades

Novel approaches for long wavelengths: AlGaN interlayers

Saito *et al.* Applied Physics Express 6 (2013) 111004



Koleske *et al.* J. Crystal Growth 415, 57 (2015)



- Quantum wells are capped with AlGaN interlayers before growing barrier layers at higher temperature

↑Reduced non-radiative recombination rate (fewer point defects)

↑Smoother interfaces between quantum well and barrier layers

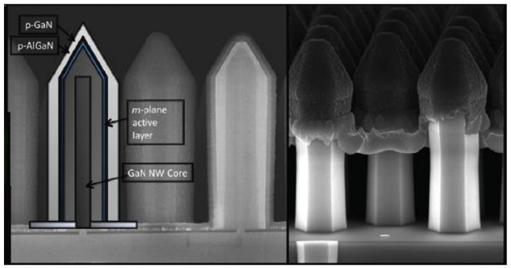
↑Increased polarization field can further redshift the emission wavelength

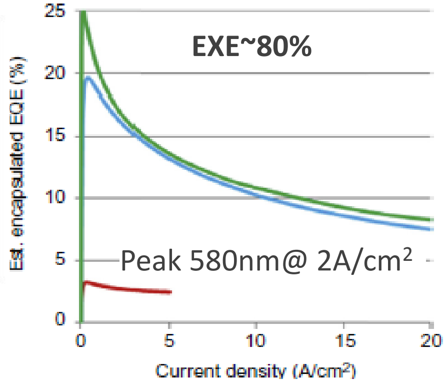
↔Clear improvement for yellow and red, but not yet sufficient to enable applications

↓Appears to give smaller IQE improvement for green and likely uncompetitive in WPE if the high Vf reported (>4V at 20mA) is an inherent drawback of this method

Novel approaches for long wavelengths: Strain relaxation

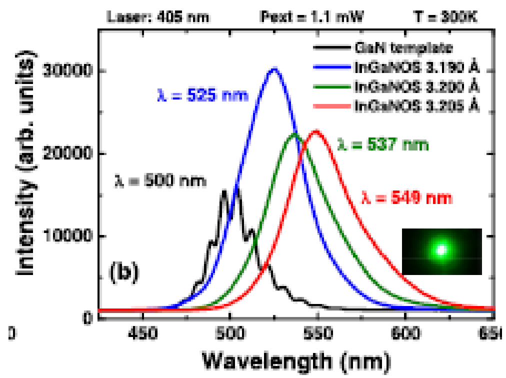
Nanoheteroepitaxy





B. Monemar, B.J. Ohlsson, N. Gardner, L. Samuelson
Semiconductor Nanowires II: Properties and Applications, Ch. 7 pp. 227-271 (2016)

Relaxed InGaN templates



PL IQE=36% @536nm
PL IQE=10% @566nm

Even *et al.* Appl. Phys. Lett. 110, 262103 (2017)

Use of either nanoheteroepitaxy or larger lattice parameter templates for relaxation during active region growth:

↑Increases QW critical thickness

↑Greater InN incorporation during QW growth → can allow higher growth temperature for desired wavelength

↑Nanowires - Core-shell LEDs have possibility to increase emitting volume per unit area on wafer

↔ Nanowires - Lack of clear demonstrations of IQE improvement (IQE values from PL can be difficult to interpret and there is a scarcity of EQE data)

↔While higher growth temperatures are expected to produce higher IQE, few careful experimental studies have been published in literature to verify that the magnitude of temperature increase allowed by this strategy is significant for IQE improvement

- ↔ InGaN templates alone are not sufficient to achieve high IQE – reported IQE values at 536nm are below industry level

↓Nanowires - Guiding carriers within 3D nanostructures to desired regions for recombination is challenging

Conclusion

- High current efficiency of Blue LEDs has progressed rapidly due to improvements in
  - Carrier overlap
  - Carrier spreading
  - Material quality improvement within low-droop designs

- Efficiency Droop challenges are greater in Green LEDs than in Blue LEDs
  - Carrier transport and carrier overlap challenges are greater due to higher InN composition in QWs
  - Material quality is more sensitive to low-droop design changes

- While new novel approaches will be required for III-nitride LEDs to compete in Amber and Red wavelengths, these approaches have yet to demonstrate more promise than conventional c-plane thin-film approaches for Green wavelengths

- While it seems like a mature technology, there is still a great deal of basic science R&D and improvement left to do on c-plane III-nitride LEDS
  - Developing low-droop epi structures
  - Understanding defect formation
  - Understanding the epi growth physics to prevent defect formation

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