Nanowires: A Future Architecture for Solid-State Lighting

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Sandia MESA Facility

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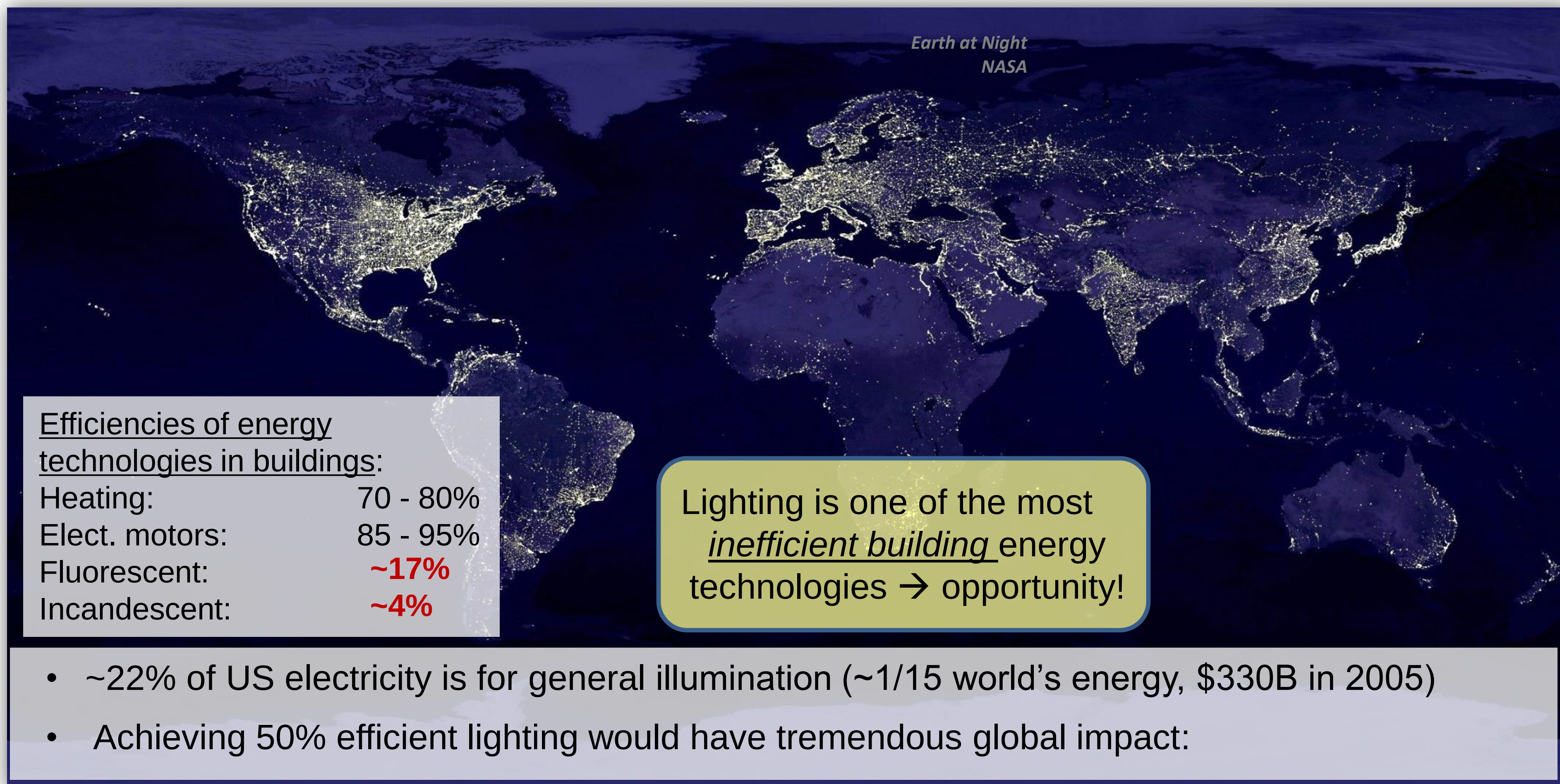
Lighting: large fraction of energy use and low efficiency



Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	**~17%**
Incandescent:	**~4%**

Lighting is one of the most *inefficient building* energy technologies → opportunity!

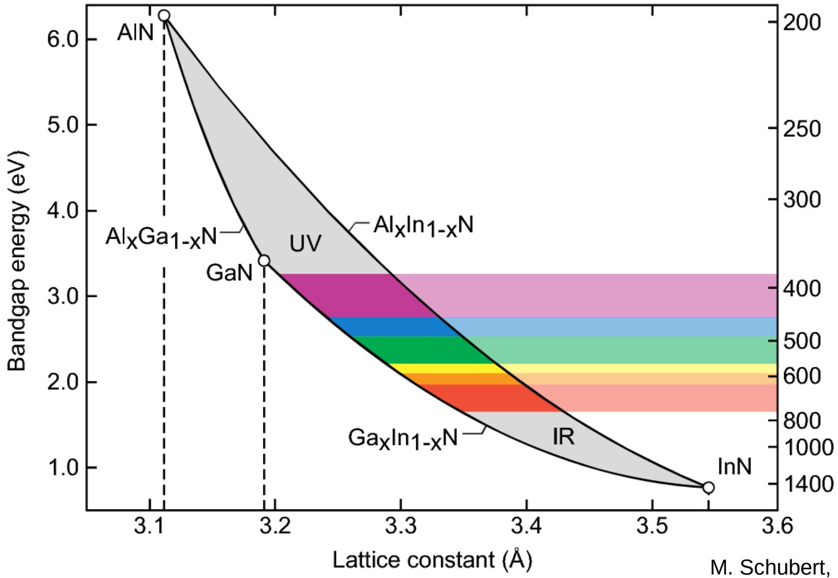
- ~22% of US electricity is for general illumination (~1/15 world's energy, $330B in 2005)
- Achieving 50% efficient lighting would have tremendous global impact:

US DOE target: 50% efficiency

- **decrease electricity consumed by lighting by > 50%**
- **decrease total electricity consumption by 10%**

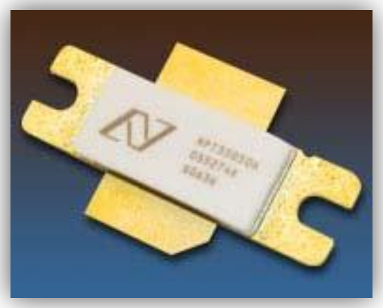
Foundation of SSL: III-Nitride (AlGaInN) Semiconductors

- **Direct RT bandgaps: ~0.7-6.2 ev**
- Solid alloy system (tuneable bandgaps)
- High breakdown field, mobility, thermal conductivity, melting temperature
- Radiation resistant and chemically inert
- InGaN covers entire visible & bulk of solar spectrum (PV material?)



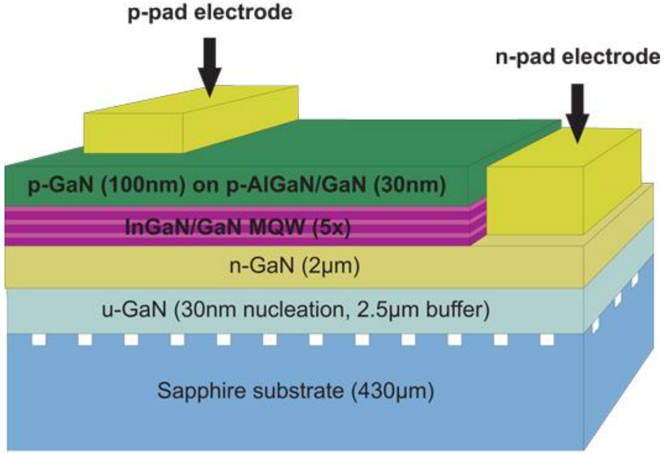
M. Schubert, RPI

- *Used in LEDs, blue laser diodes, high power transistors, HEMTs*

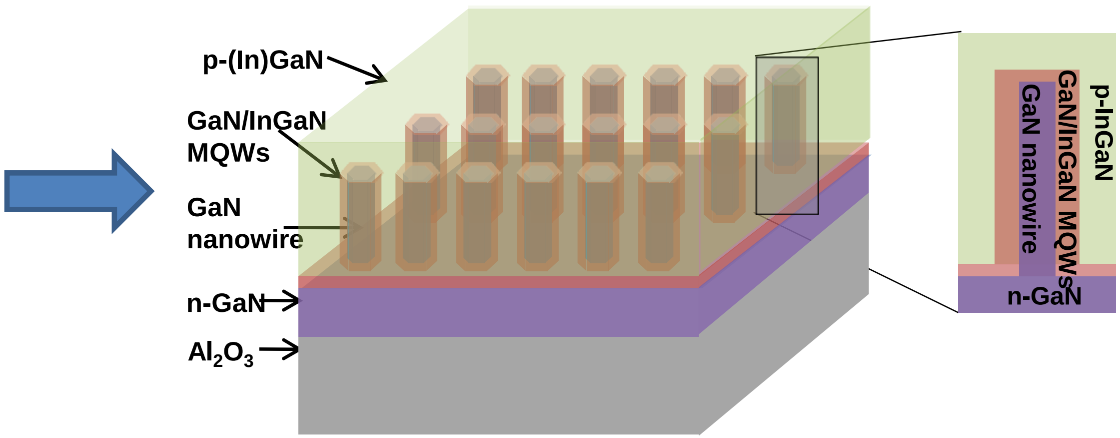


Nitronex GaN power transistor

Why III-nitride (AlGaInN) nanowires for SSL?



Y.S. Lin and J. A. Yeh, Appl. Phys. Express, vol4, p092103, 2011



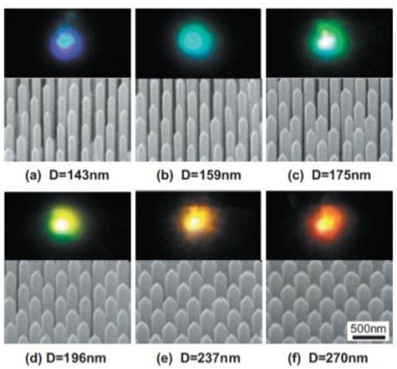
SSLS EFRC

Why III-nitride nanowires for SSL?

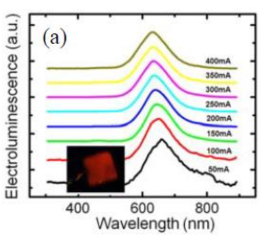
Advantages due to enhanced strain accommodation in nanowires

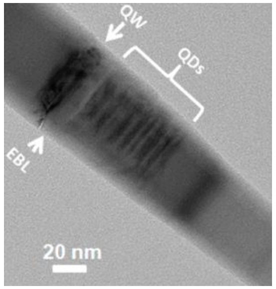
elastic strain relaxation at surface

benefit: heterostructures with high In content (e.g. green-yellow-red gap)

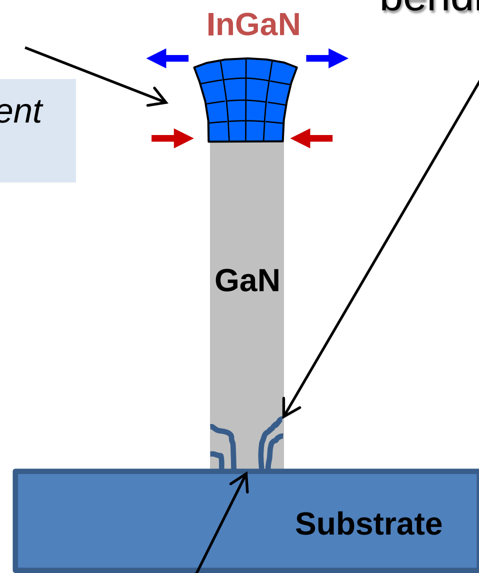


Sekiguchi et al., APL **96**, 231104 (2010) – Sophia U.



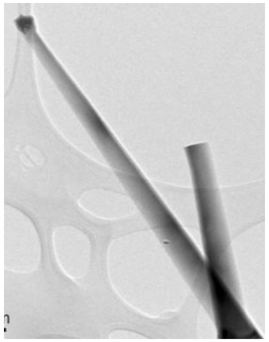


Nguyen et al., PTL IEEE **24**, 321 (2012) - McGill

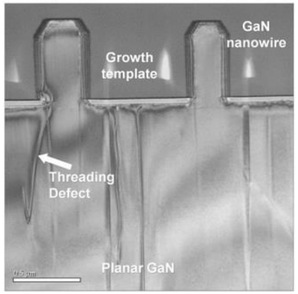


bending of dislocations (TDs) toward surface

benefit: reduced TDs, higher IQE



VLS-grown TD-free GaN NWs - Sandia

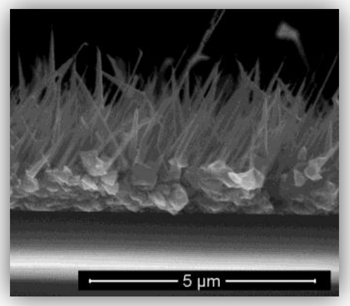


Hersee et al., J. Mat. Res. **17**, 2293 (2011) - UNM

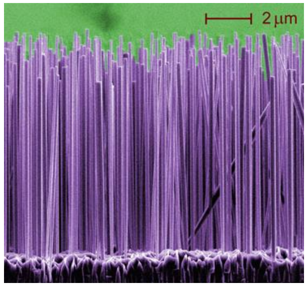
Bending & termination of TDs at nanowire base

small interfacial area

benefit: can grow on cheaper, lattice mismatched substrates; integration with Si devices



GaN NWs on tungsten foil - Sandia

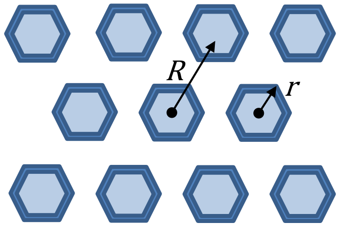


GaN NWs on Si - NIST

Why III-nitride nanowires for SSL?

vertical device integration

benefit: *higher device area per chip (cost/droop)*

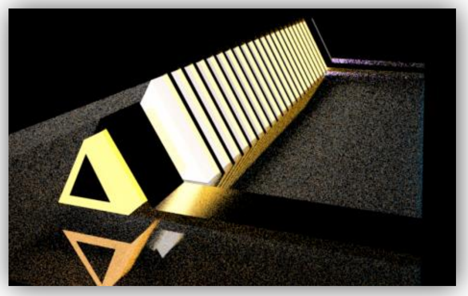


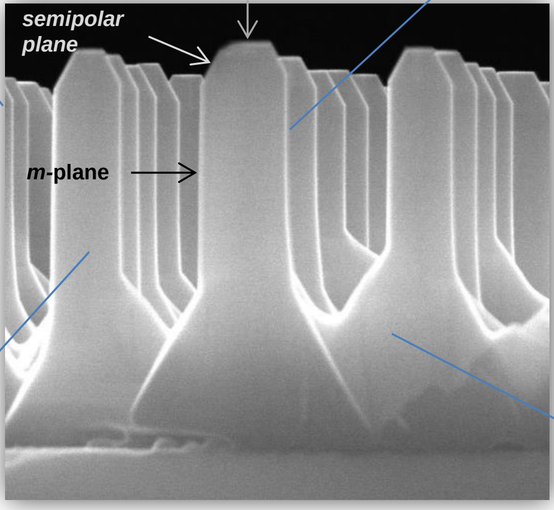
$$\frac{A_{sidewall}}{A_{substrate}} = \frac{6rh}{2.6R^2} \cong \mathbf{4.6F \cdot AR}$$

*example: 4.6·0.5·3=**6.9× increase!***

nanolasers

benefit: *ultracompact, low power coherent light source*

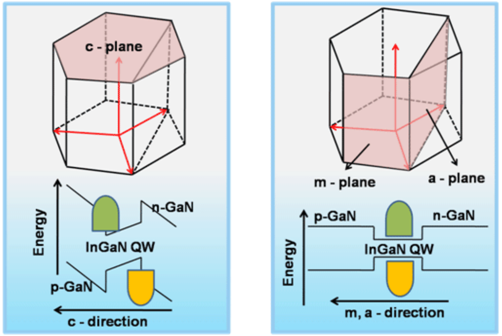




Radial GaN/InGaN MQW NW (Sandia)

access to nonpolar & semipolar planes

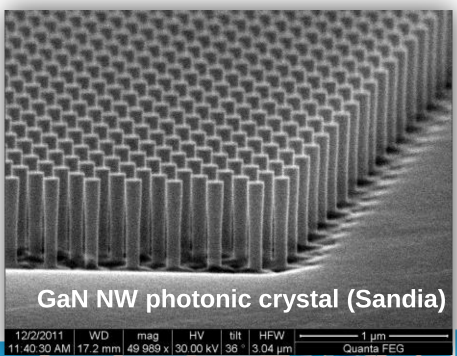
benefit: *higher IQE, reduced wavelength shift*



http://csel.snu.ac.kr/research/LED.php

2D arrangements (photonic crystals)

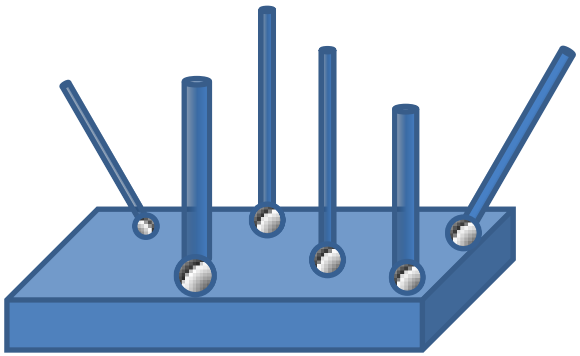
benefit: *higher light extraction, IQE, wavelength tuning*

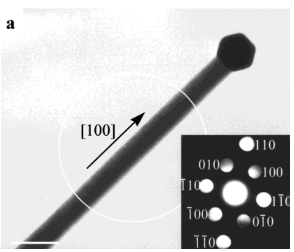


GaN NW photonic crystal (Sandia)

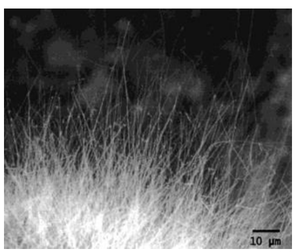
Bottom-up growth of GaN-based nanowires

Metal catalyzed (vapor-liquid-solid)





C. Lieber, 2000

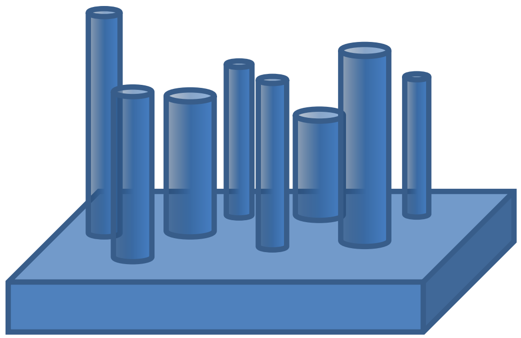


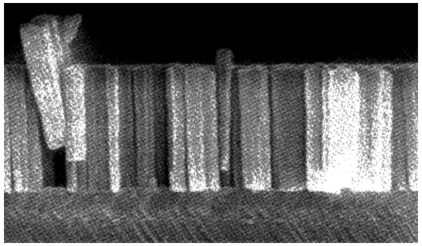
C.C. Chen, 2001

Methods: PLD, thermal evaporation, (MO)CVD

Historically popular (ease & low cost of entry), but falling out of favor due to limitations

"Self-catalyzed"



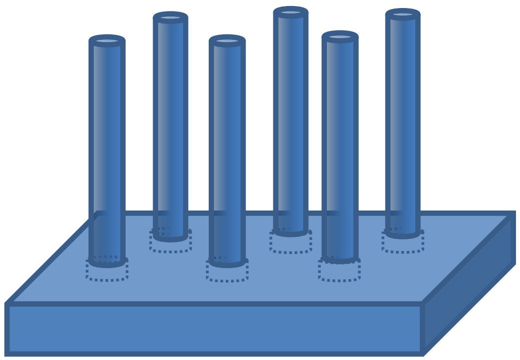


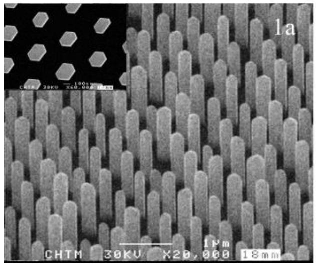
K. Kishino, 1997

Methods: (PA)MBE, HVPE, (MO)CVD

Cons include slow growth rates and random ordering

Selective area growth (SAG)





S. Hersee, 2006

Methods: (PA)MBE, MOCVD

Currently popular, but may require growth conditions that limit materials & architectural flexibility

Worldwide GaN-based nanowire SSL-related research

North America

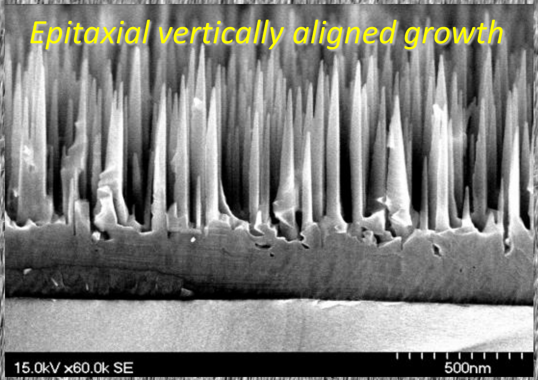
Europe

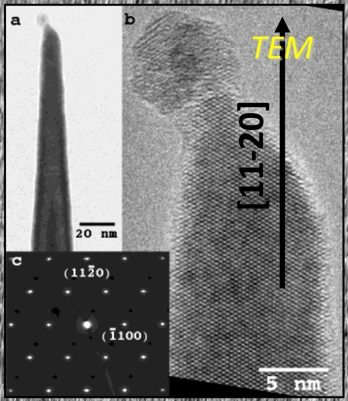
Asia

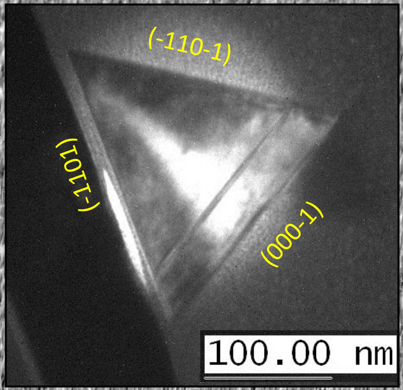
Bottom-up III-Nitride Nanowires

Sandia Research Highlights

"Bottom Up" aligned GaN nanowire growth



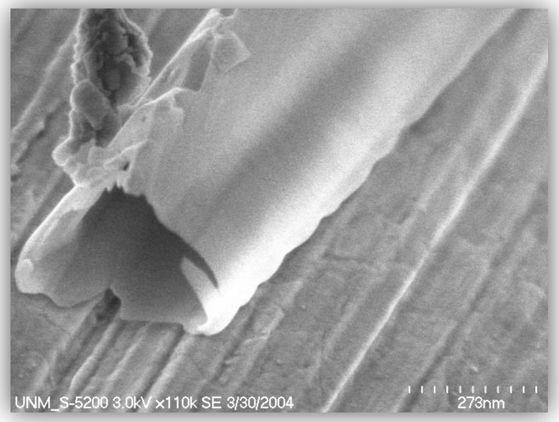




- Nanowires grown by Ni-catalyzed MOVPE/MOCVD (VLS)
- Highly-aligned vertical growth over large areas (2" r-sapphire wafer)
- Controllable densities as high as ~150 nanowires μm^{-2}
  - **Q. Li, G. T. Wang, *Appl. Phys. Lett. 93, 043119* (2008)**
  - **Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth 310 3706-3709* (2008)**
- Primary [11-20] growth orientation (⊥ to (11-20) *a*-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)**

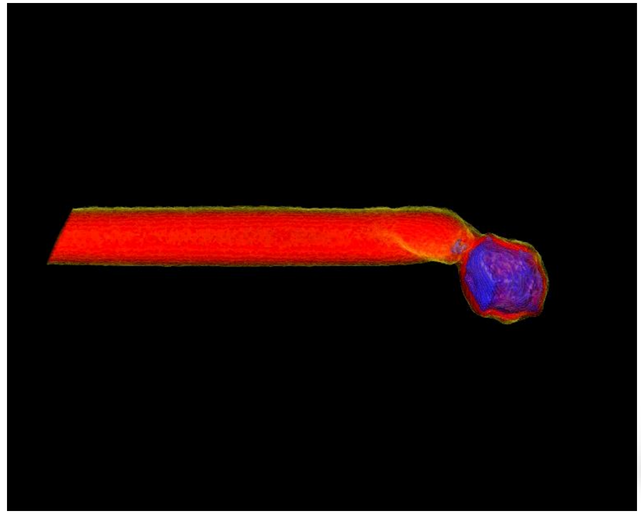
100 µm

Radial heterostructure nanowire growth

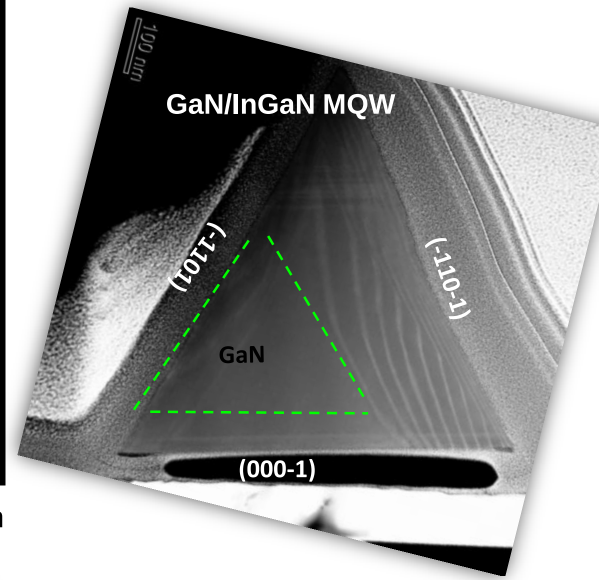


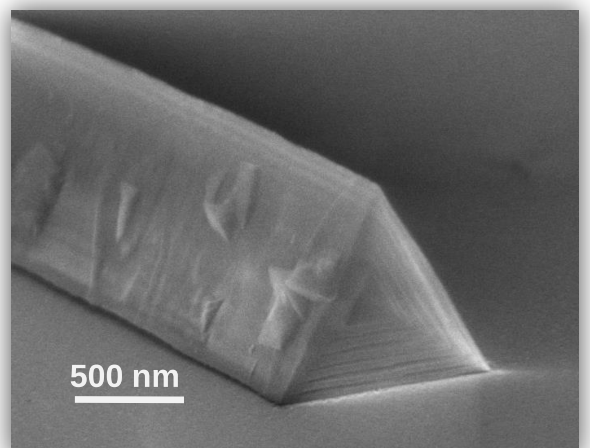
G. Stan et al. , *Nanotechnology*, ***20***, **2009**

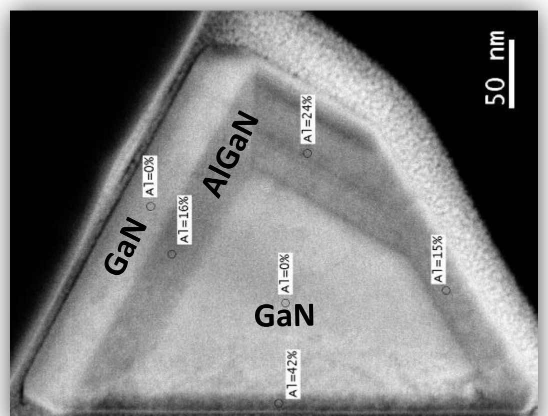
AlN Nanotubes



GaN/AlN NW I. Arslan

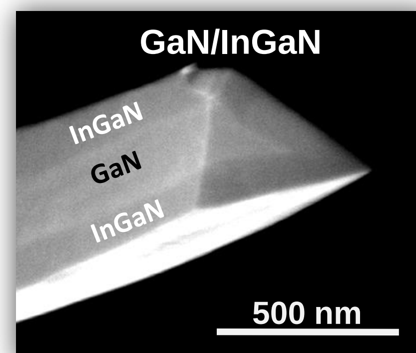






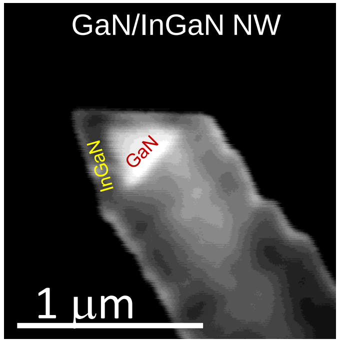
GaN/AlGaN/GaN

Double heterostructure

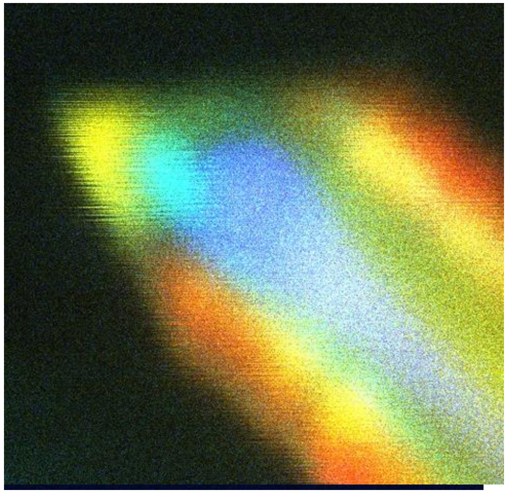


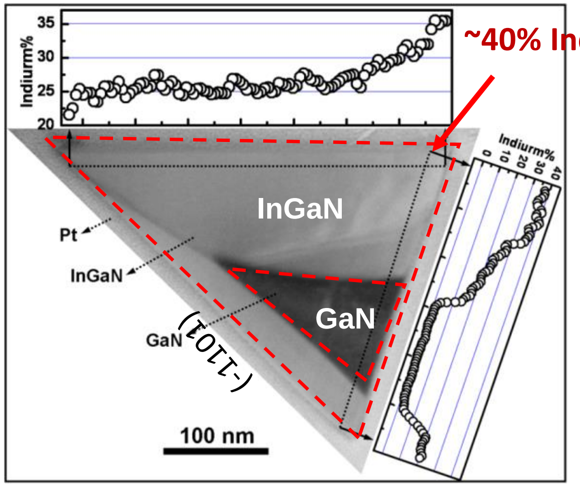
Core-shell NWs – A good platform for high In InGaN?

- ***Issue: Strain limits In incorporation in InGaN thin films (green-yellow-red gap)***
- Radial core-shell NWs: much higher active region area than axial NW or planar heterostructures



GaN core – 900 ˚C, 10 min.
InGaN shell – 760 ˚C, 60 min.



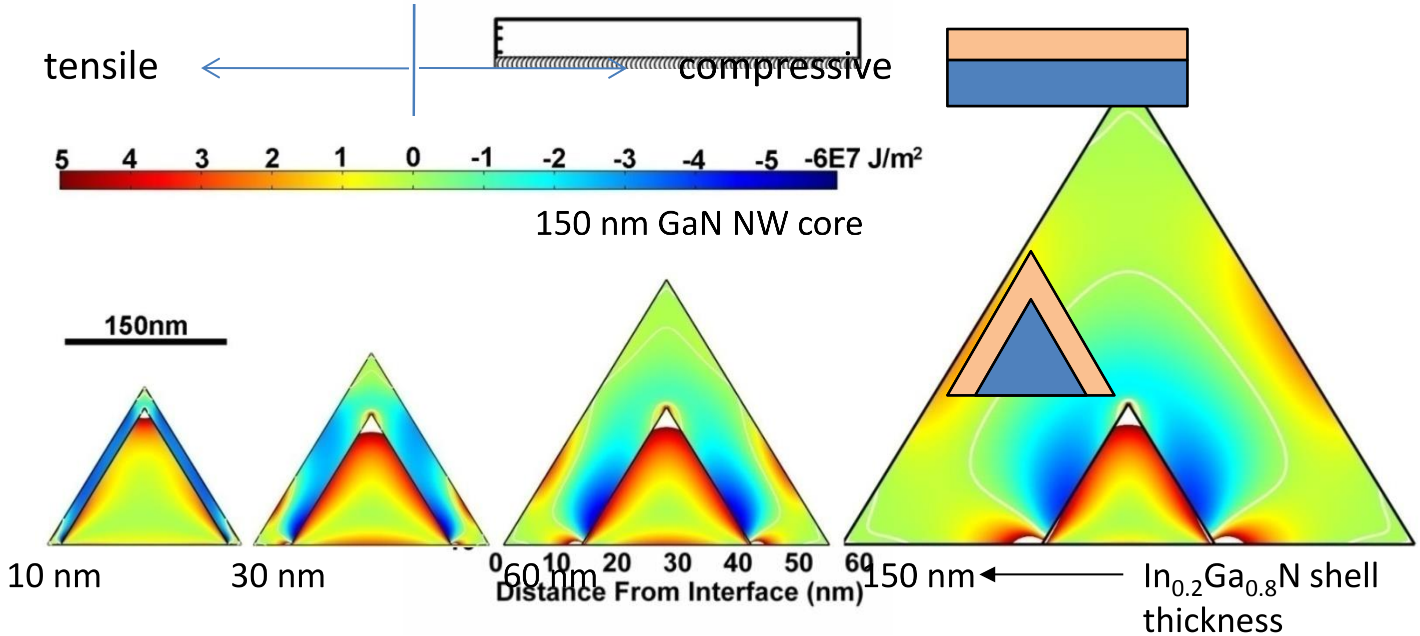


CL shows strong multicolor emission up into the IR!

- **high In incorporation with high material quality**
- nonuniform In composition?

STEM/EDS shows In distribution, **highest at surface/corners**

Reduced strain in nanowires allows higher In incorporation

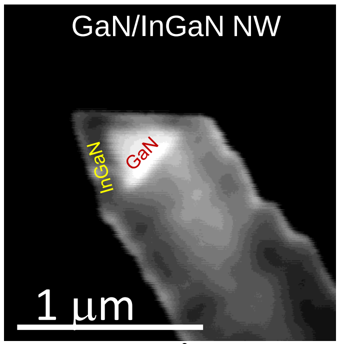


- Strain lower for GaN/InGaN nanowire than for GaN/InGaN thin film
- Compressive strain decreases away from GaN/InGaN interface, lowest in corners

Q. M. Li, G. T. Wang, "*Appl. Phys. Lett.*, ***97***, 181107 **2010**.

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

- ***Issue: Strain limits In incorporation in InGaN thin films (green-yellow-red gap)***
- Radial core-shell NWs: much higher active region area than axial NW or planar heterostructures



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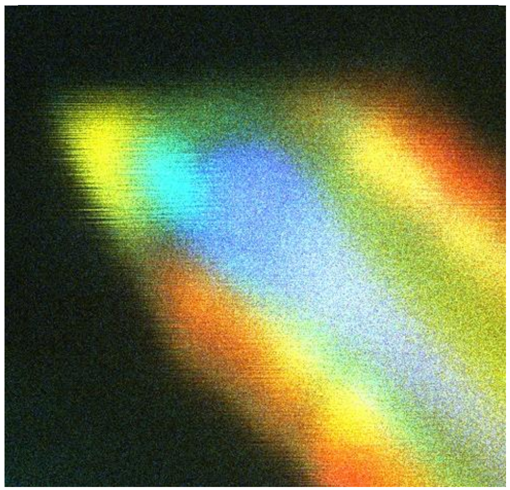

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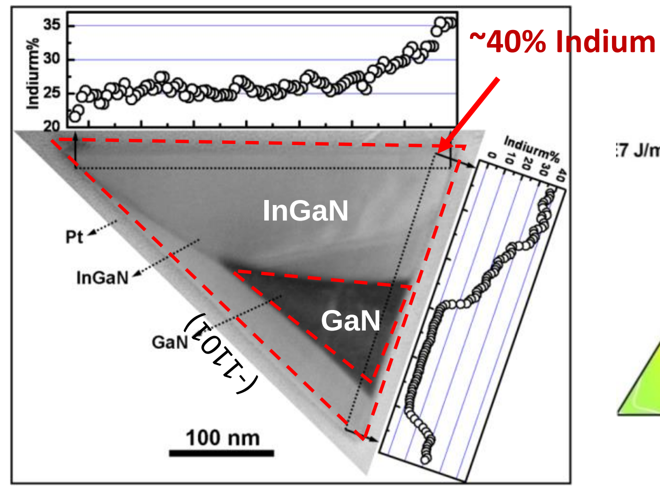
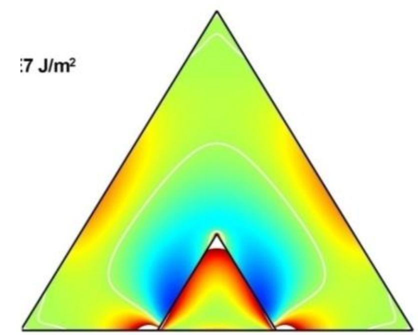


STEM/EDS shows In distribution, **highest at surface/corners**

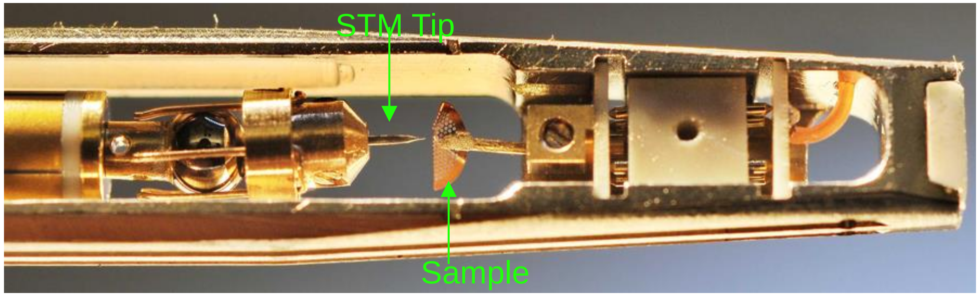


2D FEA: highest In regions correlated w/lowest compressive strain regions

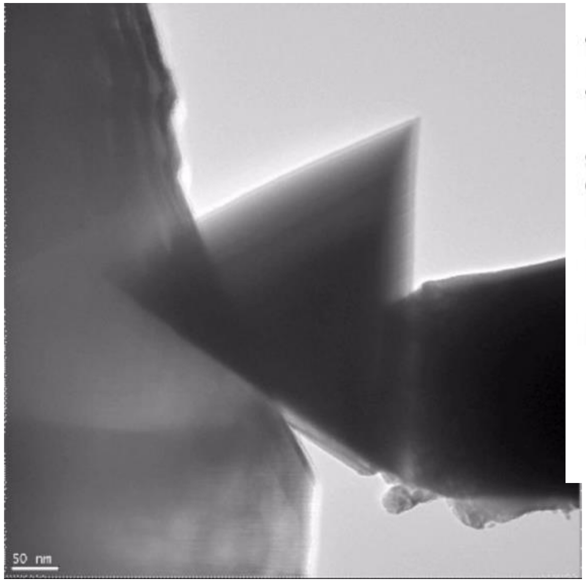
Q. M. Li, G. T. Wang, "*Appl. Phys. Lett.*, ***97***, 181107 **2010**.

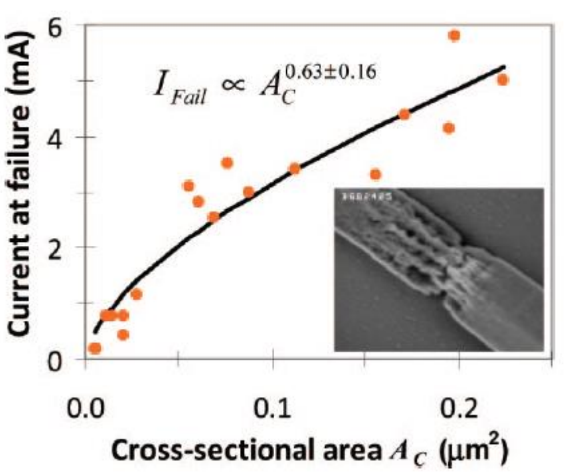
Radial InGaN/GaN nanowires promising for addressing green-yellow-red gap

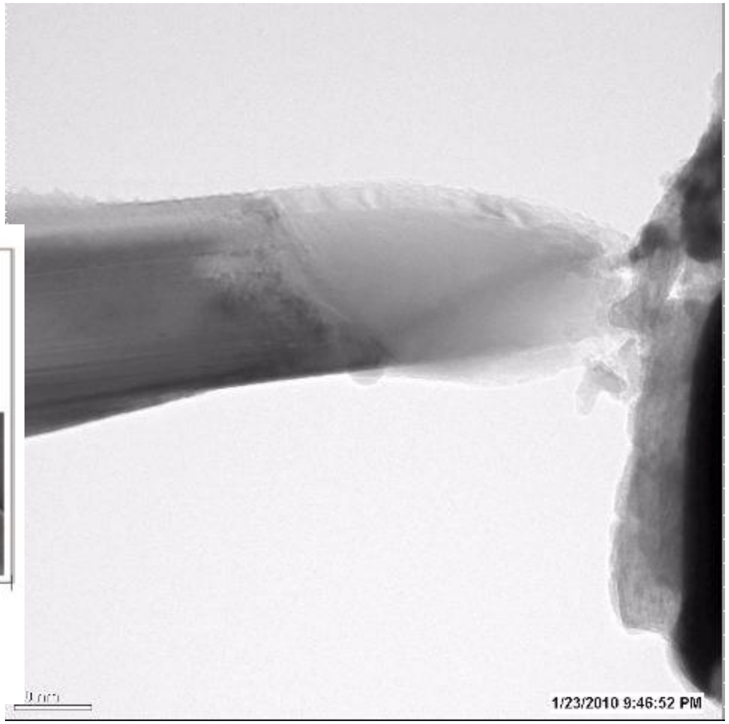
In-situ TEM studies – nanowire electrical breakdown



NW decomposition via Joule heating
(relevant for NW devices)







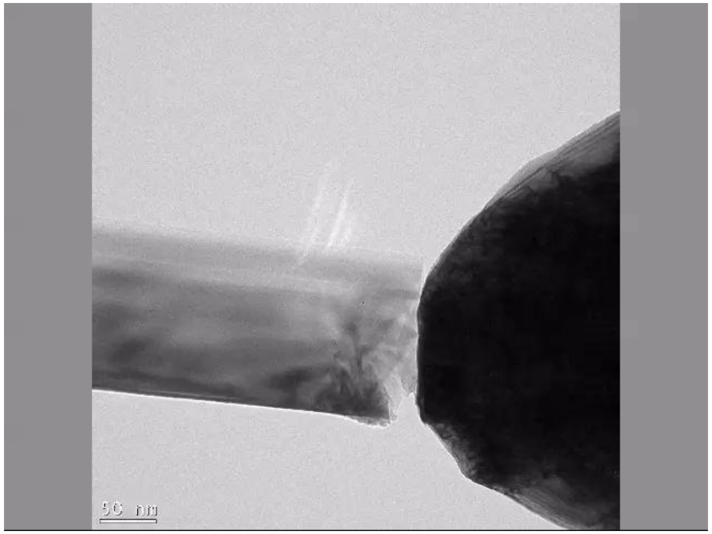
NW breakdown at 60V, 20 µA
(avg. breakdown I ~3000 kW/cm^2)

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

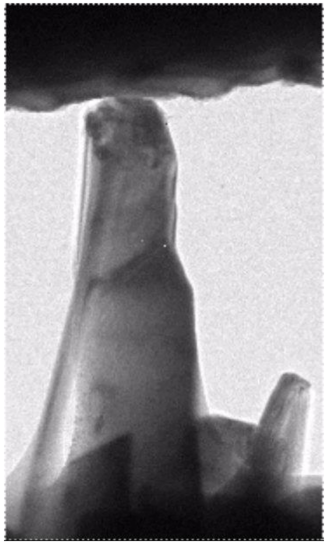
PI: J. Huang

SSLS EFRC

Real time *In-situ* TEM nanomechanics of GaN NWs



- Dislocation-free NW shows significant surface plastic deformation
- Mediated by dislocation nucleation & pile up, grain boundary sliding



- Plastic deformation often observed before fracture
- Plasticity is local, not global

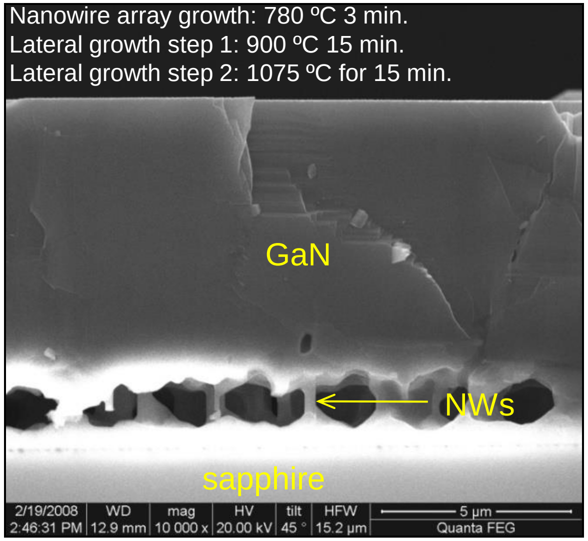
Study provides unique insight into the nanomechanical properties which may impact nanowire device processing and operation

J. Y. Huang, H. Zheng, S. X. Mao, Q. Li, and G. T. Wang, *Nano Lett,* **11 (4),** 1618 (2011).

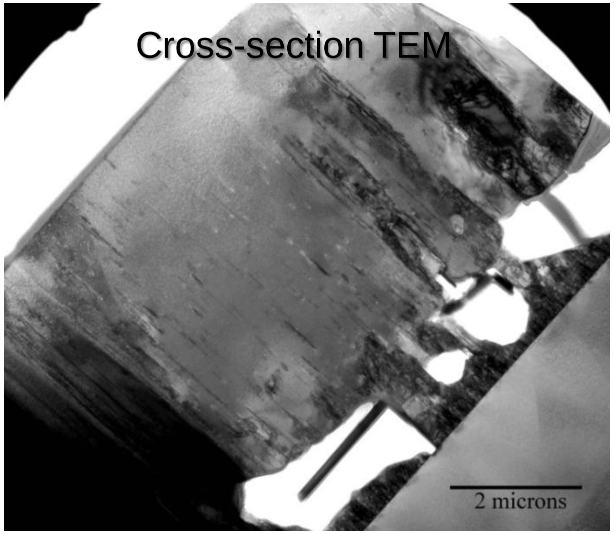
PI: J. Huang

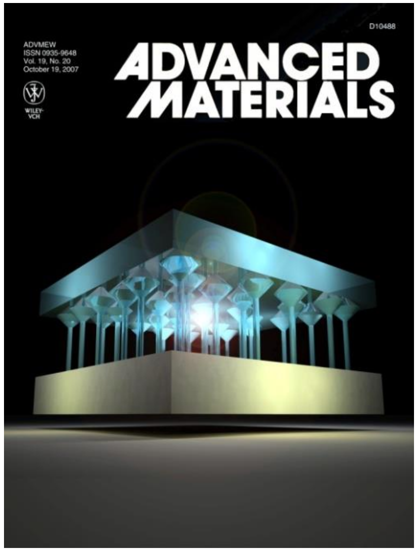
Nanowire-templated lateral epitaxial growth (NTLEG) of GaN

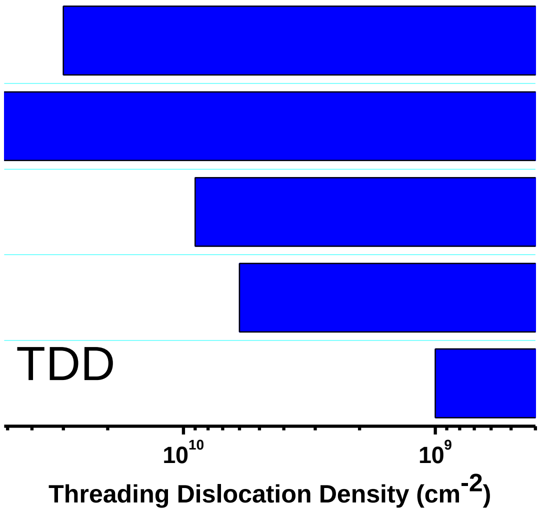
Inexpensive method to reduce dislocation density in GaN films growth on lattice mismatched substrates



Cross-section SEM







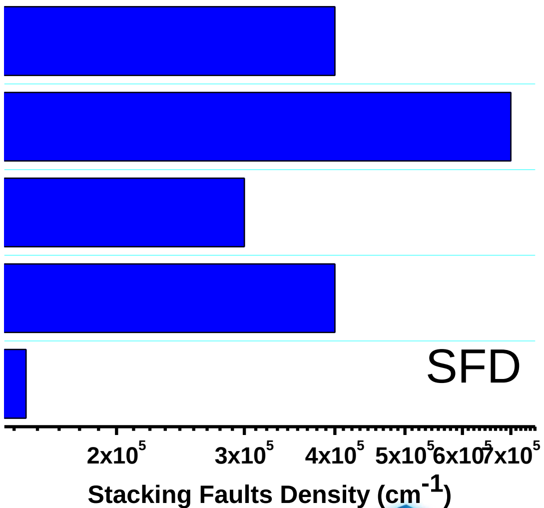
Craven et al., *APL* 81(2002), 469 (LT nucl. Layer)

Chakraborty et al. *APL* 89(2006), 041903 (LT nucl. Layer)

Chakraborty et al. *APL* 89(2006), 041903 (SiNx Nanomask)

Qian et al, *JAP* 106(2009), 123519 (HT AlN nucl. Layer and 3-step growth)

Li et al. *Adv. Mat.*, 21(2009), 2416 (NTLEG) THIS WORK

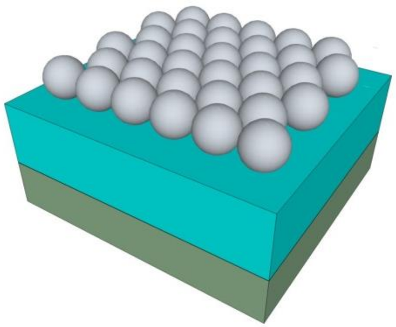


Q. Li, Y. Lin, J. R. Creighton, J. J. Figiel, and G. T. Wang, *Adv. Mat.*, **21**, 2416–2420 (2009)

Top-down III-Nitride Nanowires

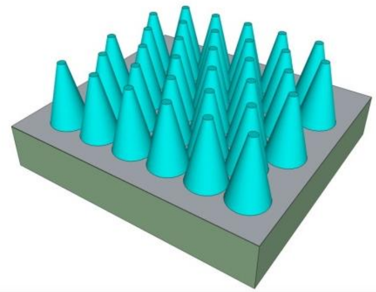
Sandia Research Highlights

New dry + wet top-down ordered nanowire fabrication process

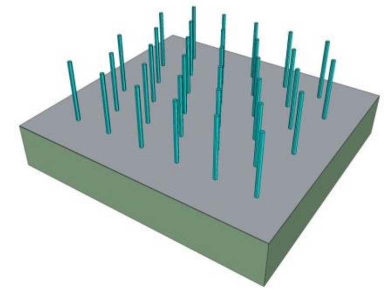


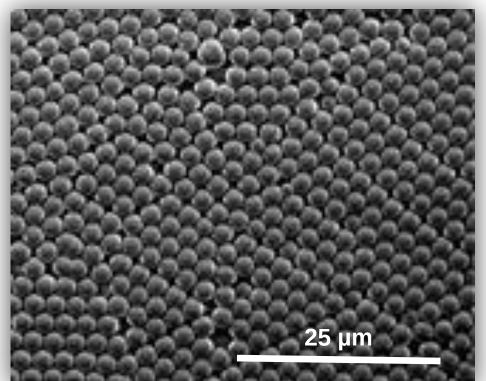
(0001) GaN on sapphire

ICP etch

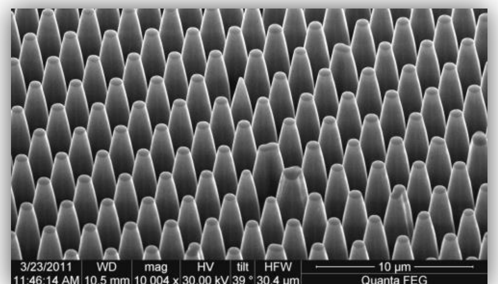


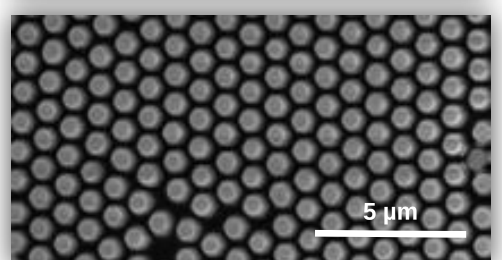
Selective wet etch
(AZ-400K developer)





Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).

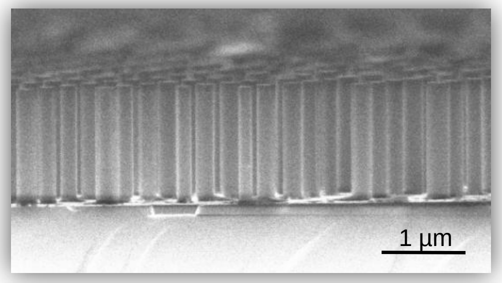


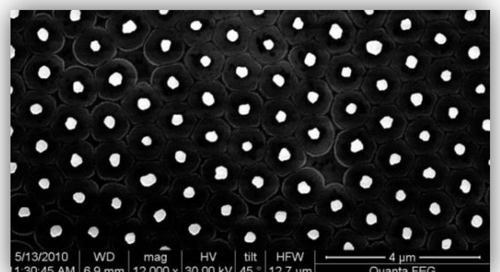


Plasma etch causes sidewall damage

C. Y. Wang et al., Opt. Expr. *16,* 10549–10556, 2008.

Tapered; no well-defined facets



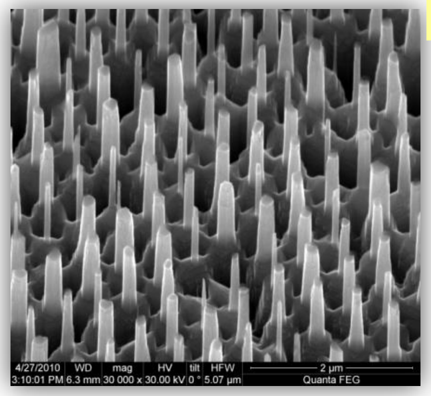


Wet etch: straight sidewalls, removes sidewall damage

Straight GaN nanowires with controllable geometries

Wet etch rate negligible for top (Ga-polar) *c*-face & fast for [10-10], leads to hexagonal NWs with **straight & smooth** *m*-facets

0.5 µm sphere size

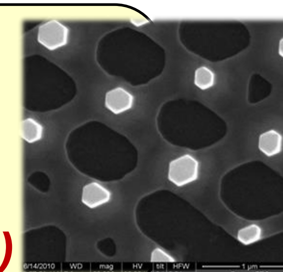


Superior and independent control of:

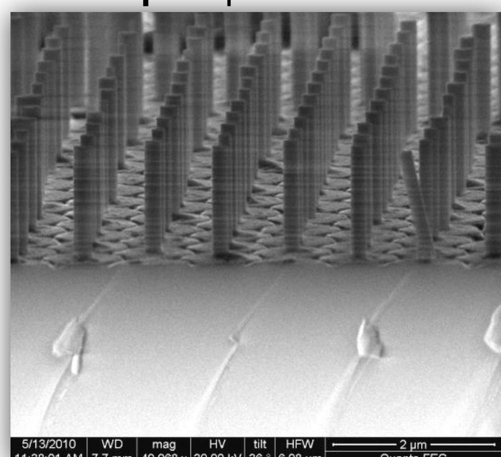
Height (dry etch depth)

Diameter (wet etch time)

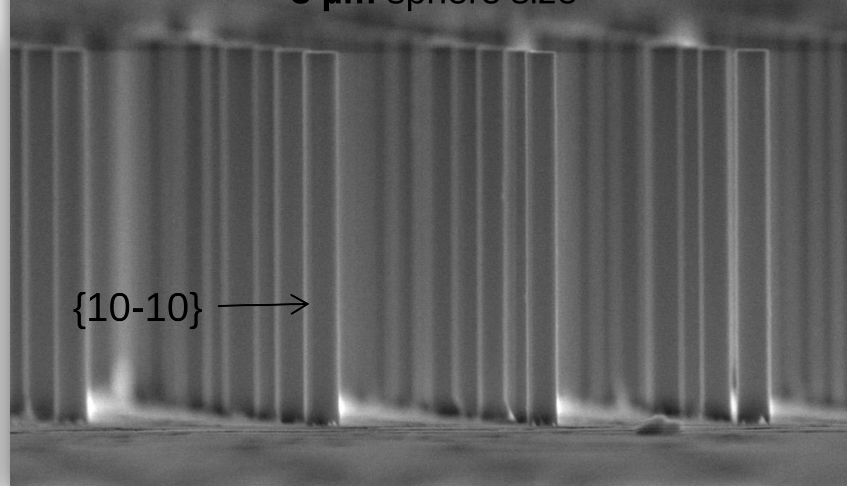
Pitch/arrangement (defined by masking template)

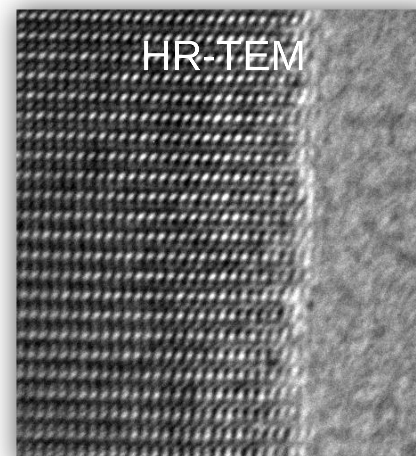


1 µm sphere size



3 µm sphere size

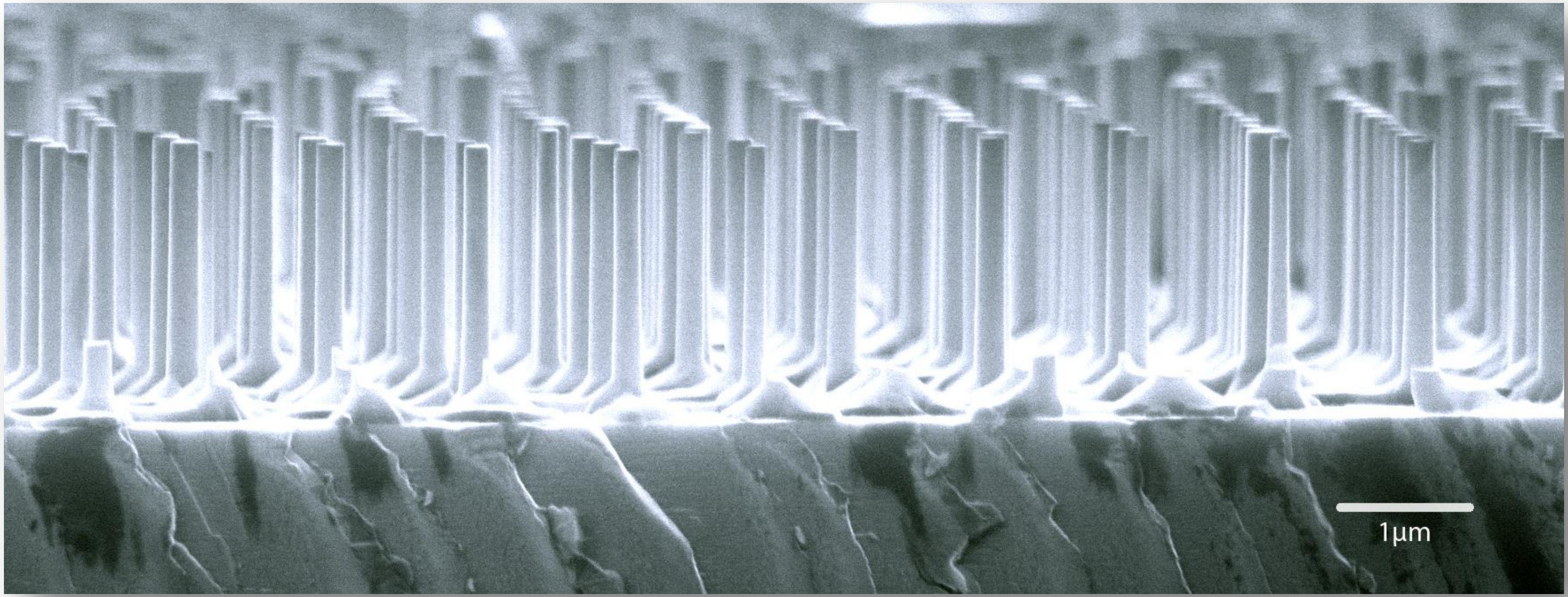




Smooth sidewall created by wet etch

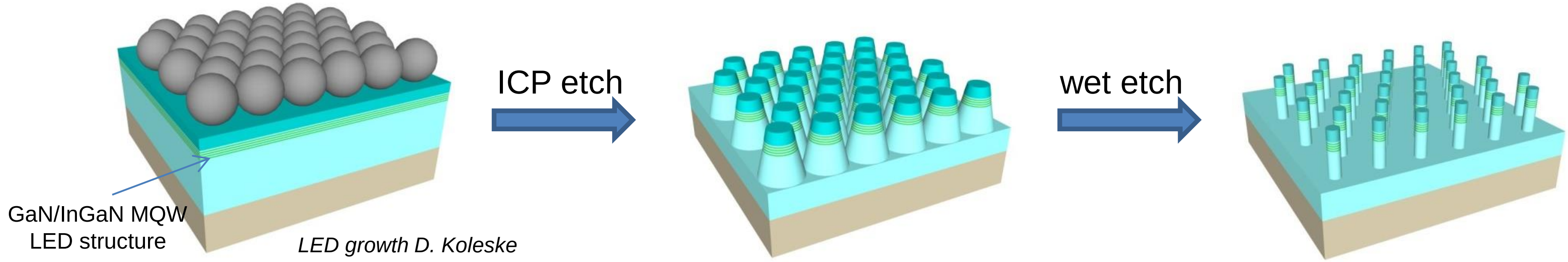
SSLS EFRC

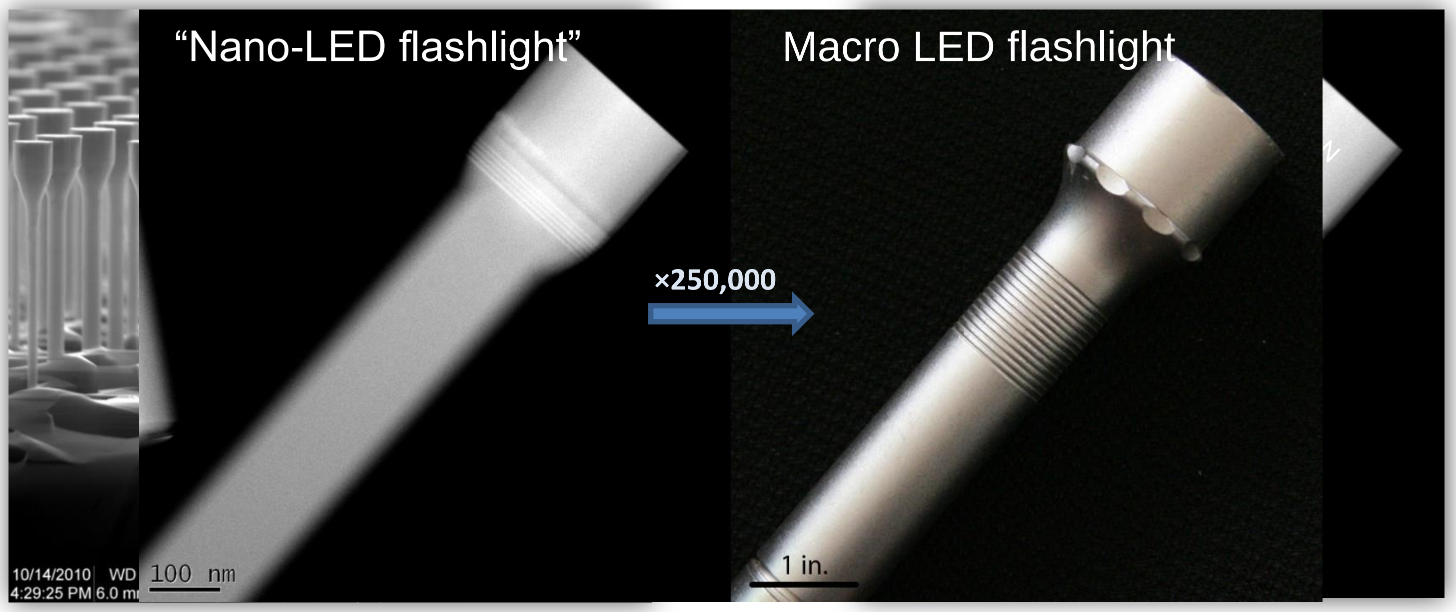
Advantages of new top-down nanowire fabrication method



- Wider range of growth conditions, material tunability (1D growth cndns not needed)
- Lower point defect densities (higher growth temperature)
- Ordered/periodic arrays (difficult with catalyst/VLS-based methods)
- Axial III-nitride nanowire heterostructures possible by MOCVD
- Better control of geometry (independent control over height, width, & pitch)
- Improved uniformity
- Easier vertical device integration (height uniformity, base GaN-layer)

Axial GaN/InGaN nanowire LEDs

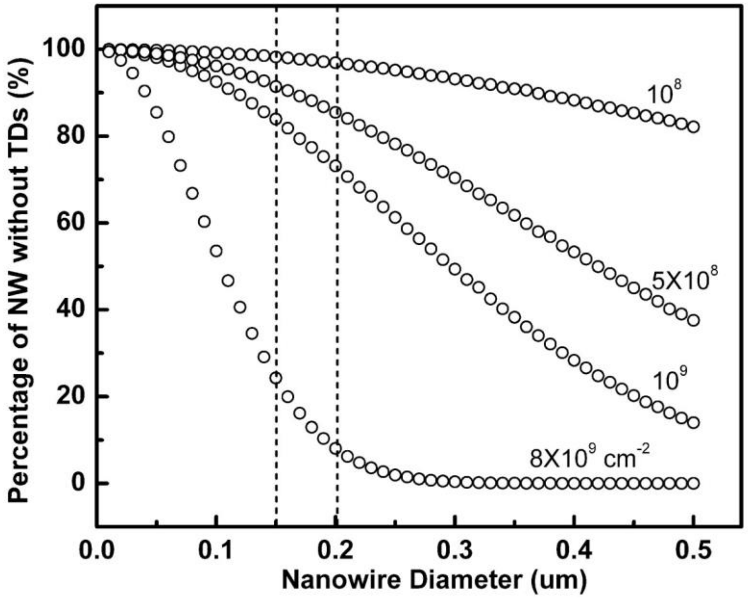




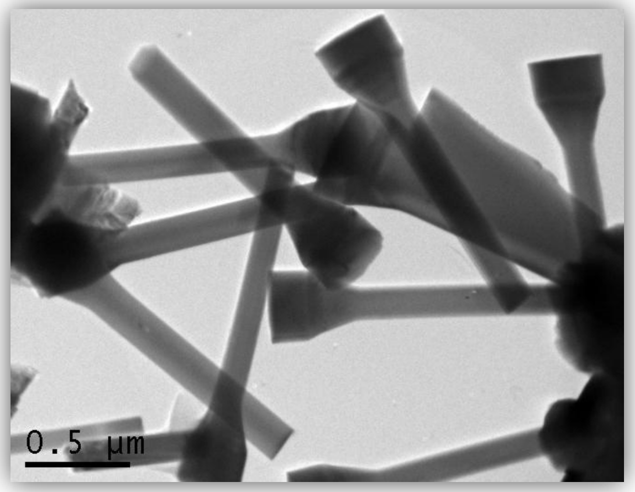
Q. Li et al., *Optics Express* **19**, 25528 (2011)

Top-down nanowire threading dislocations

Monte Carlo simulation



Bright-field TEM

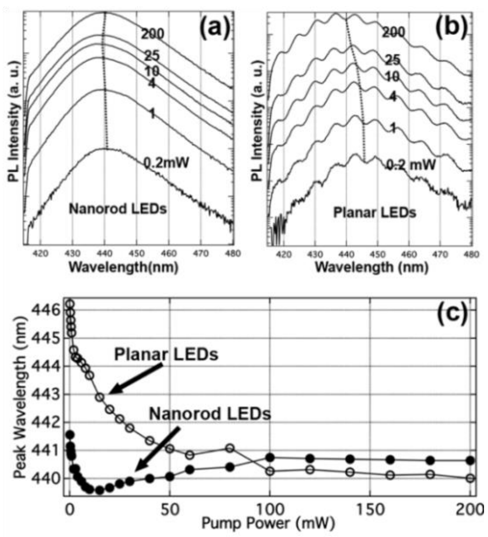


Nanowires etched from ~5e8 cm^{-2} planar LED

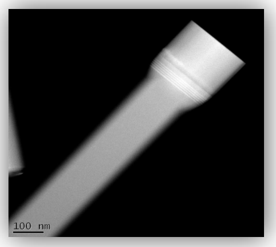
- Etched nanowires inherit the dislocation density of the parent film
- However, as the diameter approaches zero, the *fraction* of nanowires with one or more dislocations also approaches zero! [# TDs per rod ~ (TDD)×($A_{cross\text{-}section}$)]
- ~94% of nanowires ~150 nm in diameter from TDD~5e8 cm^{-2} film dislocation free!
- *Thus, nanowire LEDs can function as arrays of largely dislocation-free individual lighting elements*

Optical performance – axial nanowire LEDs vs. planar LED

InGaN peak position vs pump power

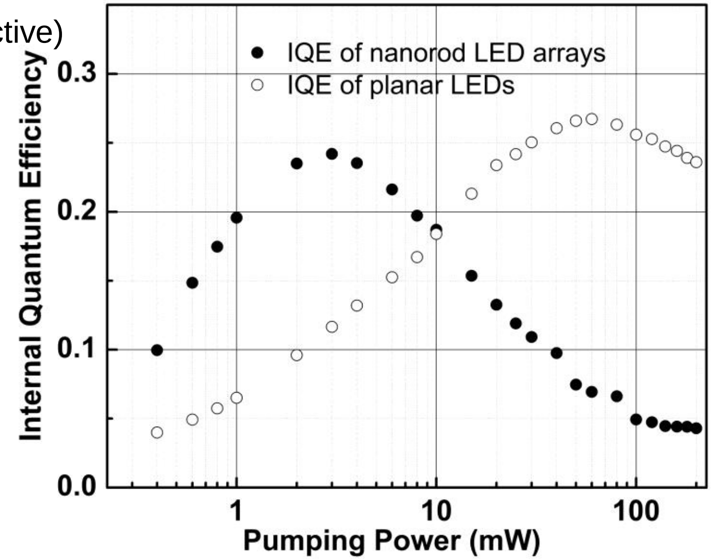


413 nm pump (InGaN selective)



Q. Li et al., *Optics Express* **19**, 25528 (2011)

IQE – nanowire vs Film



PL, IQE: K. Westlake, M. Crawford

- XRD shows ~16±4% strain reduction in InGaN QWs in nanowire LEDs

  XRD measurement courtesy Steve Lee
- Little wavelength shift at higher pump powers for nanowire LEDs (no/reduced QCSE)

- nanowire LED: comparable IQE to planar LED but peak IQE occurs at much lower pumping power (enhanced light absorption, heating)

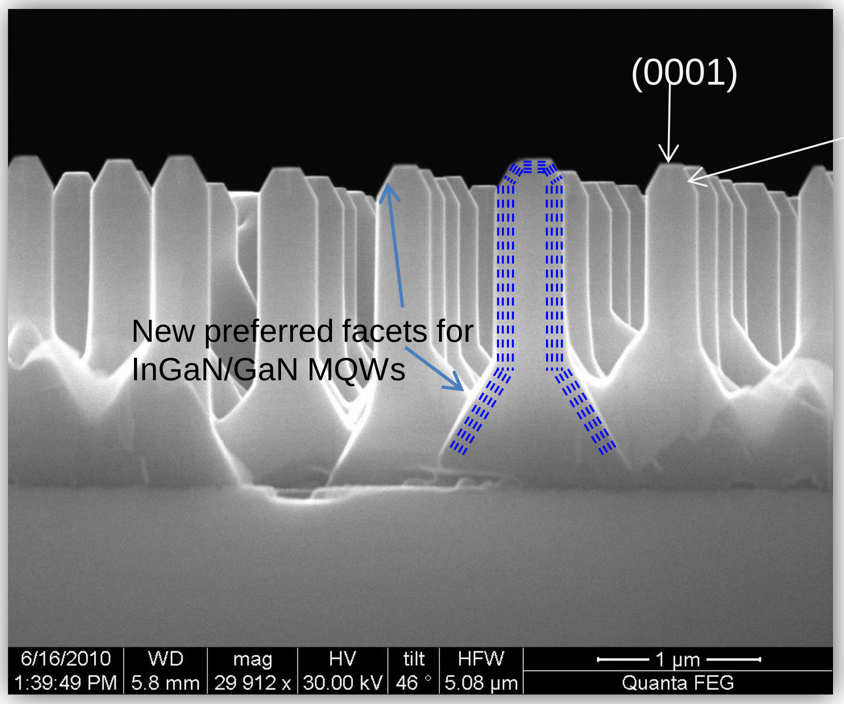
No obvious benefit for LED performance/cost ratio (loss of device area), but possibility for very high IQE single NW emitters for nanophotonic applications

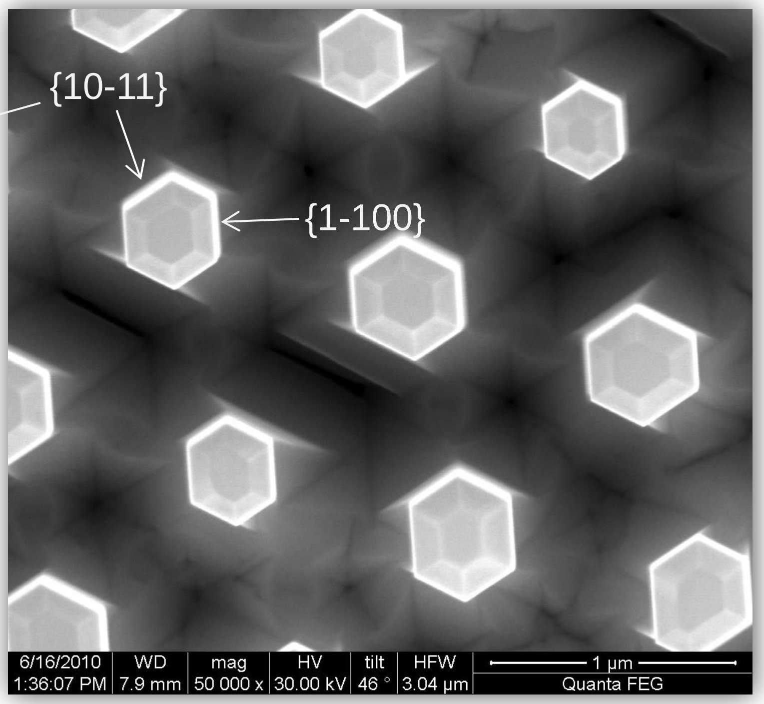
Radial core-shell InGaN/GaN MQWs on top-down NWs

Radial core-shell NW LEDs:

- Much higher active area than axial NW or planar structures
- Reduced strain InGaN growth for higher In incorporation
- Being pursued by a number of groups/companies (MOCVD)

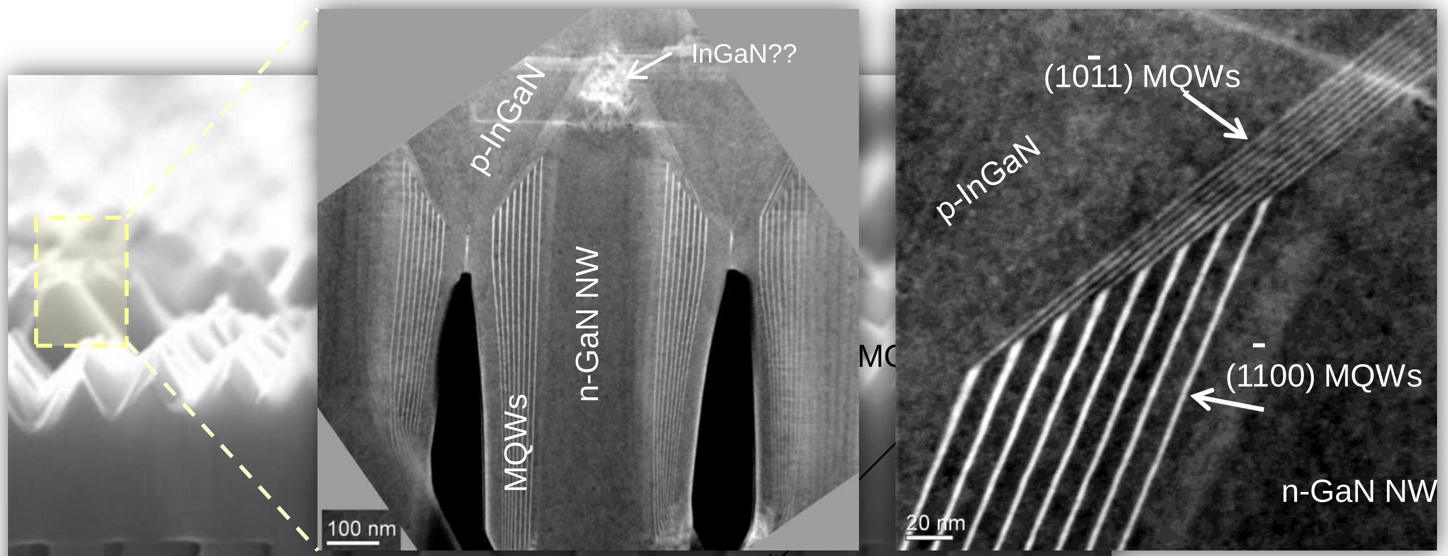
After 5-period MQW GaN/InGaN shell growth



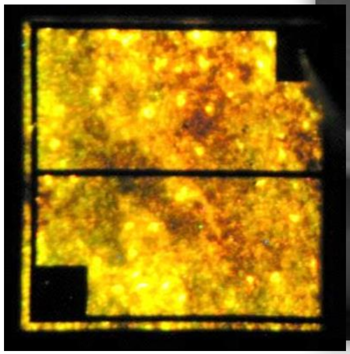


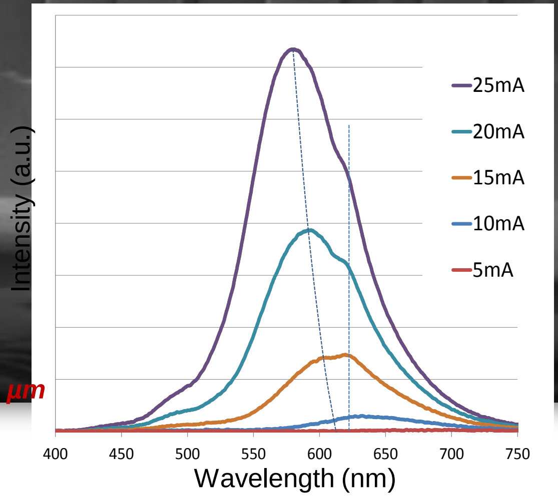
New semipolar facets form with InGaN/GaN MQW growth

Highlight: Electrically injected core-shell nanowire based "3D" LED emitting at yellow-red wavelengths



J. Wierer et al., *Nanotechnology* **23** 194007 (2012)





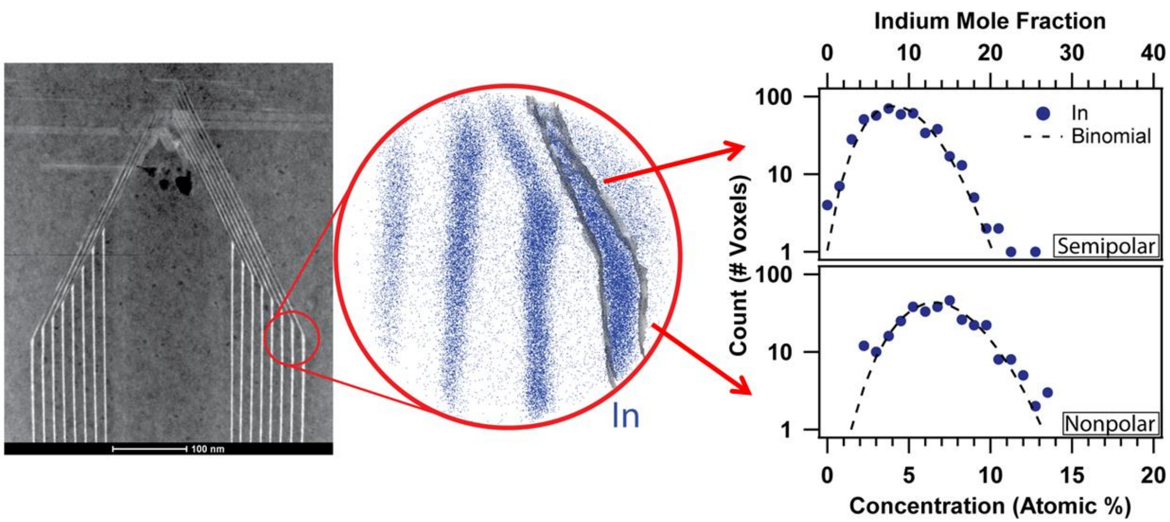
- Yellow-red electroluminescence!
- Two EL peaks:
  - 615 nm (const) red
  - 600-565 nm (shift) yellow

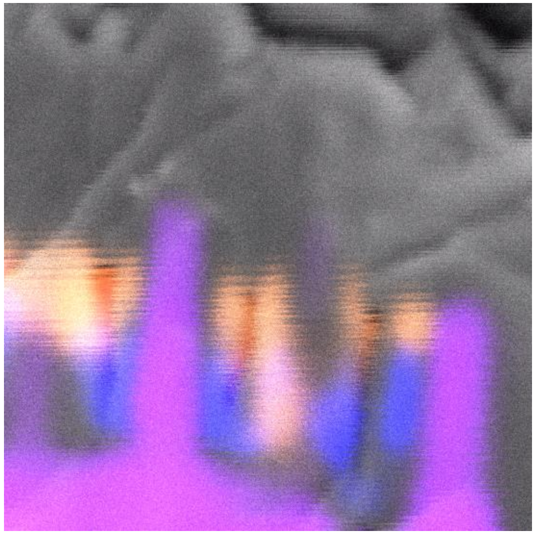
3-D Mapping of Quantum Wells in a GaN-InGaN Core-Shell Nanowire – a Correlated Study

STEM-EDS

Atom probe tomography (APT)

Cathodoluminescence



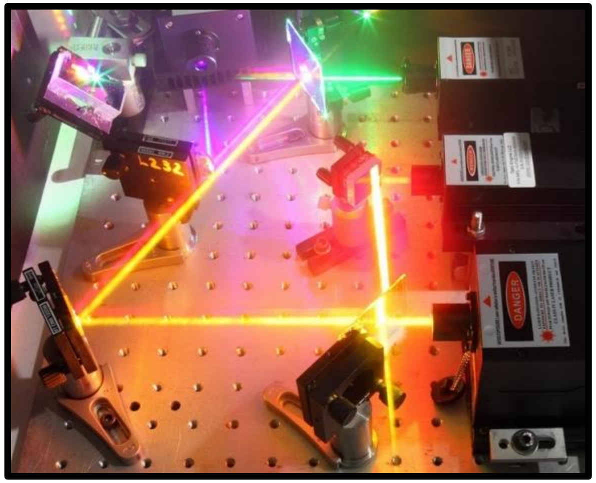


365 nm, 402 nm, 442 nm

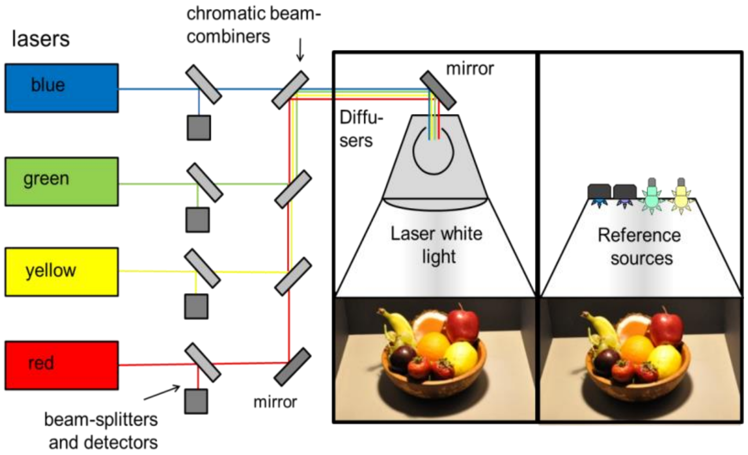
- Nonpolar and semipolar QWs from radial NW LED were imaged by APT and correlated with scanning TEM and cathodoluminescence data
- Results suggest yellow-red emission originates from In-rich tip regions, not sidewalls

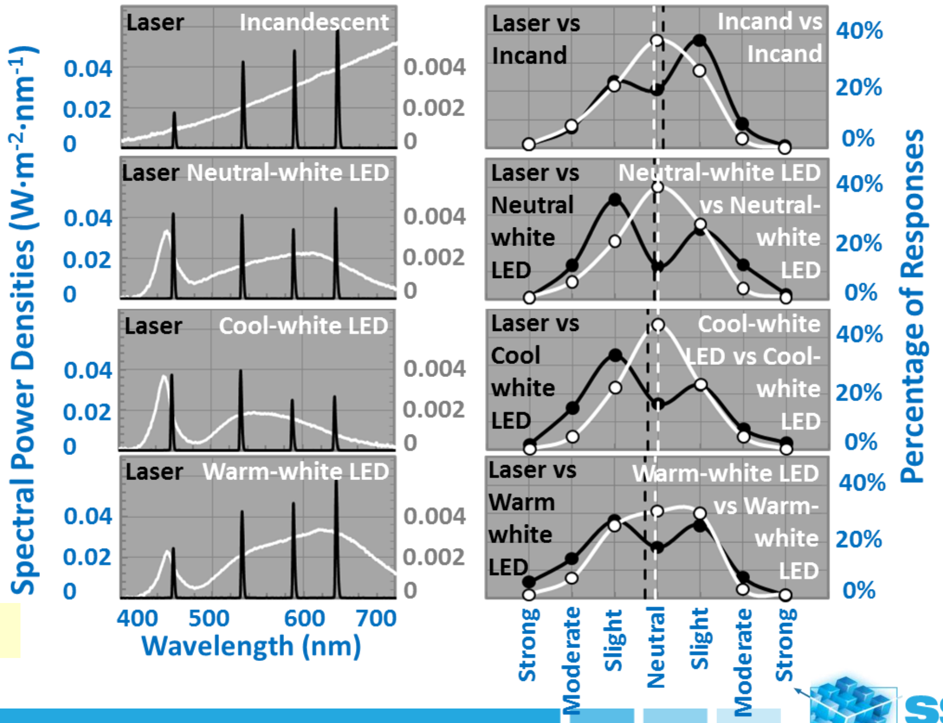
Lasers for Solid-State Lighting?

A Human Factors Study: RYGB Laser Illuminant



- Constructed an RYGB laser white-light source
  - Compare Laser, Incandescent, and LEDs
- Laser sources are virtually indistinguishable from broadband sources
- Paves the way for serious consideration of lasers for SSL





A. Neumann et al, *Optics Express*, **19**, A982-A990 (2011)

after A.J. Fischer

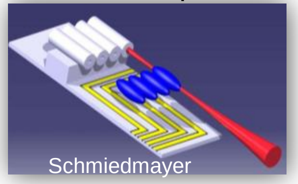
Nanowire Lasers

Why Nanowire Lasers?

- ***Nanowire forms a freestanding, low loss optical cavity***
- ***Compact and low power due to small mode volume***
- ***Possibility of high efficiency lasers at green and yellow wavelengths***
- ***Potential applications including electronic/optical integration, sensing, imaging, lithography, lighting***

Integrated nanophotonics, atom trapping, optical MEMS

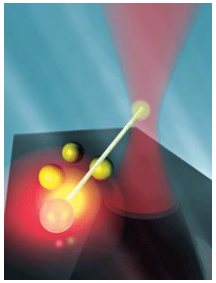
atom trap

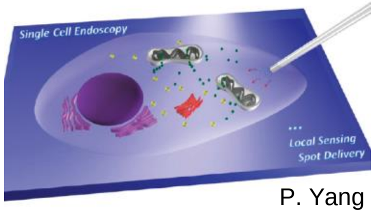


J. Ford, Lucent

Small UV-visible laser for trapping, interconnects, switching, etc.

Optical nanoprobes & chem/bio detection/sterilization





P. Yang

Sub-wavelength resolution probes for localized excitation, detection

Lighting, projection, & holographic displays

Sony Crystal LED Display prototype

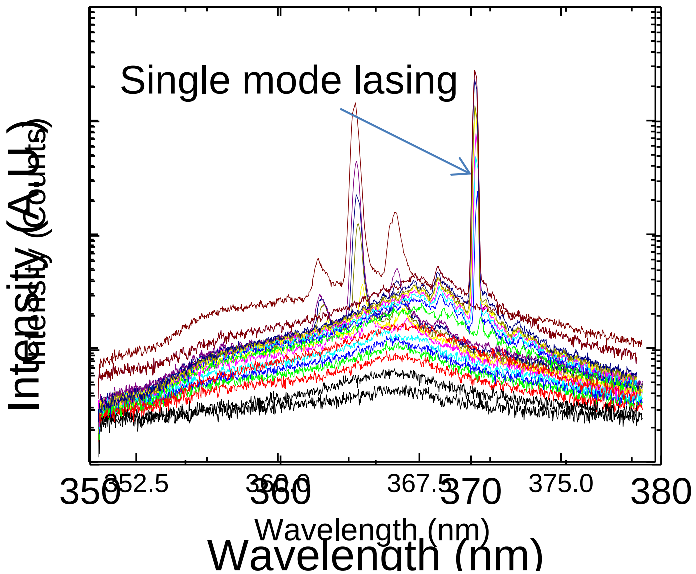
Low-power, speckle-free low coherence (random lasers)

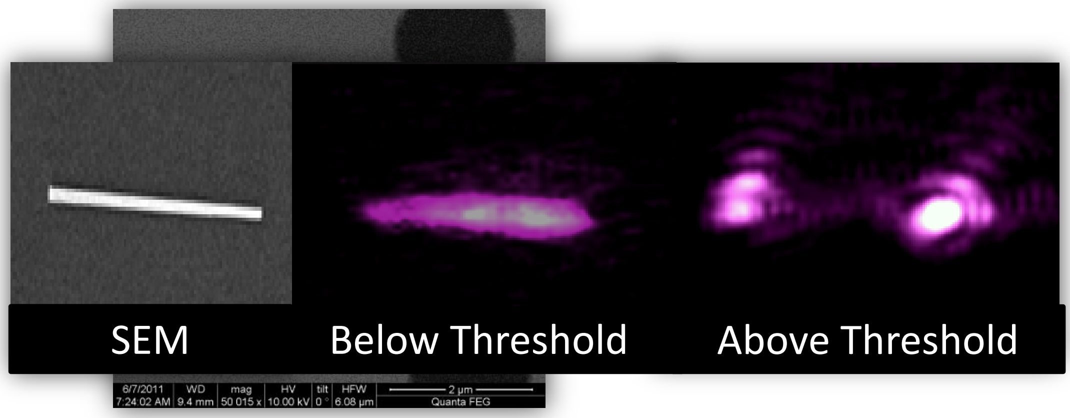
Mode control (i.e. How to make a single-mode GaN nanowire laser)

- Nanowire lasers generally exhibit *multiple modes*
- *Single mode* behavior desired for highest resolution and beam quality

Method 1: Single-mode GaN nanowire laser via geometry control

- Single-mode lasers are desirable (higher resolution, lower threshold & noise)





Nanowire dimensions: ~**130nm** x 4.7µm

Nanowire dimensions: ~**500 nm** x 4.7µm

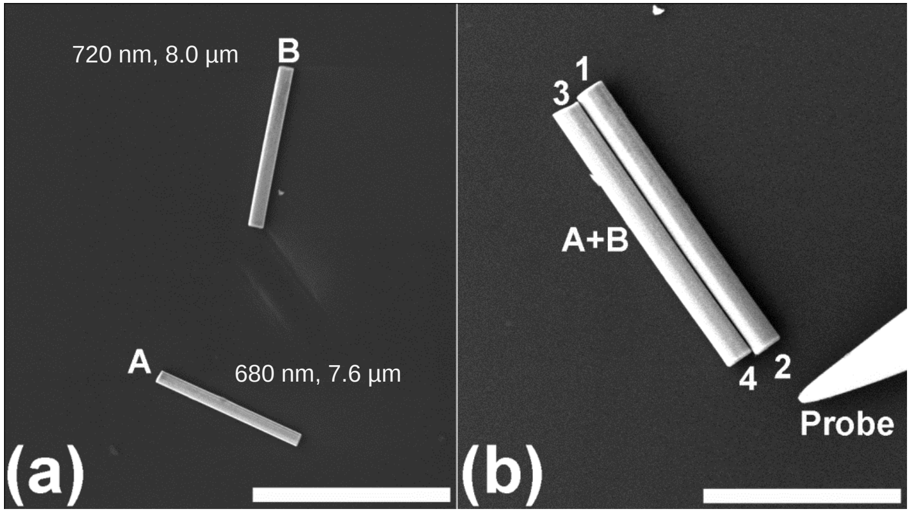
Q. Li et al., *Opt. Exp.* ***20*** *17873 (2012)*

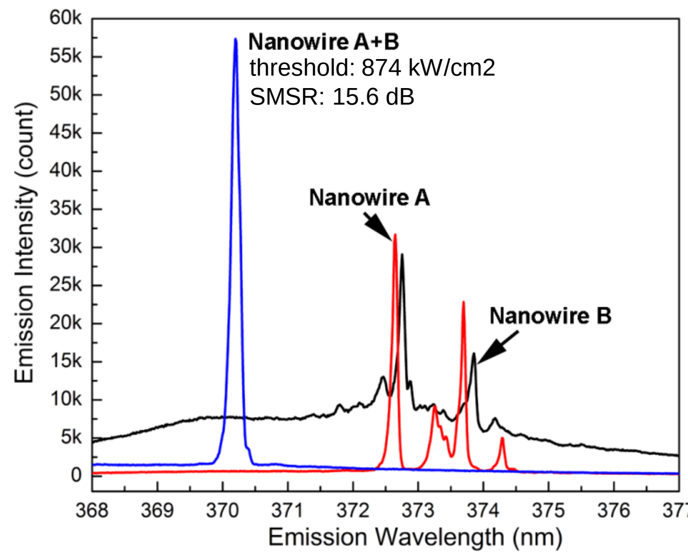
Single-mode: Narrow linewidth (<0.1 nm), 15dB Side Mode Suppression Ratio, and **Low Threshold** (~250 kW/cm^2)

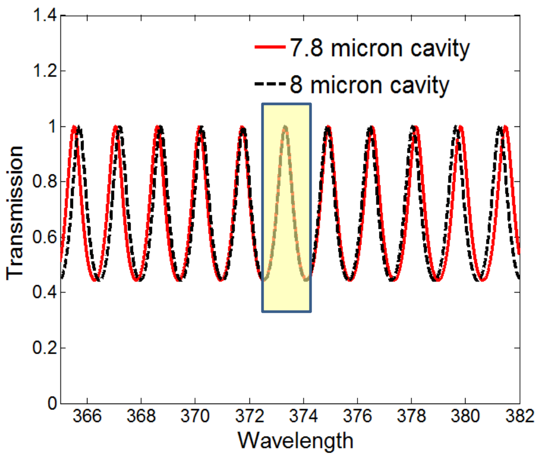
Multi-mode: Threshold ~500 kW/cm^2

Reducing the dimensionality of the wire (< ~130 nm diameter and < ~6 µm length) lowers the number of competing modes, leading to single-mode lasing.

Method 2: Single-mode lasing via coupled nanowire cavities





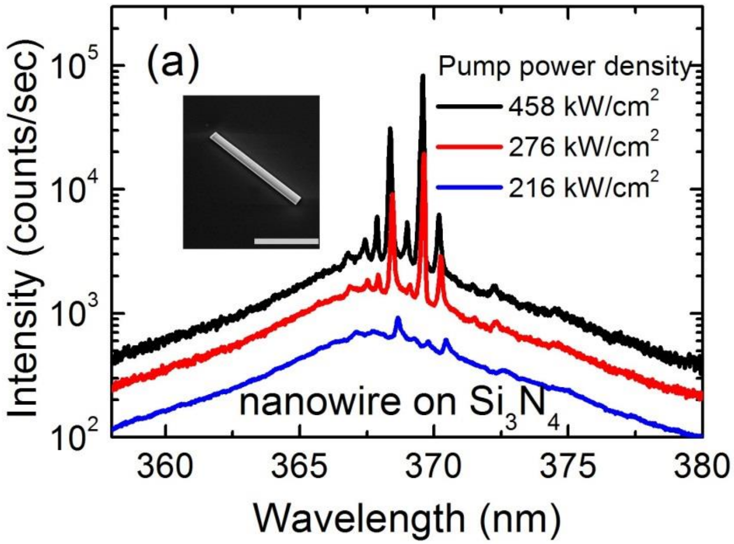


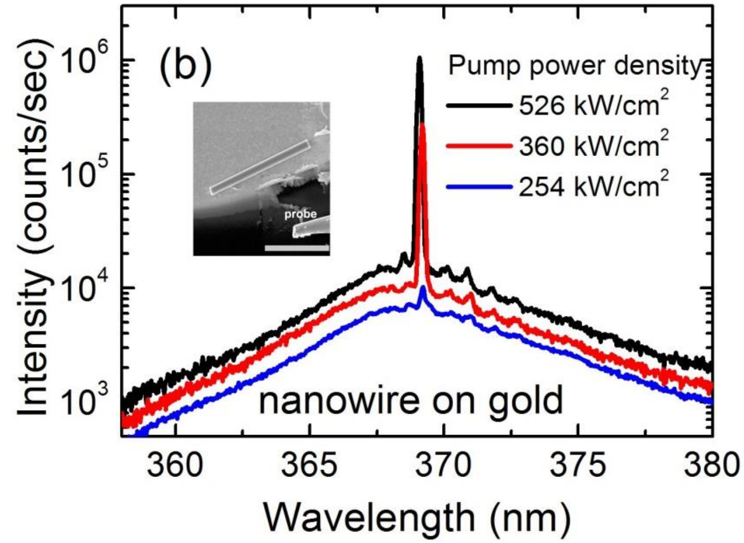
- GaN NWs need to be <~130 nm for single transverse mode behavior; larger single-mode NWs?
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

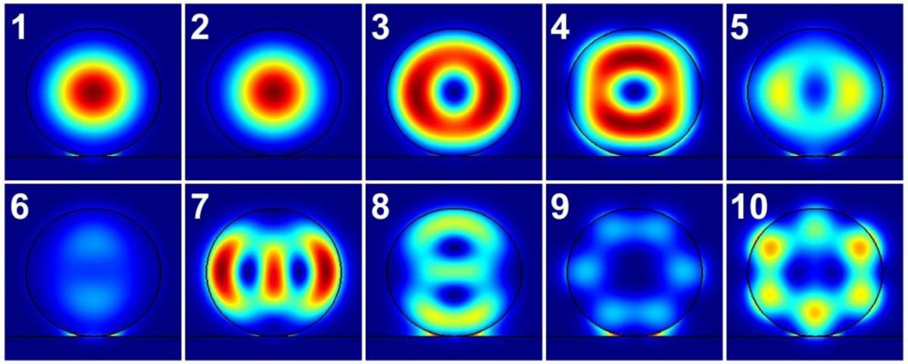
modeling: Huiwen Xu (UNM)

H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

Method 3: Metal substrate induced single-mode nanowire lasing





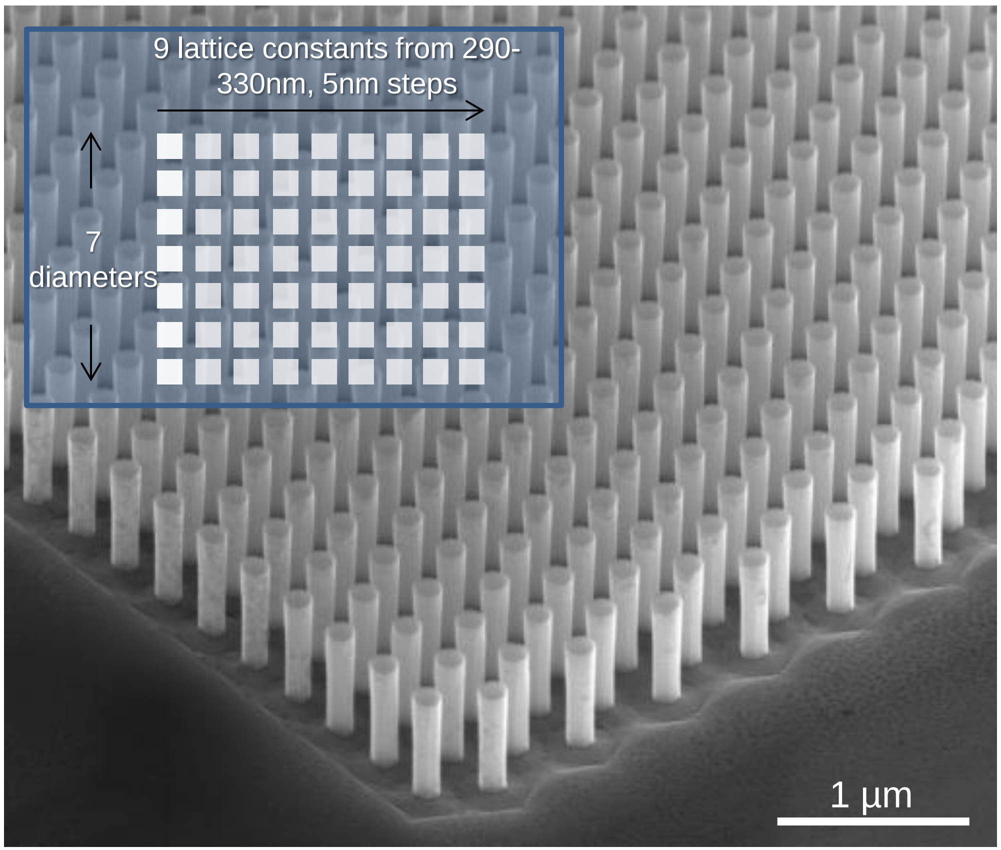


- NWs on Si_3N_4 show multi-mode lasing
- Same NWs moved onto gold-coated spot show single-mode lasing!
- Metal substrate induces mode-dependent loss mechanism

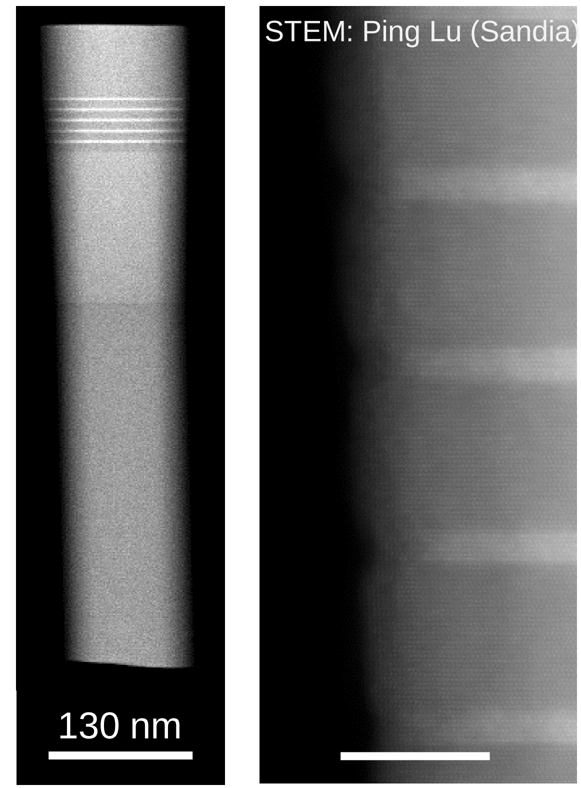
H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

III-N Nanowire Photonic Crystal (PC) Lasers

Motivation: Achieve single-mode, tunable lasing on same chip. Applications in optical information processing, biology, solid state lighting, displays, etc.



Nanowire PCs fabricated by top-down method using e-beam lithographic mask

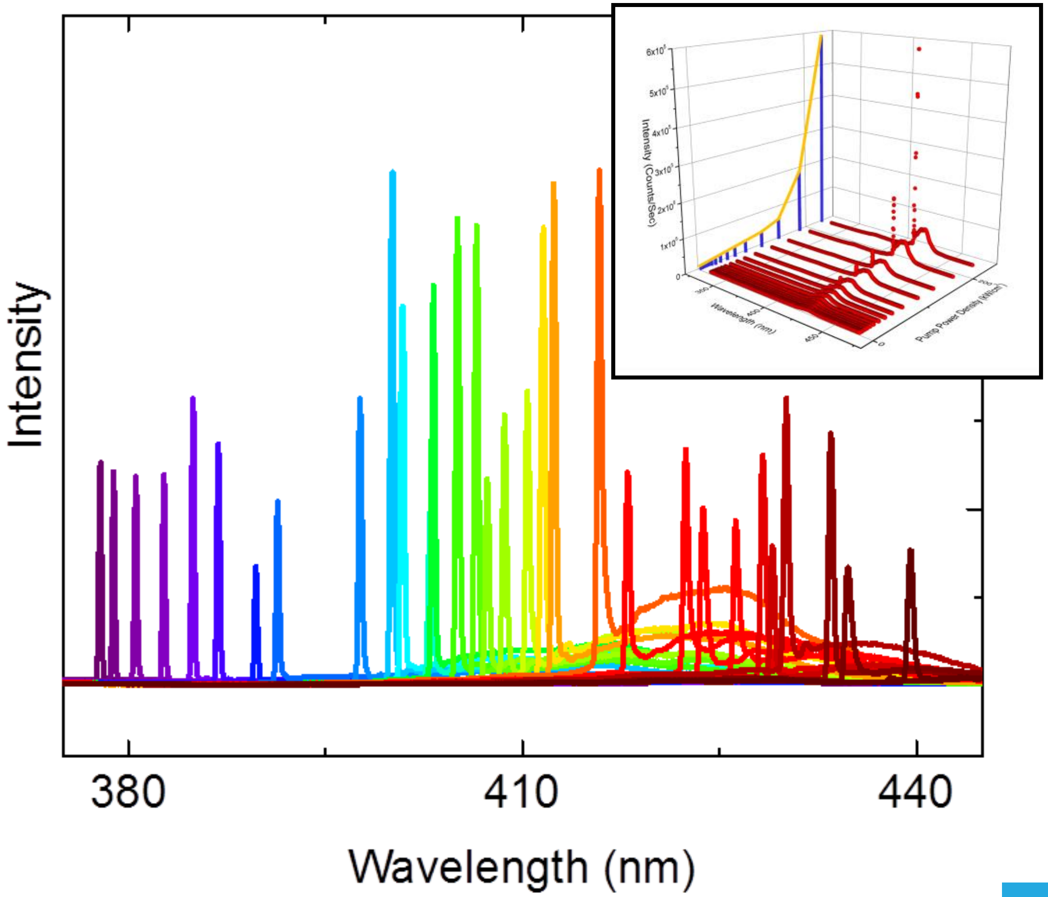


NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

III-N Nanowire Photonic Crystal Lasers

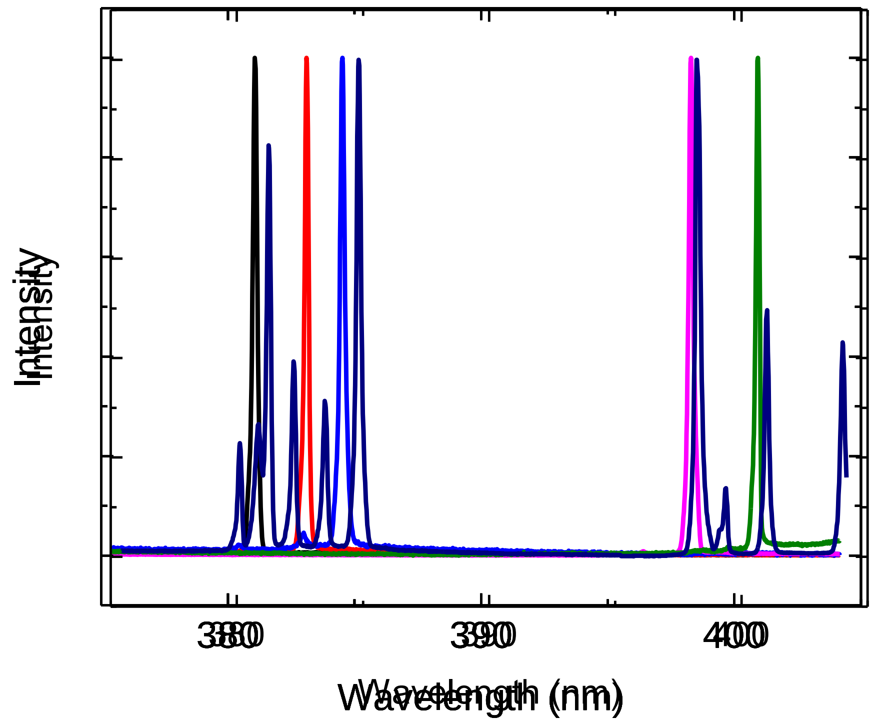
Broad gain width of InGaN MQWs with PC design allows for tunable single mode lasing over large range on same chip

61 color nanowire laser array



- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm^2 for all devices)

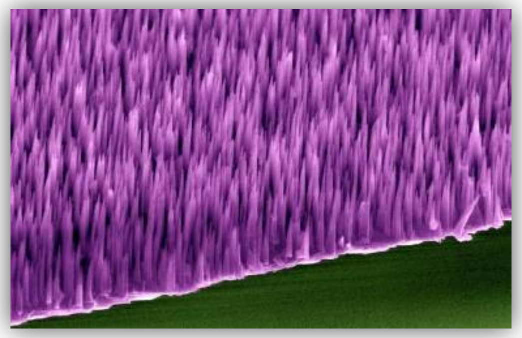
III-N Nanowire Photonic Crystal Lasers



pitch: 320 nm
diameter: 130-140nm

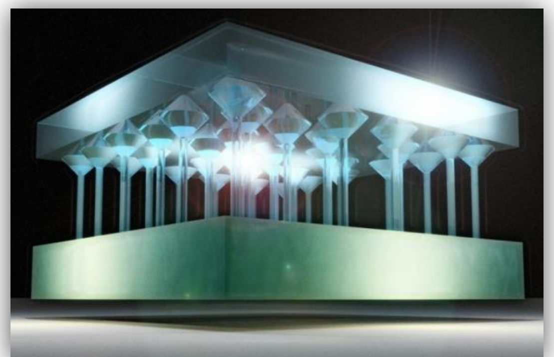
Summary - Bottom-up III-nitride nanowires

Vertically-aligned growth



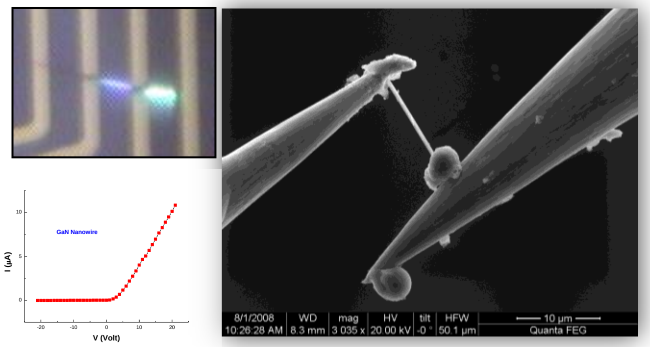
G. T. Wang et al., *Nanotechnology 17 5773-5780* (2006)
Q. Li, G. T. Wang, *Appl. Phys. Lett. 93, 043119* (2008)
Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth 310 3706-3709* (2008)

Nanowire-templated growth



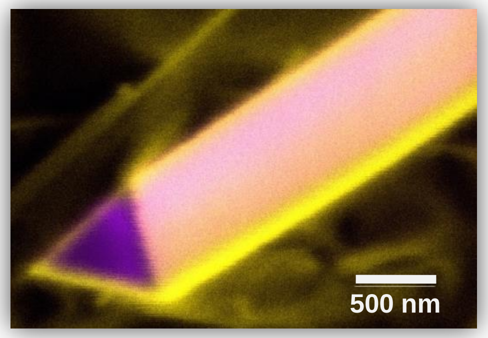
Q. Li, Y. Lin, J.R. Creighton, J. Figiel, G.T. Wang, *Adv. Mat.*, **21** 2416–2420 (2009)

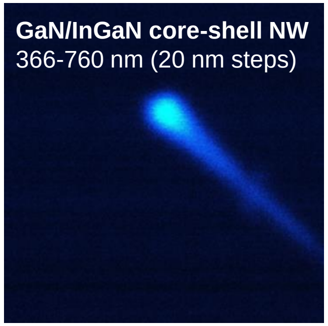
Electrical characterization



A. A. Talin, G. T. Wang, E. Lai, R. J. Anderson, *Appl. Phys. Lett.* **92** 093105 (2008)
Y. Lin, Q. Li, A. Armstrong, and G. T. Wang, *Solid State Commun.*, ***149***, *1608 (2009)*

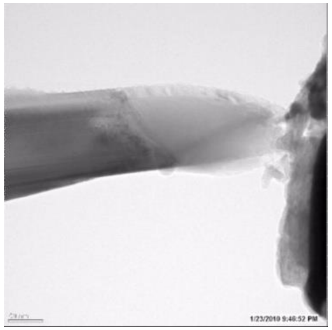
Optical imaging and spectroscopy





Q. Li, G. T. Wang, *Nano Lett.*, 2010, 10 (5), 1554 [GaN defect CL]
Q. M. Li, G. T. Wang, "*Appl. Phys. Lett.*, ***97***, 181107, 2010. [Gan/InGaN]
P.C. Uppadhya et al. *Semicond. Sci. Tech.* **25** 024017 (2010) [Ultrafast]
A. Armstrong, Q. Li, Y. Lin, A. A. Talin, G. T. Wang, APL **96**, 163106 (2010). [DLOS]

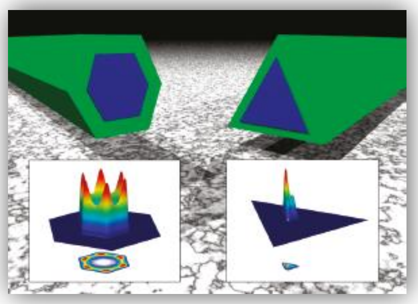
In-situ TEM



T. Westover et al., *Nano Lett.*, **9**, 257 (2009). [*in-situ* NW breakdown]

J. Y. Huang et al., *Nano Lett, **11 (4),** 1618 **(2011).*** [*in-situ* nanomechanics]

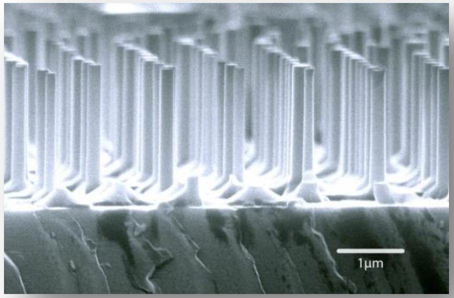
Theory



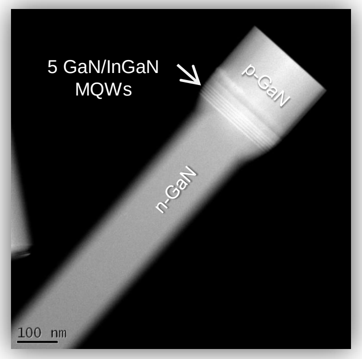
B. Wong et al., *Nano Lett **11 (8)**, 3074, 2011*

Summary – Top-down III-nitride nanowires

Top-down fabrication

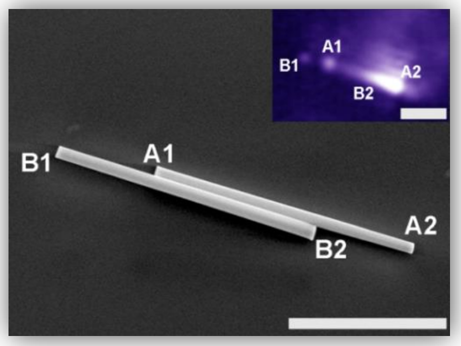


Nanowire LED "flashlight"



Q. Li et al., *Optics Express* **19**, 25528 (2011)

Single-mode GaN nanowire lasers

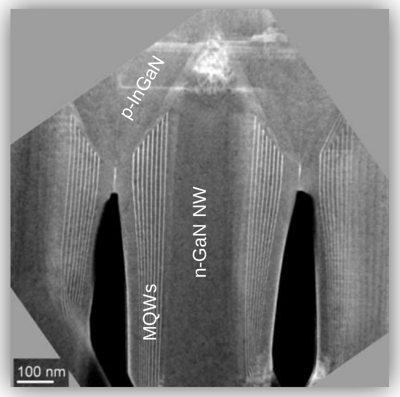


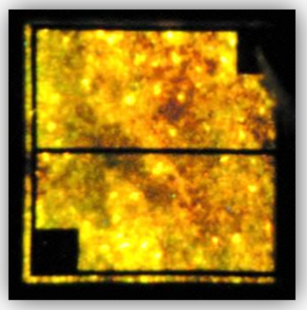
Q. Li et al., *Optics Express* **20** 17874 (2012)

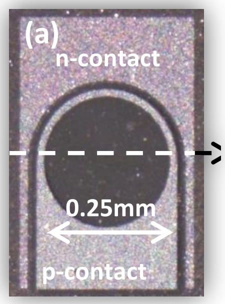
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

Vertically integrated radial nanowire LEDs and solar cells

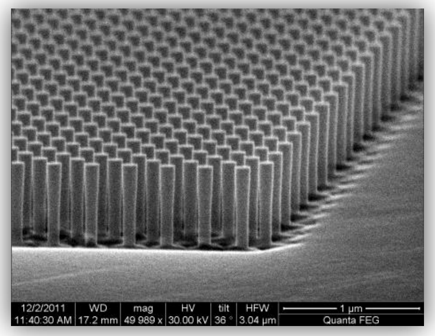


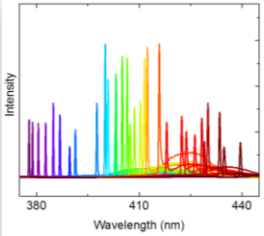




J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

Tunable nanowire photonic crystal lasers





J.B. Wright et al., *in preparation*

Summary

- III-nitride nanowire based architectures have several potential advantages over planar-based devices for solid-state lighting, but numerous scientific & technical challenges in fabrication, performance, device contacts

- Sandia research highlights
  - Growth and properties of bottom-up III-nitride nanowires
  - New top-down NW fabrication: controlled geometries, high material quality, high uniformity, greater design flexibility & facile vertical device integration
  - Axial NW LED/laser: not a clear winner over planar LEDs, but lasing emission can be tuned via photonic crystal designs.
  - Radial NW LED/laser: most potential due to high surface area, but complicated by device growth on competing facets

Acknowledgments

Qiming Li - nanowire growth, nano-CL, TEM/EDXS, nanofabrication, strain-modeling

Jeffrey Figiel, Randy Creighton, Karen Cross –MOCVD growth, device processing & support

Jianyu Huang – In-situ SPM-TEM for correlated structure-property studies

Jonathan Wierer – LED/solar cell device fabrication/characterization

Karl Westlake, Mary Crawford – PL, IQE measurements

Daniel Koleske – LED growth

Igal Brener, Willie Luk, Weng Chow, Jeremy Wright, (Ph.D student), Huiwen Xu (Ph. D student), Ganesh Subramania – NW [PC] lasers

Funding Acknowledgment: **DOE Basic Energy Sciences (BES) DMSE, Sandia's Solid-State-Lighting Science Energy Frontier Research Center (DOE BES), and Sandia's LDRD program**

Contact: e-mail: gtwang@sandia.gov http://www.sandia.gov/~gtwang

Backup/Extra Slides

U.S. DEPARTMENT OF ENERGY

Director: Mike Coltrin

Chief Scientist: Jeff Tsao

Senior Leadership Council: Jerry Simmons, Mary Crawford, George Wang, Igal Brener

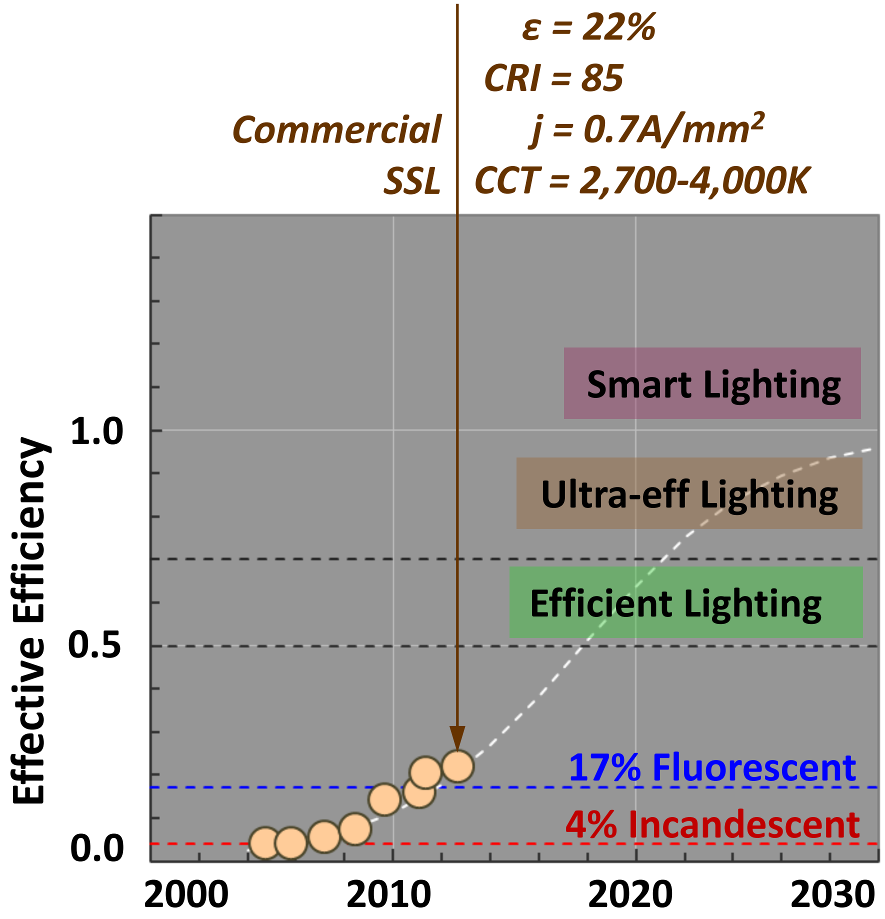
http://energy.sandia.gov/?page_id=452

- **Sandia National Laboratories (lead lab) and 9 partner institutions**
- **Budget: $3.6M/year for 5 years, FY10-FY14 ($415K/year to partners)**

Research plan: Investigate conversion of electricity to light using radically new designs, such as luminescent nanowires, quantum dots, and hybrid architectures; study energy conversion processes in structures whose sizes are even smaller than the wavelength of light; understand and eliminate defects in SSL semiconductor materials that presently limit the energy efficiency.

Sandia National Laboratories · The University of New Mexico · Los Alamos National Laboratory · PHILIPS · Yale University

Efficiency, Ultra-efficiency, and Beyond



<u>**"Ultra-efficient" SSL: > 70%**</u>

Achieves the greatest savings in energy consumption and gains in human productivity

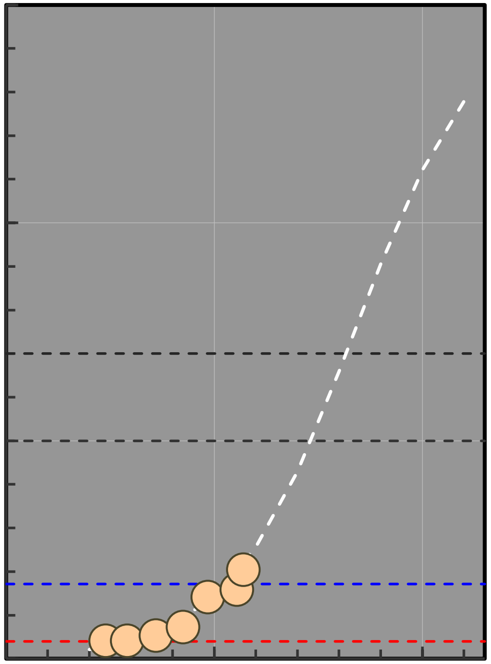
Requires fundamentally new architectures and understanding, *enabled* by basic research

Solid-State Lighting Science EFRC

Energy ⟺ Technology ⟺ Science

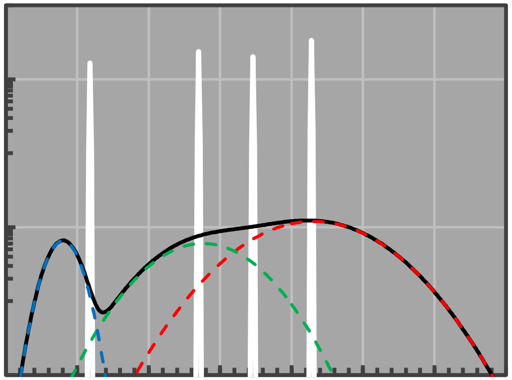
1

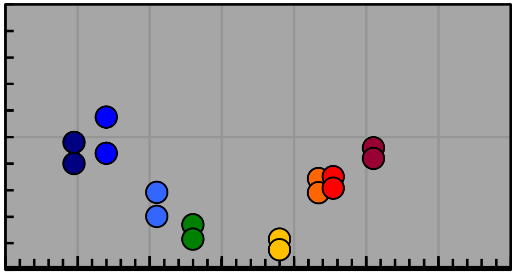
Plenty of room for improvement



2

Formidable technology challenges





3

Scientific Research Challenges

1. Nanowires
2. Quantum Dots & Phosphors
3. Competing Radiative and Non-Radiative Processes
4. Defect-Carrier Interactions
5. Enhanced Spontaneous Emission
6. Beyond Spontaneous Emission

J.Y. Tsao, Sandia

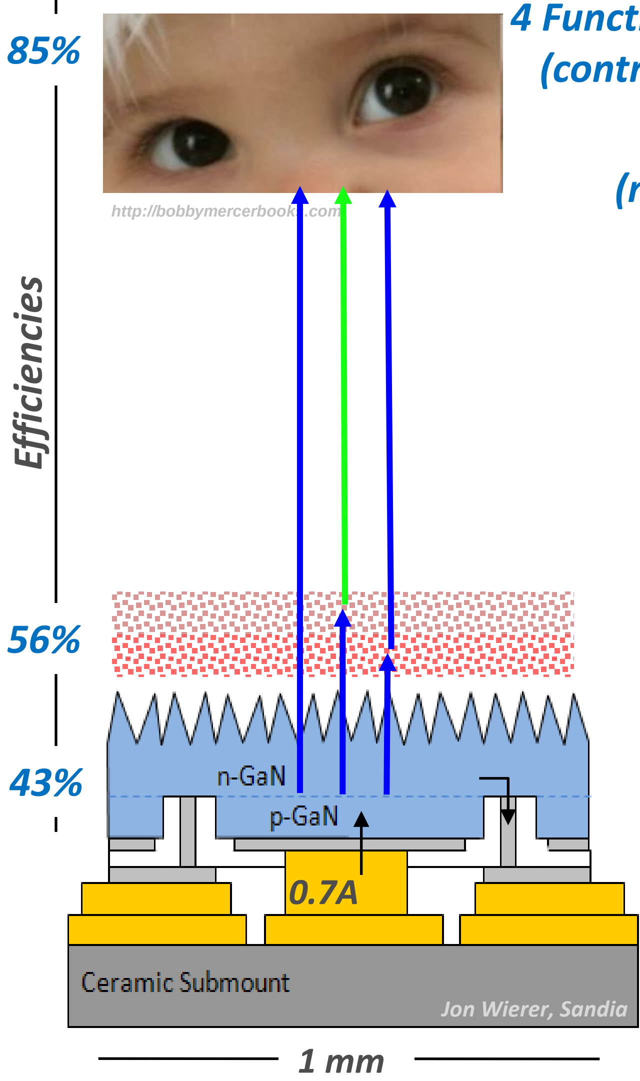
Why Only 30% Efficient?
Four SSL Technology Grand Challenges

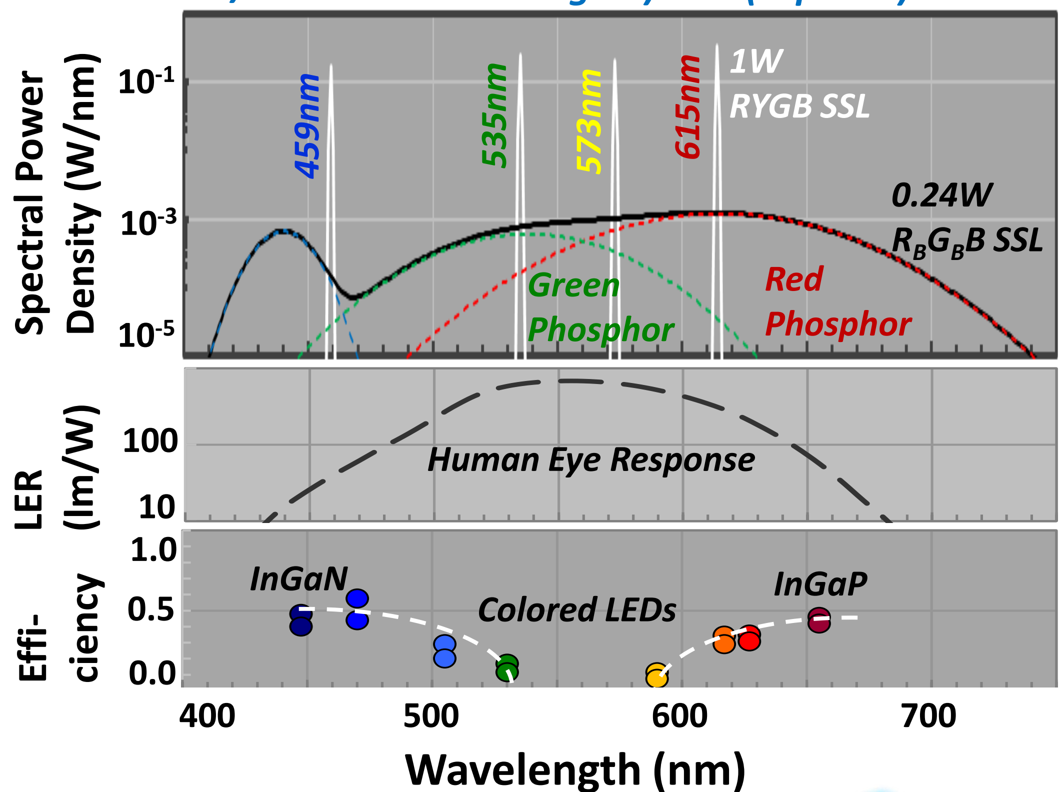
4 Functional Light
(control of light in intensity, chromaticity, time, and space)

1 Efficiency Droop
(near-100% efficiency at all currents)

2 Green-Yellow Gap
(near-100% efficiency at all wavelengths)

3 Narrow-linewidth λ downconversion (esp. red)





SSLS EFRC

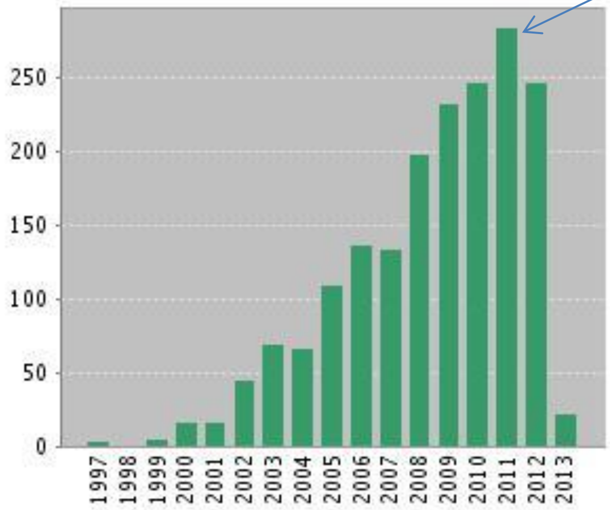
GaN-based nanowire research: publications & citations

Search: Title=((((gan or gallium nitride or ingan or iii-nitride) and (nanowire or nanowires or nanocolumn or nanocolumns or nanopillar or nanopillars or nanorod or nanorods) not (ZnO or zinc oxide))))

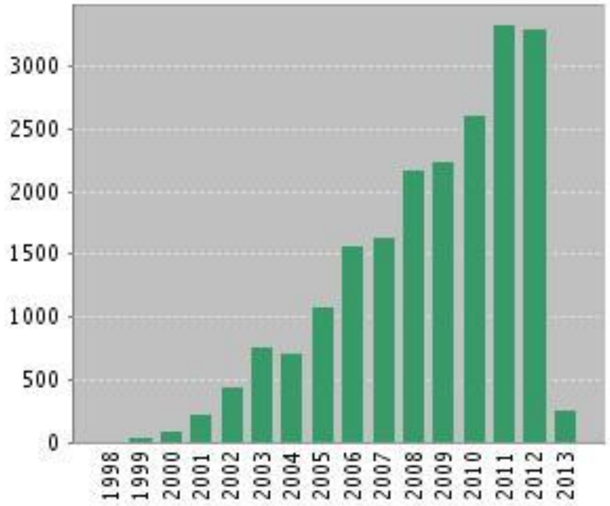
- Web of Knowledge, retrieved 3/4/2013

peak GaN NW?

published items each year



citations each year



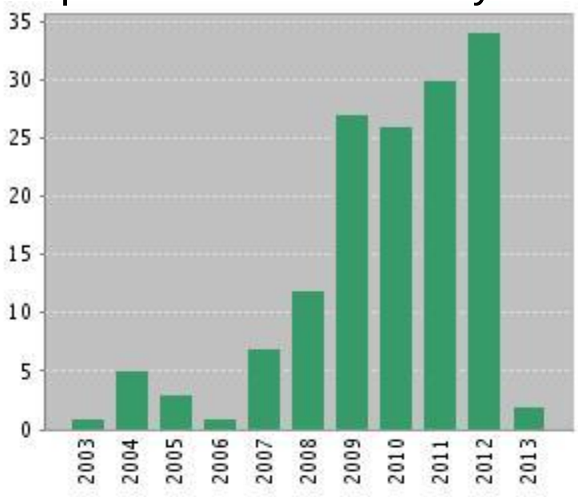
Results found:	**1834**
Sum of the Times Cited:	20536
Sum of Times Cited without self-citations:	11966 (58%)
Citing Articles:	7973
Citing Articles without self-citations:	6787
Average Citations per Item:	11.20
h-index:	61

GaN-based nanowire LED research: publications & citations

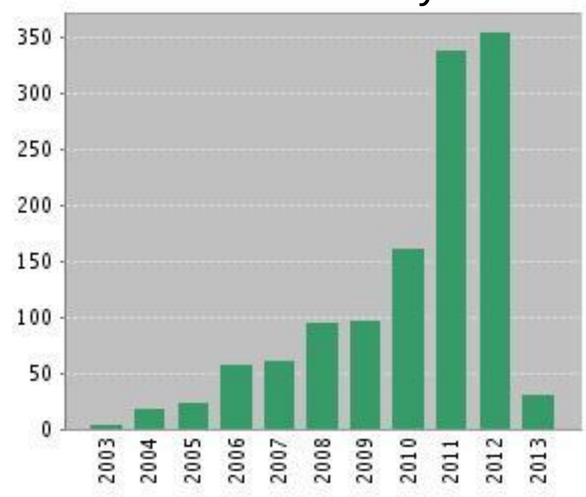
Search: Title=((((gan or gallium nitride or ingan or iii-nitride) and (nanowire or nanowires or nanocolumn or nanocolumns or nanopillar or nanopillars or nanorod or nanorods) and ***(light emitting diode or led or leds or light emitting diodes)*** *not (ZnO or zinc oxide))))*

- Web of Knowledge, retrieved 3/4/2013

published items each year



citations each year



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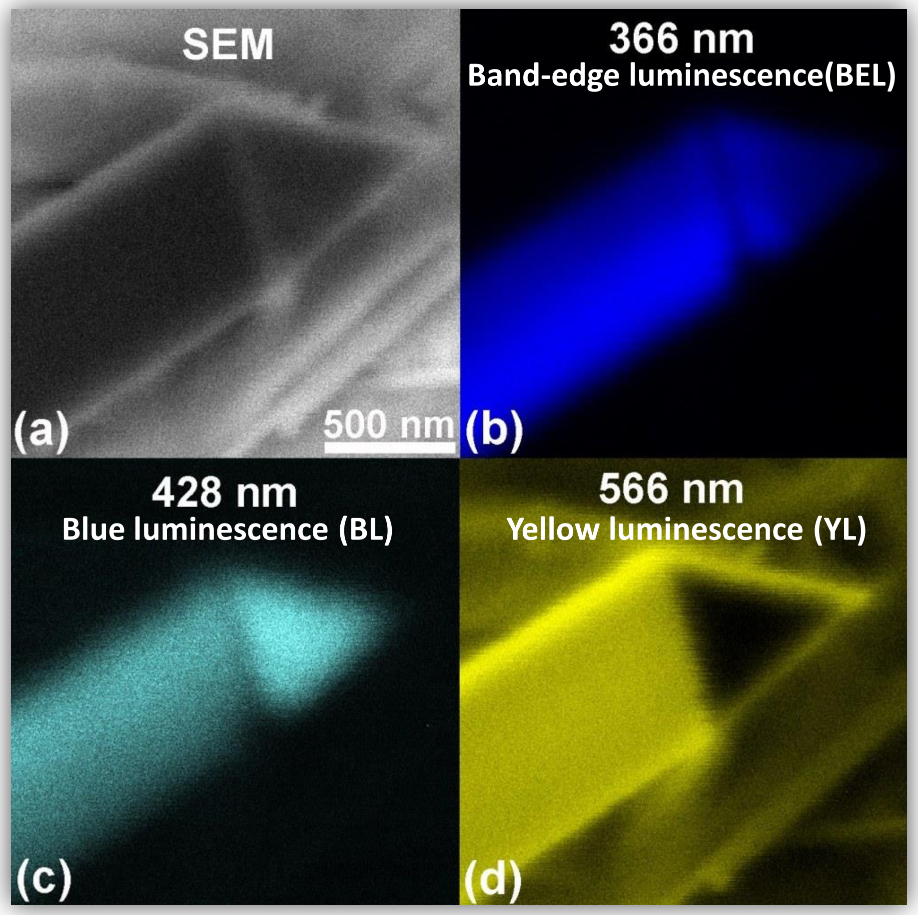
Sum of Times Cited without self-citations:	1079 (87%)
Citing Articles:	828
Citing Articles without self-citations:	764
Average Citations per Item:	8.41
h-index:	17

Spatial distribution of luminescence in GaN NWs



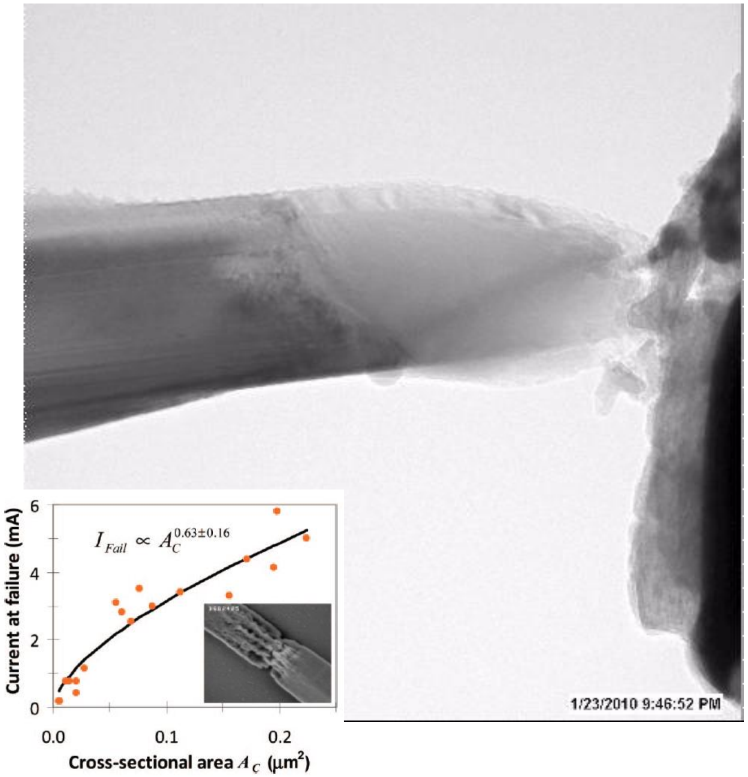
***Nanoscale Cathodoluminescence (CL) imaging:* Cross-section GaN NW**

- 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
- 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_{Ga}-O_N (D ~2.2 eV), less mobile

Q. Li, G. T. Wang, *Nano Lett.*, 2010, 10 (5), 1554

In-situ TEM studies

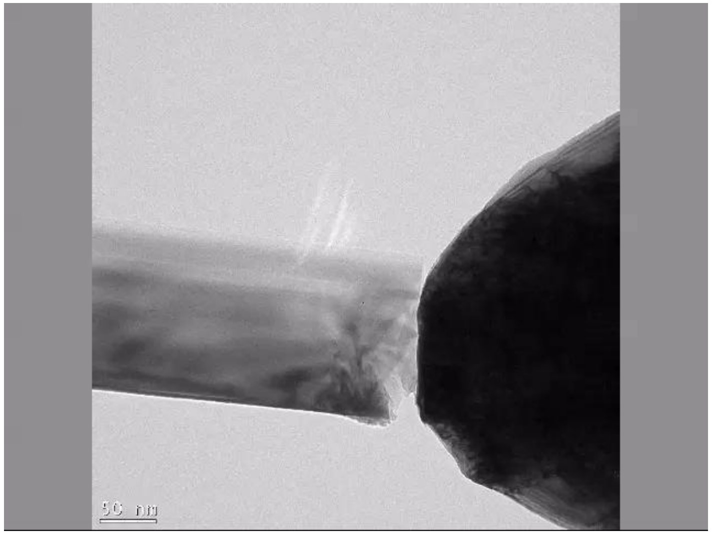
GaN NW decomposition via Joule heating
(relevant for NW devices)



NW breakdown at 60V, 20 µA
(avg. breakdown I ~3000 kW/cm^2)

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

Local plastic deformation of GaN NW
(relevant for NW devices)

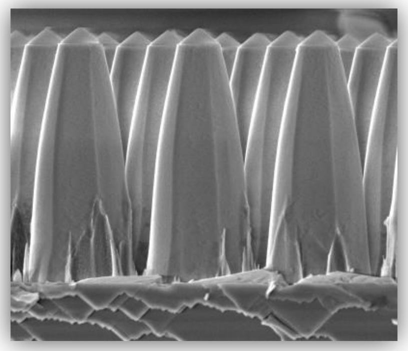


- Dislocation-free NW shows significant surface plastic deformation
- Mediated by dislocation nucleation & pile up, grain boundary sliding

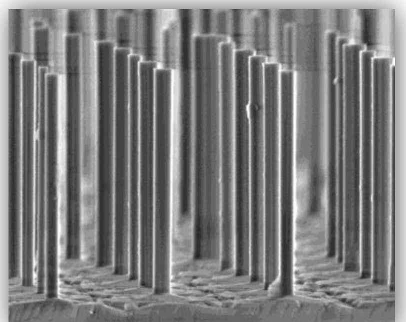
J. Y. Huang, H. Zheng, S. X. Mao, Q. Li, and G. T. Wang, *Nano Lett,* **11 (4),** 1618 (2011).

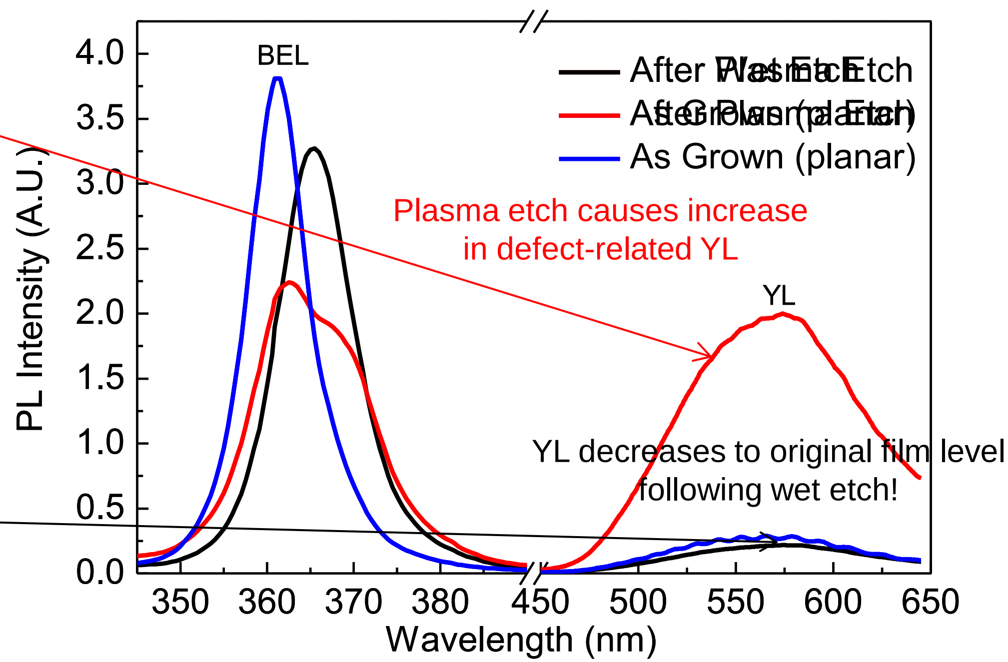
Wet etch step removes plasma etch damage

Plasma etch only



After wet etch

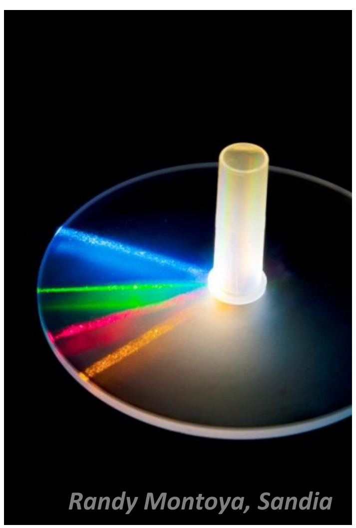




Lasers for Solid State Lighting

Advantages of lasers for lighting:

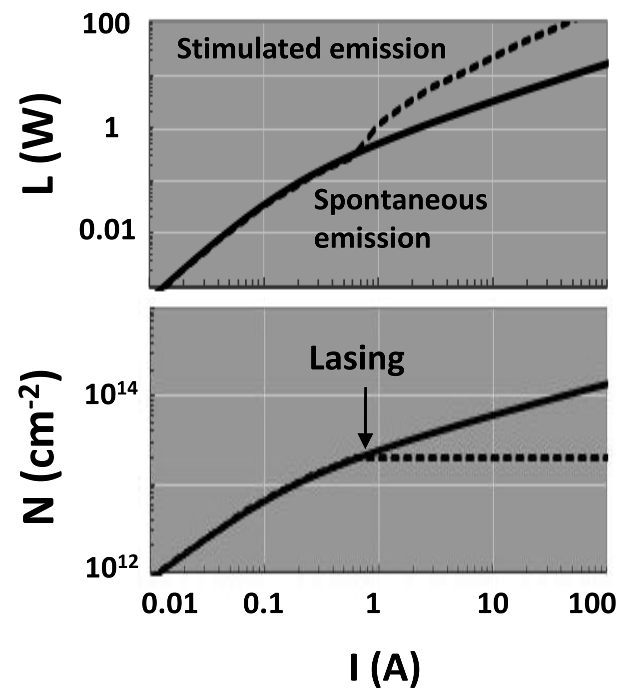
- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
    - Circumvent the droop problem in LEDs
    - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission, modulation



Laser Sources For SSL:

- High efficiency
- Low threshold
- Focus on III-nitrides
- Nanowire lasers
    - Low threshold
- Polariton lasers
    - Ultralow threshold
    - New physics

Clamped carrier density

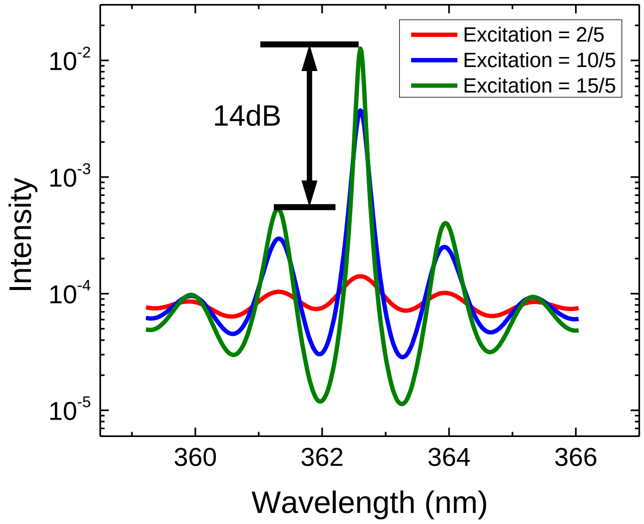


Are narrow linewidth sources acceptable?

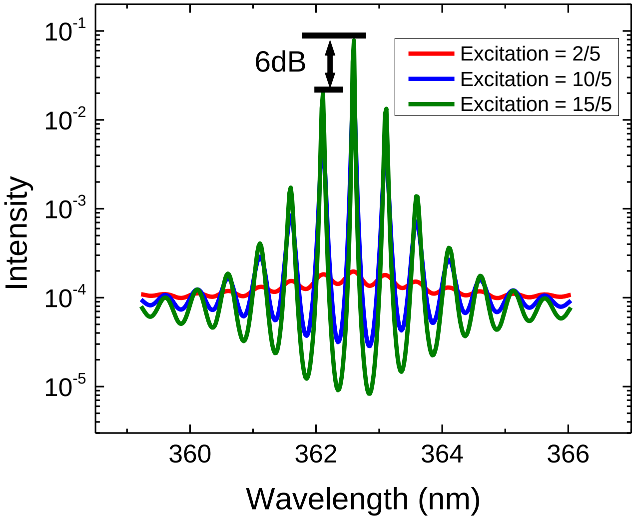
A.J. Fischer, Sandia

Single mode GaN nanowire laser

4 µm long, 140 nm dia. nanowire



12 µm long, 140 nm dia. wire



- Multimode laser theory calculations to determine which of the passive-cavity eigenmodes will be above lasing threshold for given experimental conditions.
- Modeling shows that by reducing the dimensionality of the wire we can reduce the number of competing modes, leading to single-mode lasing.

Sandia National Laboratories

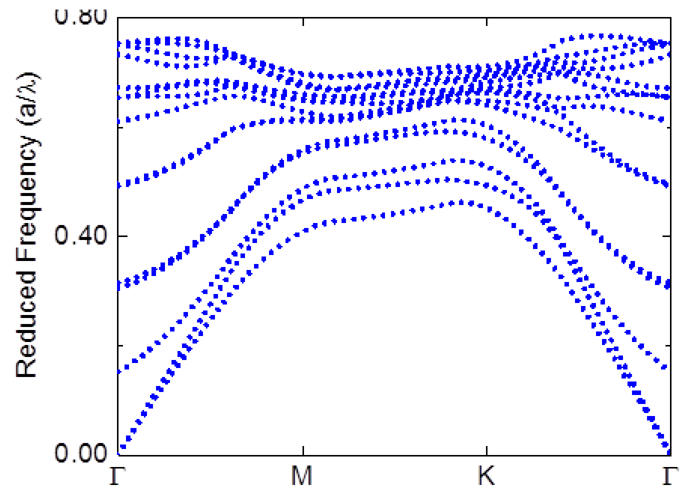
Outline

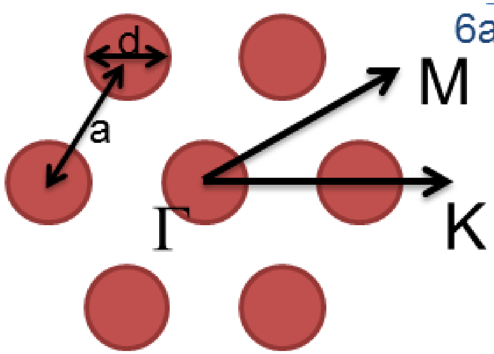
- Why III-nitride nanowires for solid-state lighting, PV, etc. ?
- Bottom-up nanowires
    - Growth, characterization, nanowire-templated film growth
- Top-down nanowires
    - Fabrication, axial and radial LEDs, solar cell, lasers
- Summary

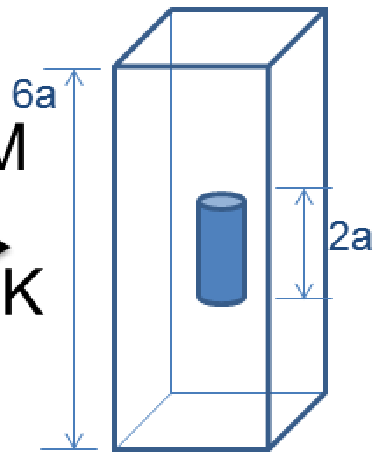
SSLS EFRC

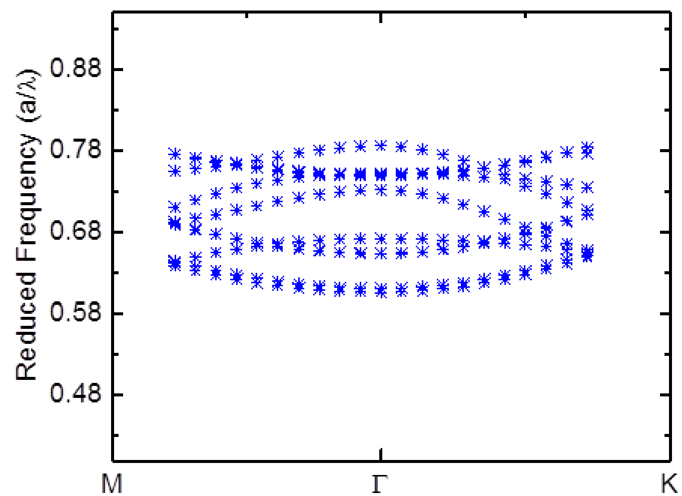
Design Rationale

- Higher order bands have low dispersion
- We desire low group velocity to enhance the light matter interaction and the formation of standing waves within the gain medium, to allow low lasing thersholds in materials that exhibit reduced gain over larger bandwith



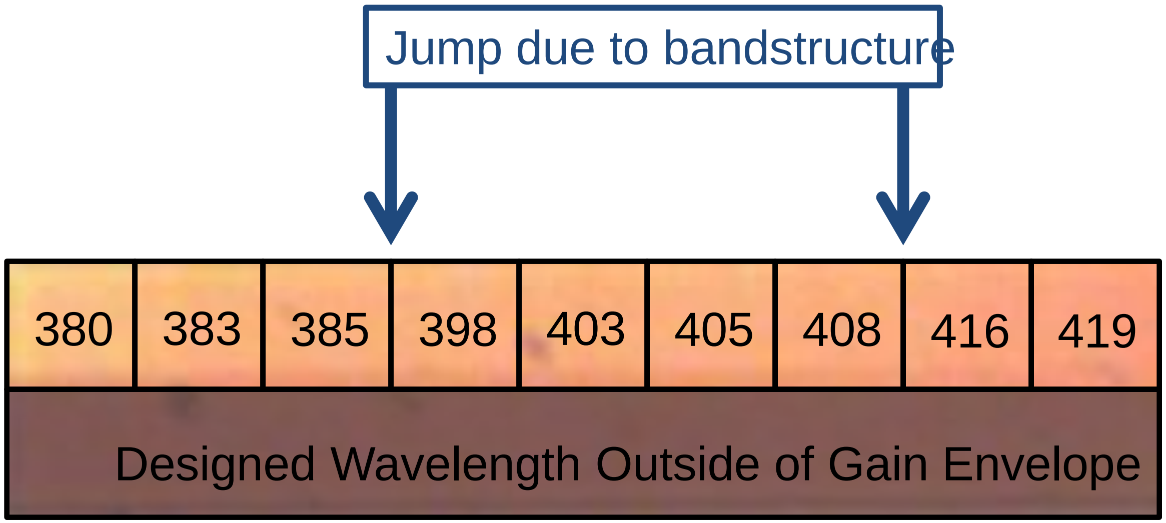






III-N Nanowire Photonic Crystal Lasers

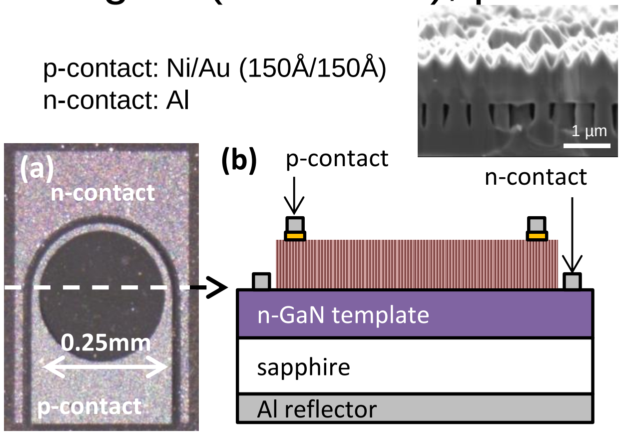
Continuously tuned photonic crystal stripe

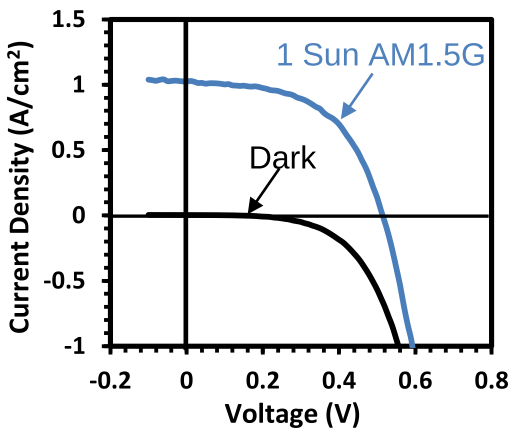


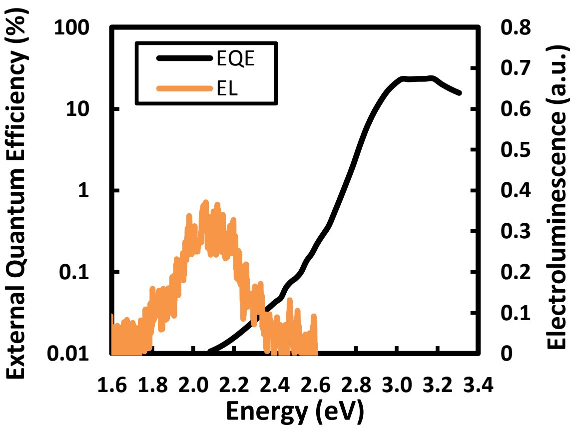
III-nitride nanowire arrayed solar cell

- <u>III-nitride solar cells</u>: InGaN bandgap (0.7-3.4 eV) covers solar spectrum; high rad. resistance
- <u>Nanowire solar cells</u>: increased light scattering/absorption, short carrier collection lengths (core-shell), potentially smaller bandgap cell (higher In content InGaN layers)

p-contact: Ni/Au (150Å/150Å)
n-contact: Al







J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

- *First vertically integrated III-nitride nanowire solar cell*

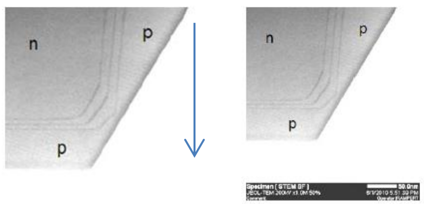
Previous Work: Single III-nitride NW solar cell:
Dong, Y. et al., *Nano Lett.* **9** 2183 (2009)

- Peak EQE ~23% at 3.0 eV; Photoresponse to 2.1 eV (590 nm), lowest bandgap reported for III-nitride solar cell; V_{OC} ~ 0.5 V; FF ~ 54%; Power conversion efficiency ~0.3% (shorting from defects in nanowire templates)

Radial c-axis GaN/InGaN nanowire LEDs

A. Waag (Braunschweig U. of Tech.)

S. Li & A. Wagg, *J. App. Phys.*, **111**, 071101 (2012)



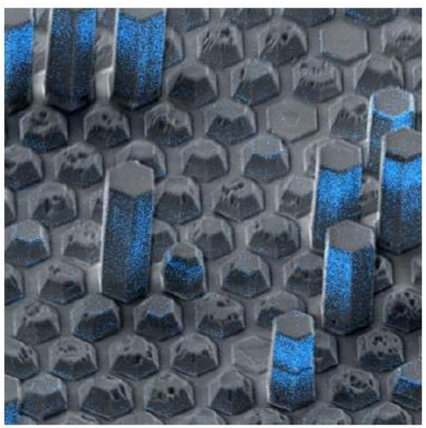
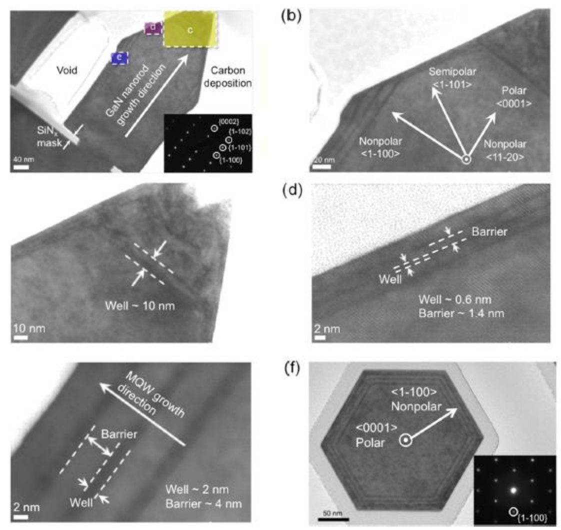


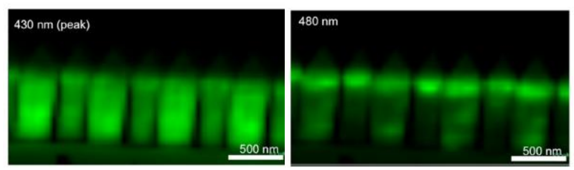
Figure 7 Cathodoluminescence from isolated NanoLEDs, indicating a core-shell geometry. The nanorods have N-face orientation. The peak wavelength of the quantum well emission is 400 nm.

- 400 nm sidwall emission
- semipolar region appears small

D. Dapkus (USC)

T. Yeh et al, *Nano Lett.* ***12****, 3257 (2012)*

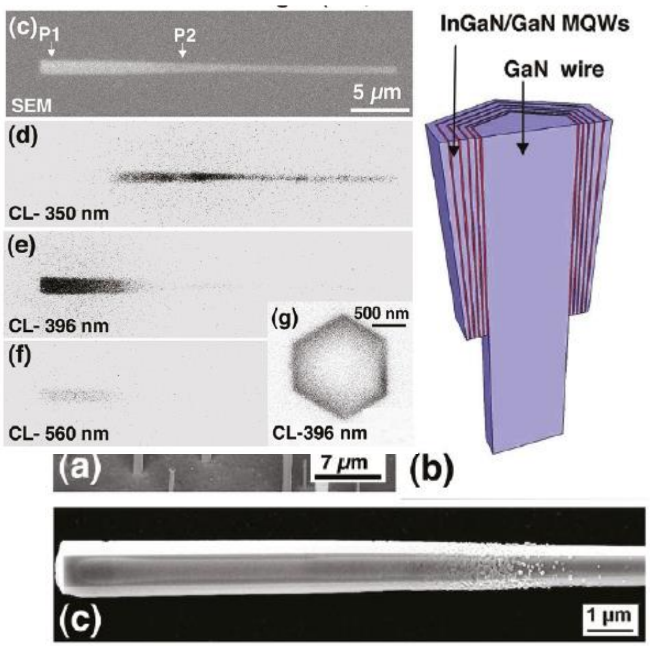


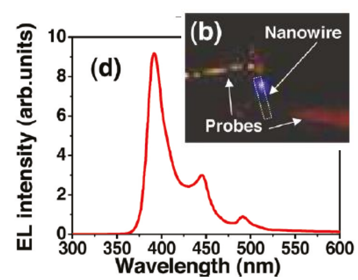


- grows c-plane to extinction before MQW growth (bottom CL images)
- 430 nm sidewall emission, 480 nm near semipolar/nonpolar, semipolar wells too thin for signal? no EDX

J. Eymery (CEA-CNRS-UJF, Grenoble, FR)

Koester et al., *Nano Lett.* ***11,*** *4839 (2011)*





- 396 nm CL & EL from sidewall (In~.16)
- 445 & 491 nm from “localized states & longitudinal QWs at top of wire” (c-plane?)

Radial c-axis GaN/InGaN nanowire LEDs

C. C. Yang (National Taiwan U.)

C.H. Liao et al., *Opt. Expr.* **20**, *15859 (2012)*

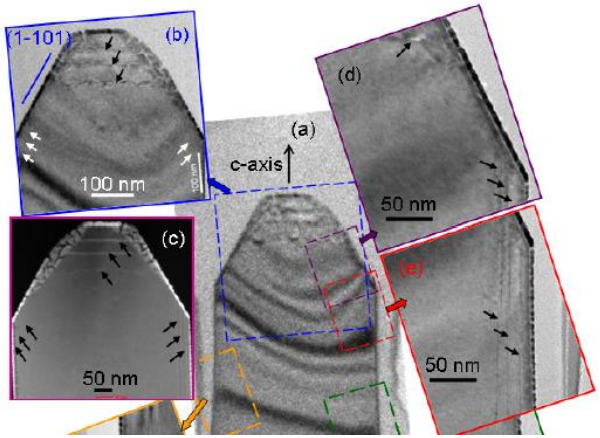


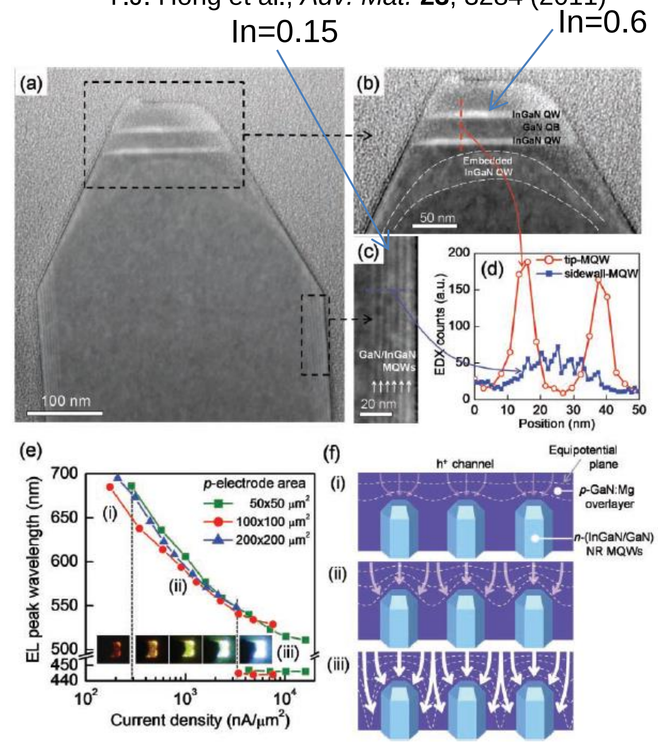
Table 2. Average QW Widths, Indium Contents, and Their Product Values of the QWs at Different Locations.

	QW width (nm)	Indium content (%)	Product (nm %)
Top-face QW	4.72	12.72	60.04
Sidewall QW near the top	1.28	21.19	27.12
Sidewall QW near the middle height	1.56	19.20	29.95
Sidewall QW near the bottom	2.00	16.39	32.78

- claims no semipolar {10-11} InGaN QWs
- m-plane QWs get thinner near top (opposite our structures)
- c-plane In ~ 0.13 (CL: 450 nm), m-plane ~ 0.16-0.21 (CL: 450 nm)
- m-plane emission wavelength is not higher than c-plane despite higher In % due to quantum confinement and zero QCSE

G.C. Yi (Seoul National University)

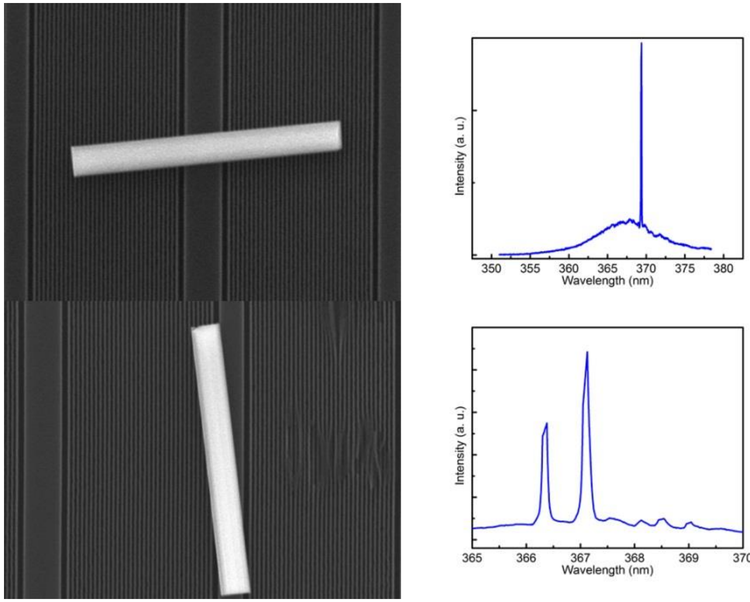
Y.J. Hong et al., *Adv. Mat.* **23**, 3284 (2011)



- Claims In ~ 0.60! for c-plane, 0.15 for m-planes
- EL from red to blue as V increases from 3-10 V
- “W/increasing applied bias V, the equipotential plane shapes change into a curved surface along the tips (panel (ii) in Figure 3 f), resulting in the gradual change of EL from red to cyan with a tail due to a buried long-wavelength EL ensemble.”

Mode control in GaN nanowire lasers

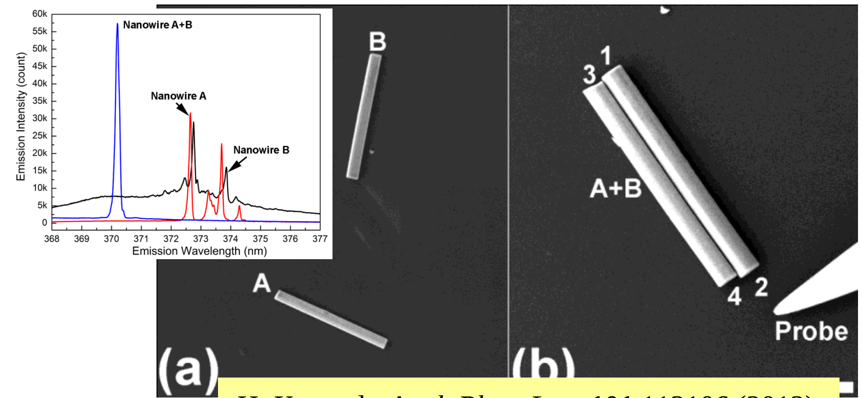
Distributed feedback grating coupling



J. B. Wright et al., in preparation

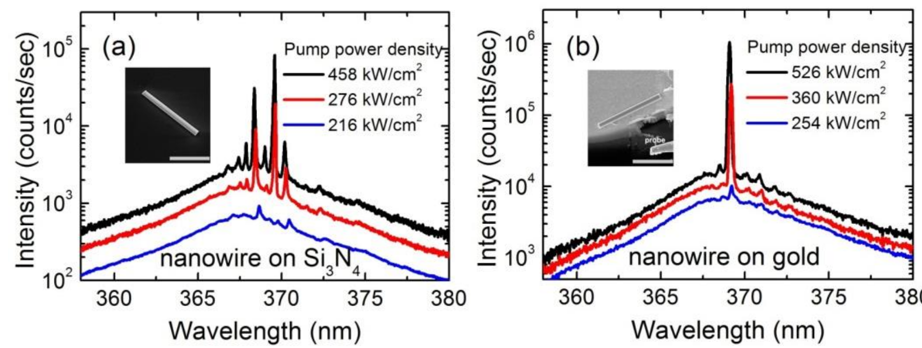
[8625-84] J. Wright et al., Wed. 6 Feb., poster

Coupled pair cavity



H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

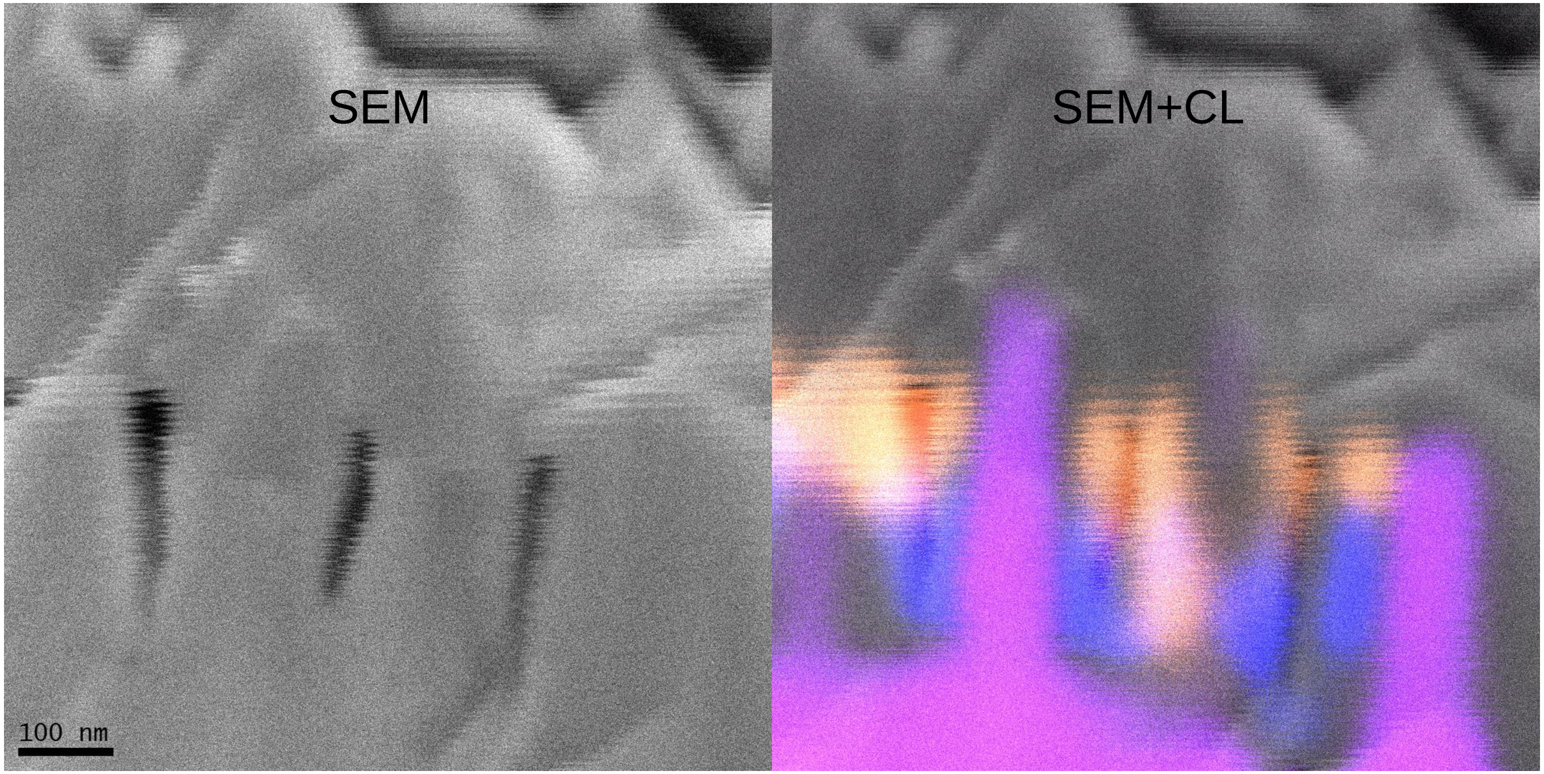
Metal substrate coupled



H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

[8625-27] H. Xu et al., Tues. 5 Feb., 3:15p

Cathodoluminescence of radial nanowire LED

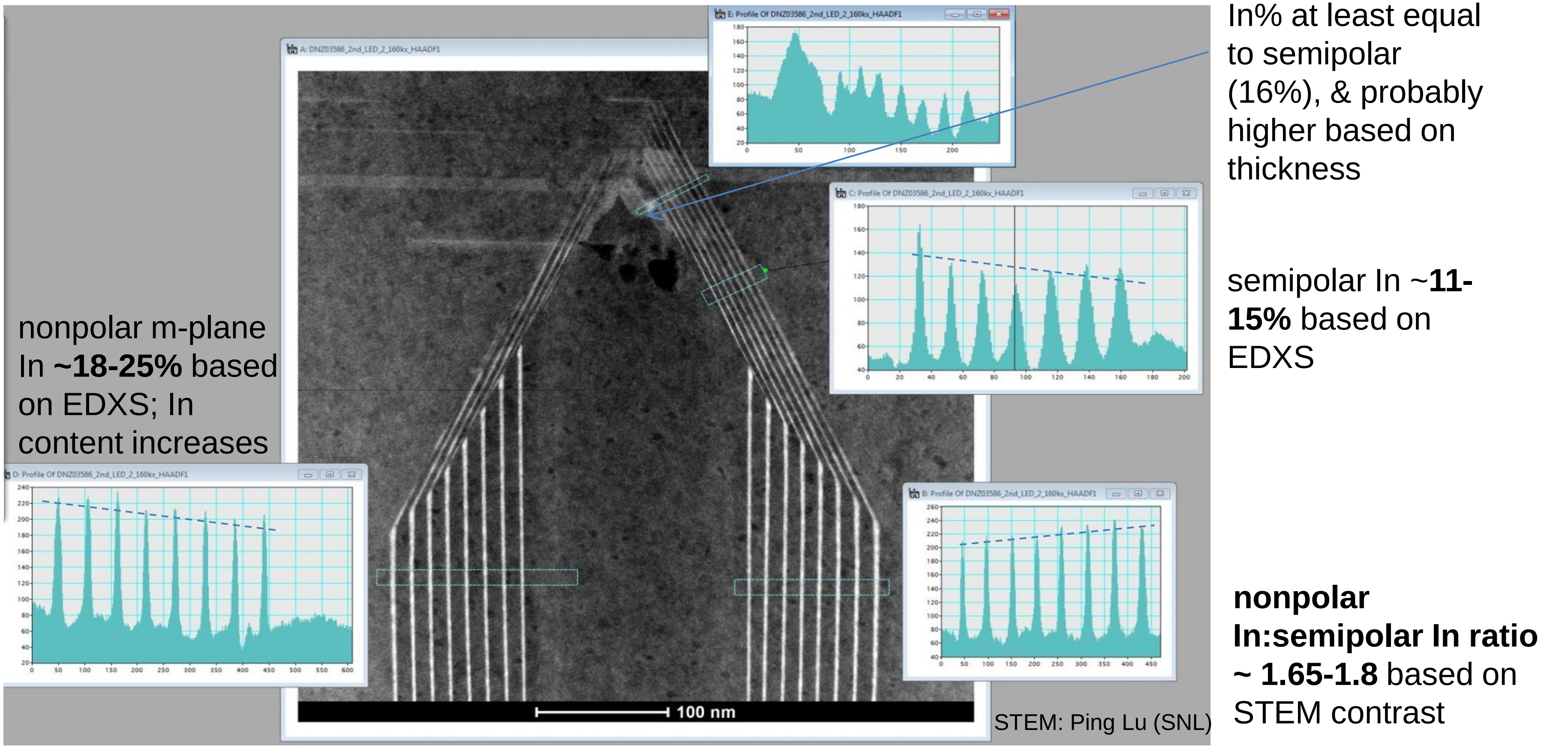


w/Jim Riley (Northwestern)

365 nm, 402 nm, 442 nm

- No significant emission from semipolar QWs observed
- Sidewall nonpolar QWs emit from ~410-440nm, increases towards tops

Further STEM/EDX Analysis of yellow-red nanowire LED



- Yellow-red EL may come from In rich clusters at nanowire tip
- Atom probe tomography experiments underway for 3D composition analysis (L. Lauhon, Northwestern)