SAND2014-15251PE

Top-Down III-Nitride Nanowire LEDs and Lasers

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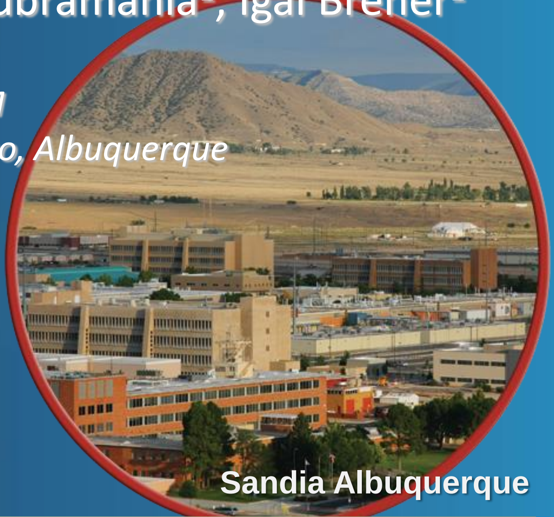


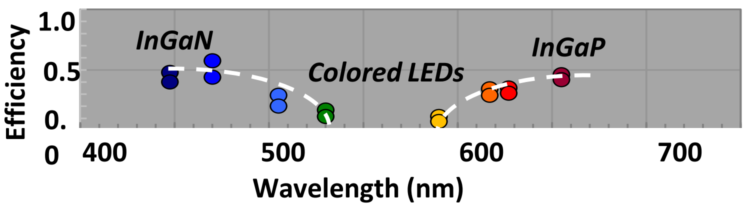
Funding Acknowledgment: Sandia's Solid-State-Lighting Science Energy Frontier Research Center (DOE BES) and Sandia's LDRD program; European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PIOF-GA-2010-273822.

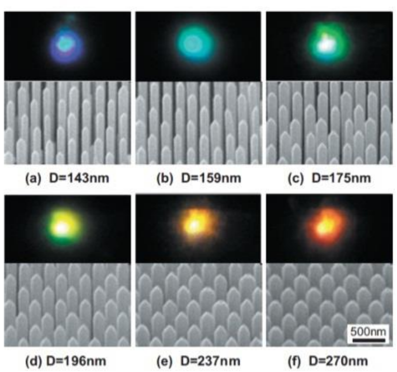
Why III-nitride nanowires for SSL?

Advantages due to enhanced strain accommodation in nanowires

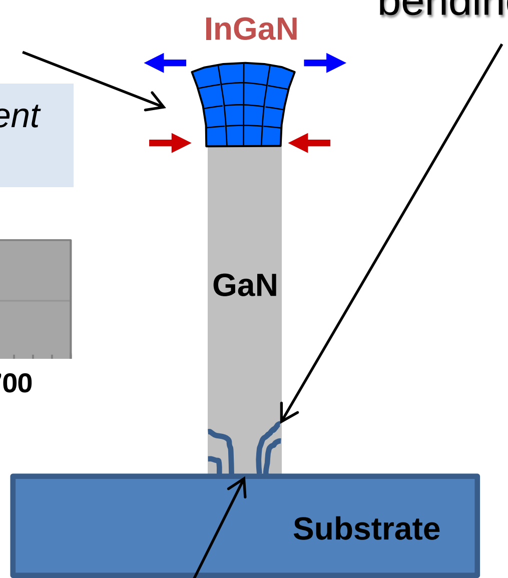
elastic strain relaxation at surface

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





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

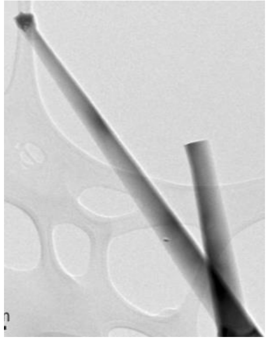


small interfacial area

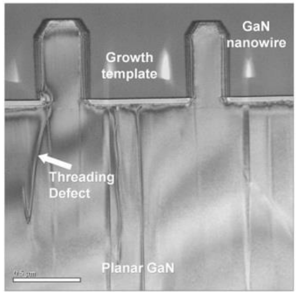
benefit: can grow on cheaper, lattice mismatched substrates; integration with Si devices

bending of dislocations (TDs) toward surface

benefit: reduced TDs, higher IQE

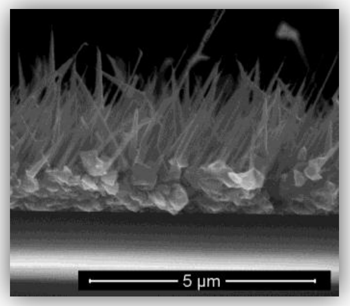


VLS-grown TD-free GaN NWs - Sandia

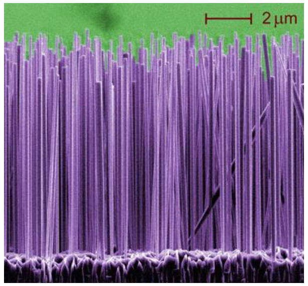


Hersee et al., J. Mat. Res. **17**, 2293 (2011) - UNM

Bending & termination of TDs at nanowire base



GaN NWs on tungsten foil - Sandia

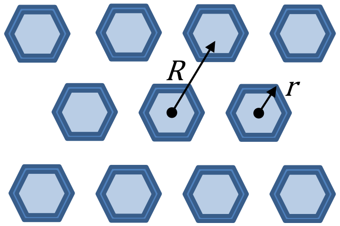


GaN NWs on Si - NIST

Why III-nitride nanowires for SSL?

vertical device integration

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

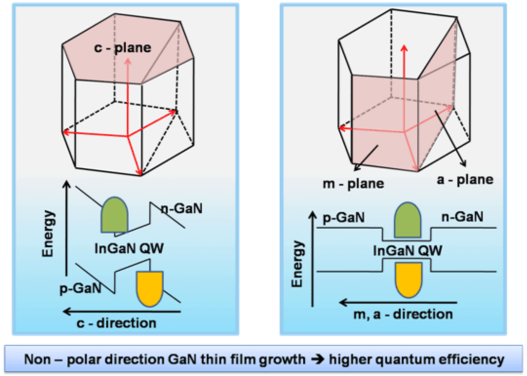


$$\frac{A_{sidewall}}{A_{substrate}} = \frac{6rh}{2.6R^2} \cong \mathbf{4.6F \cdot AR}$$

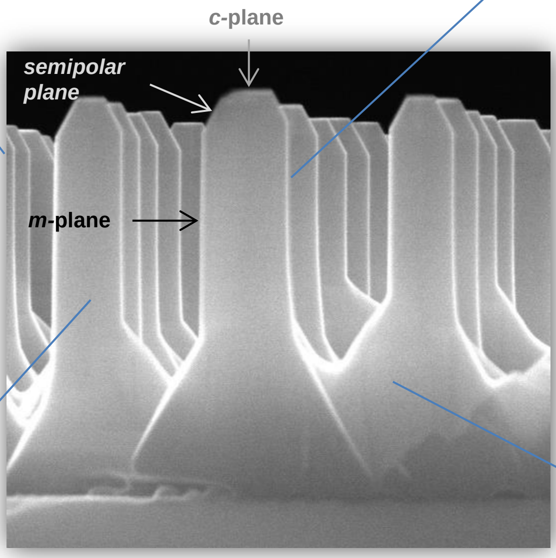
*example: 4.6·0.5·3=**6.9× increase!***

access to nonpolar & semipolar planes

<u>benefit:</u> *higher IQE, reduced wavelength shift*



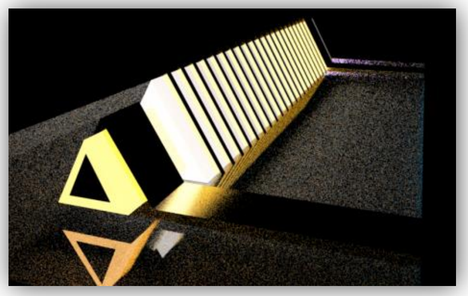
http://csel.snu.ac.kr/research/LED.php



Radial GaN/InGaN MQW NW (Sandia)

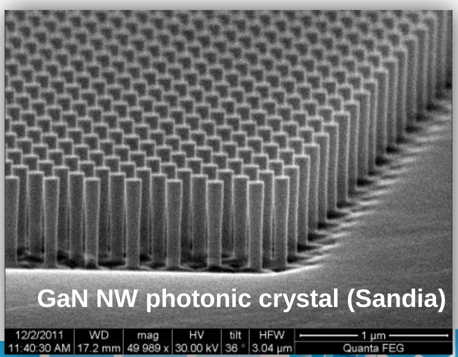
nanolasers

<u>benefit:</u> *ultracompact, low power coherent light source*



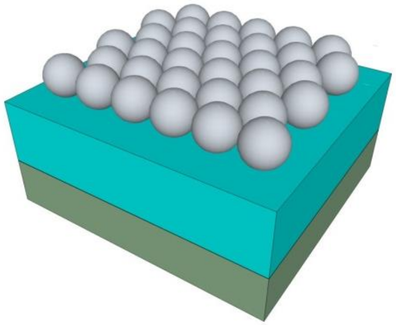
2D arrangements (photonic crystals)

<u>benefit:</u> *higher light extraction, IQE, wavelength tuning*



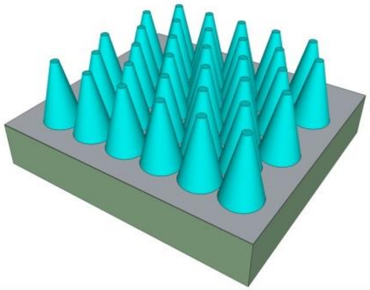
GaN NW photonic crystal (Sandia)

New dry + wet top-down ordered nanowire fabrication process

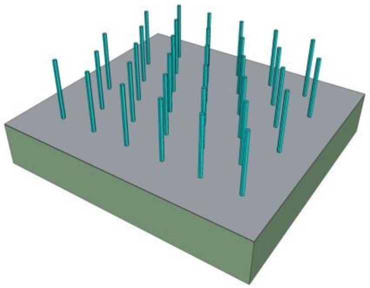


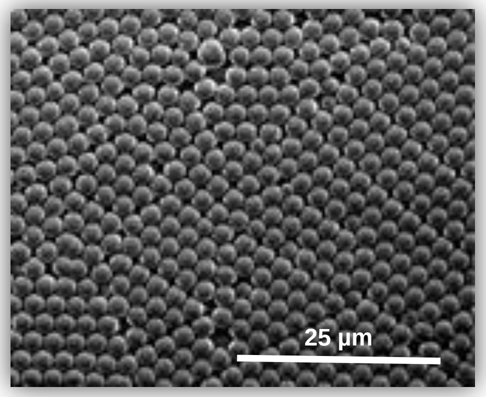
(0001) GaN on sapphire

ICP etch

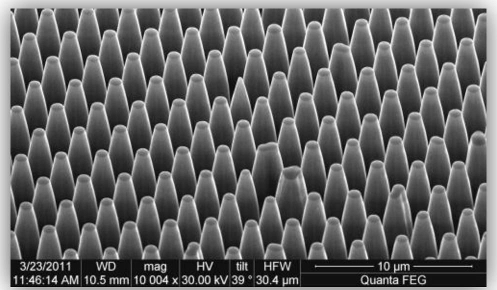


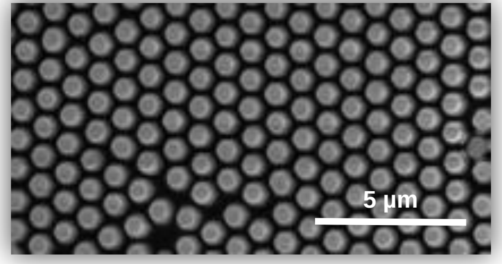
Selective wet etch
(AZ-400K developer)





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

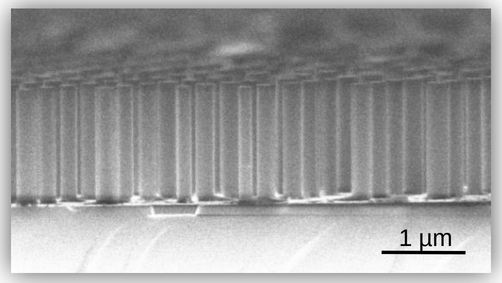


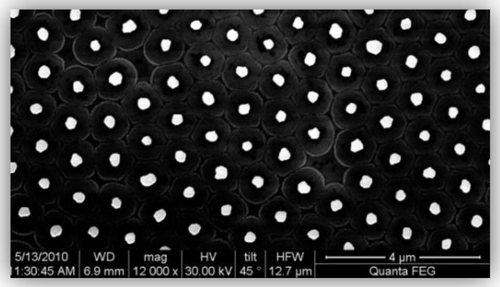


Plasma etch causes sidewall damage

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

Tapered; no well-defined facets



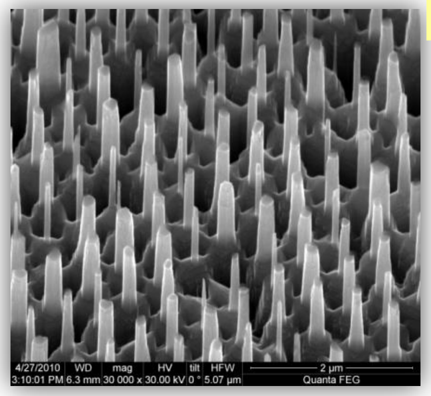


Wet etch: straight sidewalls, removes sidewall damage

Straight GaN nanowires with controllable geometries

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

0.5 µm sphere size

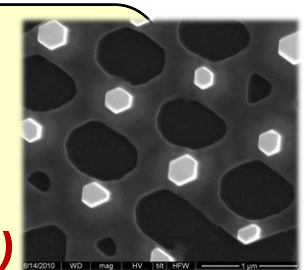


<u>*Superior and independent control of:*</u>

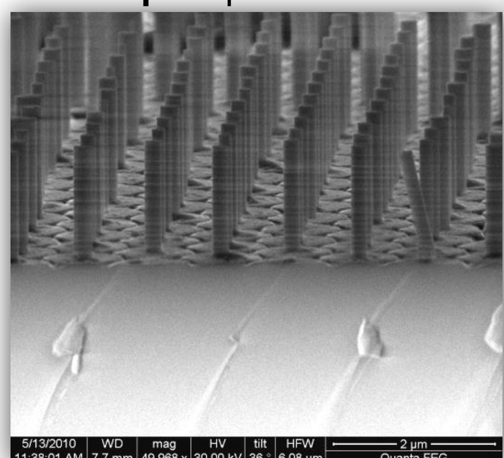
Height (dry etch depth)

Diameter (wet etch time)

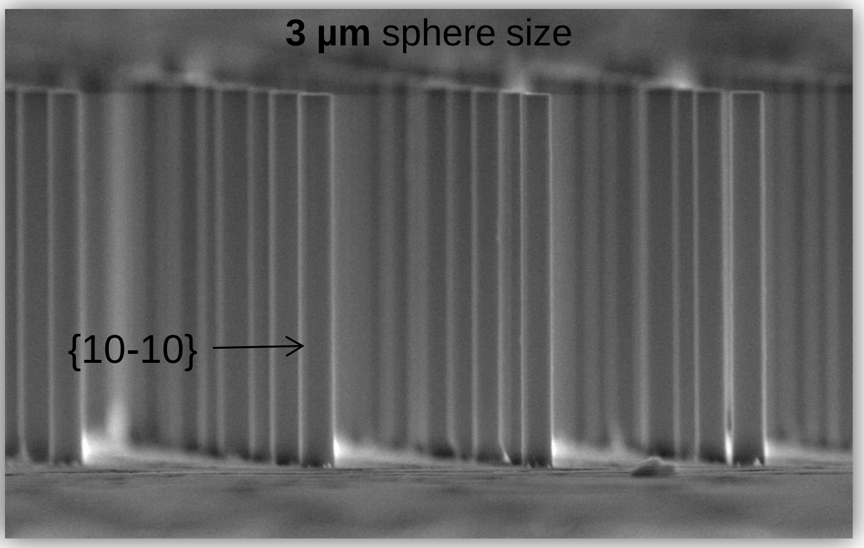
Pitch/arrangement (defined by masking template)

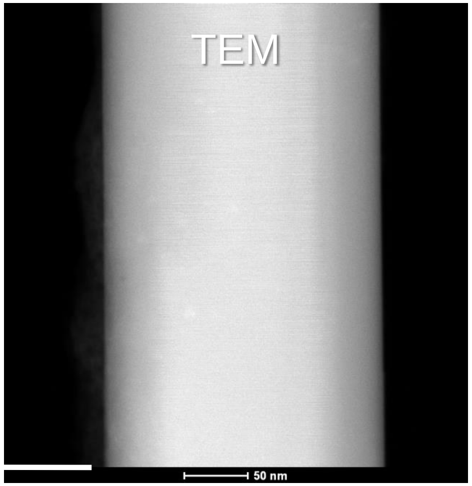


1 µm sphere size



3 µm sphere size





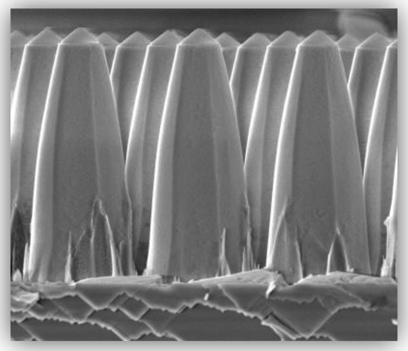
Smooth sidewall created by wet etch

TEM: Ping Lu, SNL

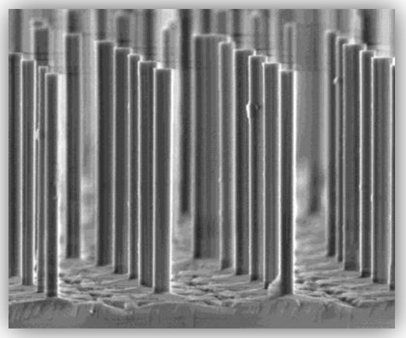
See: Q. Li et al., *Optics Express* **19**, 25528 (2011)

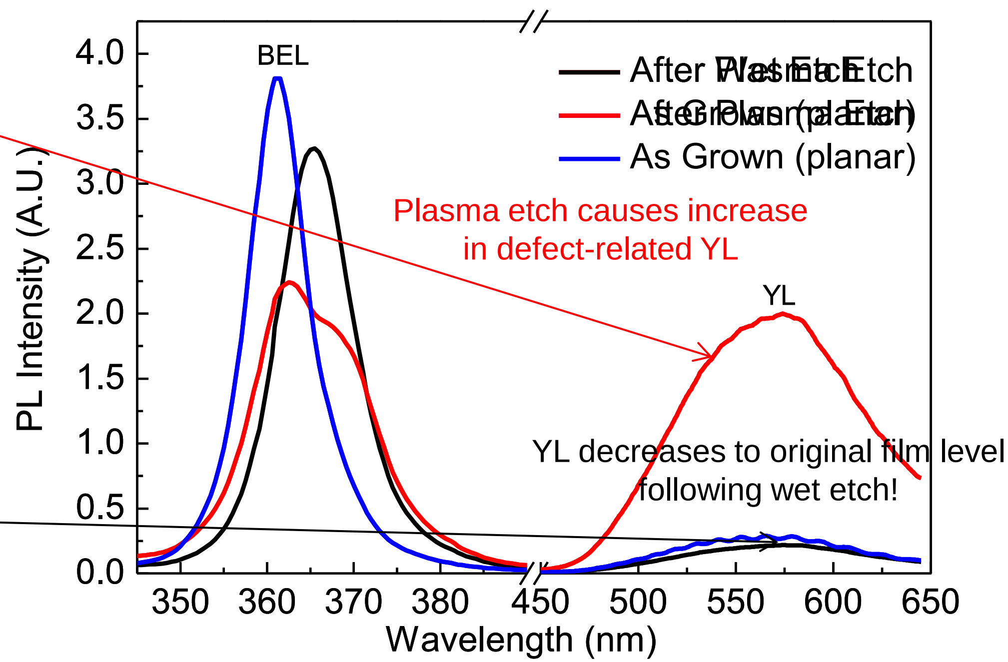
Wet etch step removes plasma etch damage

Plasma etch only

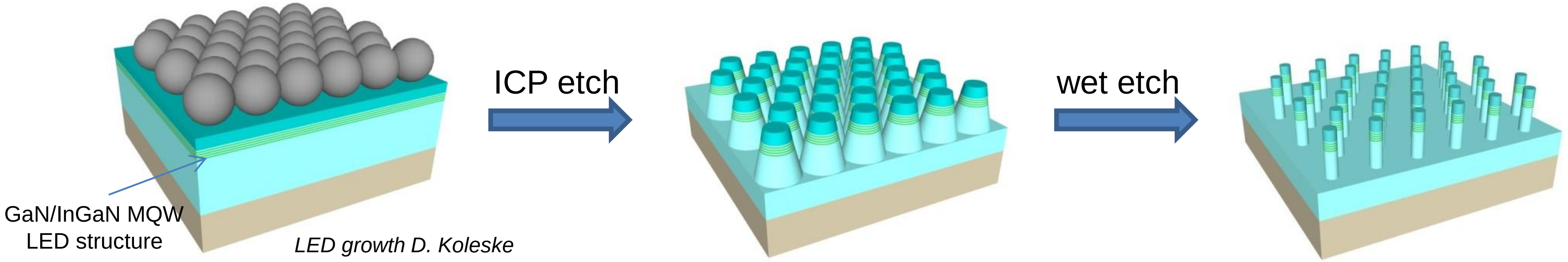


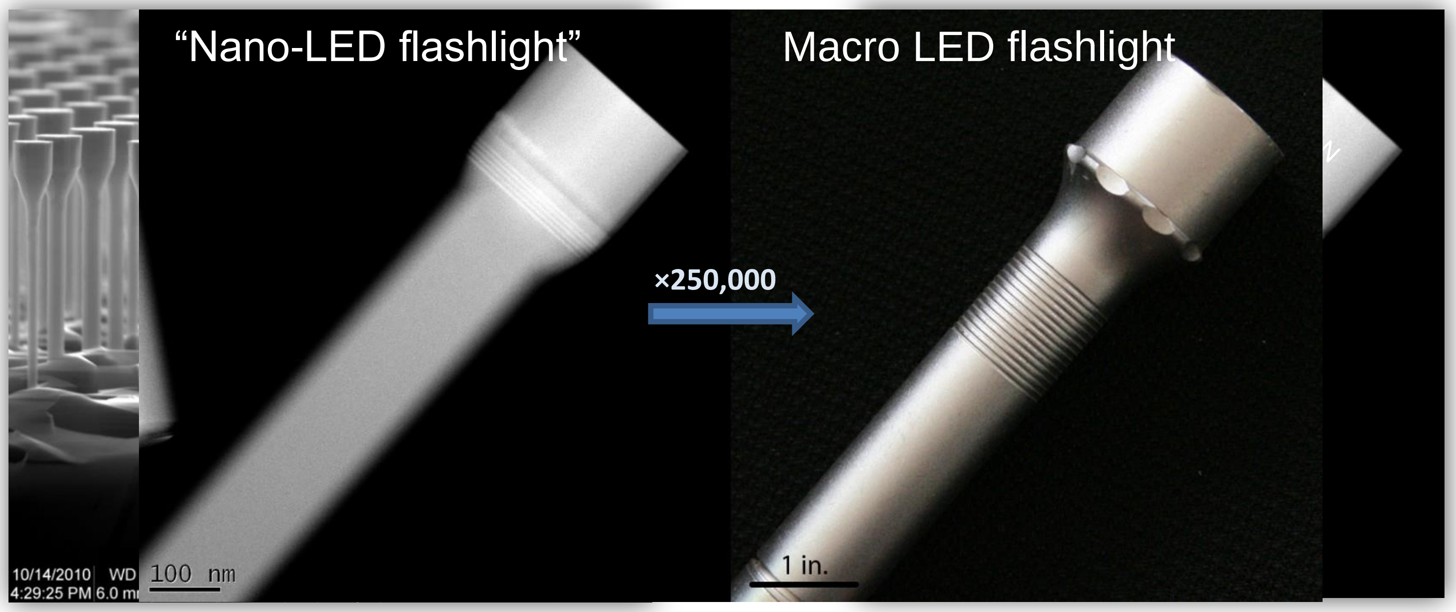
After wet etch





Axial GaN/InGaN nanowire LEDs

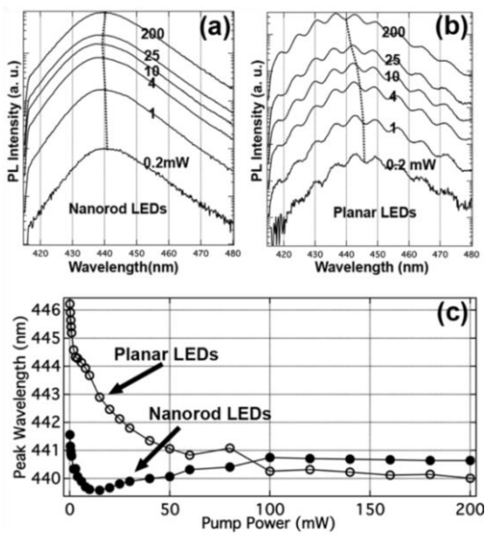




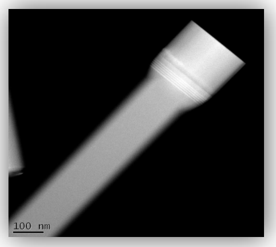
Q. Li et al., *Optics Express* **19**, 25528 (2011)

Optical performance – axial nanowire LEDs vs. planar LED

InGaN peak position vs pump power

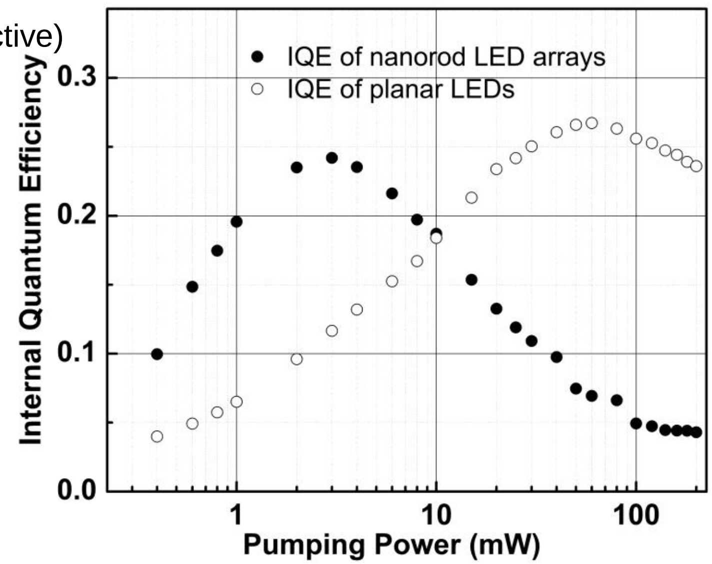


413 nm pump (InGaN selective)



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

IQE – nanowire vs Film



PL, IQE: K. Westlake, M. Crawford

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

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

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

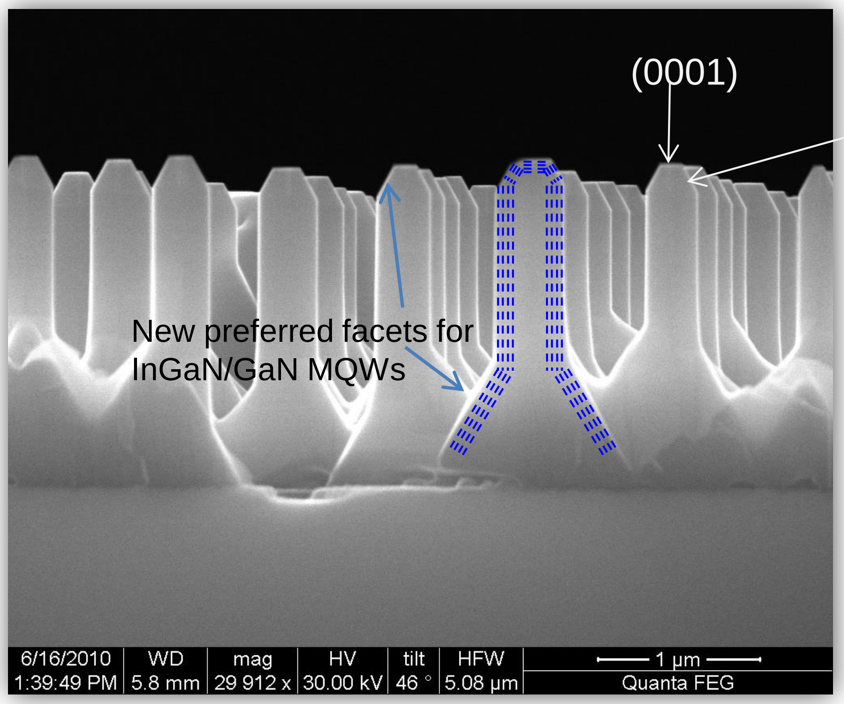
No obvious benefit for LED performance/cost ratio (loss of device area), but possibility for very high IQE single NW emitters for nanophotonic applications

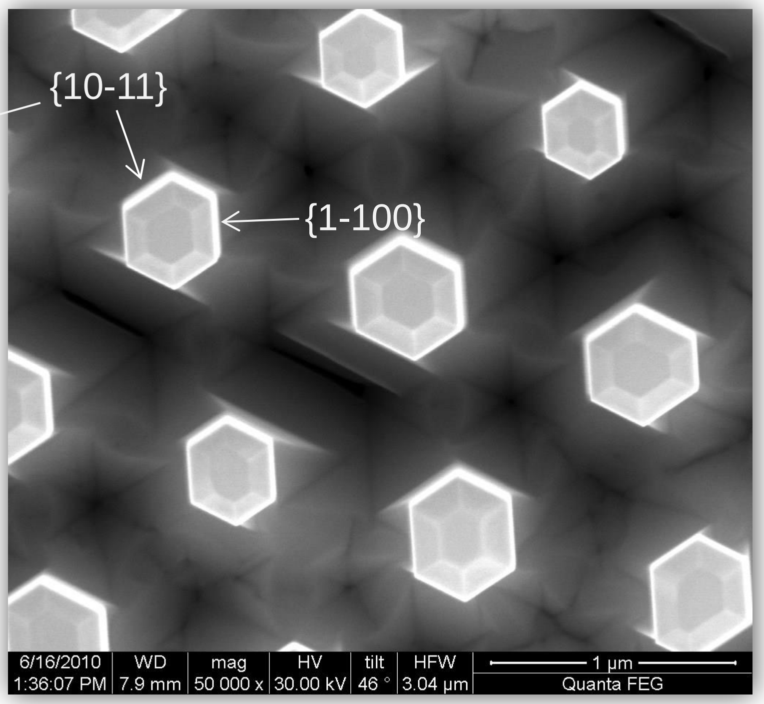
Radial core-shell InGaN/GaN MQWs on top-down NWs

Radial core-shell NW LEDs:

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

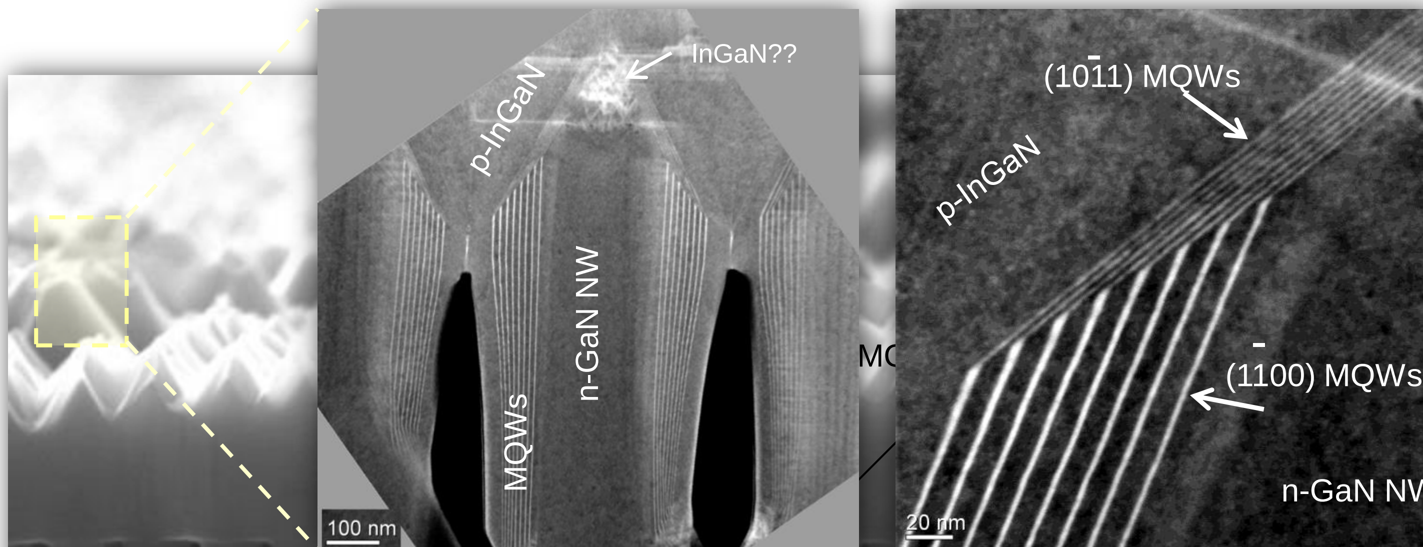
After 5-period MQW GaN/InGaN shell growth



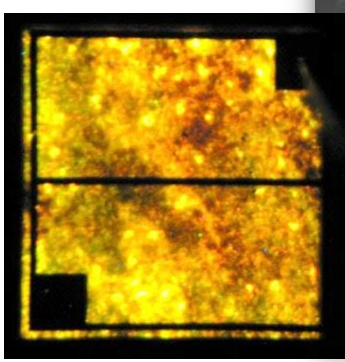


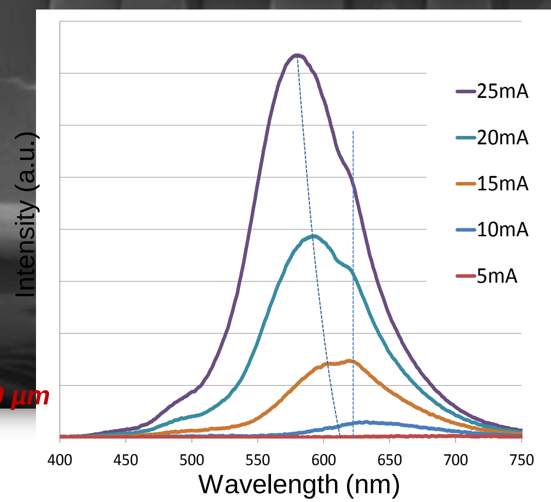
New semipolar facets form with InGaN/GaN MQW growth

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



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



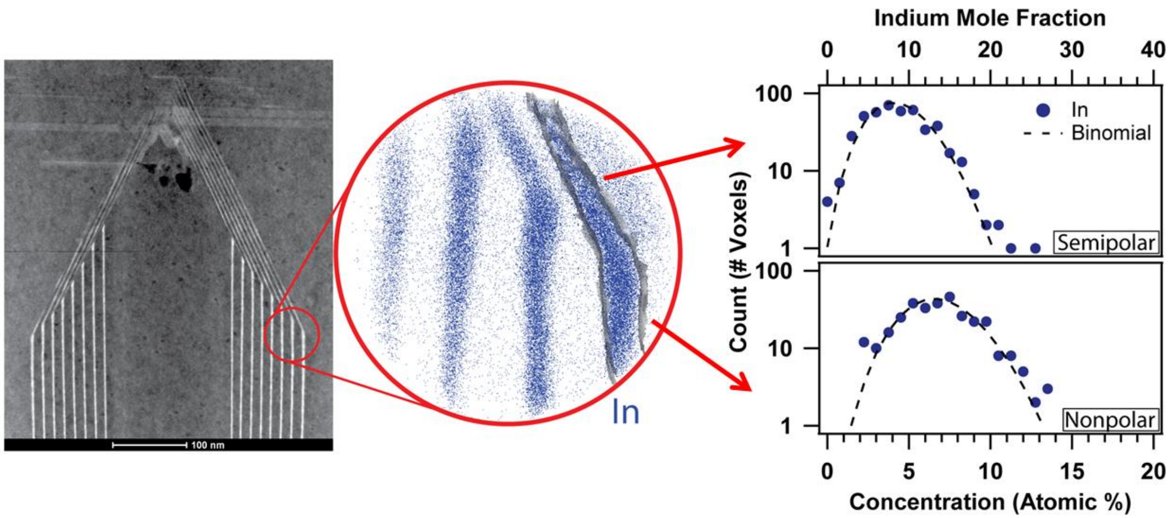


- Yellow-red electroluminescence!
- Two EL peaks:
  - 615 nm (const) red
  - 600-565 nm (shift) yellow

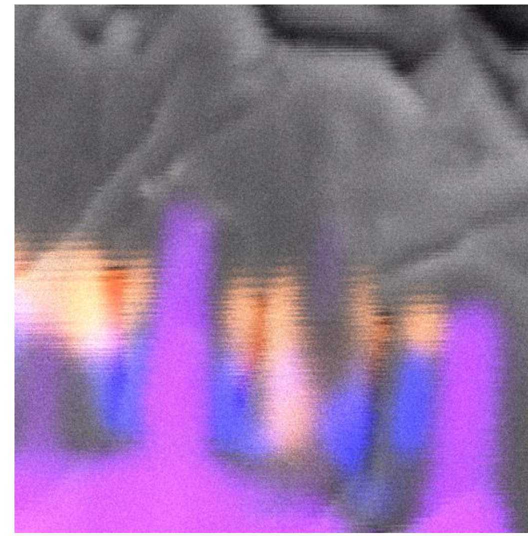
3-D Mapping of Quantum Wells in a GaN-InGaN Core-Shell Nanowire – a Correlated Study

STEM-EDS

Atom probe tomography (APT)



Cathodoluminescence

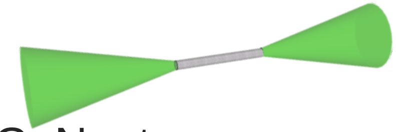


365 nm, 402 nm, 442 nm

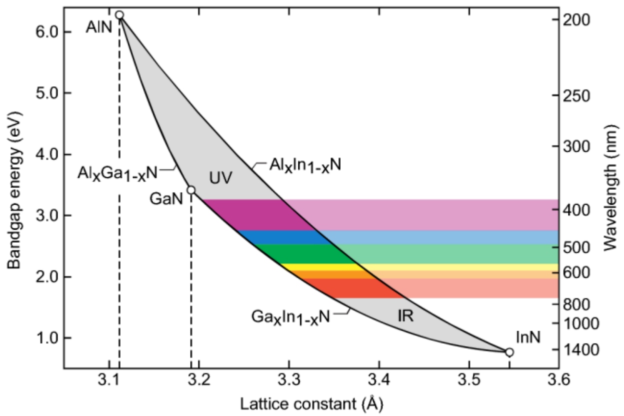
Riley, J.; Padalkar, S.; Li, Q.; Lu, P.; Koleske, D. D.; Wierer, J. J.; Wang, G. T.; Lauhon, L. J., *Nano Lett.* **2013**.

- 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

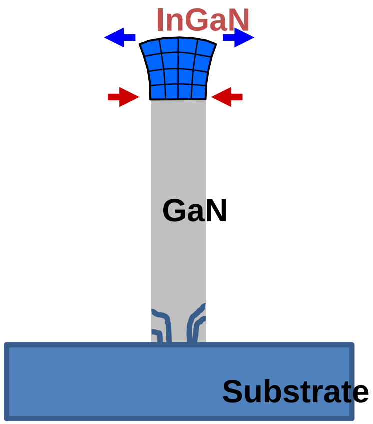
Nanowire Lasers



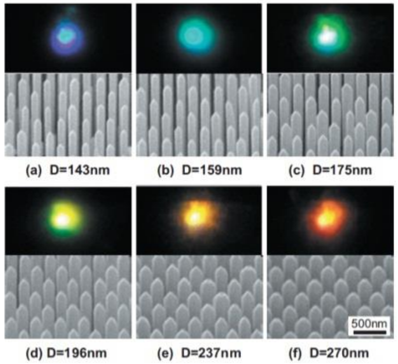
- Nanowire forms a freestanding, low loss optical cavity
- Optically pumped nanowire lasers: ZnO, CdS, GaAs, GaSb, GaP, GaN, etc.
- Most commonly Fabry-Perot type lasing from end facets
- Compact and low power due to small mode volume
- Strain accommodation in GaN nanowires opens up possibility of high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



M. Schubert, RPI



Multi-color [spontaneous] emission



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

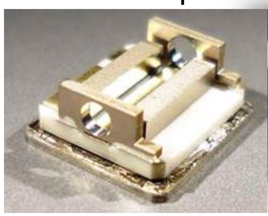
See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7,** 074599-1 (2013)

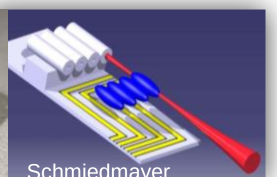
Why Nanowire Lasers?

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

Integrated nanophotonics, atom trapping, optical MEMS

atom trap



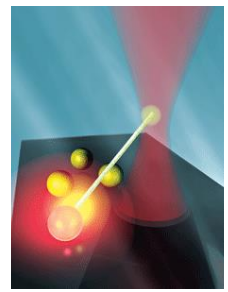


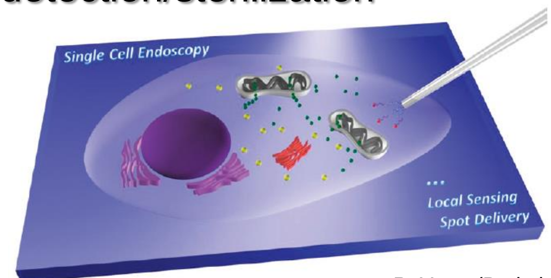
J. Ford, Lucent

P. Schwindt (1725)

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

Optical nanoprobes & chem/bio detection/sterilization

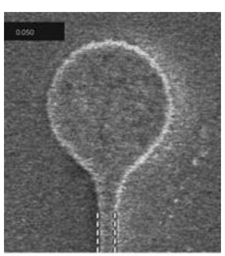


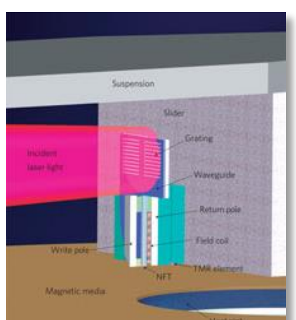


P. Yang (Berkeley)

Sub-λ resolution probes for localized excitation, detection

Nanolithography & Heat-assisted Magnetic Recording





Nature Photonics 3, 220 (2009)

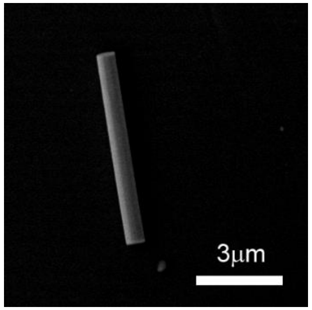
Seagate

Subwavelength & efficient laser spot

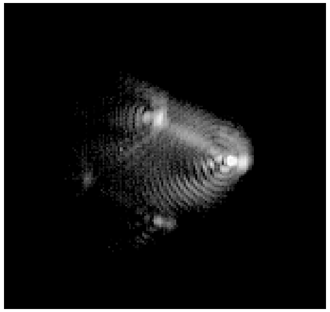
Lighting, projection, & holographic displays

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

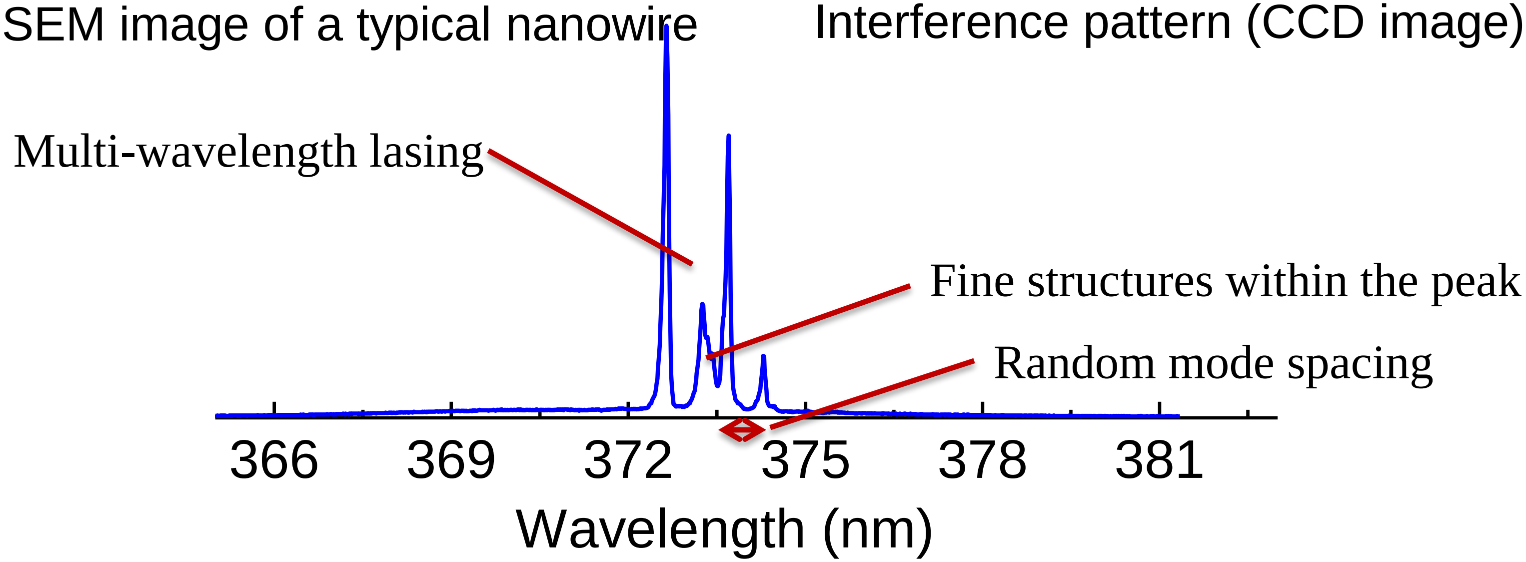
Typical GaN Nanowire Lasing: Multimode Operation



SEM image of a typical nanowire

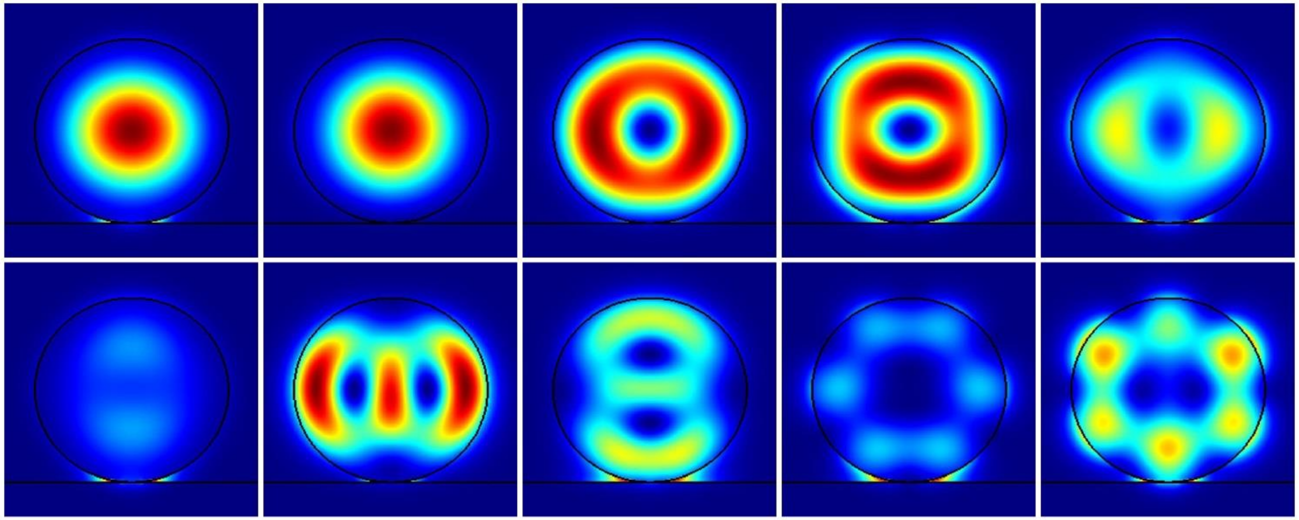


Interference pattern (CCD image)



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

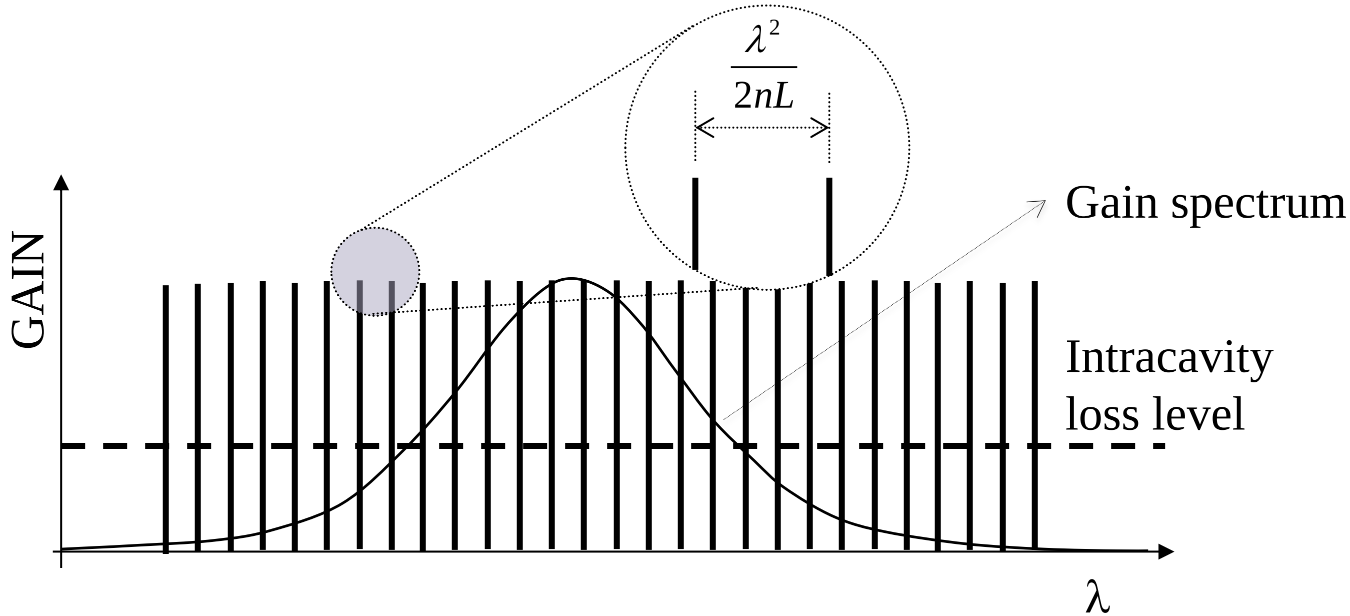
Why Multimode Lasing Occurs



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

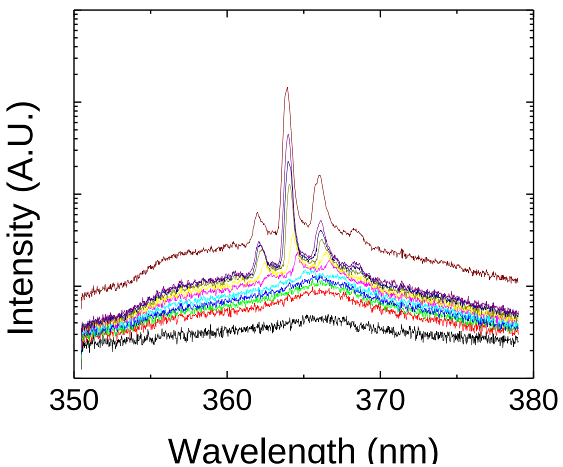
- ✓ Multiple transverse mode waveguide;
- ✓ Single-mode cutoff diameter ~120 nm;
- ✓ Lasing in multiple transverse mode operation
- ✓ Polarization is mode-dependent

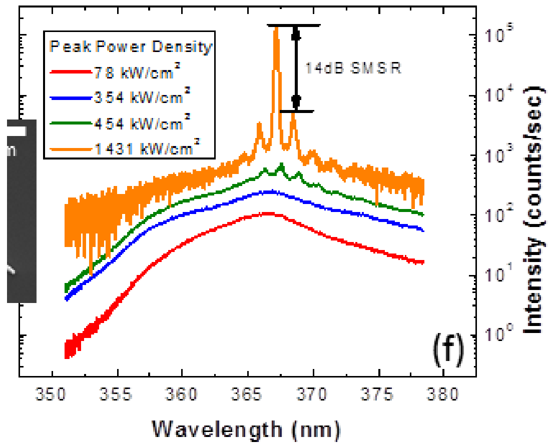
Why Multimode Lasing Occurs

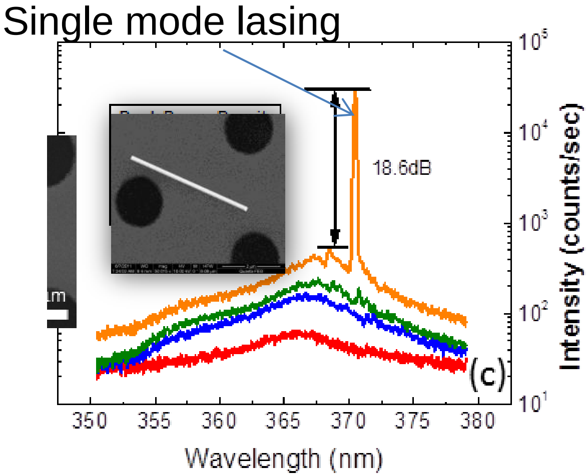


- ✓ Gain bandwidth ~7 nm;
- ✓ Longitudinal mode spacing ~1 nm;
- ✓ Several modes located in the gain spectrum;
- ✓ Multiple longitudinal mode oscillation

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)**

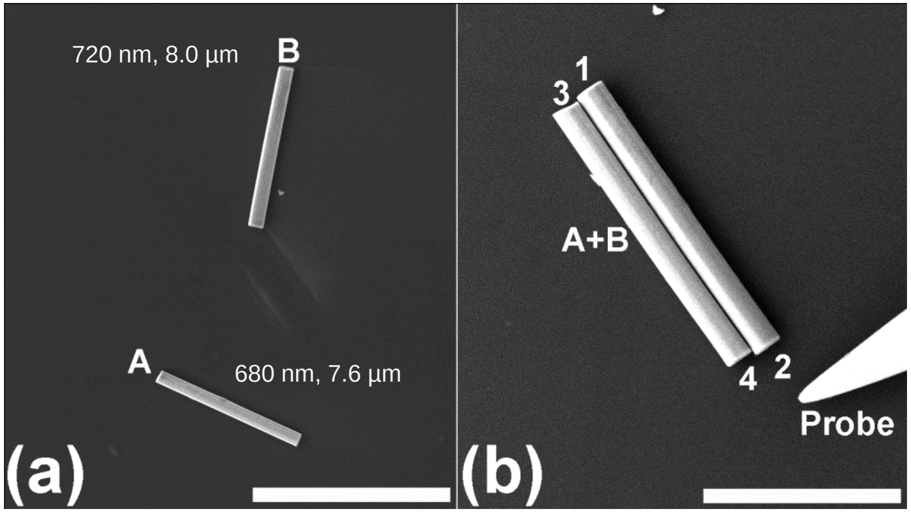
NW diameter x length

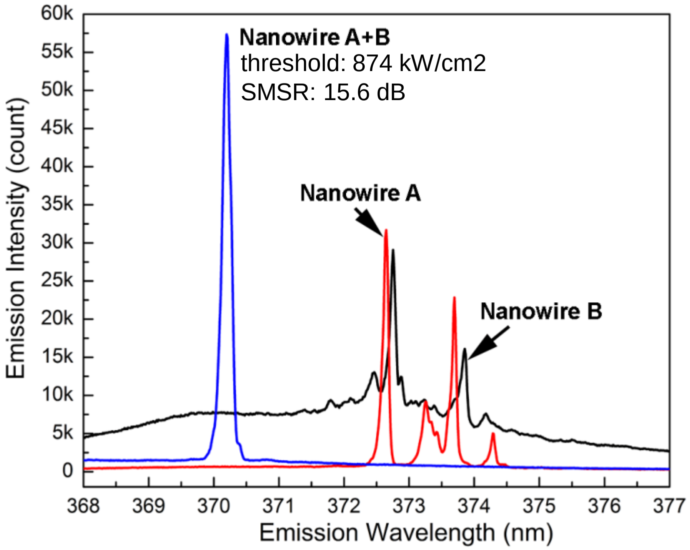
Q. Li et al., *Opt. Exp.* ***20*** *17873 (2012)*

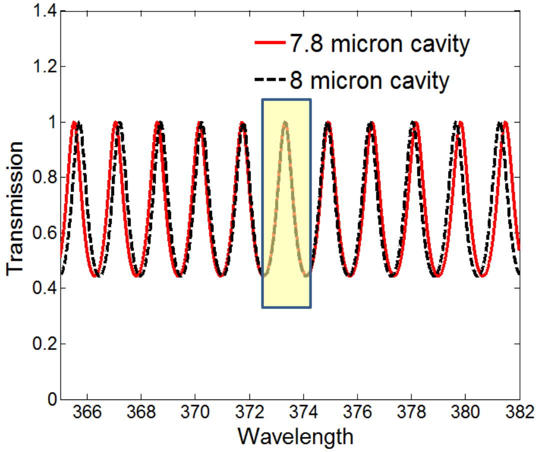
Single-mode: Narrow-Linewidth (<0.1 nm), 18.6 dB Side Mode Suppression Ratio

- 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





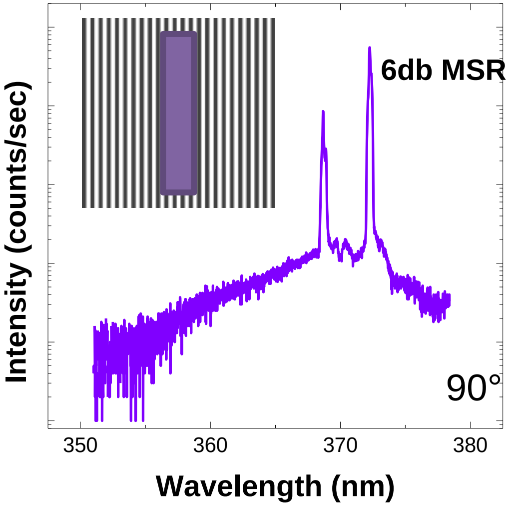


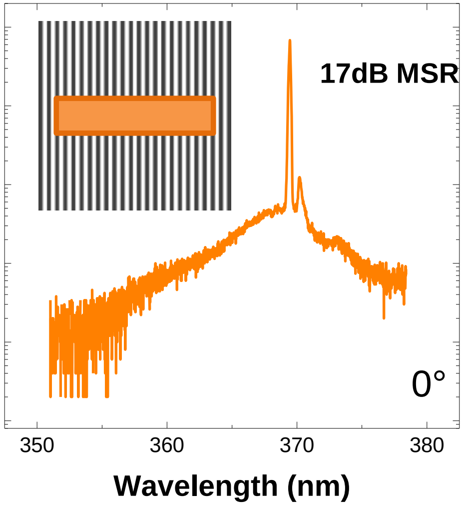
- GaN NWs need to be <~130 nm for single transverse mode behavior; larger single-mode NWs?
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

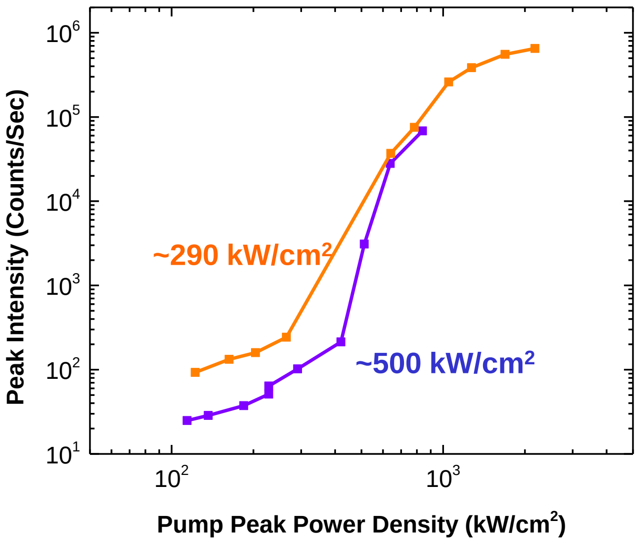
modeling: Huiwen Xu (UNM)

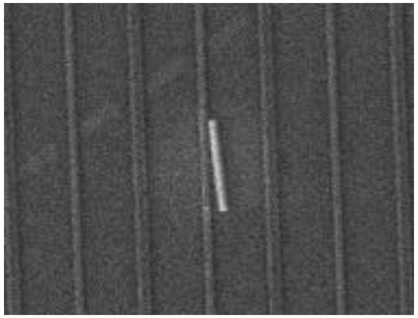
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

Method 3: DFB Nanowire - Optical Results

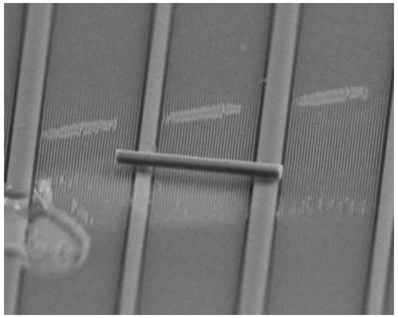








NW diameter ~180 nm

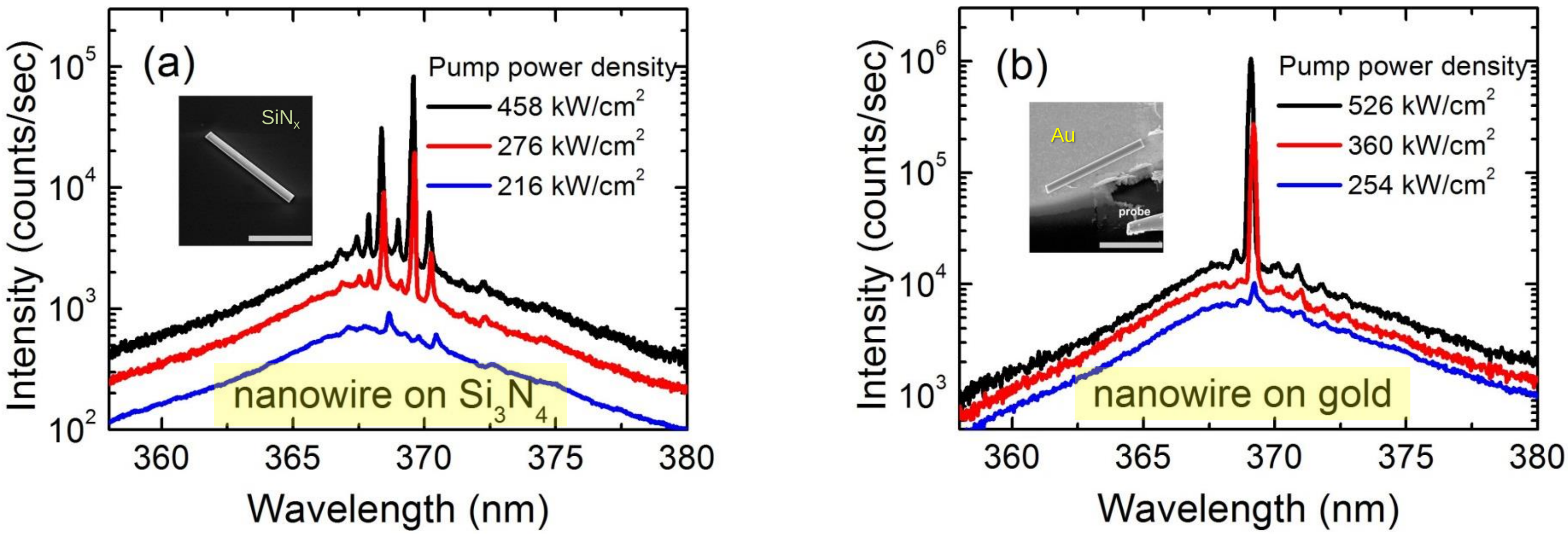


- At the designed alignment single-mode lasing was achieved with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

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

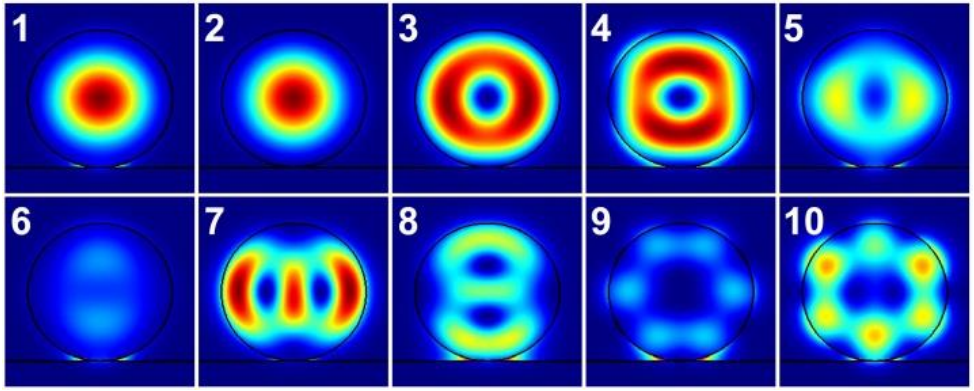
diameter~350 nm, length ~5.3 µm



- 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., *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.

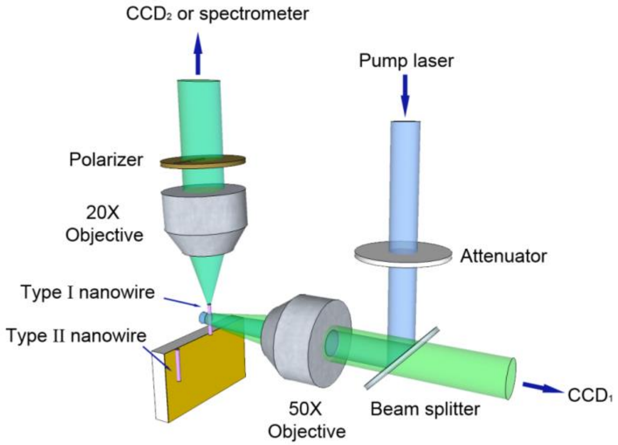
Only surviving mode

	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

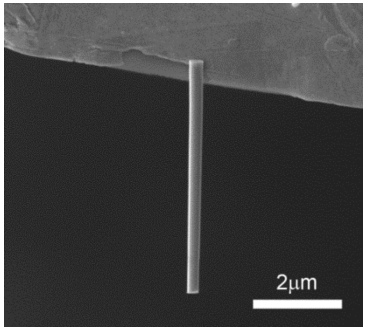
Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss

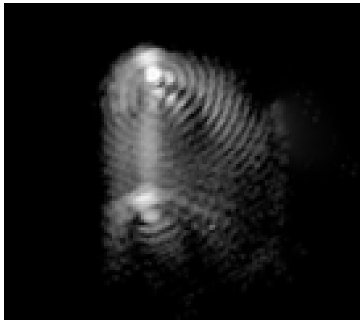
Lasing Polarization Properties of Freestanding GaN NWs



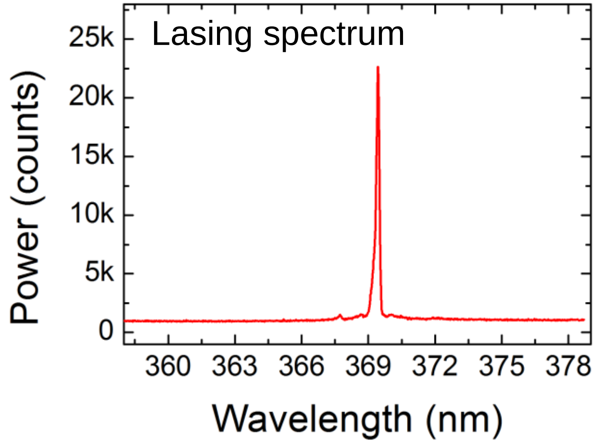
End-facet optical characterization setup

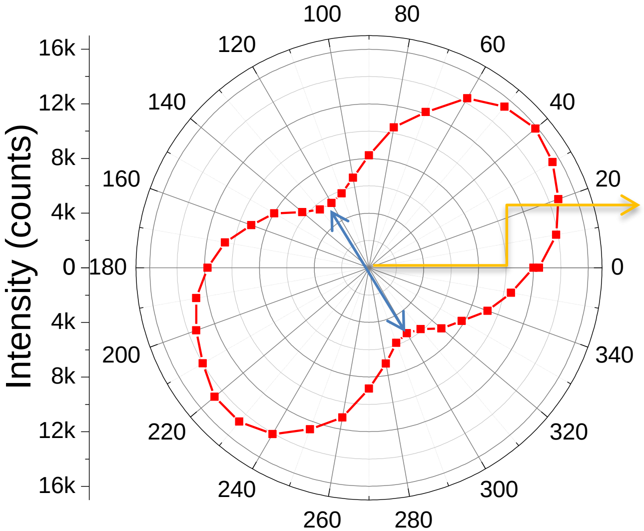


SEM image of a nanowire hanging off substrate



CCD image of lasing nanowire hanging off substrate





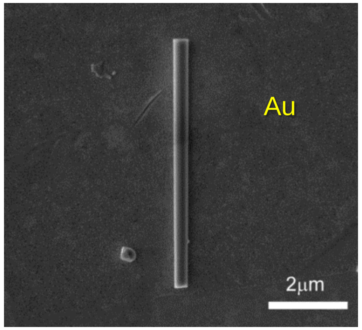
Intensity vs. the rotation of the polarizer

Indicative of elliptical polarization

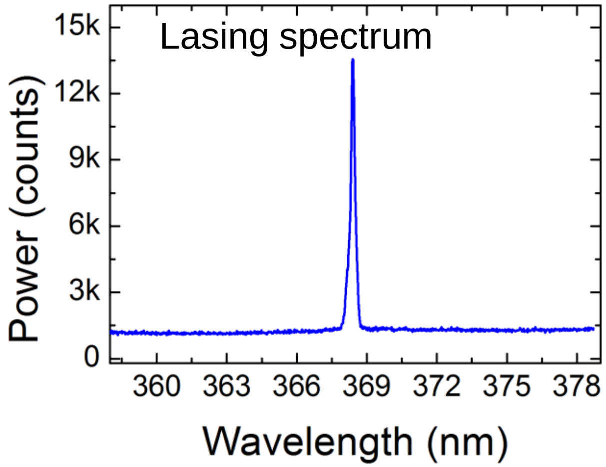
Polarization angle random wrt surface

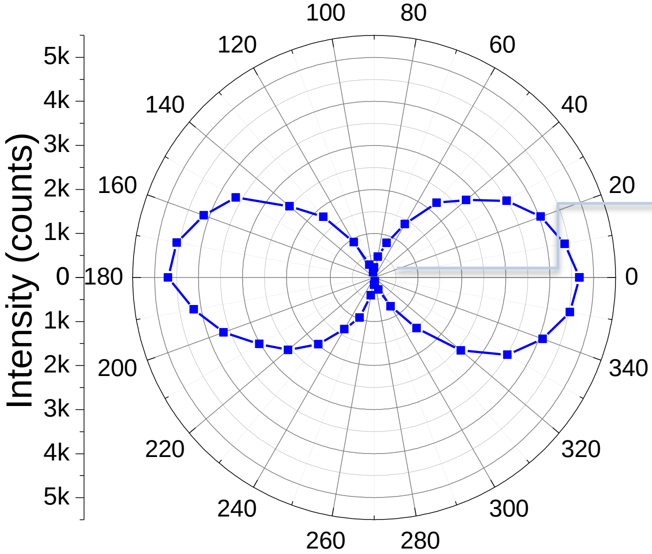
Polarization Control: Nanowire on Gold Substrate

Polarization control (linear polarization) desired for many applications



nanowire on **gold**

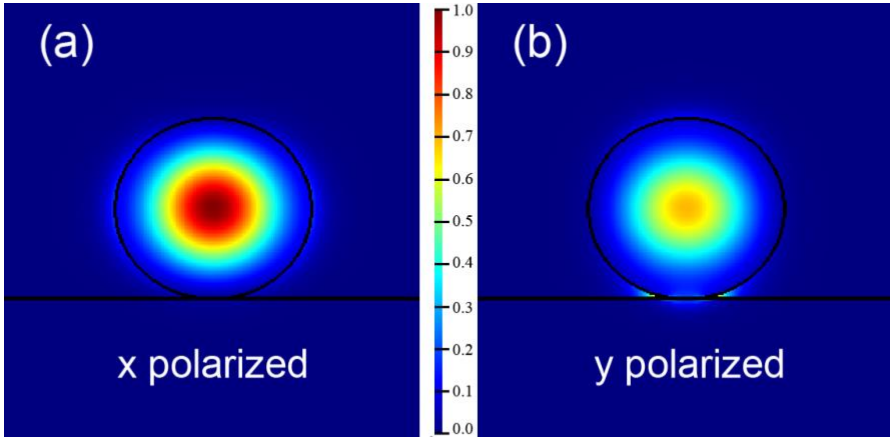




Intensity vs. the rotation of the polarizer

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

Why Does Linear Polarization Happen on Gold?



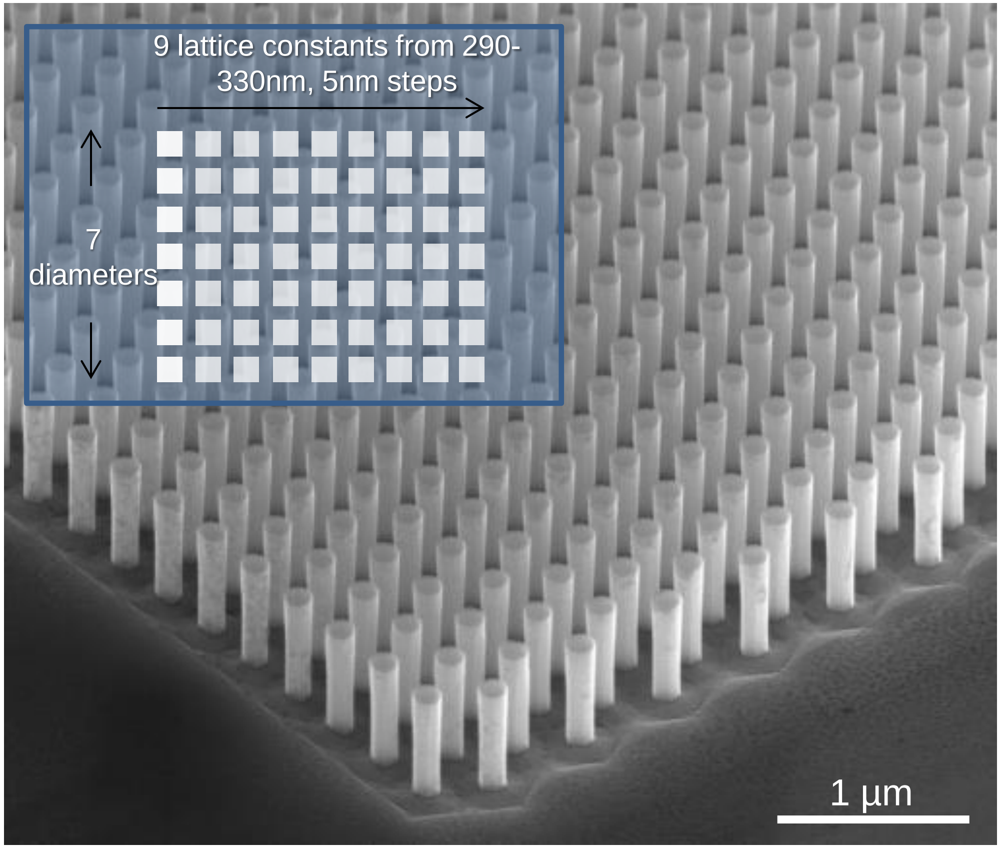
Fundamental modes supported by the nanowire-gold geometry

- ✓ 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

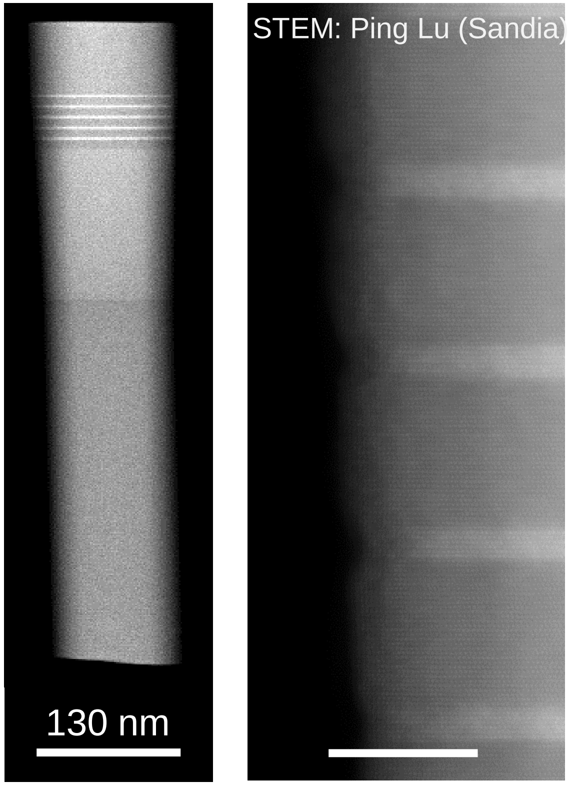
A nanowire on gold substrate experiences a larger cavity loss for the perpendicularly polarized mode, leading to *linear polarization* with a fixed polarization parallel to the substrate

III-N Nanowire Photonic Crystal (PC) Lasers

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



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

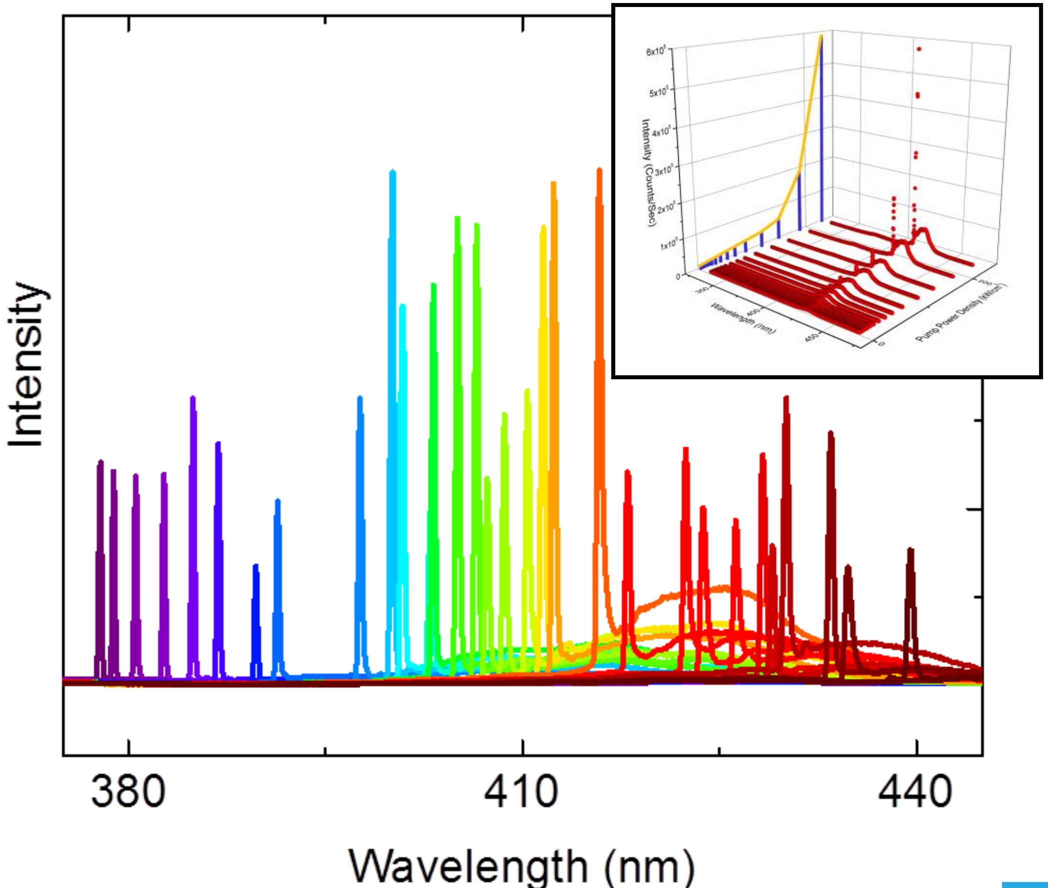


NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

III-N Nanowire Photonic Crystal Lasers

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

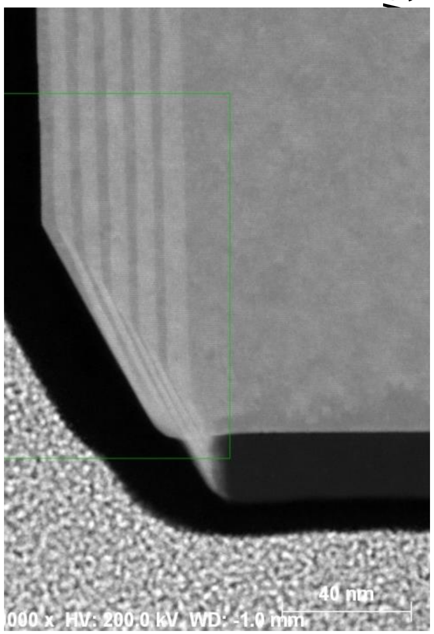
61 color nanowire laser array

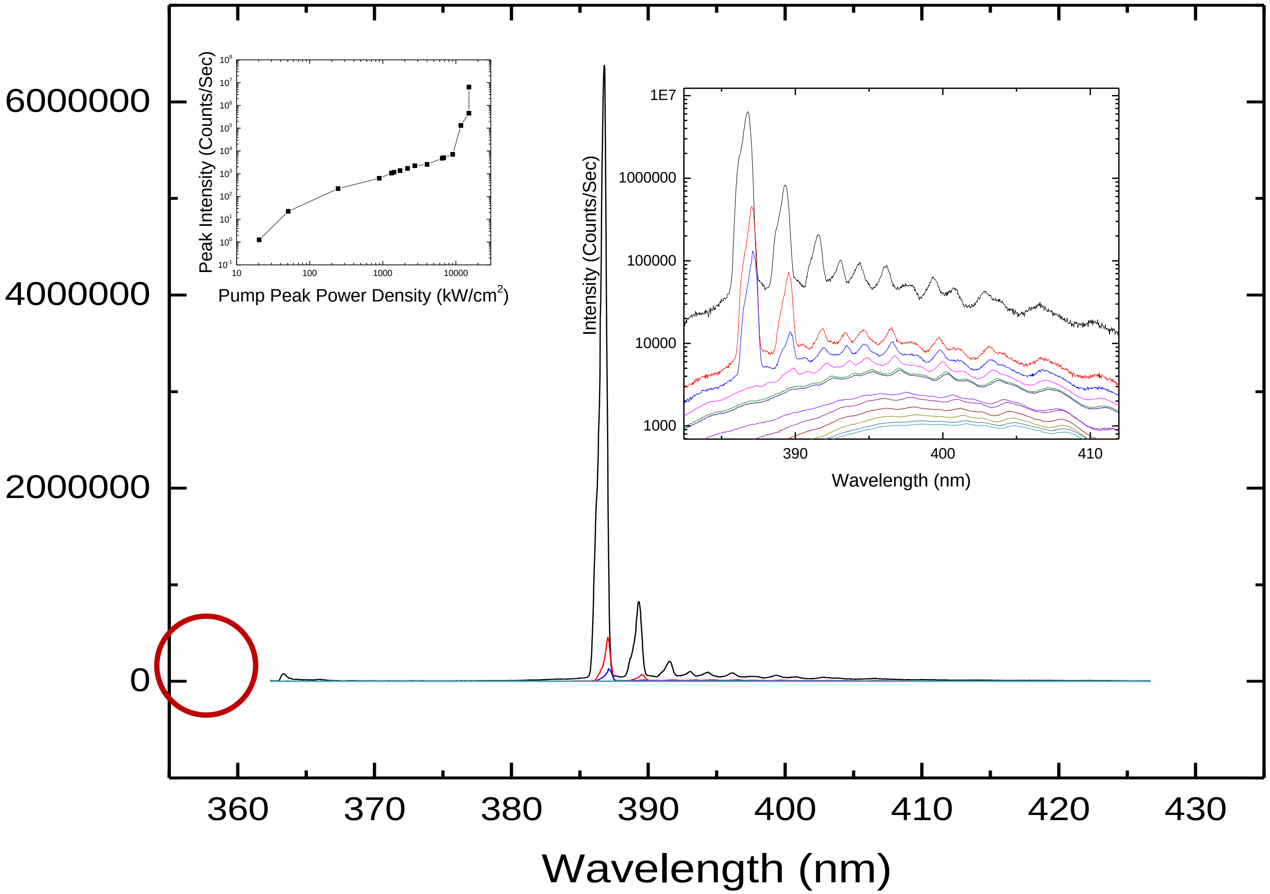


- High-yield >95% (2 of the PCLs were accidentally removed during sample handling.)
- Spectral Coverage from 380-440nm.
- Emission wavelength increases with the diameter and the lattice constant
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm^2 for all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

Key Accomplishments

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

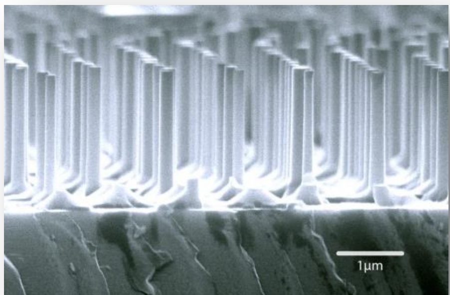




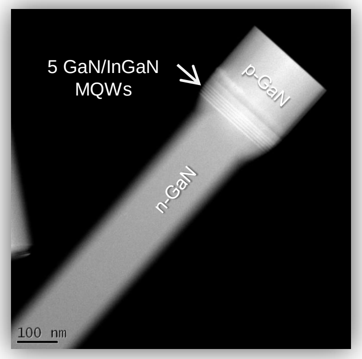
Result confirms radial InGaN/GaN MQW NW can lase

Summary – Top-down III-nitride nanowires

Top-down fabrication

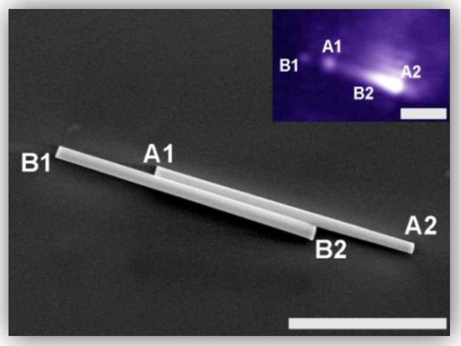


Nanowire LED "flashlight"



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

Single-mode GaN nanowire lasers

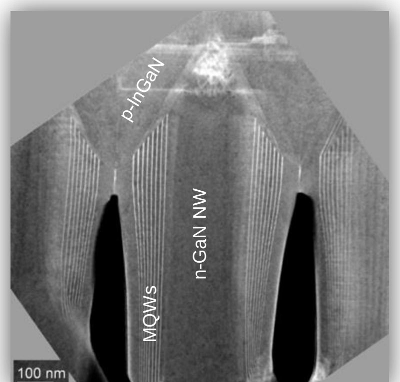


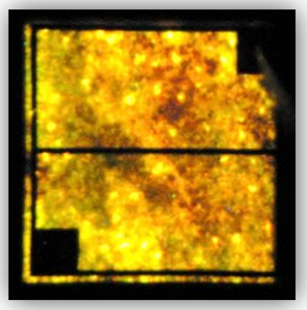
Q. Li et al., *Optics Express* **20** 17874 (2012)

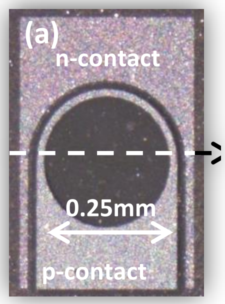
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

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

Vertically integrated radial nanowire LEDs and solar cells

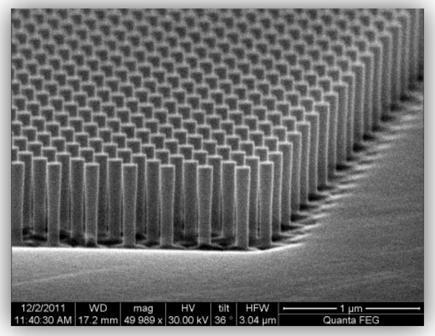


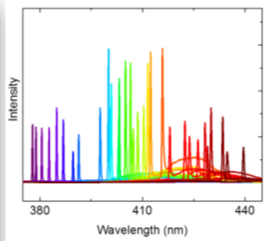




J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

Tunable nanowire photonic crystal lasers

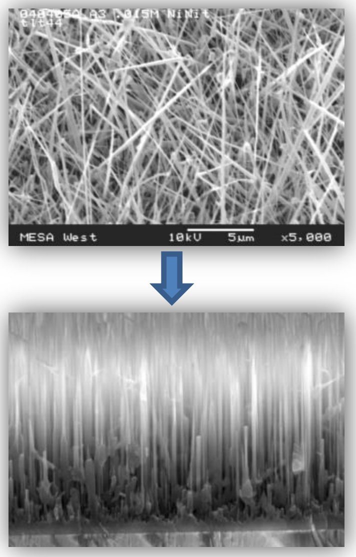




J.B. Wright et al., *in preparation*

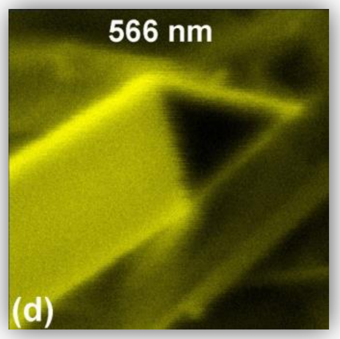
Backup/Extra Slides

Challenges for nanowire-based SSL



Synthesis/Fabrication

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

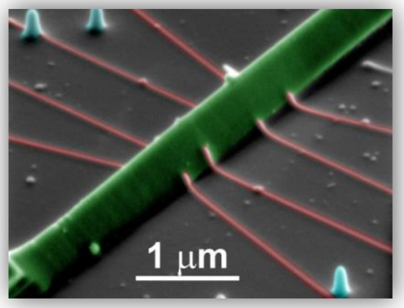


surface defect luminescence

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

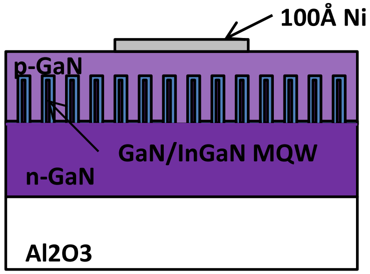
Properties (electrical, optical, thermal, mechanical)

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



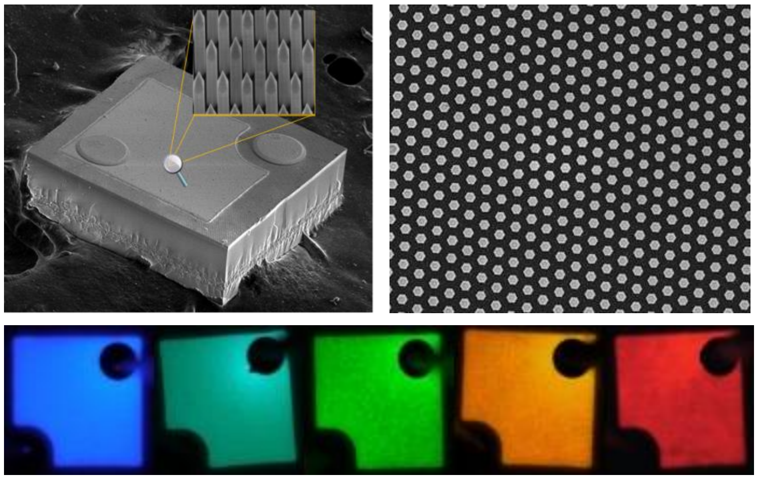
Electrically-integrated devices

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



Nanowire LED Commercialization/Industry Efforts

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

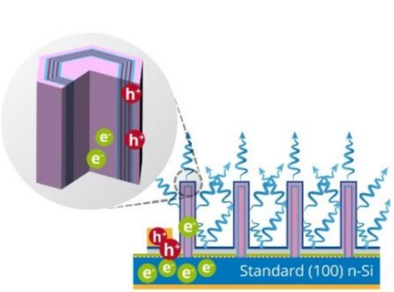


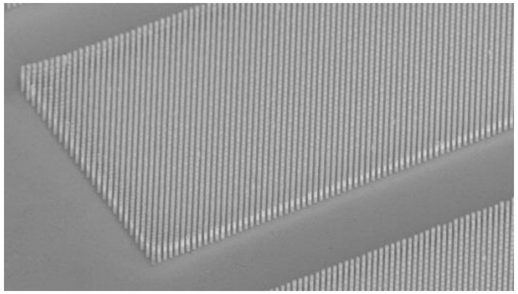
www.glo.se   Bottom-up grown nanowires with *m*-plane MQWs

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)

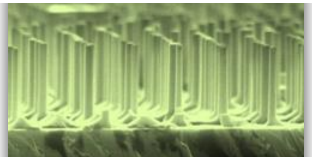




http://www.eetimes.com/document.asp?doc_id=1280676

- goal is to manufacture 3D micro/nanowire-based LEDs for on thin silicon wafers ≥ 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

Bottom-up vs. Top-down nanowires

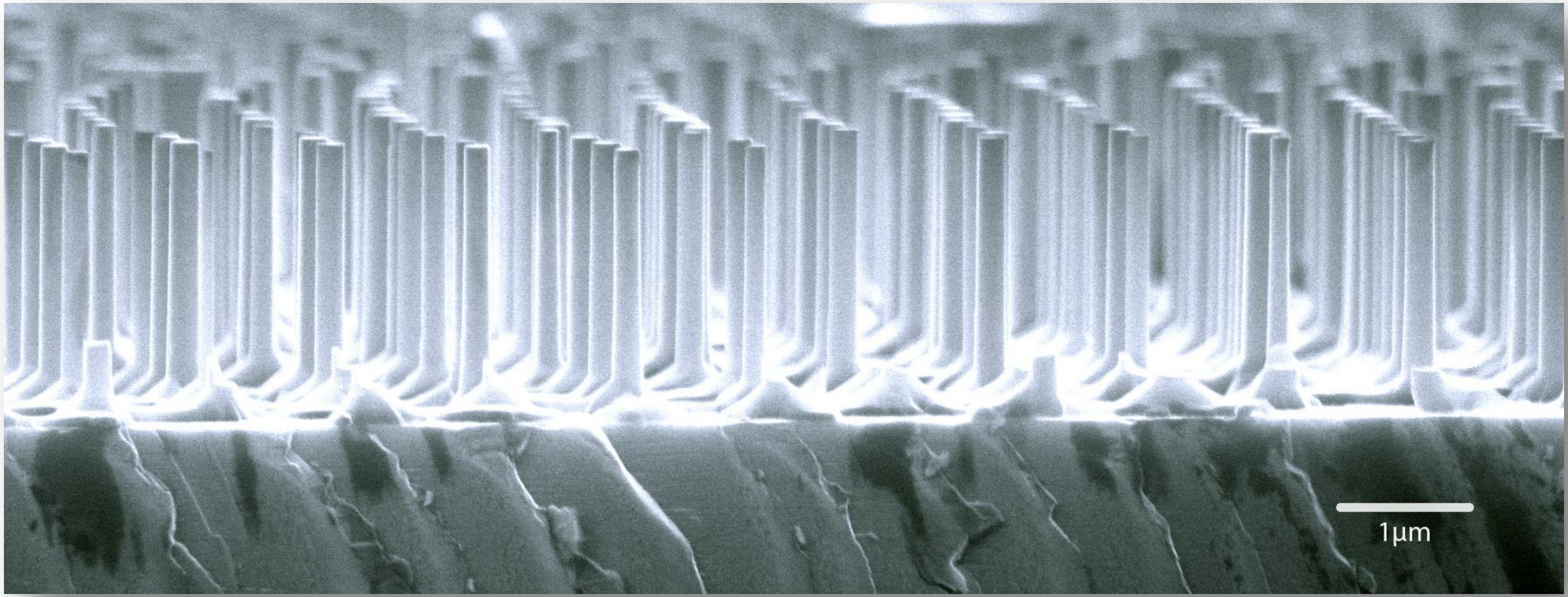


	Bottom-up	Top-down (+ regrowth)
Length	Up to hundreds of µm	Several µm
Diameter	~30 nm to microns	~10 nm to microns
Dislocations	Few or none	Depends on density in film
Radial architectures	Yes, typically by MOCVD	Yes, by MOCVD regrowth
Axial architectures	Yes, typically by MBE	Yes, but not strain relaxed
Substrate	Lattice matching less critical	Lattice matched
Characterization	Some properties difficult to measure (e.g. doping)	Starting material can be measured using standard techniques
Material Quality:	Point defect density may be high due to growth conditions needed	Starting material can be grown under optimal growth conditions
Uniformity	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…

Advantages of new top-down nanowire fabrication method

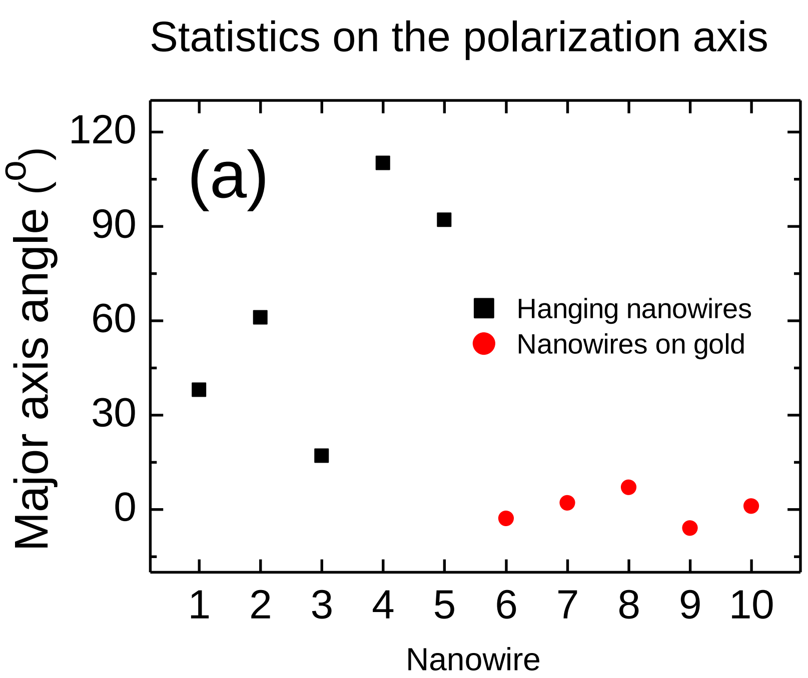


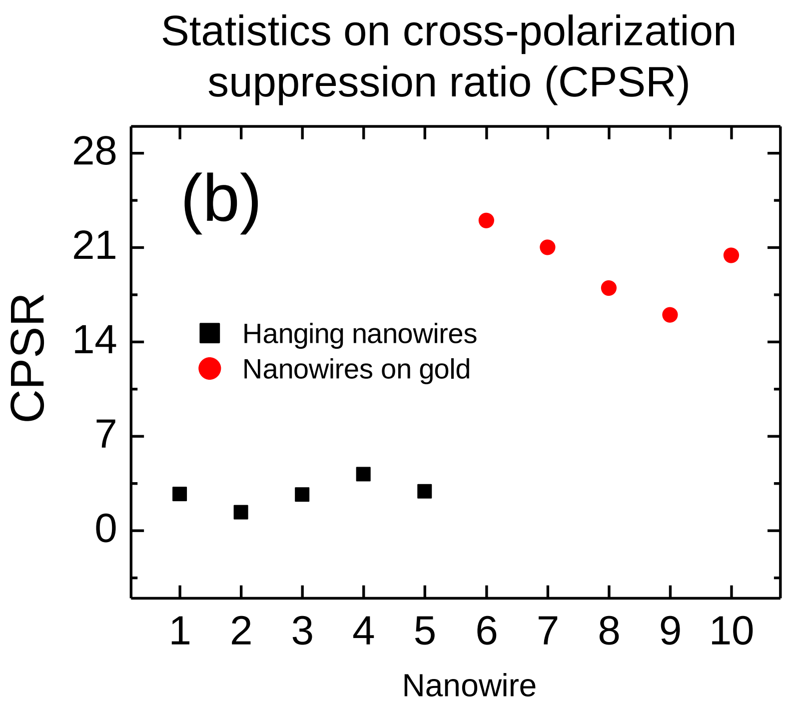
- Wider range of growth conditions, material tunability (1D growth cndns not needed)
- Lower point defect densities (higher growth temperature)
- Ordered/periodic arrays (difficult with catalyst/VLS-based methods)
- Axial III-nitride nanowire heterostructures possible by MOCVD
- Better control of geometry (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 Statistics of Free Standing and on-Gold Nanowires

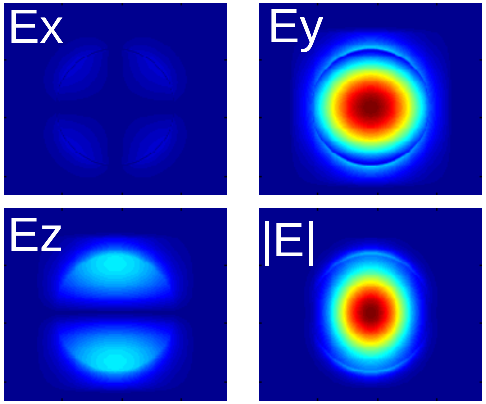




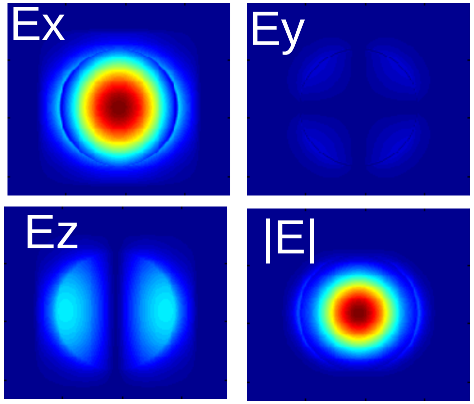
- ✓ Free standing nanowires are polarized with random axes and a small CPSR
- ✓ On-gold nanowires have fixed polarization angle and large CPSR

Why nanowire laser elliptically polarized?

Mode 1 $HE11_a$ -n_{eff}=2.1



Mode 2 $HE11_b$ - n_{eff}=2.1

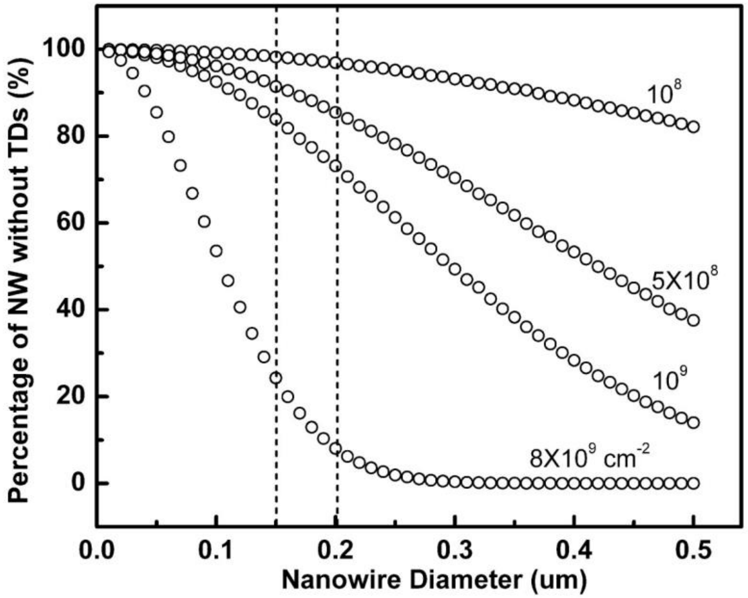


Two orthogonal polarized fundamental modes supported by a 200 nm diameter nanowire in air

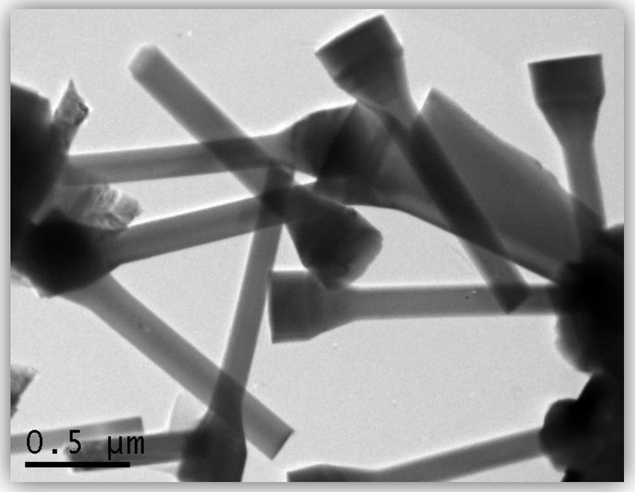
- ✓ Both fundamental transverse modes
- ✓ Same electric field intensity
- ✓ **Two degenerate modes superimpose resulting in elliptical polarization**

Top-down nanowire threading dislocations

Monte Carlo simulation



Bright-field TEM



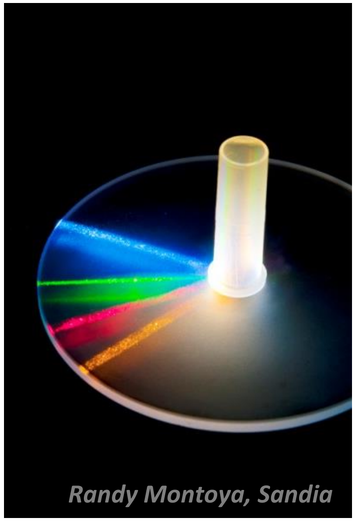
Nanowires etched from ~5e8 cm^{-2} planar LED

- 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*

Lasers for Solid State Lighting

Advantages of lasers for lighting:

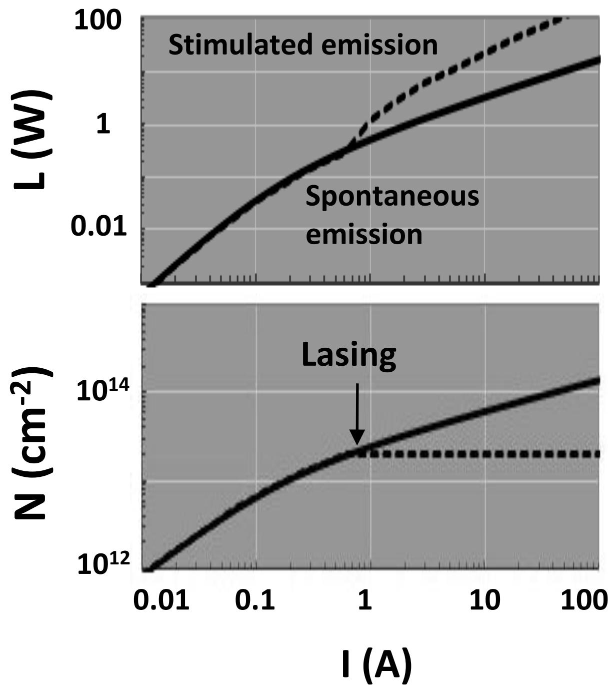
- Lasers show very high efficiency at high power
- LED and LD current densities are converging
- Carrier density is clamped at threshold
  - Circumvent the droop problem in LEDs
  - Need to reduce threshold to avoid losses
- After threshold slope efficiency is one
- Directionality, polarized emission,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



Laser Sources For SSL:

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

Clamped carrier density

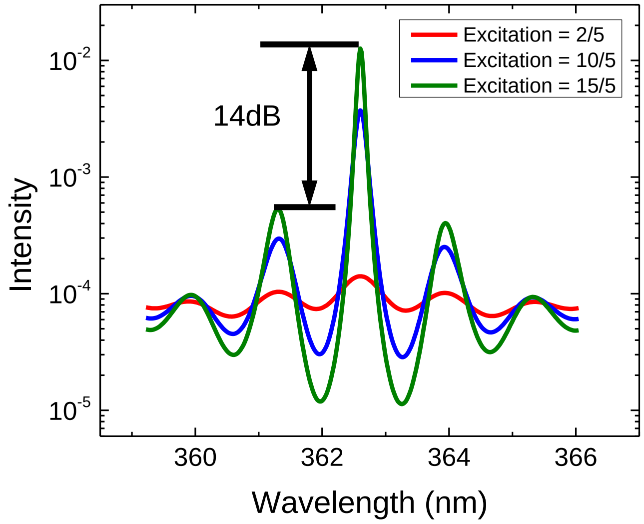


Are narrow linewidth sources acceptable?

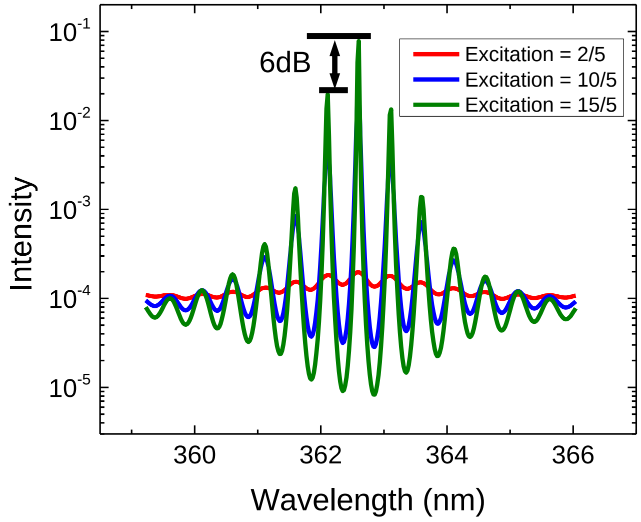
A.J. Fischer, Sandia

Single mode GaN nanowire laser

4 µm long, 140 nm dia. nanowire

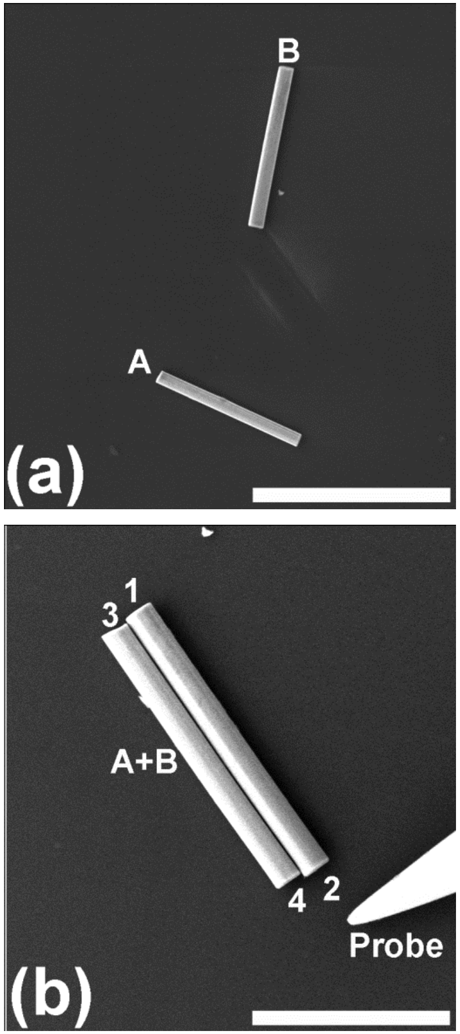


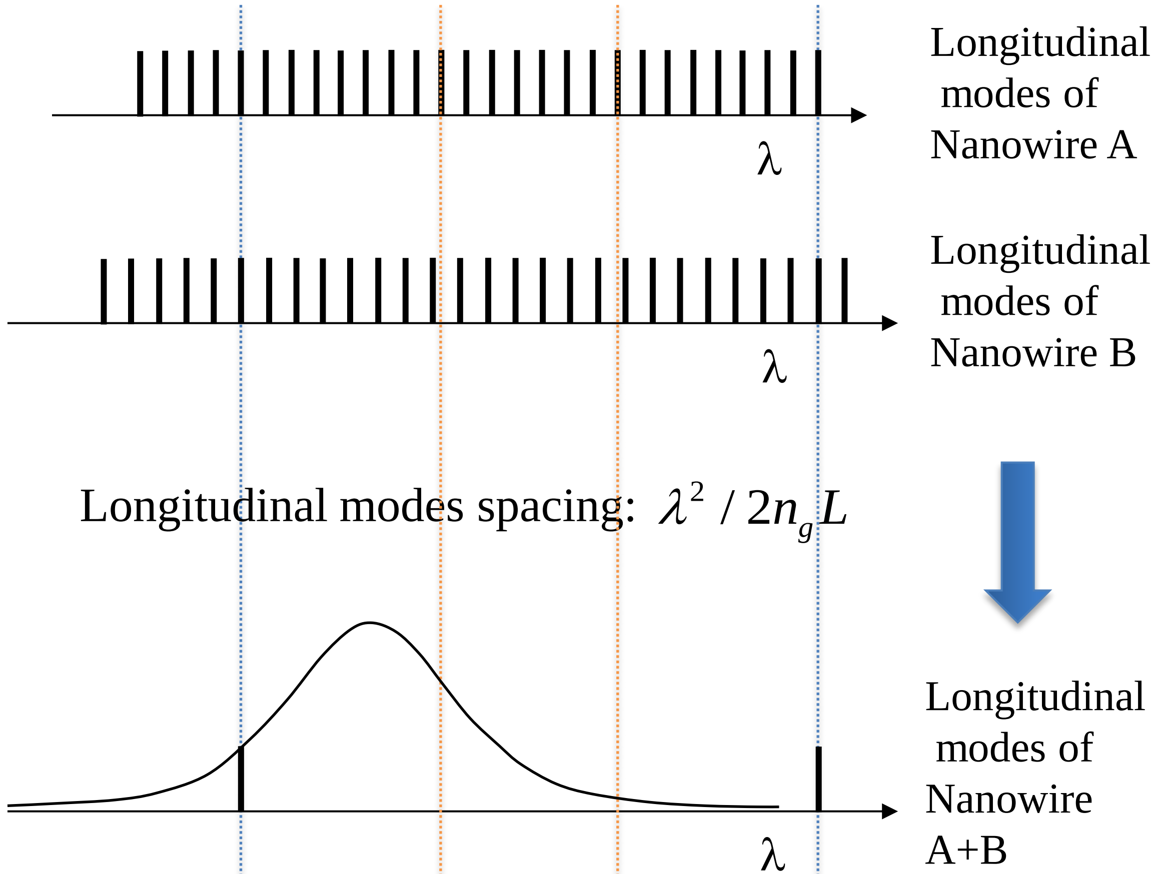
12 µm long, 140 nm dia. wire



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

Method 2: Vernier Effect From a Coupled Cavity

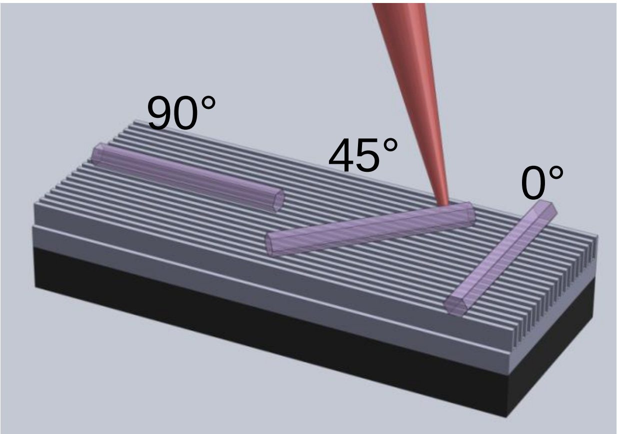




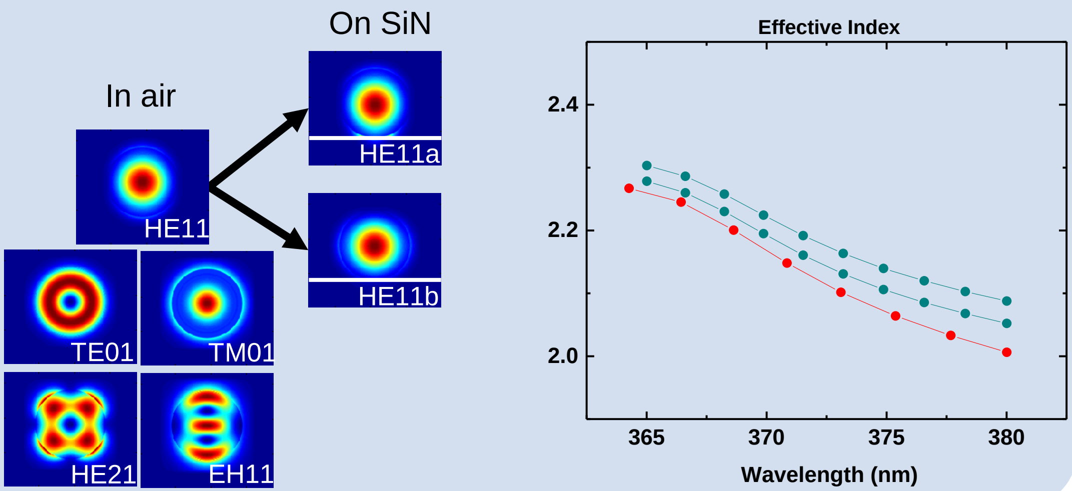
Longitudinal mode spacing greatly enhanced!
(10s of nanometers in this coupled cavity)

Method 3: Distributed Feedback (DFB) Nanowire Laser

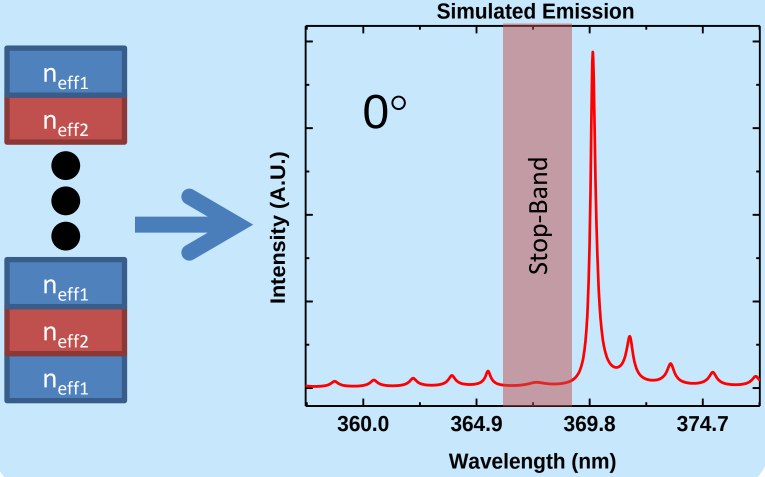
- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve distributed feedback
- Tuned stop-band position and width via nanomanipulation of the angular alignment of NW to change effective periodicity of grating



Mode Calculations

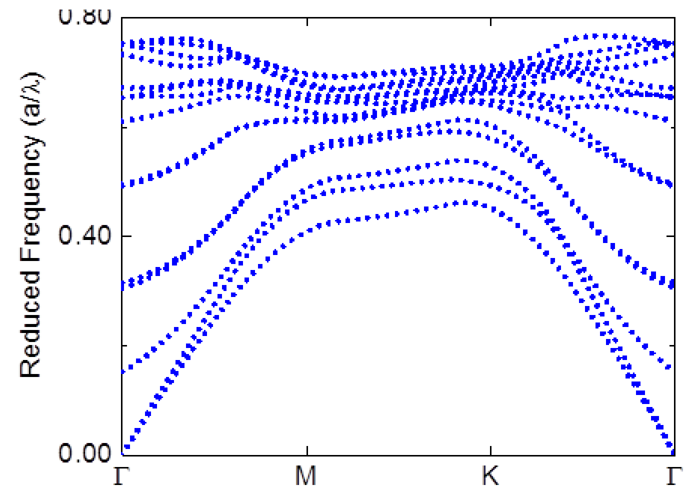


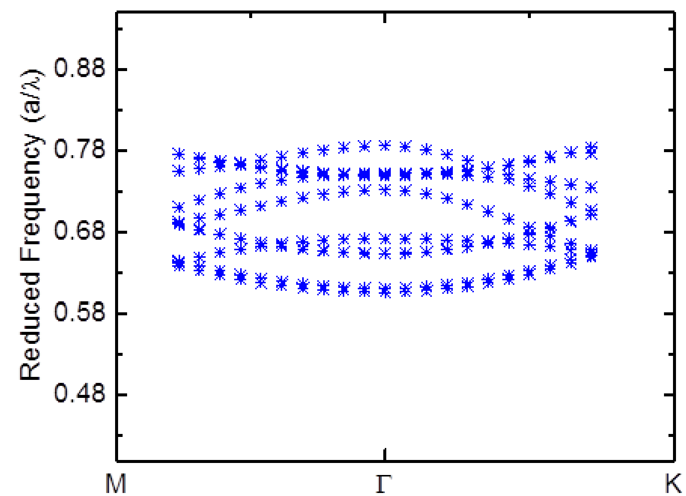
Transfer Matrix Method

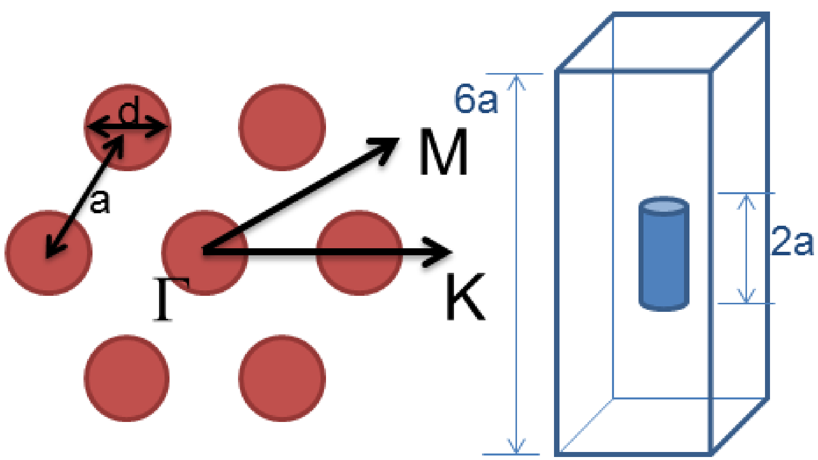


Design Rationale

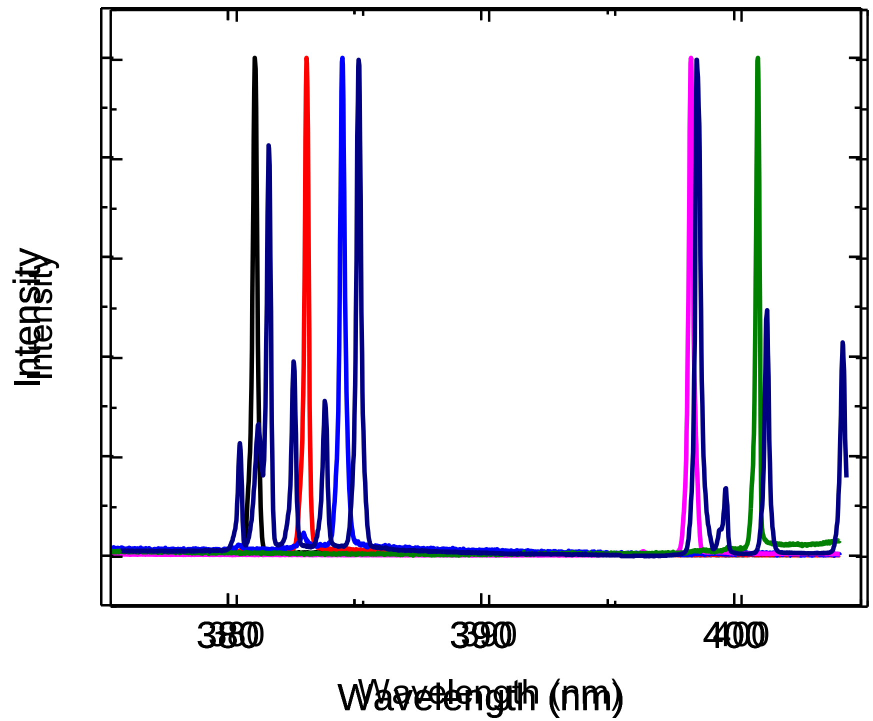
- Higher order bands have low dispersion
- We desire low group velocity to enhance the light matter interaction and the formation of standing waves within the gain medium, to allow low lasing thersholds in materials that exhibit reduced gain over larger bandwith







III-N Nanowire Photonic Crystal Lasers

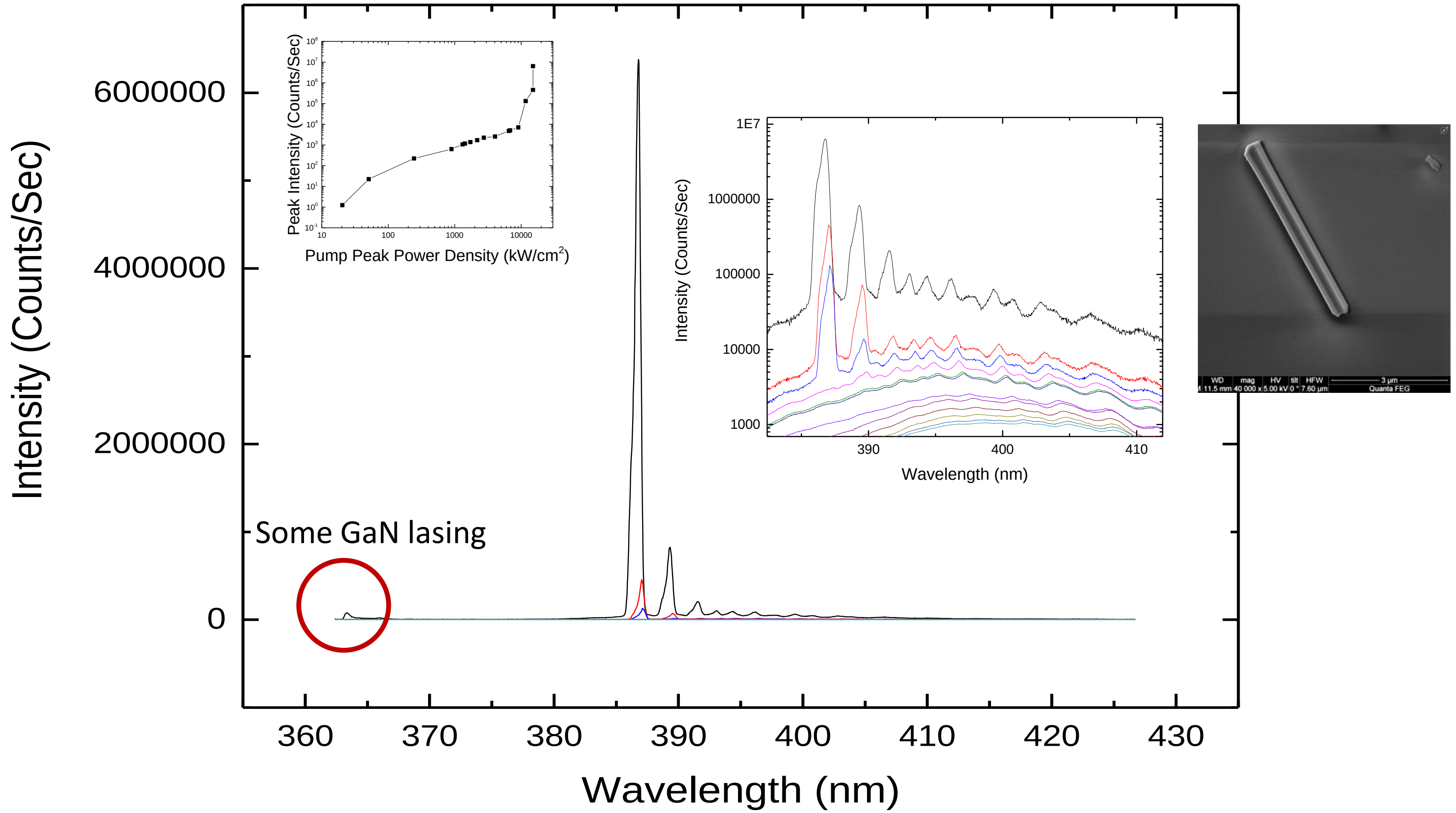


pitch: 320 nm
diameter: 130-140nm

10 um

Key Accomplishments

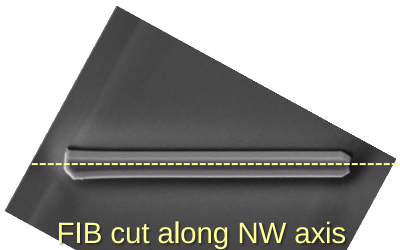
First known demonstration of optically-pumped lasing in radial m-plane GaN/InGaN MQW nanowires

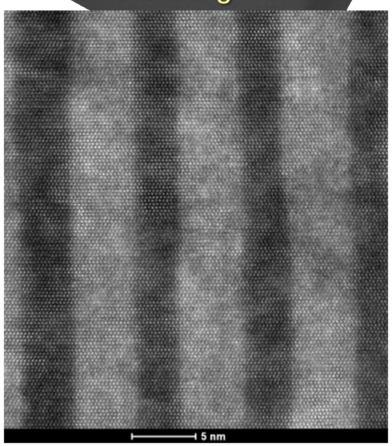


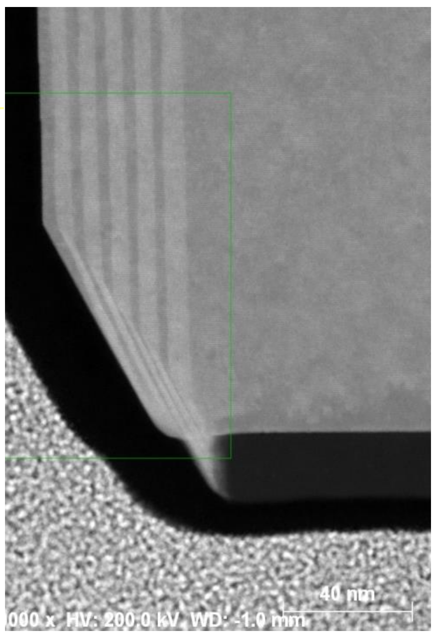
Result confirms radial InGaN/GaN MQW NW can lase (note: not optimized designs)

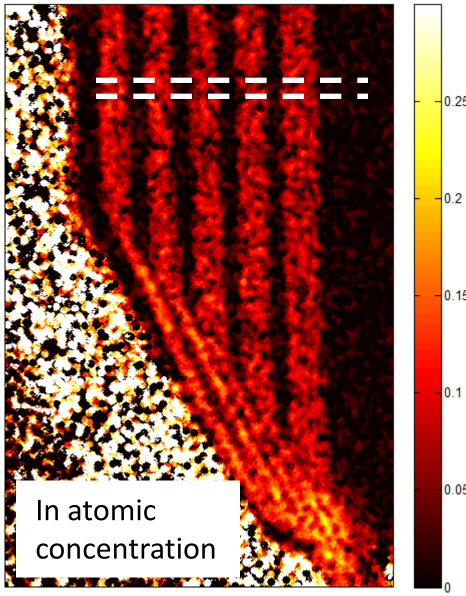
Key Accomplishments

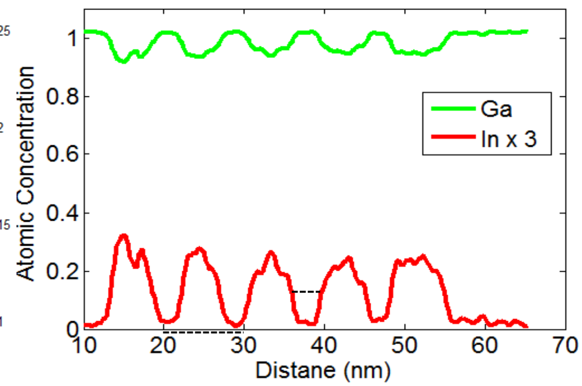
Optically-pumped lasing in radial m-plane GaN/InGaN MQW nanowires – STEM/EDS analysis











Near tip region

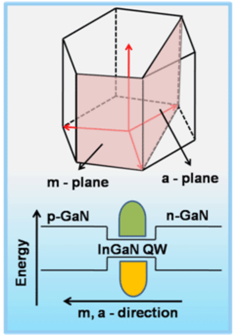
- In composition ~6-10%
- InGaN QWs ~4-6 nm
- GaN barriers ~2.5-4 nm

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

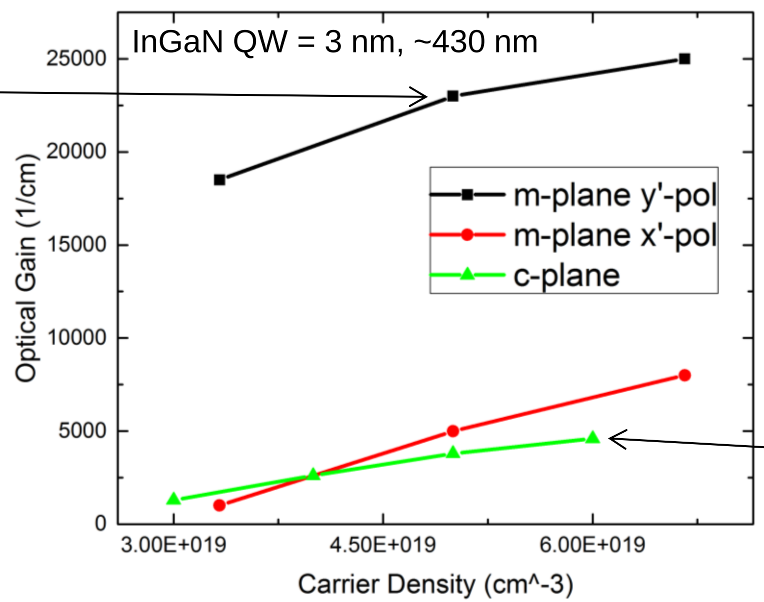
Key Accomplishments

Analysis of axial vs radial NW designs

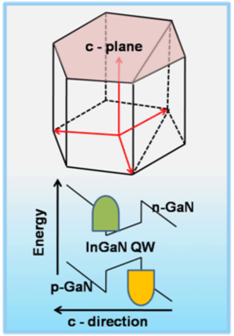
Radial NW



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

$\lambda := 420nm$

$Length := 5\mu m$

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

$\Gamma_{xy} := 1$

Overlap Calculation

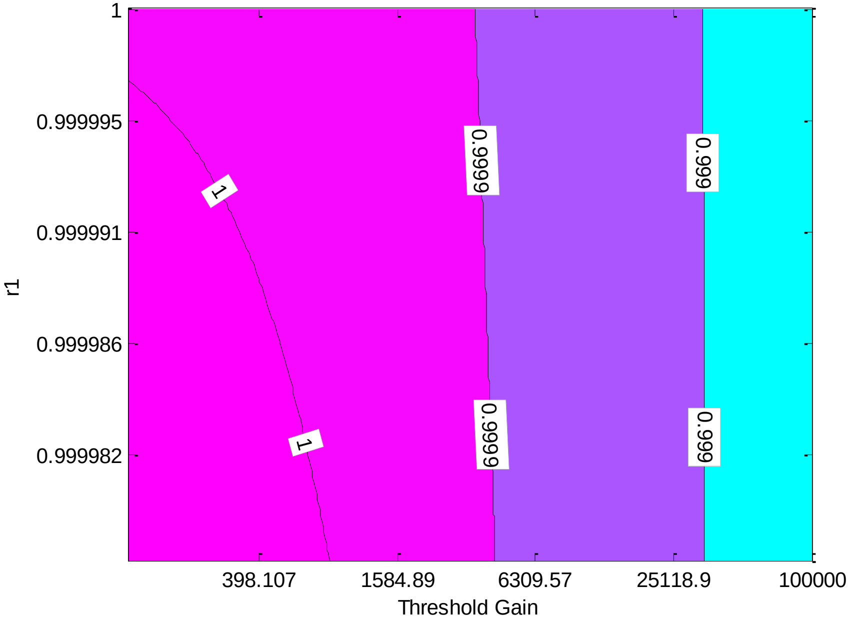
$$\Gamma_z := \frac{t_{QW} \cdot N_{wells}}{Length} = 3 \times 10^{-3}$$

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

Threshold Gain

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

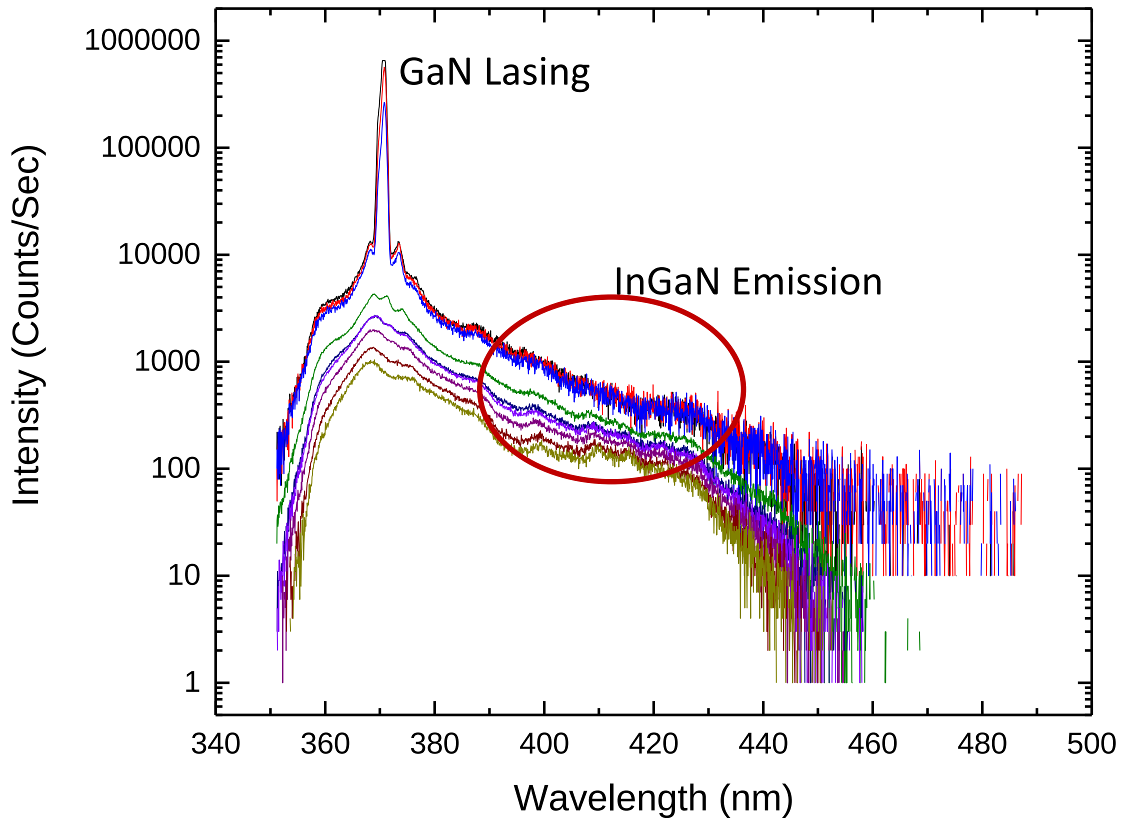
c-plane GaN/InGaN MQWs

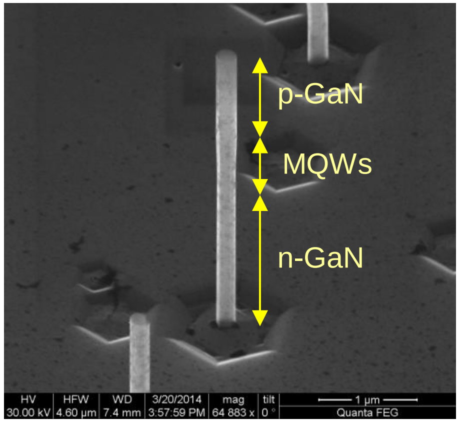


Need unrealistically high mirror reflectivities for axial NW design!
(focus on radial NW design)

Key Accomplishments

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





No InGaN lasing observed for axial NW laser diode structure