Nanowire White LEDs for Phosphor-Free Solid State Lighting

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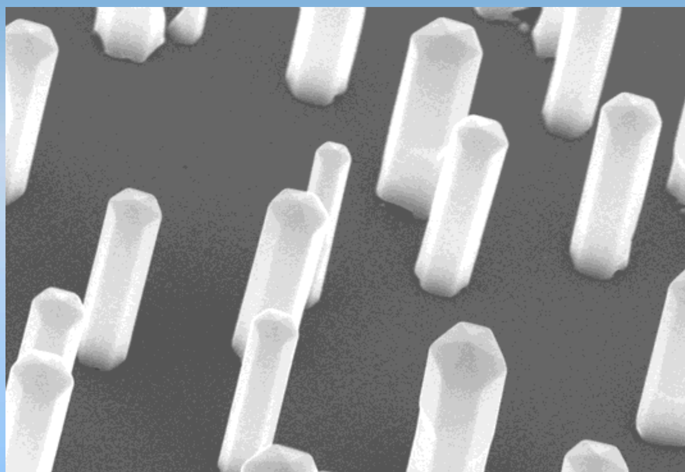
Outline

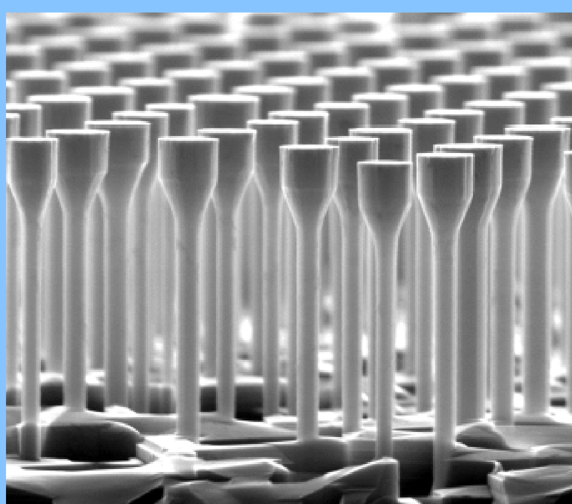
- Introduction and background
- Promises and challenges of GaN-based nanowire LEDs
- High efficiency InGaN/GaN dot-in-a-wire white LEDs
  - p-type modulation doping to enhance hole transport
  - AlGaN electron blocking layer to reduce carrier overflow
- Conclusion and future work

Advantages of Nanowire LEDs

Bottom-up approach



Top-down approach



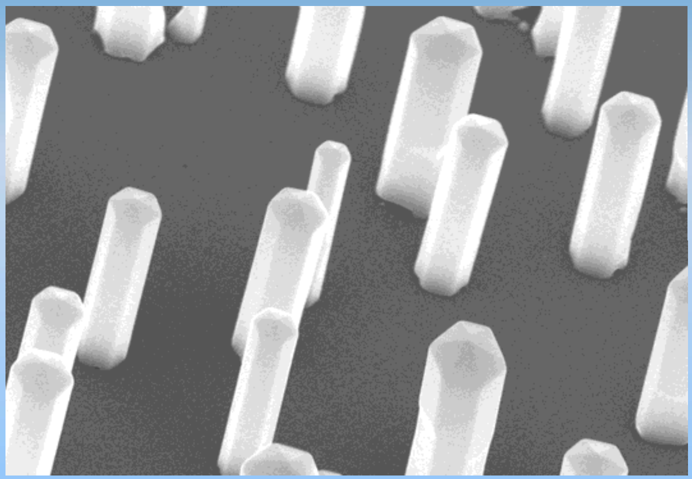
Advantages:

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

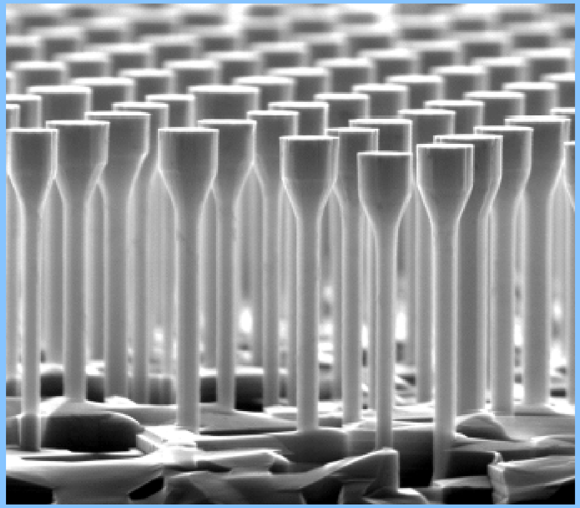
Nanotechnol., vol. 21, 125201, 2009. *Adv. Funct. Mater.*, vol. 20, 4146, 2010. *J. App. Phys*. **100**, 054314, 2006.
Nano Lett., vol. 10, 3355, 2010. Opt. Exp., vol. 19, 25529, 2011.

Challenges of Nanowire LEDs

Bottom-up approach

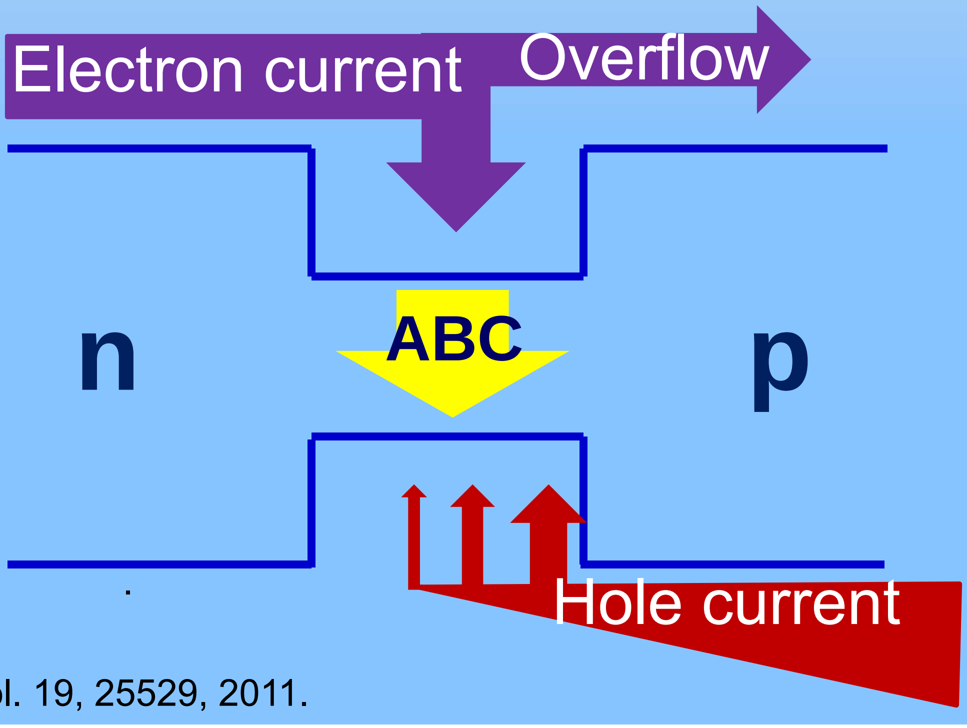


Top-down approach



Challenges:

- <u>Surface states and band bending</u>
  →low quantum efficiency
- <u>Poor hole transport</u>
  →low efficiency, efficiency droop
- <u>Electron overflow</u>
  → low efficiency, efficiency droop



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Challenges and Solutions of Nanowire LEDs

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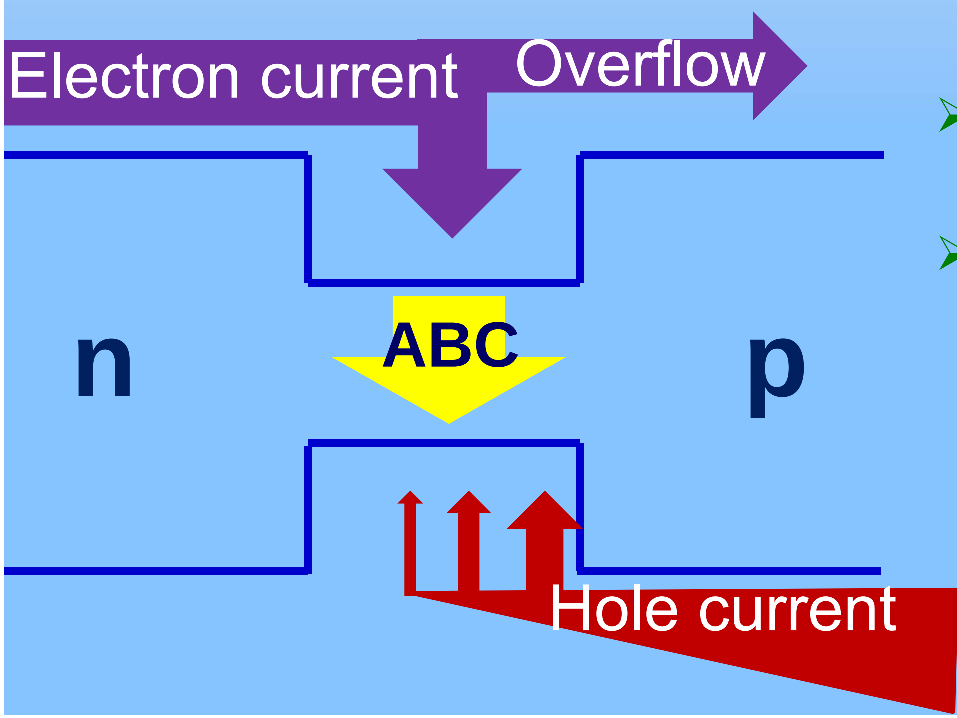
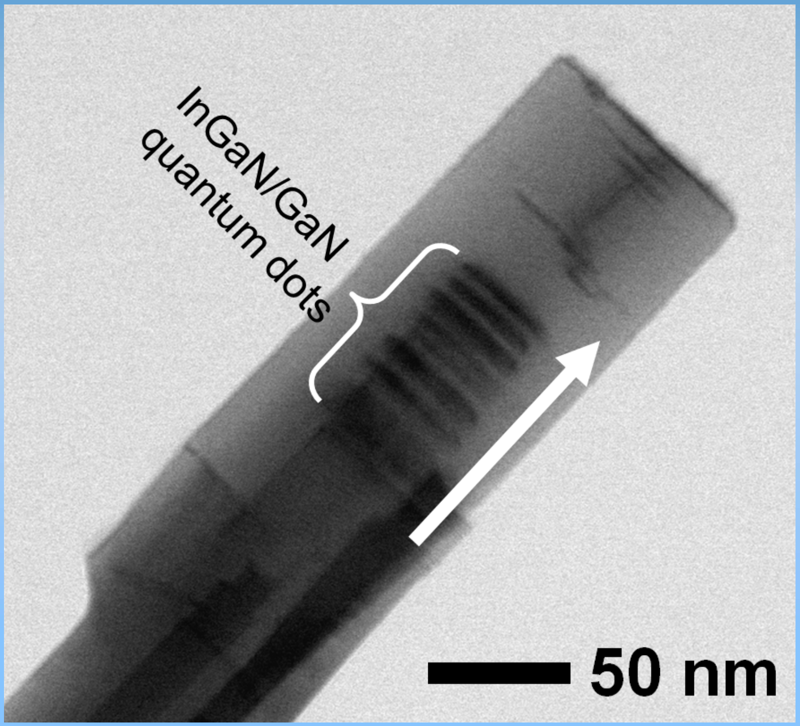


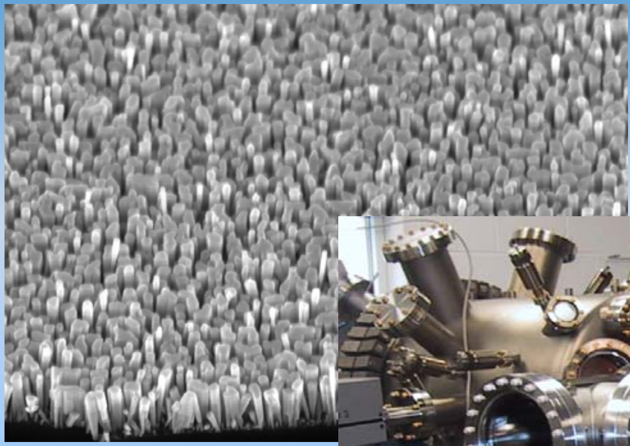
Solutions:

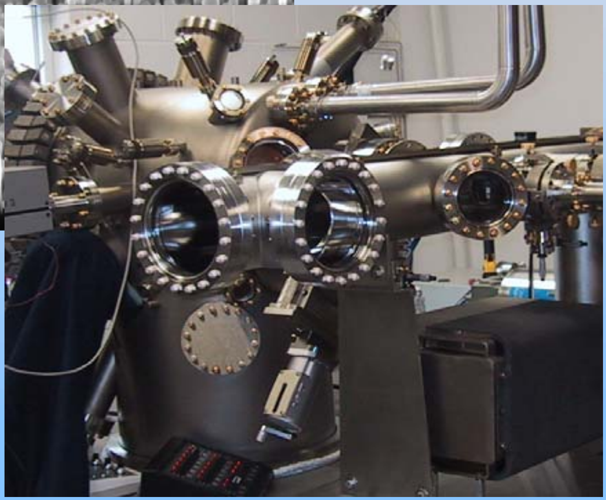
- Self-catalytic growth
  → controlled wire morphology and surface charge properties
- Dot-in-a-wire nanoscale heterostructures
  →drastically reduce carrier recombination on the surface due to the superior carrier confinement
- P-type modulation doping
  →enhance hole transport
- Electron blocking layer
  → prevent electron overflow

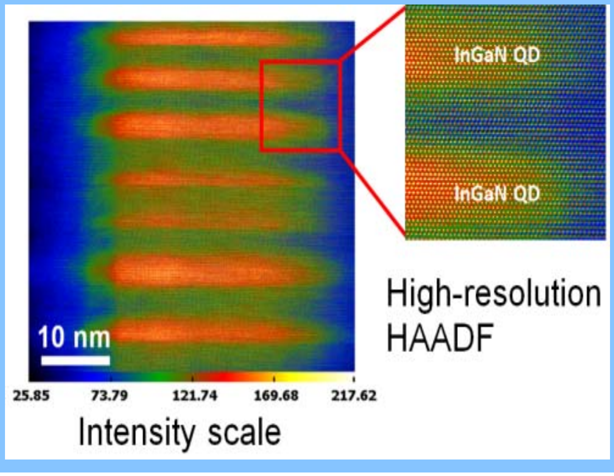
Nanotechnol., vol. 21, 125201, 2009. *Adv. Funct. Mater.*, vol. 20, 4146, 2010. *Appl. Phys. Lett., vol. 96, 013106, 2010. Nano Lett.*, vol. 11, 1919, 2011.*Nano Lett.*, vol. 12, 1317, 2012.

InGaN/GaN Dot-in-a-Wire Nanoscale Heterostructures on Si





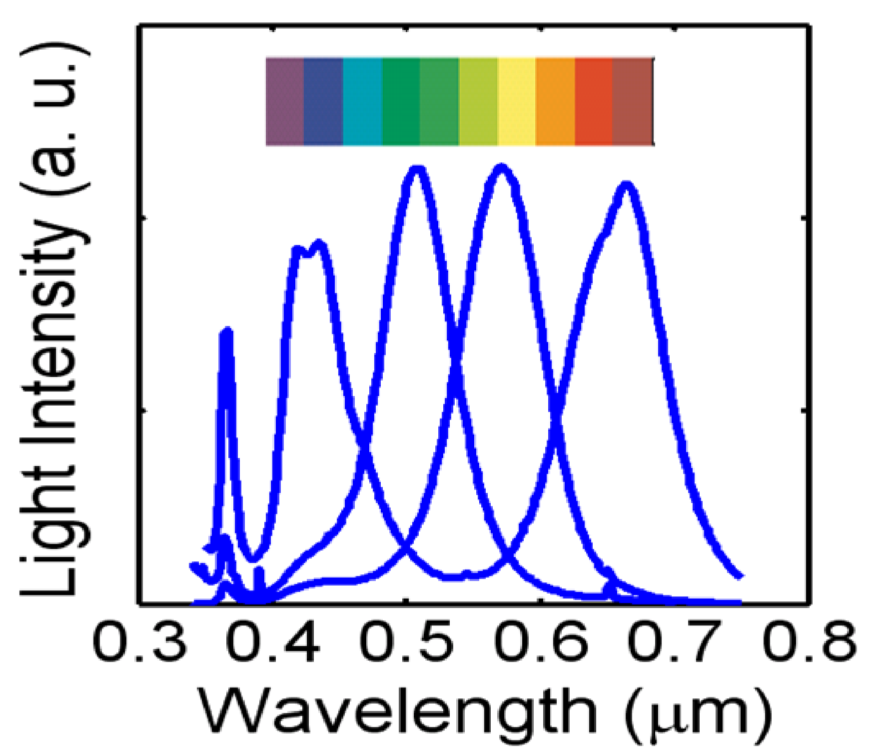




- **Catalyst-free InGaN/GaN dot-in-a-wire heterostructures are grown by molecular beam epitaxy on Si(111) substrates.**

Appl. Phys. Lett., vol. 96, 013106, 2010.
Nano Lett., vol. 11, 1919, 2011.
Nano Lett., vol. 12, 1317, 2012.

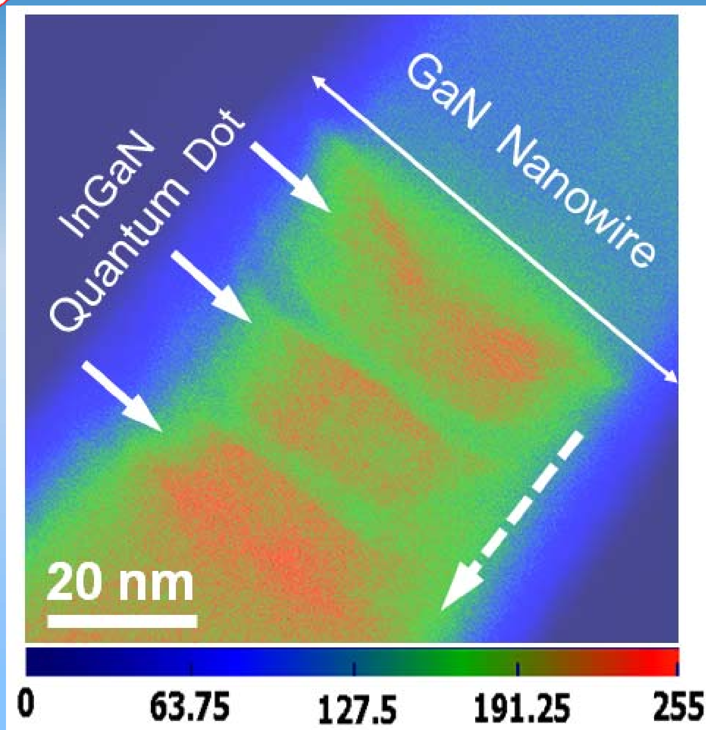
Controlled Emission Wavelengths

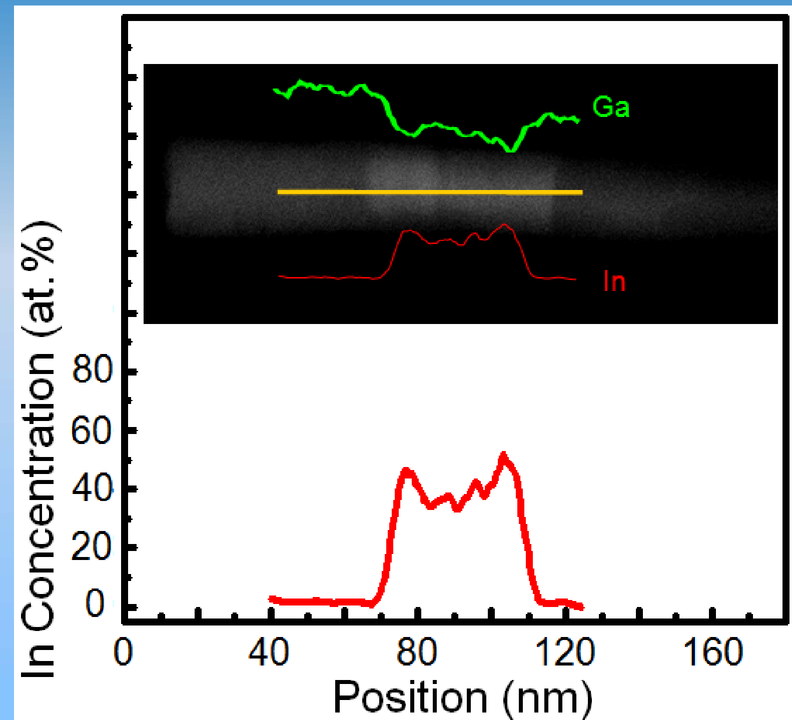


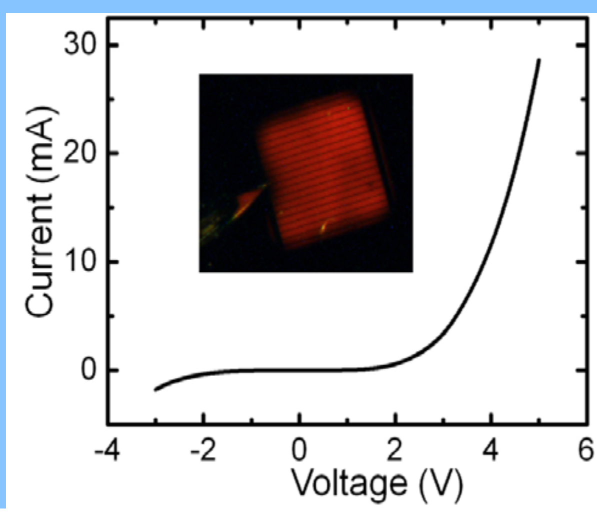
- White light emission without using phosphors
- Stable emission
- Better light quality
- Improved reliability
- Reduced manufacturing cost

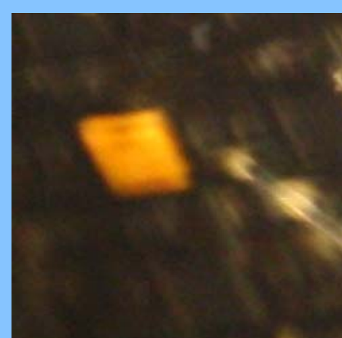
- **By varying the In compositions in the InGaN dots, the emission wavelengths can be controllably tuned from blue, green, yellow to red wavelength range.**

Full-Color InGaN/GaN Dot-in-a-Wire LEDs

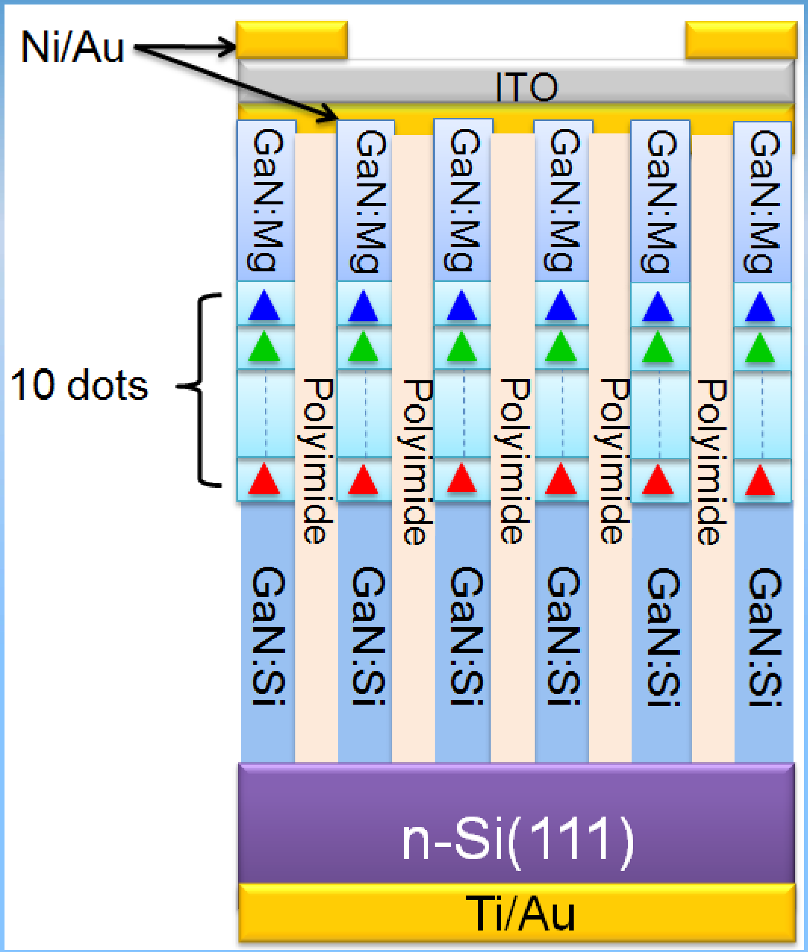


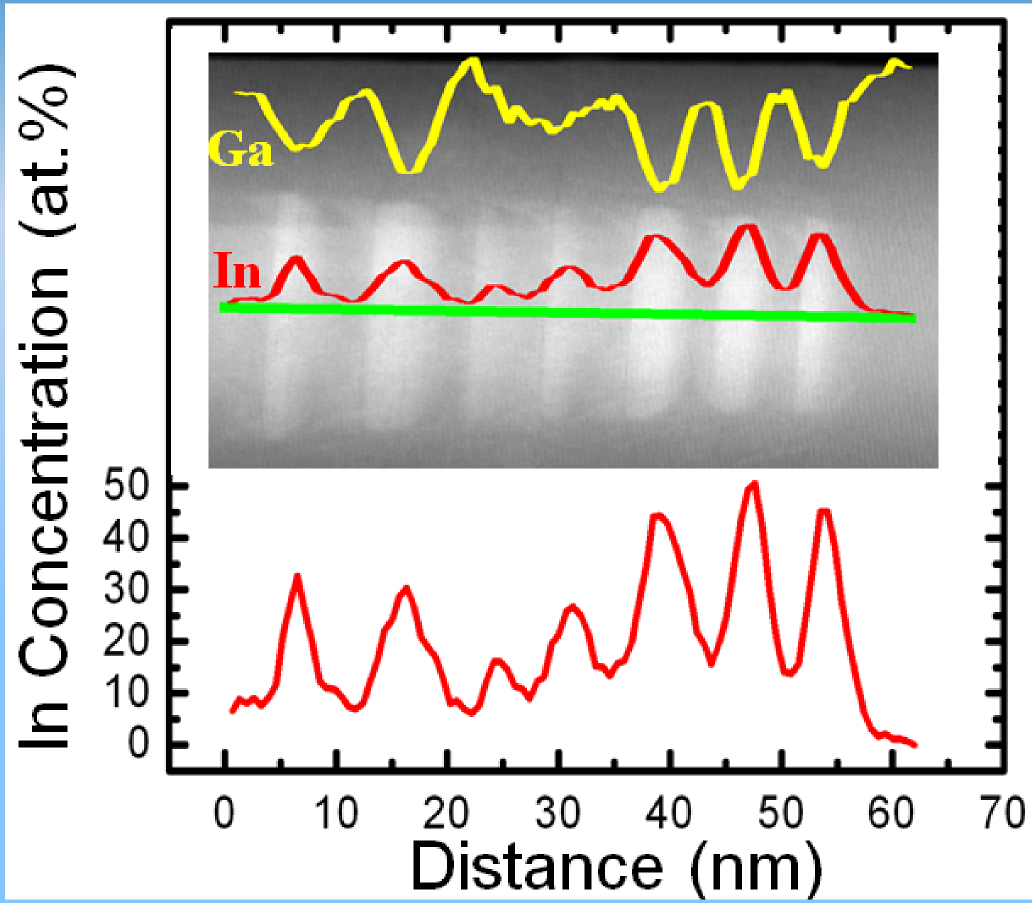






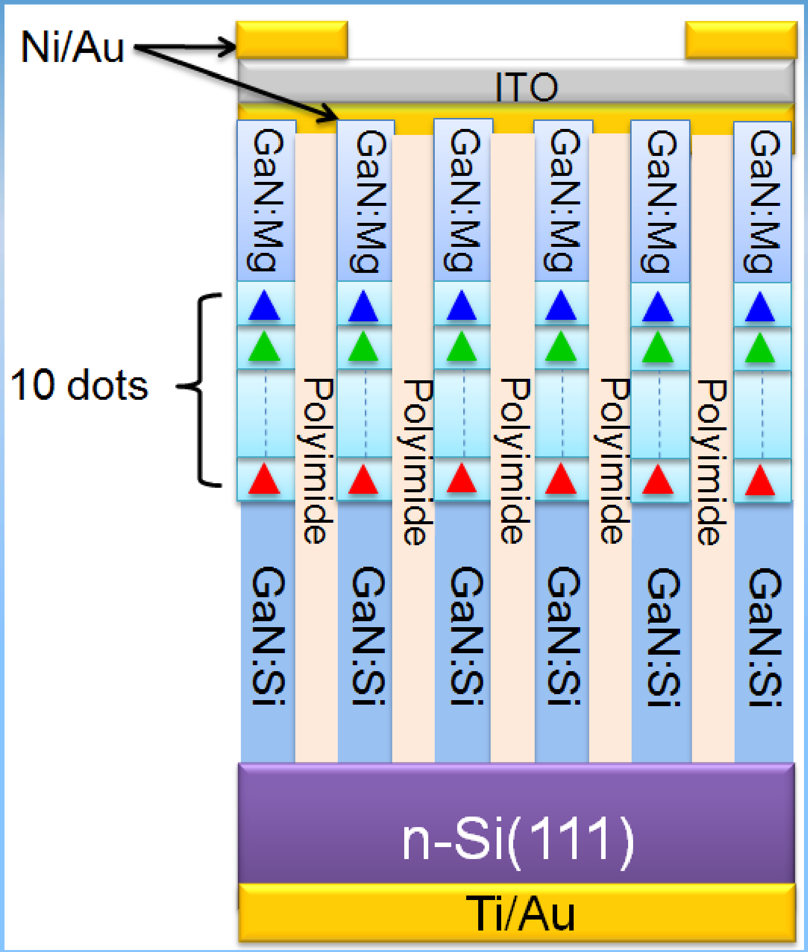
InGaN/GaN Dot-in-a-Wire White LEDs

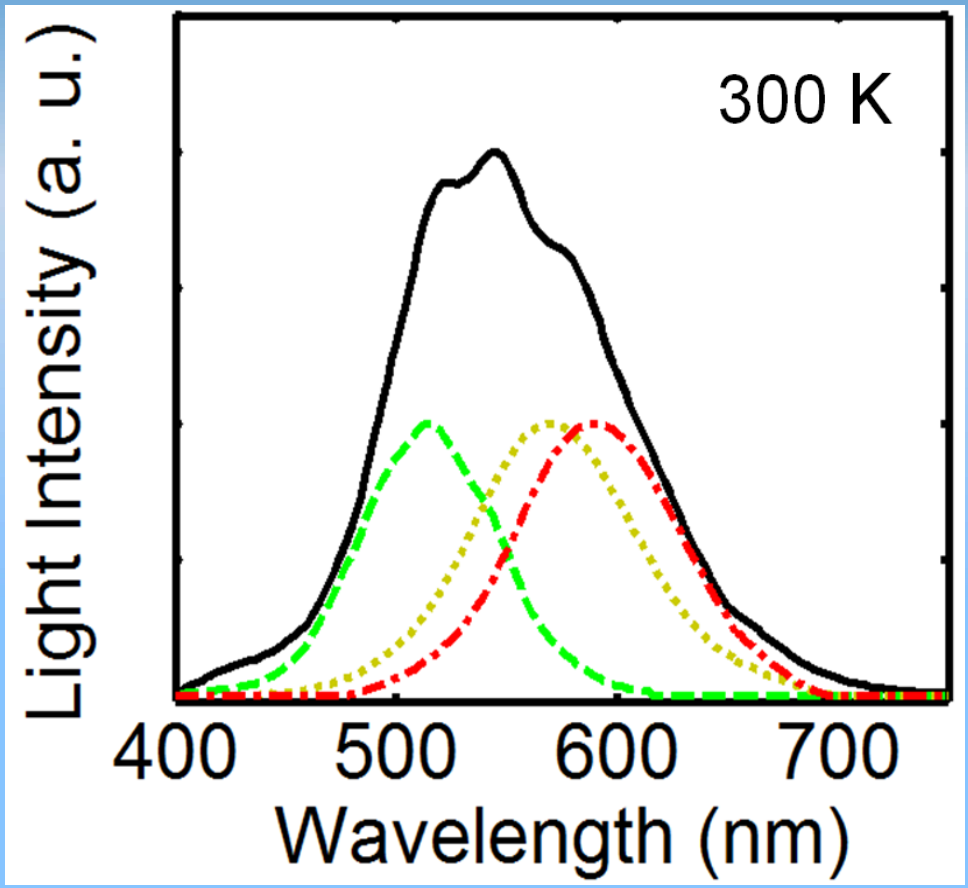




- Intrinsic white light emission is achieved by modulating the indium compostions in the quantum dots.

InGaN/GaN Dot-in-a-Wire White LEDs





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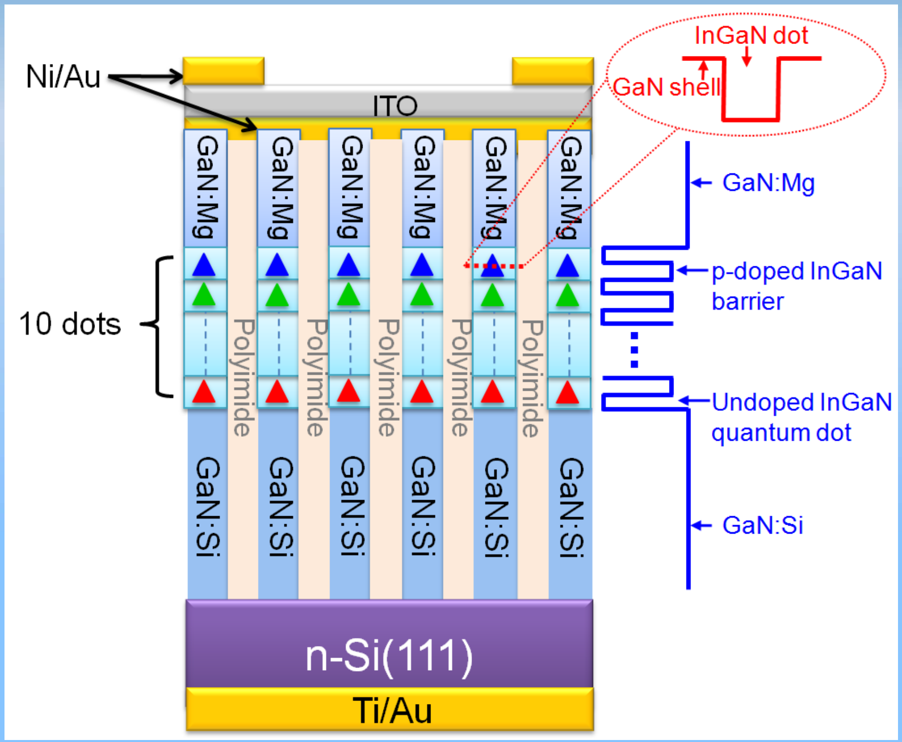
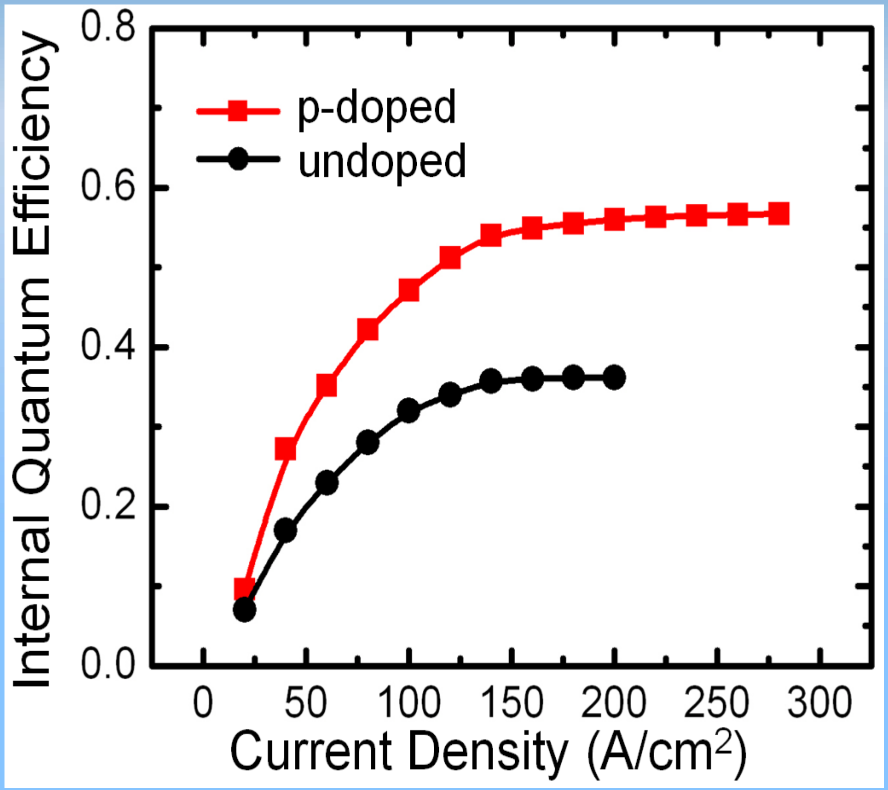
p-Doped InGaN/GaN Dot-in-a-Wire White LEDs

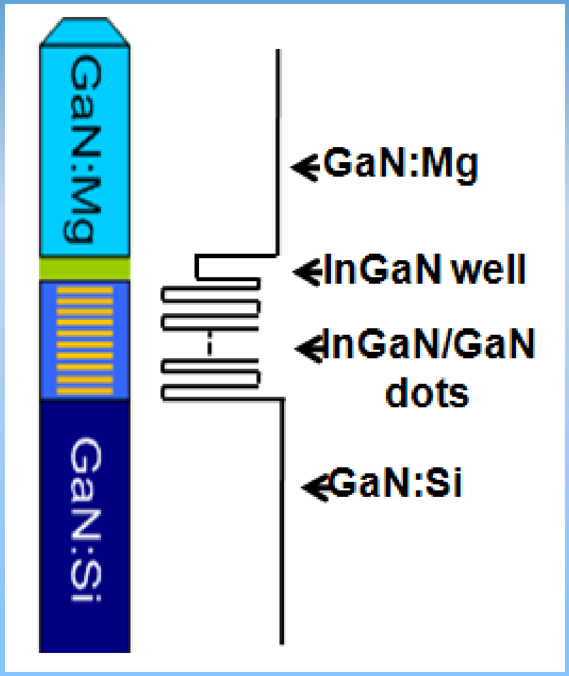




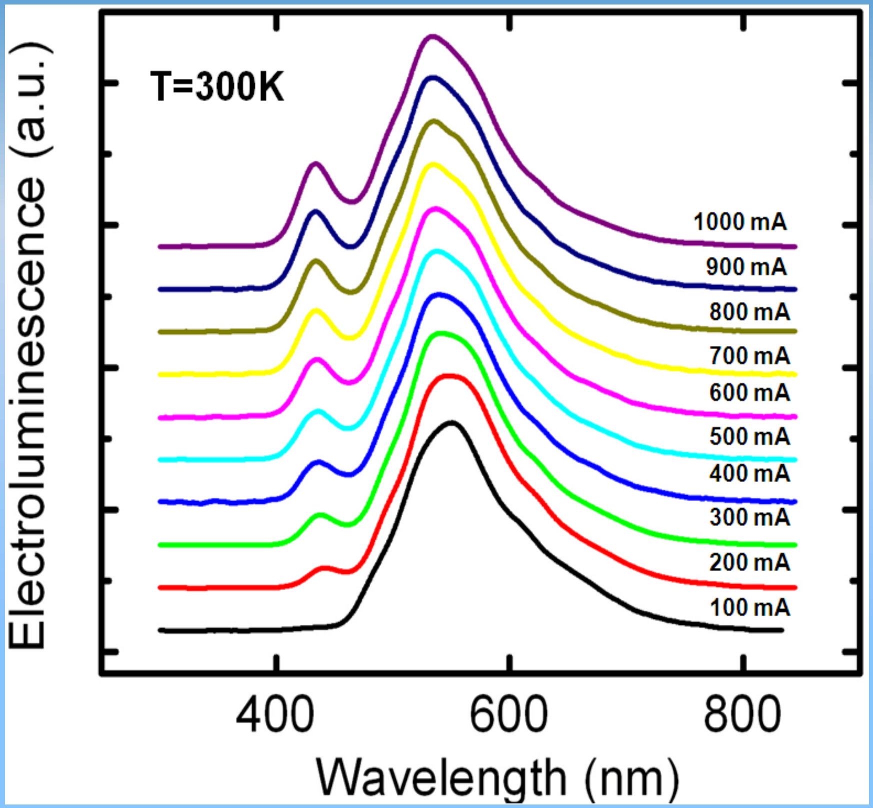
- ➢ The performance of nanowire LEDs is severely limited by the poor hole transport process.
- ➢ The use of p-type modulation doping can significantly enhance the quantum efficiency.

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

Electron Overflow in Nanowire LEDs



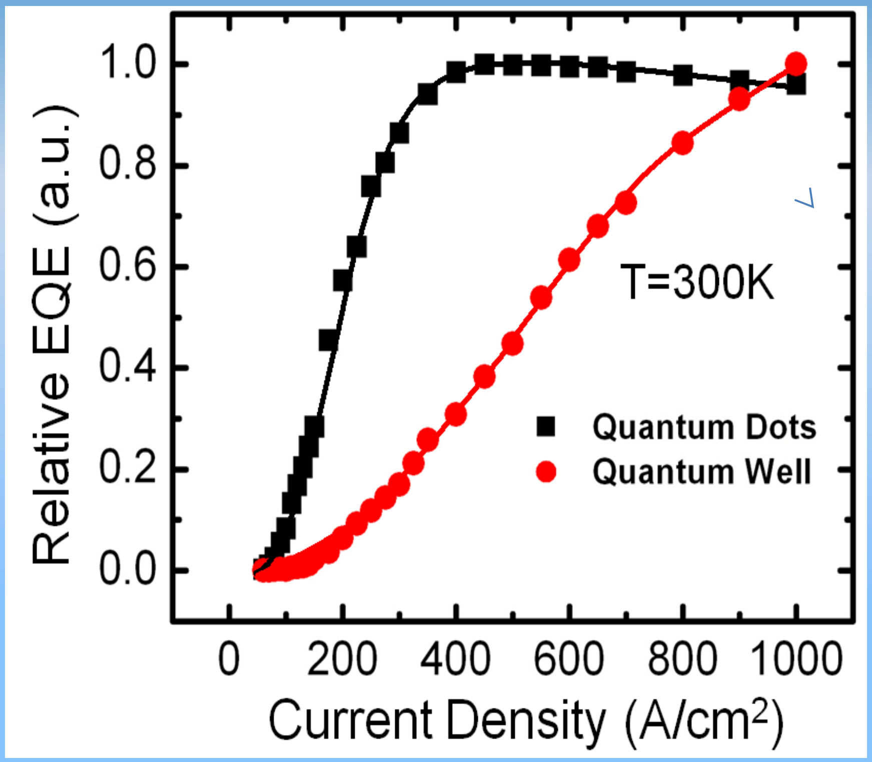
LED I

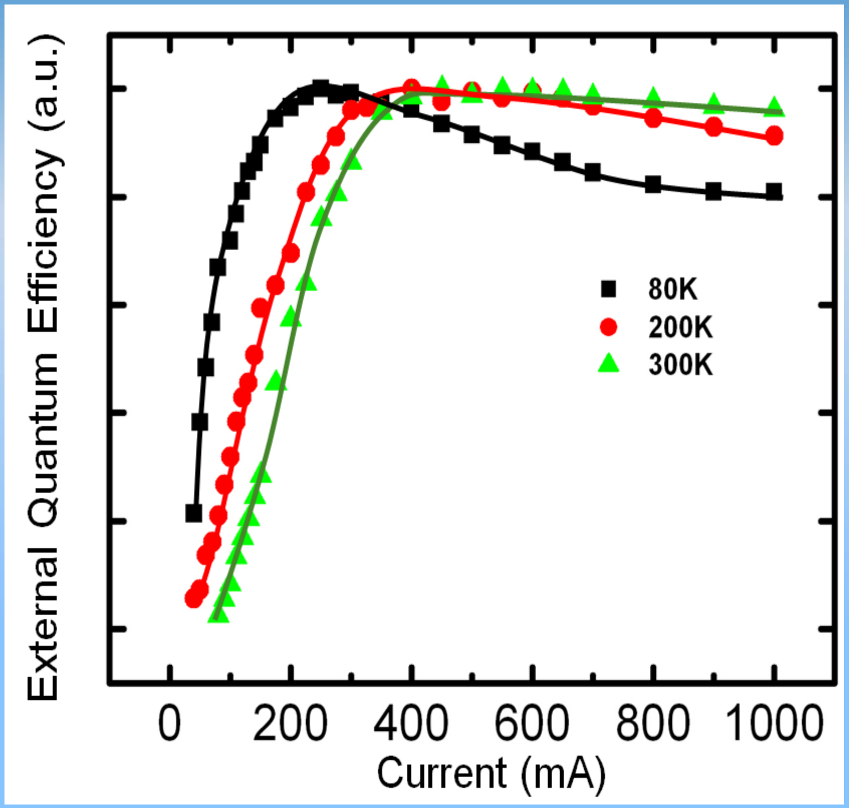


- With the use of a test well (λ ~ 430 nm) between the quantum dot active region (λ ~ 550 nm) and the p-GaN, electron overflow is clearly measured in nanowire LEDs.

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

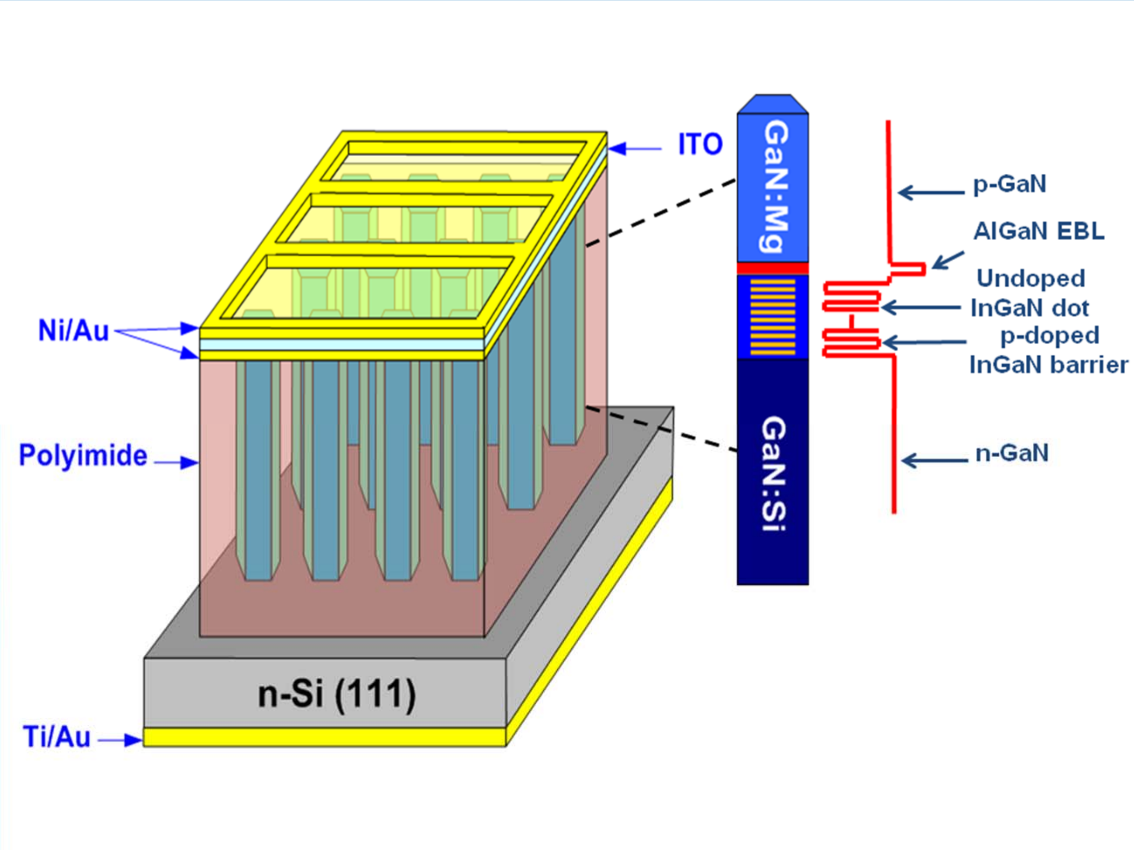
Electron Overflow in Nanowire LEDs

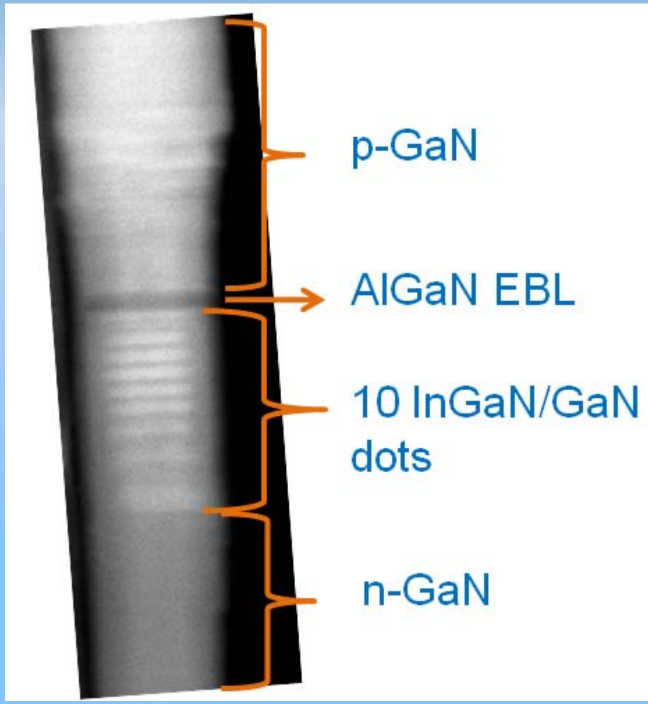




- The presence of electron overflow leads to efficiency droop for the quantum dot emission at relatively high injection conditions.

InGaN/GaN Dot-in-a-Wire White LEDs

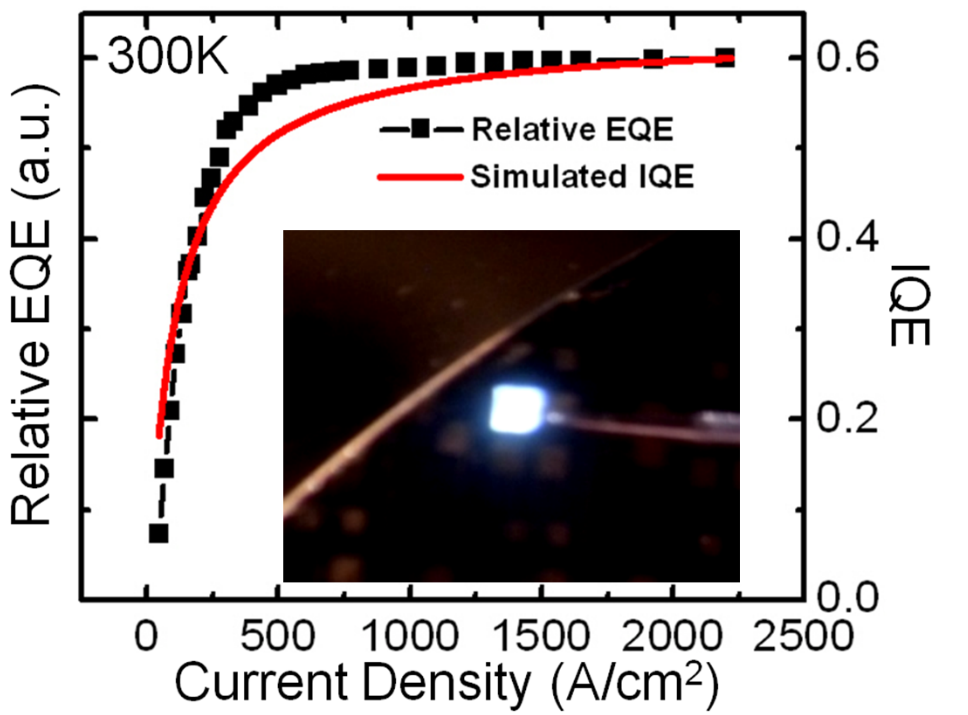


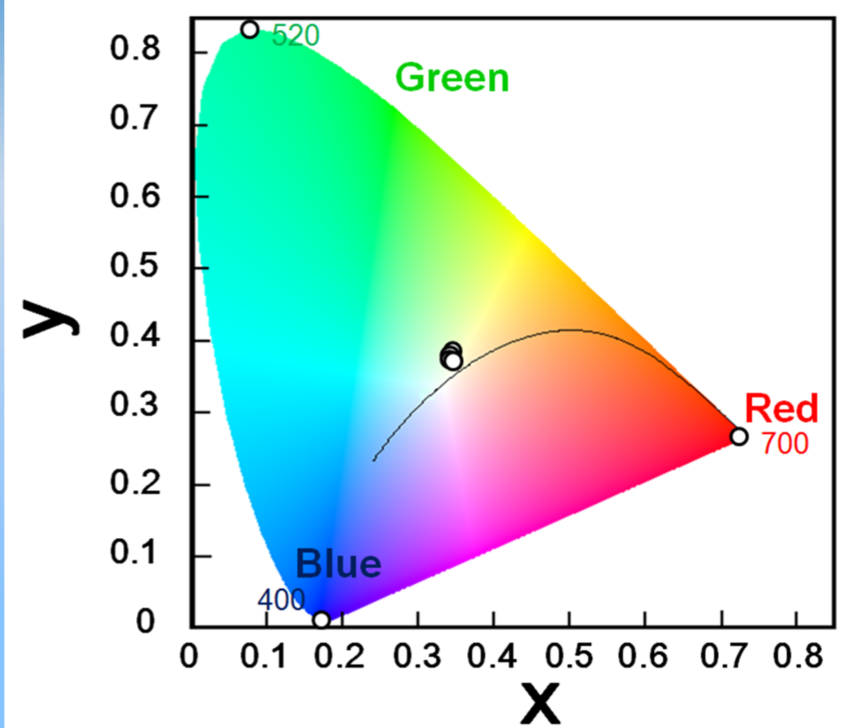


- AlGaN electron blocking layer and p-type modulation doping are incorporated in the device active region to reduce electron overflow and to enhance the hole transport, respectively.

Nano Lett., vol. 11, 1919, 2011. *Nano Lett.*, 12, 1317, 2012.

InGaN/GaN Dot-in-a-Wire White LEDs





- **InGaN/GaN dot-in-a-wire white LEDs can exhibit a record high internal quantum efficiency (~ 60%) and are virtually free of efficiency droop for injection current density up to ~ 2,200 A/cm^2 at room temperature.**

Nano Lett., vol. 11, 1919, 2011. *Nano Lett.*, 12, 1317, 2012.

Conclusion

- We have demonstrated that InGaN/GaN dot-in-a-wire LEDs can exhibit nearly ideal attributes, including stable white light emission, relatively high internal quantum efficiency and reduced efficiency droop for the emerging phosphor-free solid state lighting.

- Within this network, we will further develop (1) core-shell nanowire LEDs, (2) LEDs on semipolar/nonpolar templates, and (3) LEDs on amorphous glass substrates and demonstrate, for the first time in the world, phosphor-free white LEDs with over 200 lumens/watt.

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