Technical Group Leadership

OSA Laser Systems Technical Group

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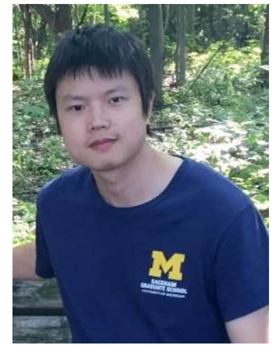
University of Iowa
Chair

Kaikai Xu
Univ. Electro Sci & Tech of China
Vice Co-Chair

David James Spence
Macquarie University
Vice Co-Chair



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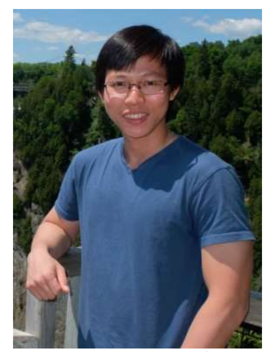

Tam N. Huynh
IBM T.J. Watson Research Center
Conference Events Officer

Laser Systems Technical Group

The Optical Society | Since 1916

Laser Systems (PL)

Laser Systems (PL)

This group encompasses novel laser system development for a broad range of scientific, industrial, medical, remote sensing and other directed-energy applications. The group addresses technical issues concerning sources that cover the full spectral range, including: ultraviolet, visible, infrared, terahertz and microwave. Strong overlap with other technical groups that study and develop laser techniques and technologies brings together researchers and engineers to produce sources with unique performance, such as high-power, ultra-short pulses and high coherence.

GROUP LEADERSHIP | UPCOMING MEETINGS | RECENTLY PUBLISHED

Name	Affiliation	Title
Fatima Toor	University of Iowa	Chair
Muhammad Faryad	Lahore University of Management Sciences	Conference Events Officer
Tam N. Huynh	IBM T.J. Watson Research Center	Conference Events Officer
Xiushan Zhu	University of Arizona	Conference Events Officer
Shamsul Arafin	University of California Santa Barbara	Events and Social Media Officer
David James Spence	Macquarie University	Vice Co-Chair

Announcements

Join the Laser Systems Technical Group for their inaugural webinar on Tuesday, 31 May 2016, at 10:00 EDT.

In this webinar, Dr. John Prineas from the University of Iowa will present an overview of his research on InAs/GaSb mid-wave, cascaded superlattice light emitting diodes.

Register for the Webinar Now>>

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Work in Optics

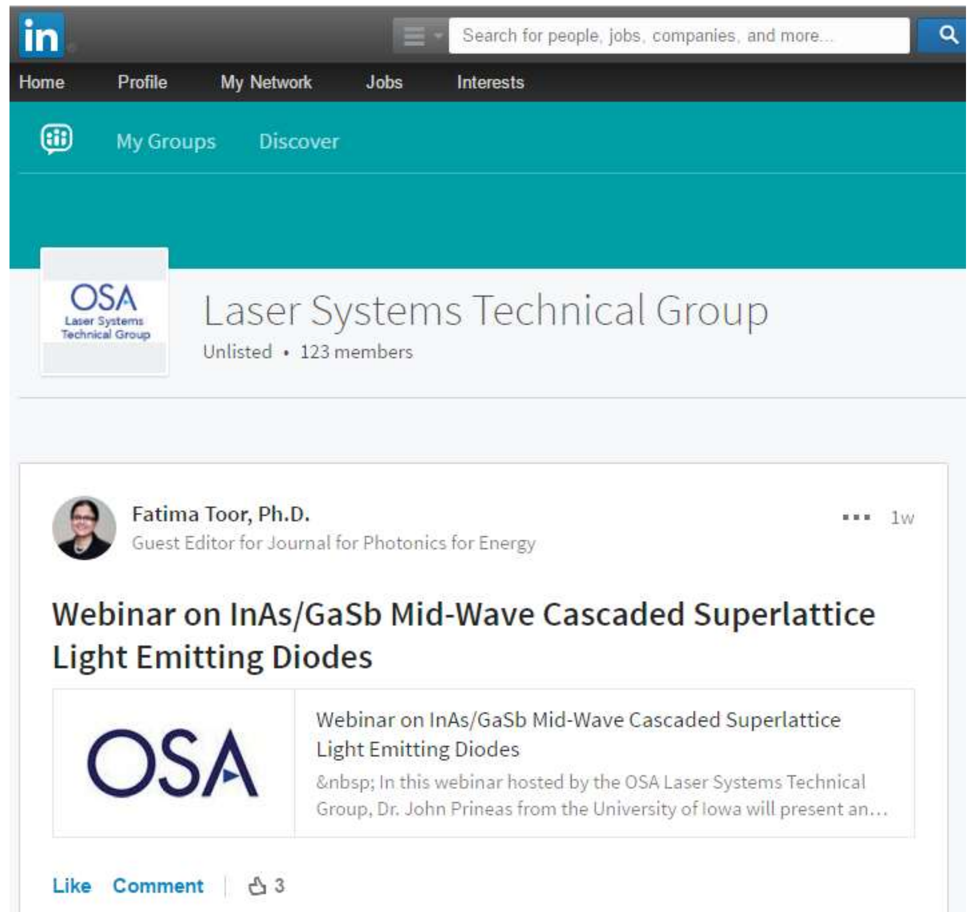
FIELD SERVICE MANAGER | Checkpoint Technologies
Thu, 05 May 2016 14:31:00 EST

Sales Account Manager | Optometrics Corporation

OSA Laser Systems Technical Group

Contact your Technical Group and Get Involved!

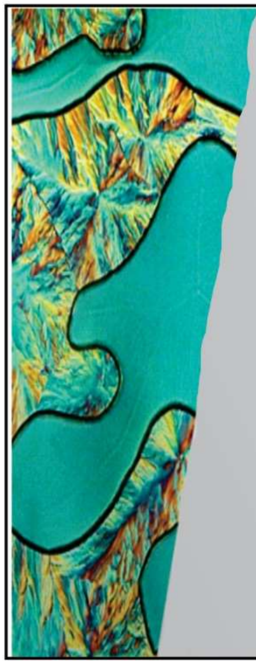
- LinkedIn site (global reach)
- Announce new activities
- Promote interactions
- Complement the OSA Technical Group Member List



Welcome to Today's webinar!

OSA Laser Systems Technical Group

WEBINAR SERIES



III-Nitride Nanowire Light-Emitting Diodes Grown by Molecular Beam Epitaxy

27 July 2016 • 12:00 PM EDT

Register today for this free OSA Technical Group webinar >>

Dr. Hieu Nguyen, Electrical and Computer Engineering,
New Jersey Institute of Technology, USA

http://web.njit.edu/~hpnguyen/group.html/

III-Nitride Nanowire Light-Emitting Diodes Grown by Molecular Beam Epitaxy

Hieu P. T. Nguyen, Assistant Professor

Nano-Optoelectronic Materials and Devices Laboratory,

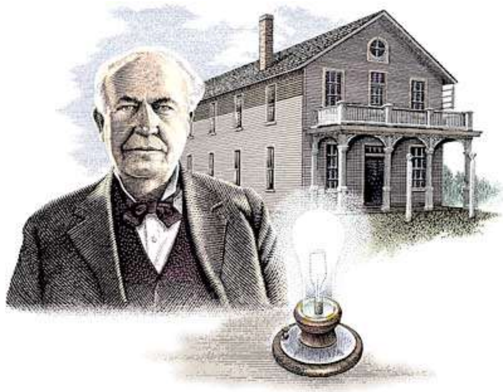
Electrical and Computer Engineering Department

New Jersey Institute of Technology

The Beginnings of Lighting

- **In 1879, Thomas A. Edison demonstrated a light bulb with a C (carbon) filament that burned for 40 hours.**

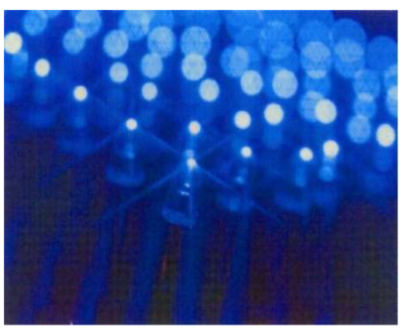
Edison's light bulb



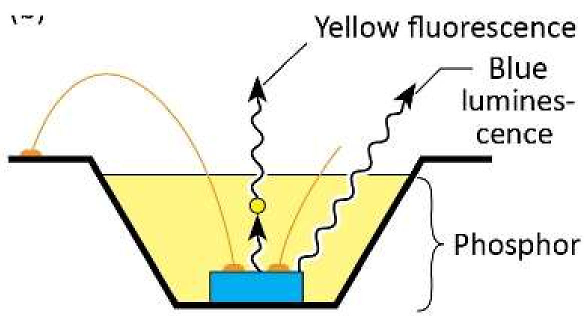
Thomas A. Edison

- **In 1989: Blue LEDs by Isamu Akasaki et al., Meijo University, Japan**

- **In 1996: White LEDs by Shuji Nakamura, Nichia, Japan-> University of California, Santa Barbara**



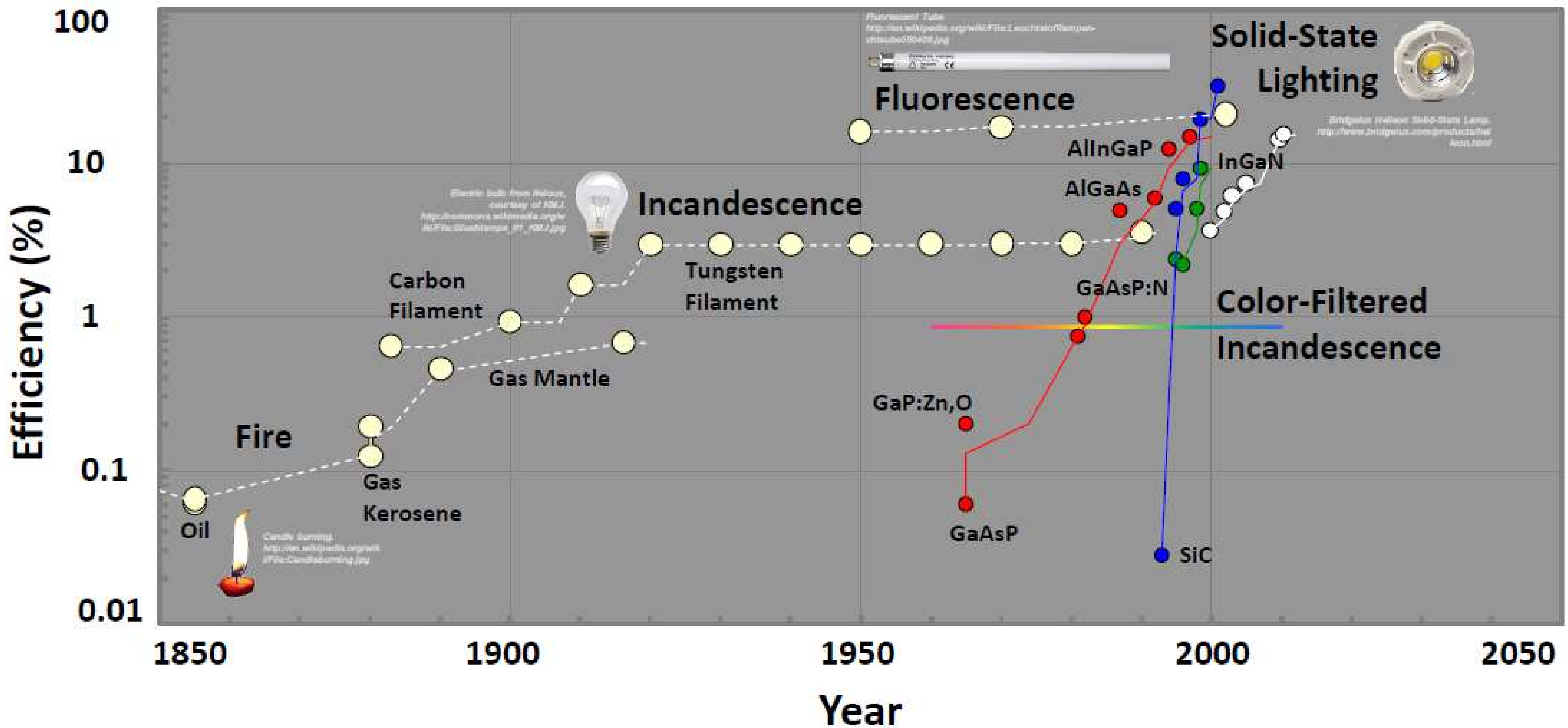
Isamu Akasaki



Shuji Nakamura

Pictures from Internet

Lighting Technologies: 200-Year Revolution of Luminous Efficacy

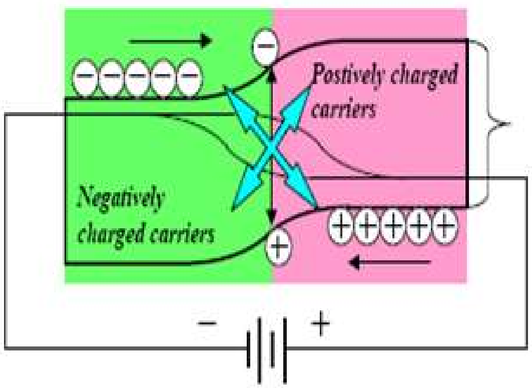


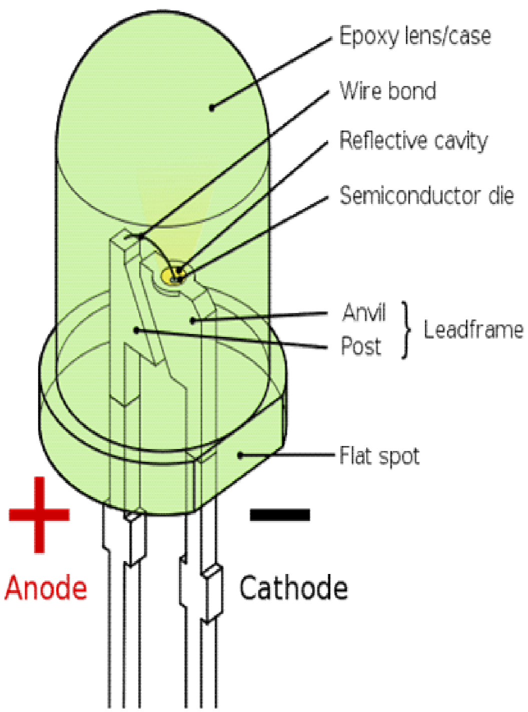
- Courtesy of J. Tsao and J.A. Simmons, Sandia National Laboratories

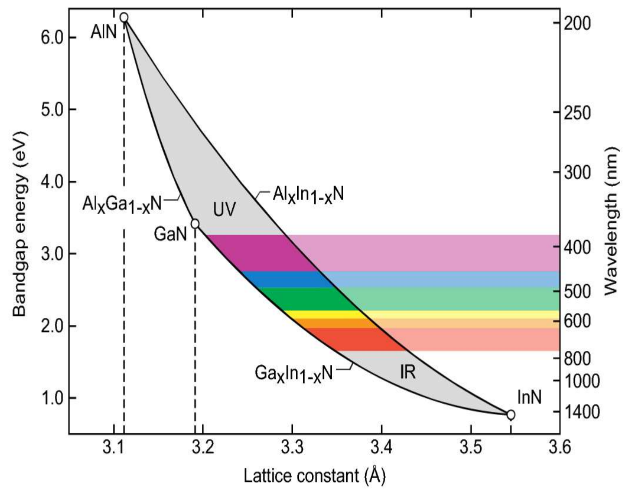
- **US DOE targets to achieve 50% efficient lighting in 2030.**

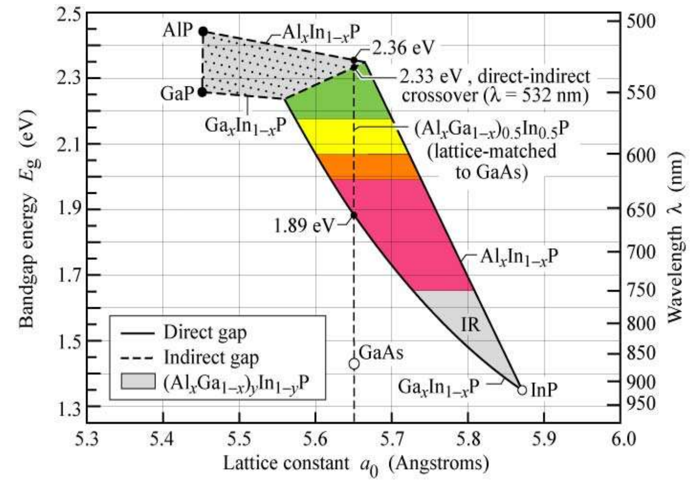
IEEE Circuits and Devices Magazine, May/June 2004

Materials







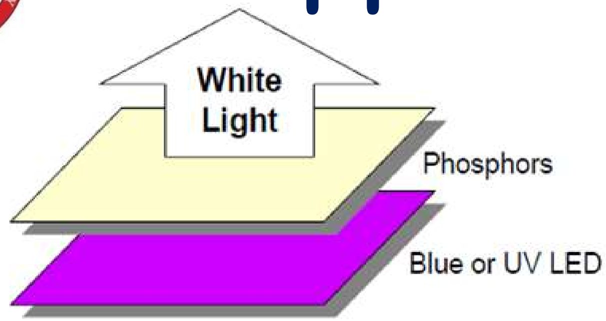


- **InGaN → blue, green**
- **AlInGaP → red, yellow**

- **Direct RT bandgaps: ~0.7-6.2 eV**
- **Solid alloy system (tuneable bandgaps)**
- **Radiation resistant and chemically inert**
- **InGaN covers entire visible & bulk of solar spectrum**

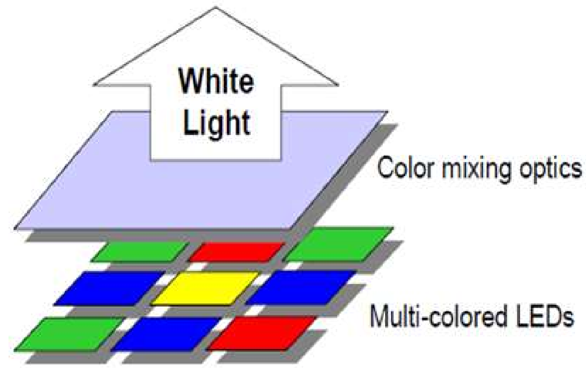
Pictures downloaded from Internet

Approaches for White LEDs



Phosphor-Converted LED

- Requires high power blue or UV LEDs
- Tuneability not possible
- Device reliability is a major concern

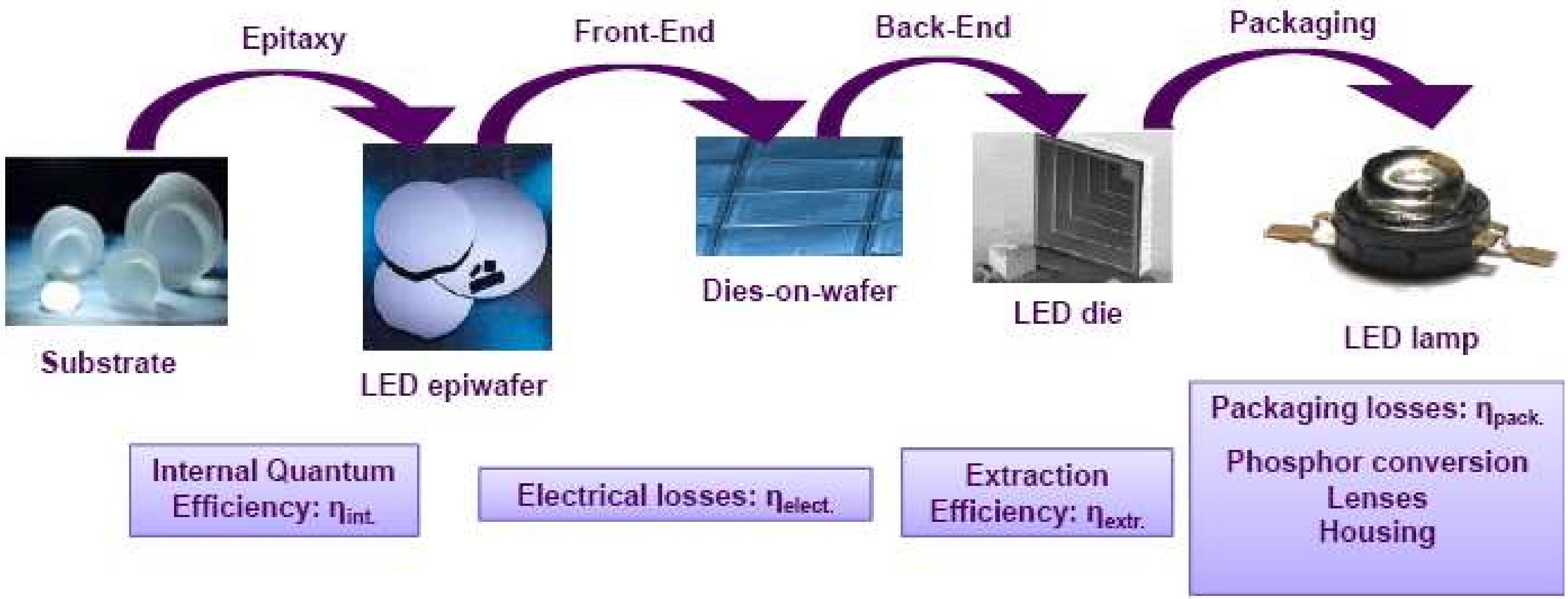


Color-Mixed LED

- Direct emission from LEDs
- Highest efficiency
- Color tuneability possible
- Long-term reliability

Pictures downloaded from Internet

Components of White LED Efficiency



100% overall efficiency is ~ 330 lm/W

Current production white LED efficiency is ~ 80 – 120 lm/W.

J. Perkins, DOE Workshop, April 2009.

Quality of Light and Color Rendition

Incandescent lamp

CFL

MHL

LED

Low CRI illumination source

High CRI illumination source

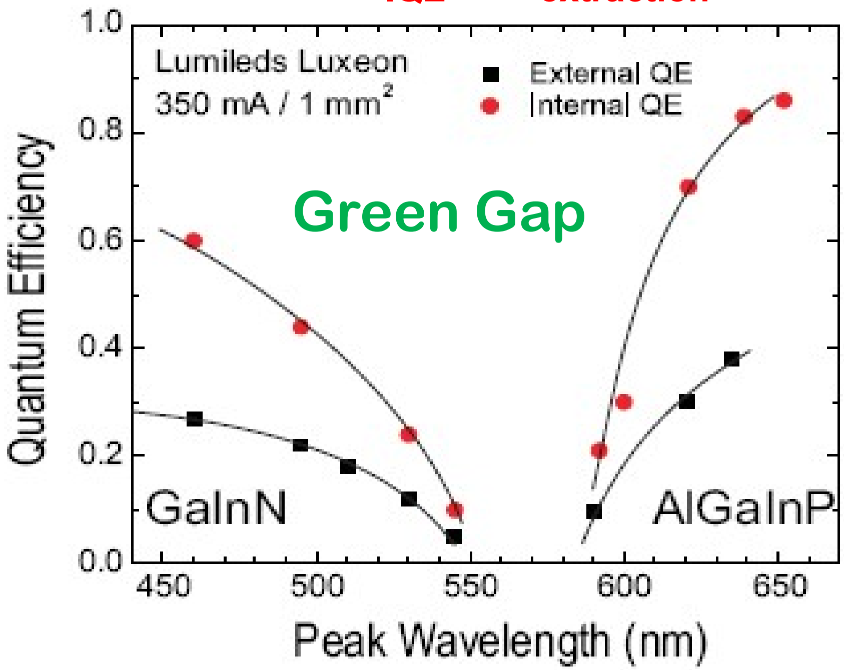
Higher CRI, colors appear more natural

- **Color rendering index (CRI) is a measure to define how closely a light source can replicate the true color of an object.**

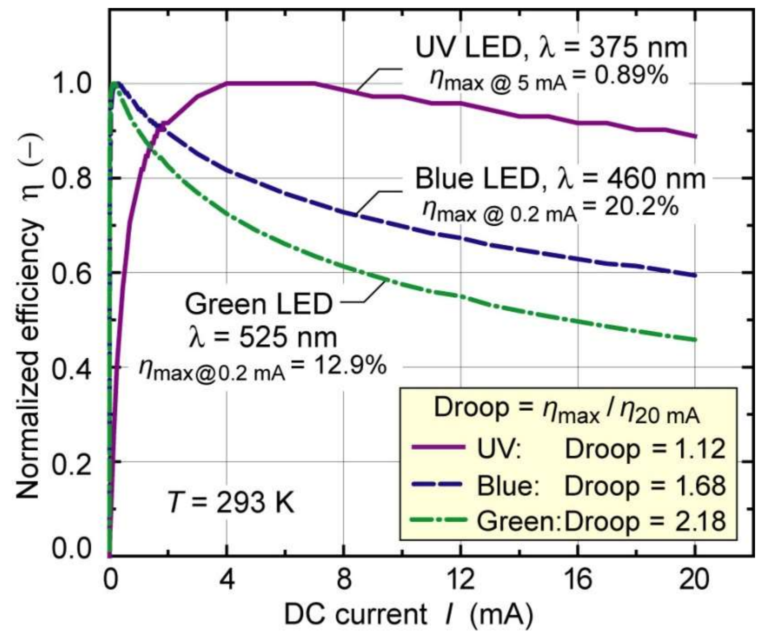
Pictures downloaded from Internet

The Green Gap and Efficiency Droop

EQE= $\eta_{IQE} \times \eta_{extraction}$



Typical green InGaN LED performance



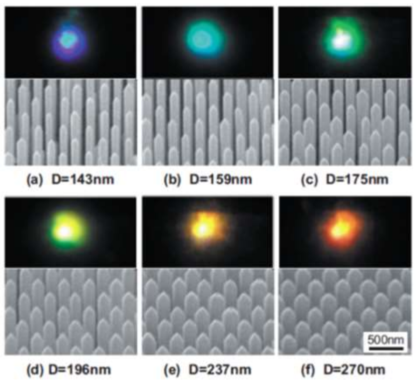
- **A substantial performance gap in the green spectral region forms a bottleneck for the realization of high efficiency phosphor-free LEDs.**

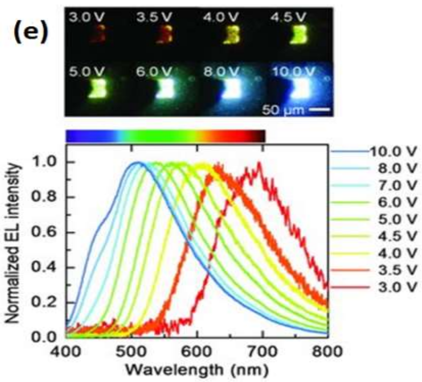
- **Peak internal quantum efficiency occurs at relatively low current densities (< 10 A/cm²), then rolls off as current density increases ("droop").**
- **Efficiency droop increases the cost per lumen.**

Data: W. Goetz, Lumileds. http://www. lumileds.com

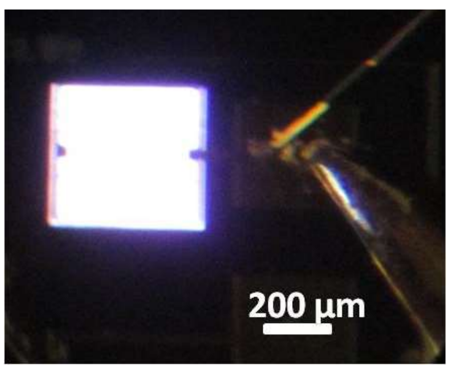
Advantages of Nanowire Structures

Tunable emission





Phosphor-free white LEDs



Advantages:

- Nearly dislocation-free, due to the effective lateral stress relaxation
  →High internal quantum efficiency
- Reduced polarization fields
  → Enhanced quantum efficiency
  → Reduced efficiency droop
- Large surface area
  → Enhanced light output efficiency
- Compatibility with Si substrates
  → Lower manufacturing cost
- Tunable emission wavelength
  → Phosphor-free white light LEDs

.

Sekiguchi et al., Appl. Phys. Lett., 96, 2010. Hong et al., Nguyen et al., Nano Lett. 10, 3355, 2011.

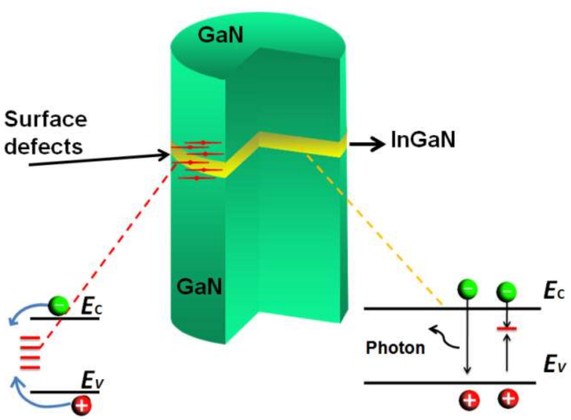
Challenges of Nanowire LEDs and Solutions

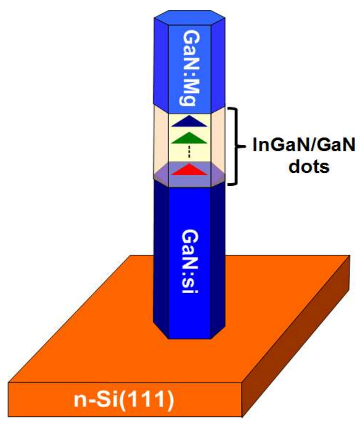
Challenges:

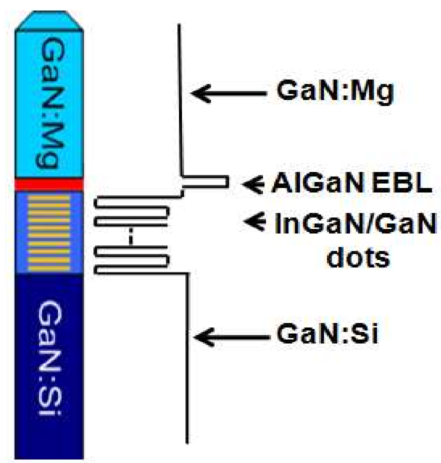
- Poor hole transport
  →low efficiency, efficiency droop
- Electron overflow
  → low efficiency, efficiency droop
- Surface states and band bending
  →low carrier injection efficiency

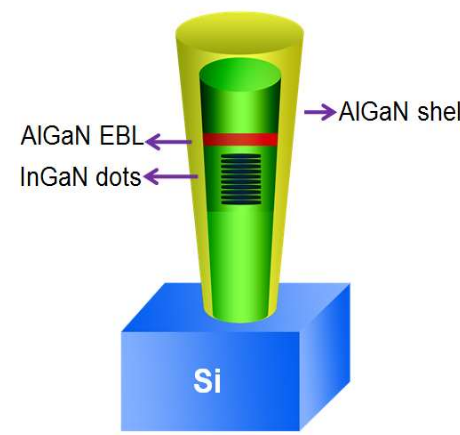
Solutions:

- P-type modulation doping:
  →enhance hole transport
- Electron blocking layer
  → prevent electron overflow
- Core-shell heterostructure
  → enhance carrier injection efficiency









Nguyen et al., Nano Lett., 11, 1919, 2011

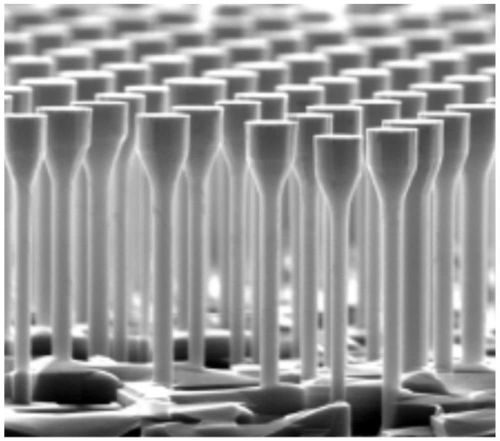
Nguyen et al., Nano Lett., 12, 1317, 2012

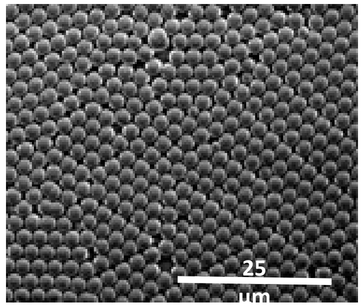
Nguyen et al., Nano Lett., 13, 5437, 2013

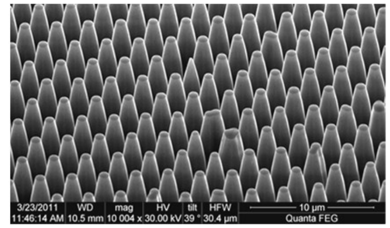
Mahboob *et al., Phys. Rev. Lett.*, 92, 036804, 2004

Nanowire Structures

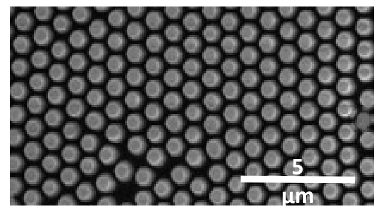
Top-down



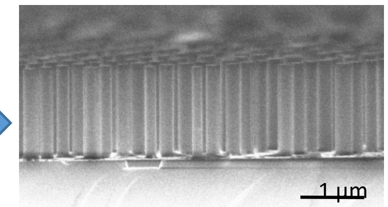




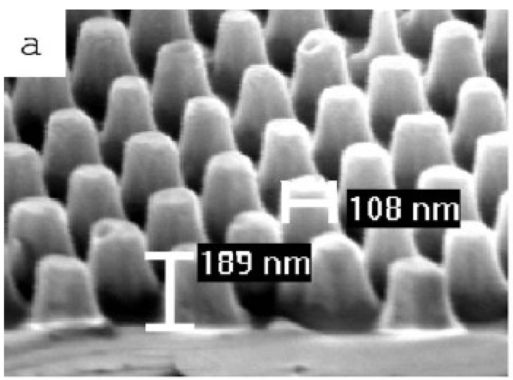
ICP etch → Selective wet etch



Plasma etch causes sidewall damage



Wet etch: removes sidewall damage

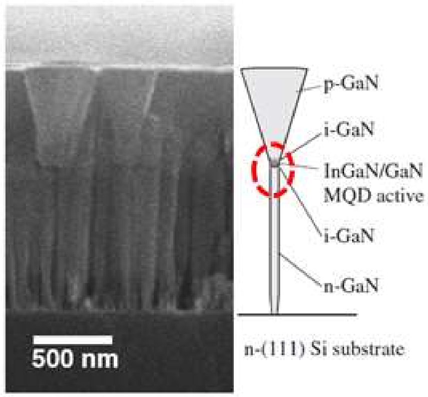


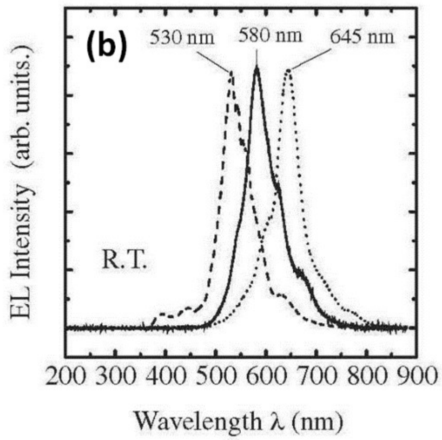
- **Device performance suffers severely from etching induced surface damage, nonradiative surface recombination, and the achievement of long wavelength LEDs has been fundamentally restricted by the epitaxial growth of planar heterostructures.**

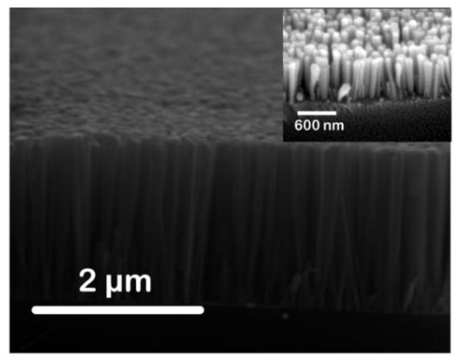
Li et al., Opt. Exp., 19, 25529, 2011. Kikuchi et al., J. J. Appl. Phys., 43, L1524, 2004. Sekiguchi et al., Appl. Phys. Lett., 96, 2010. Hong et al., Adv. Mater., 23, 3284, 2011. Lim et al., Nano Lett., 13, 331, 2013. Yet et al., Appl. Phys. Lett. 100, 03319, 2012. Guo et al., Nano Lett., 10, 3355, 2010. C. Y. Wang et al., Opt. Expr. *16,* 10549–10556, 2008. Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).

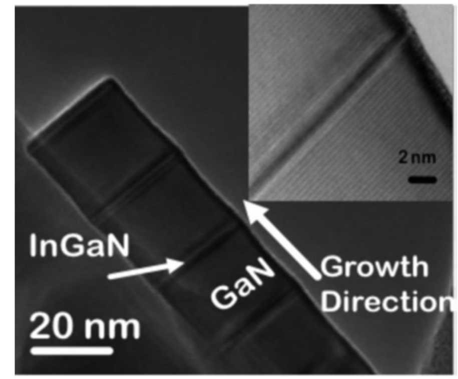
Nanowire Structures

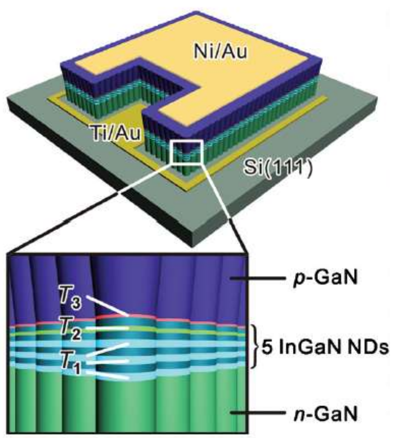
Bottom-up

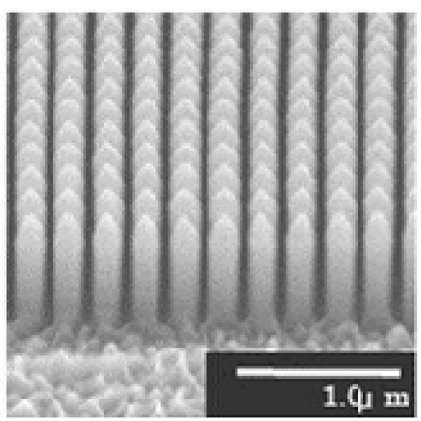


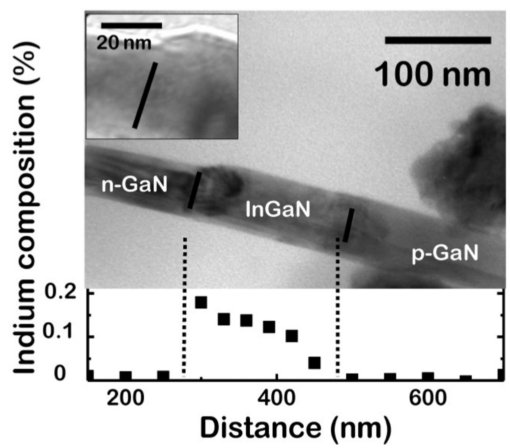


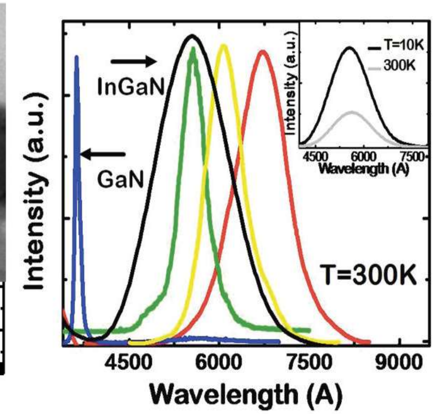






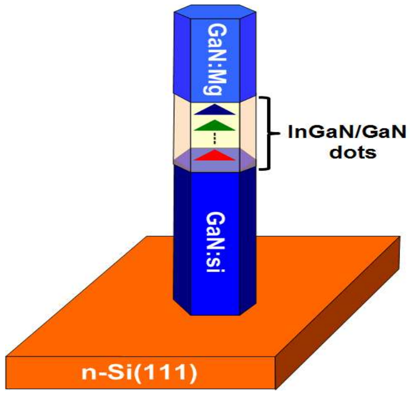


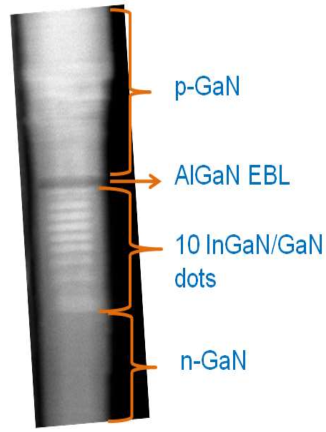


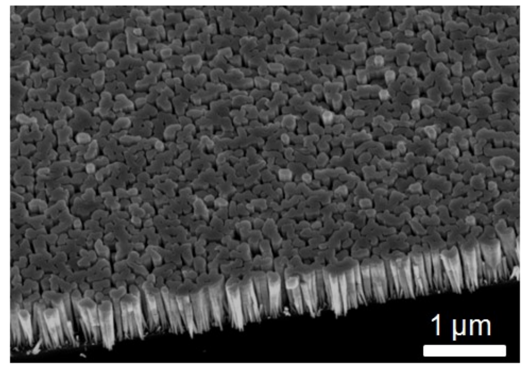


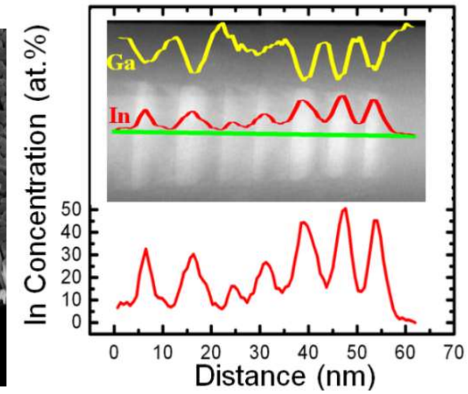
Li et al., Opt. Exp., 19, 25529, 2011. Kikuchi et al., J. J. Appl. Phys., 43, L1524, 2004. Sekiguchi et al., Appl. Phys. Lett., 96, 2010. Hong et al., Adv. Mater., 23, 3284, 2011. Lim et al., Nano Lett., 13, 331, 2013. Yet et al., Appl. Phys. Lett. 100, 03319, 2012. Guo et al., Nano Lett., 10, 3355, 2010.

Phosphor-Free InGaN/GaN Dot-in-a-Wire LEDs Grown by MBE

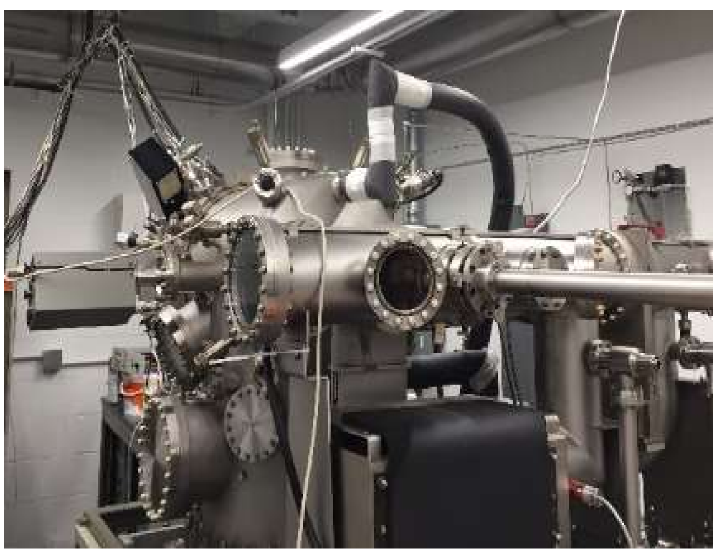


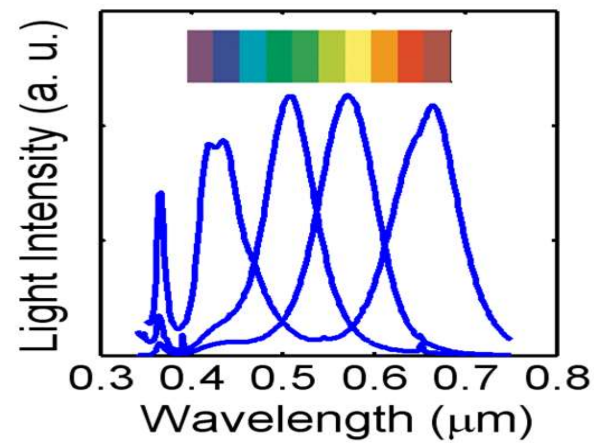


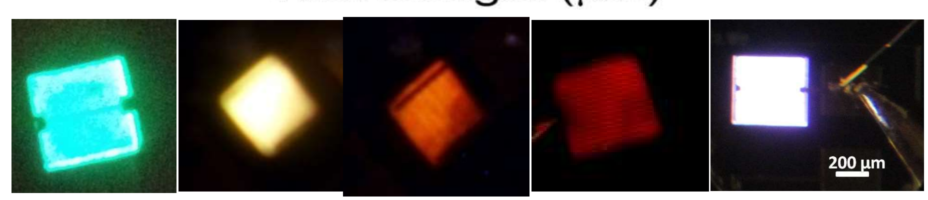




➢ **Vertically aligned InGaN nanowire arrays with controlled In composition**



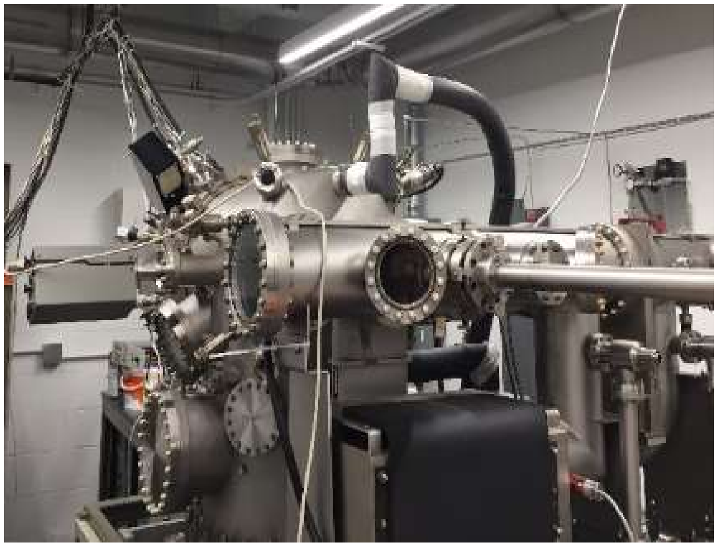


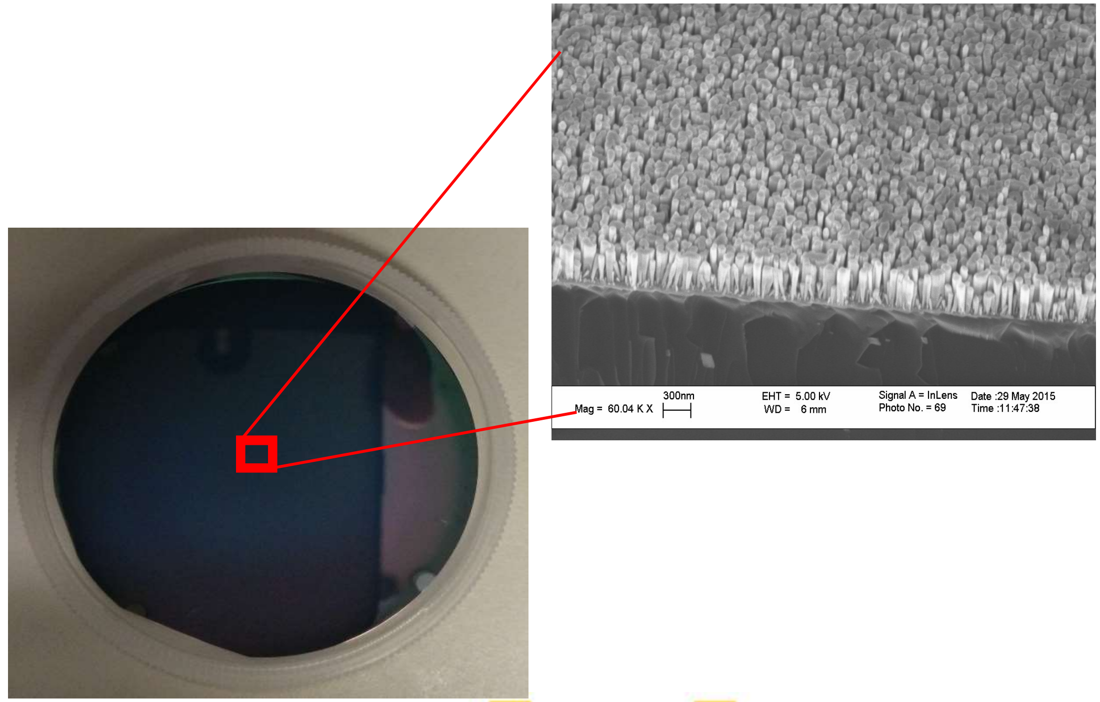


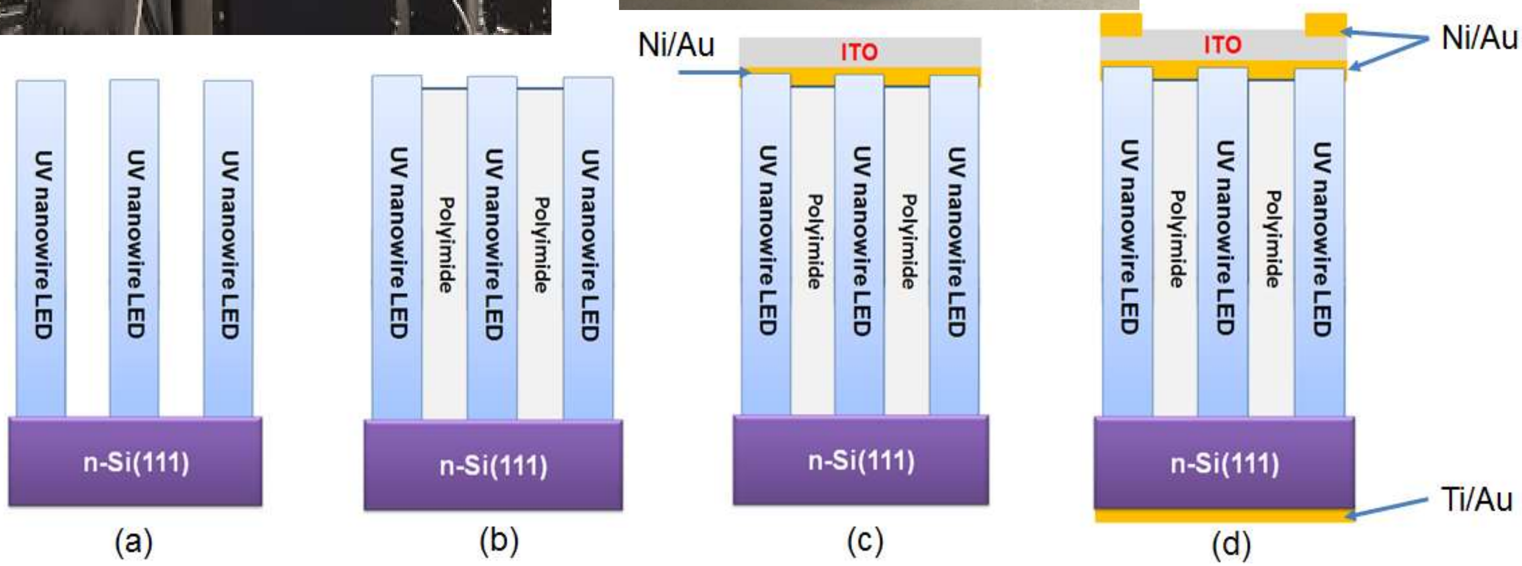
➢ **Tunable emission**

Nguyen et al., Nanotechnol. 22, 445202, 2011. Nguyen et al., Nano Lett. 11, 1919, 2011.

Device Fabrication of Nanowire LEDs

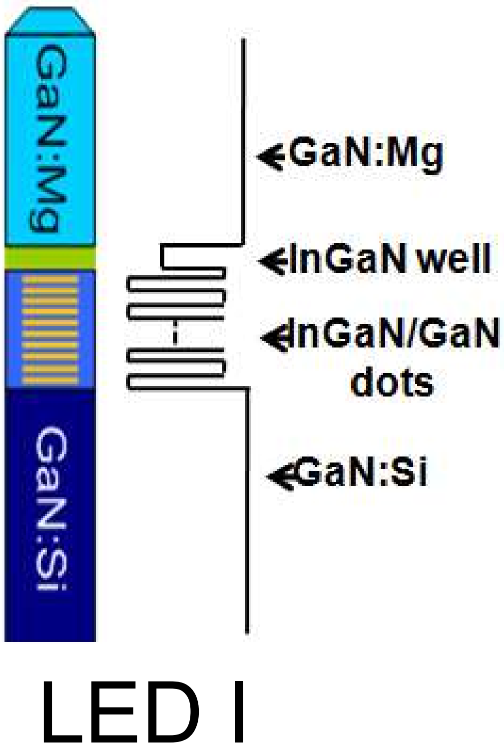


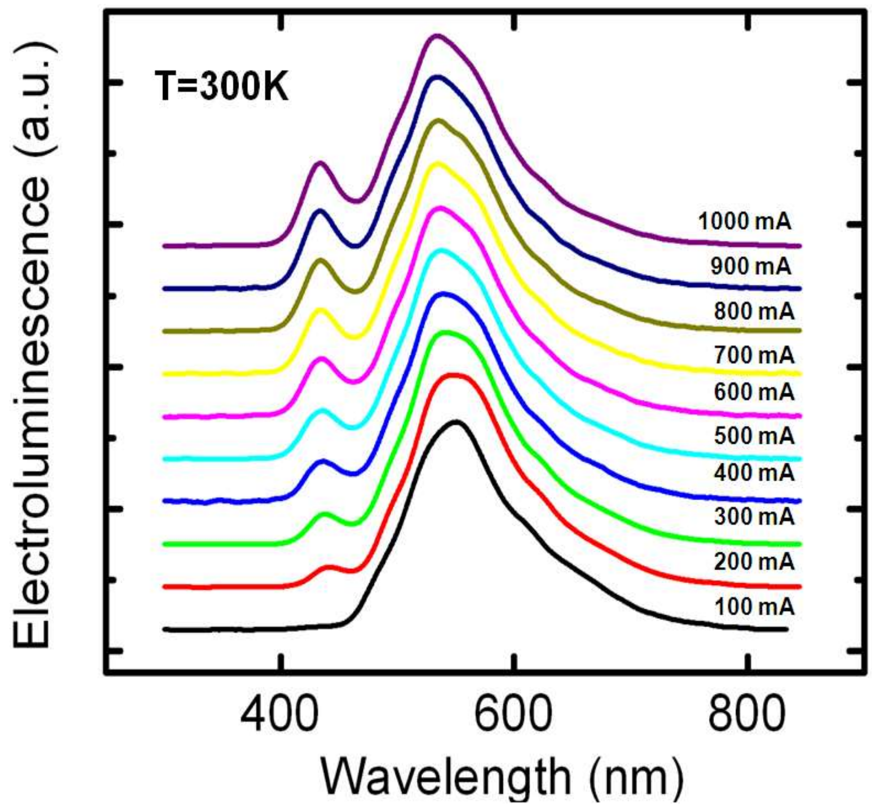




Electron Blocking Layer to Reduce Electron Overflow

Electron Overflow in Nanowire LEDs

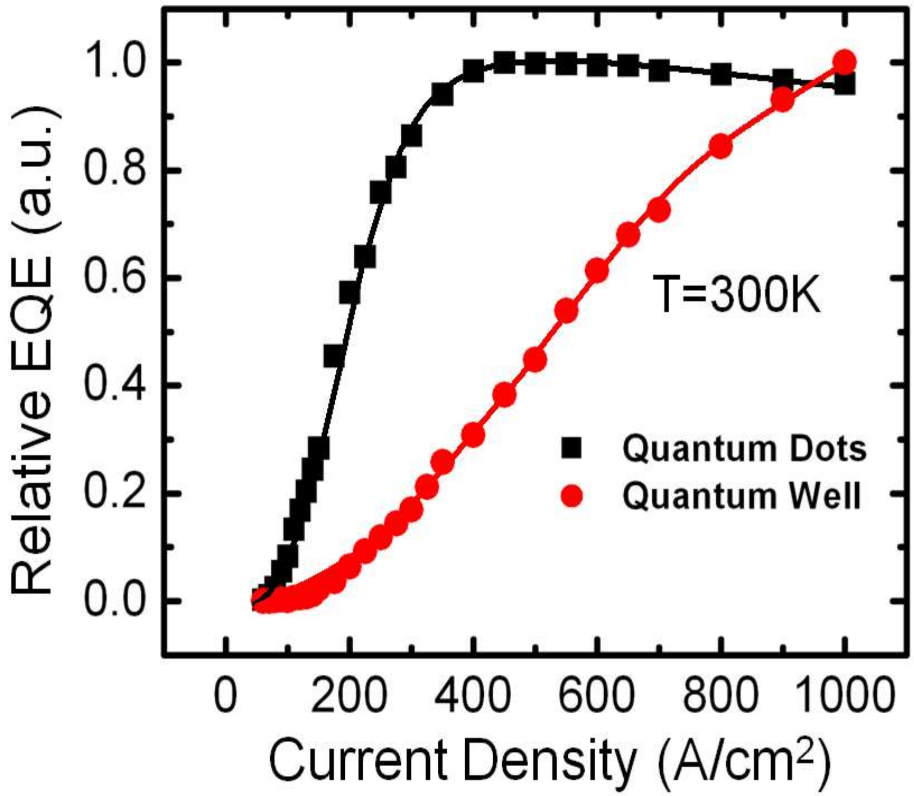


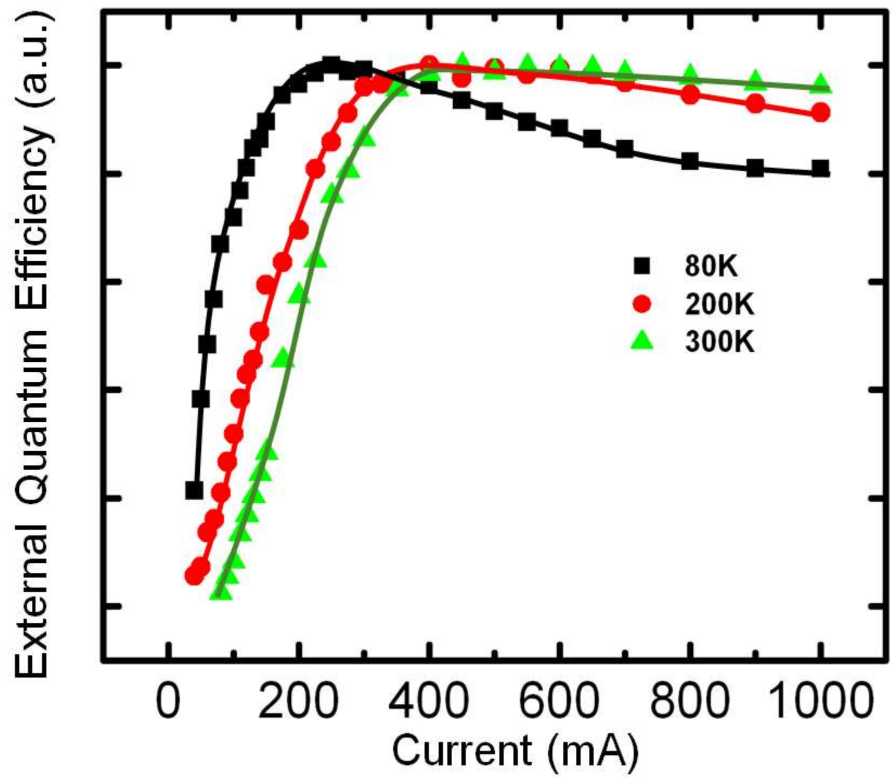


- **With the use of a test well (λ ~ 430 nm) between the quantum dot active region (λ ~ 550 nm) and the p-GaN, electron overflow is clearly measured in nanowire LEDs.**

Nguyen et al., Nano Lett., 12, 1317, 2012

Electron Overflow in Nanowire LEDs

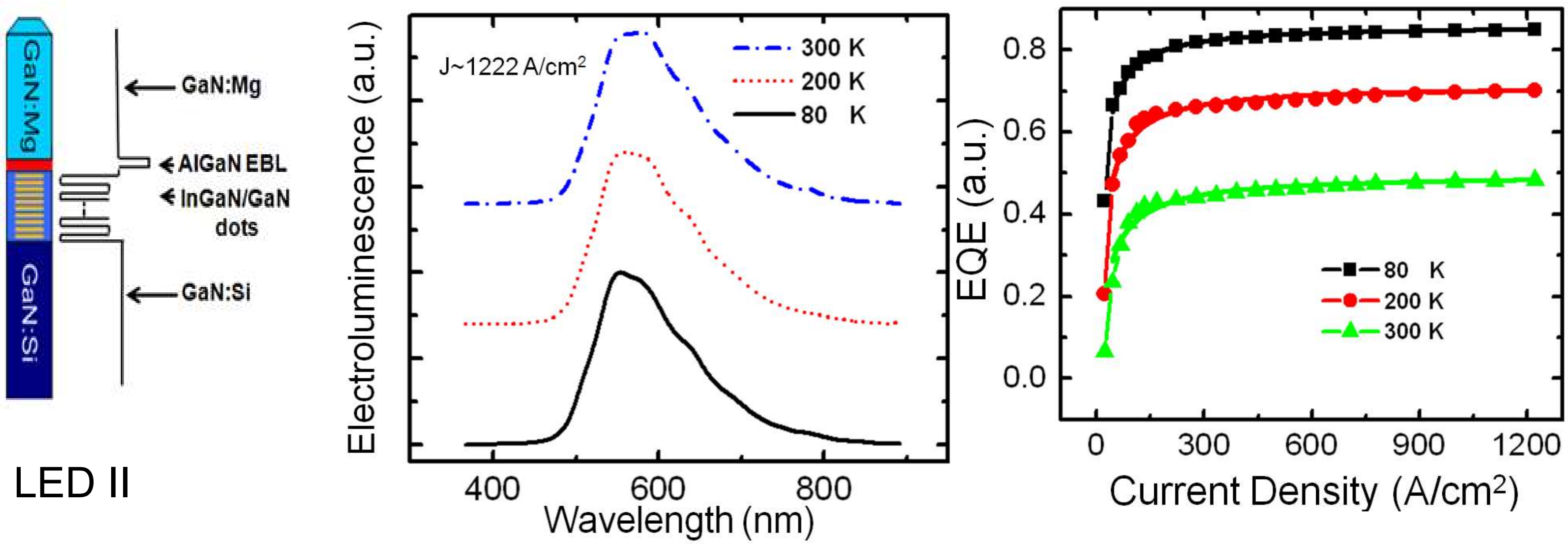




- **The presence of electron overflow leads to efficiency droop for the quantum dot emission at relatively high injection conditions.**

Nguyen et al., Nano Lett., 12, 1317, 2012

Preventing Electron Overflow in InGaN/GaN Dot-in-a-Wire White LEDs



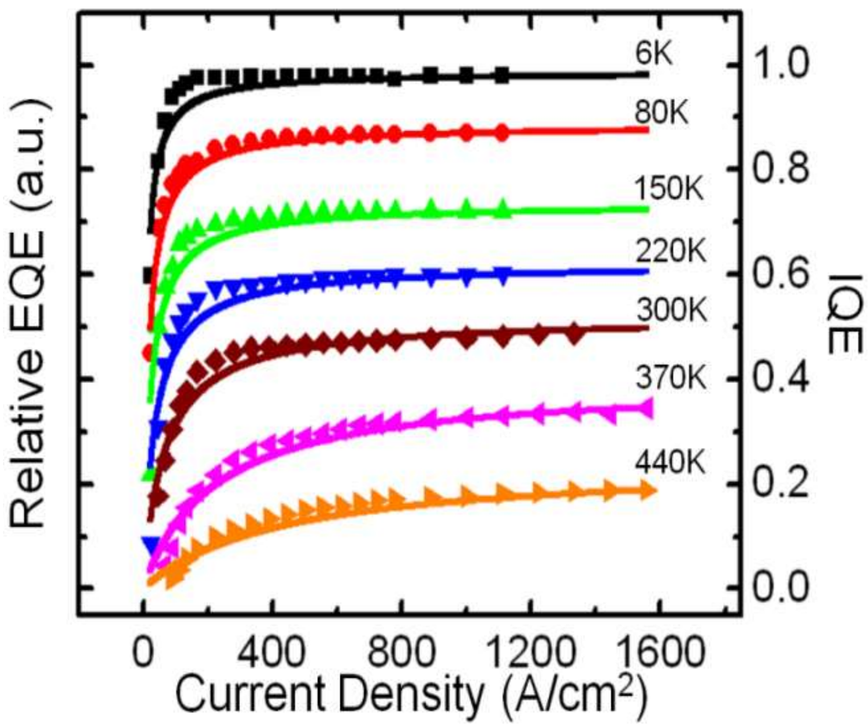
- **Electron overflow was not observed for the LEDs with AlGaN EBL.**
- **With the use of p-type modulation doping and electron blocking layer, high performance phosphor-free nanowire white LEDs, with virtually zero efficiency droop and highly stable emission, is demonstrated for the first time.**

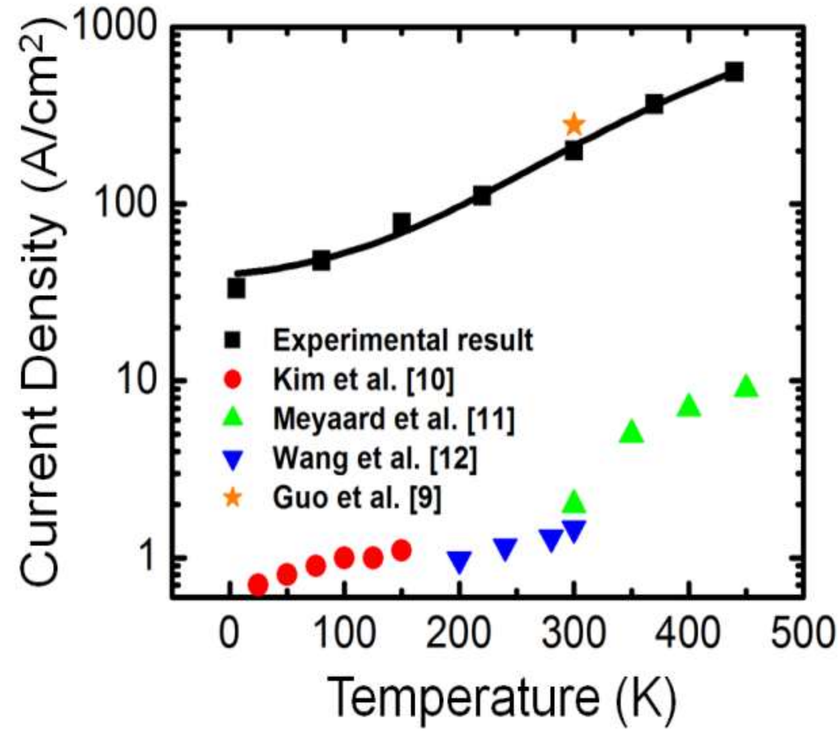
Nguyen et al., Nano Lett., 12, 1317, 2012

Core-shell Structures to Enhance Carrier Injection Efficiency

Temperature-Dependent External Quantum Efficiency

$$\eta_i = \frac{BN^2}{AN + BN^2 + f(N)}$$



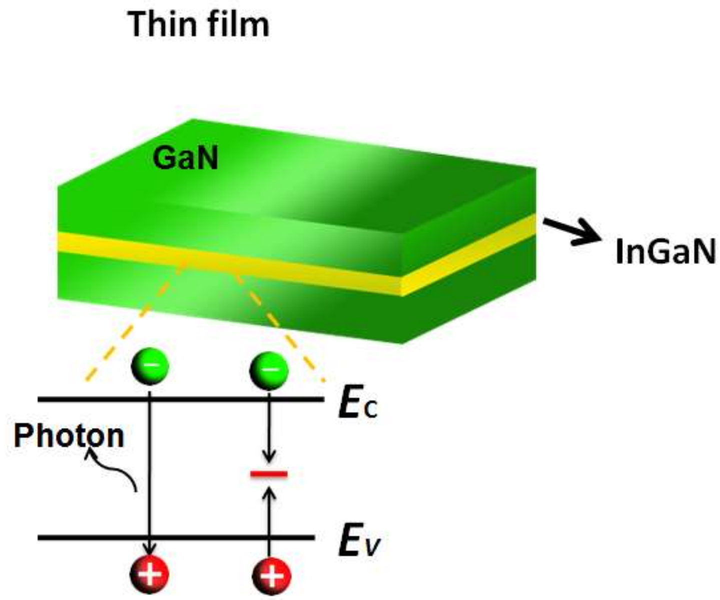


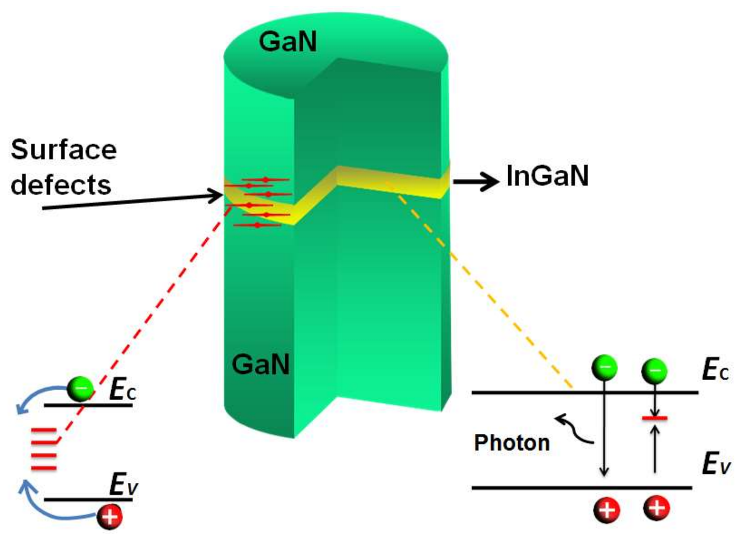
- **No efficiency droop was observed at very high injection current. However, compared to GaN-based quantum well LEDs, the peak EQE of nanowire LEDs occurs at very high injection current densities (> 100 A/cm^2). This cannot be explained by Auger recombination or electron overflow.**

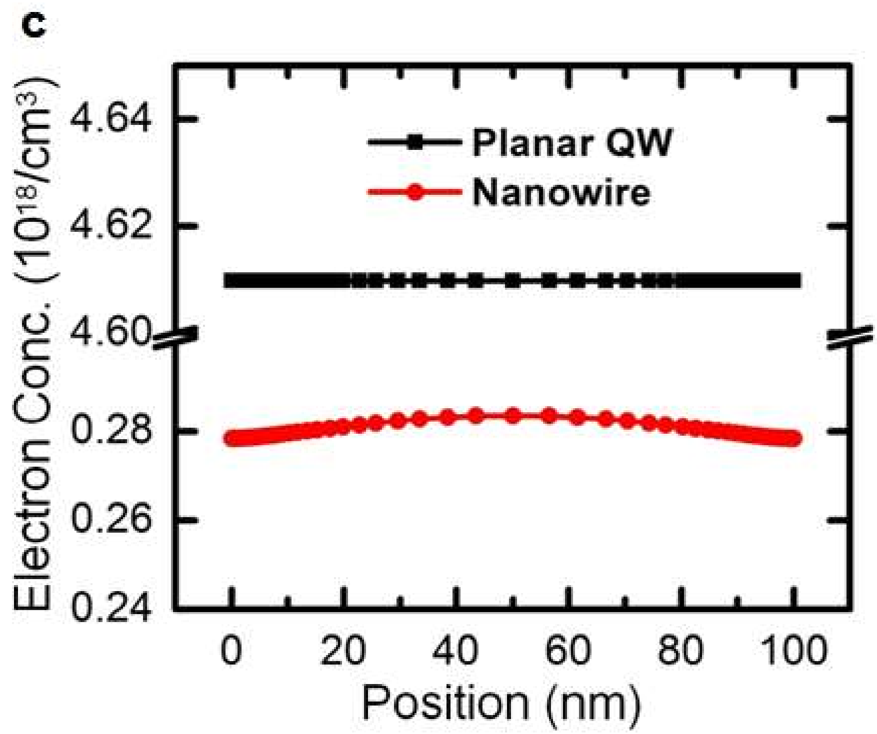
Kim et al., Appl. Phys. Lett. 91 183507
Meyaard et al., Appl. Phys. Lett. 99 041112
*Ryu et al., Appl. Phys. Lett. **95**, 081114, 2009*

Wang et al., IEEE Photonics Technol. Lett. 22, 236
Nguyen et al., Nanotechnology, 23, 194012, 2012
Guo et al., Appl. Phys. Lett. 98 193102

Surface Recombination and Carrier Injection Efficiency





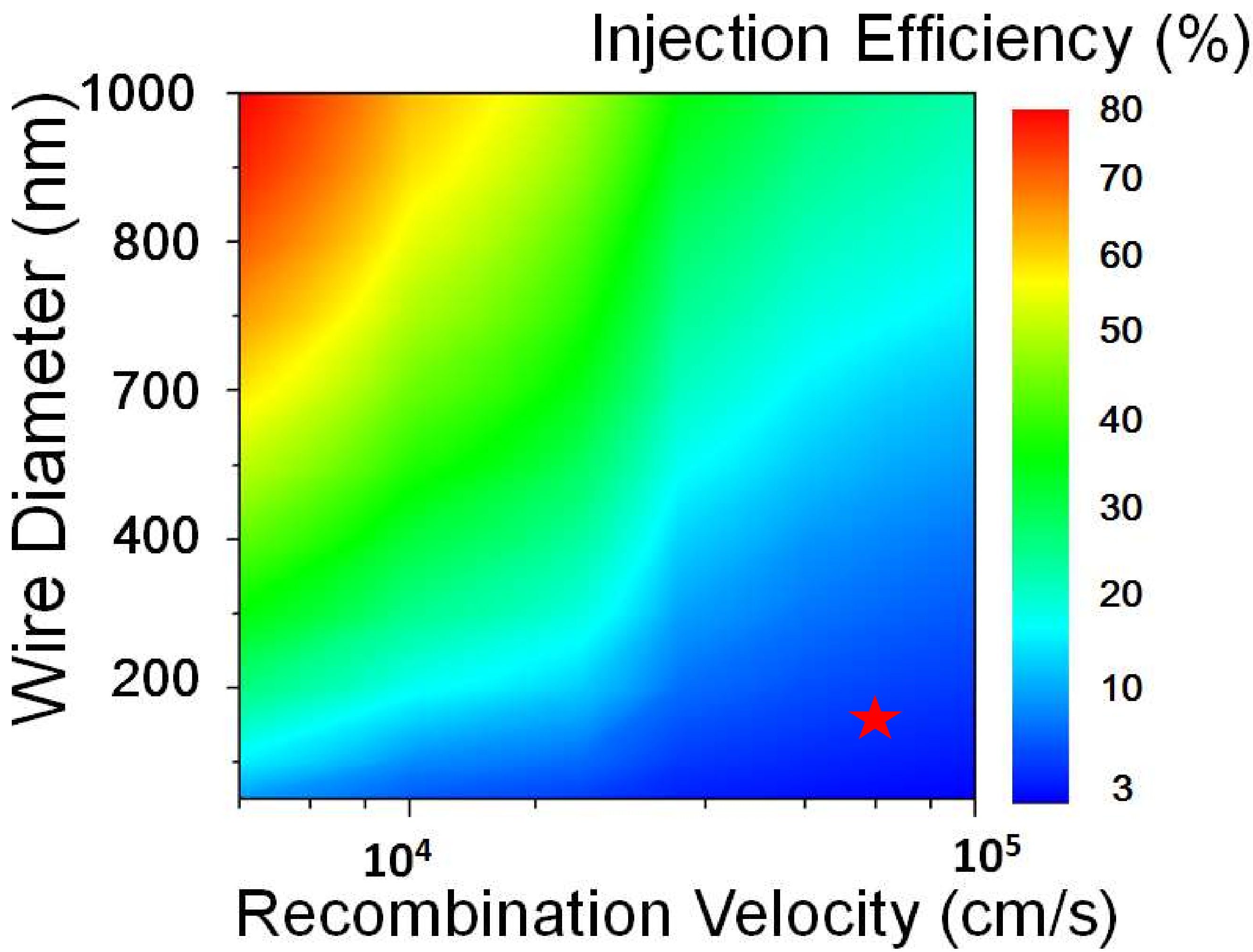


Carrier injection efficiency =

$$\frac{\text{\# of charge carriers in the active region}}{\text{\# of carriers injected from contacts}}$$

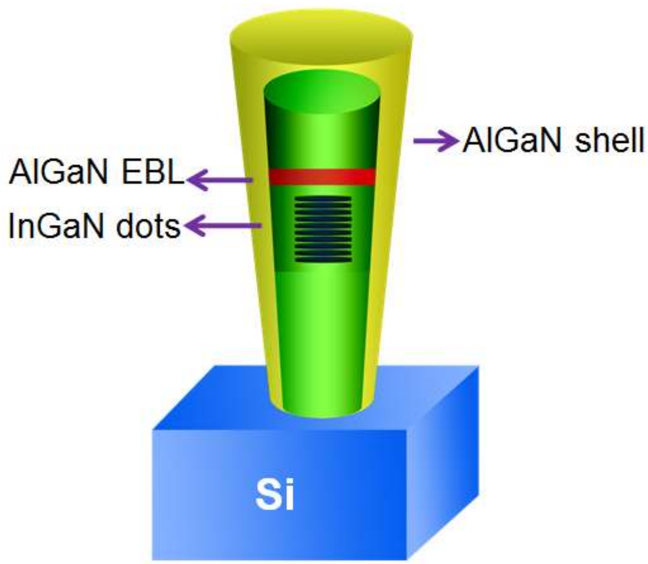
Nguyen et al., Nano Letters 13 (2013) 5437

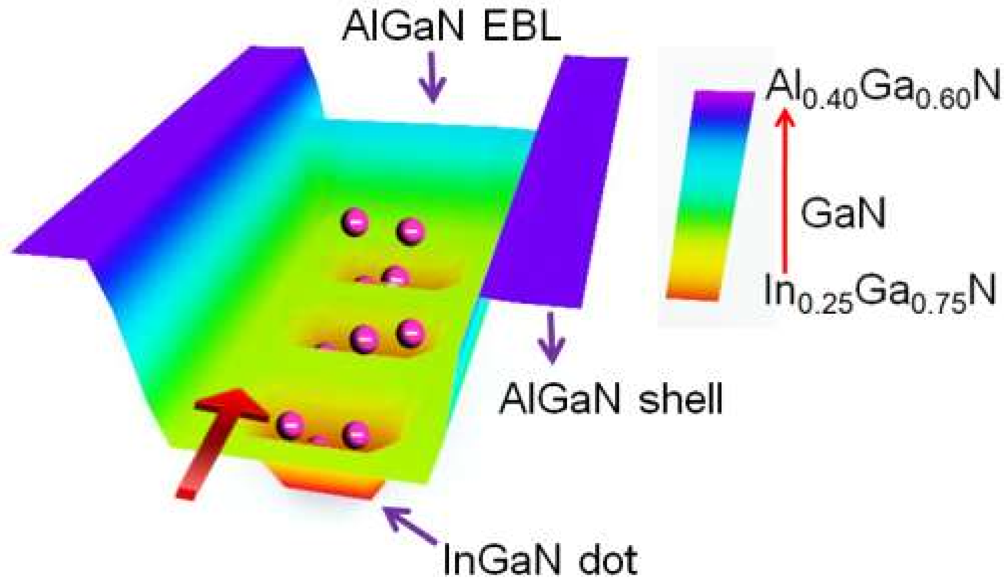
On the Carrier Injection Efficiency of Nanowire LEDs



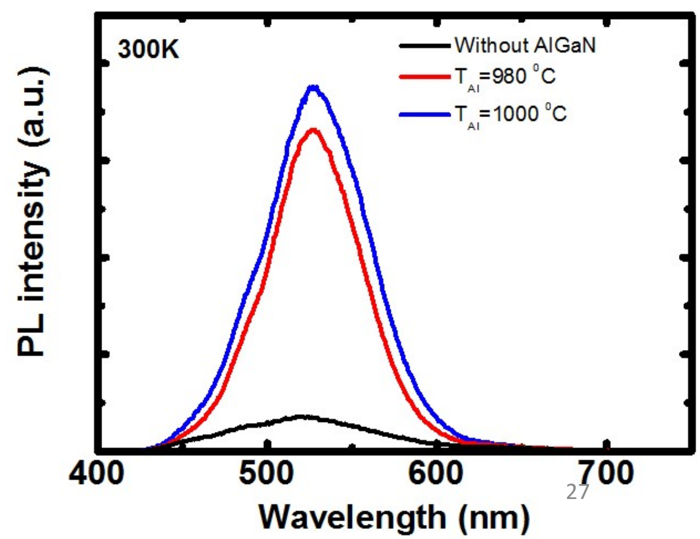
- **Currently reported nanowire LEDs generally exhibit extremely low output power, which is directly related to the poor carrier injection efficiency, due to surface recombination.**

InGaN/GaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs



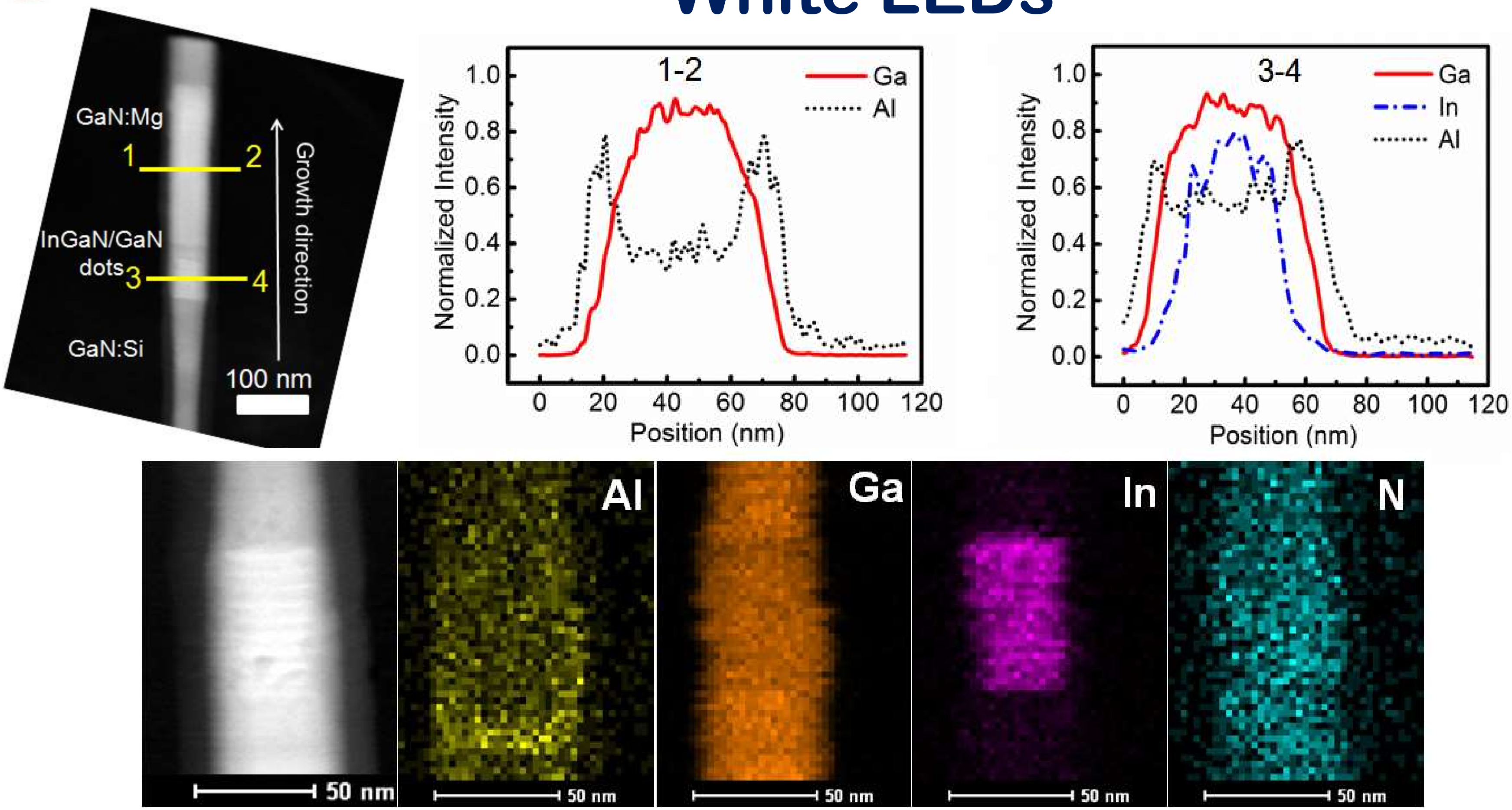


- **Nonradiative surface recombination can be minimized by using an AlGaN shell, leading to significantly enhanced optical emission.**



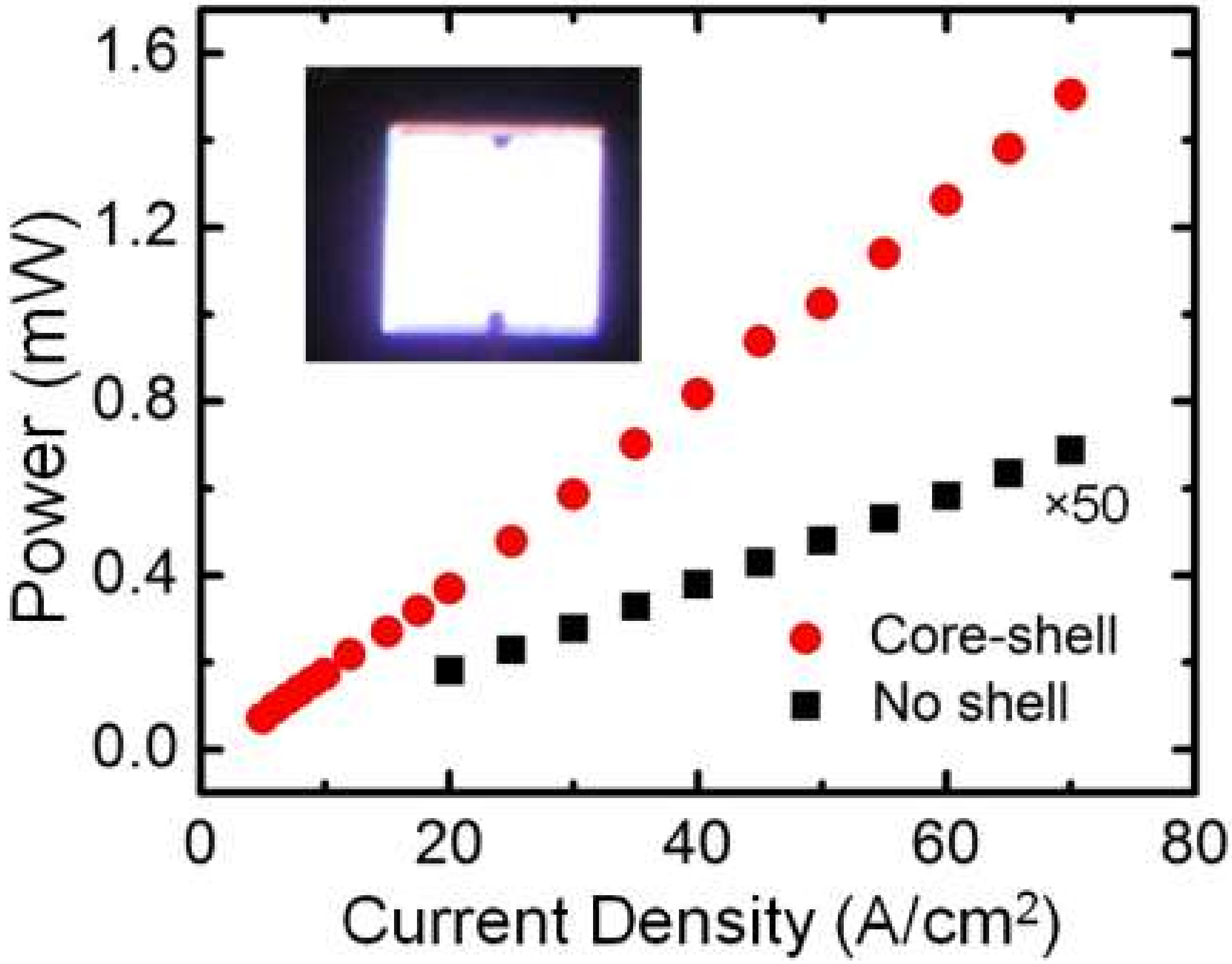
Nguyen et al., Nano Letters 13 (2013) 5437

InGaN/GaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs



- EDXS line scans analysis was performed along the lateral directions of the GaN:Mg and InGaN/GaN dot active regions.
- EDX elemental mapping image of the device active region shows the presence of InGaN/GaN quantum dots and AlGaN shell.

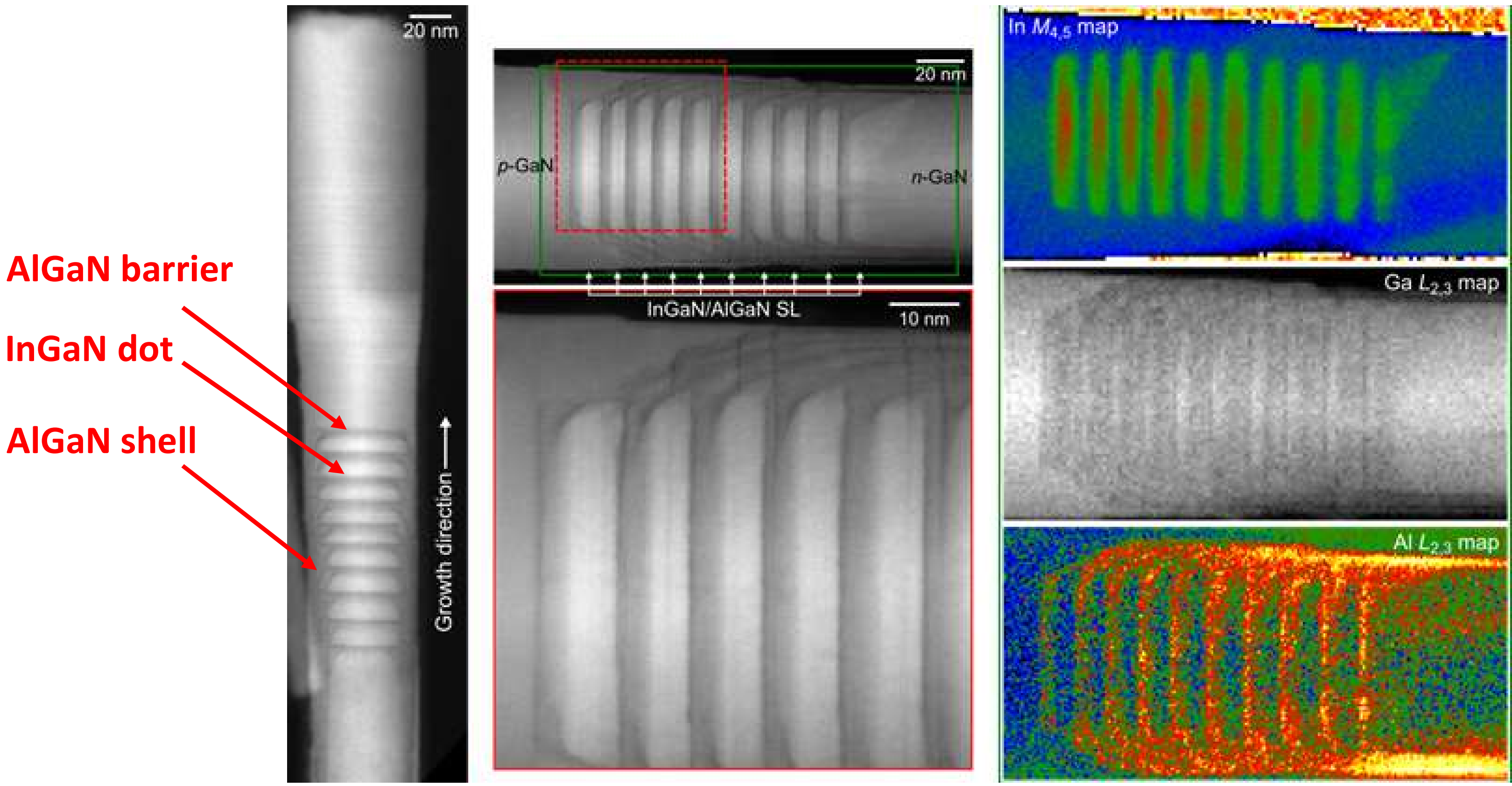
InGaN/GaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs



- ➢ **With the use of AlGaN shell, the output power is enhanced by nearly a factor of 100.**

Nguyen et al., Nano Letters 13 (2013) 5437

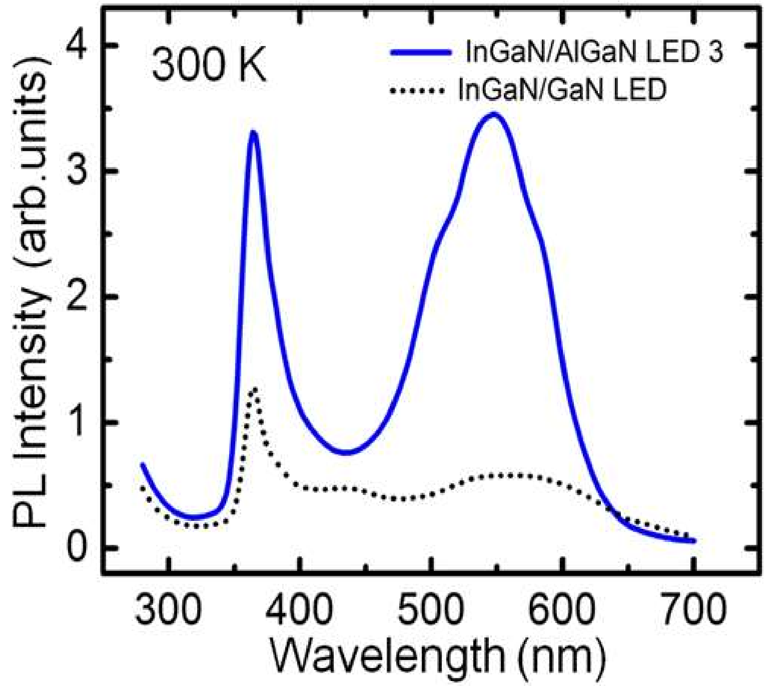
InGaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs

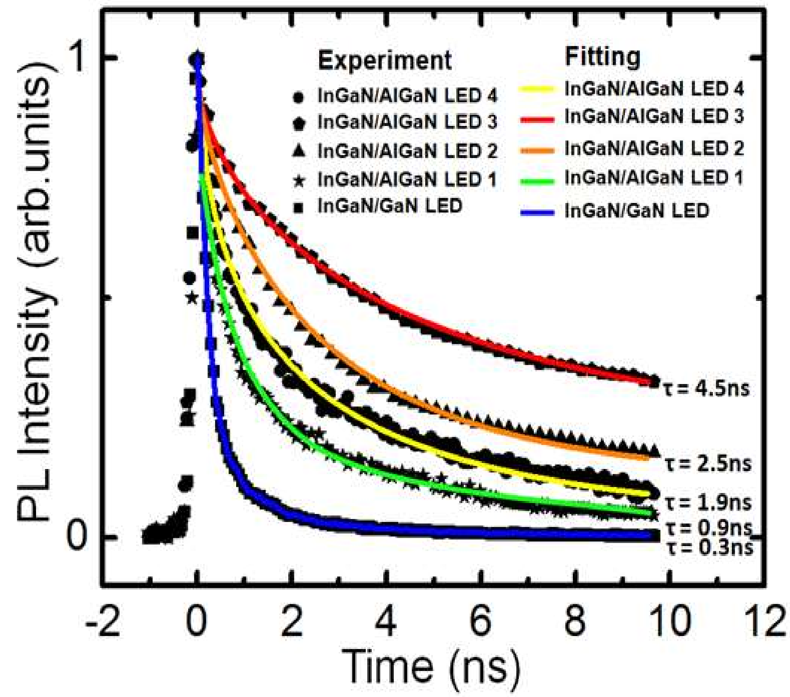


- **Self-organized InGaN/AlGaN multi-shell dot-in-a-wire LED structures offer the greatly reduced nonradiative surface recombination, leading to significantly enhanced optical emission.**

Nguyen et al., Nature Scientific Reports 5 (2015) 7744

InGaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs

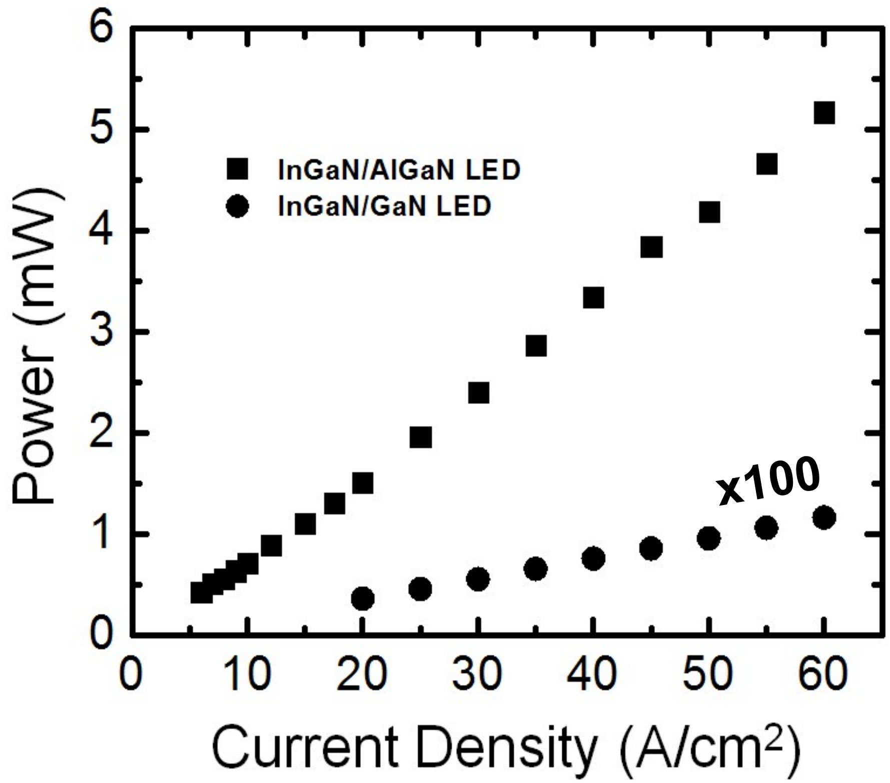


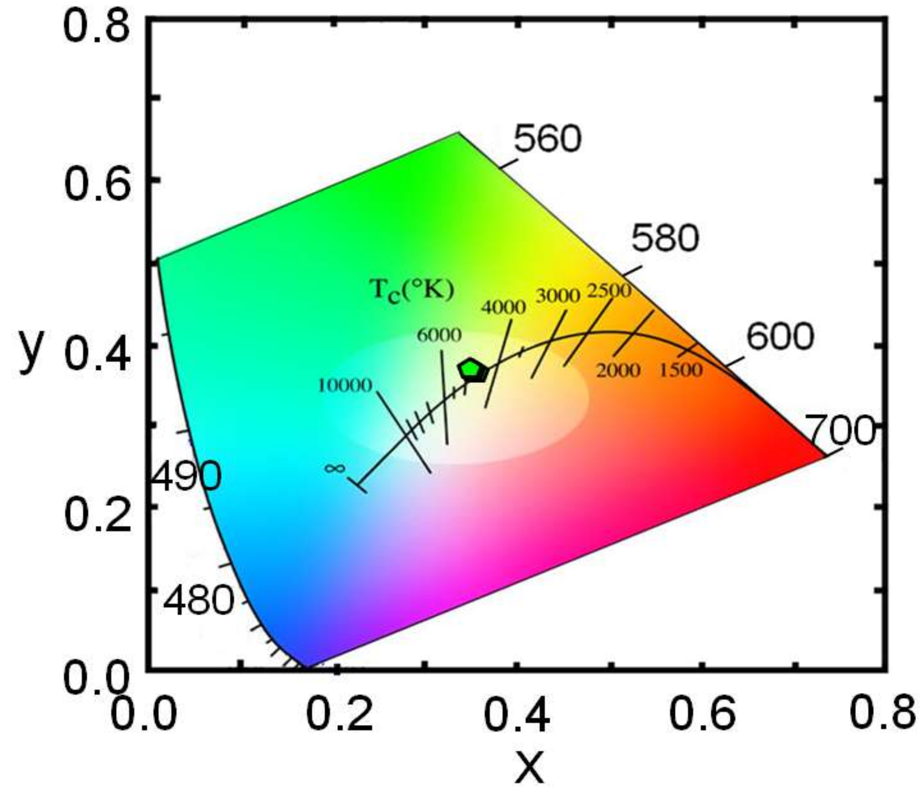


- **The enhancement in PL intensity and carrier lifetime of InGaN/AlGaN core-shell LEDs are directly correlated the drastically reduced nonradiative surface recombination, due to the presence of large bandgap AlGaN shell, that leads to much more efficient carrier injection and radiative recombination in the quantum dot active region.**

Nguyen et al., Nature Scientific Reports 5 (2015) 7744

InGaN/AlGaN Dot-in-a-Wire Core-Shell White LEDs

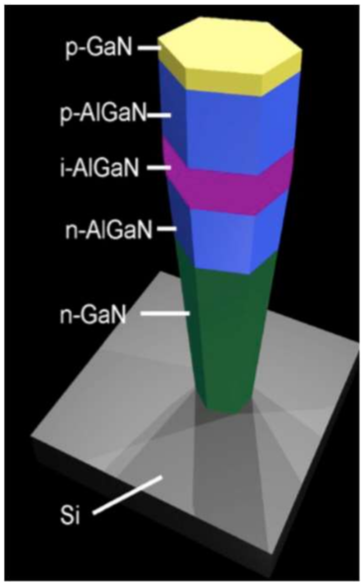


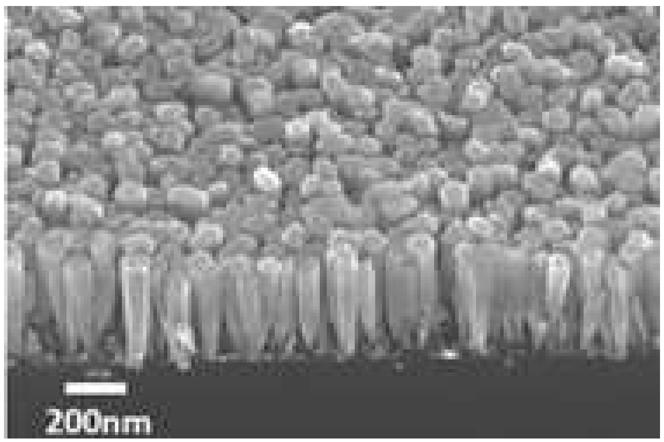


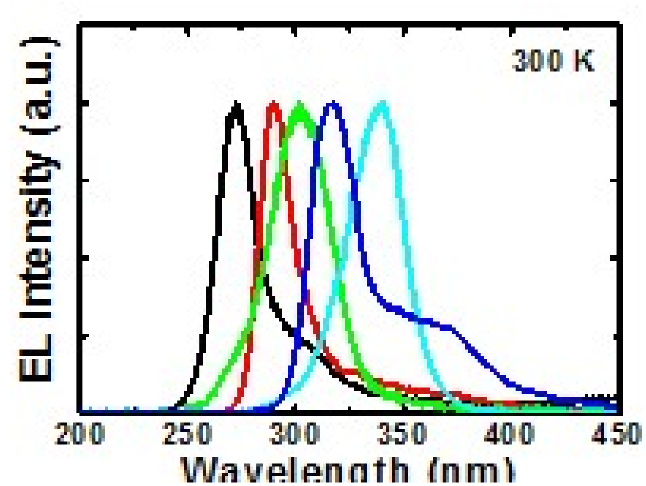
- **The dramatically enhanced output power and fast rising in EQE were recorded due to the efficient use of InGaN/AlGaN core-shell heterostructures.**
- **The phosphor-free InGaN/AlGaN nanowire white LEDs have relatively high output power of 5.2 mW and deliver an unprecedentedly high color rendering index of ~ 92-98.**

Nguyen et al., Nature Scientific Reports 5 (2015) 7744

Deep Ultraviolet III-Nitride Nanowire Light-Emitting Diodes







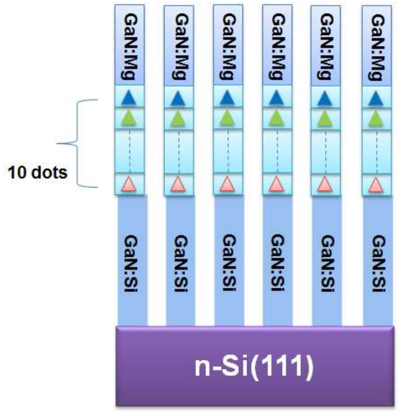
Exhibition high IQEs across the entire UV A and B spectral range at room temperature.

Wang et al., Applied Physics Letters, 110 (2012) 043115
Wang et al., Nanotechnology 24 (2013) 345201

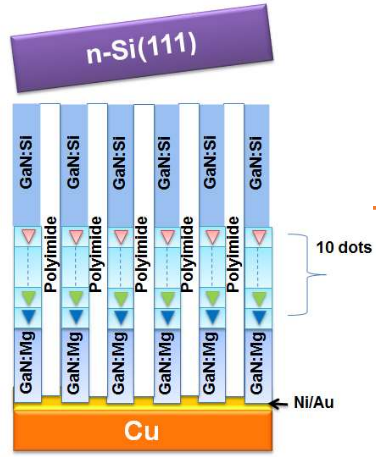
Applications of Nanowire LEDs

Transferring Nanowire LEDs onto Cu Substrate for Flexible Electronics

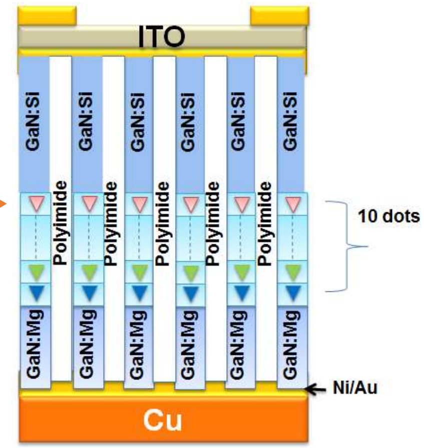
Fabrication Process Flow



Epi-Growth

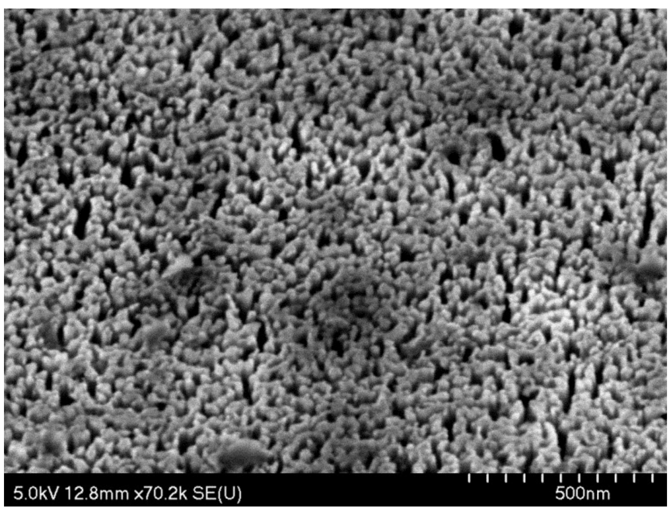


Si removal and lift-off

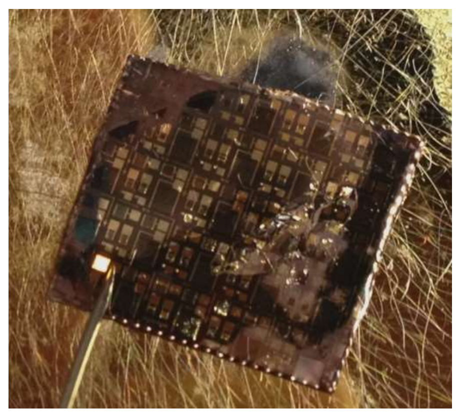


Thick Ti/Au deposited

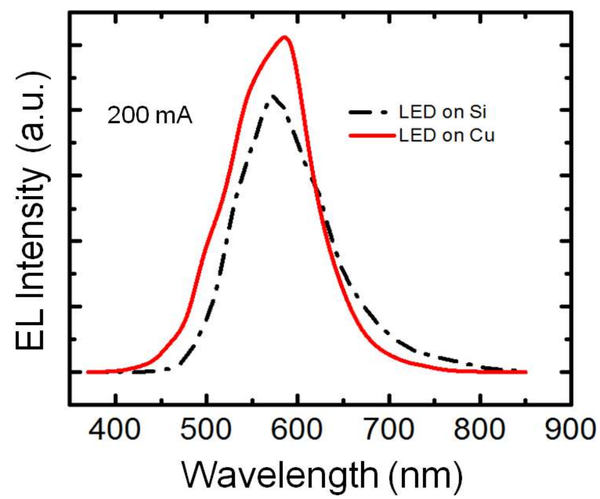
Samsung's Flexible Screen



SEM image of InGaN/GaN nanowire on Cu substrate

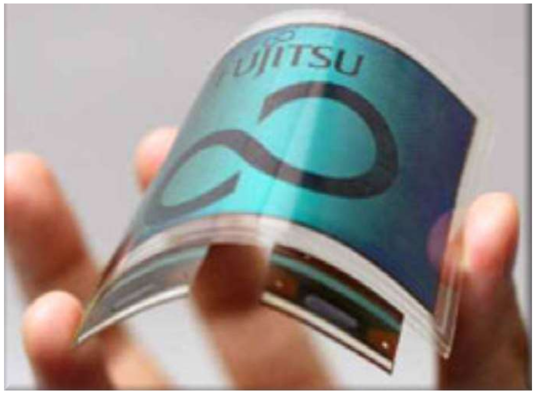


Nanowire LED on Cu substrate



Nguyen et al., J. Electron. Material, 43 (2014) 868

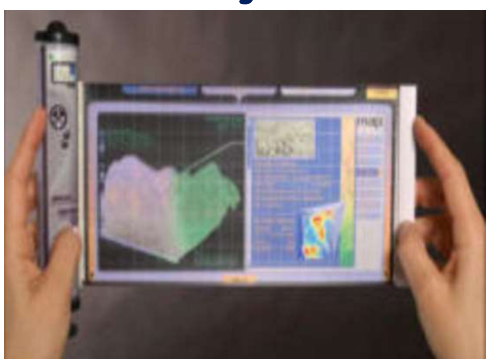
Full-color InGaN/GaN LEDs on Transparent Substrates for Flexible Electronics

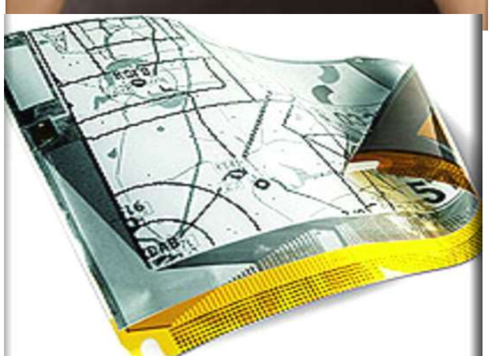


Samsung's Flexible Screen

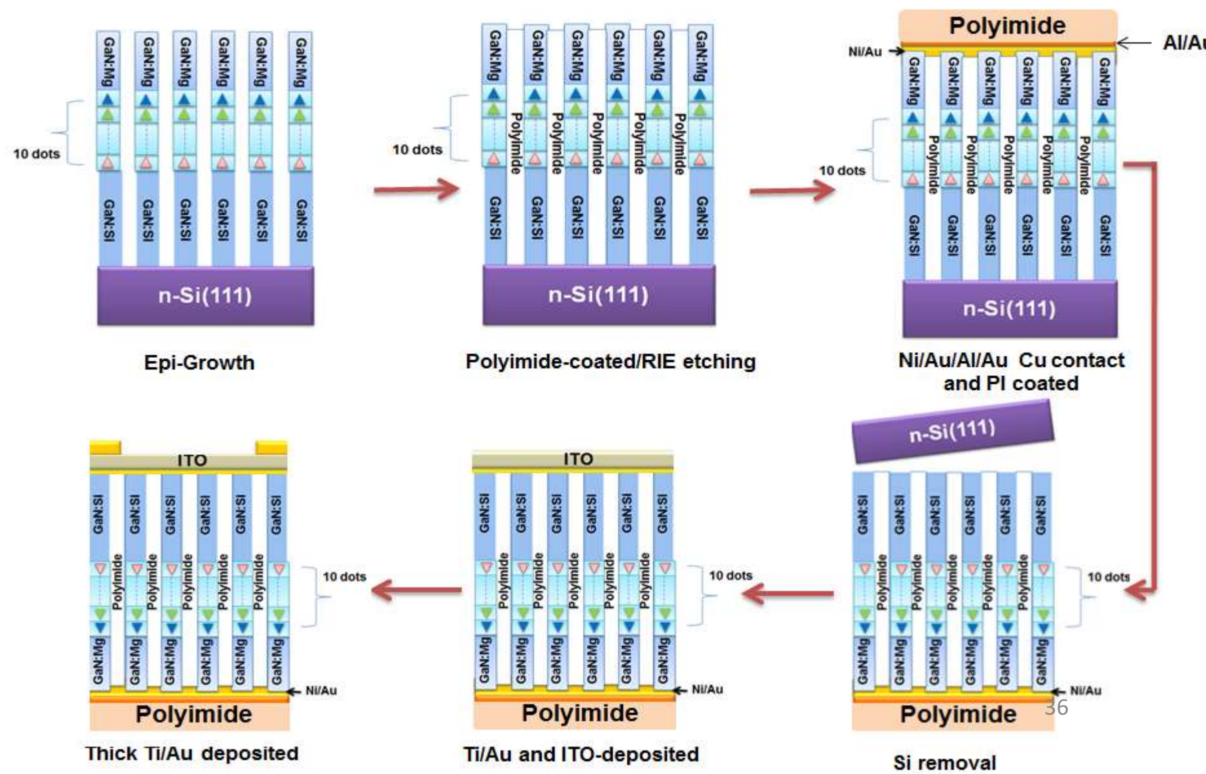
iFlex Cell Phone

For military services

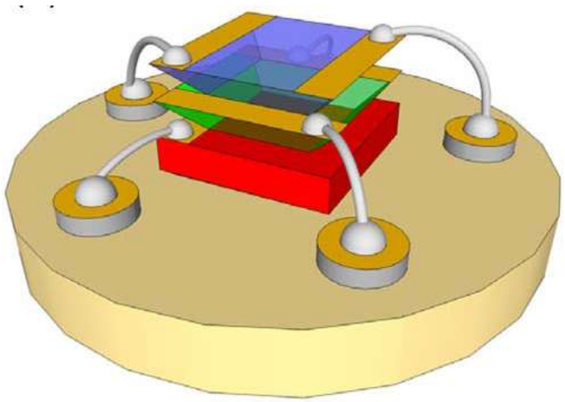


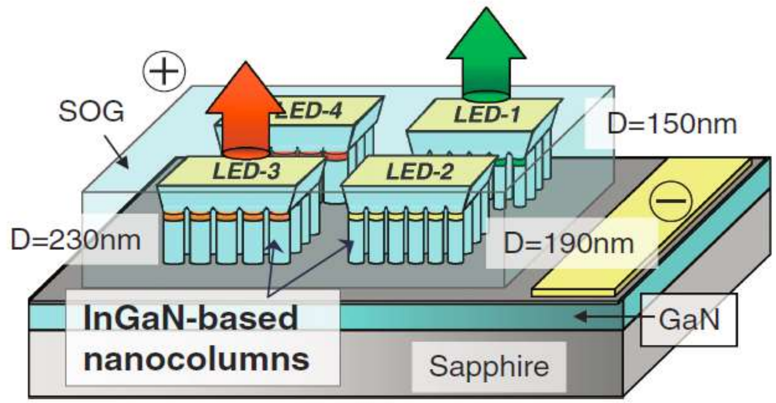


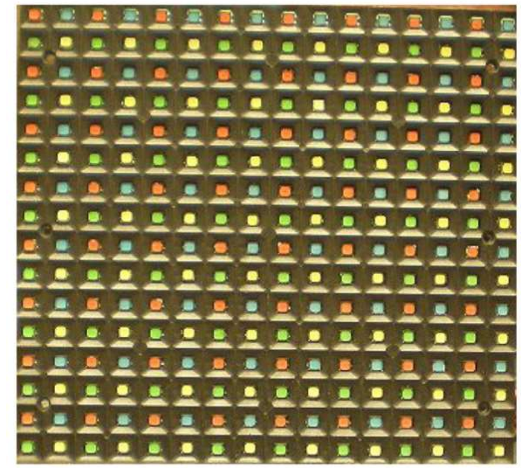
Pictures downloaded from Internet

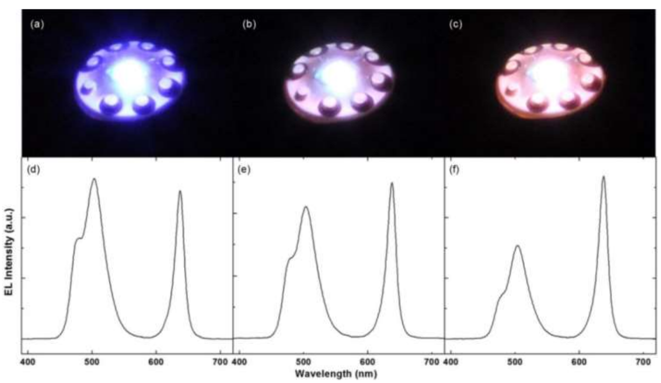


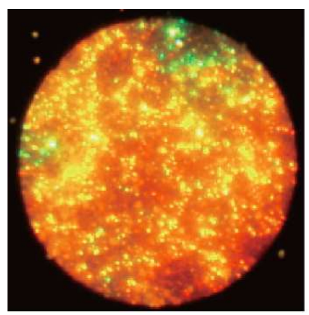
Color Tunable InGaN/GaN/AlGaN Core-Shell LEDs on Silicon

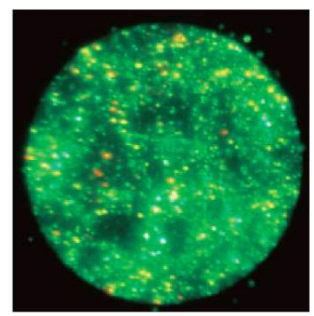












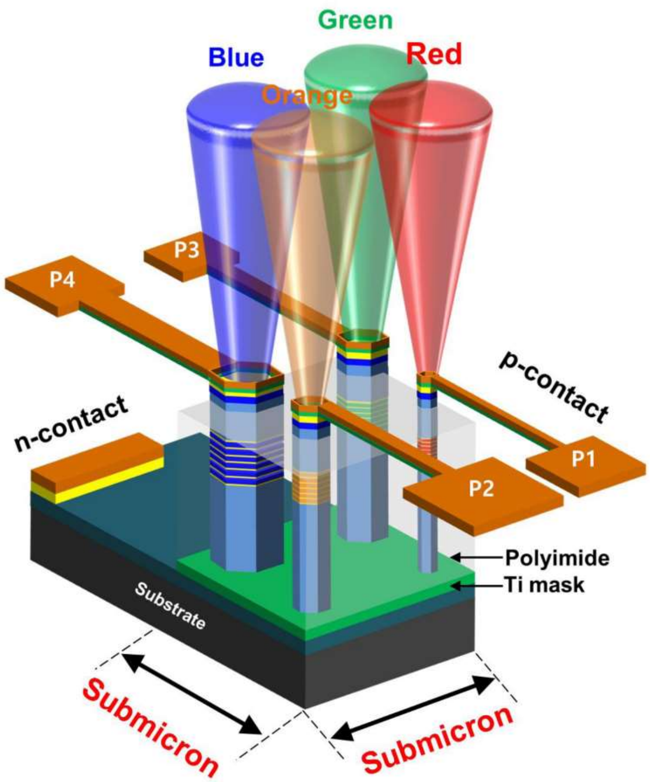
RGBW Pixel Configuration for Light-Emitting Displays

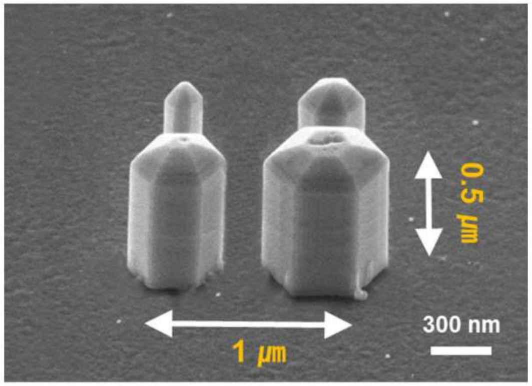
Y. F. Cheung et al., IEE Transactions on Electron Devices, 60, 333, 2013

N. Shlayan et al., J. Display Technology, Vol. 5, 2009

K. Kishino et al., Appl. Phys. Express 6, 012101, 2013

Full-Color Single Nanowire Pixels for Projection Displays





Yong-ho Ra et al., Nano Letters (In press)

More Applications of LEDs

Traffic signals (Gelcore)

Large Displays (NASDAQ)

MITSUBISHI ELECTRIC
PRESENTATION PRODUCTS

Uses Blue, Green, Red LEDs

CellPhone Camera Flash

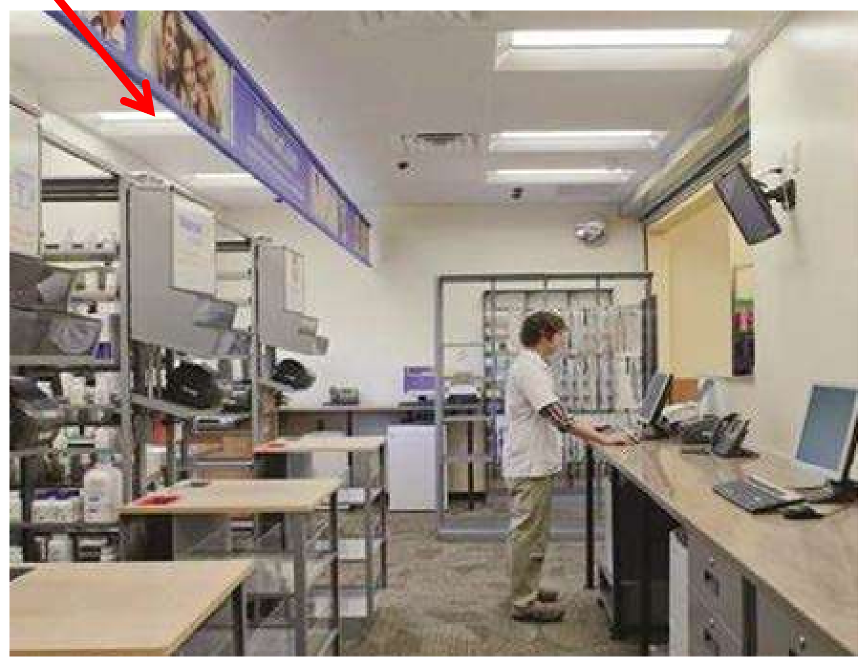
Streetlights

TVs (LED DLP^{tm}) (samsung)

Automobile

Pictures downloaded from Internet

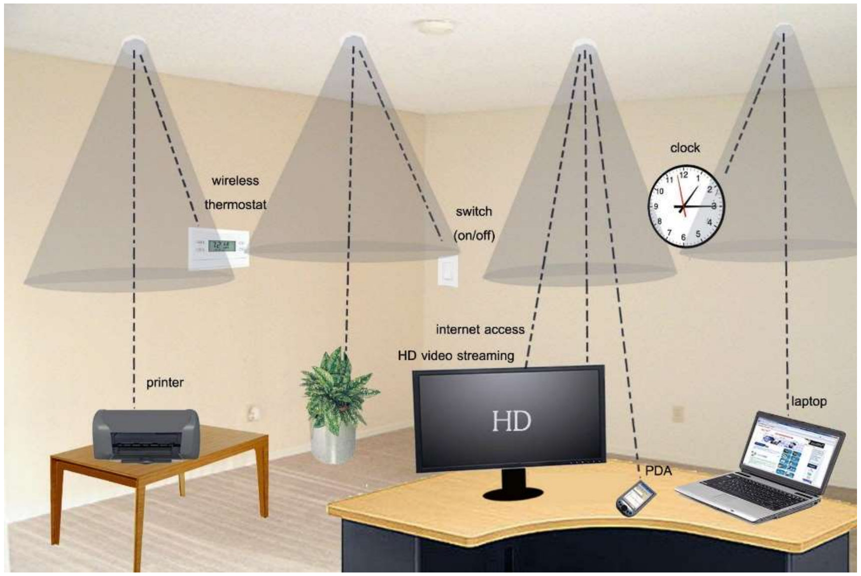
LED lighting for a comfortable atmosphere

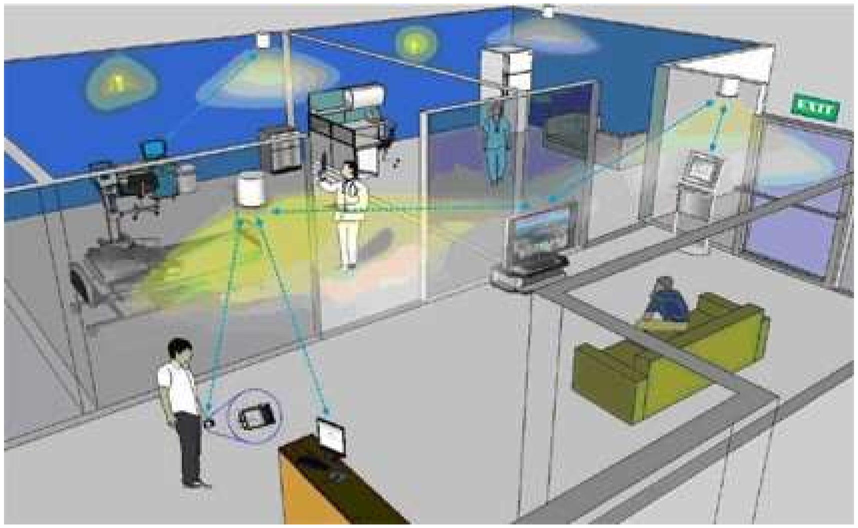


http://www.gelighting.com/LightingWeb
Borrowed from internet

Visible Light Communication

- Indoor wireless communication systems for broadband connectivity





Borrowed from interne

Conclusions

❖ **We have identified and addressed several critical challenges that are relevant for the practical applications of nanowire LEDs.**

❖ ***Phosphor-free white light emission with high output power of 5.2 mW and high color rendering index (CRI) of ~92-98 in both the warm and cool white regions were achieved by using dot-in-a-wire core-shell LED heterostructures.***

❖ **Full-color nanowire LED arrays were developed by selective area growth of multiple color LEDs on the same substrate.**

Thank You!