2016 IWN Conference

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Fabrication and Control of III-Nitride Nanowire Lasers

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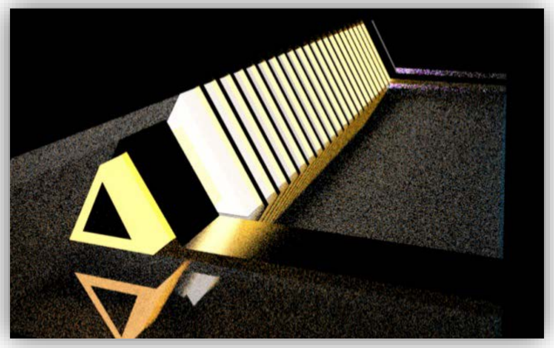
Nanowire Lasers

- 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

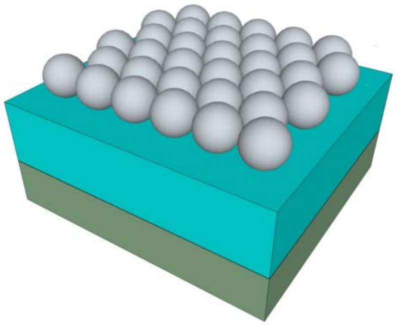


Nanowire lasers: *need to understand & control optical properties*

- **Mode control** – single vs. multi-mode behavior
- **Polarization control** – linear vs. elliptical
- **Wavelength tuning**
- **Beam shaping**
- **Beam steering**

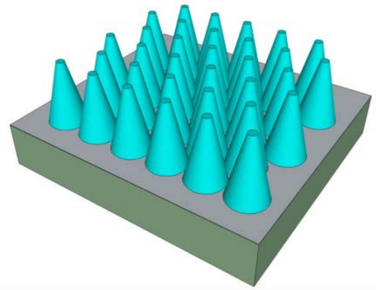
1) S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7,** 074599-1 (2013)
2) C. Couteau et al., "Nanowire Lasers," *Nanophotonics* **4**, 90 (2015)

Dry + wet top-down ordered nanowire fabrication process

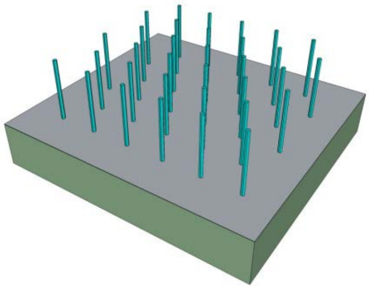


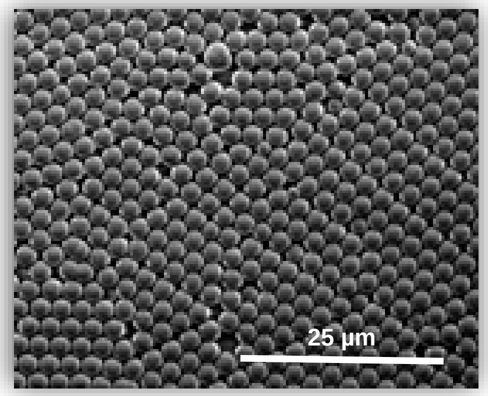
(0001) GaN on sapphire

ICP etch

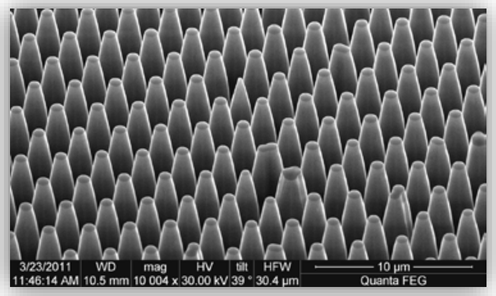


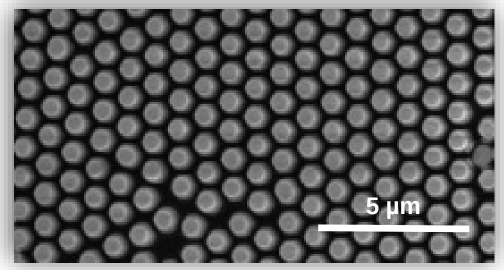
Selective KOH-based wet etch
(AZ-400K developer)





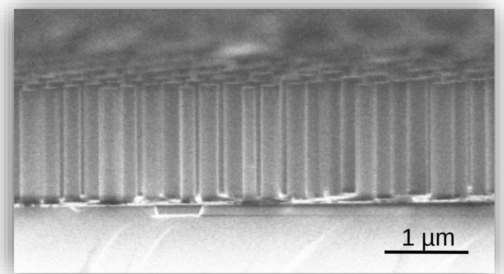
Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).

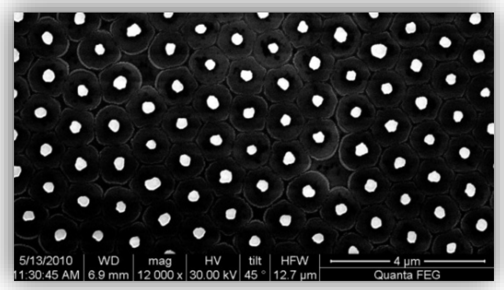




Plasma etch causes sidewall damage

Tapered; no well-defined facets





Wet etch: straight sidewalls, removes sidewall damage

Straight GaN nanowires with controllable geometries

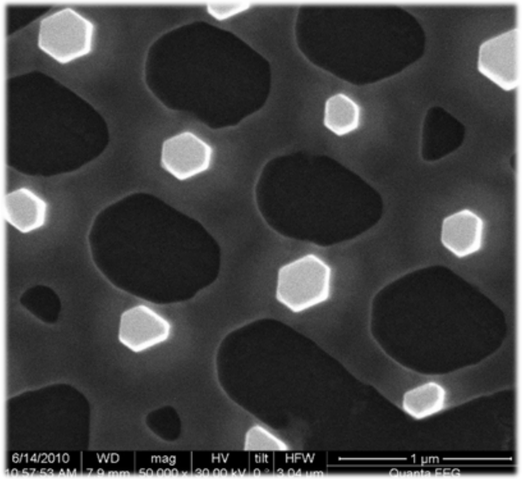
Wet etch rate negligible for top (Ga-polar) *c*-face & fast for semipolar facets, leads to NWs with **straight & smooth** *m*-facets

Superior and independent control of:

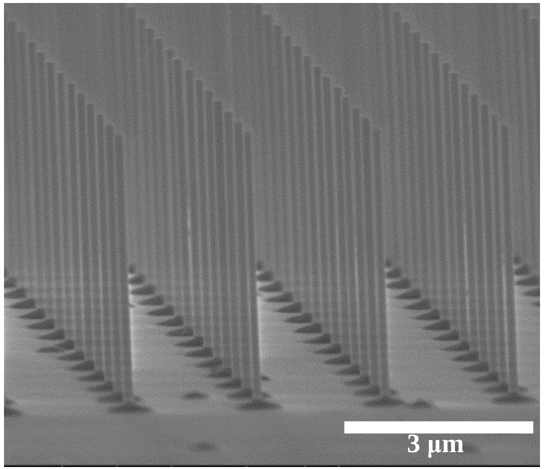
Height (dry etch depth)

Diameter (wet etch time)

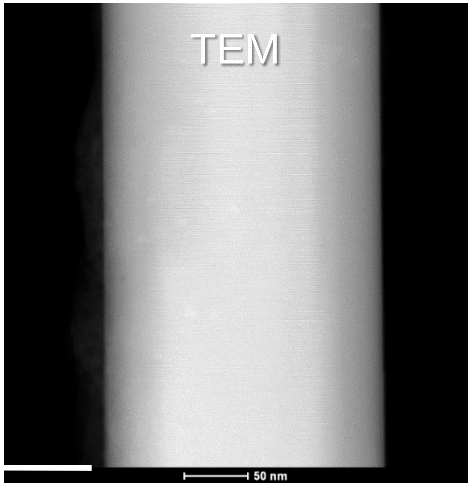
Pitch/arrangement (defined by masking template)



Following GaN regrowth



Mask using e-beam lithography

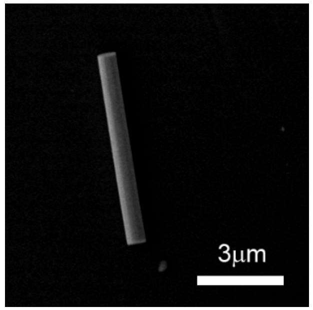


Smooth sidewall created by wet etch

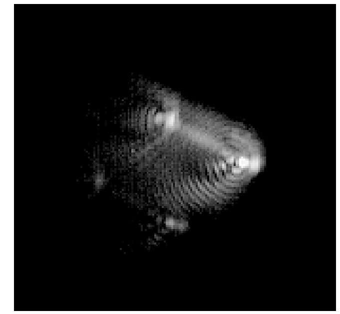
TEM: Ping Lu, SNL

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

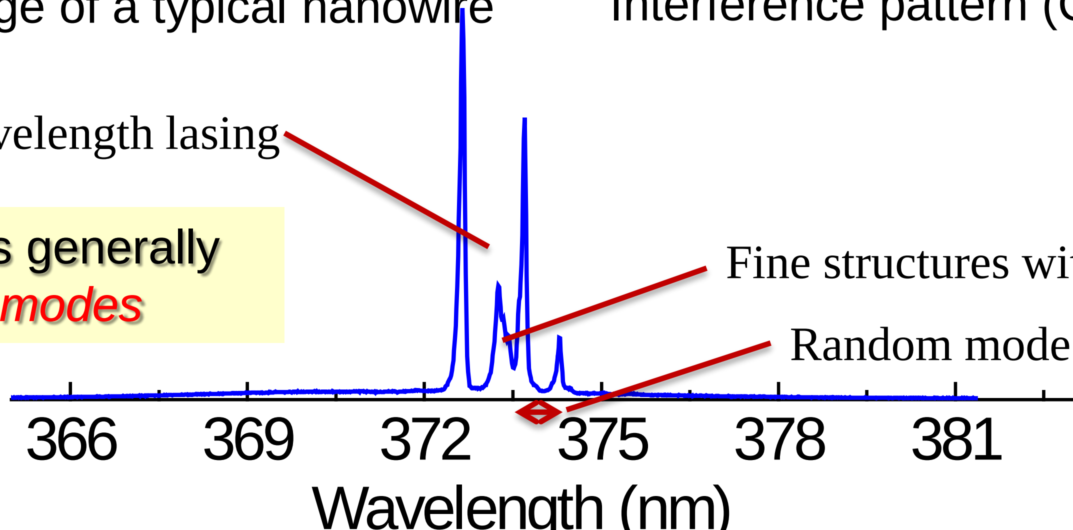
Typical GaN Nanowire Lasing: Multimode Operation



SEM image of a typical nanowire



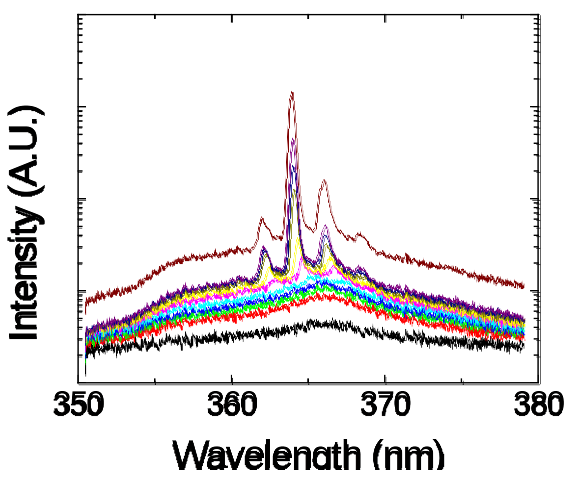
Interference pattern (CCD image)

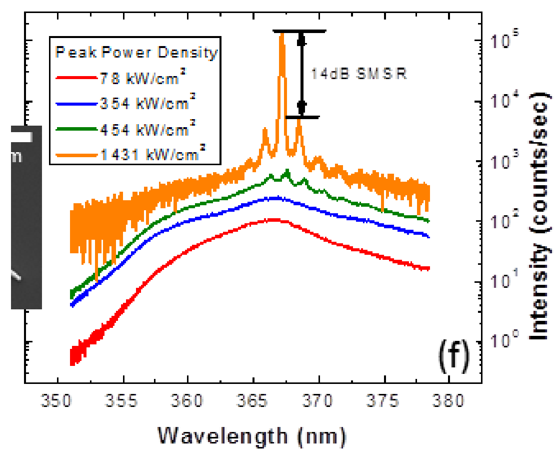


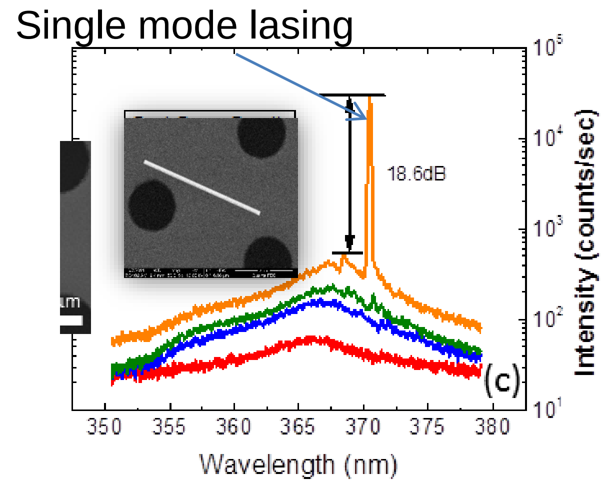
Nanowire lasers generally exhibit *multiple modes*

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

Method 1: Single-mode NW laser via geometry control







~500 nm x **4.7µm (short)** **145 nm** x 7.2 µm **(skinny)** **~130nm x 4.7µm (short & skinny)**

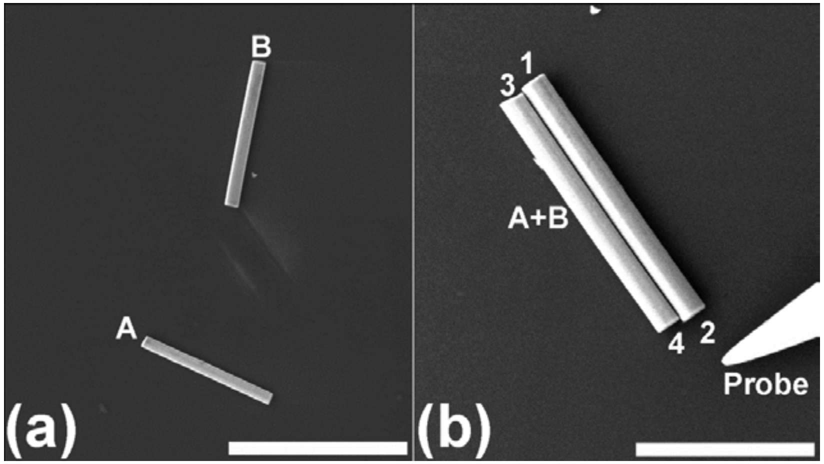
NW diameter x length

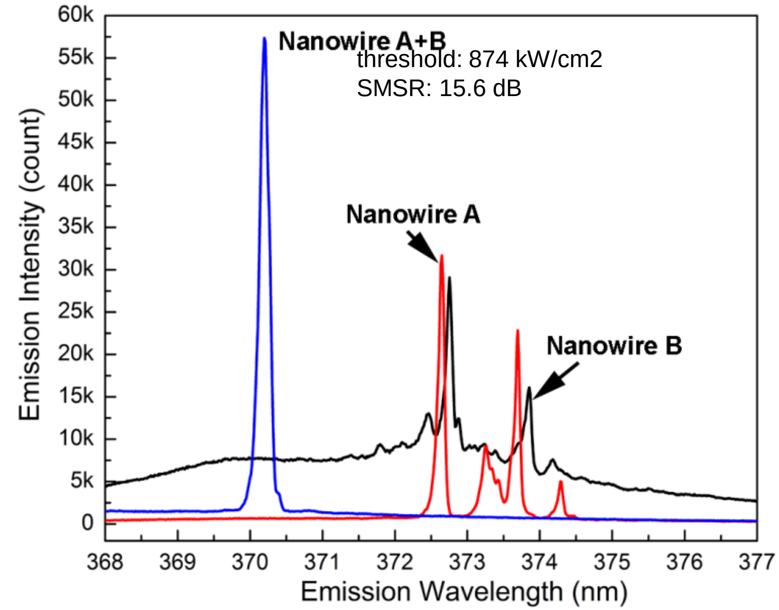
Single-mode: Narrow-Linewidth (<0.1 nm), 18.6 dB Side Mode Suppression Ratio

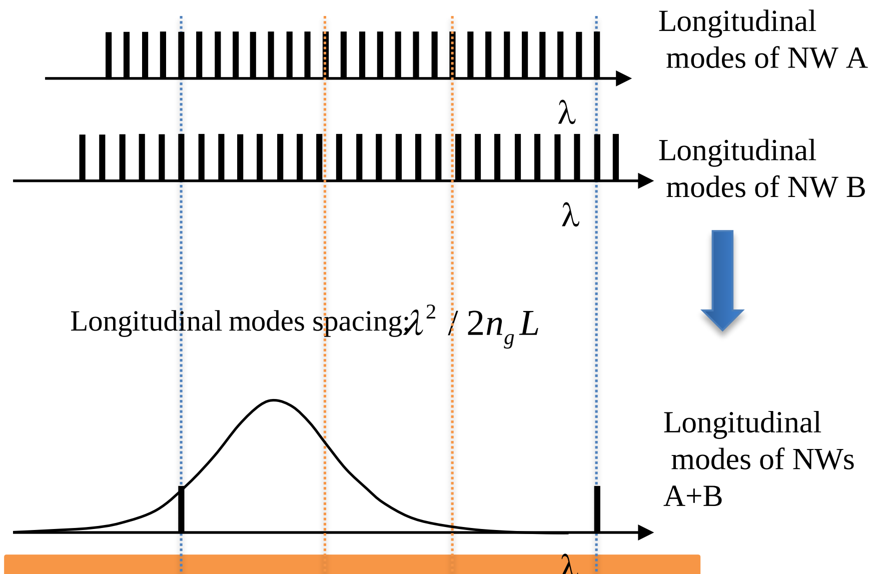
- Reduction of diameter (<~130 nm): reduction of transverse modes
- Reduction of length: (<~6 µm length): reduction of longitudinal modes
- **Reduced dimensionality leads to single mode lasing**

Q. Li et al., "Single-Mode GaN Nanowire Lasers," *Opt. Exp.* ***20*** *17873 (2012)*

Method 2: Single-mode lasing via coupled nanowire cavities







Longitudinal mode spacing greatly enhanced!

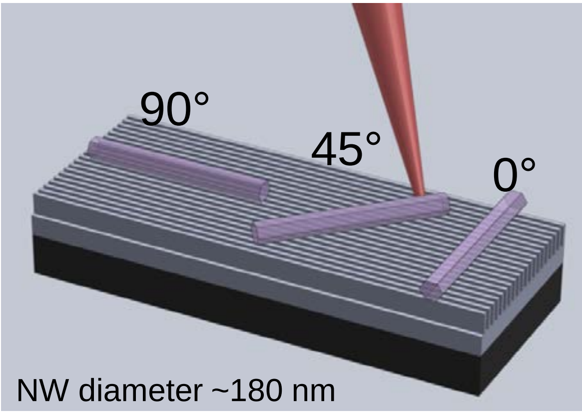
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

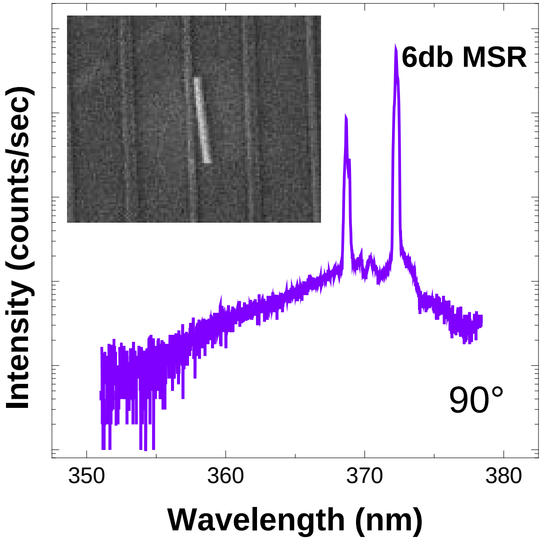
H. Xu et al., "Single-mode lasing of GaN nanowire-pairs,"*Appl. Phys. Lett.* **101** 113106 (2012)

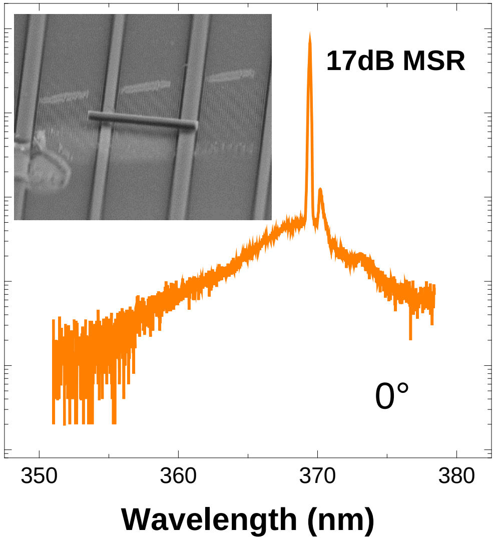
SSLS EFRC

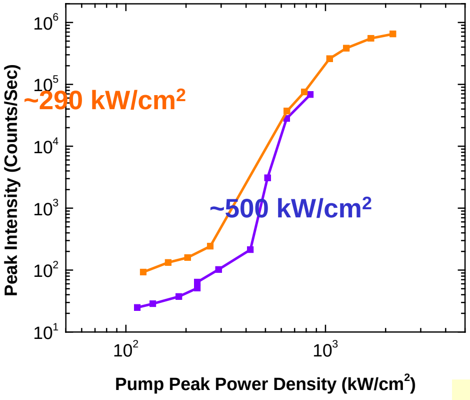
Method 3: Distributed Feedback (DFB) Nanowire Laser

- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve DFB
- Stop-band position and width tuning via nanomanipulation of the angular alignment







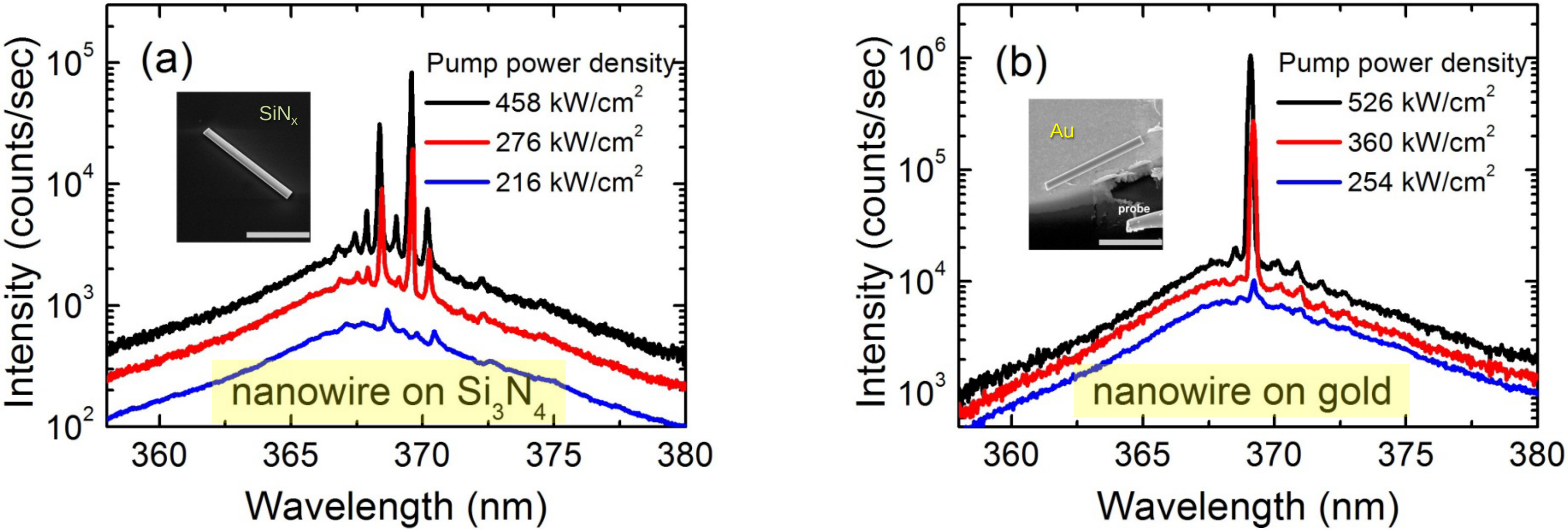


- At the designed alignment <u>single-mode lasing was achieved</u> with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

J.B. Wright, S. Campione, S. Liu, J.A. Martinez, H Xu, T.S. Luk, Q. Li, G.T. Wang, B.S. Swartzentruber, L.F. Lester, and I. Brener, APL 104 (4), 041107 2014.

Method 4: Metal substrate induced single-mode nanowire lasing

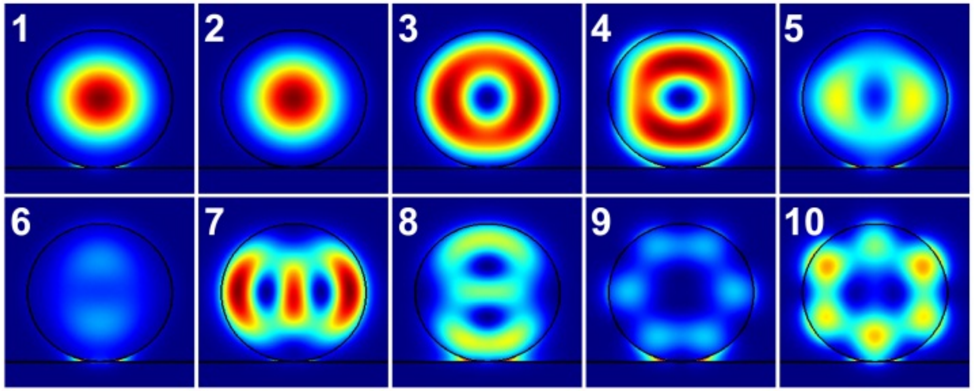
diameter~350 nm, length ~5.3 µm



- NWs on Si_3N_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., "Gold substrate-induced single-mode lasing of GaN nanowires, "*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

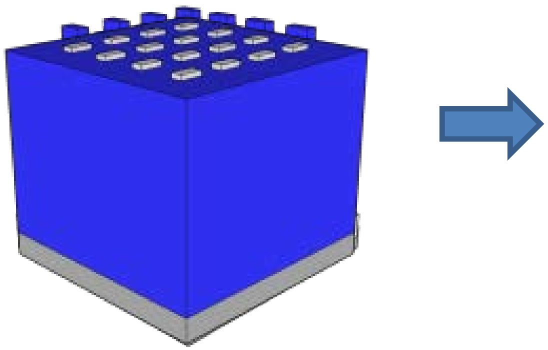
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Loss (dB/cm)	8151	1730	4806	7109	16041
	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
Loss (dB/cm)	34858	7551	22205	29175	28706

Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss

Sandia National Laboratories

Intrinsic polarization control from rectangular nanowire lasers



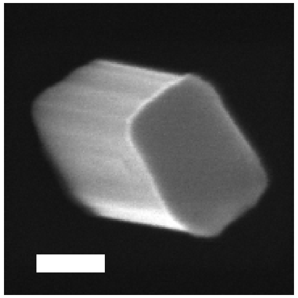
- Top-down approach enables *cross-sectional shape control* of NWs
- Previous work: change from elliptical to linearly polarized emission when nanowire placed on gold substrate

H. Xu et al., *Optics Express*, ***22***, 19198 **(2014)**.

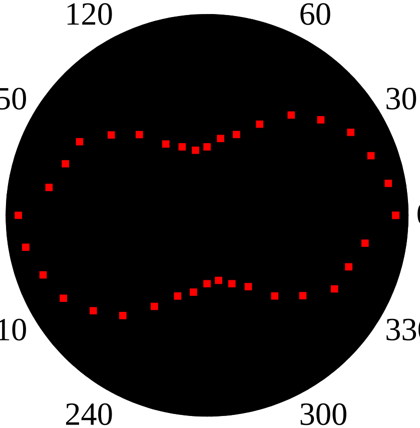
- Rectangular GaN nanowire lasers show *intrinsic linearly polarized emission*, obviating the need for manipulation by external environments

Li, Changyi, et al. "Intrinsic polarization control in rectangular GaN nanowire lasers." *Nanoscale* ***8***, 5682 (2016).

Less rectangular

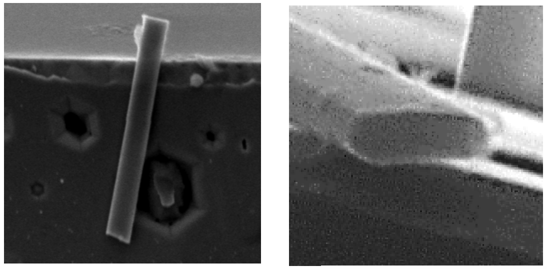


Y = 300nm
X = 450nm

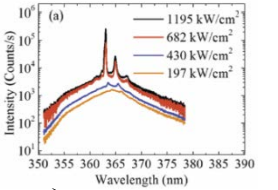


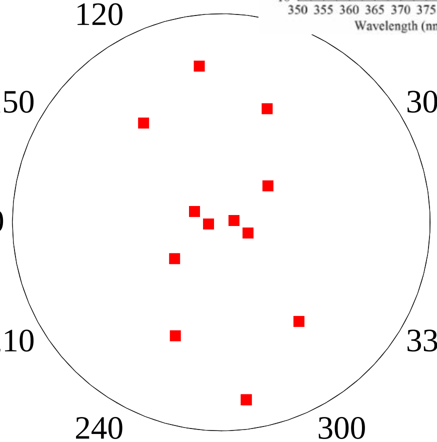
Elliptical polarization

More rectangular



Y = 120nm
X = 450nm



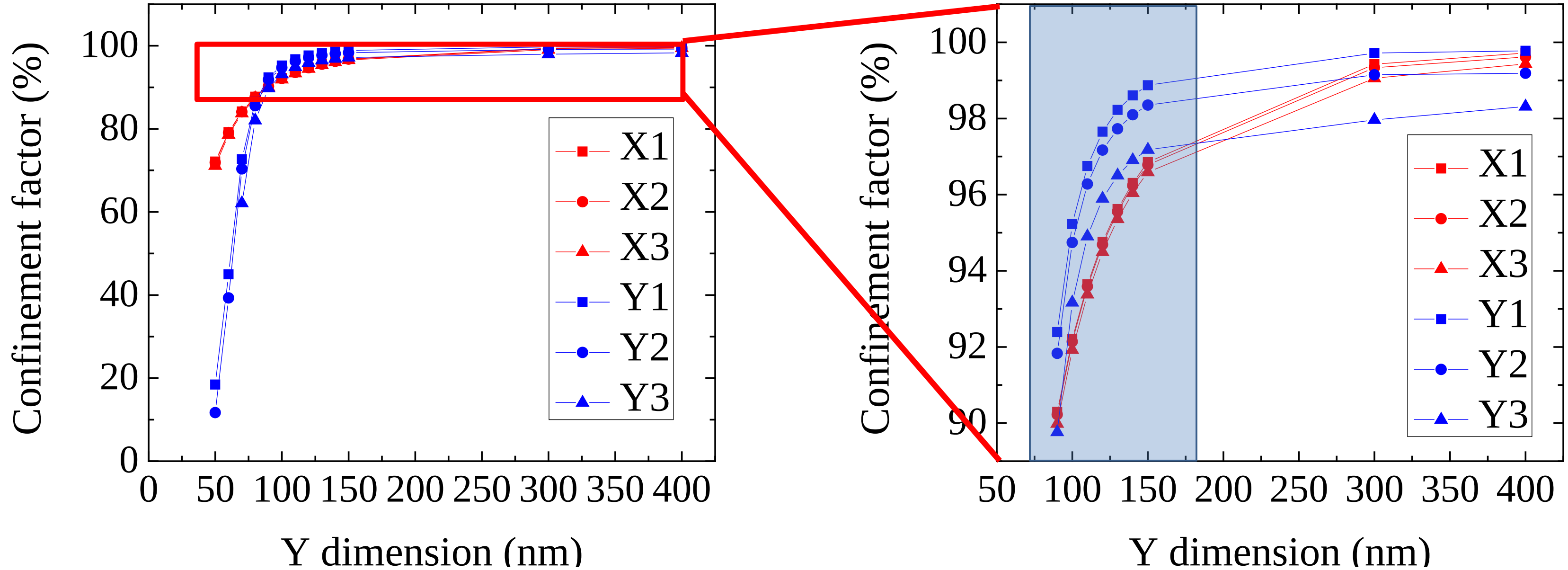


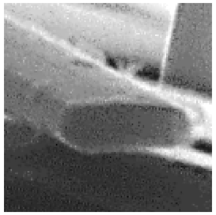
Linear polarization

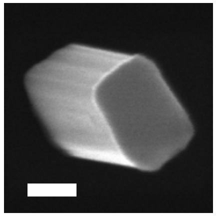
SSLS EFRC

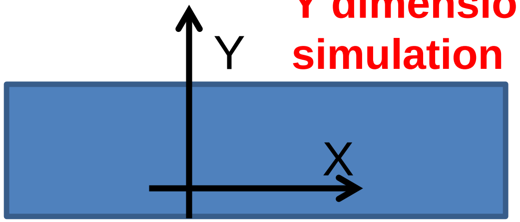
Mode simulation of rectangular cross-sectional GaN nanowire lasers

Calculated confinement factors of transverse modes









Y dimension: varied during simulation

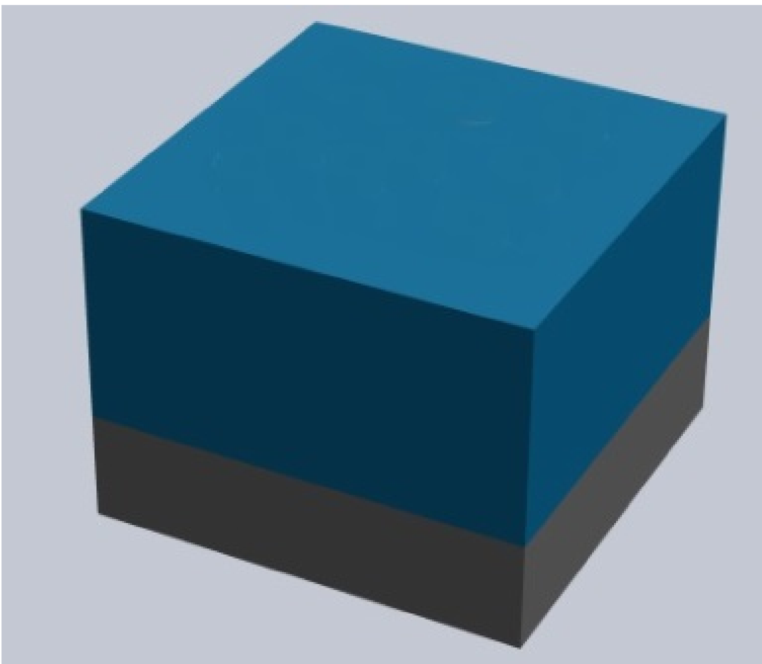
X dimension: fixed at 450 nm

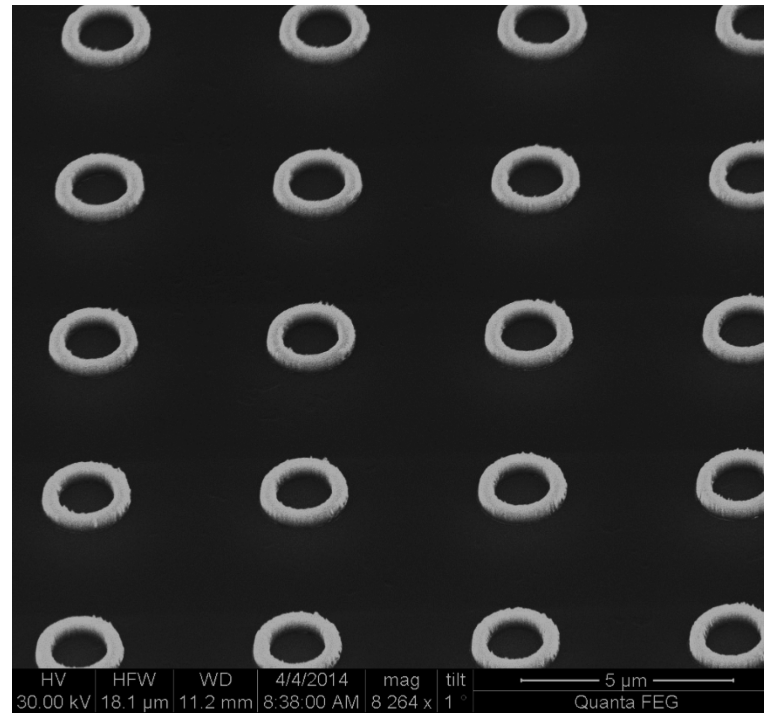
- Below Y-dimensions ~ 200 nm, confinement factors for Y-polarized modes dominate over X-polarized modes, leading to linearly polarized emission

Li, Changyi, et al. "Intrinsic polarization control in rectangular GaN nanowire lasers." *Nanoscale* ***8***, 5682 (2016).

Cross-sectional shape control- GaN nanotubes

EBL Patterning and PMMA Lift-off

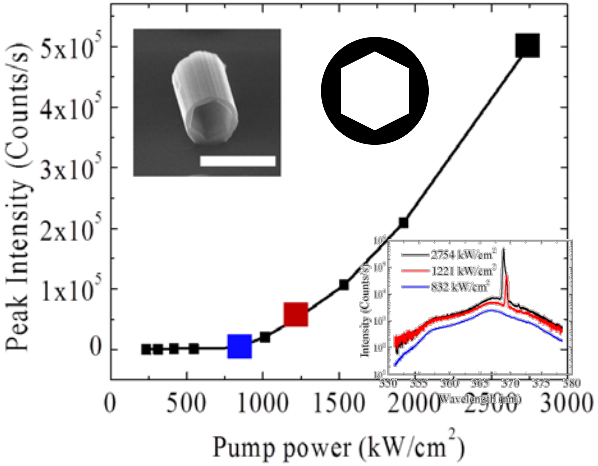


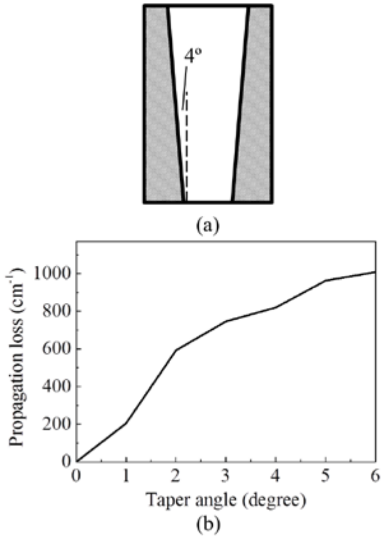


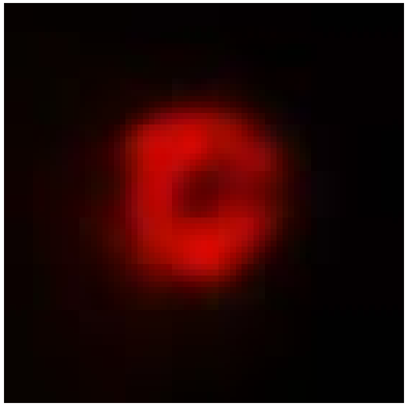
C. Li et al., "Annular-Shaped Emission from Gallium Nitride Nanotube Lasers", *ACS Photonics*, **2**, 1025 **(2015)**.

Annular emission from GaN nanotube lasers

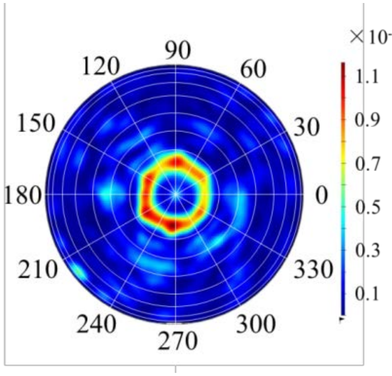
- Length: 4µm
- Outer Diameter: 1.3µm
- Thickness: 150nm







CCD image far field lasing emission from nanotube



Simulated far field pattern of nanotube

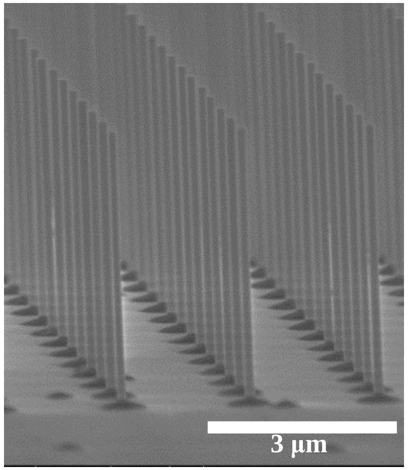
Threshold pump density = 1055 kW/cm^2

- Higher threshold of nanotube vs. nanowire may be due in part to inner taper
- Hollow nanotube geometry potentially useful for optofluidic/biosensing applications (lases in silicone oil but with higher threshold)
- Observed annular shaped emission agrees with predicted emission and shows *use of cross-sectional shape control for beam shaping* in nanowire lasers

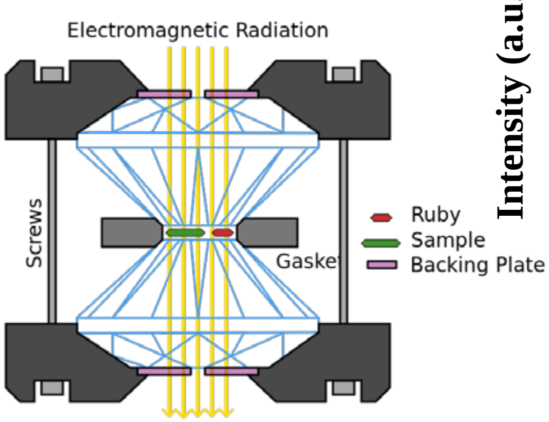
C. Li et al., "Annular-Shaped Emission from Gallium Nitride Nanotube Lasers", *ACS Photonics*, **2**, 1025 **(2015)**.

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

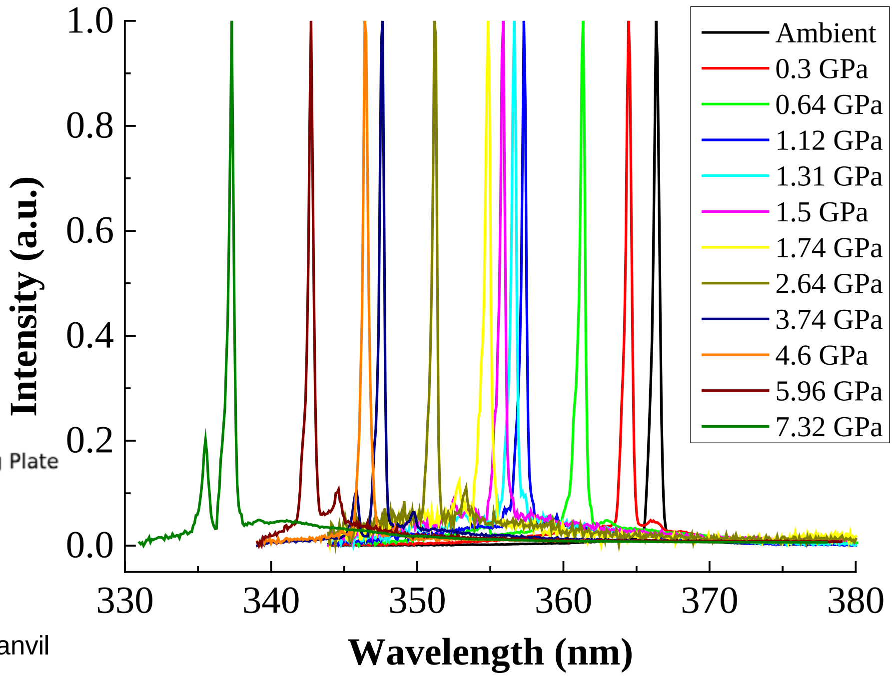
NWs patterned using e-beam lithography:
Diameter ~140 nm
Length ~ 4µm



Diamond Anvil Cell: Hydrostatic pressure medium (silicone oil) transmits pressure isotropically



http://en.wikipedia.org/wiki/Diamond_anvil_cell

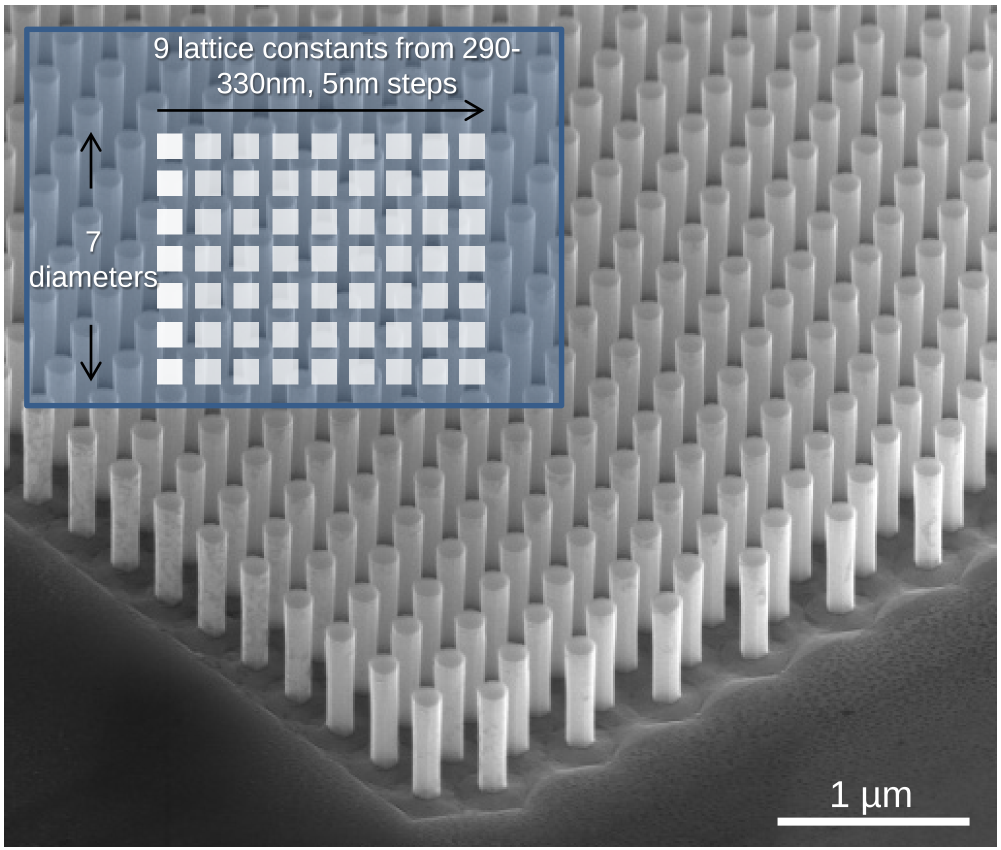


S. Liu, C. Li, J. J. Figiel, S. R. Brueck, I. Brener, G. T. Wang, *Nanoscale*, ***7***, 9581 **(2015)**.

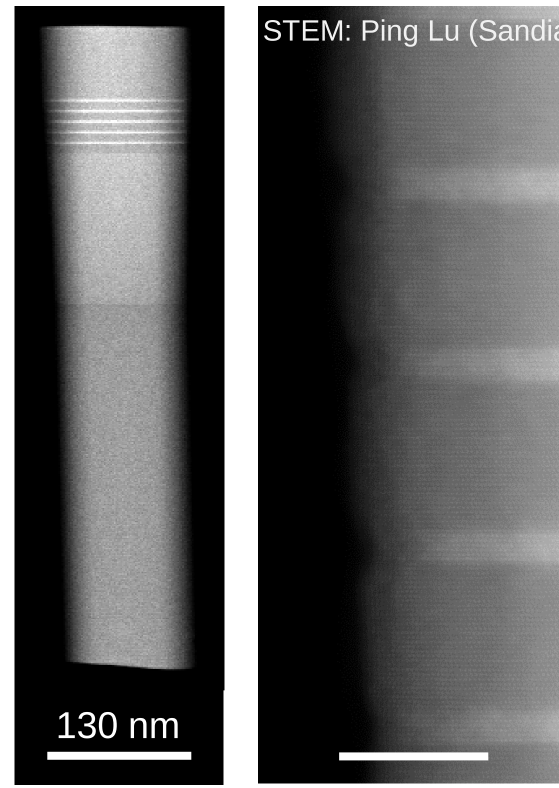
- Applied pressure induces bandgap increase
- Continuous and reversible tuning ~30 nm lasing tuning demonstrated over ~7.3 GPa (previous works were wavelength selection)
- Well defined fine tuning (<0.1nm) possible with current setup

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

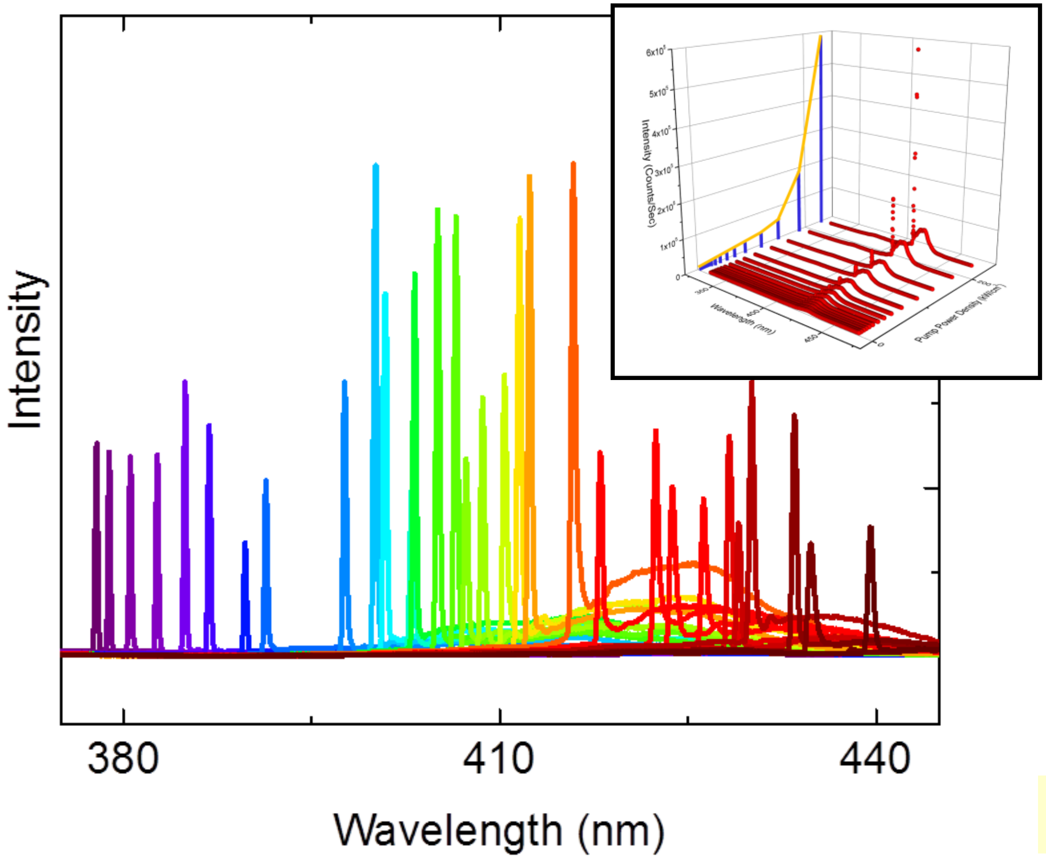


NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

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



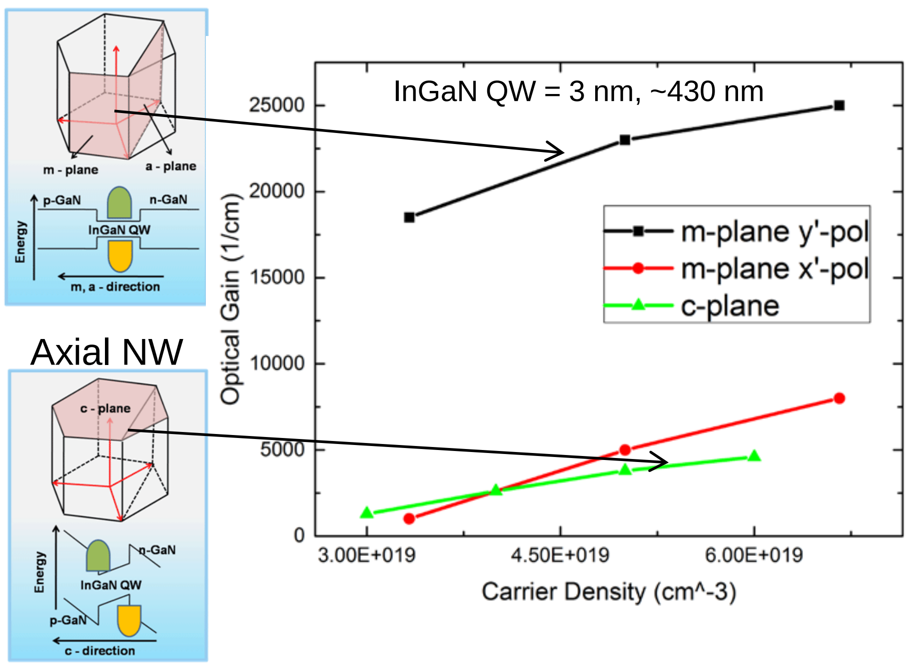
- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm^2 for all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

J.B. Wright et al., “Multi-Colour Nanowire Photonic Crystal Laser Pixels,” *Scientific Reports* 3, Article number: 2982 (2013)

Optical gain for axial vs radial InGaN/GaN nanowire designs

Optical Gain - Crystallographic Dependence

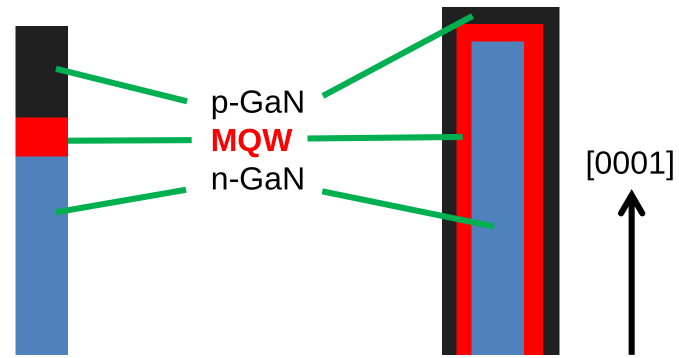
Radial NW



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

Optical Gain – Axial vs. Radial Geometry

L = 6 µm, R = 250nm, Thickness of MQW = 20nm



Axial structure

$V_{active} = 0.003925\ \mu m^3$

Radial structure

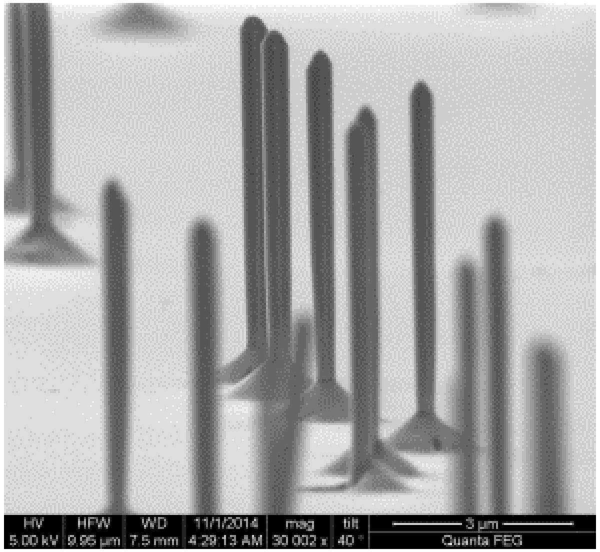
$V_{active} = 0.1884\ \mu m^3$

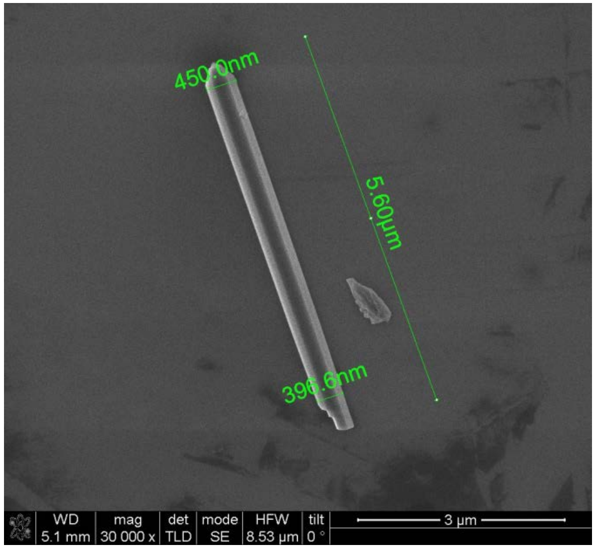
Radial: 48 times larger gain region compared to axial

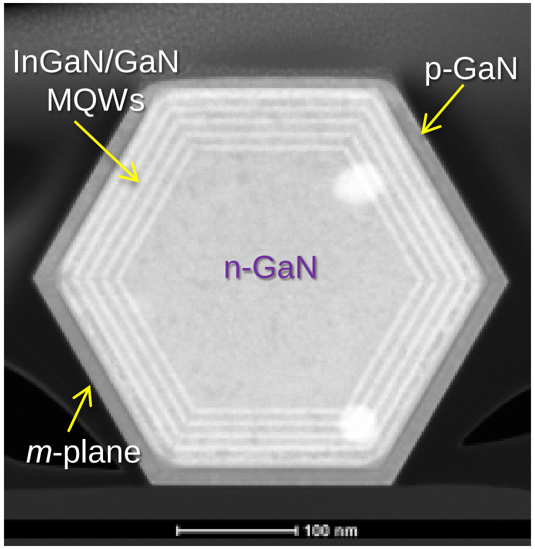
S.-H. Park and D. Ahn, "Optical polarization characteristics of m-plane InGaN/GaN quantum well structures and comparison with experiment," *Appl. Phys. Lett.*, **103**, *pp. -, (2013)*

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.

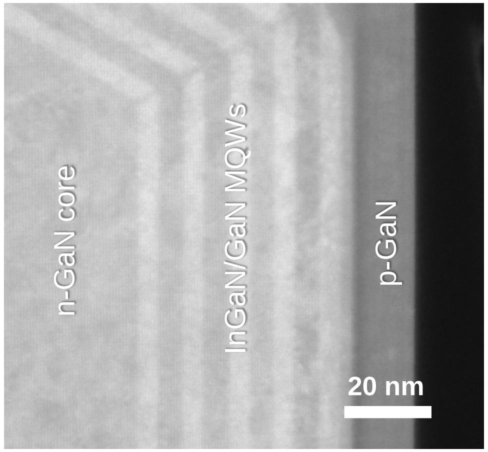
Synthesis of core-shell p-i-n InGaN/GaN core-shell NW lasers







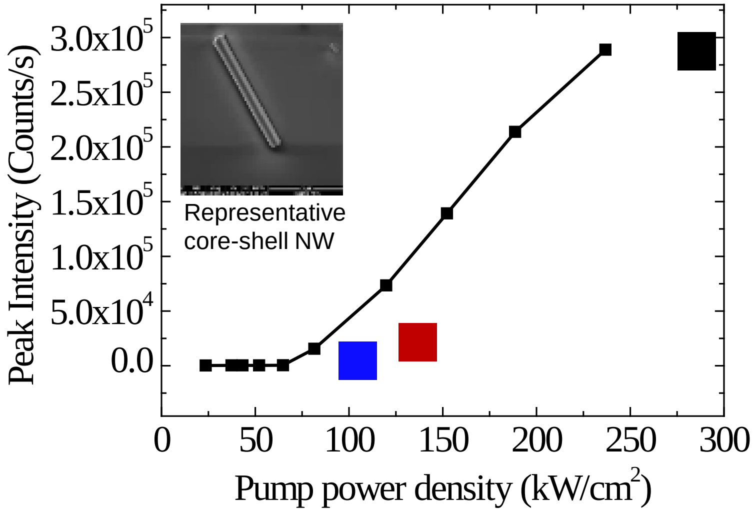
Core-shell radial p-i-n InGaN/GaN MQW nanowires following MOCVD regrowth on top-down fabricated n-type GaN nanowires



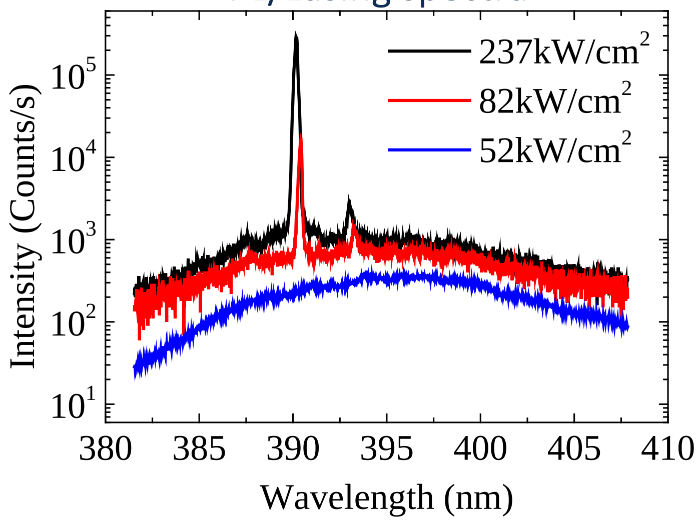
STEM by Ping Lu

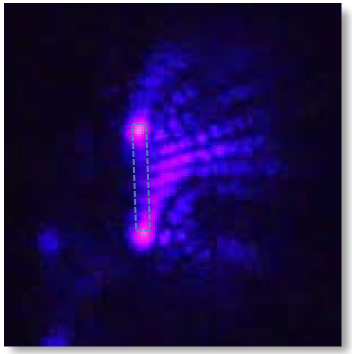
- Regrowth on top-down n-GaN nanowire results in taper. Growth of semipolar planes also results in non-flat tip, which may lower mirror reflectivity
- Growth conditions, layer thicknesses, varied over several runs, then nanowires tested by optical pumping for lasing

Optically pumped lasing from radial nonpolar p-i-n InGaN/GaN MQW nanowires



PL/Lasing spectra

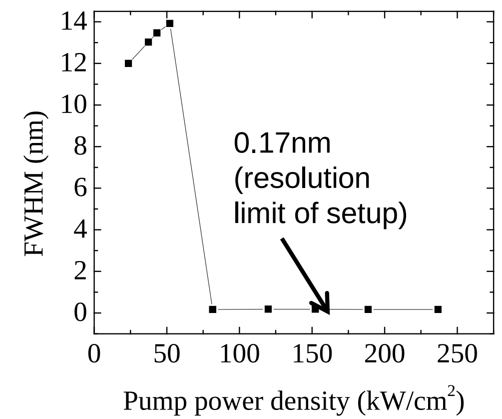



CCD image of lasing NW

Threshold pump density = 75 kW/cm^2

Lower than thresholds for semipolar InGaN/GaN core-shell nanowires (~700-2000 kW/cm^2) (Qian, F et al. C. M. *Nat. Mater.* **2008**, *7* (9), 701–706.)

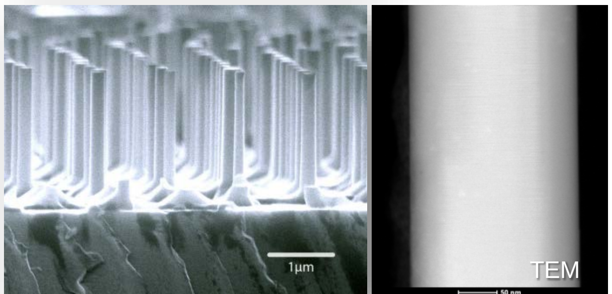
- First non-polar GaN/InGaN MQW core-shell single NW laser
- Demonstrates feasibility of p-i-n core-shell architecture for future electrically injected single nanowire lasers



C. Li et al., under preparation

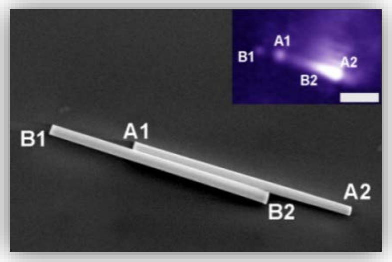
Summary

Precision top-down fabrication *controlled geometries*

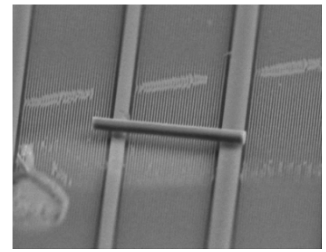


Q. Li et al., *Optics Express* **19**, 25528 (2011)

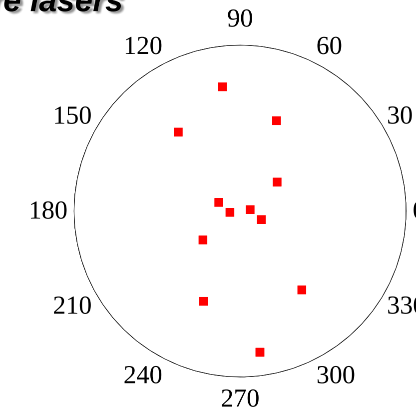
Mode & polarization control in GaN nanowire lasers



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)

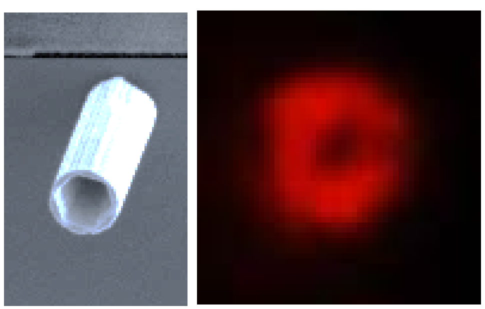


J.B. Wright et al., *Appl. Phys. Lett.*, 104, 041107 (2014).



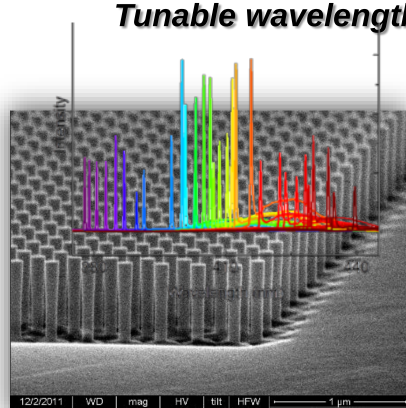
Li, Changyi, et al. *Nanoscale* ***8***, 5682 (2016).

Beam shape control nanotube lasers

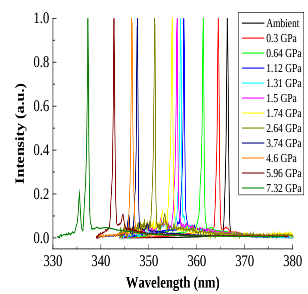


C. Li et al., *ACS Photonics*, **2**, 1025 **(2015)**.

Tunable wavelength nanowire lasers

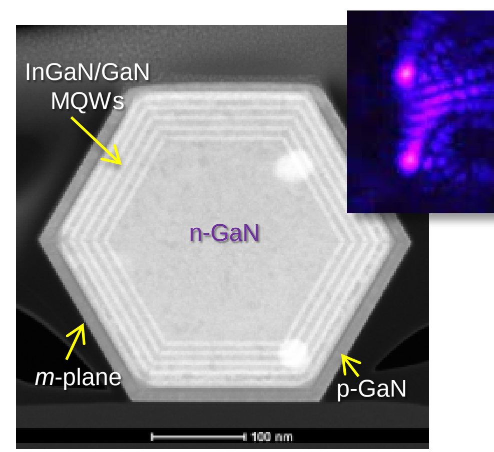


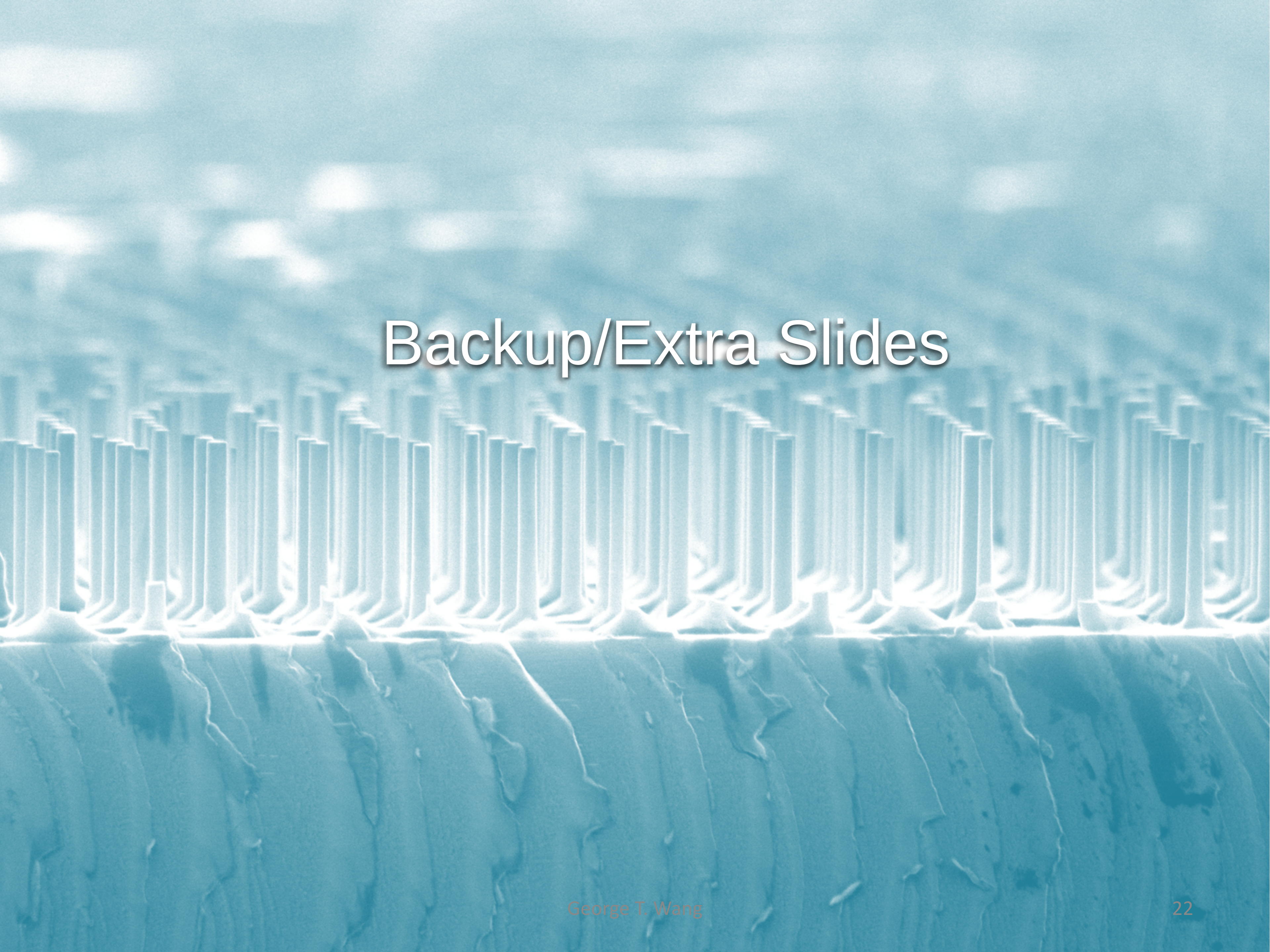
J.B. Wright et al., *Sci. Reports* 3, Art no. 2982 (2013) doi:10.1038/srep02982



S. Liu, C. Li, J. J. Figiel, S. R. Brueck, I. Brener, G. T. Wang, *Nanoscale*, *7*, 9581 **(2015)**.

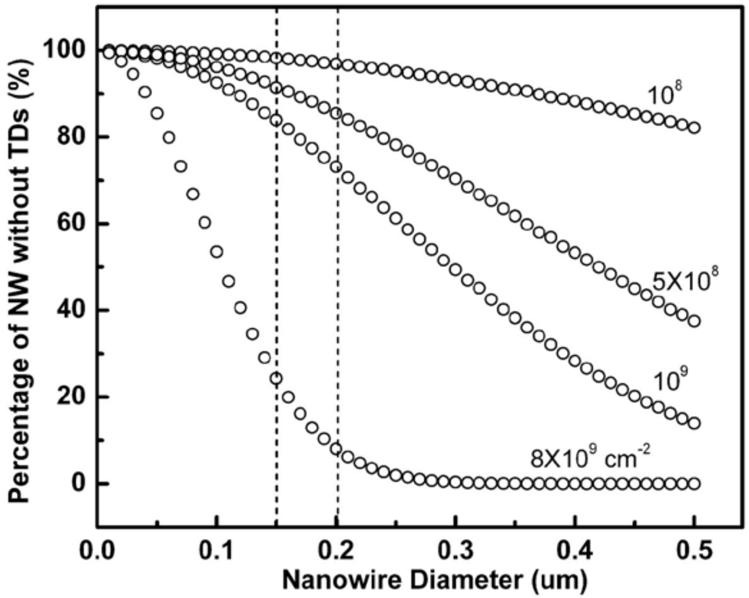
Nonpolar core-shell nanowire lasers



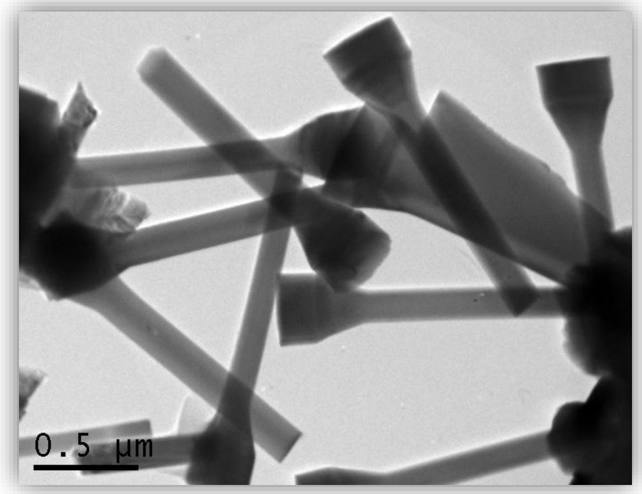

Backup/Extra Slides

Top-down nanowire threading dislocations

Monte Carlo simulation



Bright-field TEM

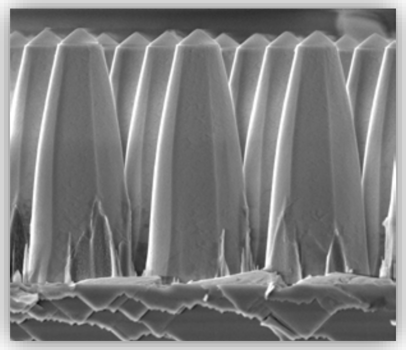


Nanowires etched from ~5e8 cm^{-2} planar LED

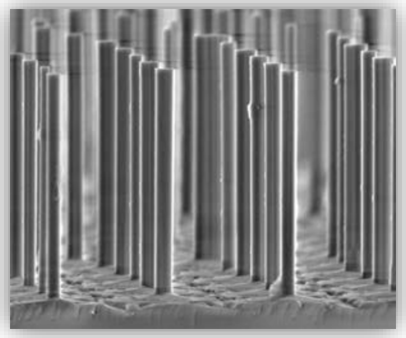
- Etched nanowires inherit the dislocation density of the parent film
- However, as the diameter approaches zero, the *fraction* of nanowires with one or more dislocations also approaches zero! [# TDs per rod ~ (TDD)×($A_{cross\text{-}section}$)]
- ~94% of nanowires ~150 nm in diameter from TDD~5e8 cm^{-2}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

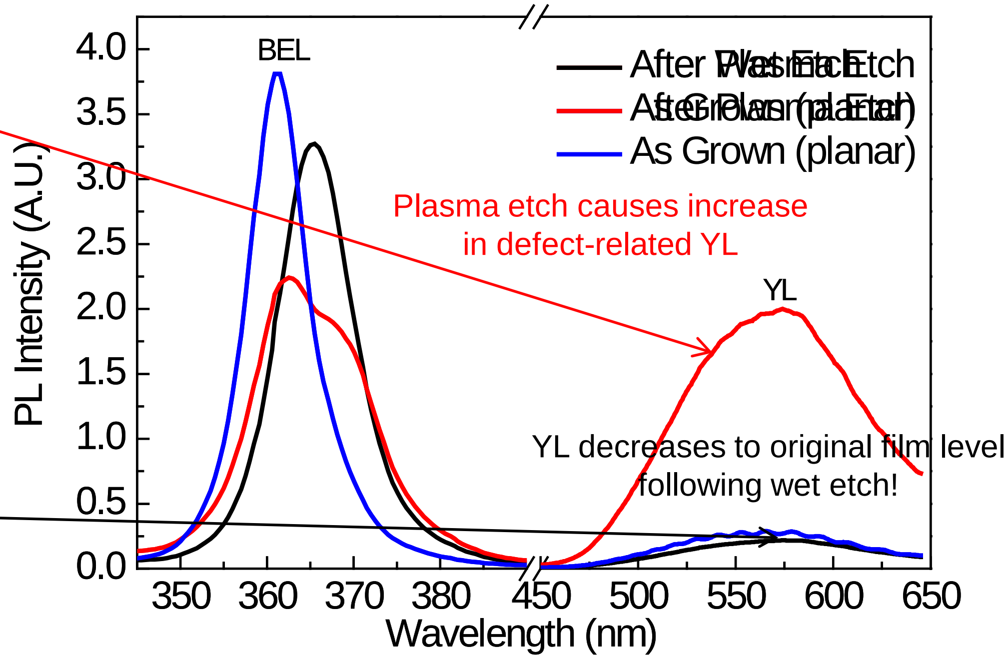
Wet etch step removes plasma etch damage

Plasma etch only



After wet etch



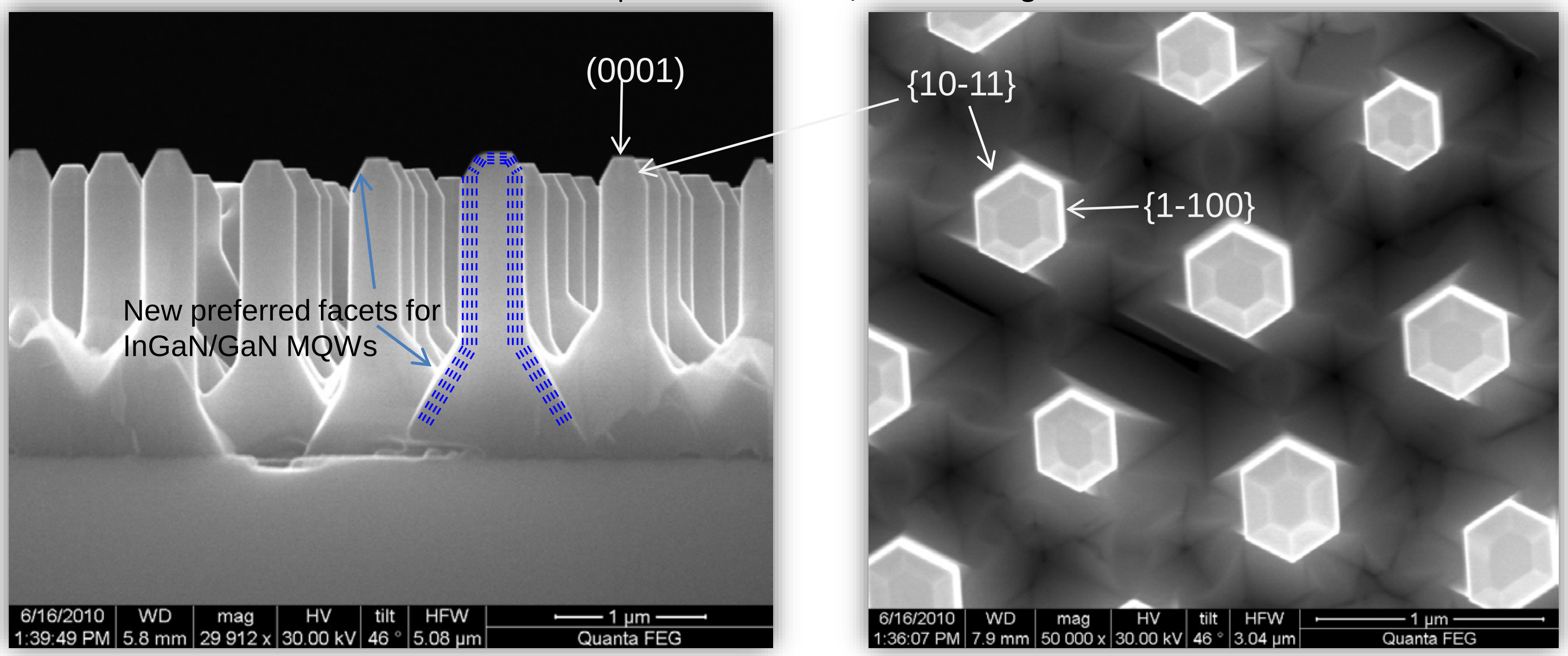


Radial core-shell InGaN/GaN MQWs on top-down NWs

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



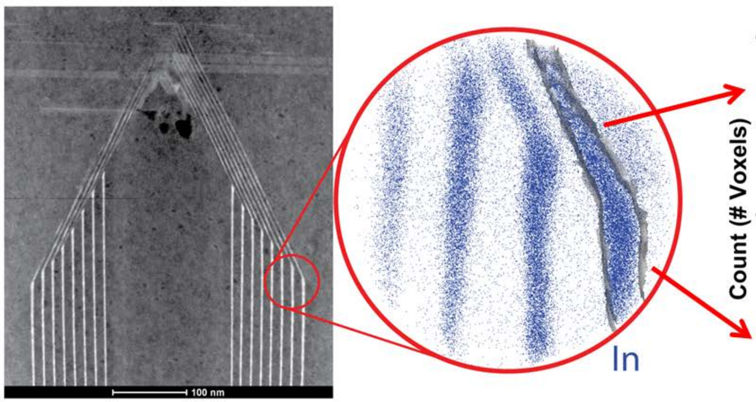
New semipolar facets form with InGaN/GaN MQW growth

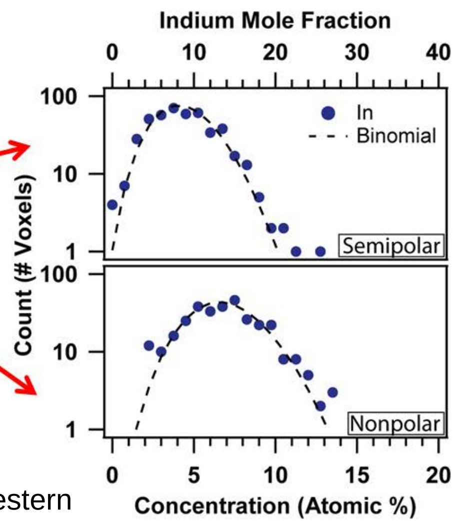
3-D Mapping of Quantum Wells in a GaN-InGaN Core-Shell Nanowire – a Correlated Study

STEM-EDS

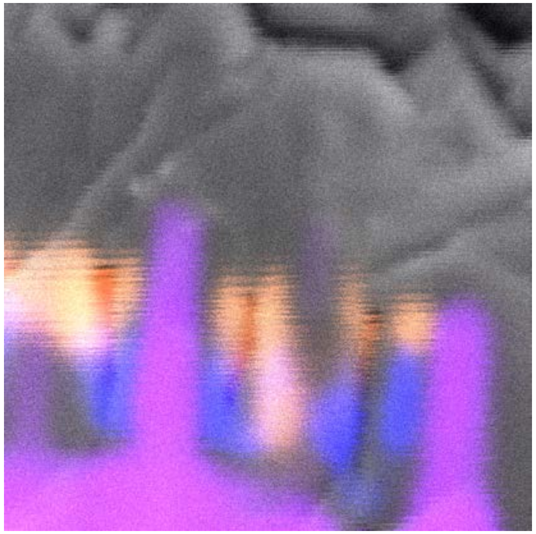
Atom probe tomography (APT)

Cathodoluminescence





APT: L. Lauhon, Northwestern



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).

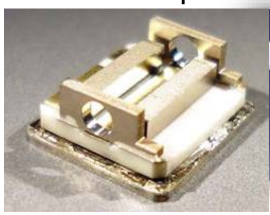
- Nonpolar and semipolar QWs from radial NW LED were imaged by APT and correlated with scanning TEM and cathodoluminescence data
- Results suggest yellow-red emission originates from In-rich tip regions, not sidewalls
- How to get long wavelength emission from m-plane sidewalls?

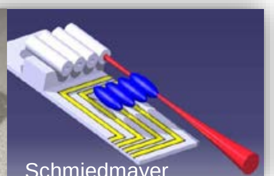
Why Nanowire Lasers?

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

Integrated nanophotonics, atom trapping, optical MEMS

atom trap



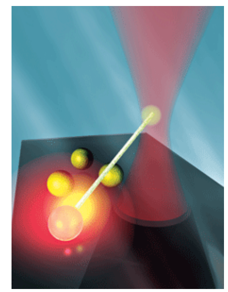


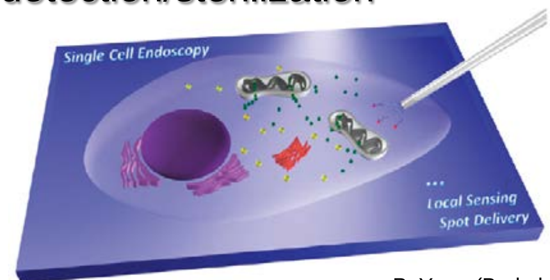
J. Ford, Lucent

P. Schwindt (1725)

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

Optical nanoprobes & chem/bio detection/sterilization

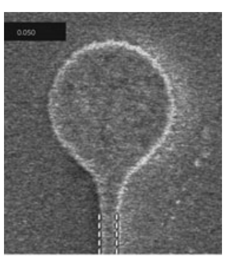


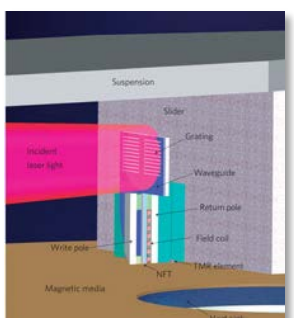


P. Yang (Berkeley)

Sub-λ resolution probes for localized excitation, detection

Nanolithography & Heat-assisted Magnetic Recording





Nature Photonics 3, 220 (2009)

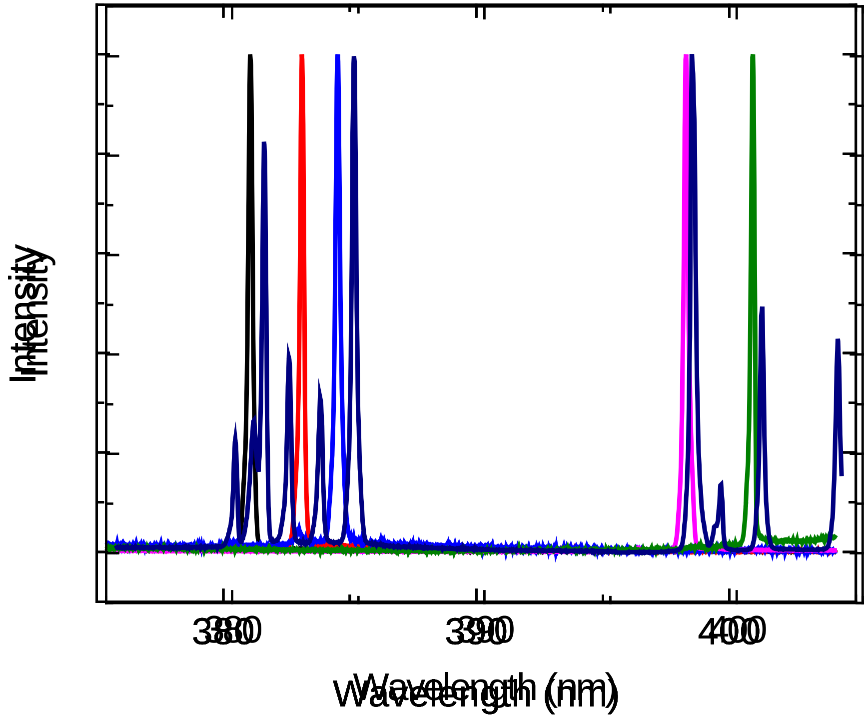
Seagate

Subwavelength & efficient laser spot

Lighting, projection, & holographic displays

Low-power, speckle-free low coherence (random laser), multicolor pixels

III-N Nanowire Photonic Crystal Lasers



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

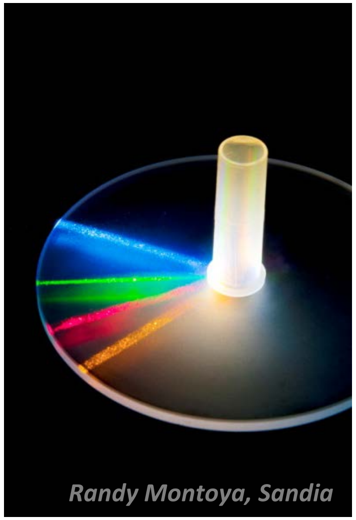
pitch: 320 nm
diameter: 130-140nm

10 um

Lasers for Solid State Lighting

Advantages of lasers for lighting:

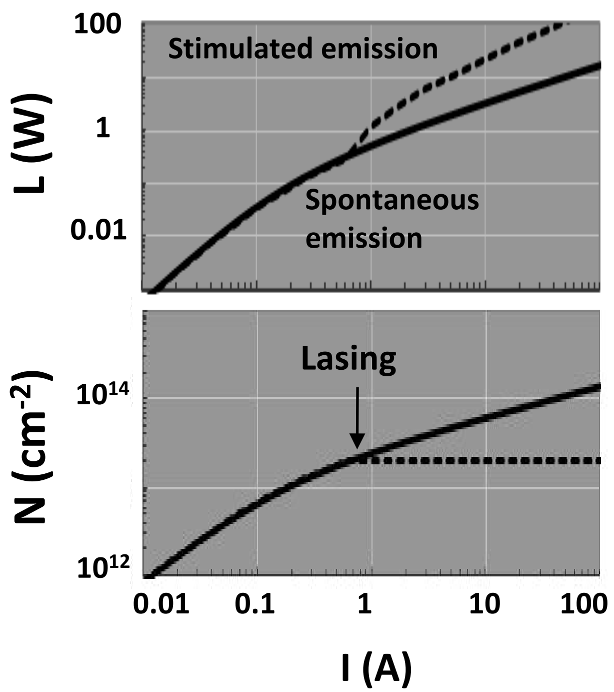
- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
  - Circumvent the droop problem in LEDs
  - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission,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



Laser Sources For SSL:

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

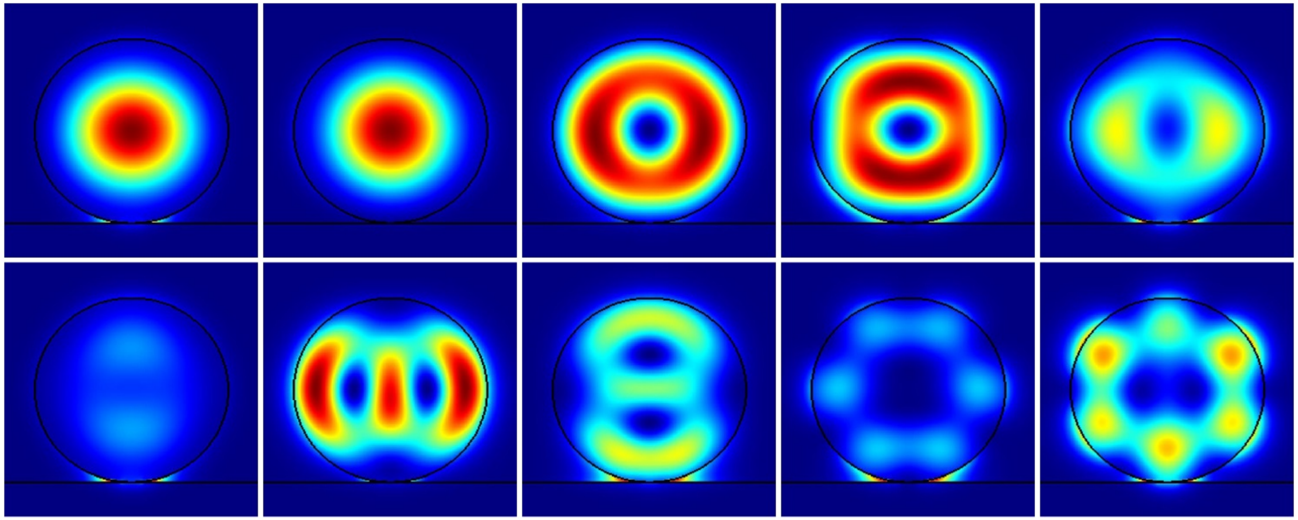
Clamped carrier density



Are narrow linewidth sources acceptable?

A.J. Fischer, Sandia

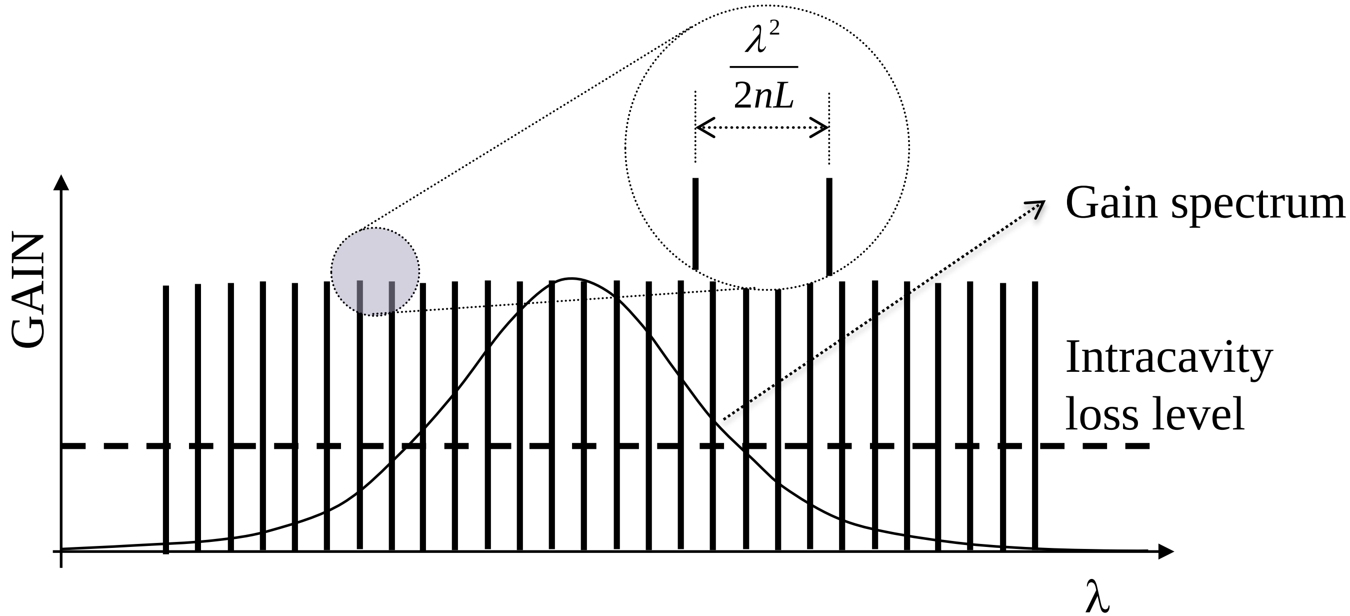
Why Multimode Lasing Occurs



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

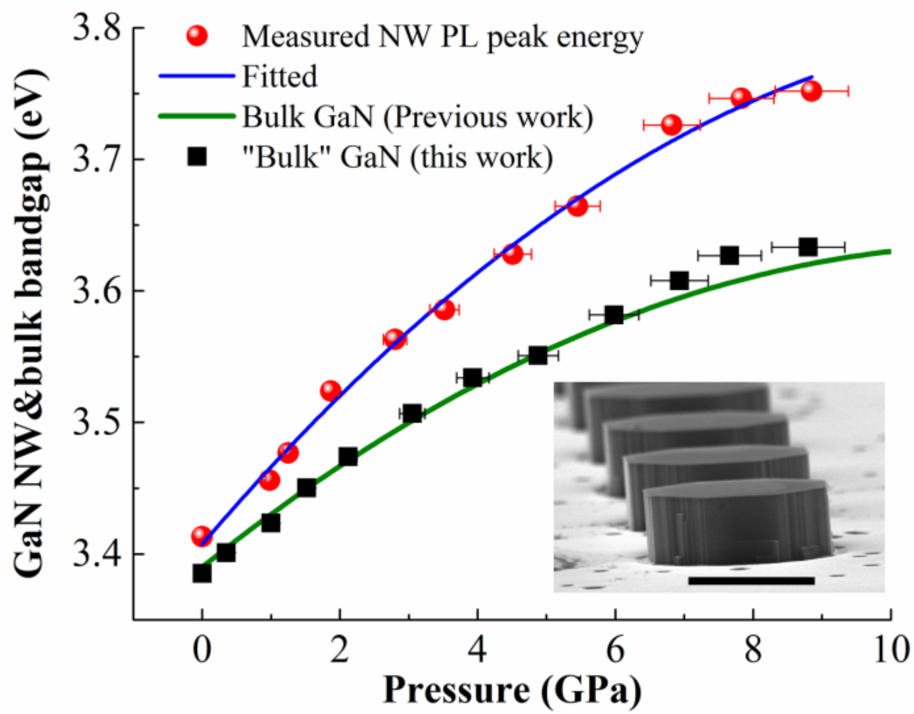
- ✓ Multiple transverse mode waveguide;
- ✓ Single-mode cutoff diameter ~120 nm;
- ✓ Lasing in multiple transverse mode operation
- ✓ Polarization is mode-dependent

Why Multimode Lasing Occurs



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

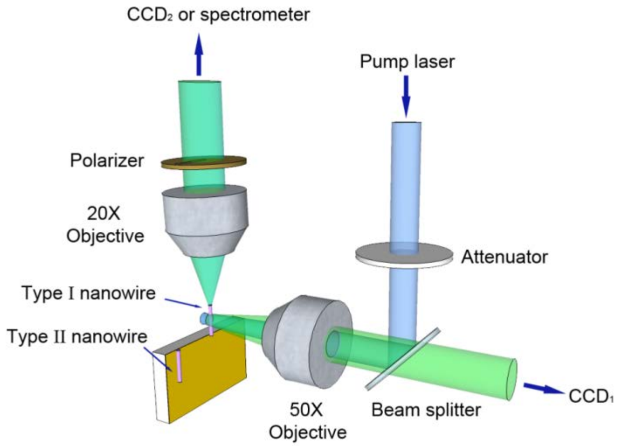
Continuous & dynamic bandgap/wavelength tuning in GaN NW lasers via hydrostatic pressure



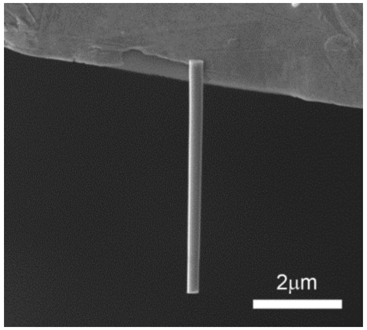
- Pressure coefficient ~40% higher for GaN NWs vs GaN micropillars or bulk GaN, allows for larger tuning range.

S. Liu, C. Li, J. J. Figiel, S. R. Brueck, I. Brener, G. T. Wang, *Nanoscale*, ***7***, 9581 **(2015)**.

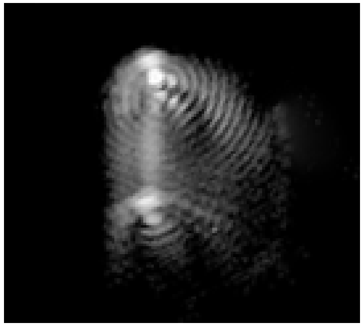
Lasing Polarization Properties of Freestanding GaN NWs



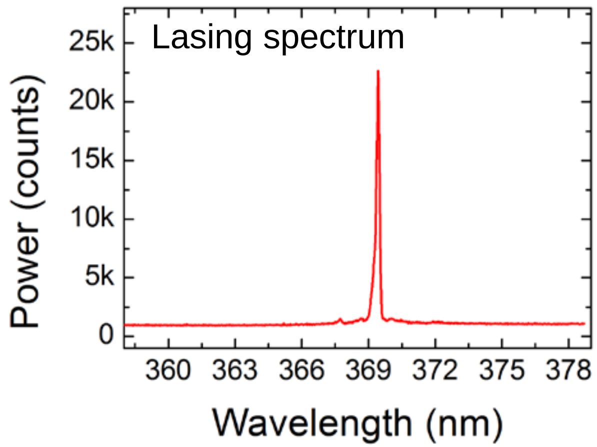
End-facet optical characterization setup

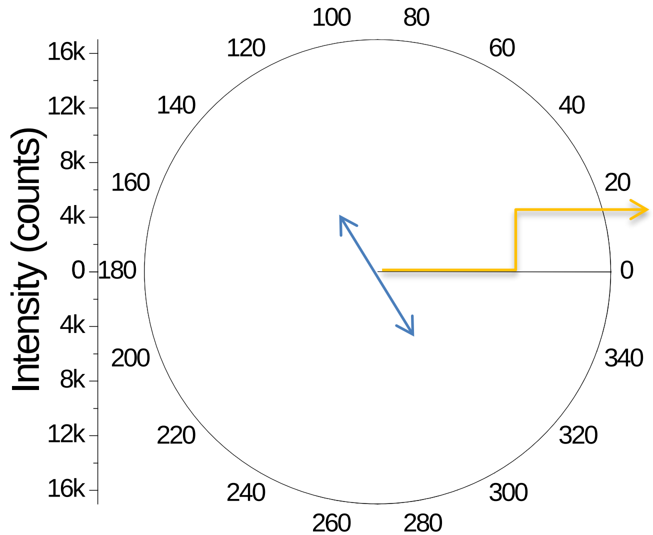


SEM image of a nanowire hanging off substrate



CCD image of lasing nanowire hanging off substrate





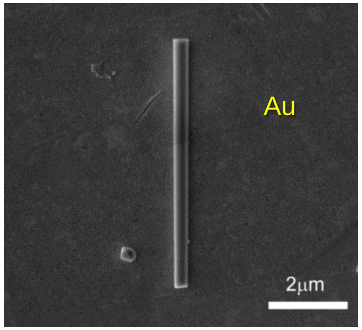
Indicative of elliptical polarization

Polarization angle random wrt surface

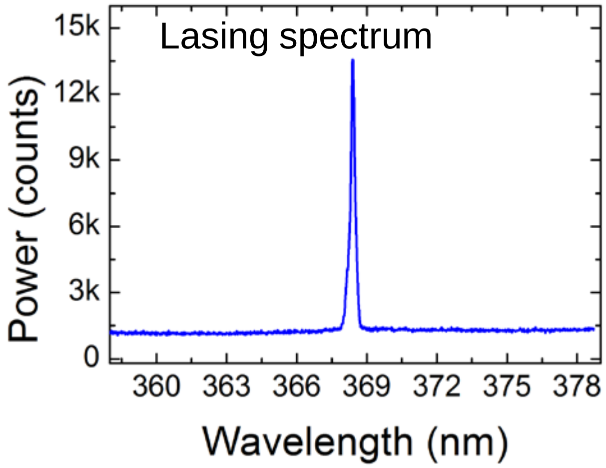
Intensity vs. the rotation of the polarizer

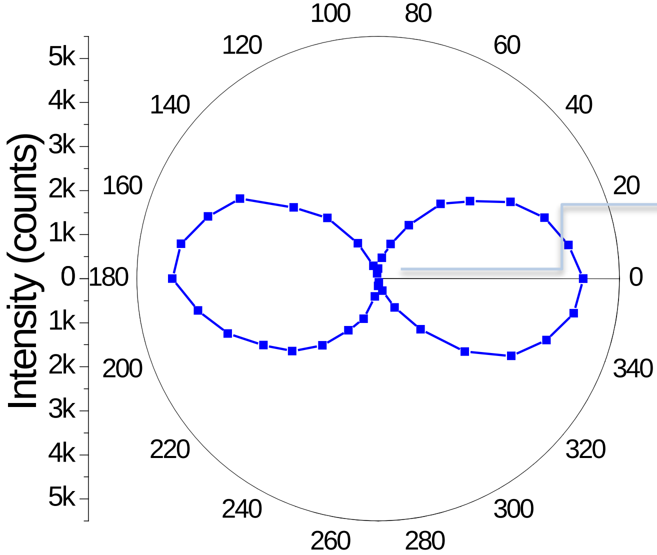
Polarization Control: Nanowire on Gold Substrate

Polarization control (linear polarization) desired for many applications



nanowire on **gold**

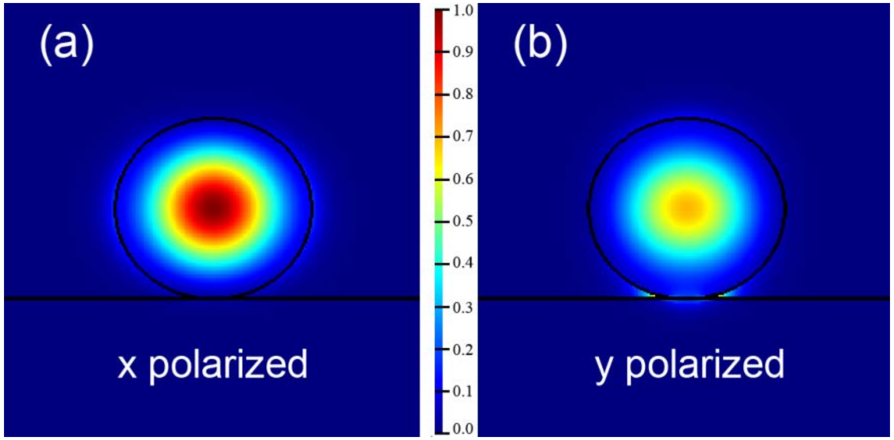




Intensity vs. the rotation of the polarizer

- ✓ Single-wavelength lasing
- ✓ Linear polarization
- ✓ Large cross-polarization suppression ratio (CPSR): 21:1
- ✓ 0^{o} 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

H. Xu et al., "Polarization control in GaN nanowire lasers", *Optics Express*, ***22***, 19198 **(2014)**.