

# III-nitride nanowires for future optoelectronics

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# Lighting: large fraction of energy use and low efficiency



Earth at Night  
NASA

## Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	<b>~17%</b>
Incandescent:	<b>~4%</b>

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%**

# A Progression of Productive Uses for Colored and White Solid-State (LED) Lighting

Center high-mount stop light (CHMSL).  
<http://www.honda-tech.com/showthread.php?t=2413558>



NASDAQ's Giant Video Display in Times Square, New York (Jeff Tsao)



Sharp QuadPixel RGBY LED-backlit LCD Display.  
[http://www.macworld.com/article/145541/2010/01/sharp\\_quadpixel.html](http://www.macworld.com/article/145541/2010/01/sharp_quadpixel.html)



SMART

COLORED



WHITE

Surefire U2 flashlight.  
<http://en.wikipedia.org/wiki/File:SurefireU2JPG.jpg>



Nokia camera phone with LED flash.  
<http://www.itechnews.net/wp-content/uploads/2009/07/Nokia-3720-Classic-the-most-rugged-mobile-phone.jpg>



2011 Philips L-prize 60W equivalent  
10W LED light bulb replacement  
<http://www.lightingprize.org/phillips-winner.stm>



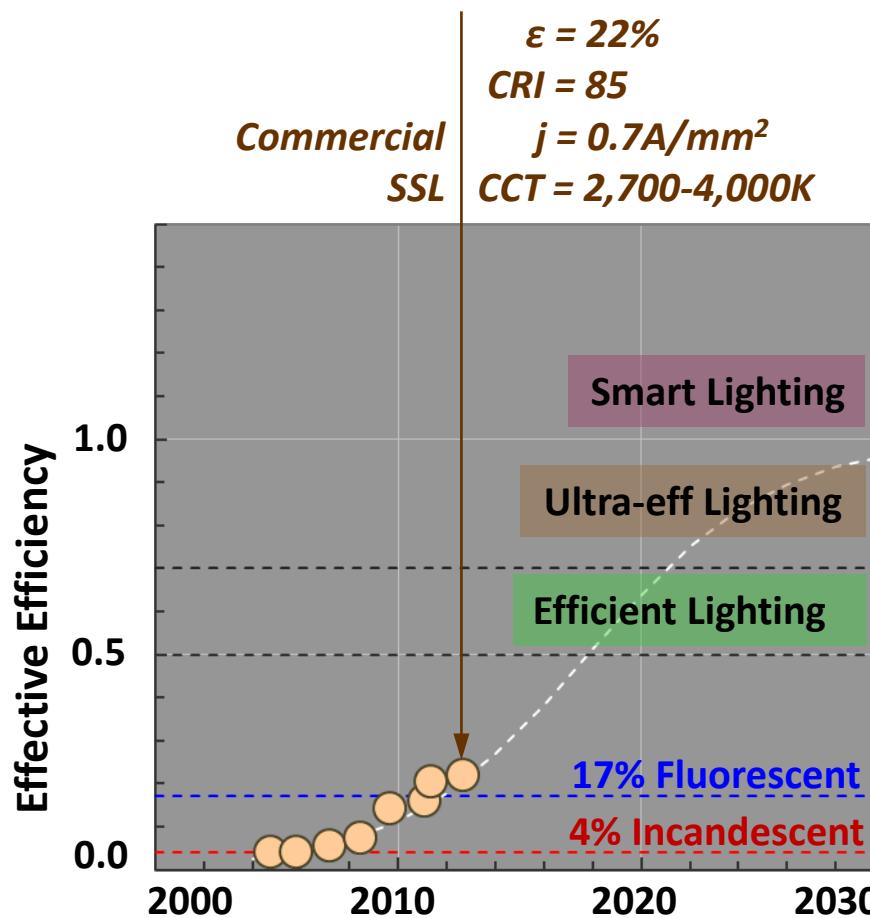
Philips HUE Connect Bulb  
<http://store.apple.com>



<http://uncrate.com/stuff/philips-hue/>

after M.E. Coltrin, Sandia

# Efficiency, Ultra-efficiency, and Beyond



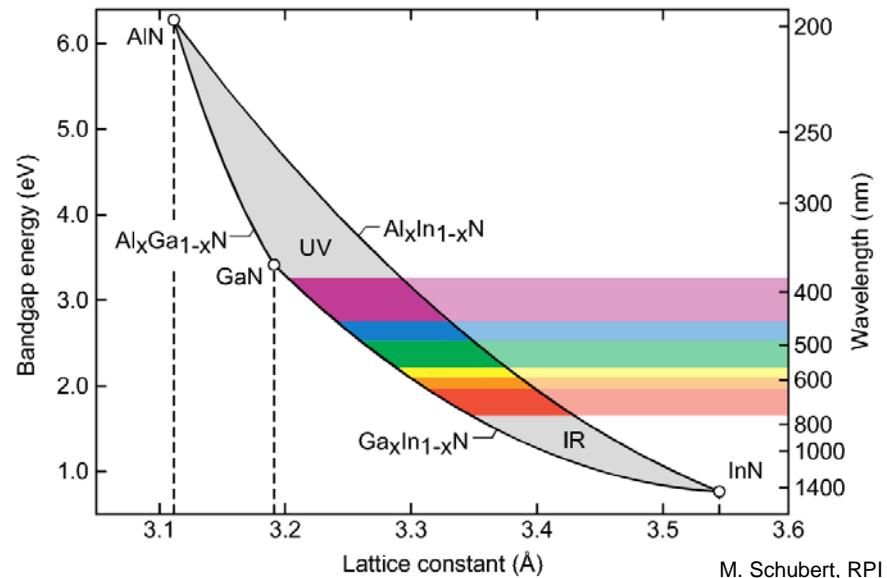
**“Ultra-efficient” SSL: > 70%**

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

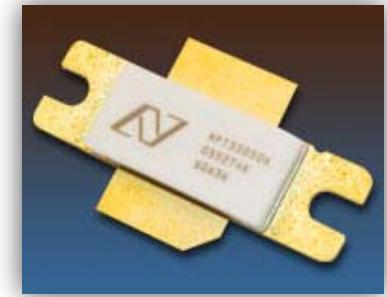
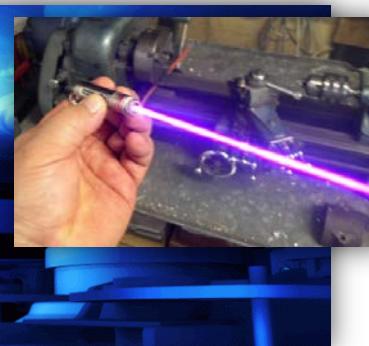
**Requires fundamentally new architectures and understanding, *enabled by basic research***

# Foundation of SSL: III-Nitride (AlGaN) Semiconductors

- Direct RT bandgaps: ~0.7-6.2 ev
- Solid alloy system (tunable bandgaps)
- High breakdown field, mobility, thermal conductivity, melting temperature
- Radiation resistant and chemically inert
- InGaN covers entire visible & bulk of solar spectrum (PV material?)
- *Used in LEDs, blue laser diodes, high power transistors, HEMTs*

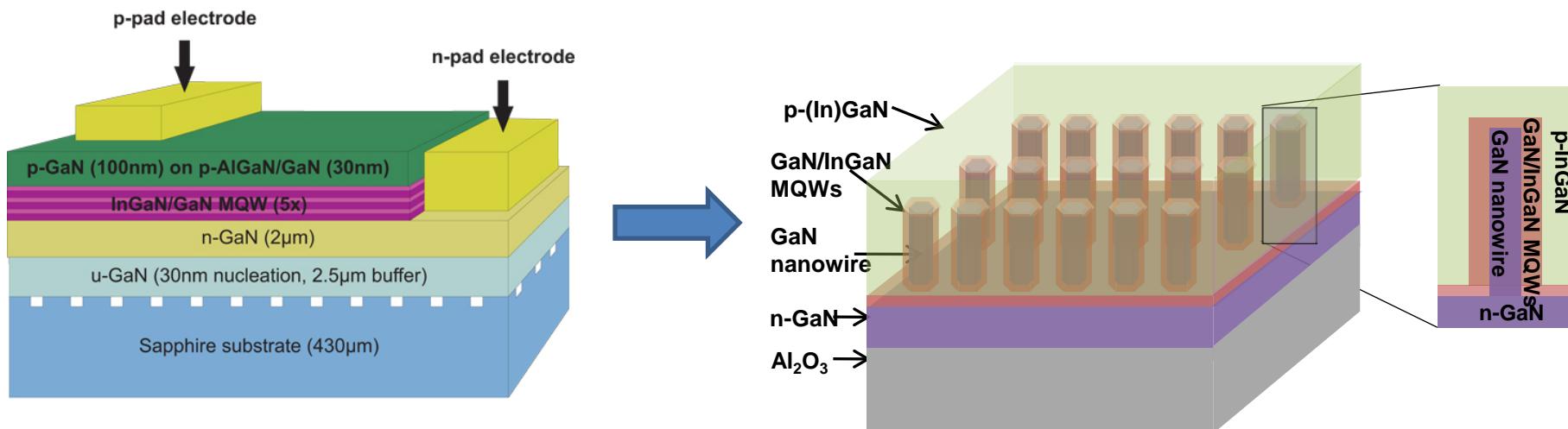


M. Schubert, RPI



Nitronex GaN power transistor

# Why III-nitride (AlGaN) nanowires for SSL?



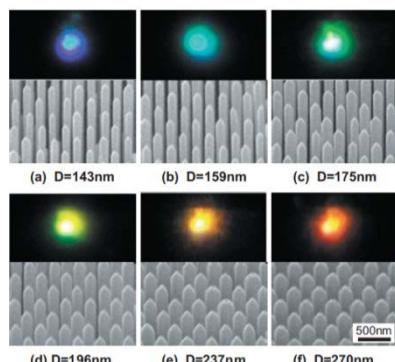
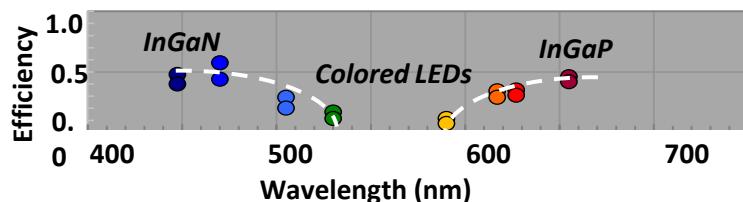
Y.S. Lin and J. A. Yeh, Appl. Phys. Express, vol4, p092103, 2011

# Why III-nitride nanowires for SSL?

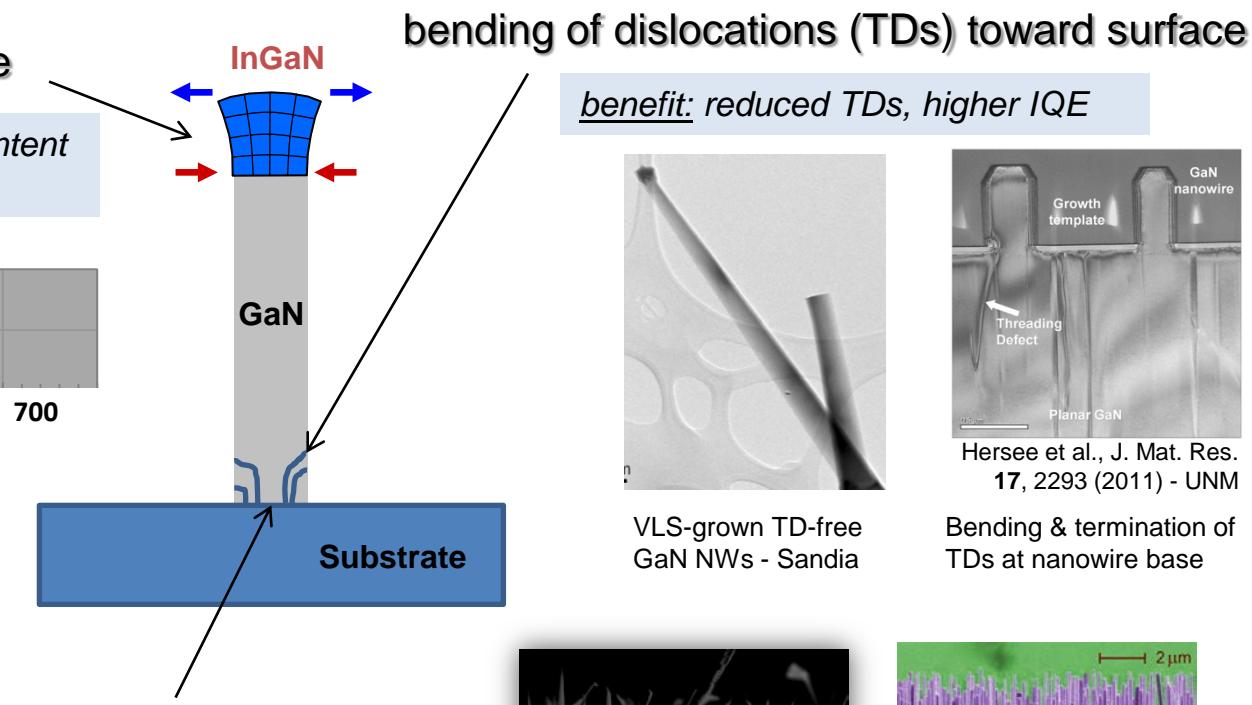
## Advantages due to enhanced strain accommodation in nanowires

### elastic strain relaxation at surface

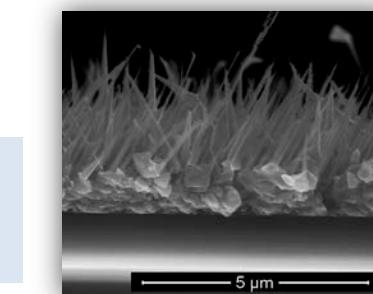
benefit: heterostructures with high In content  
(e.g. green-yellow-red gap)



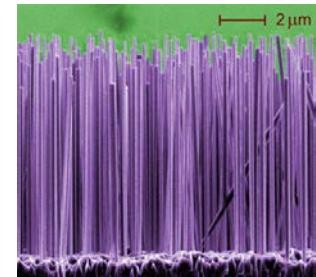
Sekiguchi et al., APL **96**, 231104 (2010) – Sophia U.



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



GaN NWs on tungsten foil - Sandia

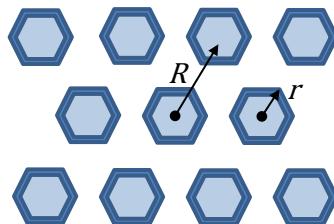


GaN NWs on Si - NIST

# Why III-nitride nanowires for SSL?

## vertical device integration

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

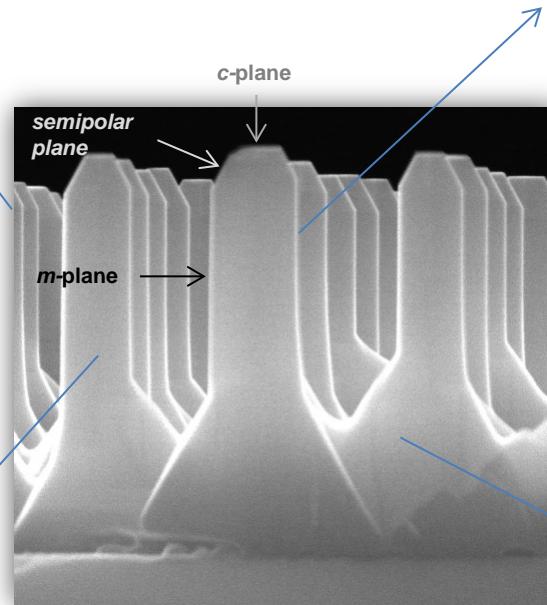
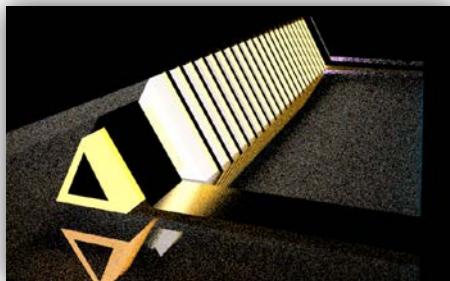


$$\frac{A_{\text{sidewall}}}{A_{\text{substrate}}} = \frac{6rh}{2.6R^2} \approx 4.6F \cdot AR$$

example:  $4.6 \cdot 0.5 \cdot 3 = 6.9 \times \text{increase!}$

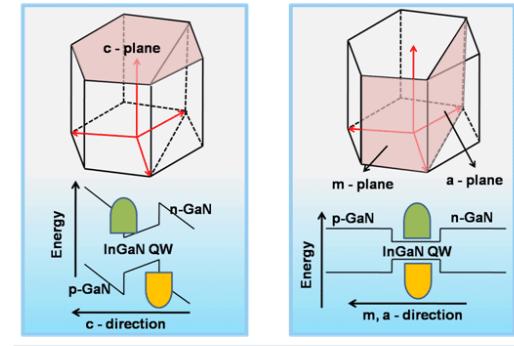
## nanolasers

benefit: ultracompact, low power coherent light source



## access to nonpolar & semipolar planes

benefit: higher IQE, reduced wavelength shift

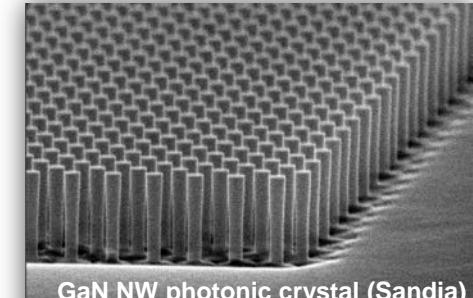


Non-polar direction GaN thin film growth → higher quantum efficiency

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

## 2D arrangements (photonic crystals)

benefit: higher light extraction, IQE, wavelength tuning

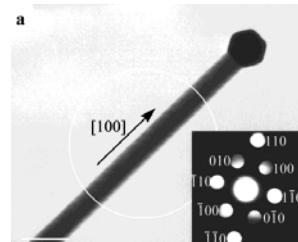
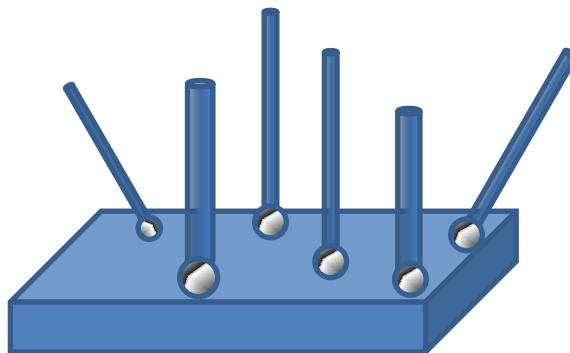


12/2/2011 11:40:35 AM WD 17.2 mm mag 49,969 x HV 30.00 kV tilt 38° HFW 3.04 μm 1 μm Quanta FEG

EFRC

# Bottom-up growth of GaN-based nanowires

## Metal catalyzed (vapor-liquid-solid)

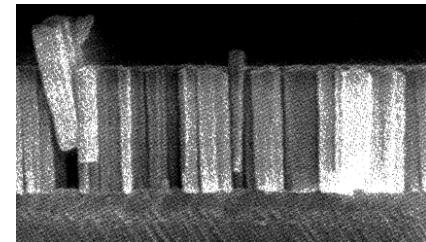
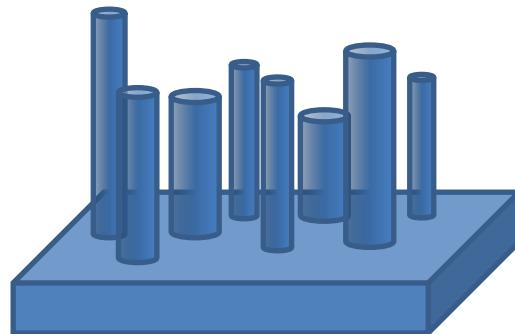


C. Lieber, 2000



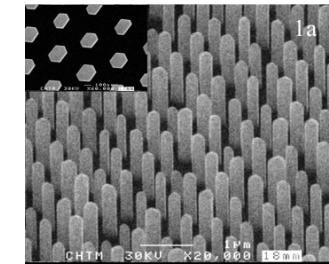
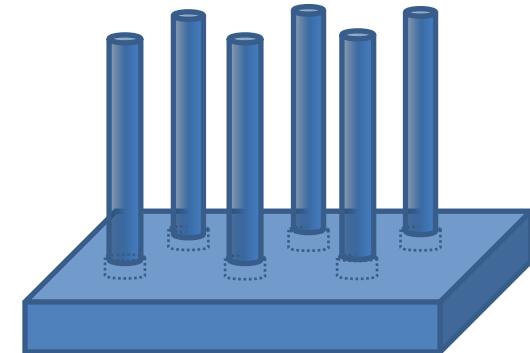
C.C. Chen, 2001

## “Self-catalyzed”



K. Kishino, 1997

## Selective area growth (SAG)



S. Hersee, 2006

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

Cons include slow growth rates and random ordering

## Methods: PLD, thermal evaporation, (MO)CVD

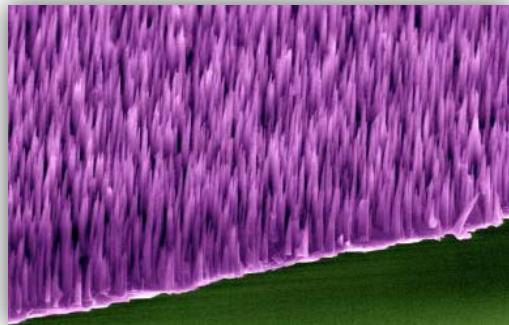
Historically popular (ease & low cost of entry), but falling out of favor due to limitations

## Methods: (PA)MBE, MOCVD

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

# Previous SNL research: bottom-up III-nitride nanowires

## Vertically-aligned growth



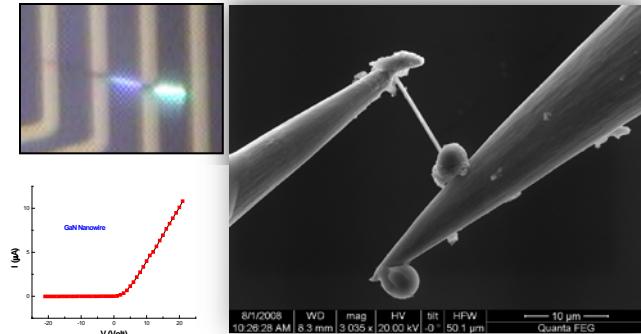
G. T. Wang et al., *Nanotechnology* **17** 5773-5780 (2006)  
 Q. Li, G. T. Wang, *Appl. Phys. Lett.* **93**, 043119 (2008)  
 Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth* **310** 3706-3709 (2008)

## Nanowire-templated growth



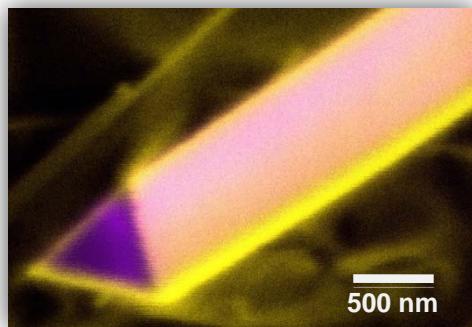
Q. Li, Y. Lin, J.R. Creighton, J. Figiel, G.T. Wang, *Adv. Mat.*, **21** 2416–2420 (2009)

## Electrical characterization

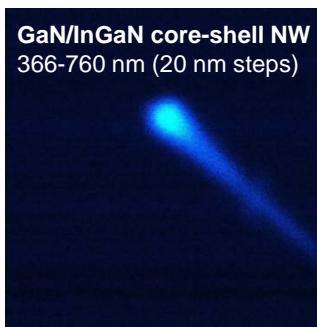


A. A. Talin, G. T. Wang, E. Lai, R. J. Anderson, *Appl. Phys. Lett.* **92** 093105 (2008)  
 Y. Lin, Q. Li, A. Armstrong, and G. T. Wang, *Solid State Commun.*, **149**, 1608 (2009)

## 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. Uppadhyaya 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]

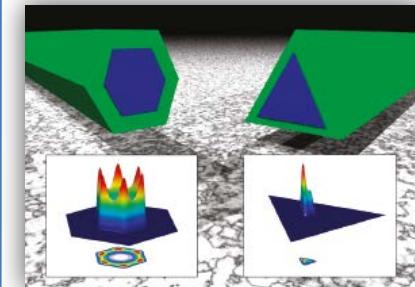


## In-situ TEM



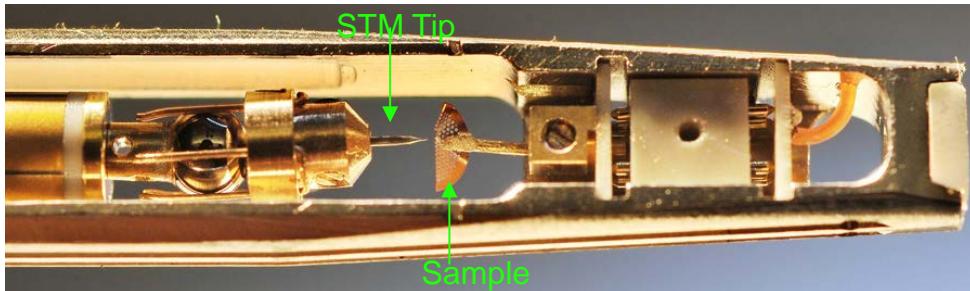
T. Westover et al., *Nano Lett.*, **9**, 257 (2009). [in-situ NW breakdown]  
 J. Y. Huang et al., *Nano Lett.*, **11** (4), 1618 (2011). [in-situ nanomechanics]

## Theory

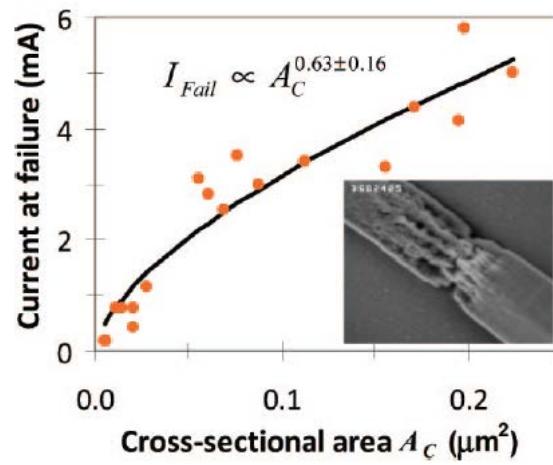
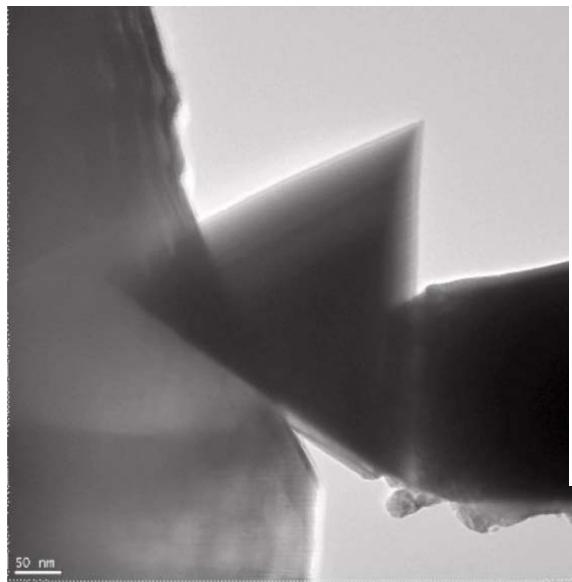
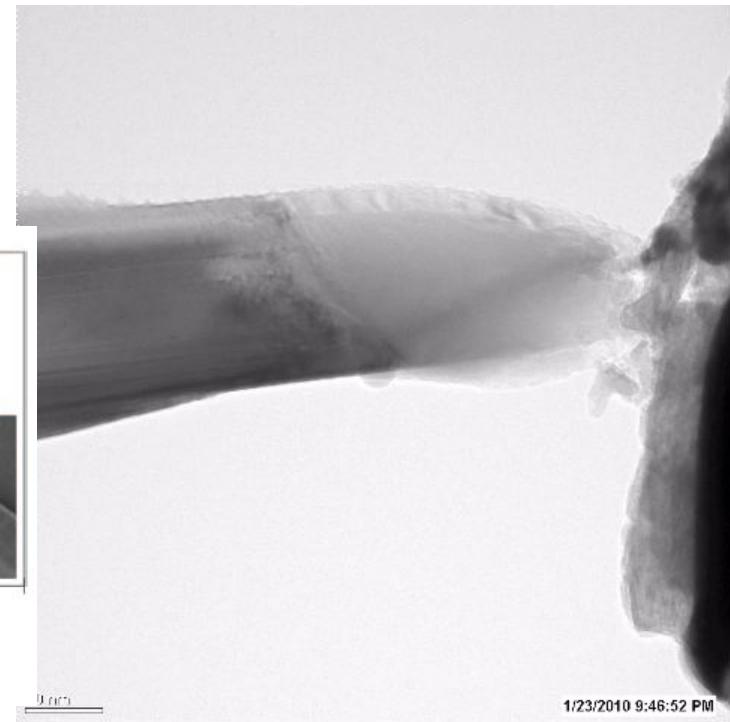


B. Wong et al., *Nano Lett.* **11** (8), 3074, 2011

# In-situ TEM studies – nanowire electrical breakdown



NW decomposition via Joule heating  
(relevant for NW devices)



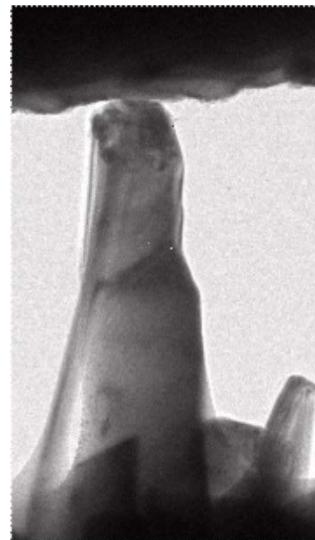
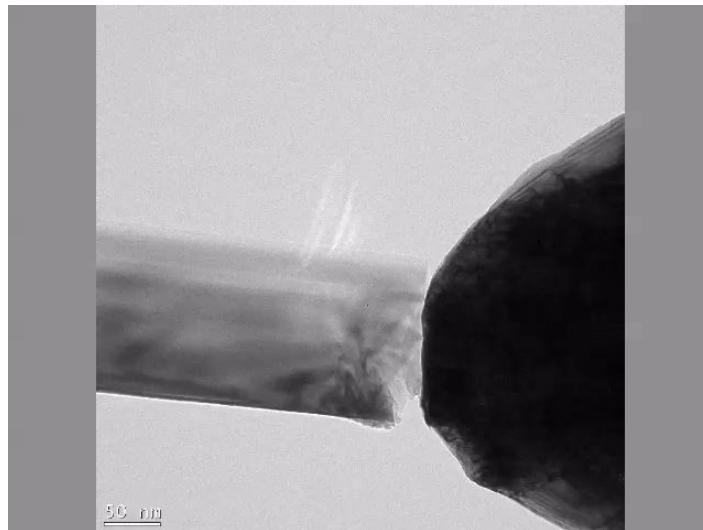
NW breakdown at 60V, 20  $\mu\text{A}$   
(avg. breakdown I  $\sim$ 3000 kW/cm $^2$ )

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

PI: J. Huang



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



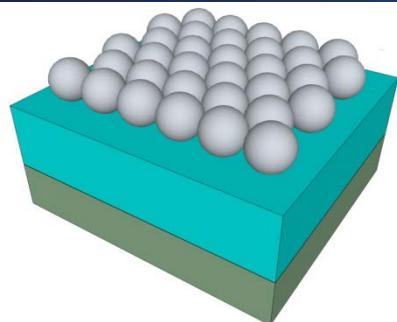
- Dislocation-free NW shows significant surface plastic deformation
- Mediated by dislocation nucleation & pile up, grain boundary sliding
- Plastic deformation often observed before fracture
- Plasticity is local, not global

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

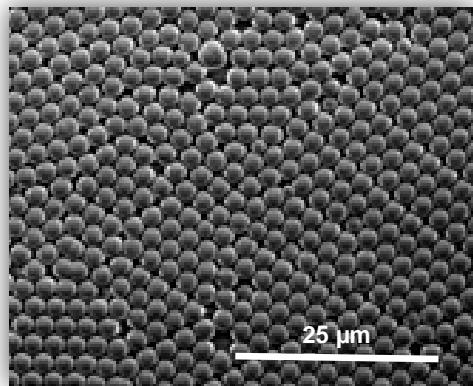
J. Y. Huang, H. Zheng, S. X. Mao, Q. Li, and G. T. Wang, *Nano Lett.*, **11** (4), 1618 (2011).

PI: J. Huang

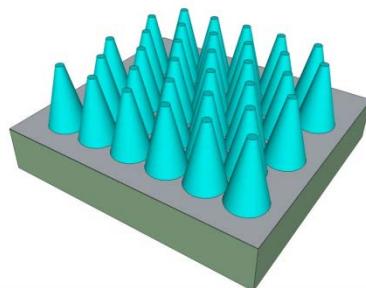
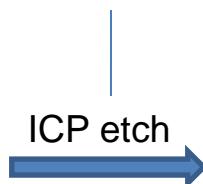
# New dry + wet top-down ordered nanowire fabrication process



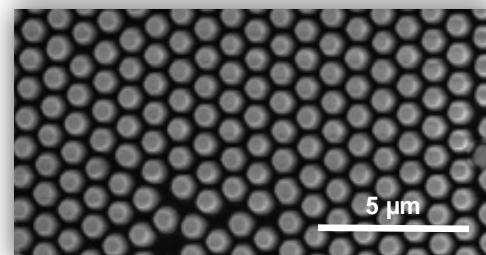
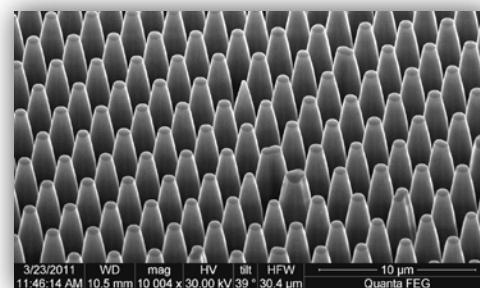
(0001) GaN on sapphire



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

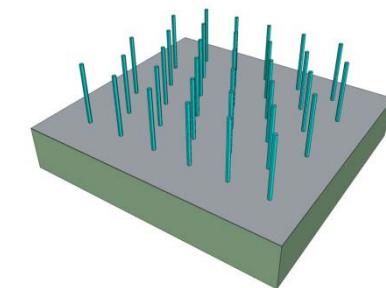
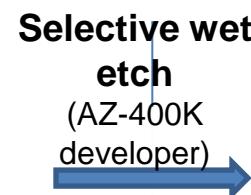


ICP etch

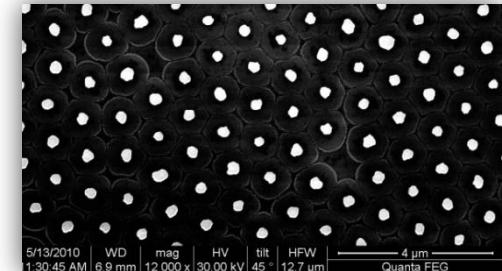
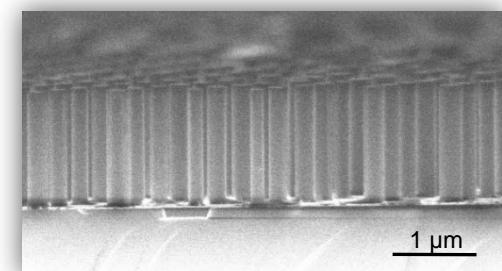


Plasma etch causes sidewall damage  
C. Y. Wang et al., Opt. Expr. 16, 10549–10556, 2008.

Tapered; no well-defined facets



Selective wet etch  
(AZ-400K developer)



Wet etch: straight sidewalls, removes sidewall damage

# Straight GaN nanowires with controllable geometries

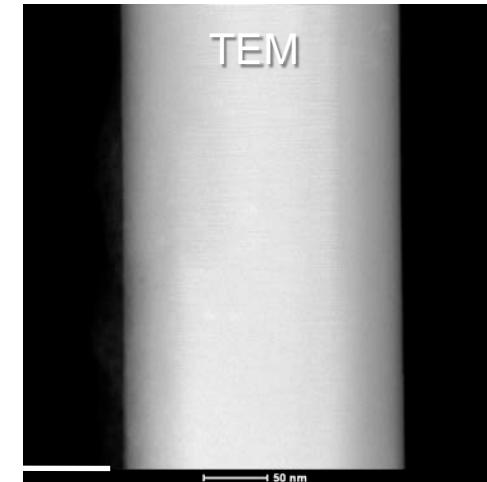
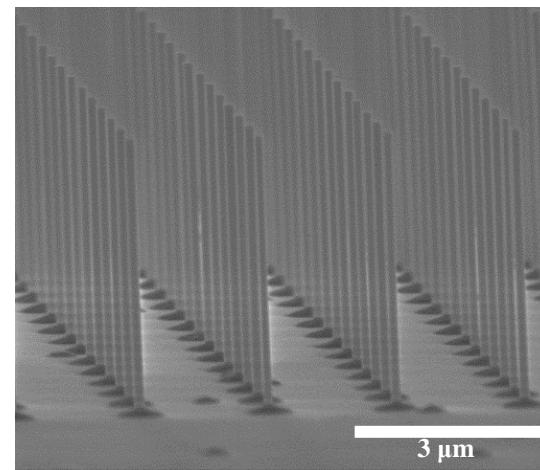
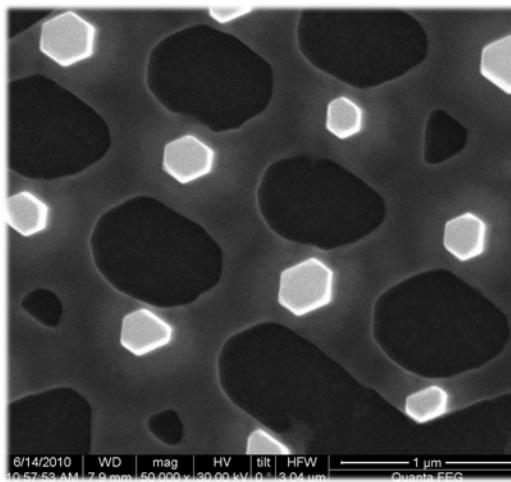
Wet etch rate negligible for top (Ga-polar) c-face & fast for [10-10], leads to nominally hexagonal NWs with **straight & smooth** *m*-facets

Superior and independent control of:

**Height (dry etch depth)**

**Diameter (wet etch time)**

**Pitch/arrangement (defined by masking template)**

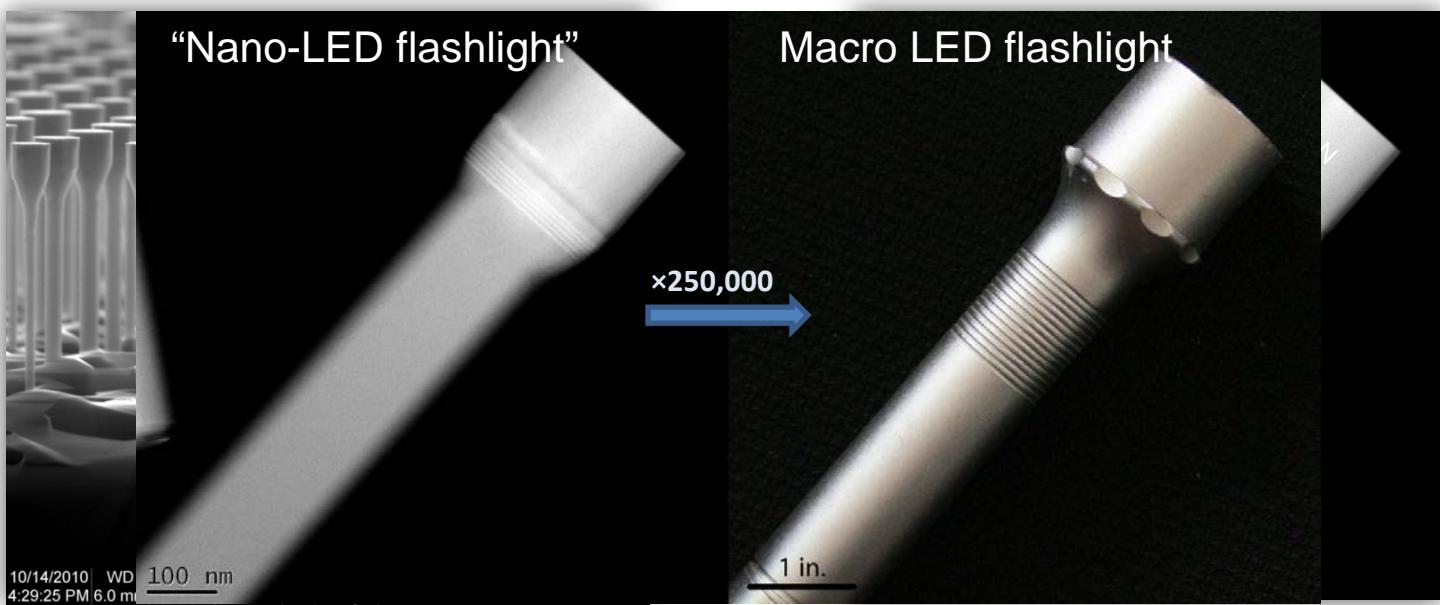
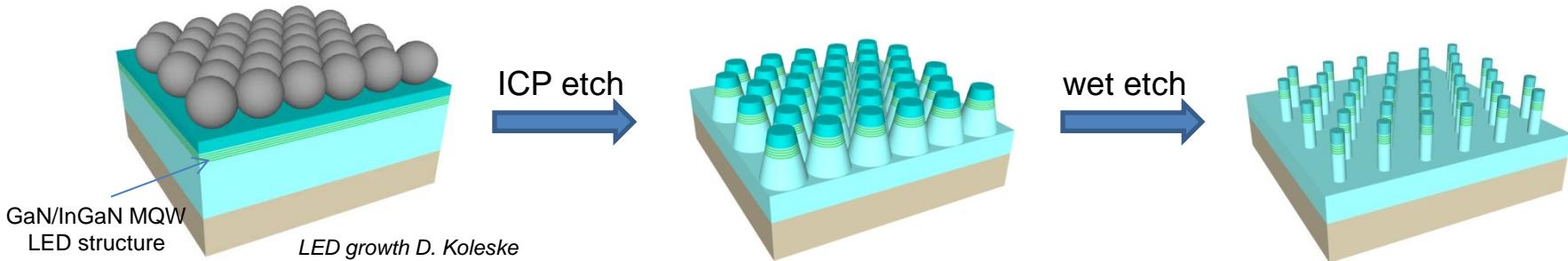


Smooth sidewall created by wet etch

TEM: Ping Lu, SNL

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

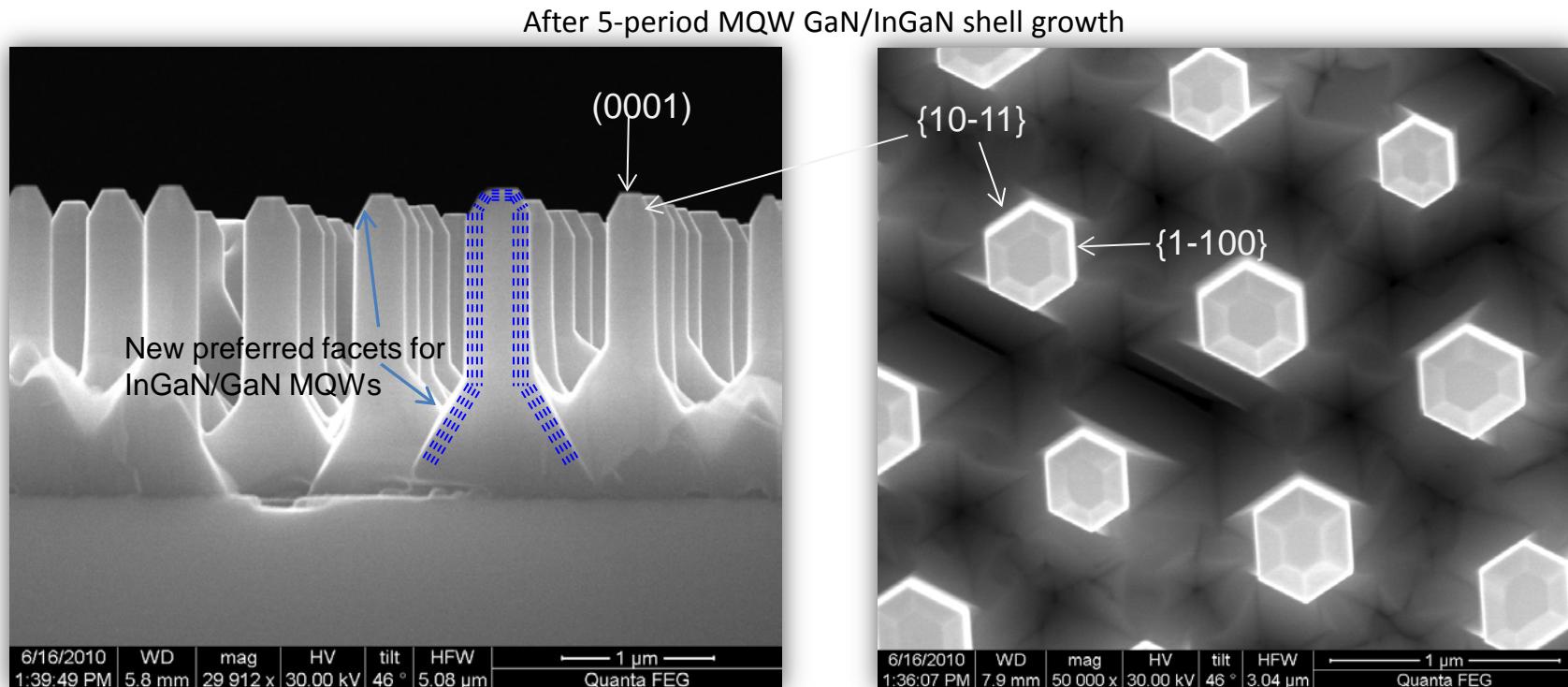
# Axial GaN/InGaN nanowire LEDs



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

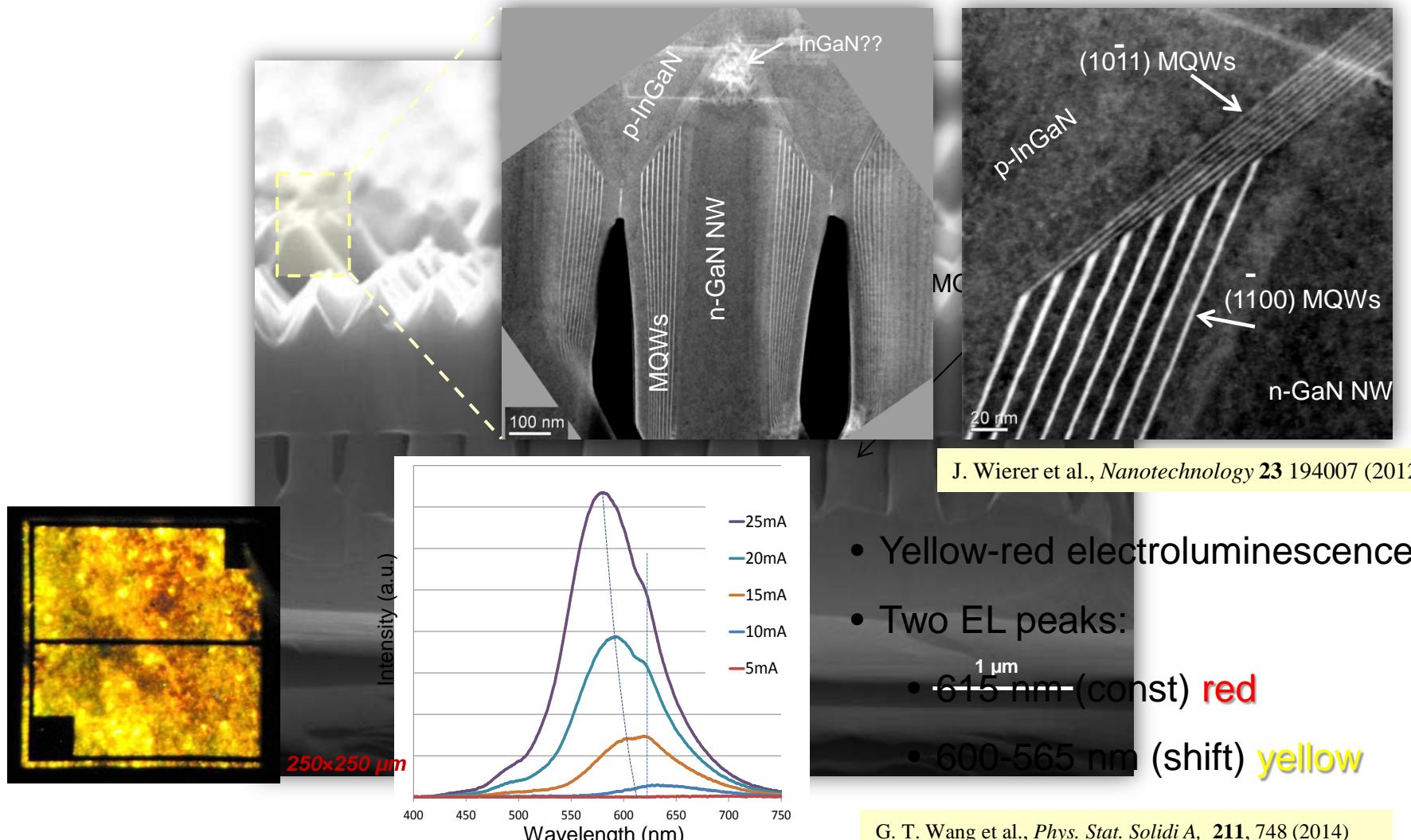
Radial core-shell NW LEDs:

- 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)



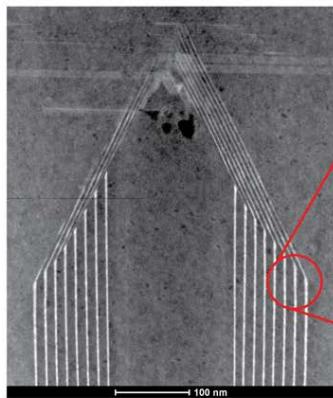
New semipolar facets form with InGaN/GaN MQW growth

# Electrically injected core-shell nanowire based “3D” LED emitting at yellow-red wavelengths

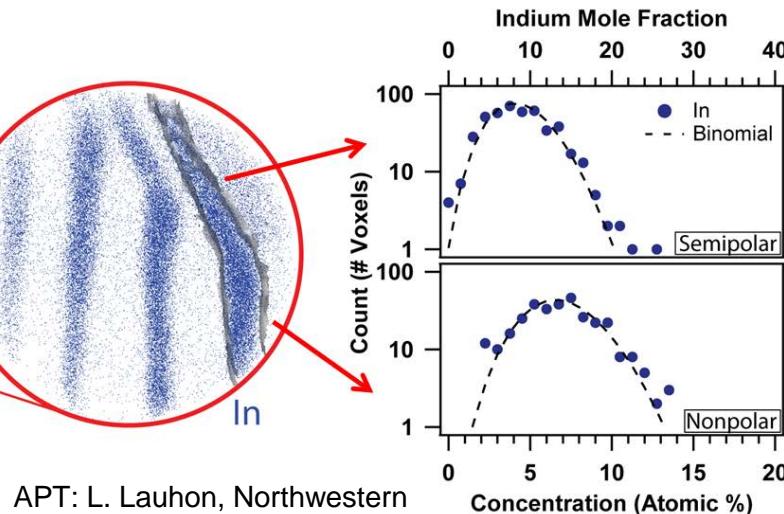


# 3-D Mapping of Quantum Wells in a GaN-InGaN Core-Shell Nanowire – a Correlated Study

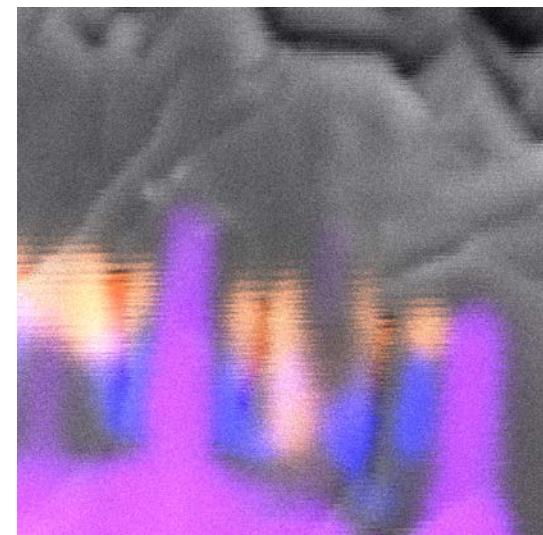
STEM-EDS



Atom probe tomography (APT)



Cathodoluminescence



365 nm, 402 nm, 442 nm

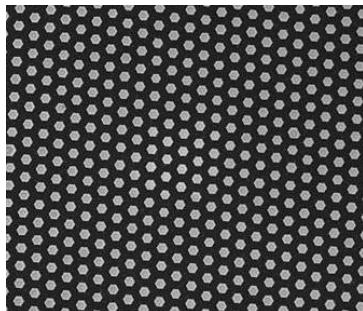
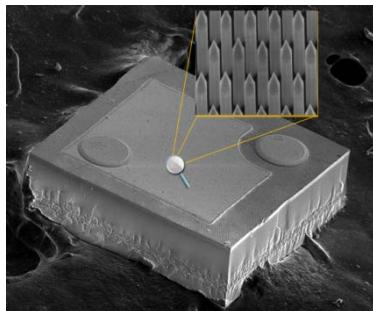
Riley, J.; Padalkar, S.; Li, Q.; Lu, P.; Koleske, D. D.; Wierer, J. J.; Wang, G. T.; Lauhon, L. J., *Nano Lett.* **14**, 4317 (2013).

- 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
- How to get long wavelength emission from m-plane sidewalls?

# Nanowire LED Commercialization/Industry Efforts



- Spun out of Lund University, Sweden
- Engineering Center in Sunnyvale, CA



[www.glo.se](http://www.glo.se)

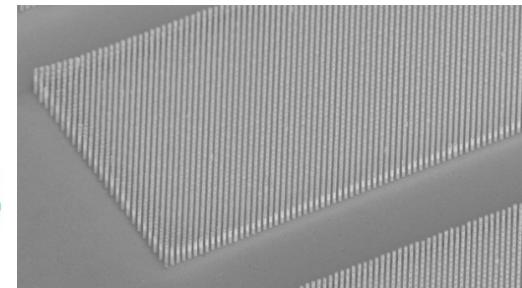
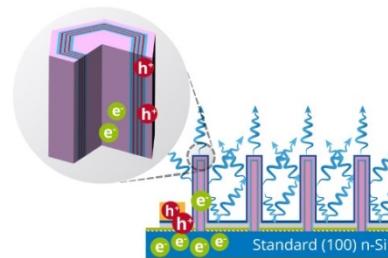
Bottom-up grown nanowires with *m*-plane MQWs

From ICNS-10 (Aug 2013):

- Claims ~80% QW IQE (via LT PL)
- Estimated 80% light extraction eff. Based on FDTD models, device data
- EL: 459 nm (1 mA), 452 nm (20 mA)
- Showed green, amber, red NW LED images (no performance data)

**Aledia SA**

- Spun out of CEA-LETI (Grenoble, France)



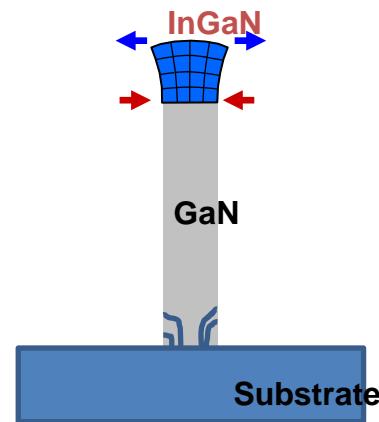
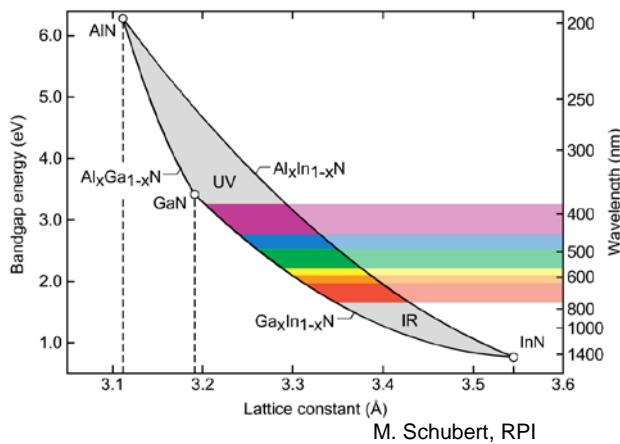
[http://www.eetimes.com/document.asp?doc\\_id=1280676](http://www.eetimes.com/document.asp?doc_id=1280676)

- goal is to manufacture 3D micro/nanowire-based LEDs for on thin silicon wafers  $\geq$  8 inches in diameter
- developed over a six-year period at the LETI research institute in Grenoble and the claim is production cost will be one quarter that of conventional planar LEDs.
- Announced 200-mm diameter wafers and raised \$13 million in a first round of venture capital finance (Mar '13)
- Claims three times more light per square millimeter of planar area
- Claims red, green WireLEDs possible and enable phosphor-free LEDs.
- Purchased Veeco's TurboDisc K465i MOCVD reactors

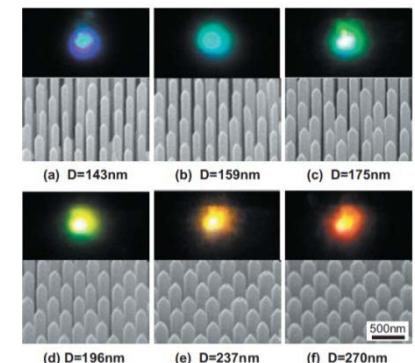


# Nanowire Lasers

- Nanowire forms a freestanding, low loss optical cavity
- Optically pumped nanowire lasers: ZnO, CdS, GaAs, GaSb, GaP, GaN, etc.
- Most commonly Fabry-Perot type lasing from end facets
- Compact and low power due to small mode volume
- Strain accommodation in GaN nanowires opens up possibility of high efficiency lasers over a wide spectral range (incl. green and yellow) through facile In incorporation



Multi-color [spontaneous] emission



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

See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7**, 074599-1 (2013)

# Why Nanowire Lasers?

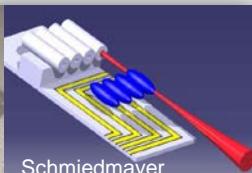
Integrated coherent nanophotonic elements for communications, sensing, imaging, lithography, lighting, etc.

Integrated nanophotonics, atom trapping, optical MEMS

atom trap



P. Schwindt (1725)



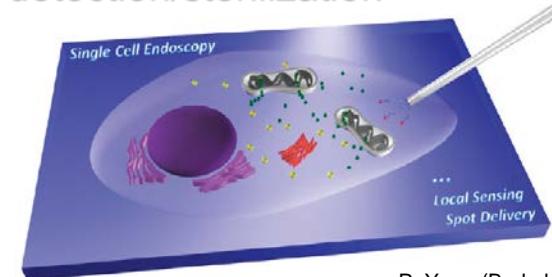
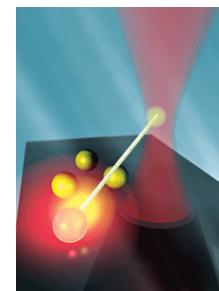
Schmiedmayer



J. Ford, Lucent

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

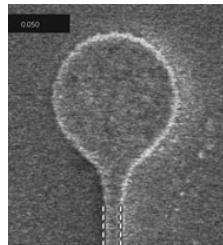
Optical nanoprobes & chem/bio detection/sterilization



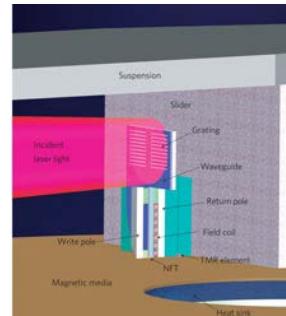
P. Yang (Berkeley)

Sub- $\lambda$  resolution probes for localized excitation, detection

Nanolithography & Heat-assisted Magnetic Recording



Nature Photonics 3, 220 (2009)



Subwavelength & efficient laser spot

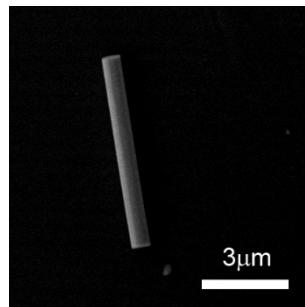
Lighting, projection, & holographic displays



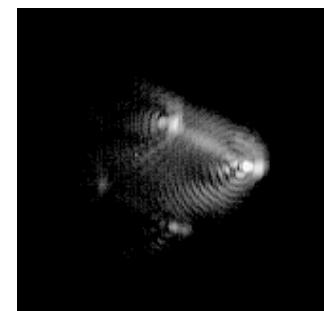
Sony Crystal LED Display prototype  
Low-power, speckle-free low coherence (random laser), multicolor pixels



# Typical GaN Nanowire Lasing: Multimode Operation



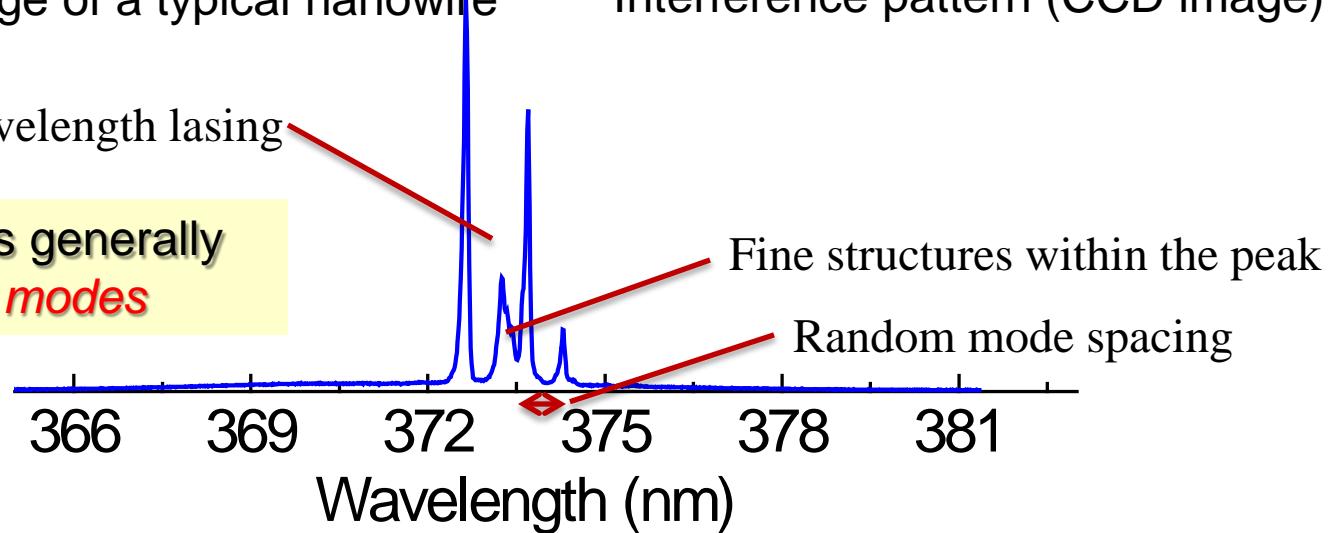
SEM image of a typical nanowire



Interference pattern (CCD image)

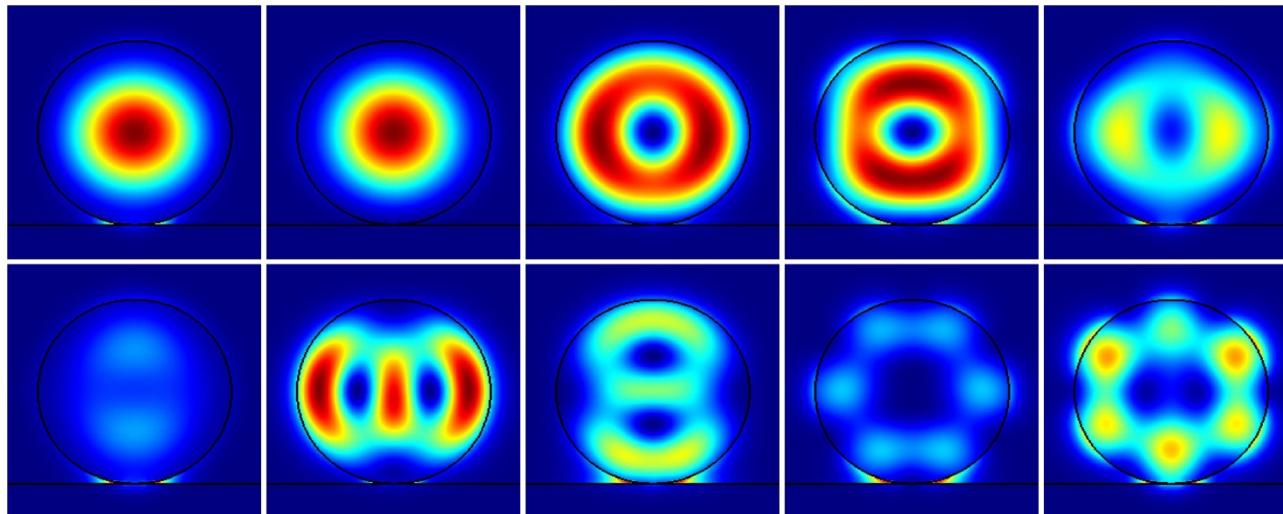
Multi-wavelength lasing

Nanowire lasers generally exhibit *multiple modes*



- *Single mode* behavior desired for highest **resolution** and **beam quality**; may also reduce **lasing threshold** due to reduced mode competition

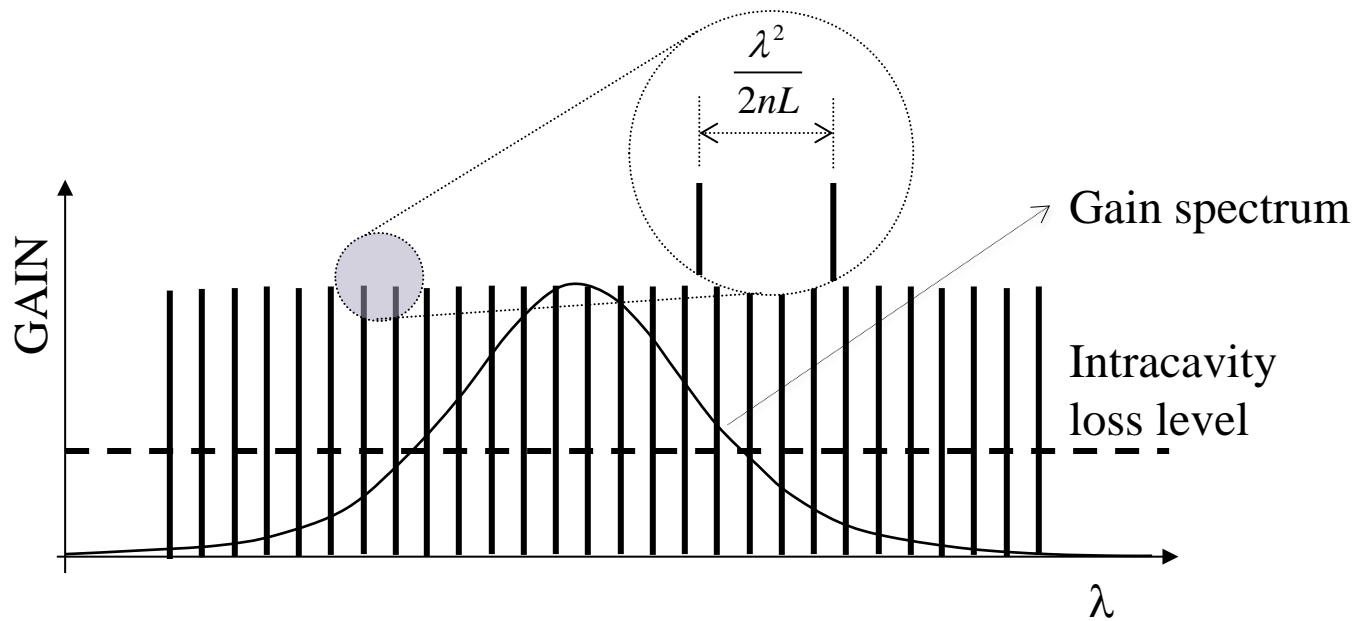
# Why Multimode Lasing Occurs



Calculated transverse modes supported by a 300 nm diameter GaN nanowire.

- ✓ Multiple transverse mode waveguide;
- ✓ Single-mode cutoff diameter  $\sim 120$  nm;
- ✓ Lasing in multiple transverse mode operation
- ✓ Polarization is mode-dependent

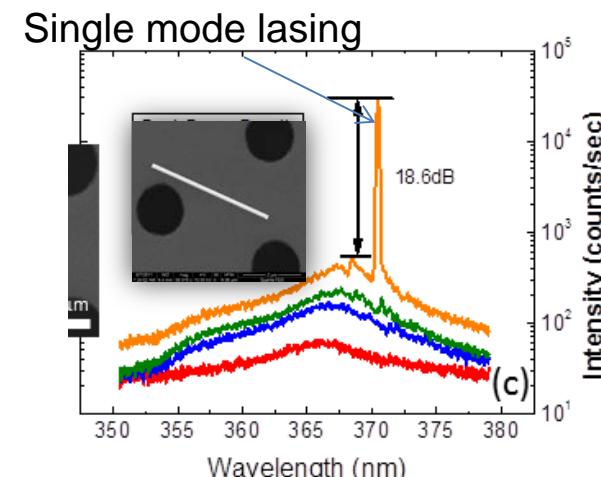
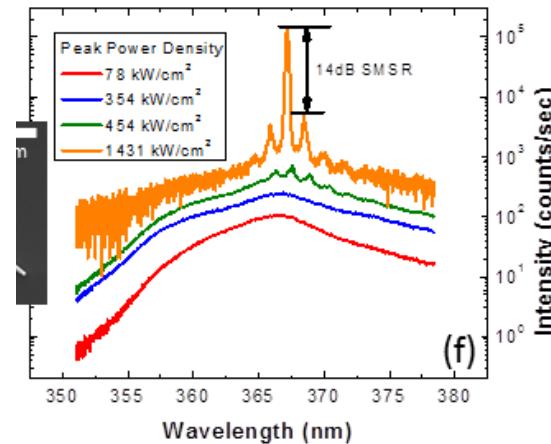
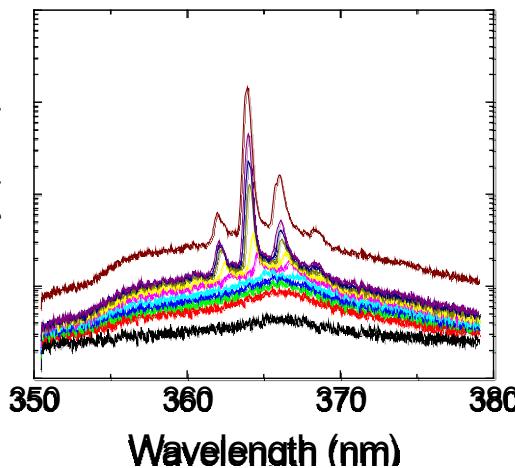
# Why Multimode Lasing Occurs



- ✓ Gain bandwidth  $\sim 7$  nm;
- ✓ Longitudinal mode spacing  $\sim 1$  nm;
- ✓ Several modes located in the gain spectrum;
- ✓ Multiple longitudinal mode oscillation

# Method 1: Single-mode NW laser via geometry control

Intensity (A.U.)



**145 nm x 7.2 μm (skinny)**

**~130nm x 4.7μm (short & skinny)**

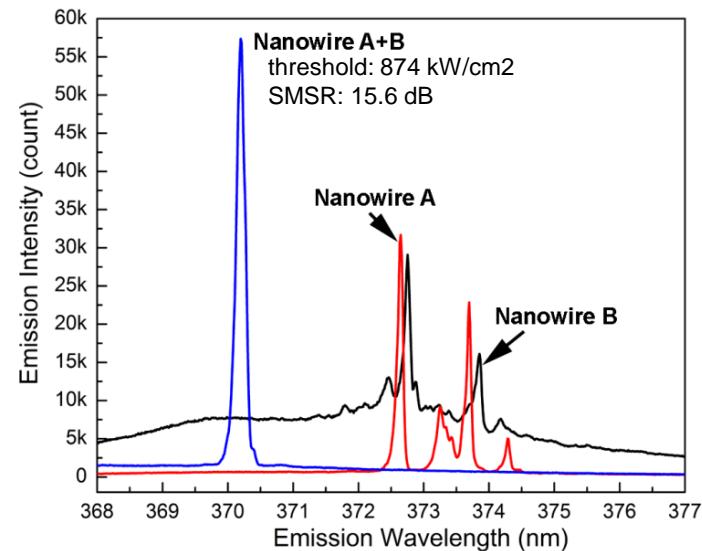
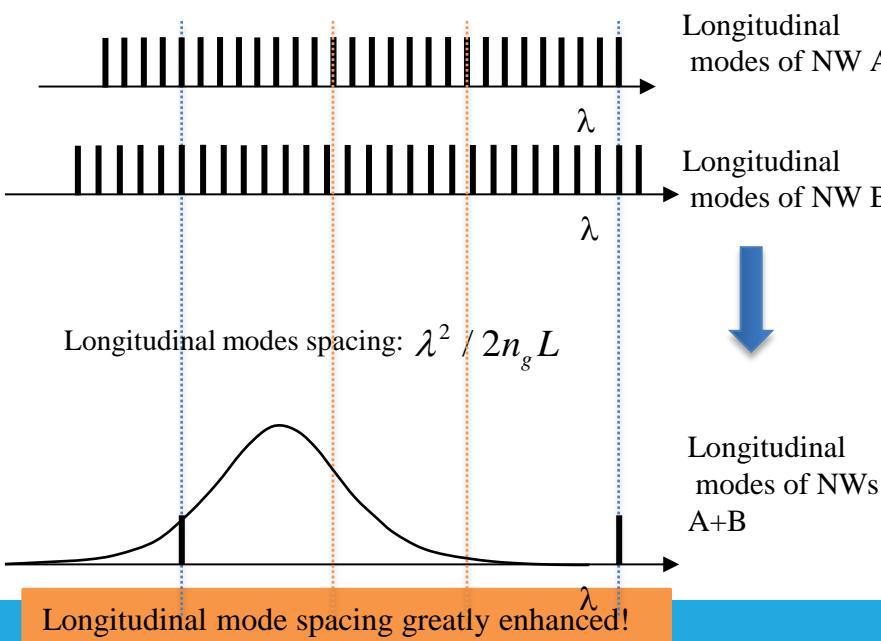
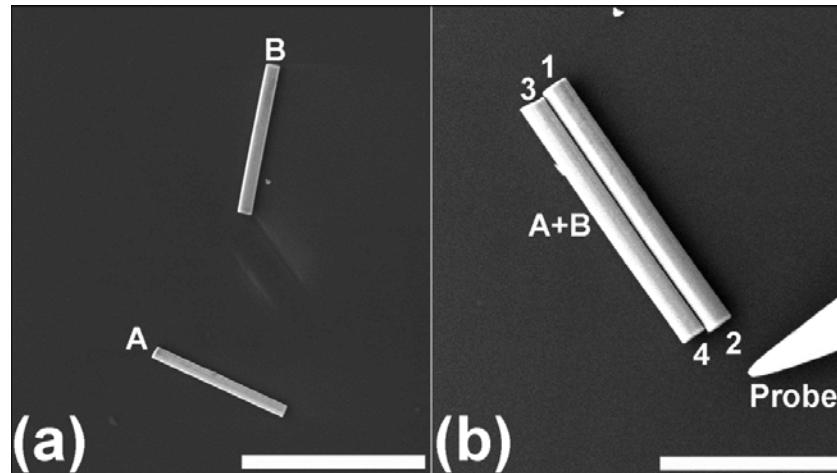
NW diameter x length

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

**Single-mode:** Narrow-Linewidth (<0.1 nm), 18.6 dB Side Mode Suppression Ratio

- Reduction of diameter (<~130 nm): reduction of transverse modes
- Reduction of length: (<~6 μm length): reduction of longitudinal modes
- **Reduced dimensionality leads to single mode lasing**

# Method 2: Single-mode lasing via coupled nanowire cavities

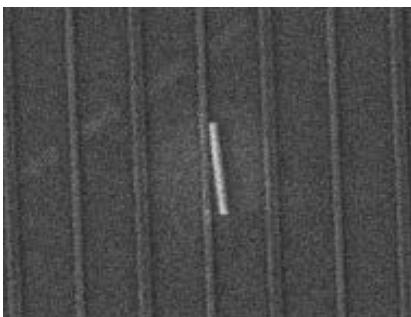
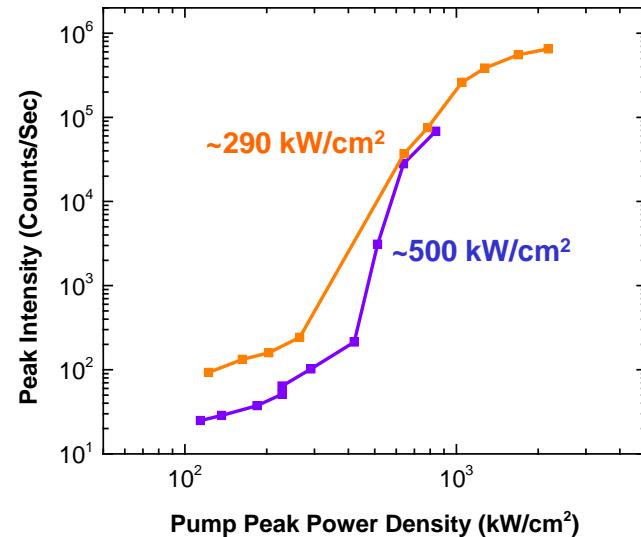
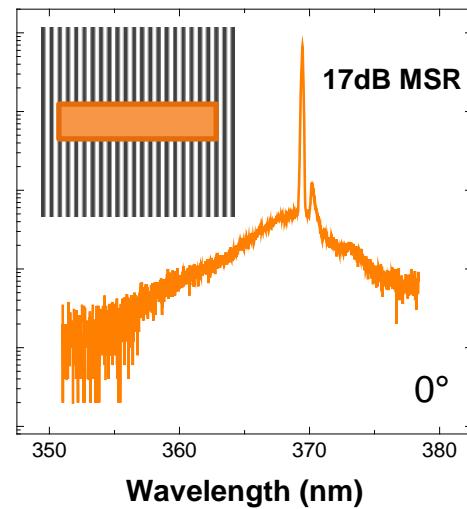
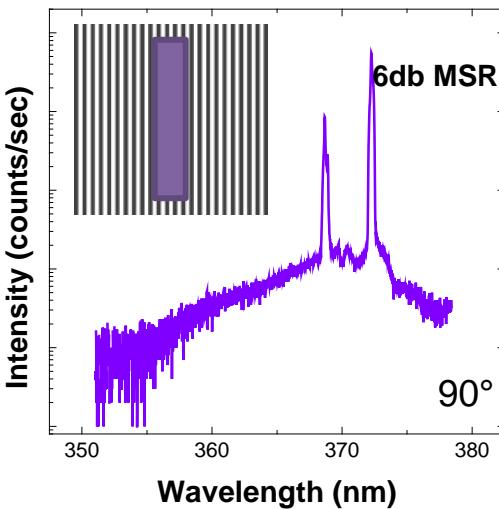


- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

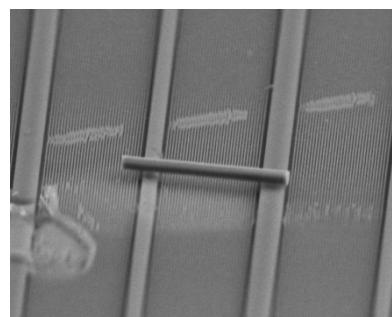
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

# Method 3: Distributed Feedback (DFB) Nanowire Laser

- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve DFB

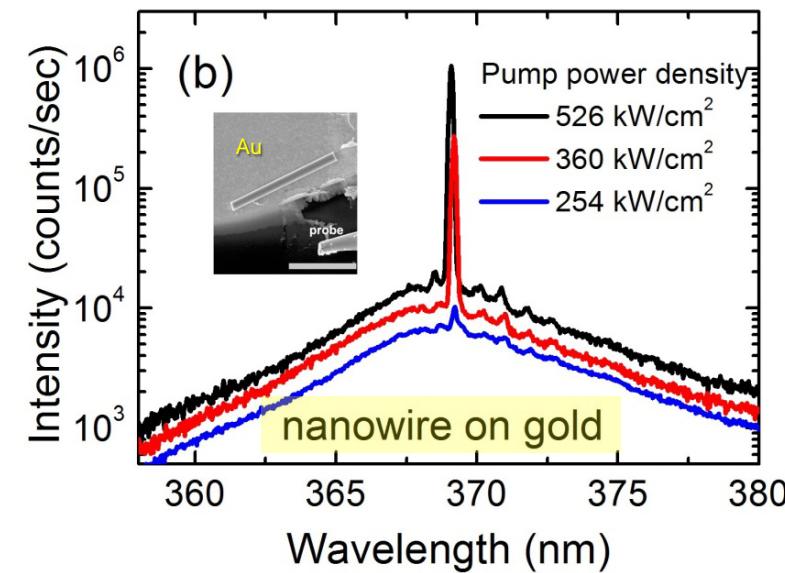
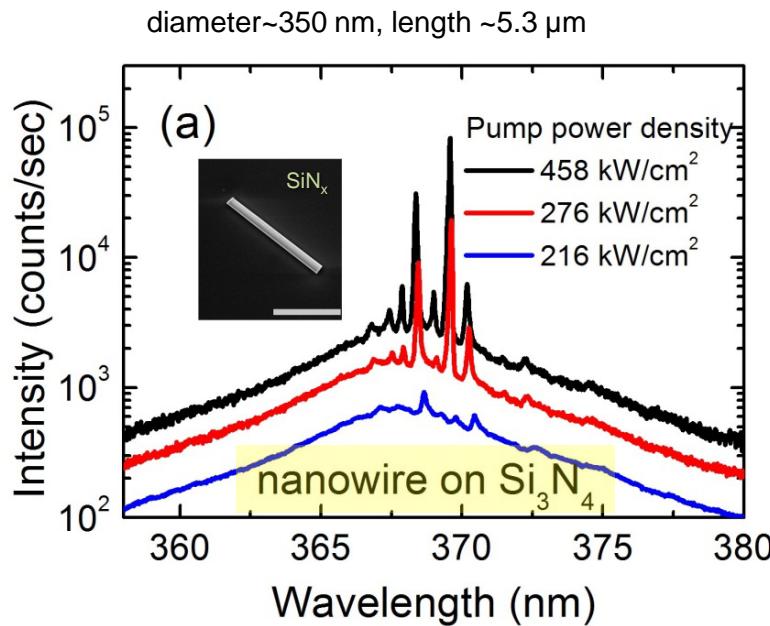


NW diameter ~180 nm



- At the designed alignment single-mode lasing was achieved with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

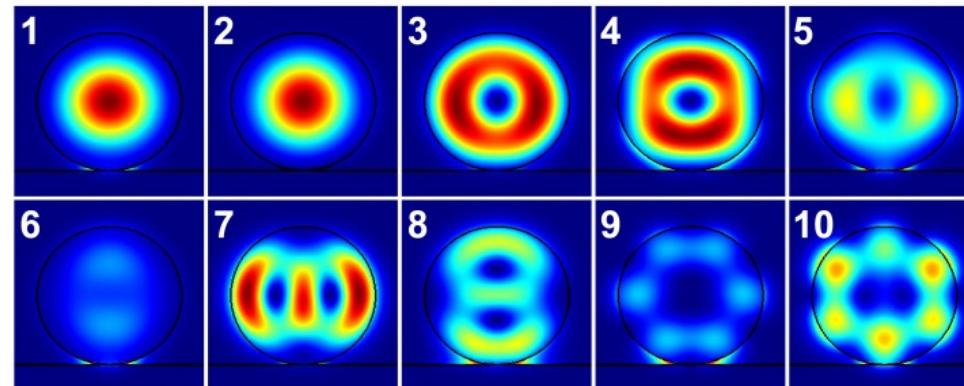
# Method 4: Metal substrate induced single-mode nanowire lasing



- NWs on  $\text{Si}_3\text{N}_4$  show multi-mode lasing
- **Same NWs moved onto gold-coated spot show single-mode lasing**
- Increase in lasing threshold of only ~13%

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

# Gold-substrate induced single-mode lasing



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

Transverse modes supported by a 300nm diameter nanowire on gold substrate.

**Only surviving mode**

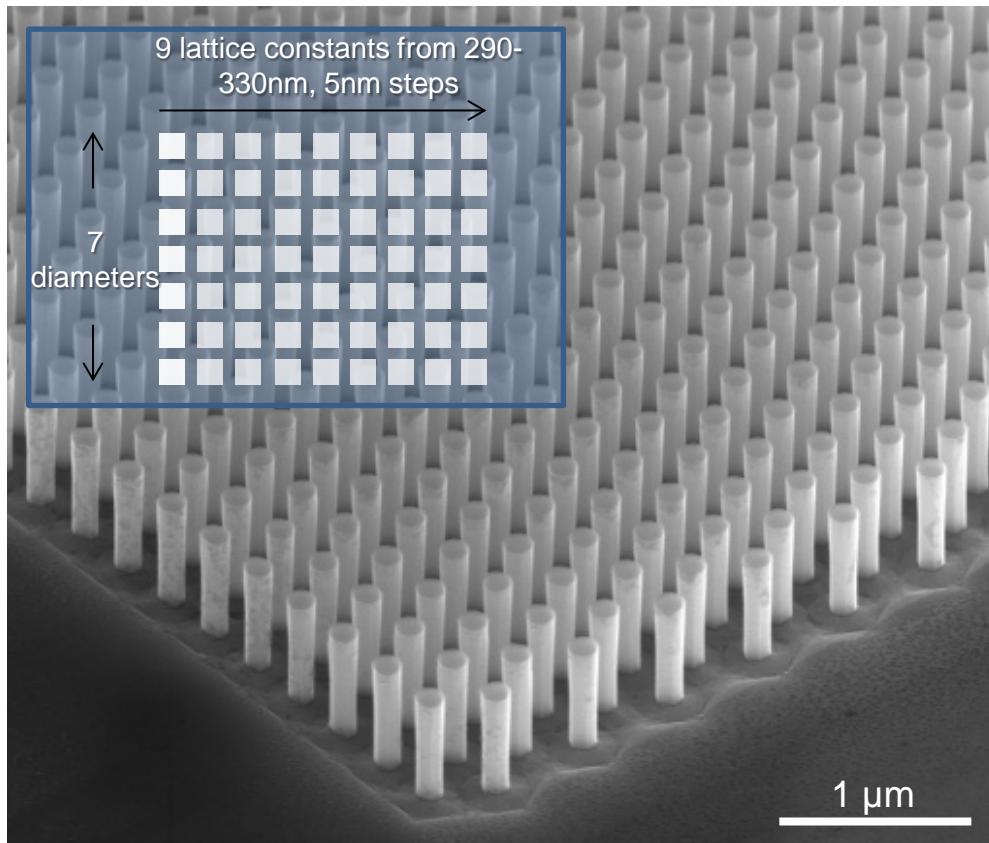
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Loss (dB/cm)	8151	1730	4806	7109	16041
	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
Loss (dB/cm)	34858	7551	22205	29175	28706

Propagation loss of different transverse modes.

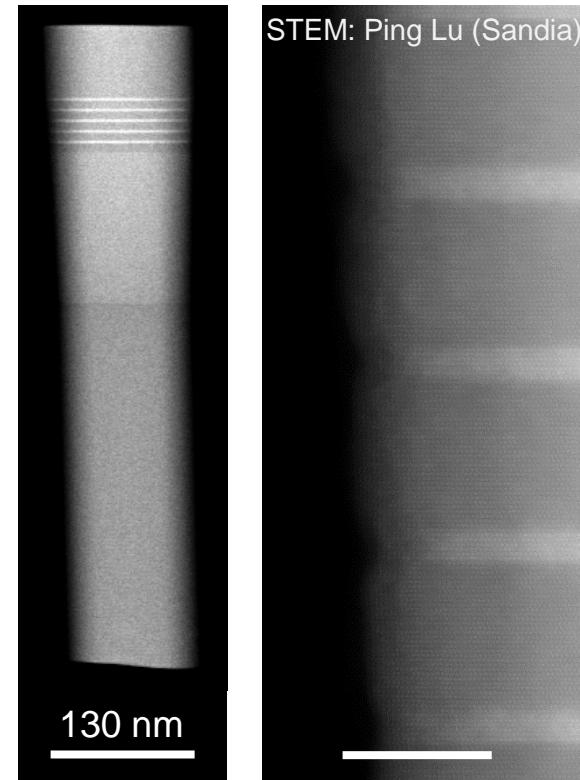
Metal substrate generates a mode-dependent propagation loss

# Wavelength tuning in III-N Nanowire Photonic Crystal 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

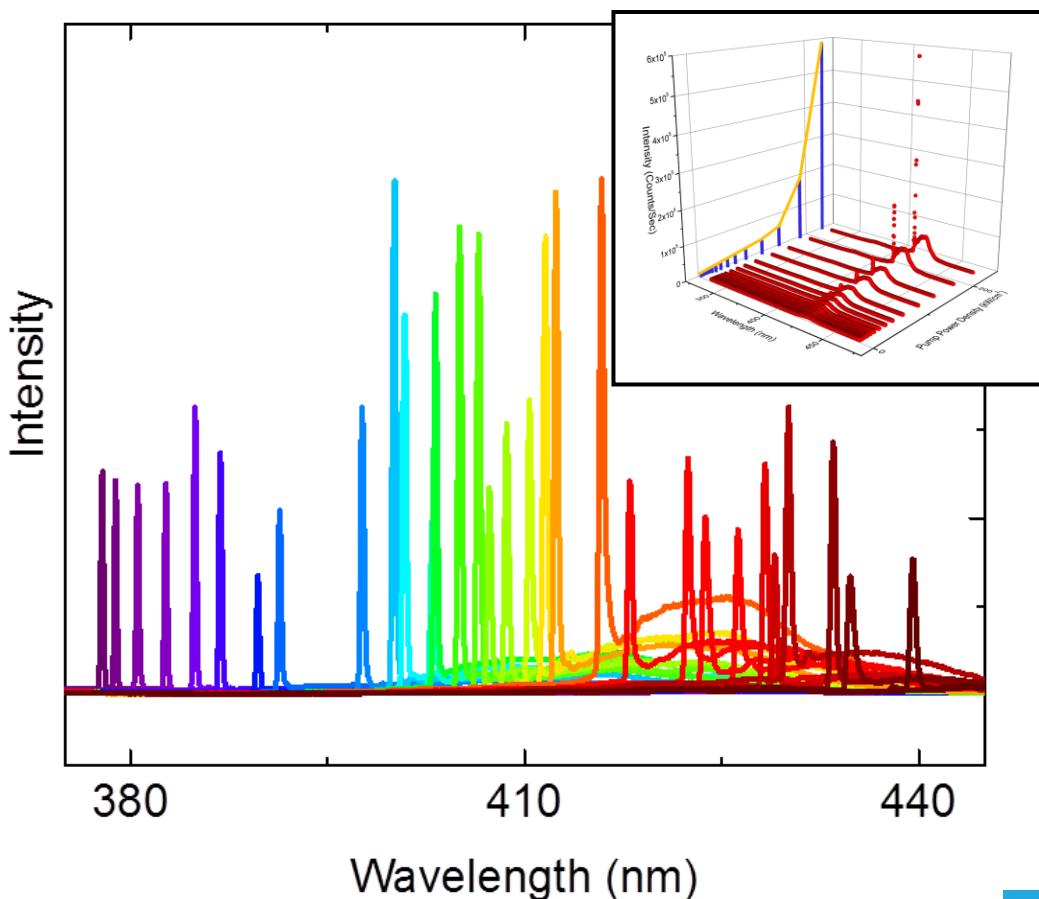


NW STEM images: 5x MQW InGaN emission centered at 420nm,  $\text{In}_{0.02}\text{GaN}$  underlayer

# Wavelength tuning in 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

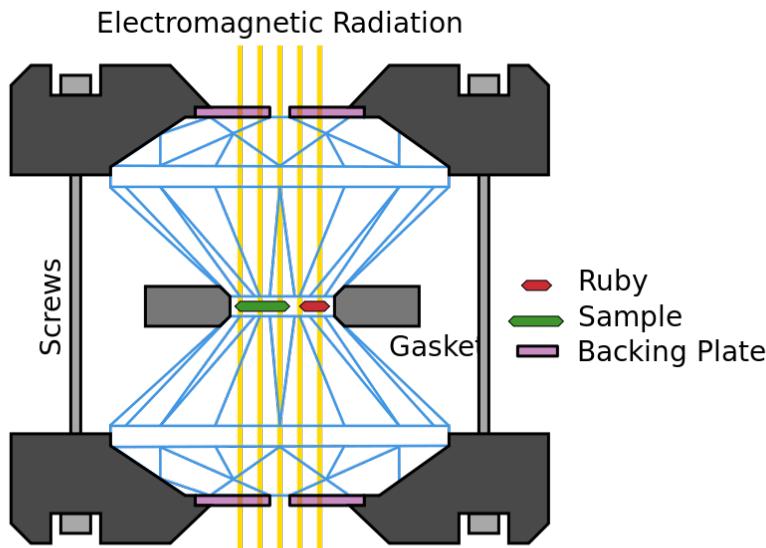


- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm<sup>2</sup>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

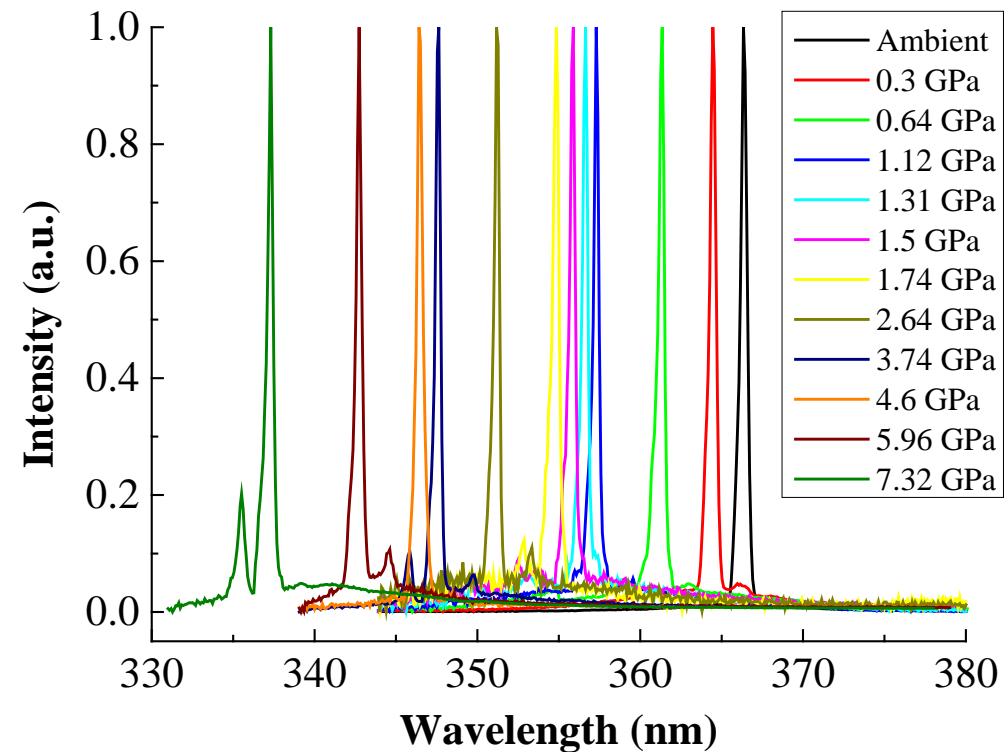
J.B. Wright et al., Scientific Reports 3, Article number: 2982 (2013) doi:10.1038/srep02982

# Continuous & dynamic bandgap/wavelength tuning in GaN NW lasers via hydrostatic pressure

Hydrostatic pressure medium (silicone oil) transmits pressure isotropically



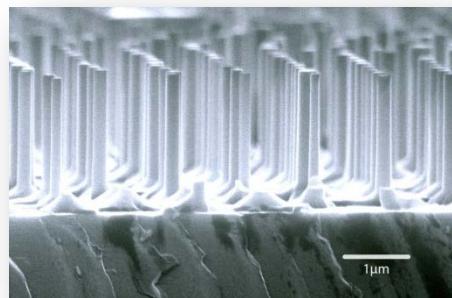
[http://en.wikipedia.org/wiki/Diamond\\_anvil\\_cell](http://en.wikipedia.org/wiki/Diamond_anvil_cell)



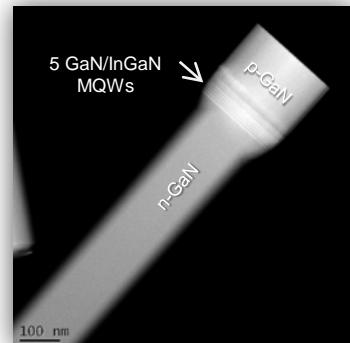
- Applied pressure induces bandgap increase
- ~30nm lasing tuning demonstrated over ~7.3 GPa
- Continuous and reversible tuning possible
- Well defined fine tuning (<0.1nm) possible with current setup

# Summary – Top-down III-nitride nanowires

## Precision top-down fabrication

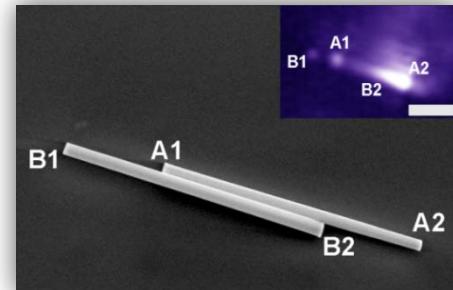


## Axial nanowire LED "flashlight"



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

## Mode & polarization control in GaN nanowire lasers

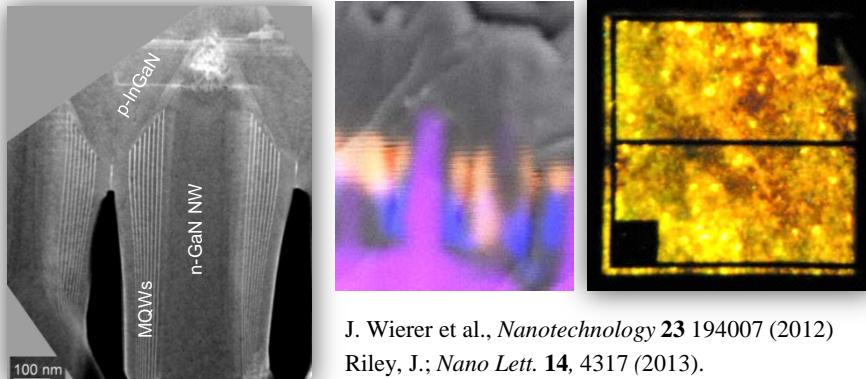


Q. Li et al., *Optics Express* **20** 17874 (2012)

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

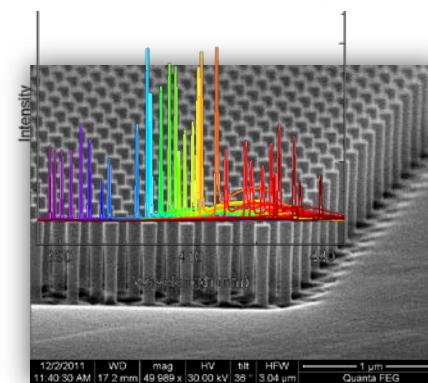


J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

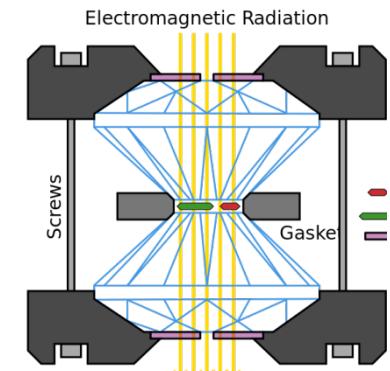
Riley, J.; *Nano Lett.* **14**, 4317 (2013).

G. T. Wang et al., *Phys. Stat. Solidi A*, **211**, 748 (2014)

## Tunable wavelength nanowire [photonic crystal] lasers



J.B. Wright et al., *Scientific Reports* **3**, Article number: 2982 (2013) doi:10.1038/srep02982



# 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

Karl Westlake, Mary Crawford – PL, IQE measurements

Daniel Koleske, Jonathan Wierer – LED growth, LED device fabrication

Igal Brener, Willie Luk, Weng Chow, Jeremy Wright, (Ph.D student),

Huiwen Xu (Ph. D student), Changyi Li (Ph. D student), Sheng Liu, Steven Brueck, Ganesh

Subramania – NW lasers

Jim Riley (Ph.D student), Sonal Padalkar, Lincoln Lauhon (Northwestern) – Atom Probe Tomography

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Science Energy Frontier Research Center (DOE BES), and Sandia's LRD program**

Contact: e-mail: [gtwang@sandia.gov](mailto:gtwang@sandia.gov)

<http://www.sandia.gov/~gtwang>

George T. Wang



# Backup/Extra Slides

# Worldwide GaN-based nanowire SSL-related research

North America



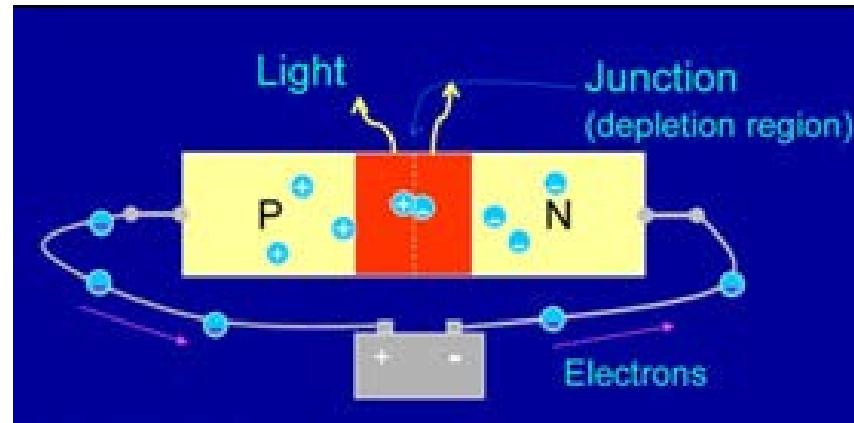
Europe



Asia



# How LEDs work



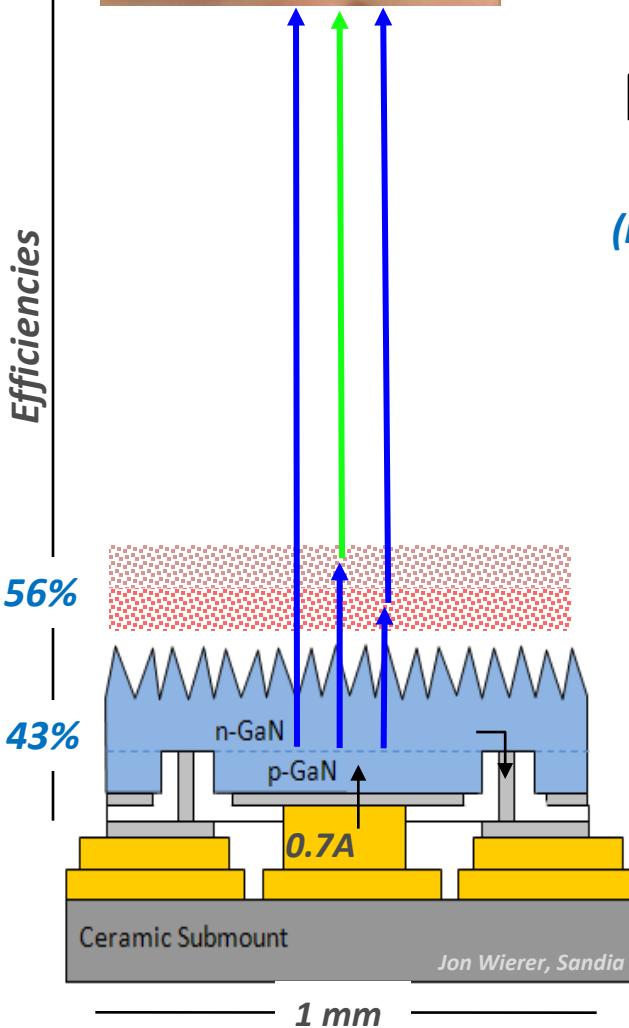
- An LED is a chip of semiconducting material treated to create a structure called a p-n (positive-negative) junction.
- Current flows from the p-side or anode to the n-side, or cathode. Charge-carriers (electrons and electron holes) flow into the junction.
- When an electron meets a hole, it falls into a lower energy level, and releases energy in the form of a photon (light).
- Depending on the composition of the semiconducting material, different colors of light are emitted.



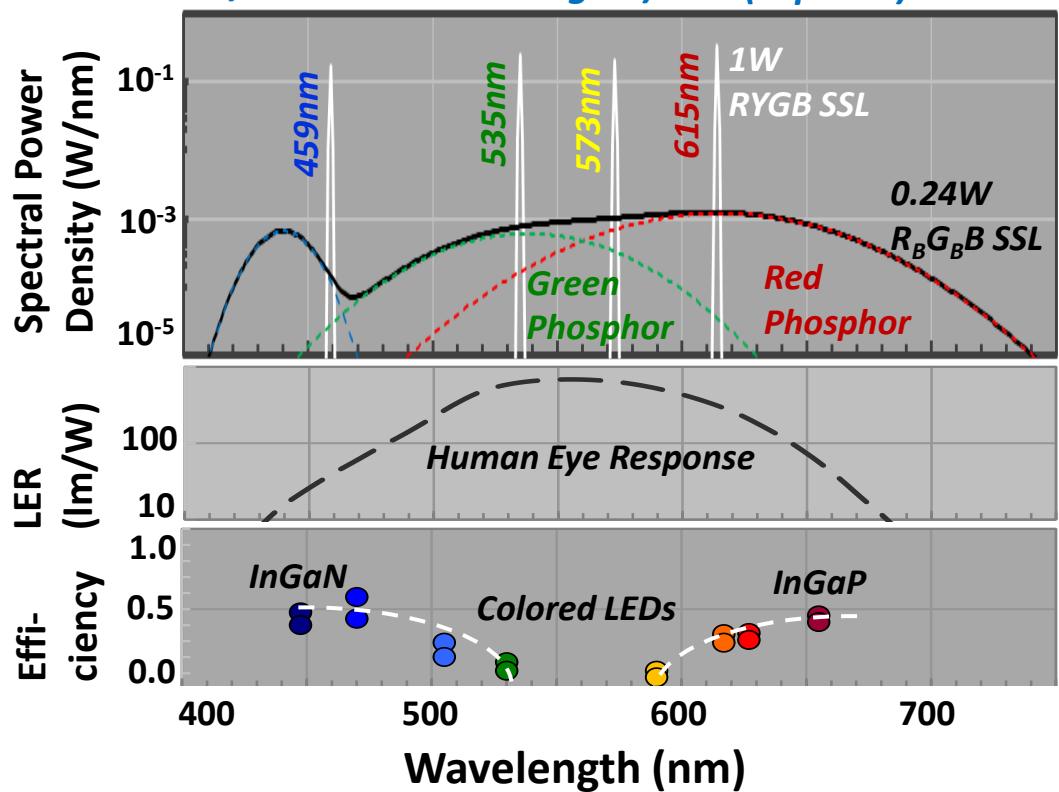
4 Functional Light  
(control of light in intensity, chromaticity, time, and space)

# Why Only 20% Efficient?

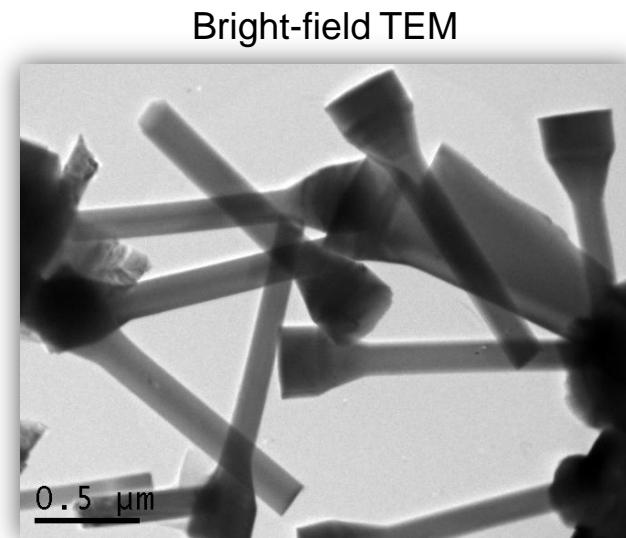
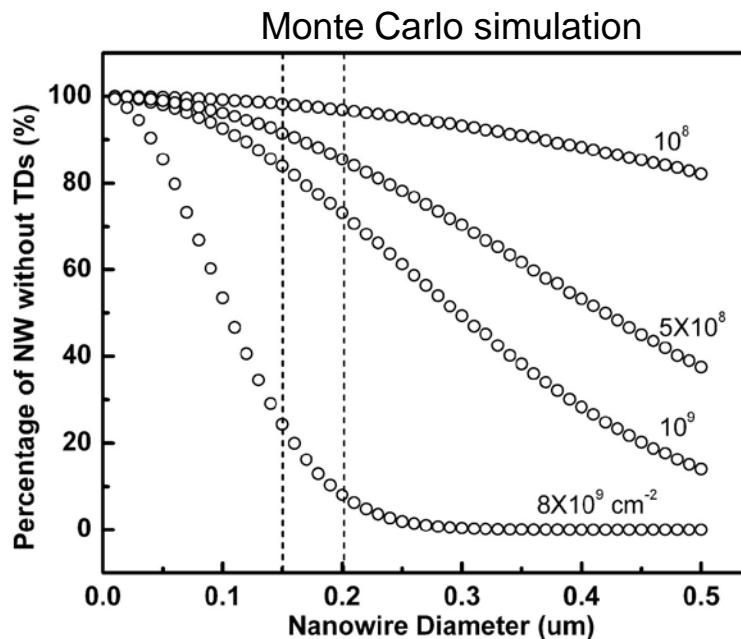
## Four SSL Technology Grand Challenges



- 1 Efficiency Droop  
(near-100% efficiency  
at all currents)
- 2 Green-Yellow Gap  
(near-100% efficiency  
at all wavelengths)
- 3 Narrow-linewidth  
 $\lambda$  downconversion  
(esp. red)



# Top-down nanowire threading dislocations

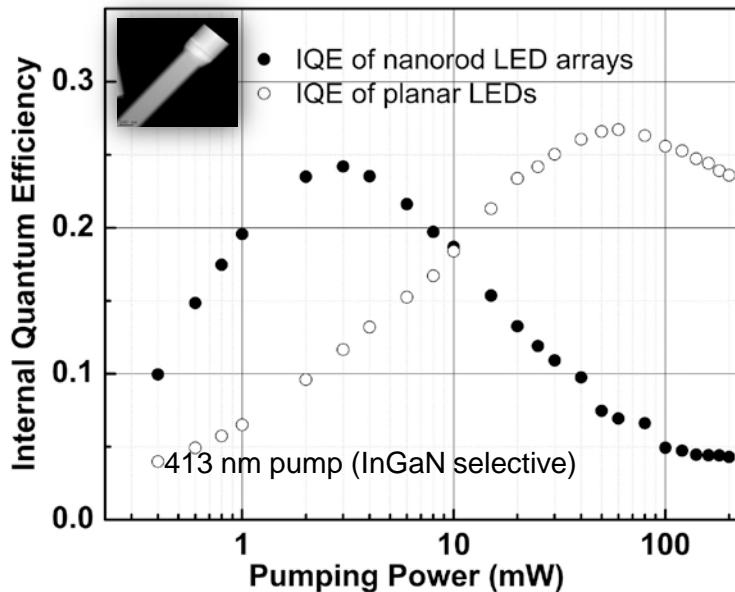


Nanowires etched from  $\sim 5\text{e}8 \text{ cm}^{-2}$  planar LED

- 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! [ $\# \text{ TDs per rod} \sim (\text{TDD}) \times (\text{A}_{\text{cross-section}})$ ]
- $\sim 94\%$  of nanowires  $\sim 150 \text{ nm}$  in diameter from  $\text{TDD} \sim 5\text{e}8 \text{ cm}^{-2}$  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

IQE – nanowire vs Film



PL, IQE: K. Westlake, M. Crawford

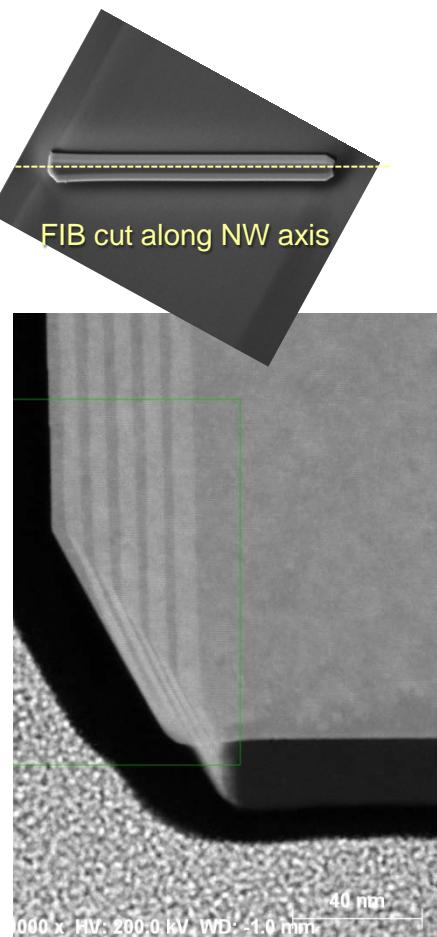
Q. Li et al., *Optics Express* **19**, 25528 (2011)

- XRD shows  $\sim 16 \pm 4\%$  strain reduction in InGaN QWs in nanowire LEDs XRD measurement: Steve Lee, Sandia
- TEM shows  $\sim 94\%$  of nanowire LEDs are dislocation free
- Little wavelength shift at higher pump powers for nanowire LEDs (no/reduced QCSE)
- But nanowire LED shows only comparable IQE to planar LED; peak IQE occurs at much lower pumping power (enhanced light absorption, heating)

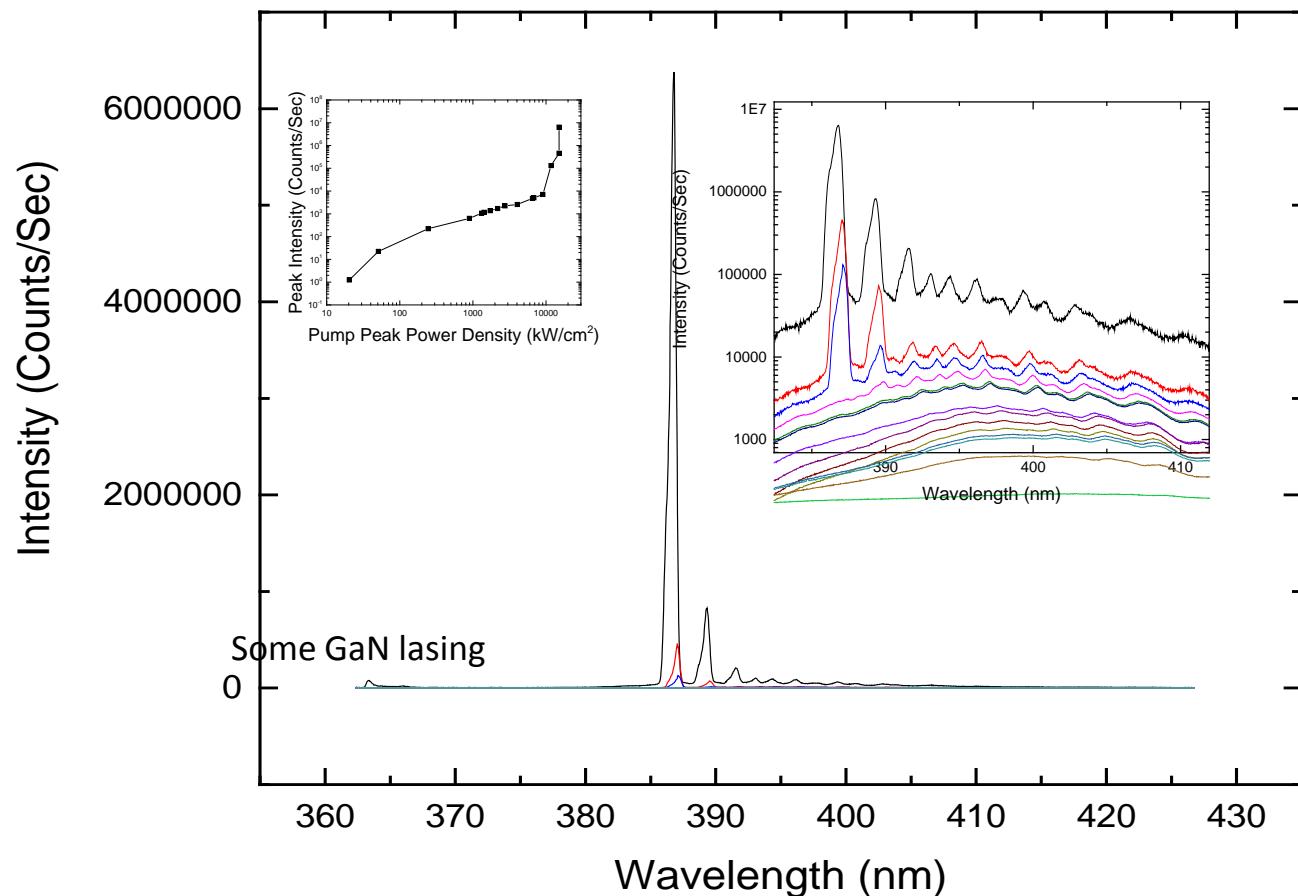
How much is surface passivation likely to improve IQE of NW LED?

No obvious benefit for blue LED performance/cost ratio (loss of device area), but possibility for very high IQE single NW emitters for nanophotonic applications by starting with commercial quality planar LEDs

# Lasing in single NWs with nonpolar *m*-plane InGaN/GaN MQWs

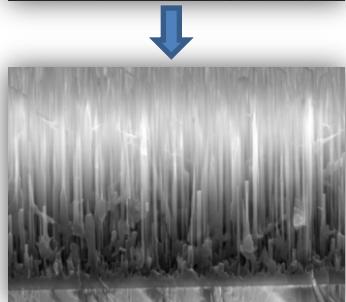
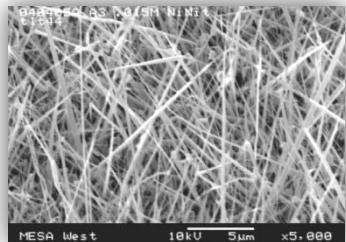


InGaN gain region needed to reach visible wavelengths



First known demonstration of optically-pumped lasing in radial nonpolar *m*-plane GaN/InGaN MQW nanowires

# Challenges for nanowire-based SSL

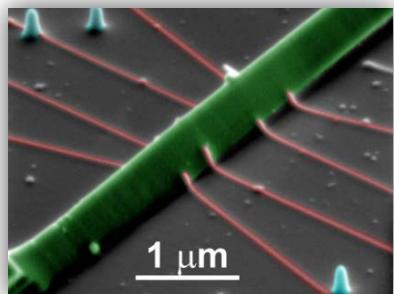


## Synthesis/Fabrication

- Ordering, alignment, density
- Size control (uniformity, diameter, height)
- Doping, heterostructures
- Growth on different facets
- Manufacturability

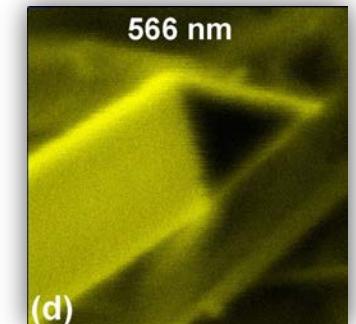
## Properties (electrical, optical, thermal, mechanical)

- Role of defects & surfaces
- Control/uniformity
- Differences from bulk/planar material



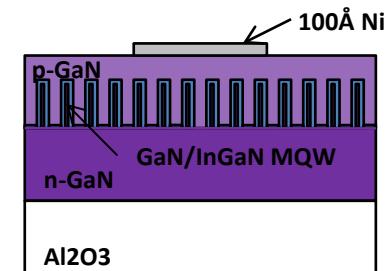
## Electrically-integrated devices

- Contacts (single NW & vertically integrated)
- Surface states
- Charge injection and transport



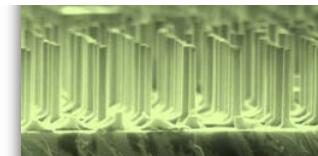
surface defect luminescence

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



# Bottom-up vs. Top-down nanowires

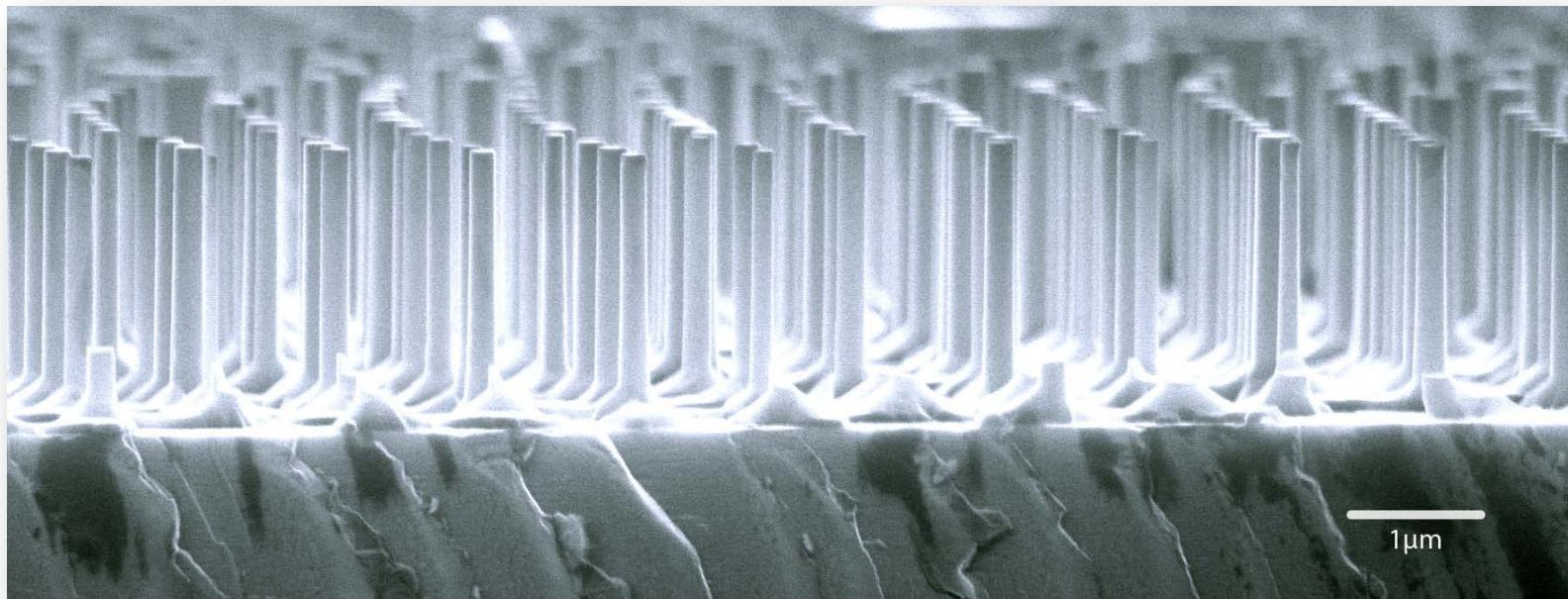
	<b>Bottom-up</b>	<b>Top-down (+ regrowth)</b>
<b>Length</b>	Up to hundreds of $\mu\text{m}$	Several $\mu\text{m}$
<b>Diameter</b>	$\sim$ 30 nm to microns	$\sim$ 10 nm to microns
<b>Dislocations</b>	Few or none	Depends on density in film
<b>Radial architectures</b>	Yes, typically by MOCVD	Yes, by MOCVD regrowth
<b>Axial architectures</b>	Yes, typically by MBE	Yes, but not strain relaxed
<b>Substrate</b>	Lattice matching less critical	Lattice matched
<b>Characterization</b>	Some properties difficult to measure (e.g. doping)	Starting material can be measured using standard techniques
<b>Material Quality:</b>	Point defect density may be high due to growth conditions needed	Starting material can be grown under optimal growth conditions
<b>Uniformity</b>	Wire-to-wire variations may occur based on pitch, diameter	Good, although regrowth has same issues as bottom-up



# Top-down III-Nitride Nanowires

- Although dominant, bottom-up nanowire approaches suffer from some limitations
- Specific growth conditions needed for anisotropic growth which may not result in optimal material quality or desired material property
- Architectures may be limited depending on growth method (MBE vs. MOCVD)
- In response, around 2010 our group began investigating new top-down approaches for fabricating III-nitride nanowires...George T. Wang

# Advantages of new top-down nanowire fabrication method

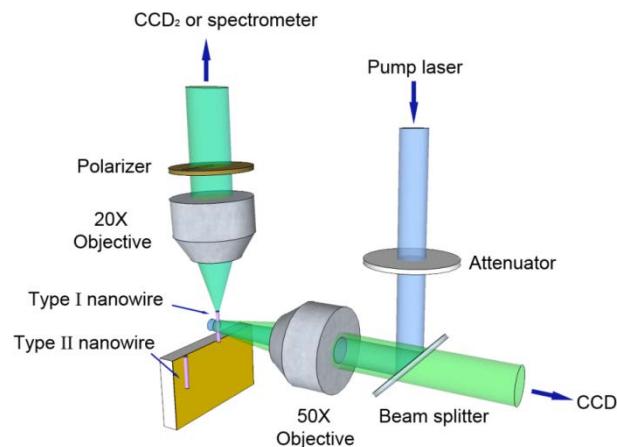


- Wider range of growth conditions, material tunability (1D growth cndns not needed)
- Lower point defect densities (higher growth temperature)
- Ordered/periodic arrays (difficult with catalyst/VLS-based methods)
- Axial III-nitride nanowire heterostructures possible by MOCVD
- Better control of geometry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

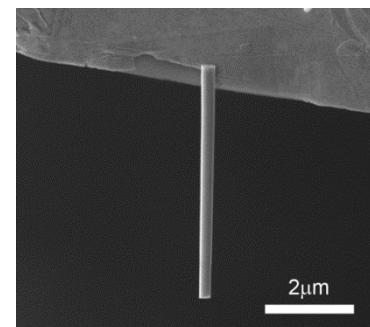
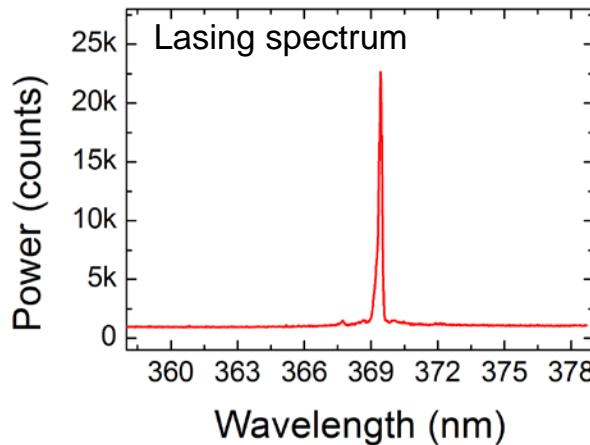
# Mode control (i.e. How to make a single-mode GaN nanowire laser)

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

# Lasing Polarization Properties of Freestanding GaN NWs



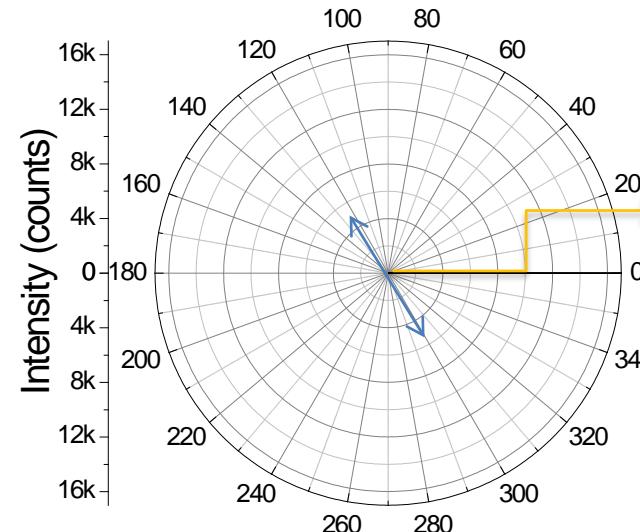
End-facet optical characterization setup



SEM image of a nanowire hanging off substrate



CCD image of lasing nanowire hanging off substrate



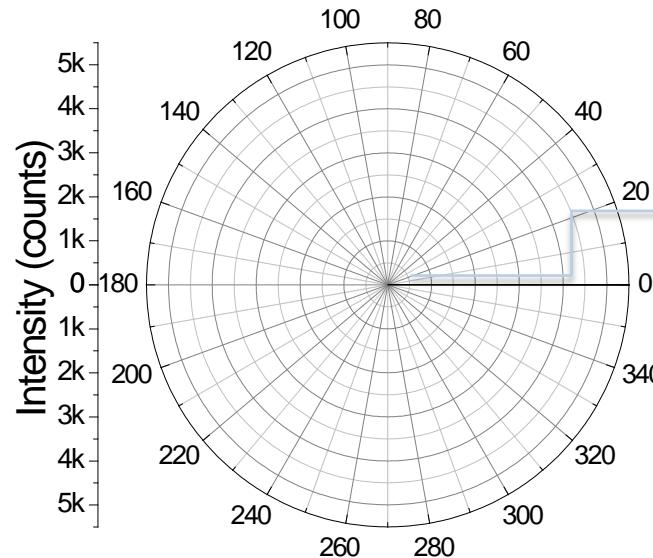
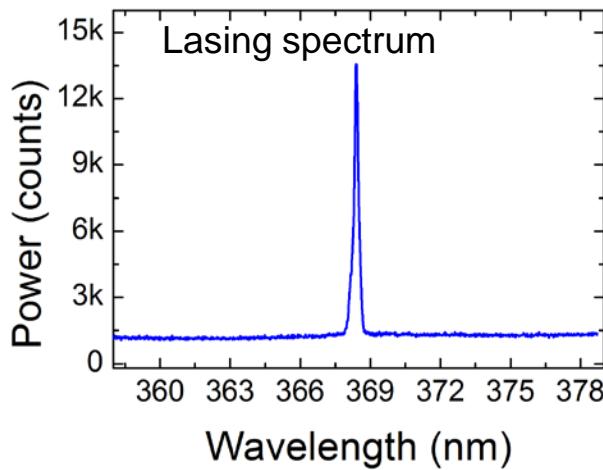
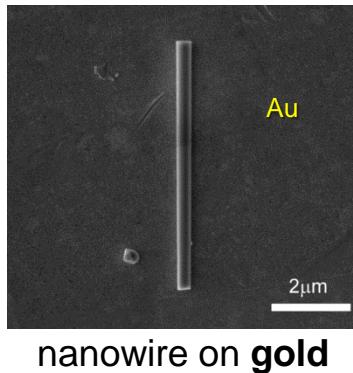
**Indicative of elliptical polarization**

Polarization angle random wrt surface

Intensity vs. the rotation of the polarizer

# Polarization Control: Nanowire on Gold Substrate

Polarization control (linear polarization) desired for many applications



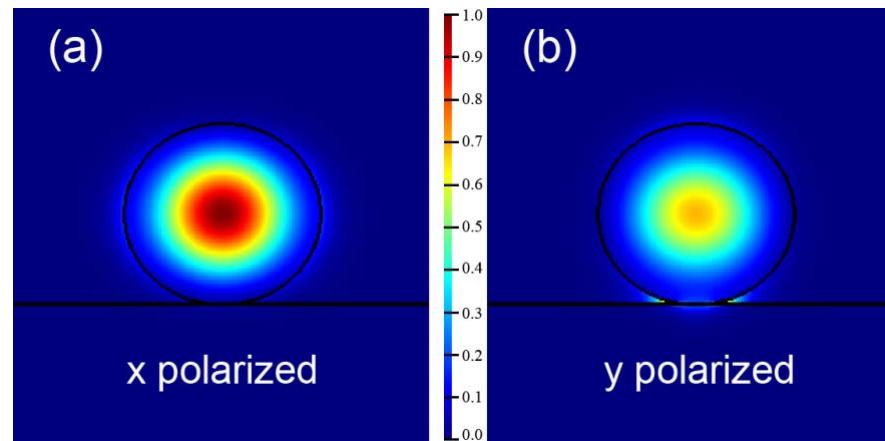
Intensity vs. the rotation of the polarizer

**Indicative of linear polarization**

Polarization angle aligned wrt surface

- ✓ Single-wavelength lasing
- ✓ Linear polarization
- ✓ Large cross-polarization suppression ratio (CPSR): 21:1
- ✓ 0° polarization angle

# Why Does Linear Polarization Happen on Gold?

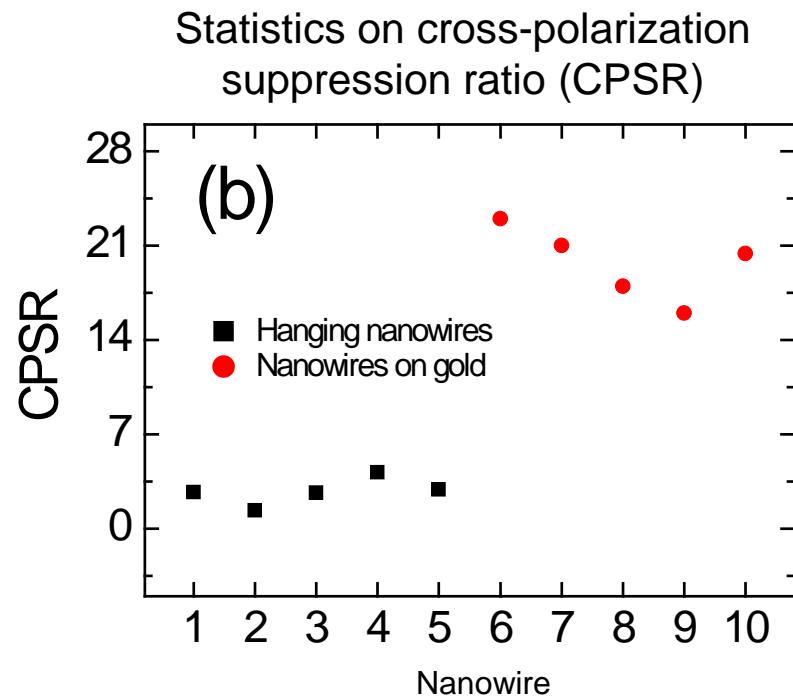
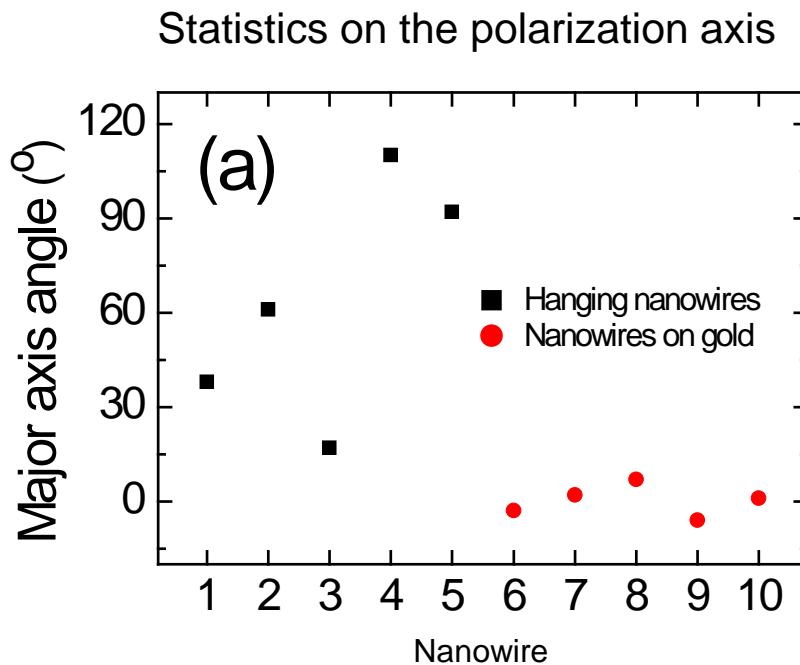


Fundamental modes supported by the nanowire-gold geometry

- ✓ Differently polarized modes experience different cavity losses
- ✓ Loss for x-polarized mode: 0.36 dB/mm
- ✓ Loss for y-polarized mode: 2.11 dB/mm

A nanowire on gold substrate experiences a larger cavity loss for the perpendicularly polarized mode, leading to linear polarization with a fixed polarization parallel to the substrate

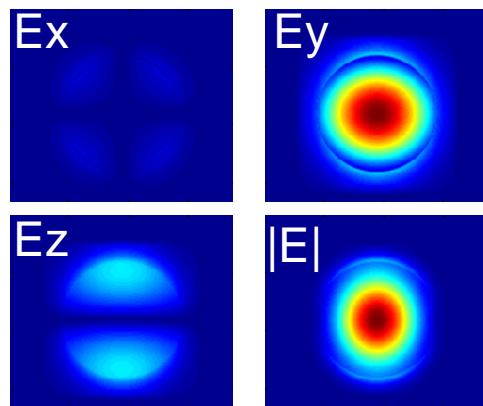
# Lasing Polarization Statistics of Free Standing and on-Gold Nanowires



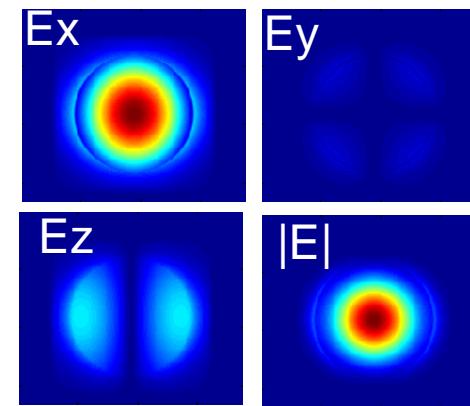
- ✓ Free standing nanowires are polarized with random axes and a small CPSR
- ✓ On-gold nanowires have fixed polarization angle and large CPSR

# Why nanowire laser elliptically polarized?

Mode 1 HE11<sub>a</sub> -  $n_{\text{eff}}=2.1$



Mode 2 HE11<sub>b</sub> -  $n_{\text{eff}}=2.1$

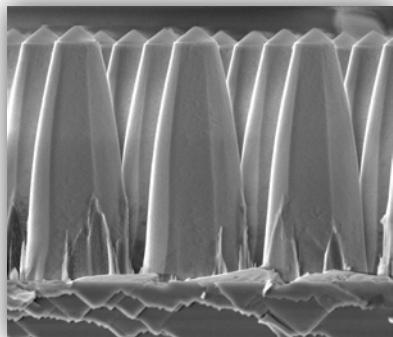


Two orthogonal polarized fundamental modes supported by a 200 nm diameter nanowire in air

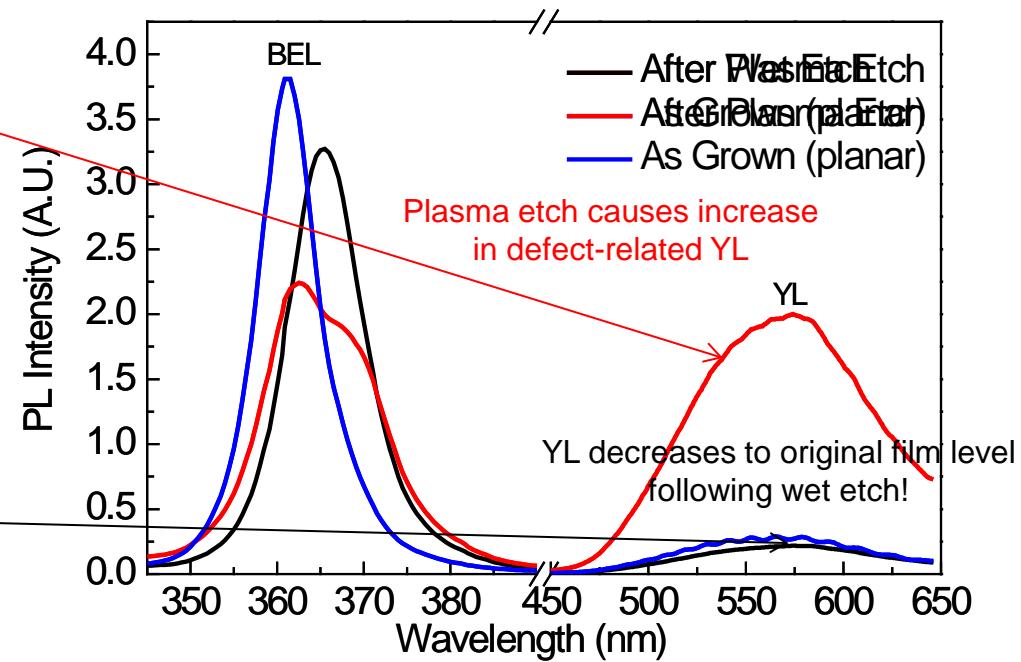
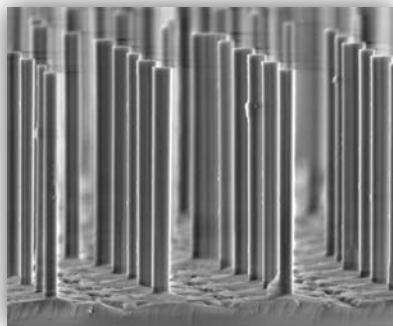
- ✓ Both fundamental transverse modes
- ✓ Same electric field intensity
- ✓ **Two degenerate modes superimpose resulting in elliptical polarization**

# Wet etch step removes plasma etch damage

Plasma etch only



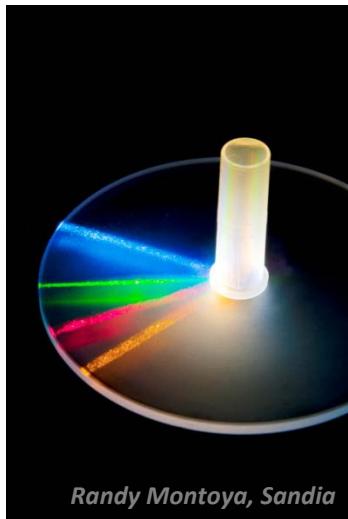
After wet etch



# Lasers for Solid State Lighting

## Advantages of lasers for lighting:

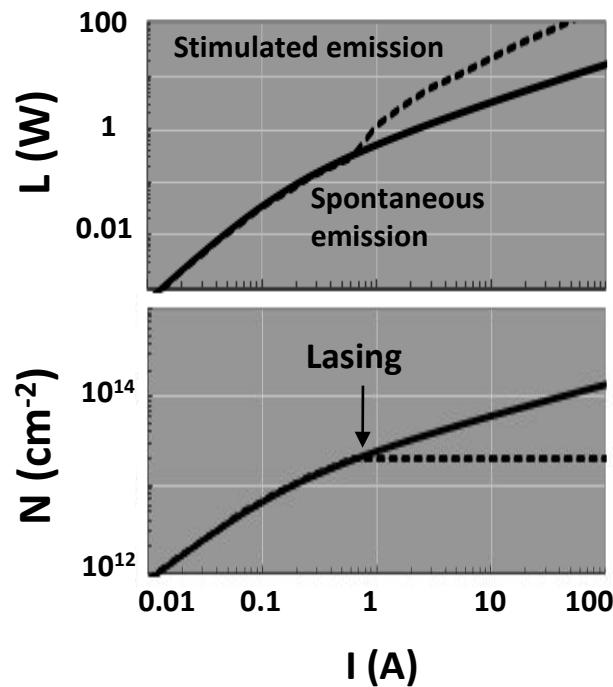
- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
  - Circumvent the droop problem in LEDs
  - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission,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



## Laser Sources For SSL:

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

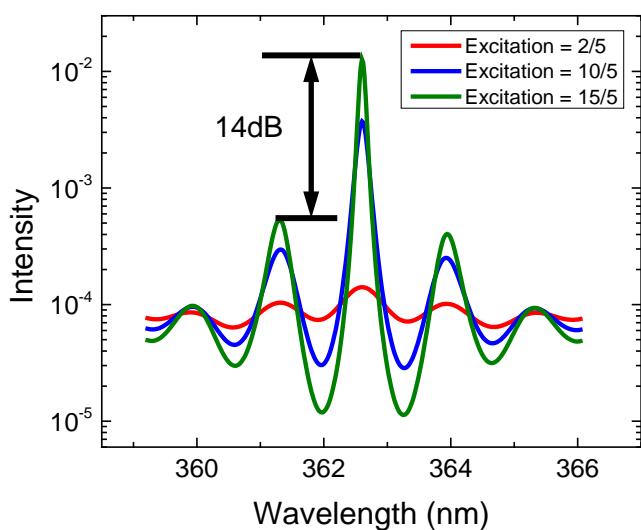
## Clamped carrier density



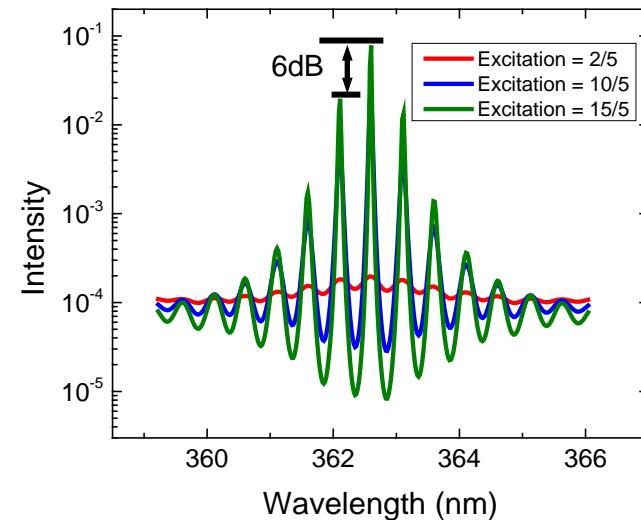
**Are narrow linewidth sources acceptable?**

# Single mode GaN nanowire laser

4  $\mu\text{m}$  long, 140 nm dia. nanowire

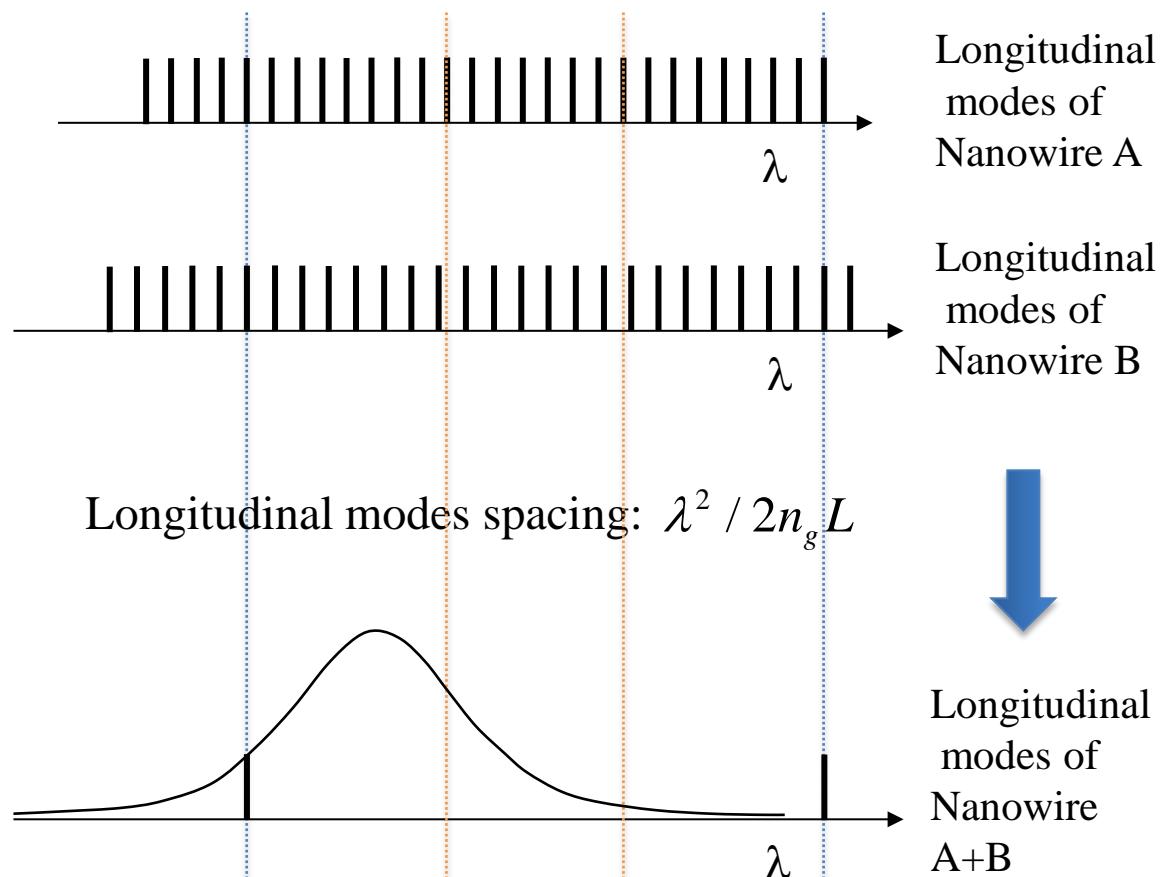
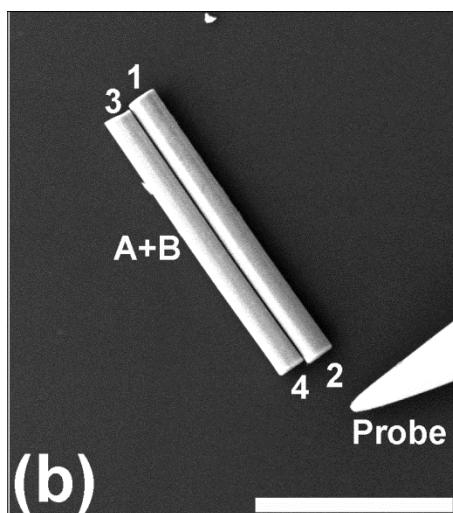
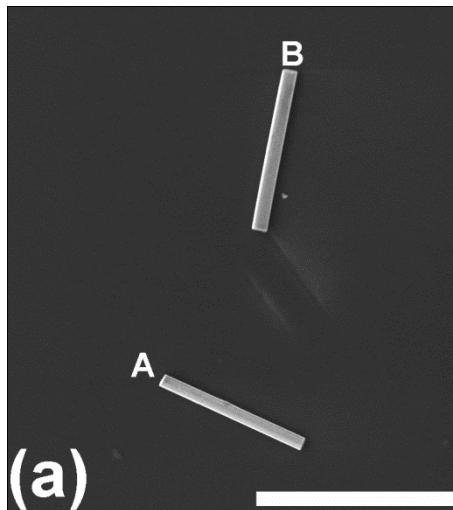


12  $\mu\text{m}$  long, 140 nm dia. wire



- 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.

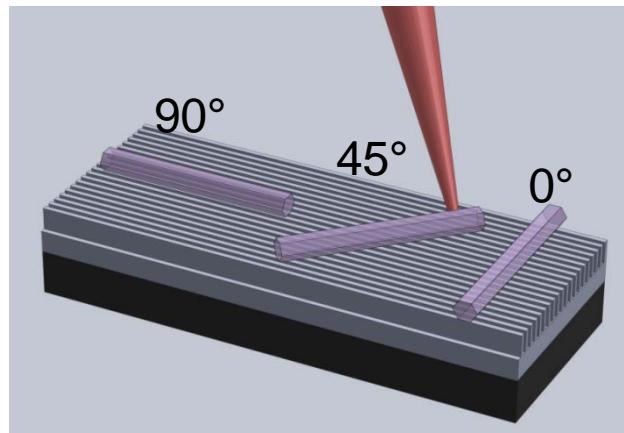
## Method 2: Vernier Effect From a Coupled Cavity



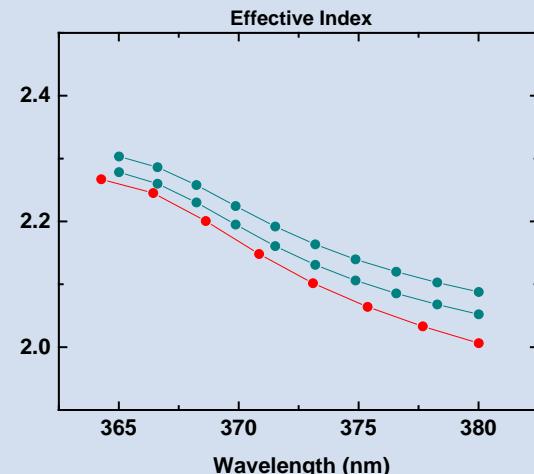
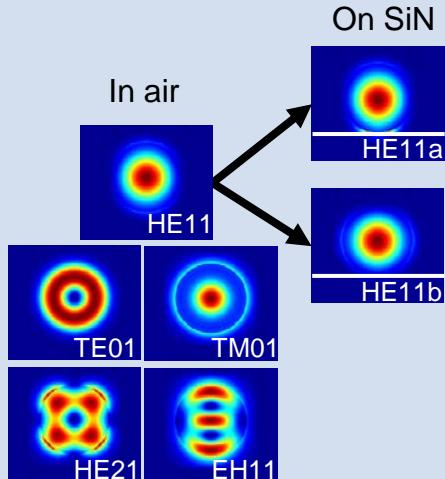
Longitudinal mode spacing greatly enhanced!  
(10s of nanometers in this coupled cavity)

# Method 3: Distributed Feedback (DFB) Nanowire Laser

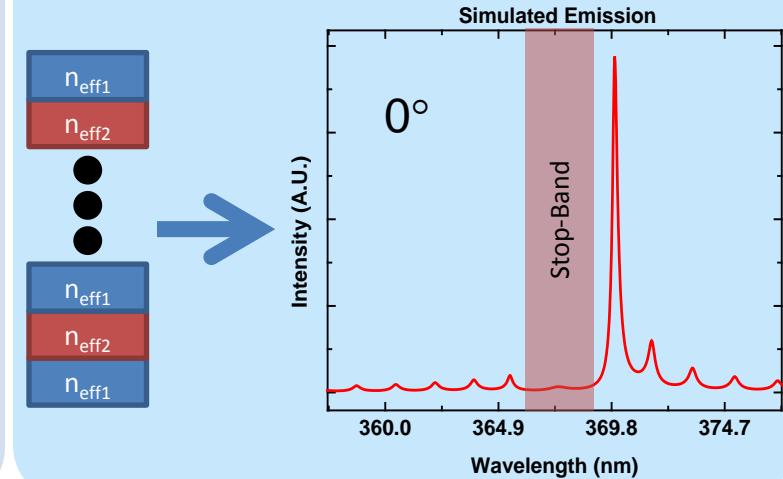
- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve distributed feedback
- Tuned stop-band position and width via nanomanipulation of the angular alignment of NW to change effective periodicity of grating



## Mode Calculations

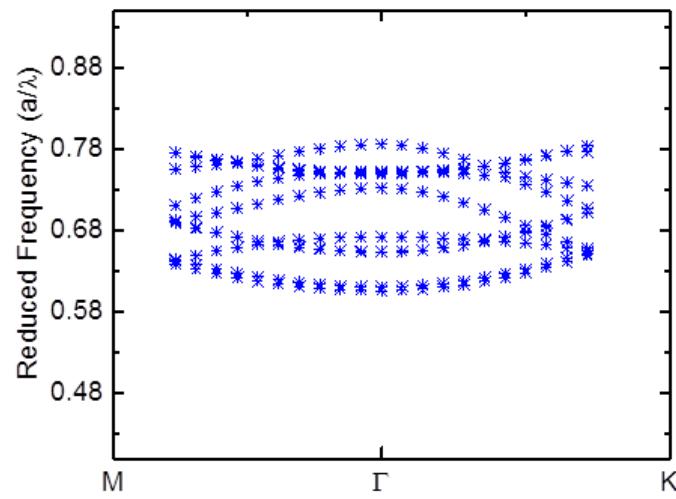
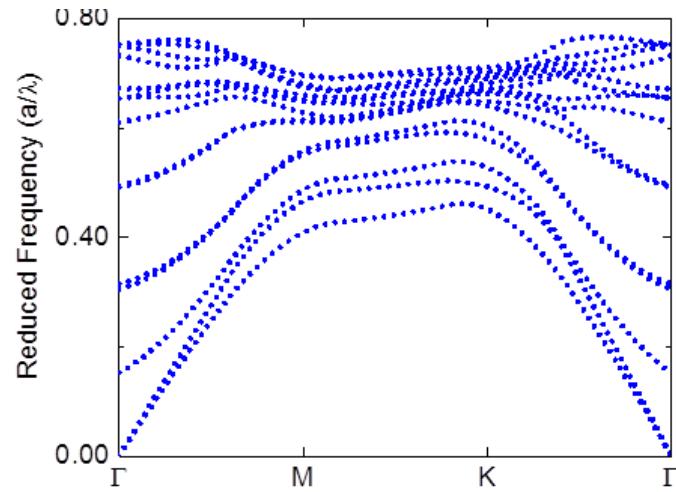
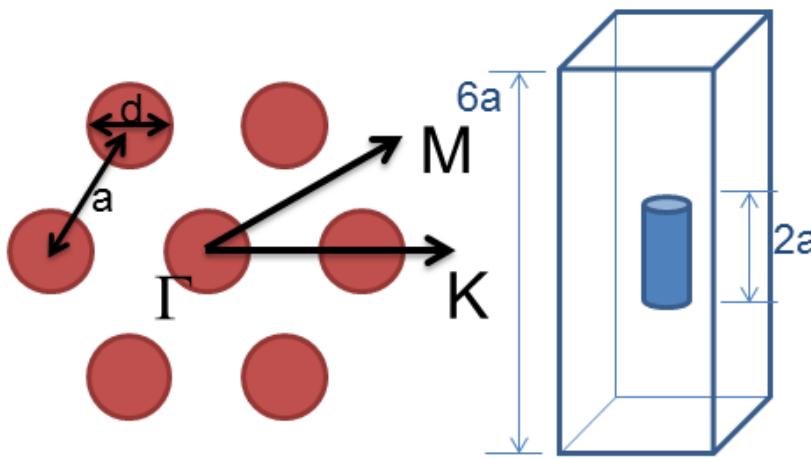


## Transfer Matrix Method

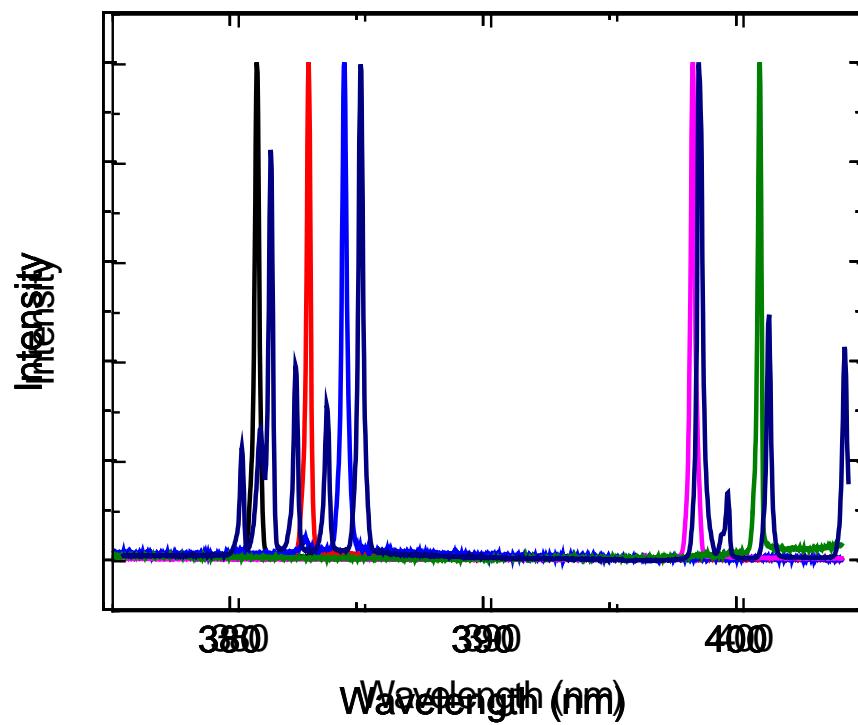


# Design Rationale

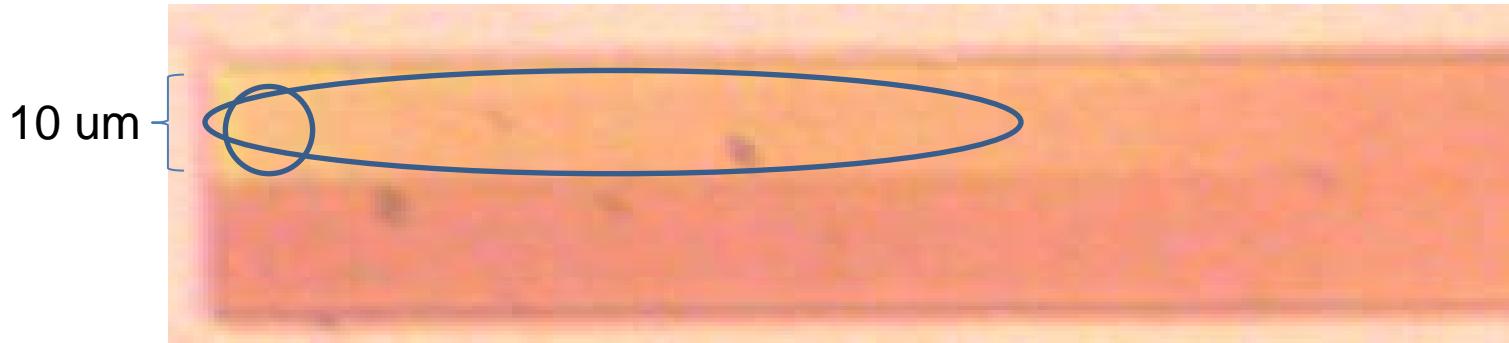
- Higher order bands have low dispersion
- We desire low group velocity to enhance the light matter interaction and the formation of standing waves within the gain medium, to allow low lasing thresholds in materials that exhibit reduced gain over larger bandwidth



# III-N Nanowire Photonic Crystal Lasers

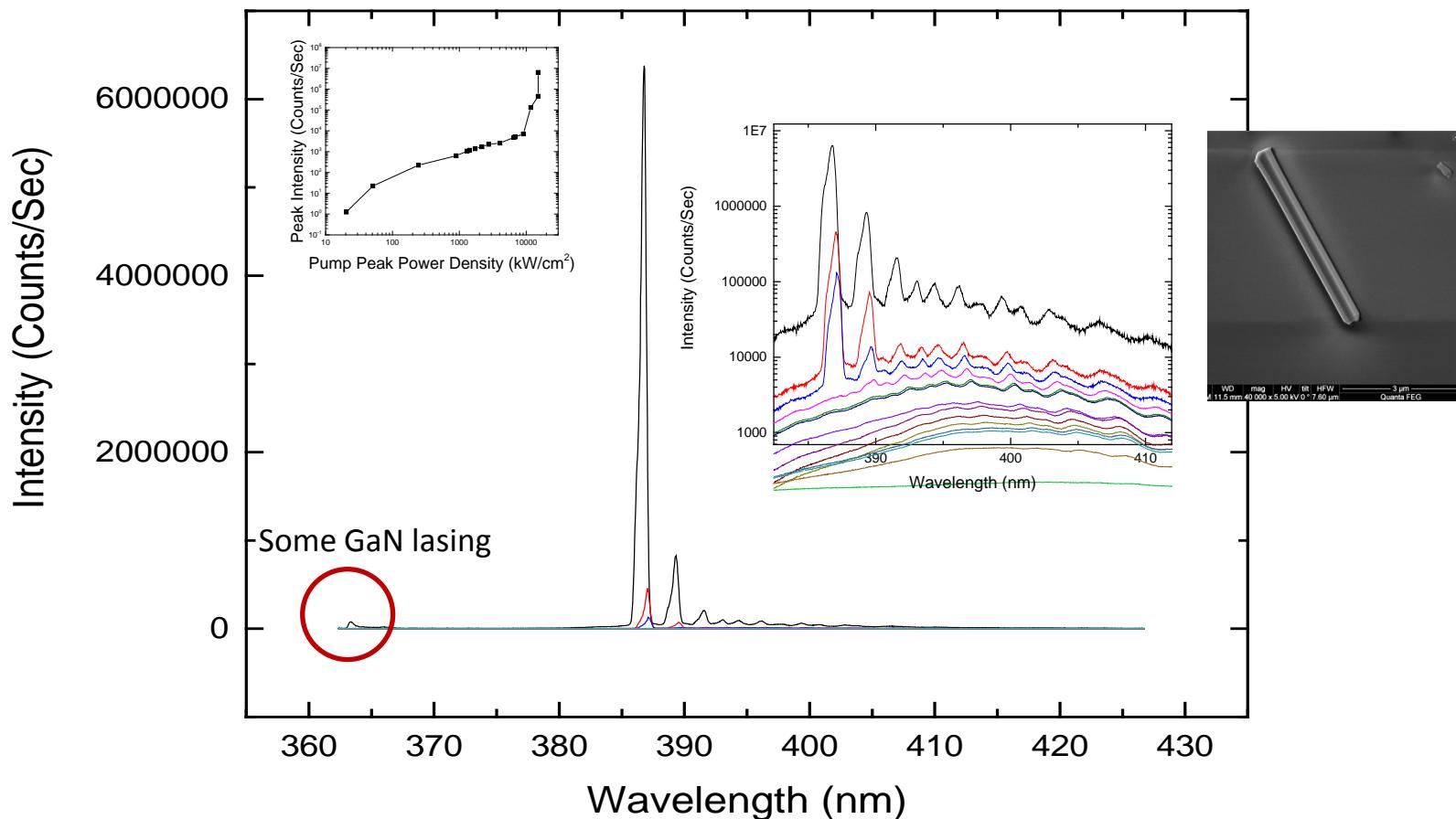


pitch: 320 nm  
diameter: 130-140nm



## Key Accomplishments

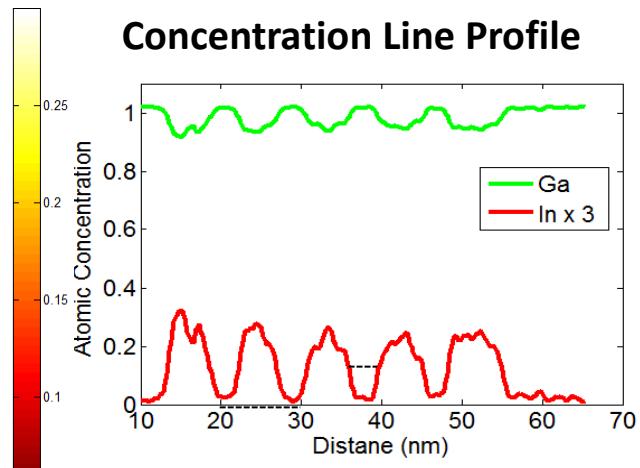
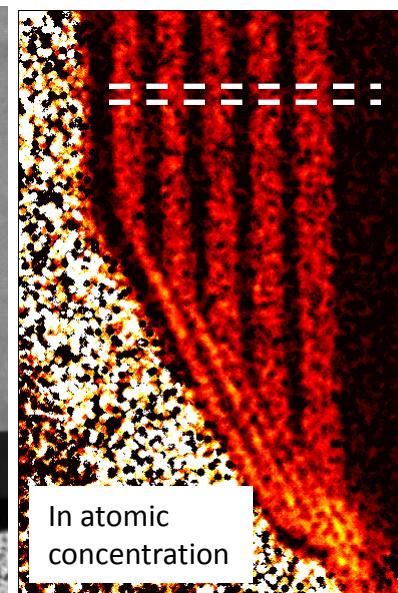
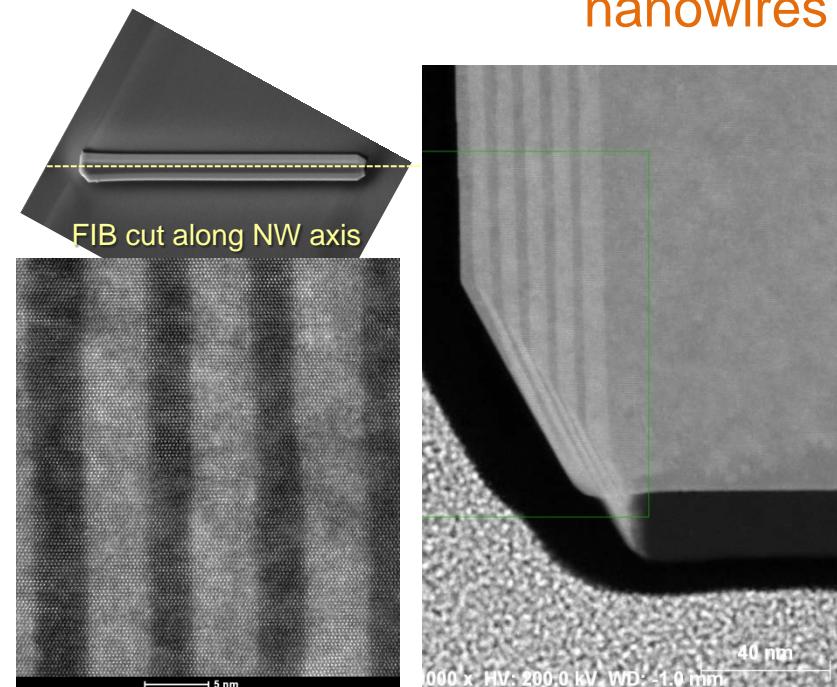
# First known demonstration of optically-pumped lasing in radial m-plane GaN/InGaN MQW nanowires



Result confirms radial InGaN/GaN MQW NW can lase (note: not optimized designs)

# Key Accomplishments

Optically-pumped lasing in radial m-plane GaN/InGaN MQW nanowires – STEM/EDS analysis



## Near tip region

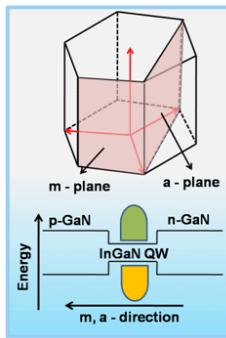
- In composition ~6-10%
- InGaN QWs ~4-6 nm
- GaN barriers ~2.5-4 nm

Cross-sectional STEM/EDS analysis enables post-growth analysis of radial InGaN/GaN NW structure needed to realize targeted design

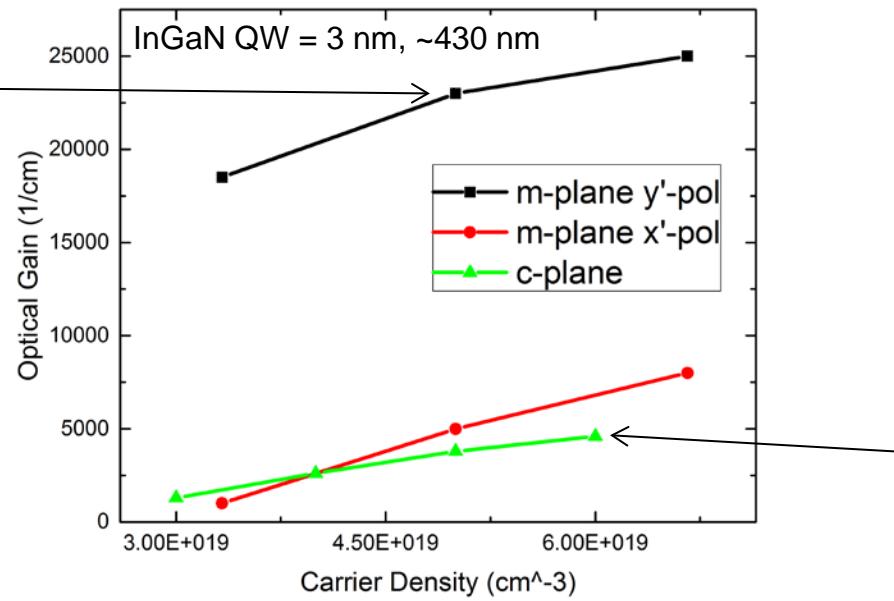
# Key Accomplishments

## Analysis of axial vs radial NW designs

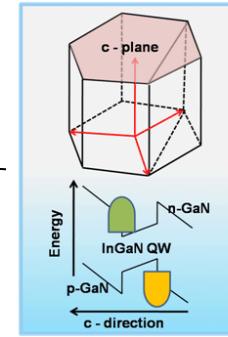
Radial NW



Optical Gain - Crystallographic Dependence



Axial NW



Much higher optical gain for m-plane QWs (benefits radial NW design)

S.-H. Park and D. Ahn, "Optical polarization characteristics of m-plane InGaN/GaN quantum well structures and comparison with experiment," *Appl. Phys. Lett.*, **103**, pp. -, (2013)

J. Piprek, R. K. Sink, M. A. Hansen, J. E. Bowers, and S. P. DenBaars, "Simulation and optimization of 420-nm InGaN/GaN laser diodes," 2000, pp. 28-39.

Crystallographic figures from: <http://csel.snu.ac.kr/research/LED.php>

# Key Accomplishments

## Analysis of axial NW laser design – needed reflectivities

### Nanowire Constants

$$\lambda := 420\text{nm}$$

$$\text{Length} := 5\mu\text{m}$$

$$t_{\text{QW}} := 3\text{nm} \quad N_{\text{wells}} := 5$$

$$\Gamma_{xy} := 1$$

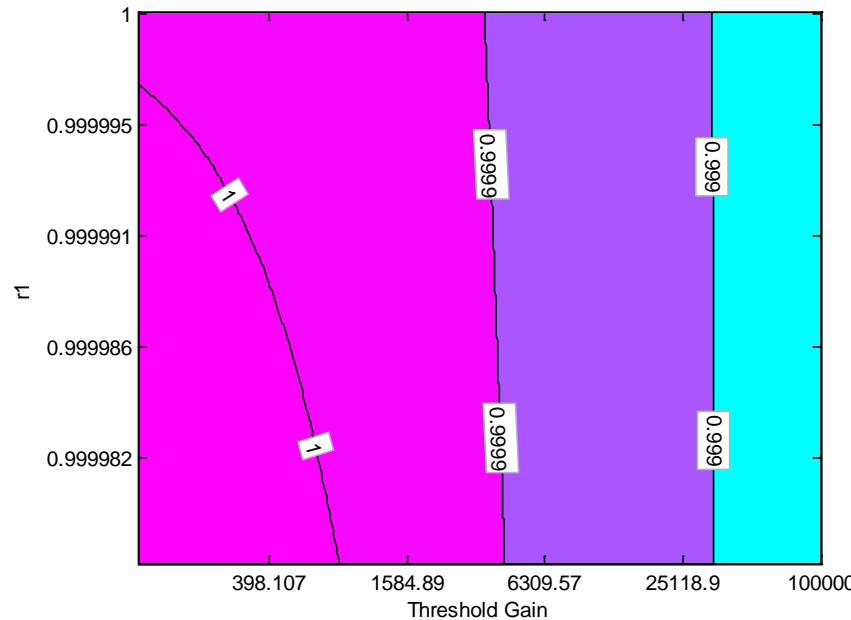
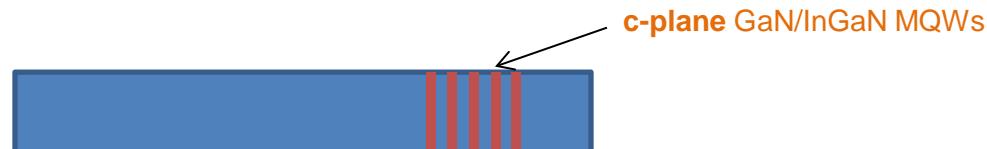
### Overlap Calculation

$$\Gamma_z := \frac{t_{\text{QW}} \cdot N_{\text{wells}}}{\text{Length}} = 3 \times 10^{-3}$$

$$\Gamma_{\text{tot}} := \Gamma_{xy} \cdot \Gamma_z$$

### Threshold Gain

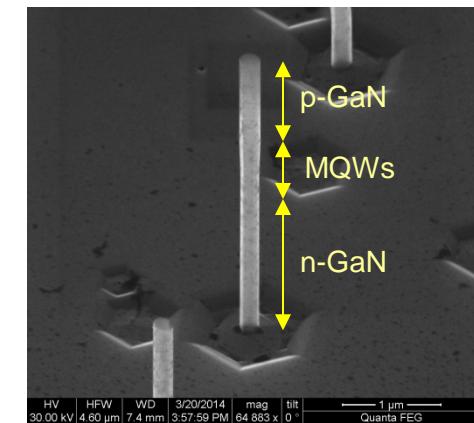
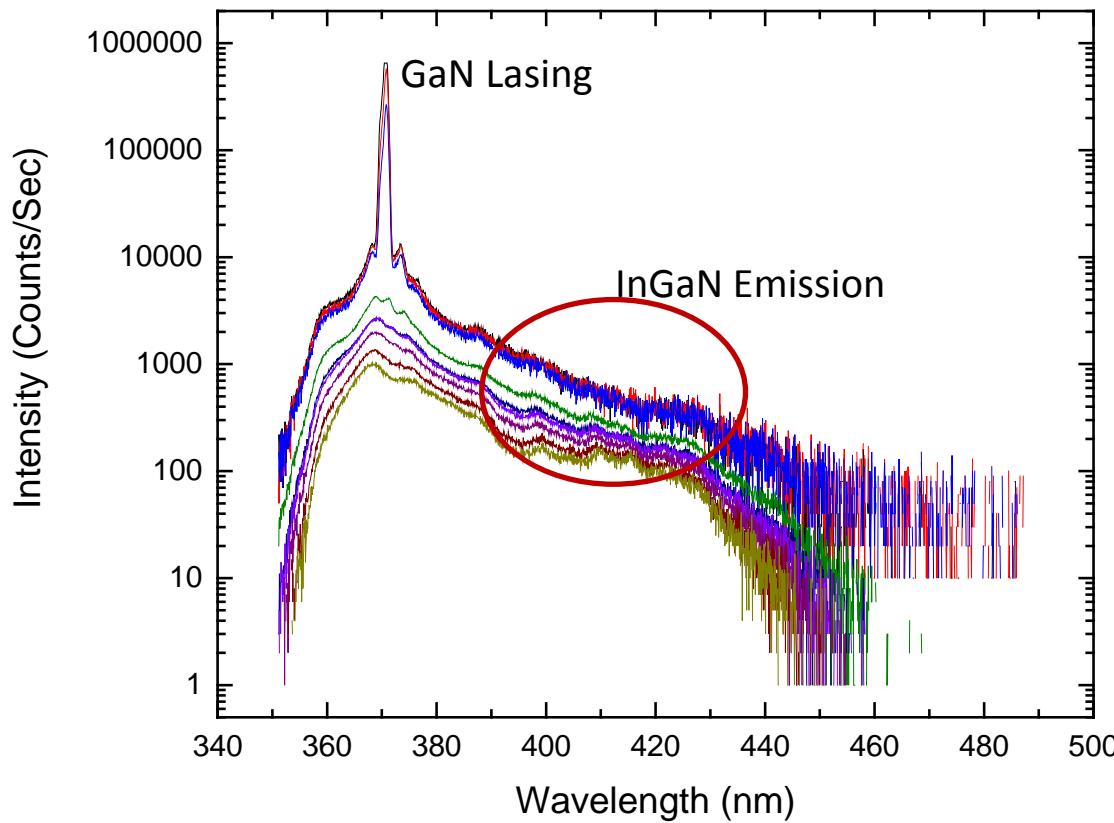
$$g_{\text{th}} := \frac{1}{\text{Length}} \cdot \ln\left(\frac{1}{r_1 \cdot r_2}\right) \cdot \frac{1}{\Gamma_{\text{tot}}}$$



Need unrealistically high mirror reflectivities for axial NW design!  
(focus on radial NW design)

# Key Accomplishments

## Fabrication and optical characterization of axial GaN/InGaN MQW NW diode



No InGaN lasing observed for axial NW laser diode structure