

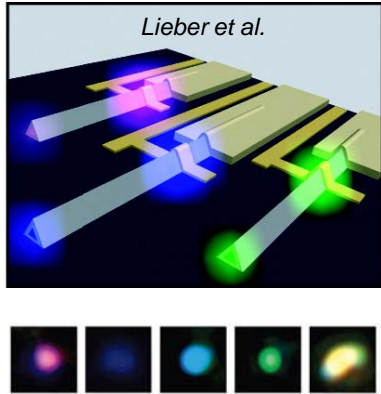
Spatially-Resolved Study of Luminescence and In Incorporation in GaN and High-In Content InGaN/GaN Nanowires

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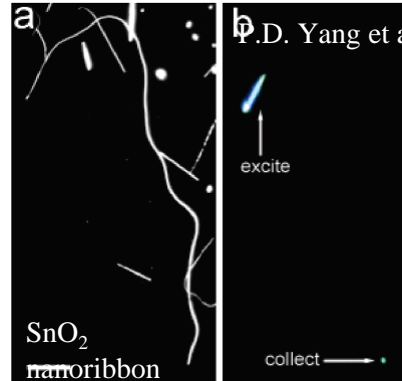
Semiconductor Nanowires (NWs)

Reduced dimensionality, high crystalline quality, and high atomic surface/bulk ratio can lead to enhanced & novel properties



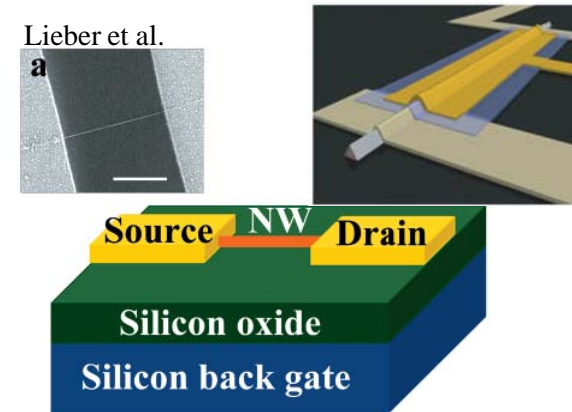
LEDs and lasers

- Nanosized light sources
- Higher efficiency due to lack of defects
- High light extraction



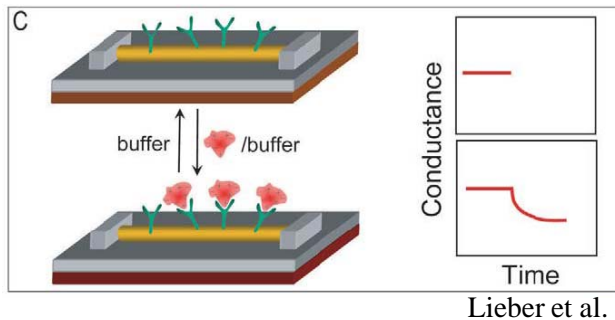
Waveguides and Filters

- coupled with nanowire light sources, building blocks for nanophotonics circuitry



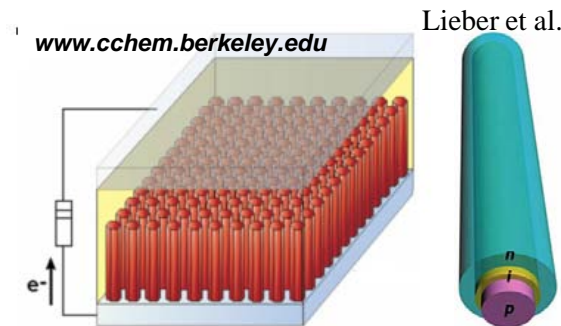
Transistors/HEMTs

- improved performance characteristics
- small size



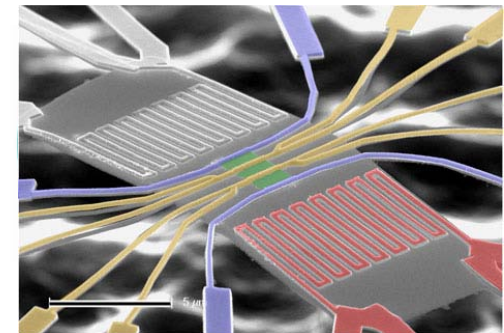
Chem/bio-sensors

- large atomic surface/bulk ratio leads nanowire depletion & ultrahigh sensitivity



Energy Harvesting

- Nanowire Photovoltaics
- Thermoelectrics
- Piezoelectric energy generation



III-Nitride (AlGaInN) Nanowires

III-Nitride (AlGaInN) Properties

Direct RT bandgaps spanning very wide energy range from ~0.7-6.2 eV

- Form solid alloy system
- High breakdown field
- High mobility
- High thermal conductivity and temperature
- Radiation resistant and chemically inert
- *Used in LEDs, blue laser diodes, UV photodetectors, HEMTs*

Compared to planar films, III-nitride nanowires ...

- Typically free of threading dislocations
- Have high aspect ratio and high surface/bulk ratio
- Are strain relaxed – can accommodate wider range of alloy compositions
- Are “discrete” – entire structure & changes to the structure can be investigated

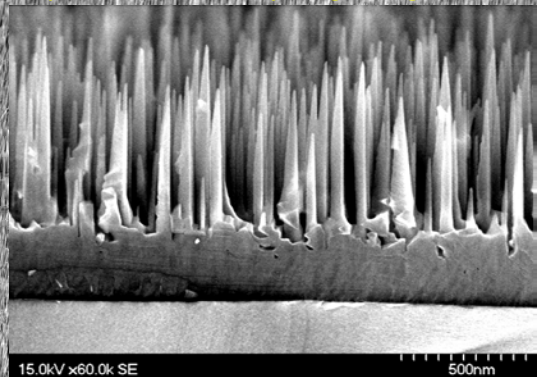
Research Goals:

- Control of nanowire orientation, alignment
- Controlled growth of heterostructure nanowires
- Understand nanowire properties as functions of growth conditions, structure, and composition
- Nanowire devices & potential applications

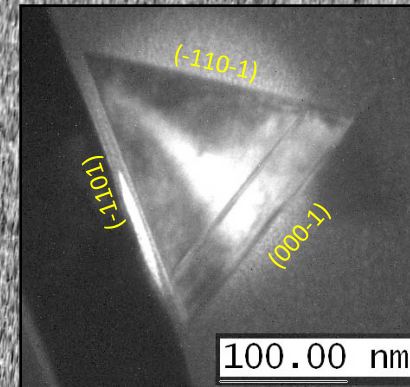
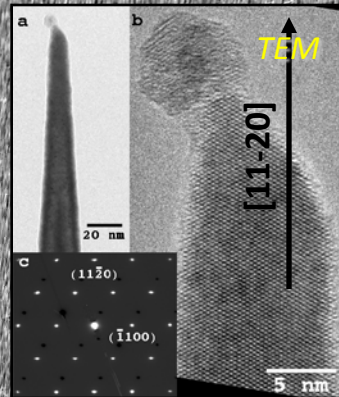


Aligned GaN NW growth

Epitaxial vertically aligned growth



$[11-20]$



- Nanowires grown by Ni-catalyzed MOCVD
- Highly-aligned, uniform vertical growth over large areas (2" wafer)
- Controllable densities as high as ~ 150 nanowires μm^{-2}

Q. Li, G. T. Wang, *Appl. Phys. Lett.* 93, 043119 (2008)

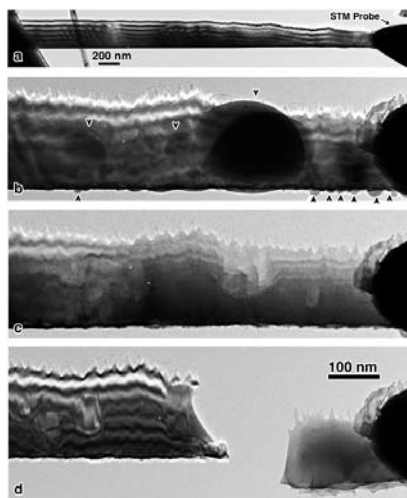
Q. Li, J. R. Creighton, G.T. Wang *J. Cryst. Growth* 310 3706-3709 (2008)

- Primary $[11-20]$ growth orientation (\perp to $(11-20)$ α -plane)
- Triangular faceted -- $(000-1)$ and equiv. (-1101) and $(-110-1)$
- TEM: Single crystal, dislocation free; c -plane stacking faults

G. T. Wang et al., *Nanotechnology* 17 5773-5780 (2006)

Structure & Properties - Vertically Aligned GaN Nanowires

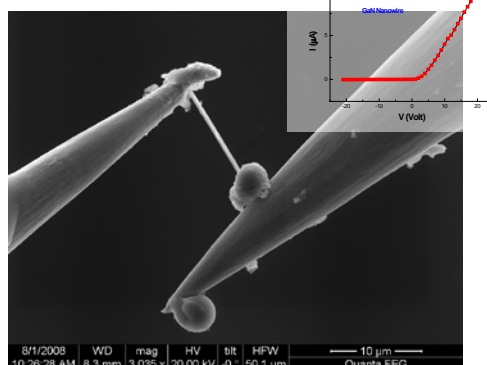
In-situ SPM-TEM



In-situ NW decomposition/failure

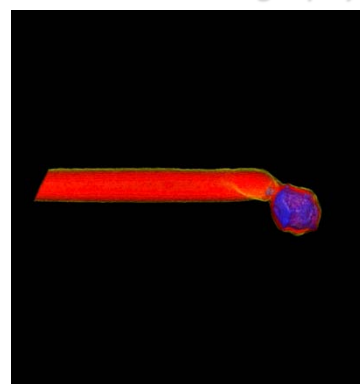
T. Westover, R. Jones, J. Y. Huang, G. Wang, E. Lai, A. A. Talin, *Nano Lett.*, **9**, 257 (2009).

In-situ SEM: I-V



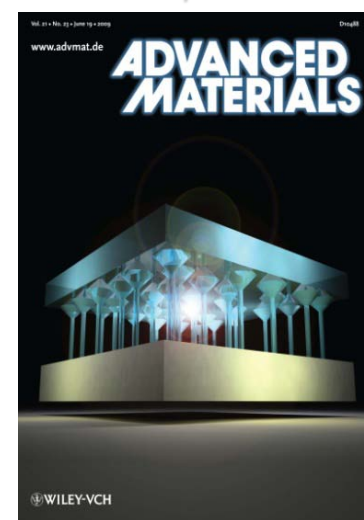
Y. Lin, Q. Li, A. Armstrong, and G. T. Wang, *Solid State Commun.*, **149**, 1608 (2009)

3D STEM tomography



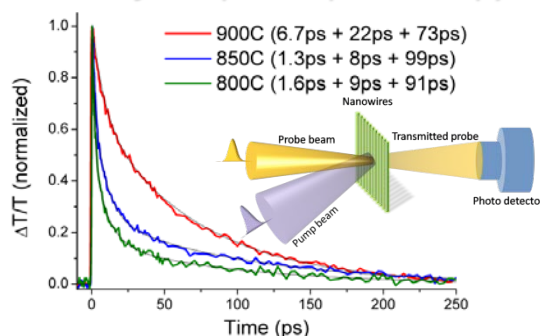
I. Arslan, A. A. Talin, G. T. Wang, *J. Phys. Chem. C* **112**, 11093. (2008)

NW-templated GaN



Q. Li, Y. Lin, J. R. Creighton, J. J. Figiel, and G. T. Wang, *Advanced Materials*, **21**, 2416–2420 (2009)

Ultrafast optical spectroscopy



P.C. Uppadhyaya et al. *Semicond. Sci. Tech.* **25** 024017 (2010)

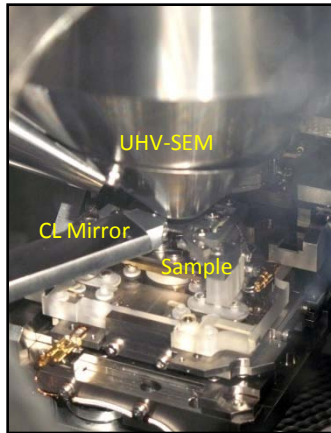
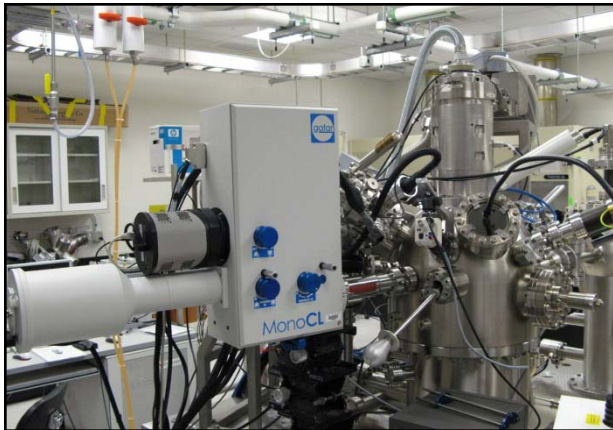
Correlated I-V/μ-PL



A. A. Talin, G. T. Wang, E. Lai, R. J. Anderson, *Appl. Phys. Lett.* **92** 093105 (2008)



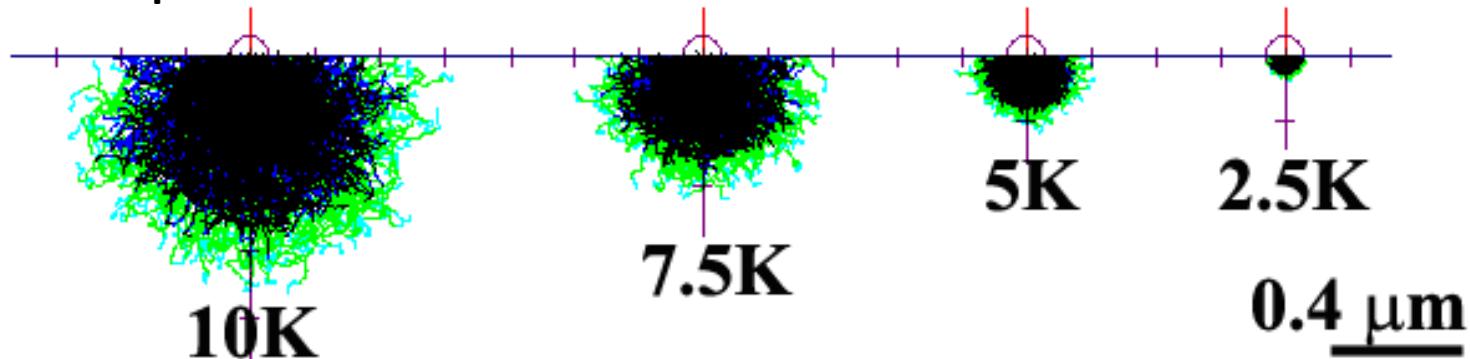
Cathodoluminescence (CL) Experimental Setup



- CL source: UHV Zeiss Gemini FE-SEM
- CL detector: Gatan MonoCL3 (GaAs:Cs PMT)
- Environment: Room-temperature, UHV
- CL Resolution: <80 nm at 2.5KeV

CL system on MESA Advanced Nanotechnology Tool (ANT)

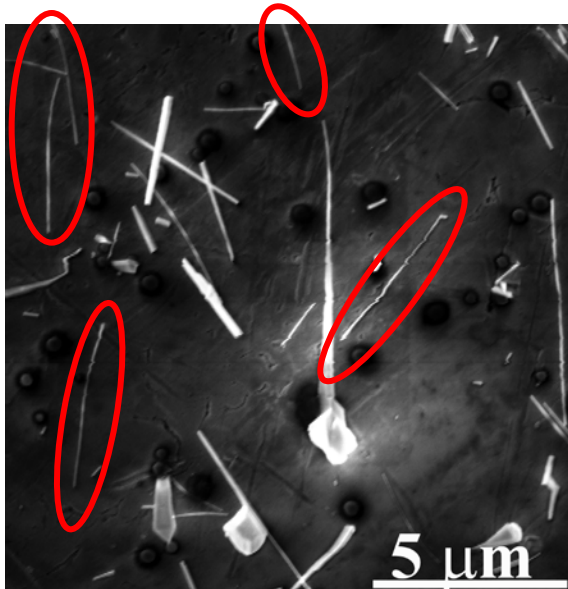
Spatial Resolution of CL – Monte Carlo Simulation for GaN





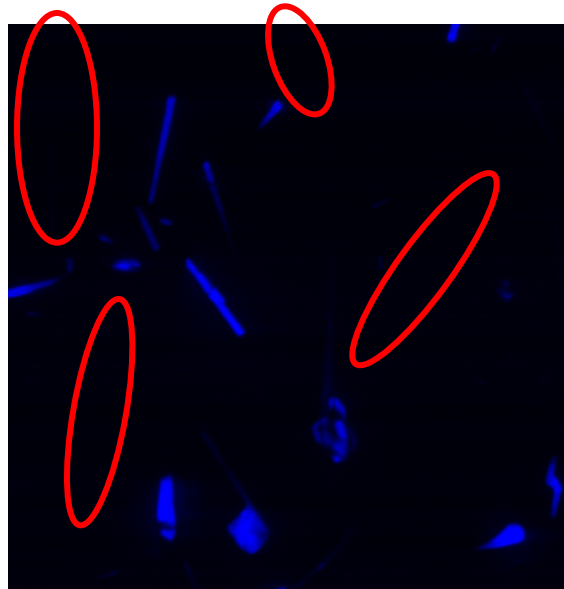
Band-edge luminescence “quenched” for thin NWs

SEM



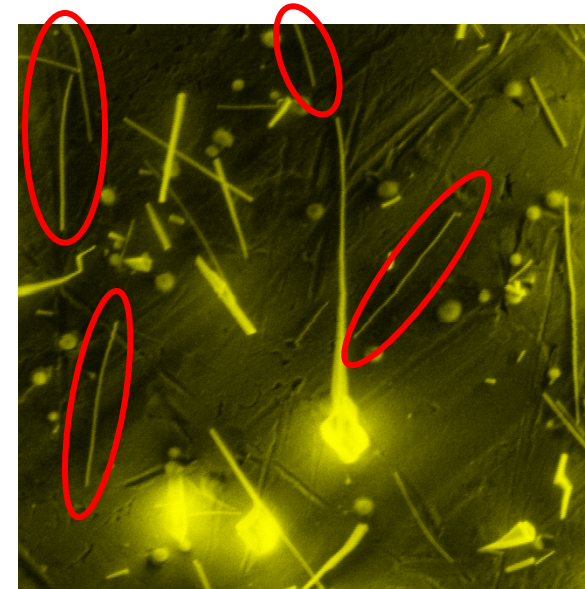
CL 360 nm

Band-edge luminescence(BEL)



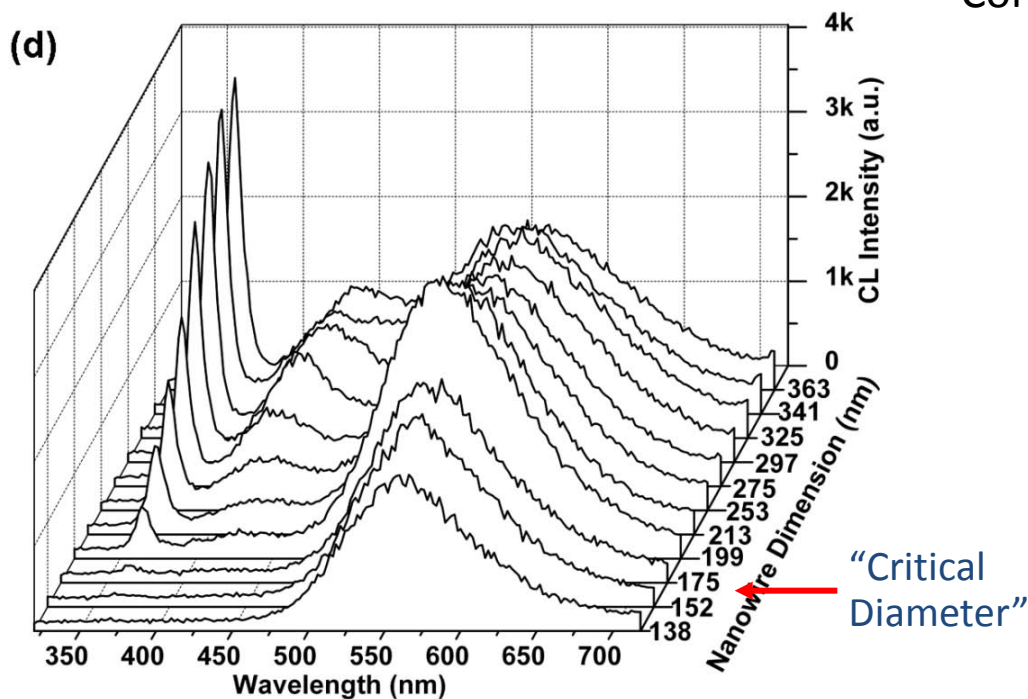
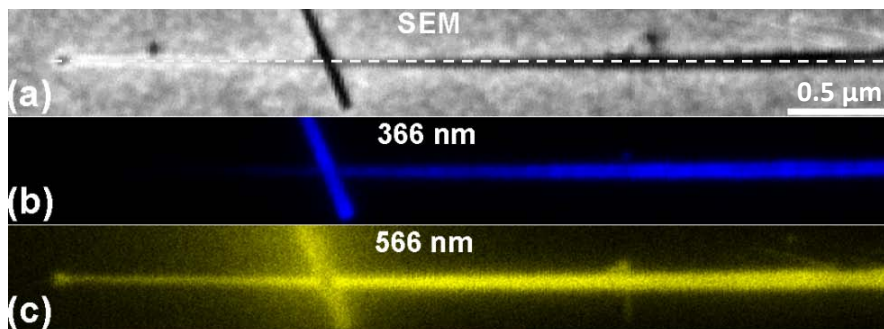
CL 550 nm

Yellow luminescence (YL)

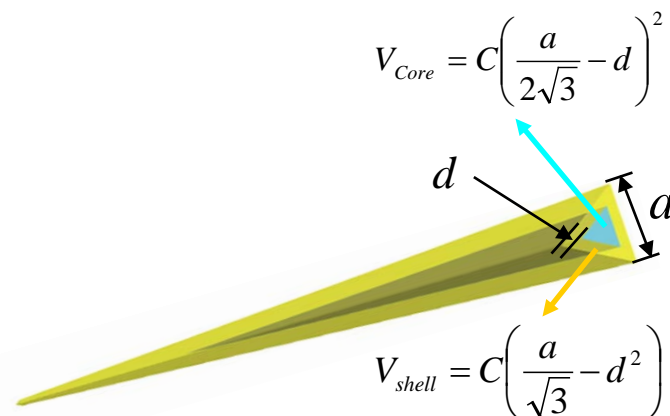


Band-edge luminescence (BEL) not observed for skinnier nanowires

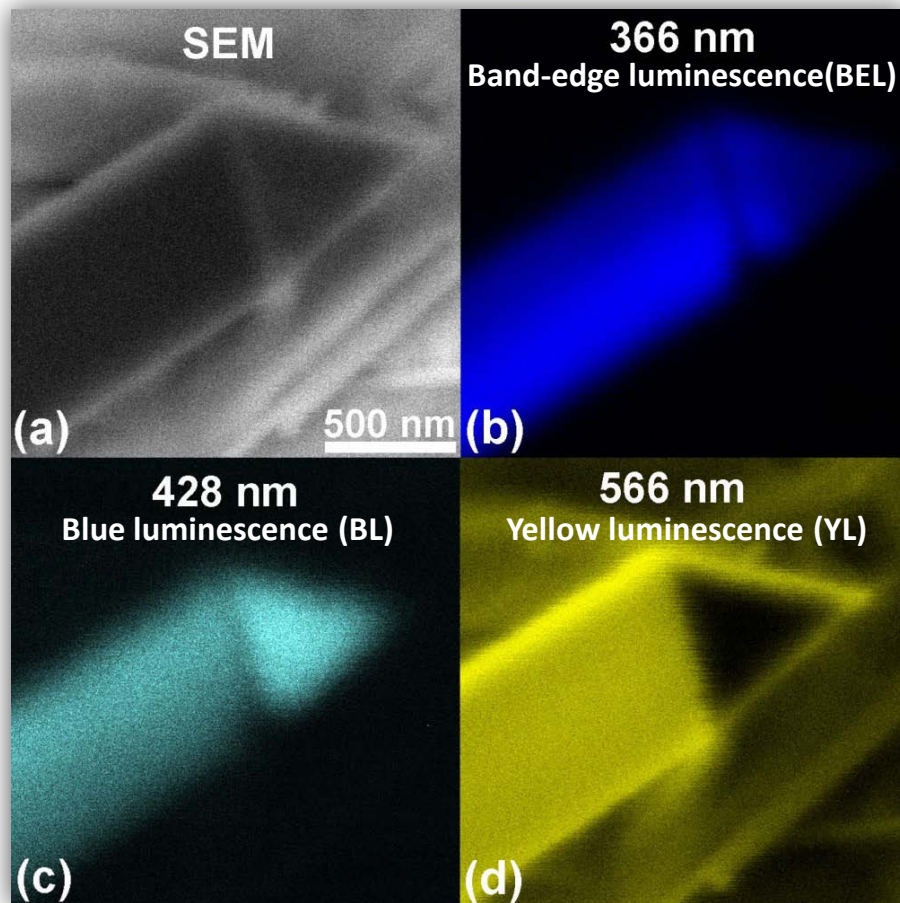
YL surface layer causes “pinch-off” of BEL



- Tapered nanowire shows “pinch-off” effect
- Spectra taken along tapered NW length, shows “critical diameter” of ~165 nm
- Consistent with YL surface layer model



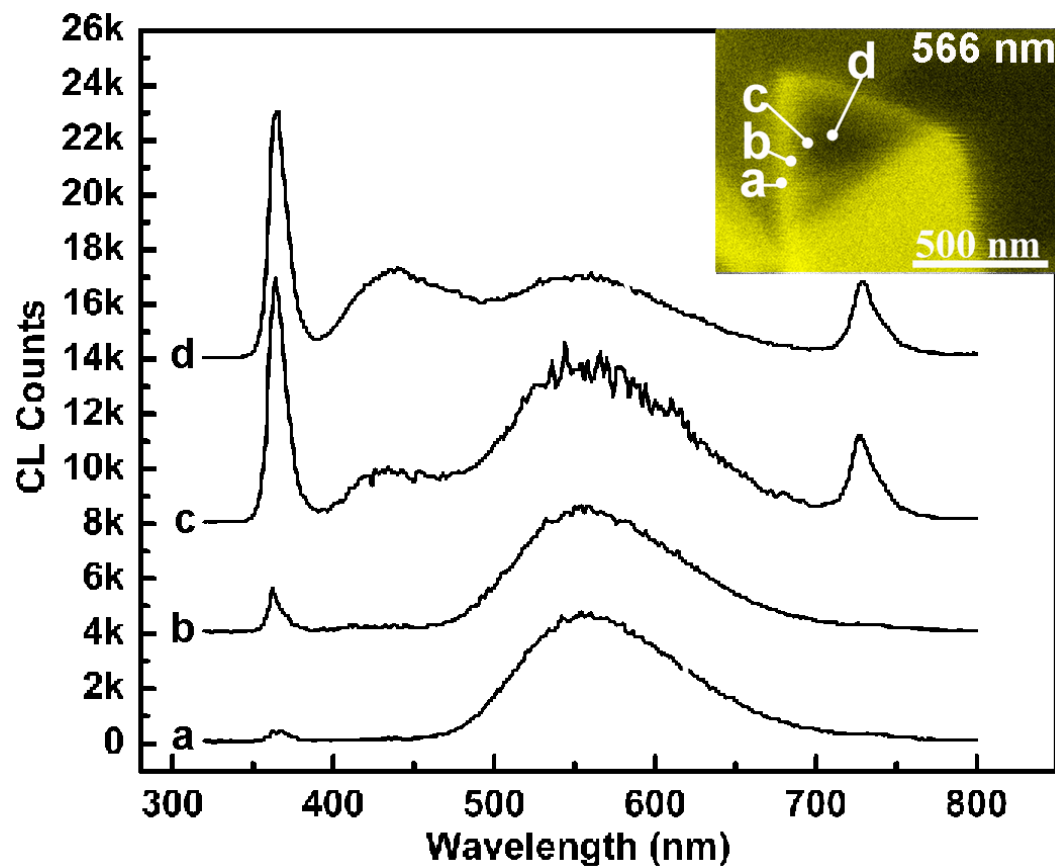
Spatially-resolved CL study of GaN NWs



Nanoscale CL imaging: Cross-section GaN NW

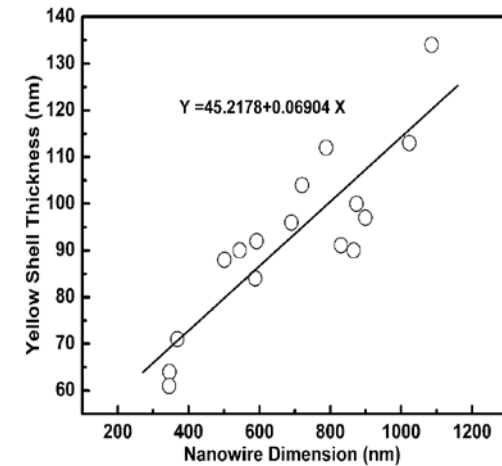
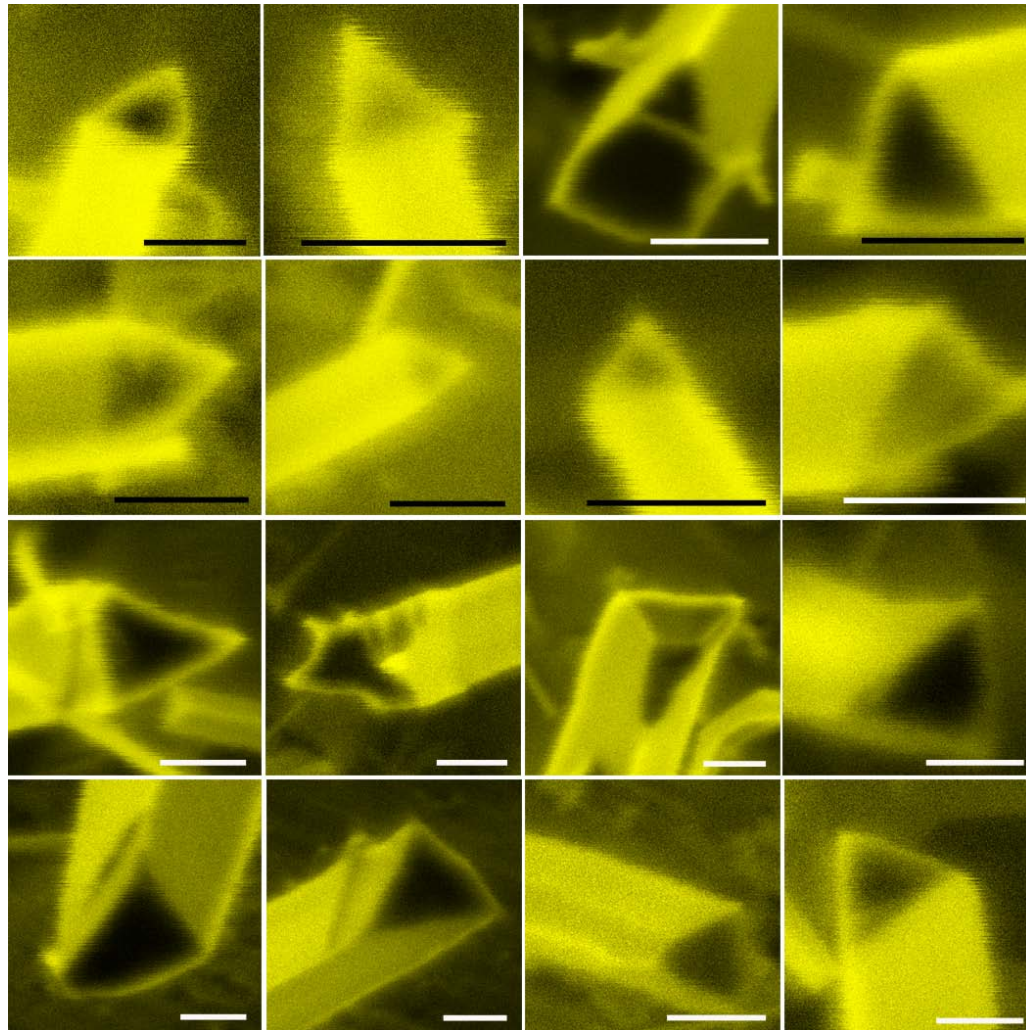
- Band-edge luminescence (BEL) at ~ 366 nm and defect-related blue luminescence (BL) at ~ 428 nm observed in NW core/bulk
- Defect-related yellow luminescence (YL) exhibits strong surface component -- associated with surface states or concentrated near surface region
- Well-known YL in GaN attributed to many possible sources (C, O impurities, Ga vacancies, etc.)
- Isolated Ga vacancies have low diffusion barrier (~ 1.5 eV) & may migrate toward surface during growth
- BL linked to $V_{\text{Ga}}\text{-O}_\text{N}$ ($D \sim 2.2$ eV), less mobile

CL study of GaN NWs – ‘Spot mode’ spectroscopy

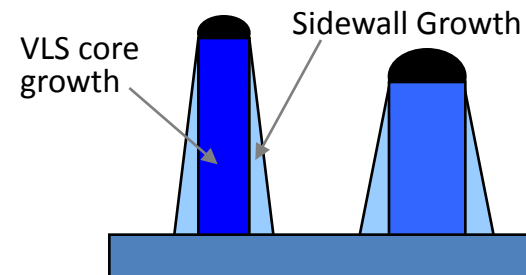


- Spot-mode: electron beam focused on different regions of NW cross-section, emission spectra collected
- YL strongest at surface
- BEL and BL strongest at NW center, quench at surface
- YL-related defects weaker but still present in the nanowire core (potentially less mobile C or O related impurities)

CL study of GaN NWs – YL surface layer

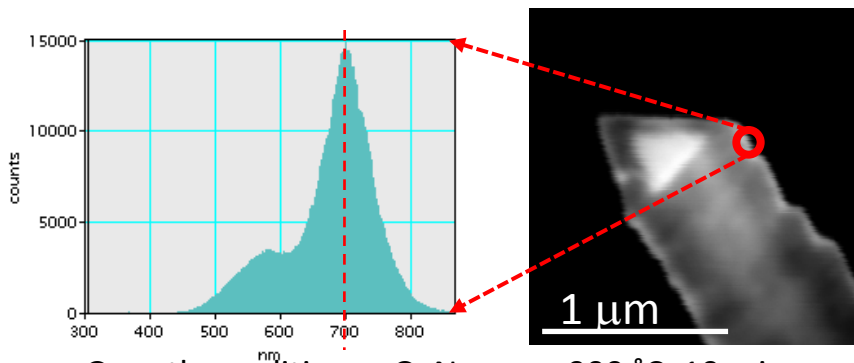


- YL thickness \propto to the NW diameter
- Indicates YL-related defects incorporate through sidewall growth



High Indium Incorporation in GaN/InGaN single core/shell NWs

- InGaN: visible wavelengths for solid-state lighting, PV, etc.
- Strain limits practical In incorporation in InGaN thin films (e.g., green-yellow-red gap)



Growth conditions: GaN core – 900 °C, 10 min.
InGaN shell – 760 °C, 60 min.

366 nm (GaN BEL)

428 nm (GaN BL)

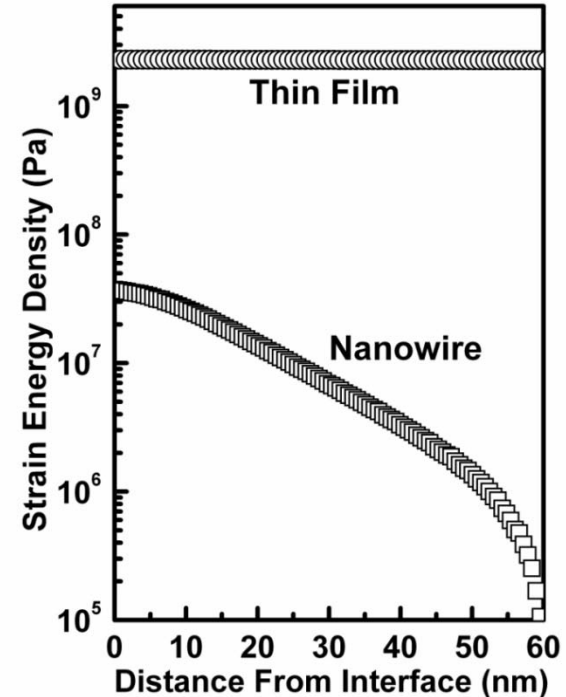
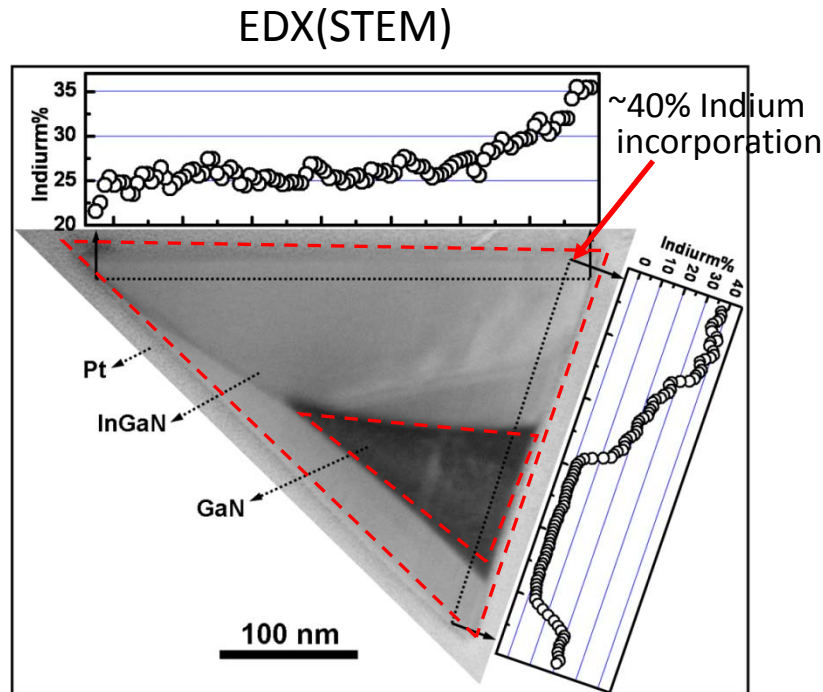
366-760 nm

480 nm (InGaN)

600 nm (InGaN)

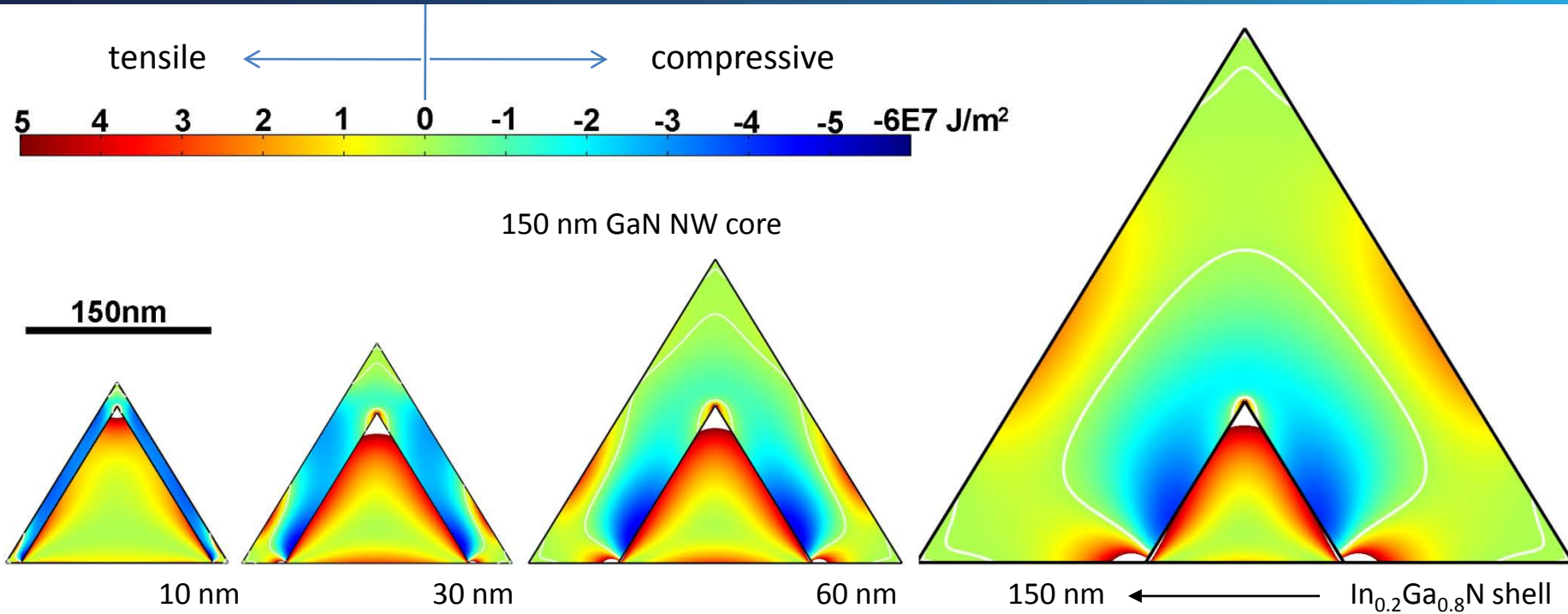
700 nm (InGaN)

In incorporation in GaN/InGaN core-shell NWs



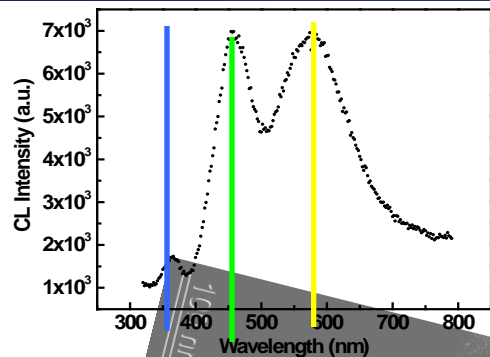
- InGaN shell growth highly facet-dependent -- no growth on (000-1) c-plane facet
- In concentration increases away from GaN/InGaN interface, highest at corners
- No dislocations observed despite very high In concentration
- Strain in InGaN NW shell much lower than for InGaN thin film

Strain-dependent In incorporation in GaN/InGaN core-shell NWs

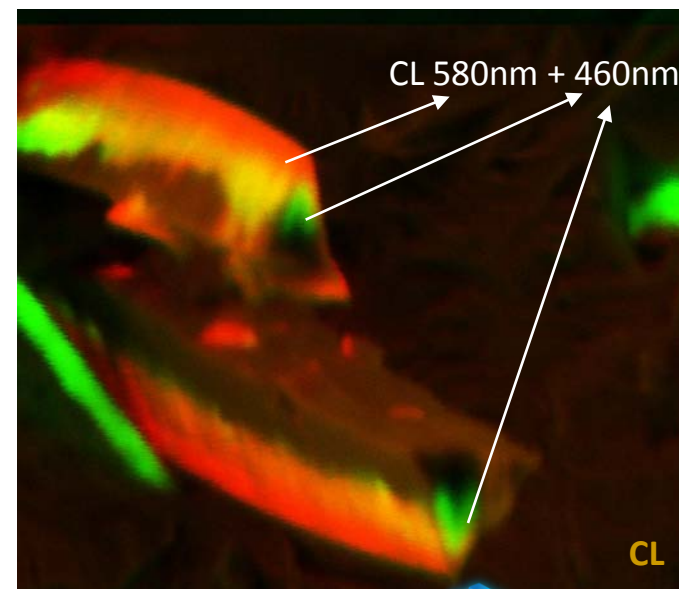
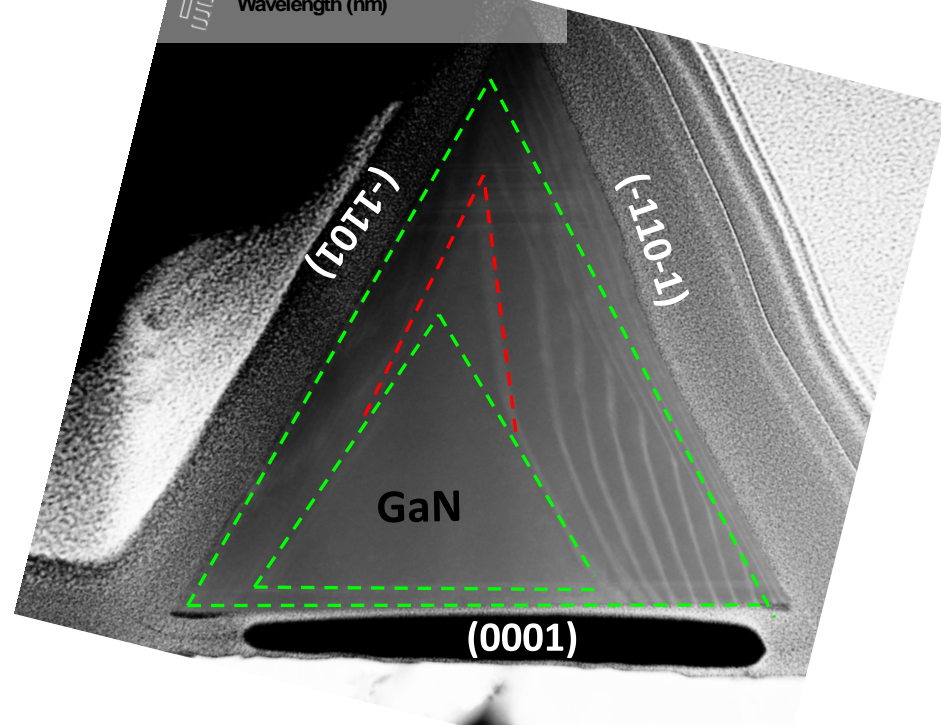
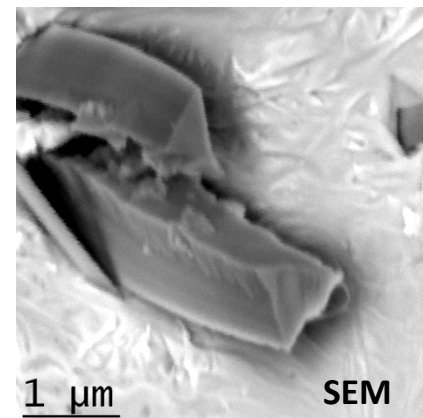


- Finite element models show compressive/tensile strain in GaN core and InGaN shell
- Compressive strain dominates in thinner shells, decreases away from interface and becoming tensile for thicker shells
- Higher In incorporation correlated with lower (compressive) strain regions

Multiquantum well InGaN/GaN nanowires



- CL shows two main InGaN peaks around 460 nm & 580 nm





Conclusions

- Spatially resolved CL reveals a yellow luminescence (YL) surface “layer” in GaN NWs
- YL-related defects may be relatively mobile & migrate to the surface region during growth
- For InGaN shell growth, up to 40% In incorporation is observed, with no observed dislocations
- CL reveals higher In incorporation at corners of InGaN/GaN NWs, explained by reduced compressive strain as shell layer gets thicker

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