Lasing from Top-Down Gallium Nitride Nanowires

SAND2012-1802C

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- **Lasers for Solid State Lighting and Nanowires for Lasing**
- **Fabrication of Top-Down GaN Nanowires**
- **Photoluminescence Top-Down Nanowires**
- **A Single Frequency Nanowire Laser**
- **Modeling and Confirmation of Single Mode Behavior**

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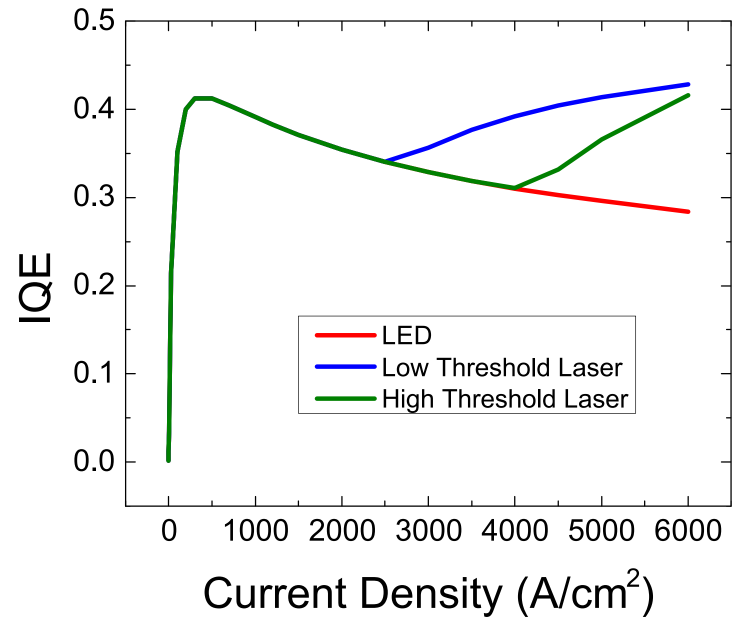
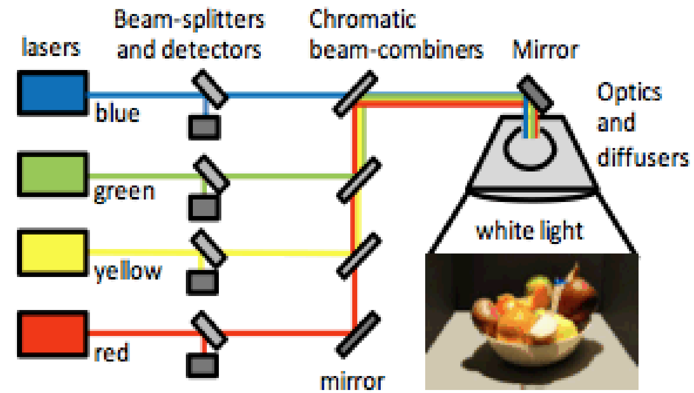
Why Lasers in Solid State Lighting?

- **InGaN LEDs exhibit a decrease in efficiency at high drive currents referred to as the "efficiency droop"**
  - **This droop in efficiency limits the operating current density of InGaN LEDs and ultimately increases the cost per lumen.**
- **Lasers offer a path around the "droop" in efficiency since above threshold the carrier density is clamped**
- **A four-color laser white illuminant has been experimentally shown to be indistinguishable from white reference illuminants.**



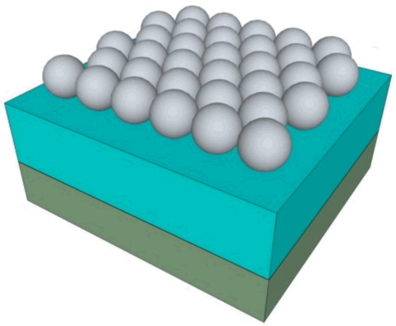


A. Neumann, J. J. Wierer, W. Davis, Y. Ohno, S. R. J. Brueck, and J.Y. Tsao, Opt. Express **19**, A982-A990 (2011)

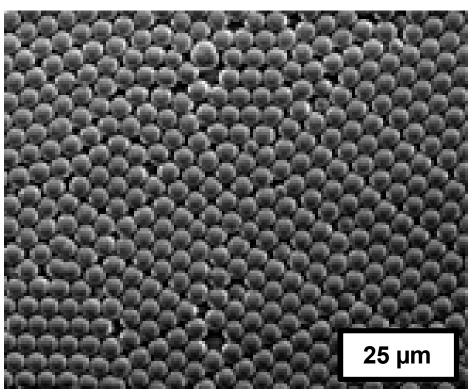
Why Nanowires for Lasing?

- Reduced strain
  - Greater range of alloy compositions
- Laser cavities
  - strong optical confinement
  - end faceting
- Low density of threading dislocations
- Integration into two-dimensional arrays
- Vertical cavities

Fabrication: A Top-Down Two-Step Etch Process



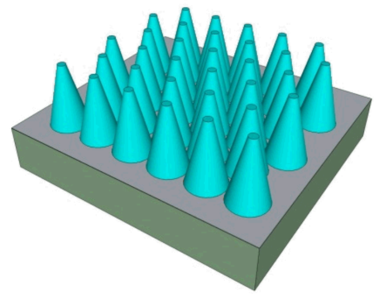
(0001) GaN on sapphire

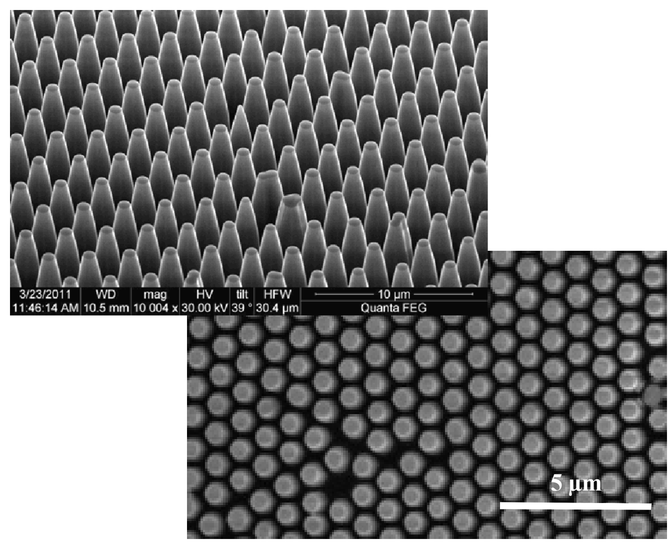


Monolayer of micro-spheres

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

ICP etch

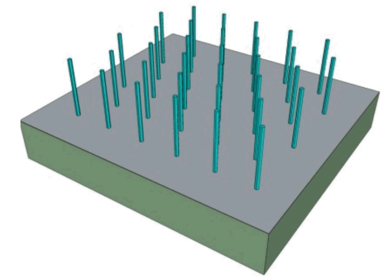


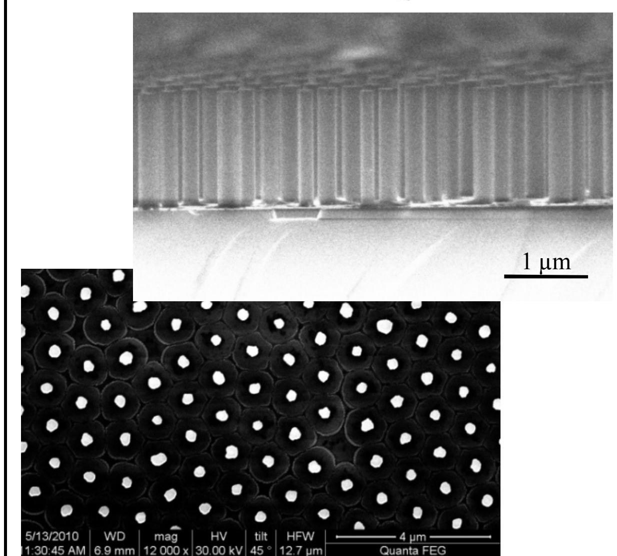


Plasma etch causes sidewall damage

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

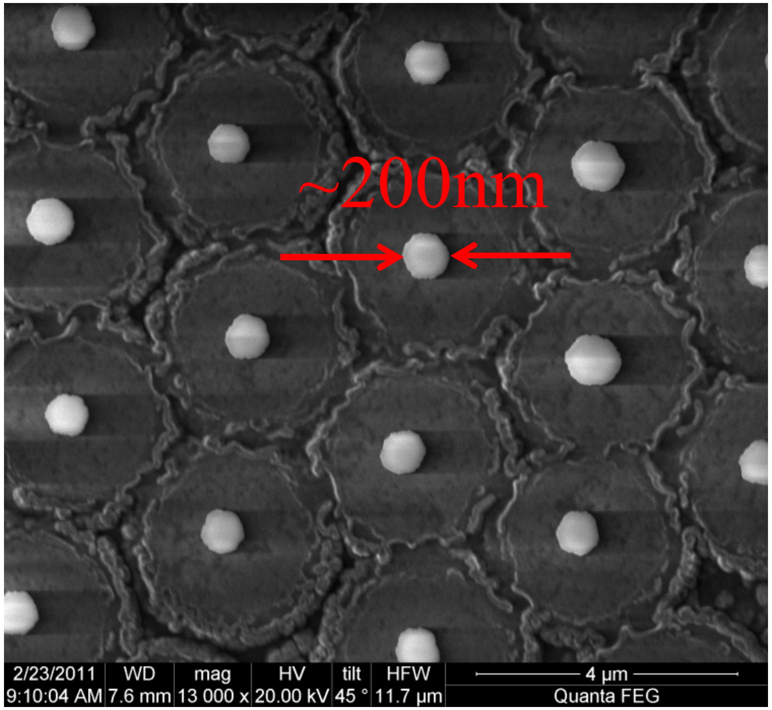
Wet Etch
(AZ-400K developer)





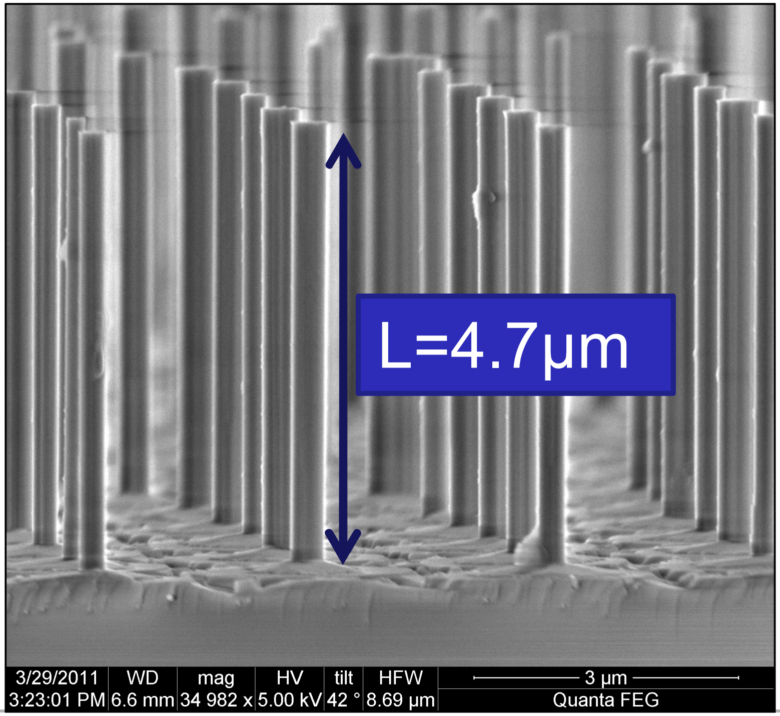
Wet etch removes sidewall damage

Cavity Geometry of the Top-Down Nanowire



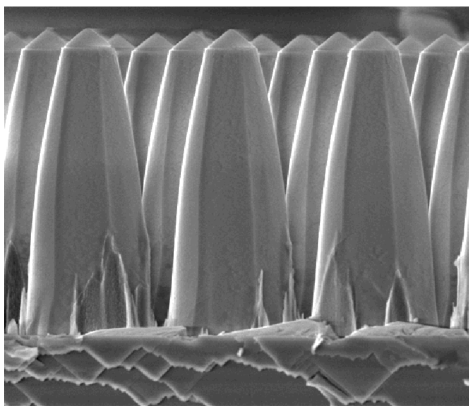
Wires fabricated using our top-down methodology exhibit a range of diameters from 80nm-300nm.

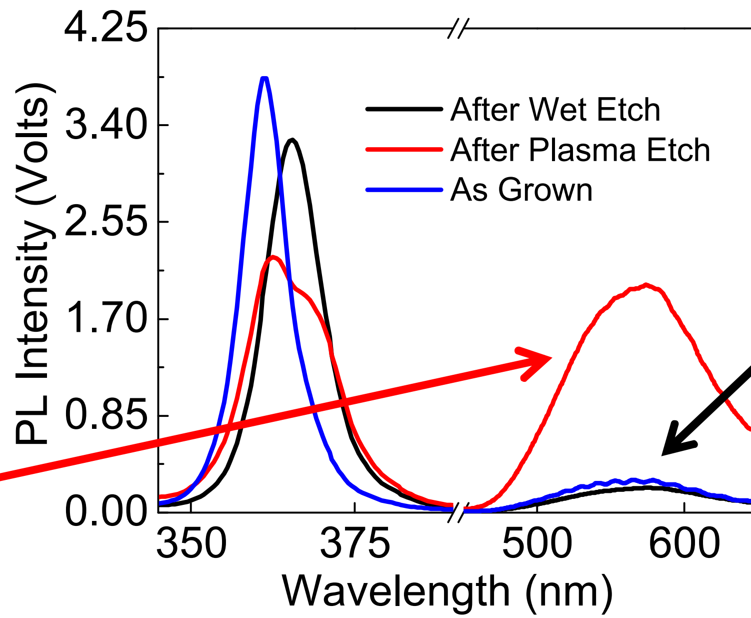
Since the C-plane is not etched, the wires are uniform in length and the length is fixed to the thickness of the epitaxial layer.



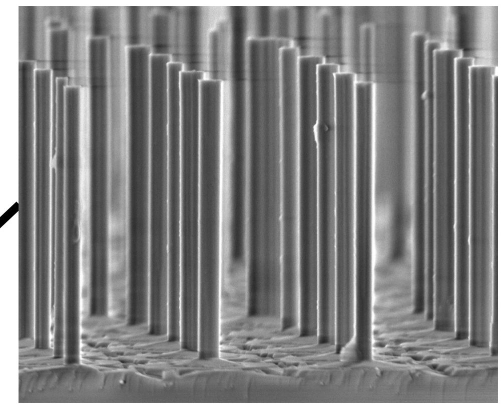
Comparison of Photoluminescence Before and After Etching

After Plasma-Etch





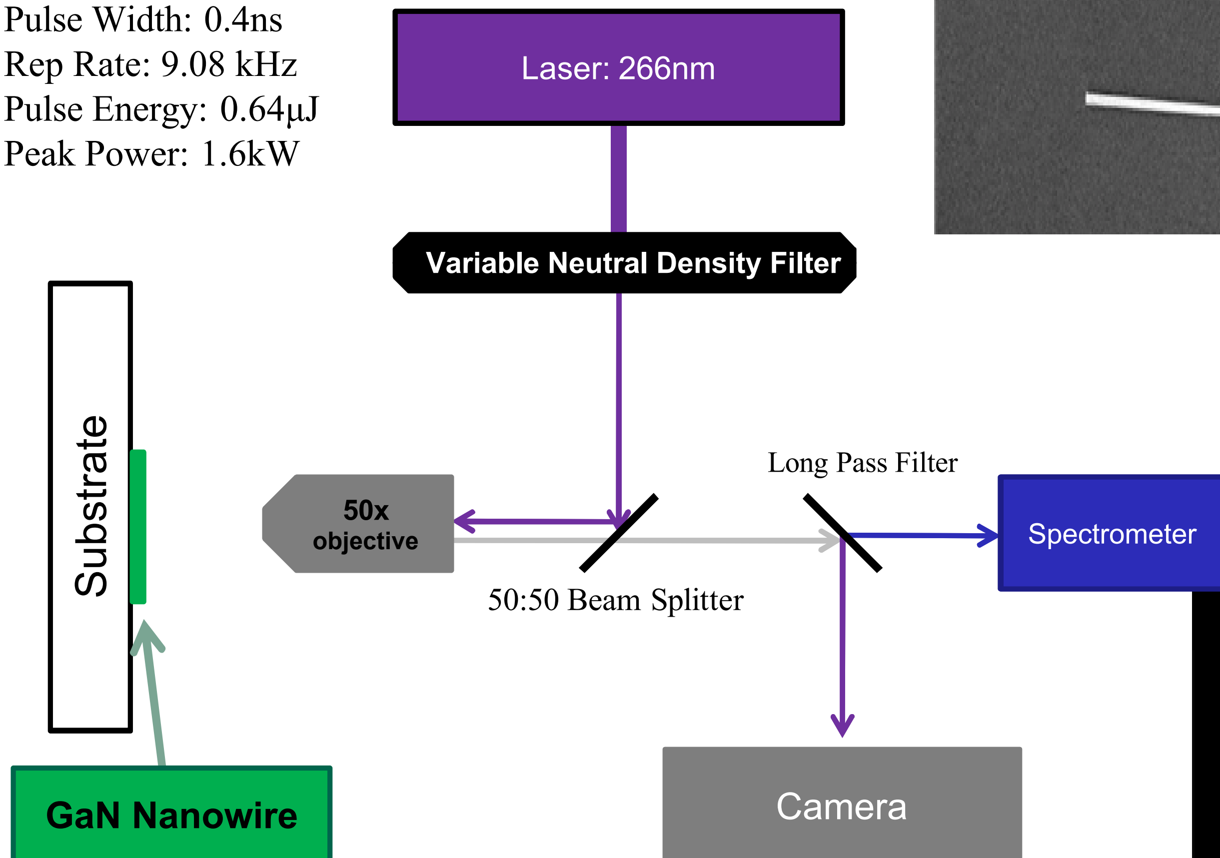
After Wet-Etch

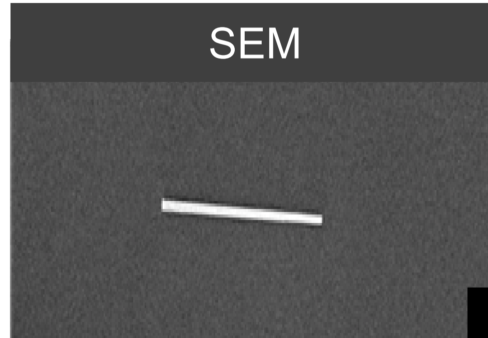


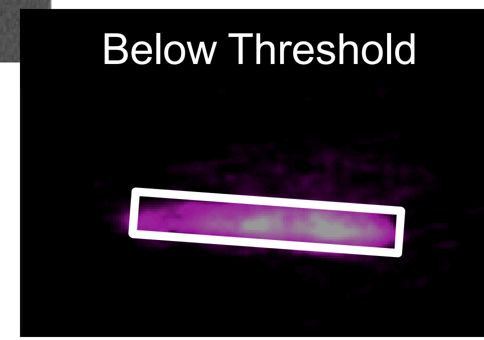
Wet-etch removes damage caused by plasma-etch, as seen by the decrease in the yellow emission.

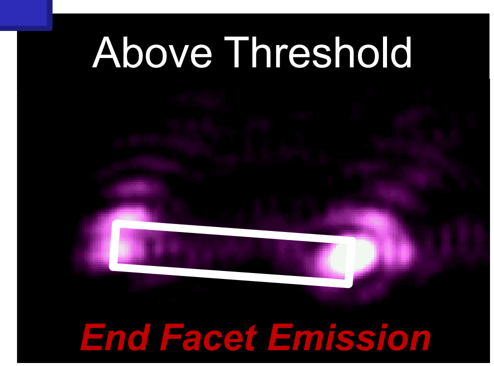
Spectral Characterization of Single Nanowires

Average Power: 5.2mW
Pulse Width: 0.4ns
Rep Rate: 9.08 kHz
Pulse Energy: 0.64μJ
Peak Power: 1.6kW



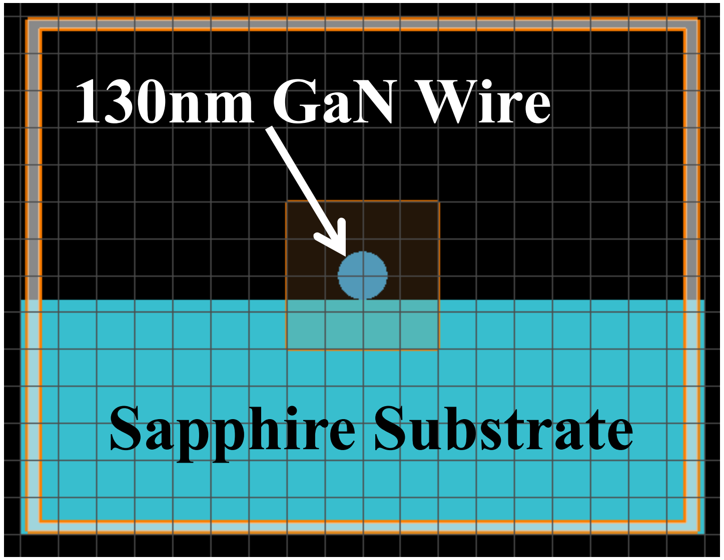




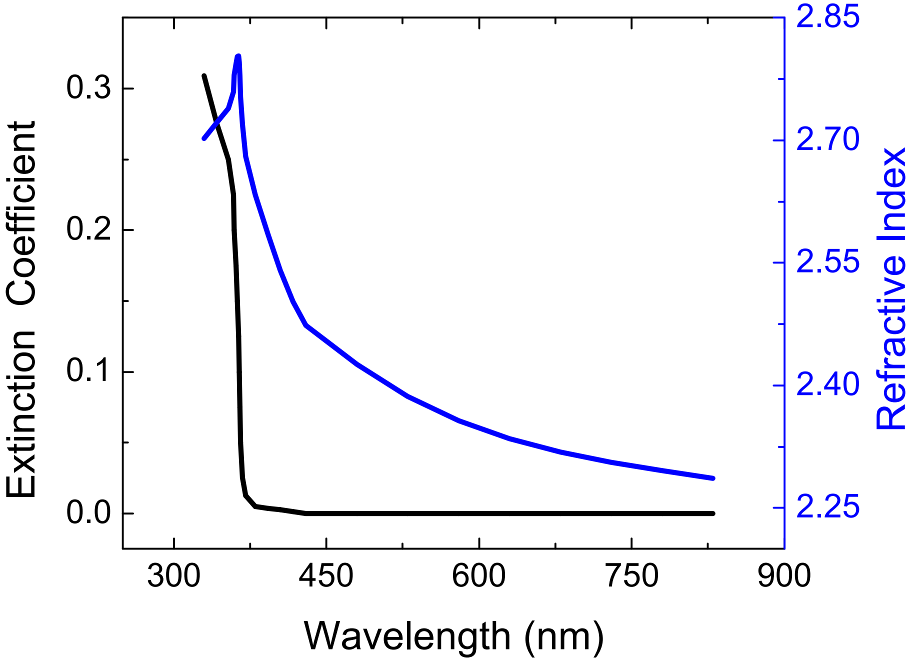


Modeling of the Nanowire Waveguide

- The modal fields and effective index of the GaN nanowire are found using Lumerical MODE Solutions
- 130nm wires are modeled lying on a sapphire substrate



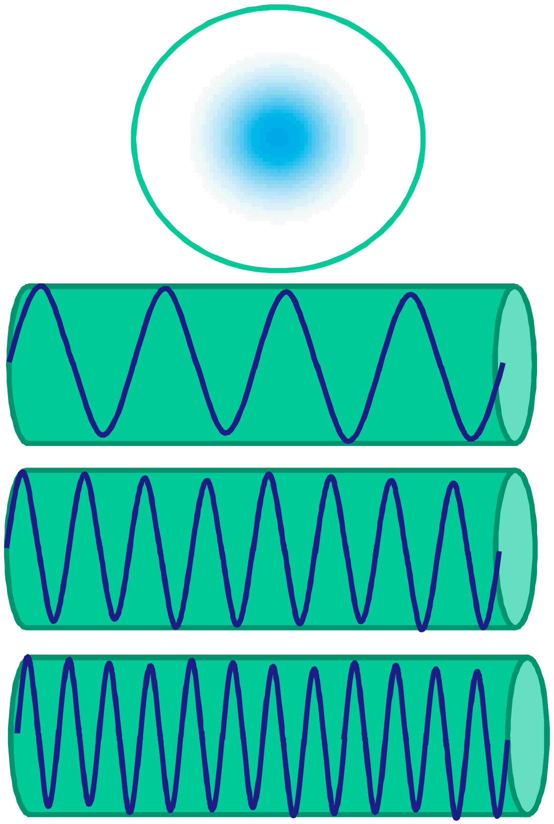
Optical Properties of GaN Thin Films



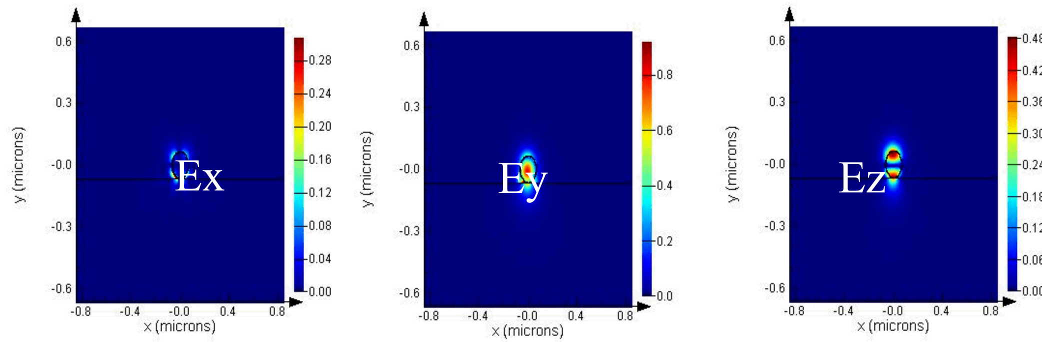
T. Yang, S. Goto, M. Kawata, K. Uchida, A. Niwa, and J. Gotoh, "Optical Properties of GaN Thin Films on Sapphire Substrates Characterized by Variable-Angle Spectroscopic Ellipsometry," Jpn. J. Appl. Phys. **37** (1998) L1105

Modal Distributions for Circular Waveguides

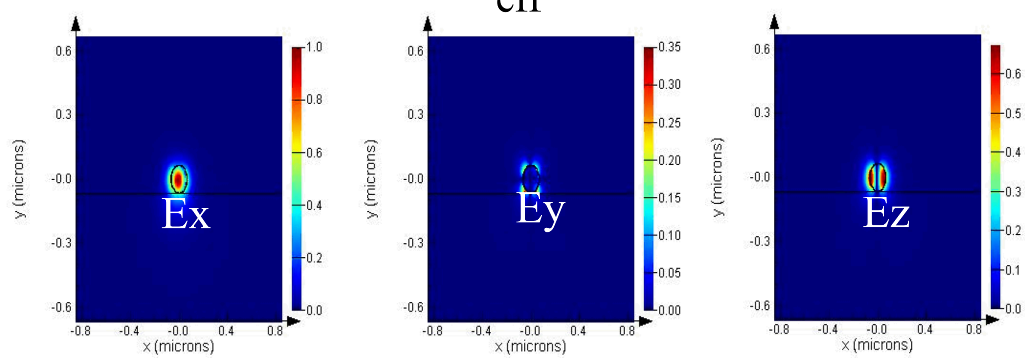
1st Transverse Mode



Mode 1: $n_{eff} = 2.06$ $\Gamma = 0.82$



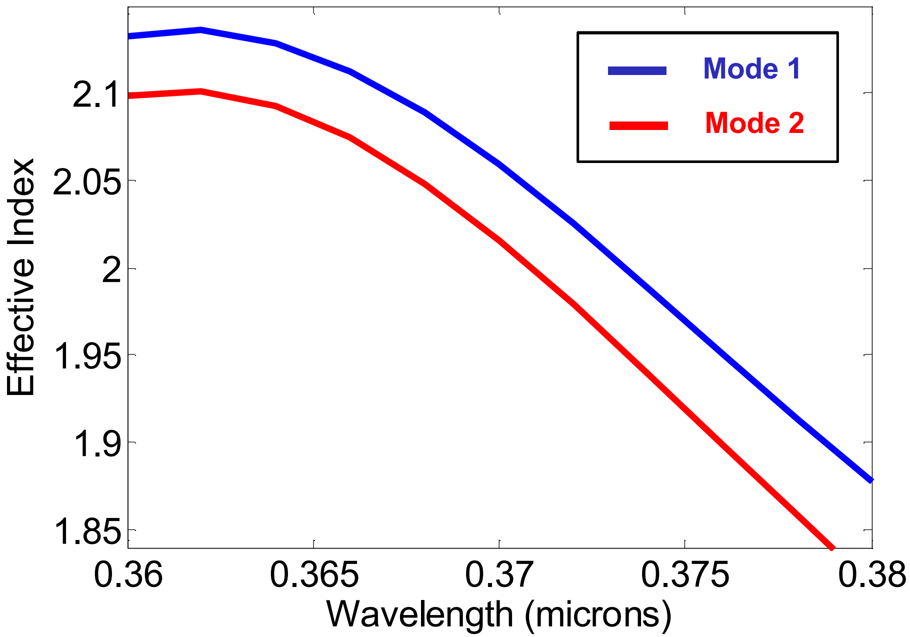
Mode 2: $n_{eff} = 2.02$ $\Gamma = 0.77$

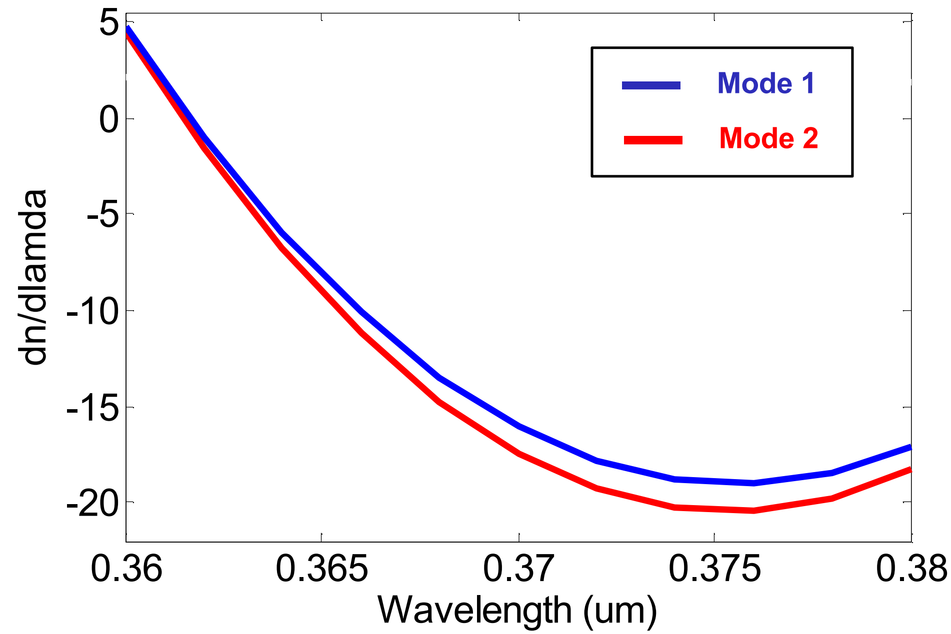


$$E_{m,n,p}(x,y,z) = E_0 u_{m,n}(x,y) e^{-jk_p z}$$

Simulations show two supported modes for a 130nm nanowire.

Estimating the Longitudinal Mode Spacing





Mode	Effective Index (370nm)	Effective Group Index (370nm)
1	2.059	7.994
2	2.016	8.464

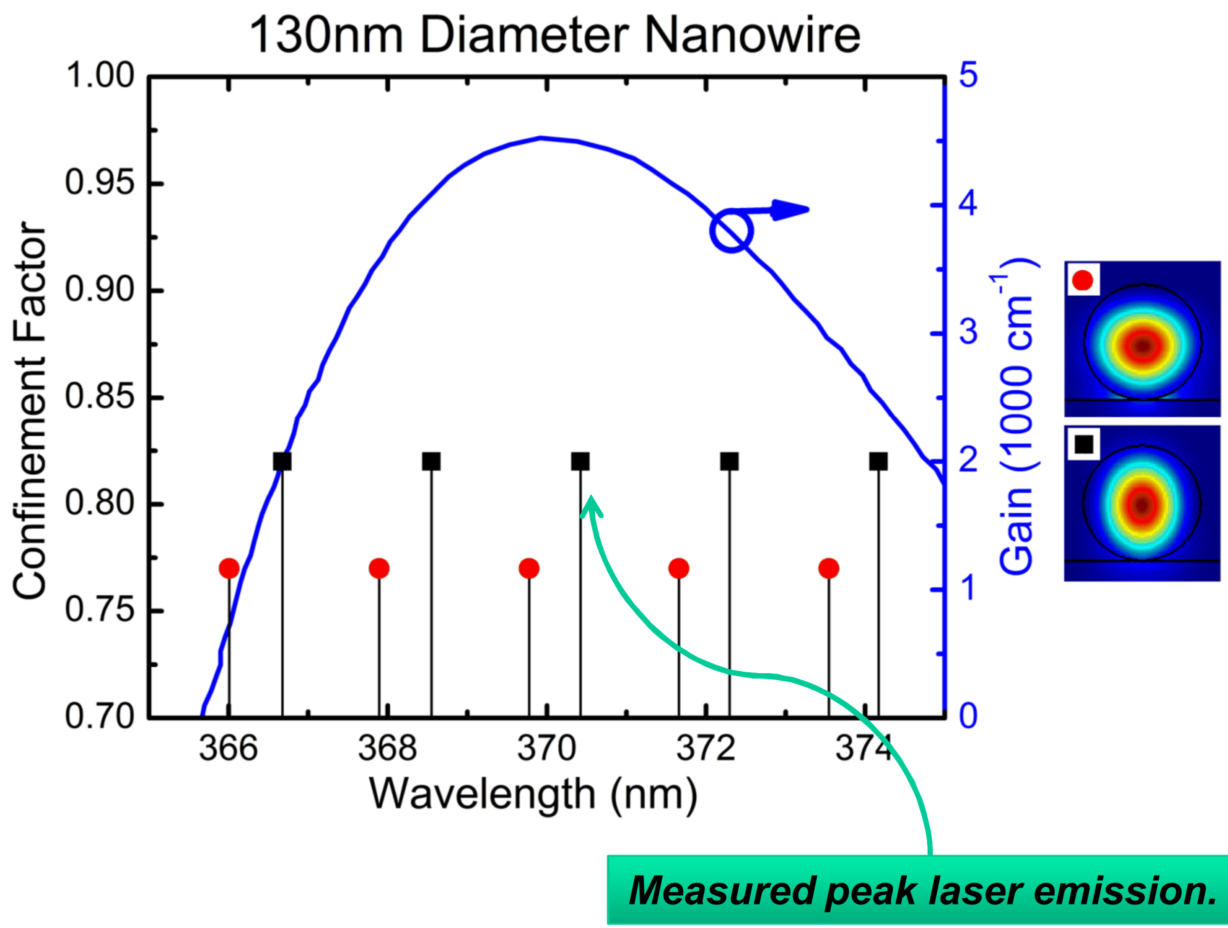
$$n_{eff-g} = n_{eff} - \lambda_0 \frac{dn_{eff}}{d\lambda_0}$$

$$\Delta\lambda_{FSR} \approx \frac{\lambda_0^2}{2 \cdot l \cdot n_{eff-g}}$$

Locations of the Transverse and Longitudinal Modes for a 130nm Nanowire

- ***The location of the competing cavity modes are calculated relative to measured peak laser emission.***

$$\Delta\lambda_{FSR} \approx \frac{\lambda_0^2}{2 \cdot l \cdot n_{eff-g}}$$

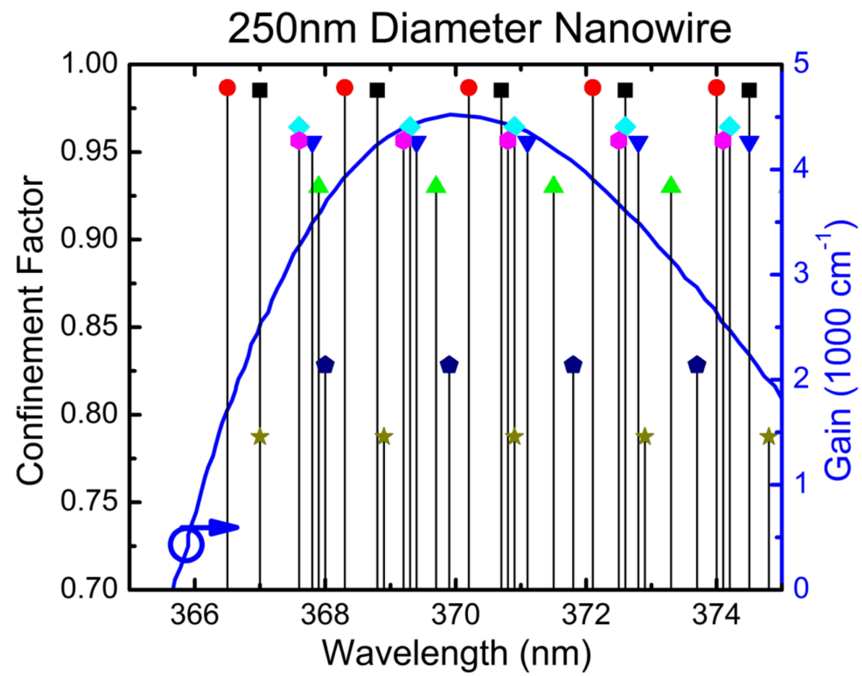


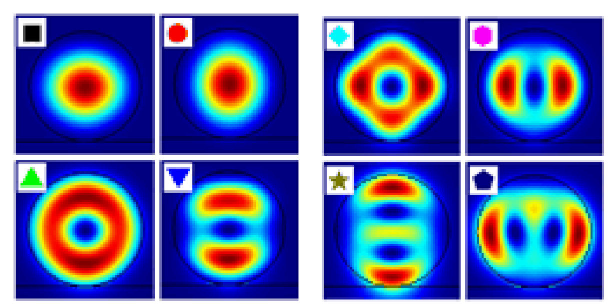
Wiesmann, D., et al. (1996). "Gain spectra and stimulated emission in epitaxial (In,Al) GaN thin films." Applied Physics Letters **69(22): 3384-3386.**

Locations of the Transverse and Longitudinal Modes for a 250nm Nanowire

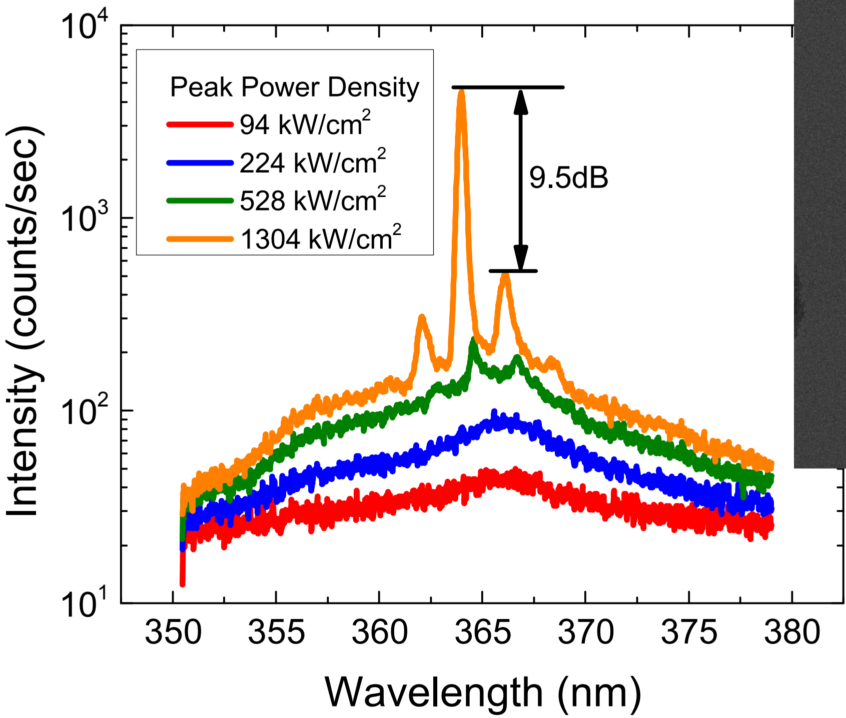
•Increasing the wire diameter to 250nm adds six additional transverse modes and many longitudinal modes.

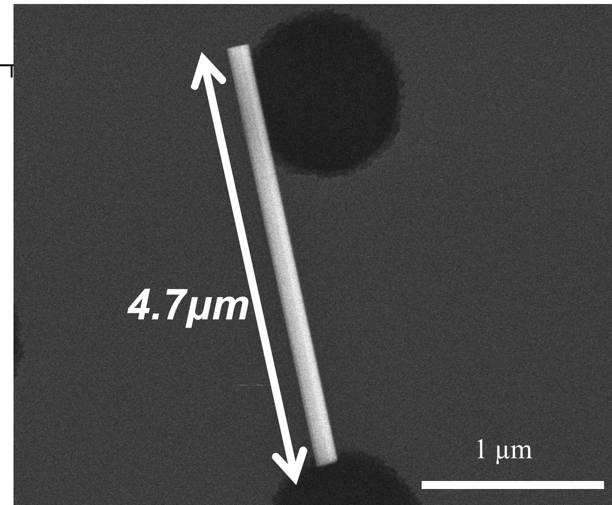
Mode	Neff	Ngroup	Γ
1	2.5386	7.7301	98.5245
2	2.5362	7.7588	98.6809
3	2.2902	8.1414	93.0141
4	2.1856	8.6073	95.5782
5	2.1776	8.7993	96.4402
6	2.1306	8.8372	95.6571
7	1.8521	7.4178	78.7448
8	1.8337	7.7519	82.8336

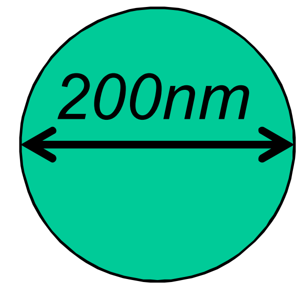


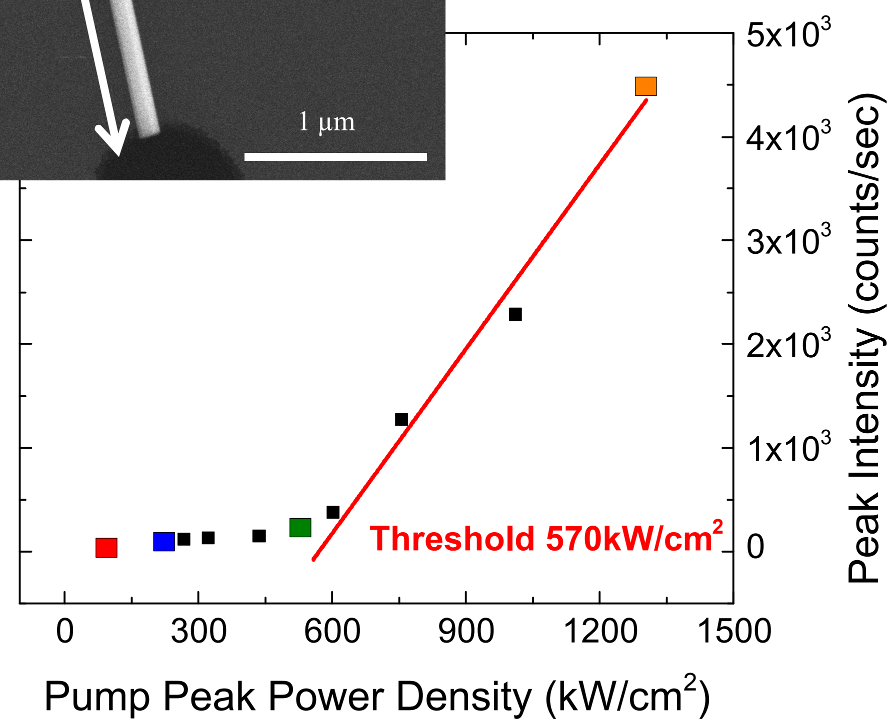


Lasing From a Large Diameter Single Nanowire



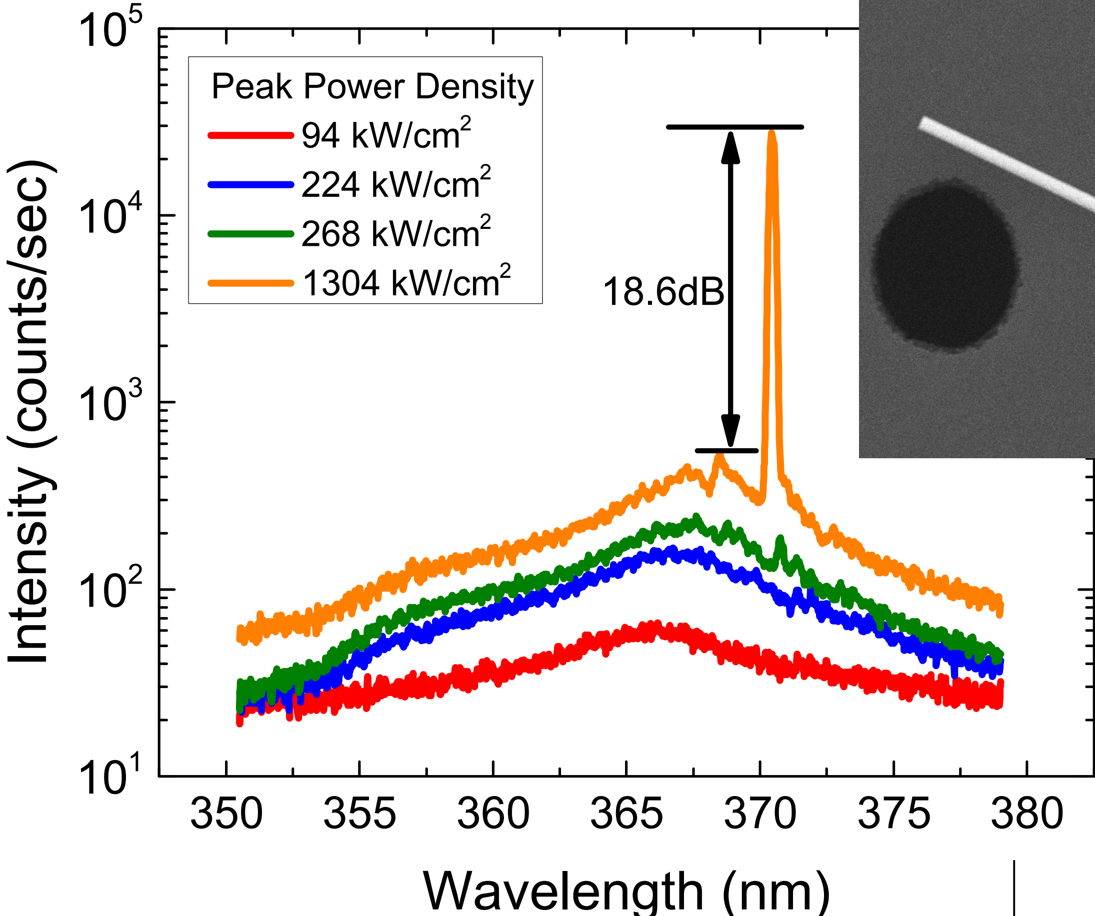


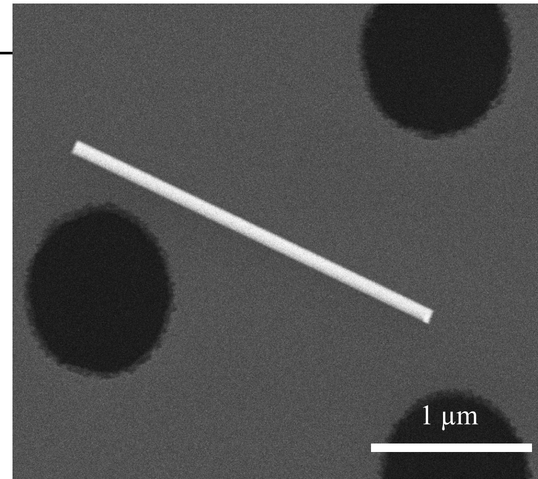


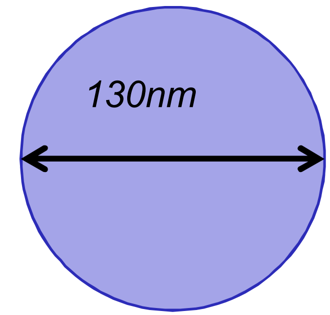


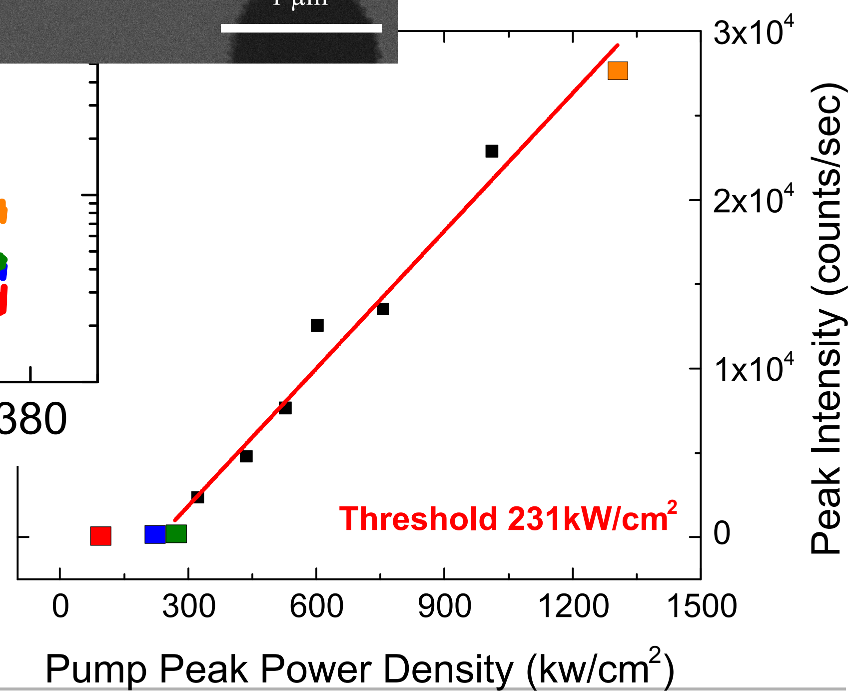
Broad linewidth indicates multiple transverse mode lasing.

Lasing from a Small Diameter Nanowire









Predicting Single Mode Behavior

- In order to understand the single mode behavior we look at the mode locations and gain spectra in order to predict a single mode
- Longitudinal modes are separated by $\Delta\lambda_{FSR}$

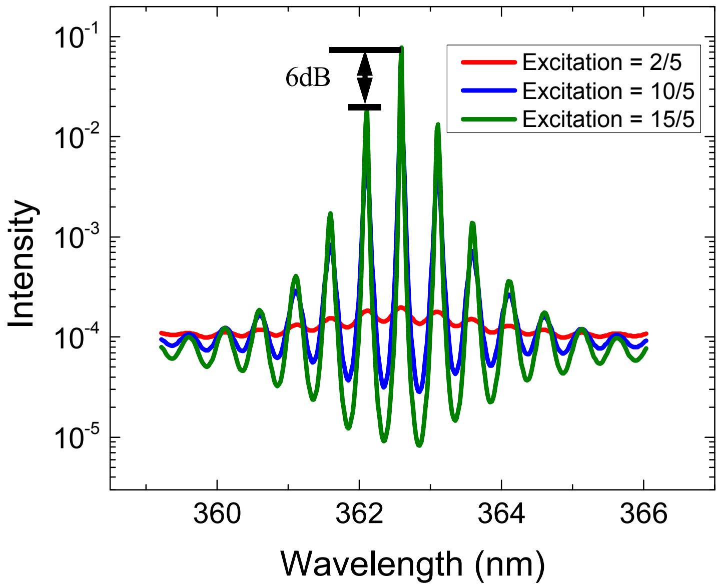
$$\Delta\lambda_{FSR} \approx \frac{\lambda_0^2}{2 \cdot l \cdot n_{eff-g}}$$

- Short cavities will have a larger mode separation
- Wires with small diameters will support fewer transverse modes
- Modes with smaller confinement and less gain overlap will likely not compete

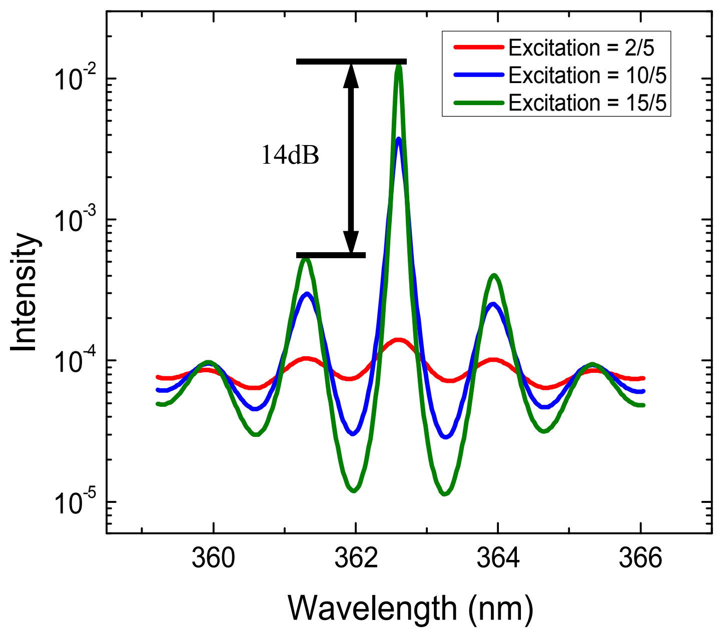
Multi-Mode Laser Theory Indicates Single-Mode Lasing

Modeling shows that by reducing the dimensionality of the wire we can reduce the number of competing modes.

12µm Long



4µm Long



Summary

- **Demonstrated high quality top-down fabricated GaN nanowires using a two-step etch process**
- **Observed lasing from individual top-down fabricated nanowires with thresholds comparable to bottom-up nanowires**
- **In a small diameter nanowire we observed single-mode operation due to the unique cavity dimensions and high quality material**
- **Modeling of the nanowire gives insight into single-mode behavior**

Thank you for your attention.

Backup Slides

Estimating the Laser Threshold Gain

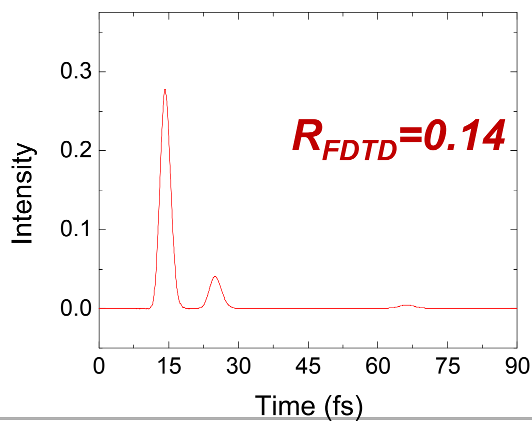
Estimating the reflectivities using the effective index of the waveguide we find the threshold gain to be on the order of <u>5.5 x 10^3 cm^{-1}</u>.

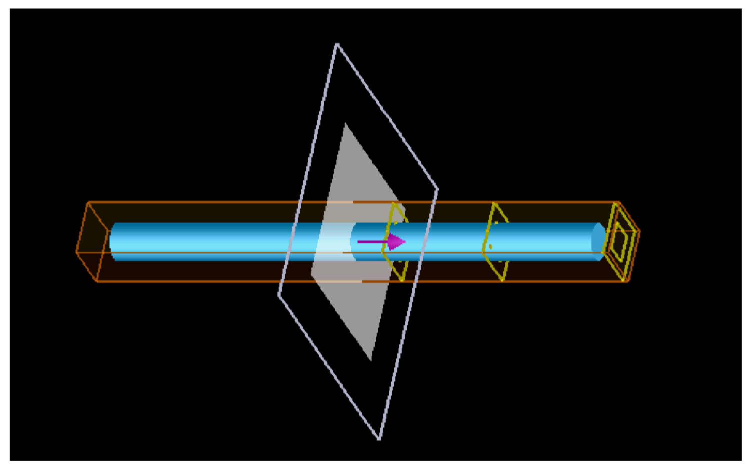
GaN $n_{eff} \approx 2.045$

$R_{estimated}$=0.12

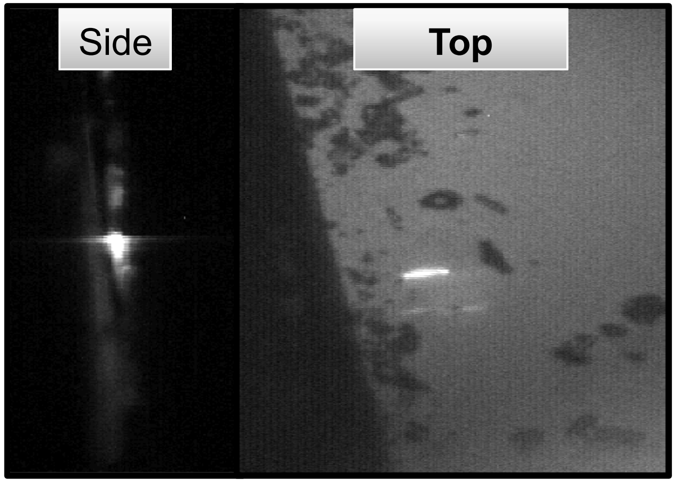
$$g_{th} \approx \frac{1}{2\Gamma L}\ln\left(\frac{1}{R}\right)$$

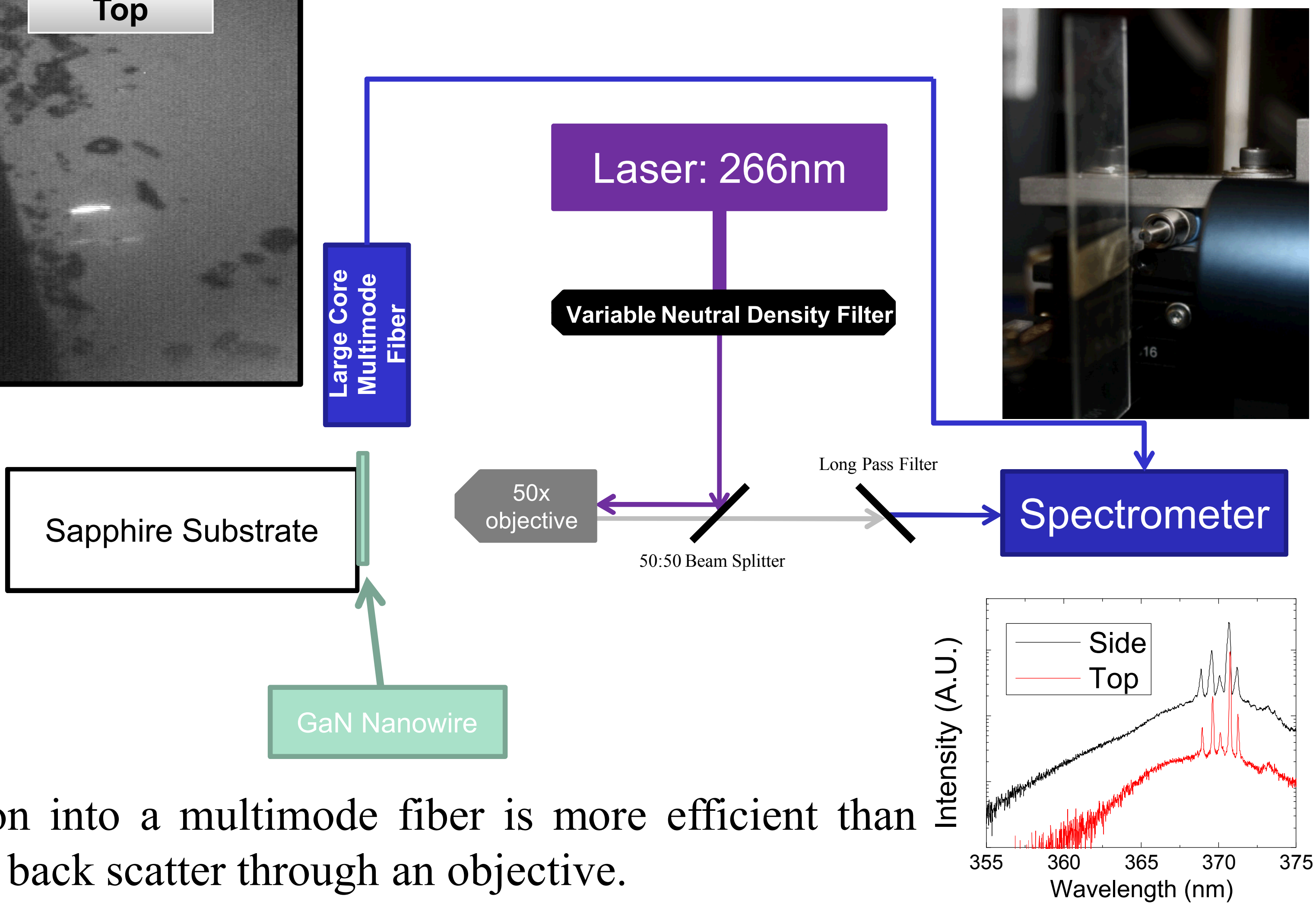
Estimating the reflectivities using the reflected power from an FDTD model we find the threshold gain to be on the order of <u>5.1 x 10^3 cm^{-1}</u>.





End-On Facet Spectral Characterization





Side collection into a multimode fiber is more efficient than collecting the back scatter through an objective.