SAND2014-15582PE

Mode and Polarization Control in Gallium Nitride Nanowire Lasers

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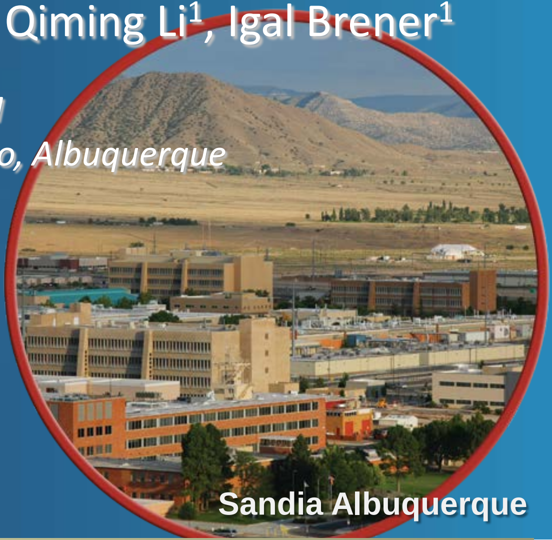
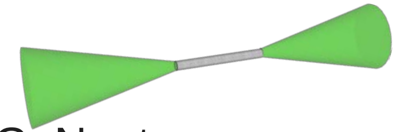
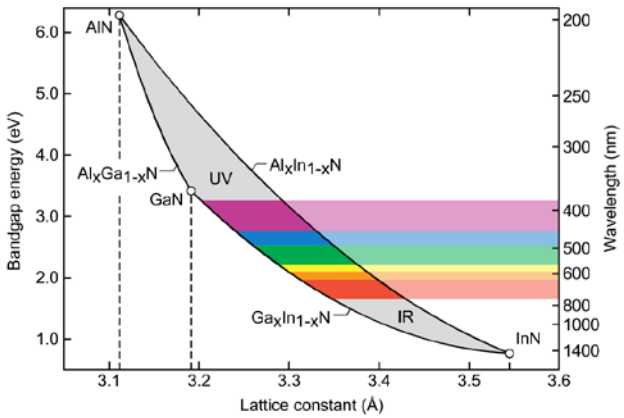


Funding Acknowledgment: Sandia's Solid-State-Lighting Science Energy Frontier Research Center (DOE BES) and Sandia's LDRD program; European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PIOF-GA-2010-273822.

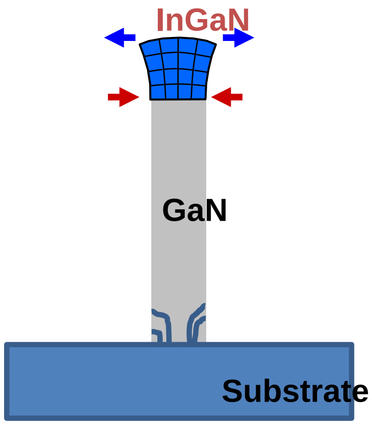
Nanowire Lasers



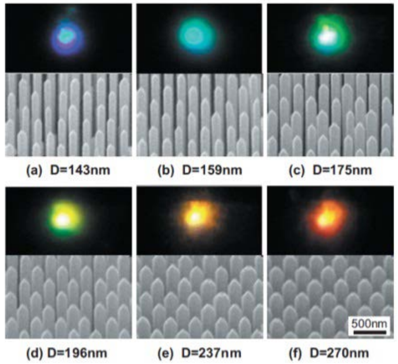
- Nanowire forms a freestanding, low loss optical cavity
- Optically pumped nanowire lasers: ZnO, CdS, GaAs, GaSb, GaP, GaN, etc.
- Most commonly Fabry-Perot type lasing from end facets
- Compact and low power due to small mode volume
- Strain accommodation in GaN nanowires opens up possibility of high 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.

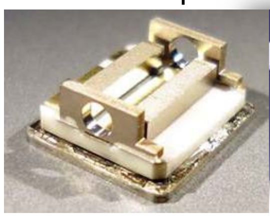
See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7,** 074599-1 (2013)

Why Nanowire Lasers?

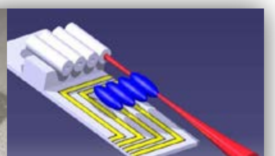
Integrated coherent nanophotonic elements for communications, sensing, imaging, lithography, lighting, etc.

Integrated nanophotonics, atom trapping, optical MEMS

atom trap



P. Schwindt (1725)

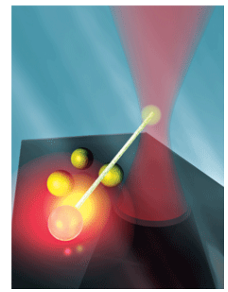


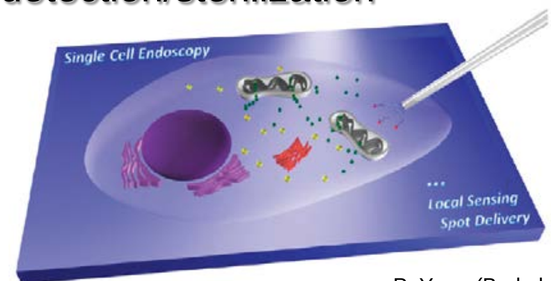
Schmiedmayer

J. Ford, Lucent

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

Optical nanoprobes & chem/bio detection/sterilization

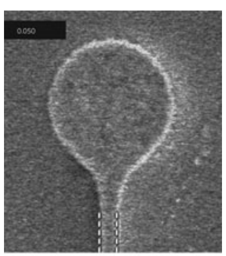




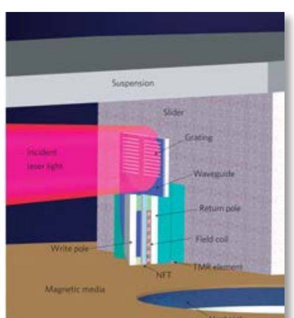
P. Yang (Berkeley)

Sub-λ resolution probes for localized excitation, detection

Nanolithography & Heat-assisted Magnetic Recording



Nature Photonics 3, 220 (2009)



Seagate

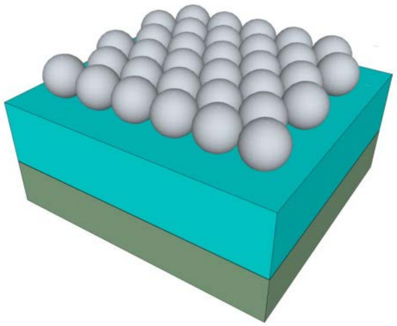
Subwavelength & efficient laser spot

Lighting, projection, & holographic displays

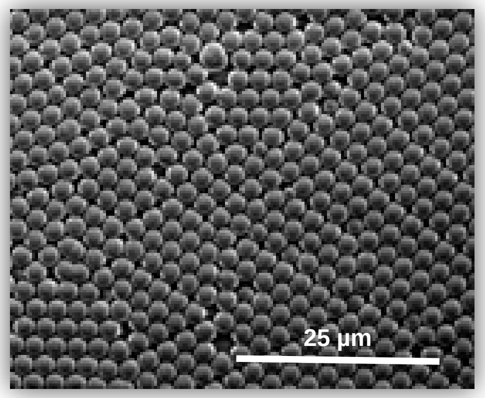
Sony Crystal LED Display prototype

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

New dry + wet top-down ordered nanowire fabrication process

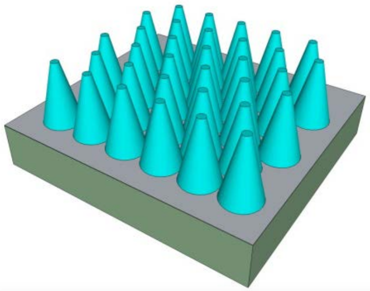


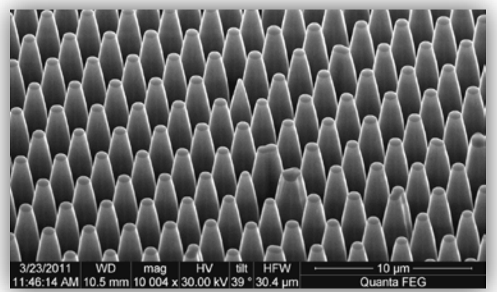
(0001) GaN on sapphire

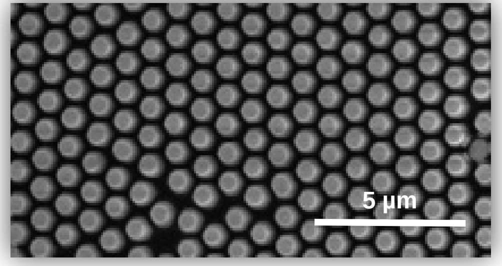


Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).

ICP etch







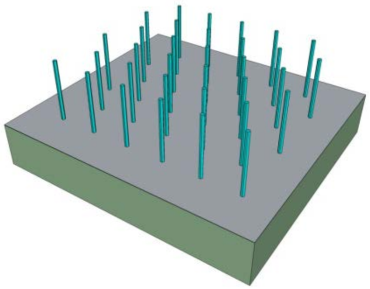
Plasma etch causes sidewall damage

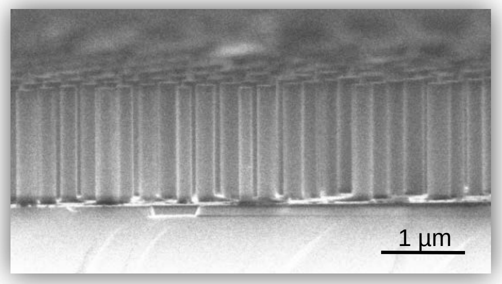
C. Y. Wang et al., Opt. Expr. *16,* 10549–10556, 2008.

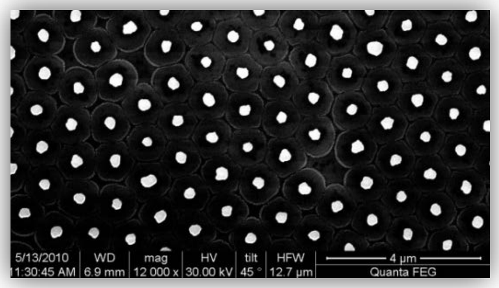
Tapered; no well-defined facets

Selective wet etch

(AZ-400K developer)







Wet etch: straight sidewalls, removes sidewall damage

Straight GaN nanowires with controllable geometries

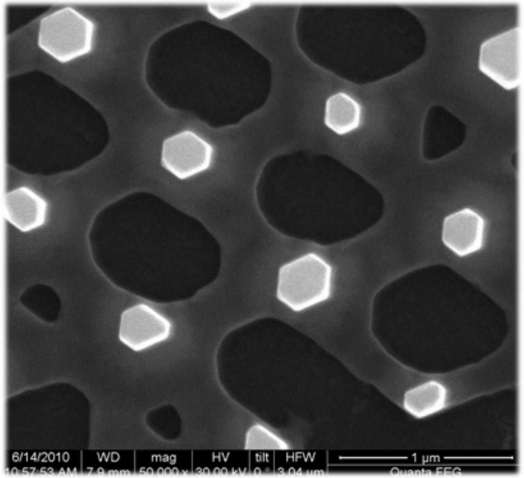
Wet etch rate negligible for top (Ga-polar) *c*-face & fast for [10-10], leads to nominally hexagonal NWs with **straight & smooth** *m*-facets

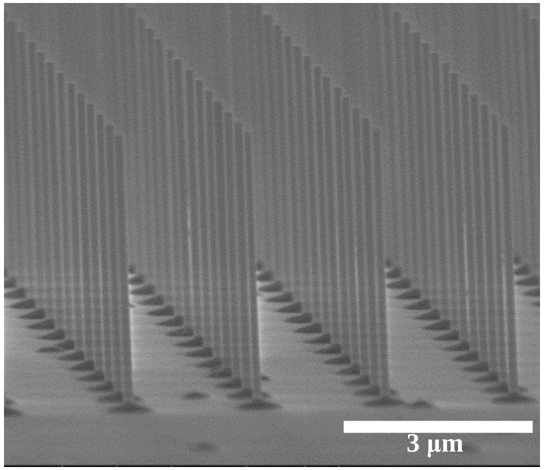
Superior and independent control of:

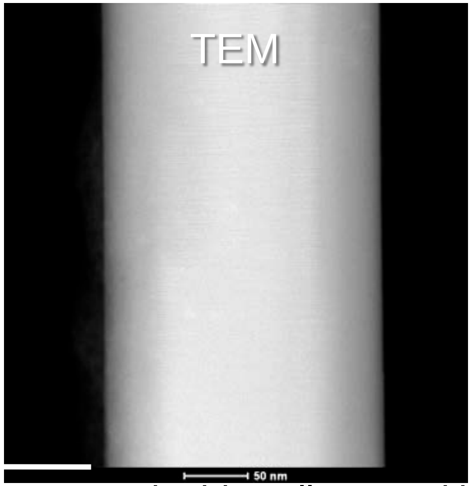
Height (dry etch depth)

Diameter (wet etch time)

Pitch/arrangement (defined by masking template)





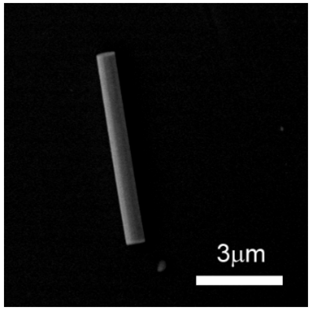


Smooth sidewall created by wet etch

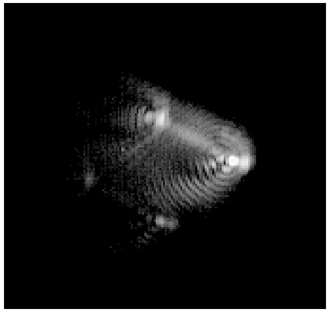
TEM: Ping Lu, SNL

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

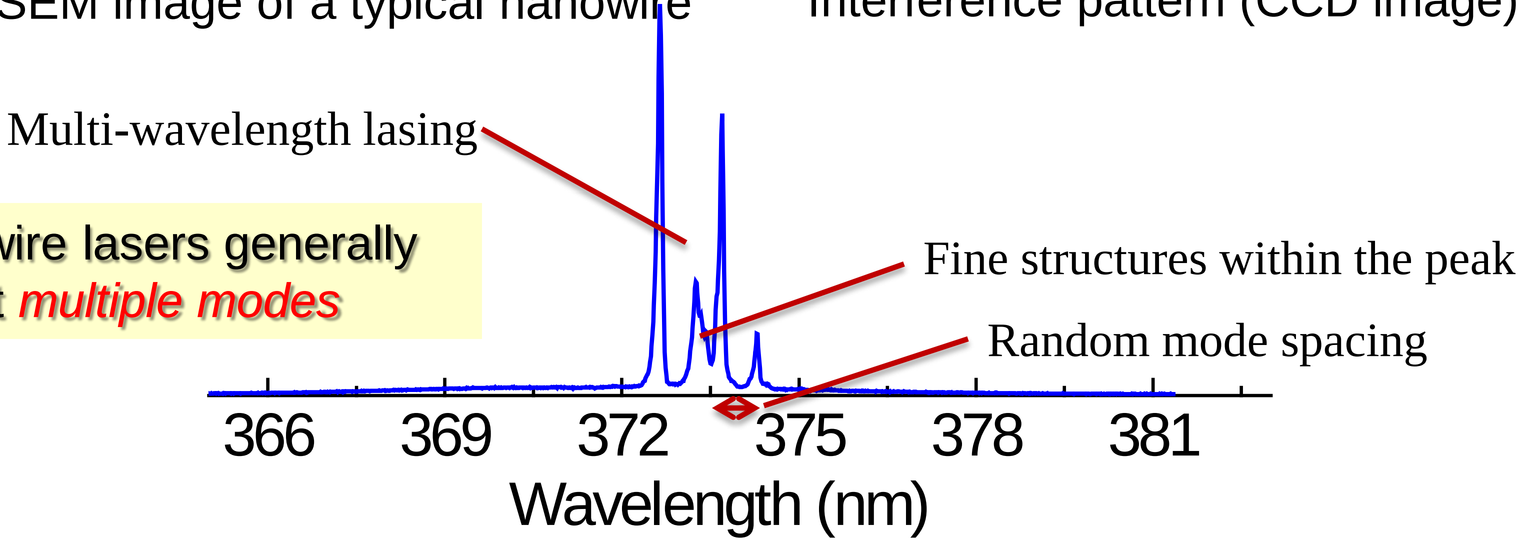
Typical GaN Nanowire Lasing: Multimode Operation



SEM image of a typical nanowire



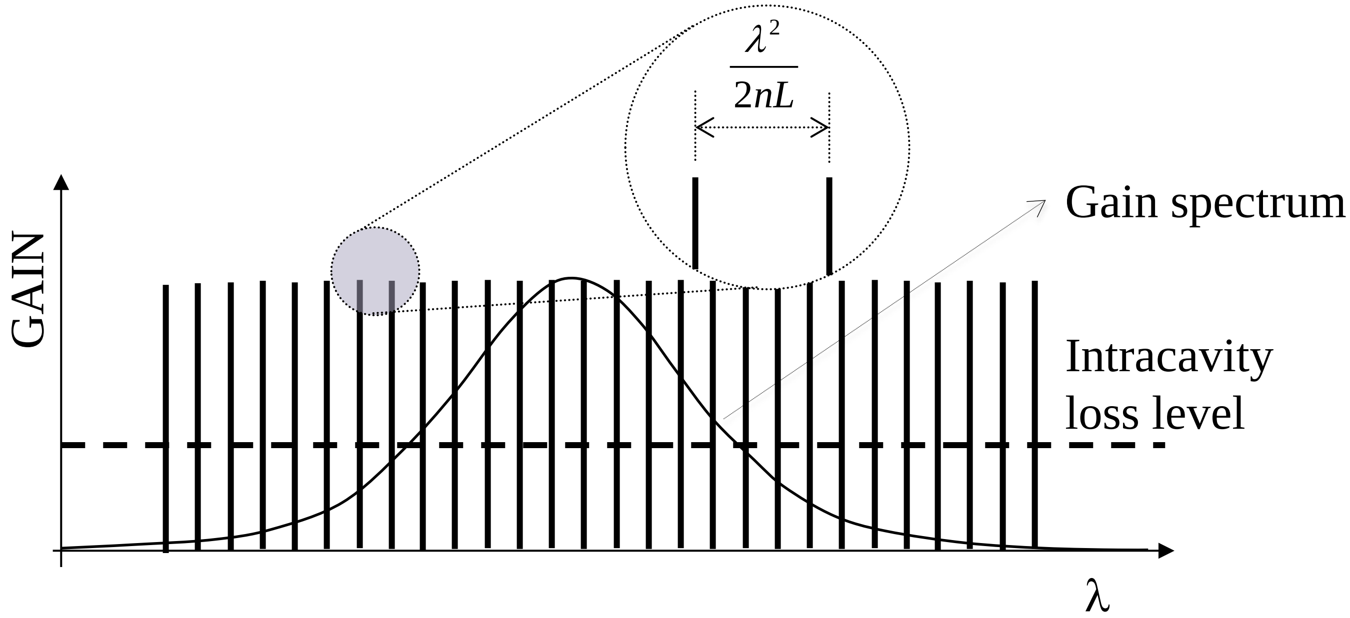
Interference pattern (CCD image)



Nanowire lasers generally exhibit *multiple modes*

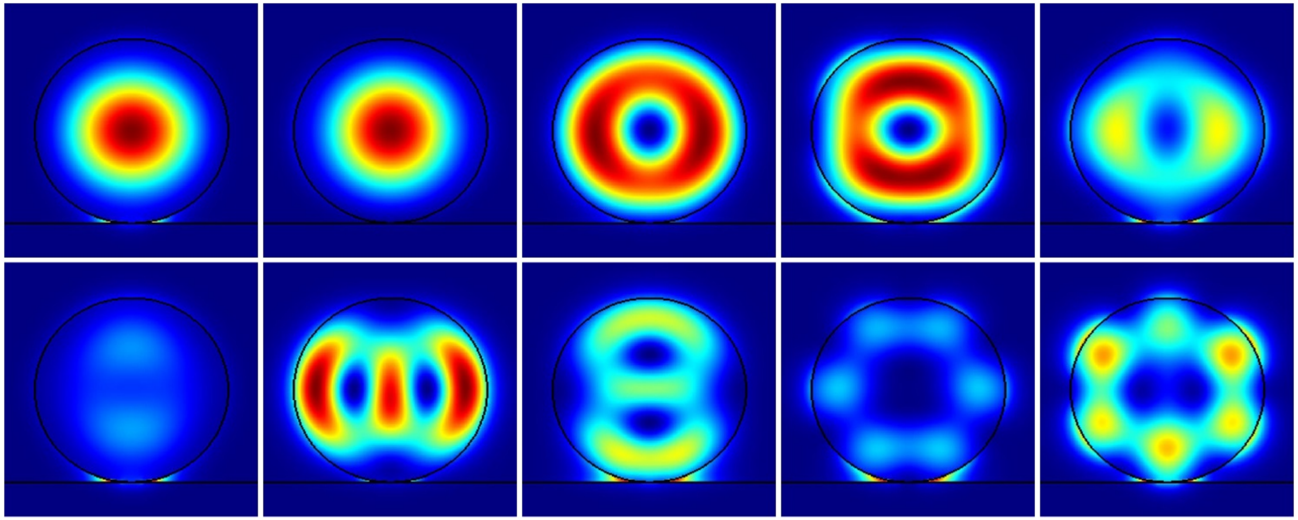
- *Single mode* behavior desired for highest resolution and beam quality; may also reduce lasing threshold due to reduced mode competition

Why Multimode Lasing Occurs



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

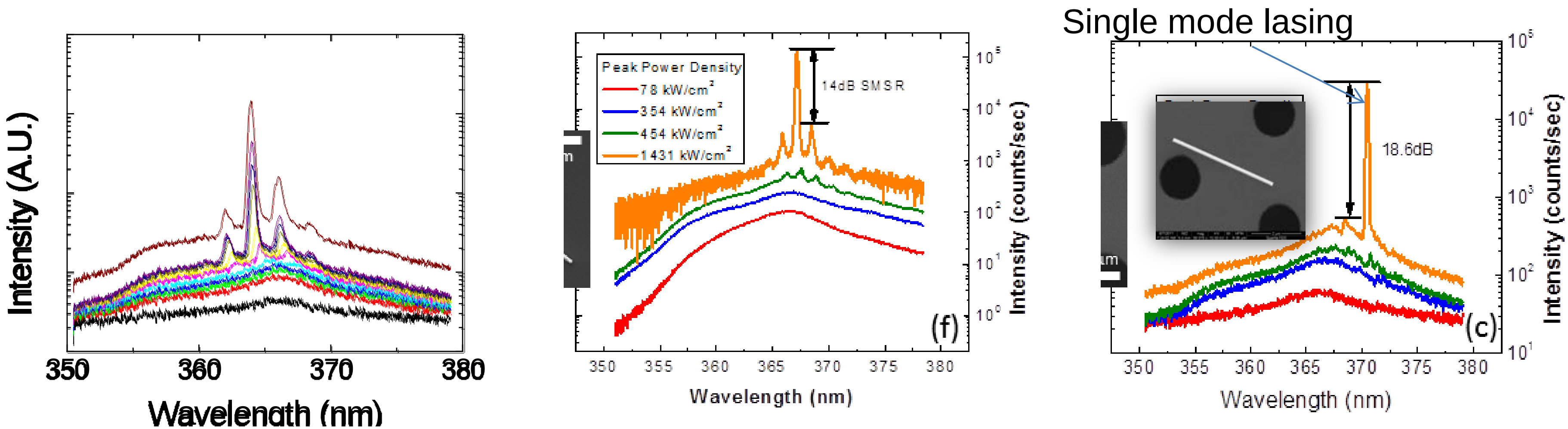
Why Multimode Lasing Occurs



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

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)**

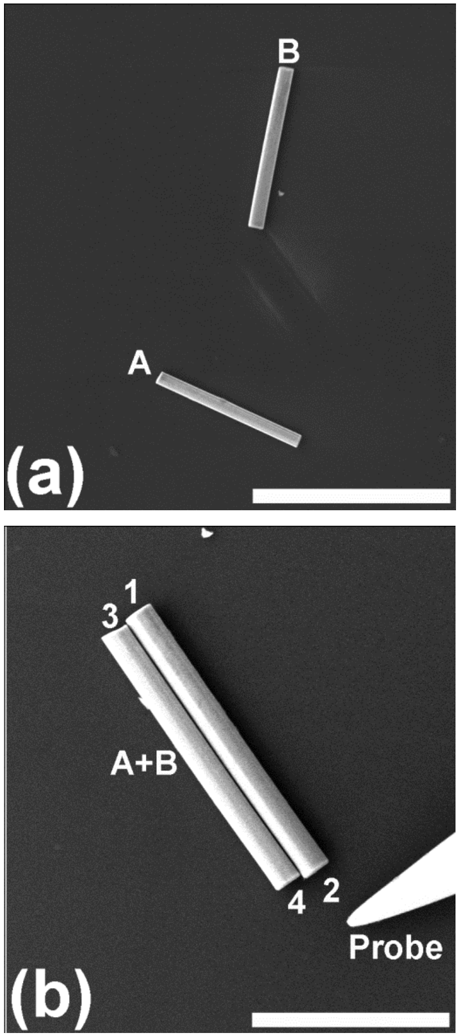
NW diameter x length

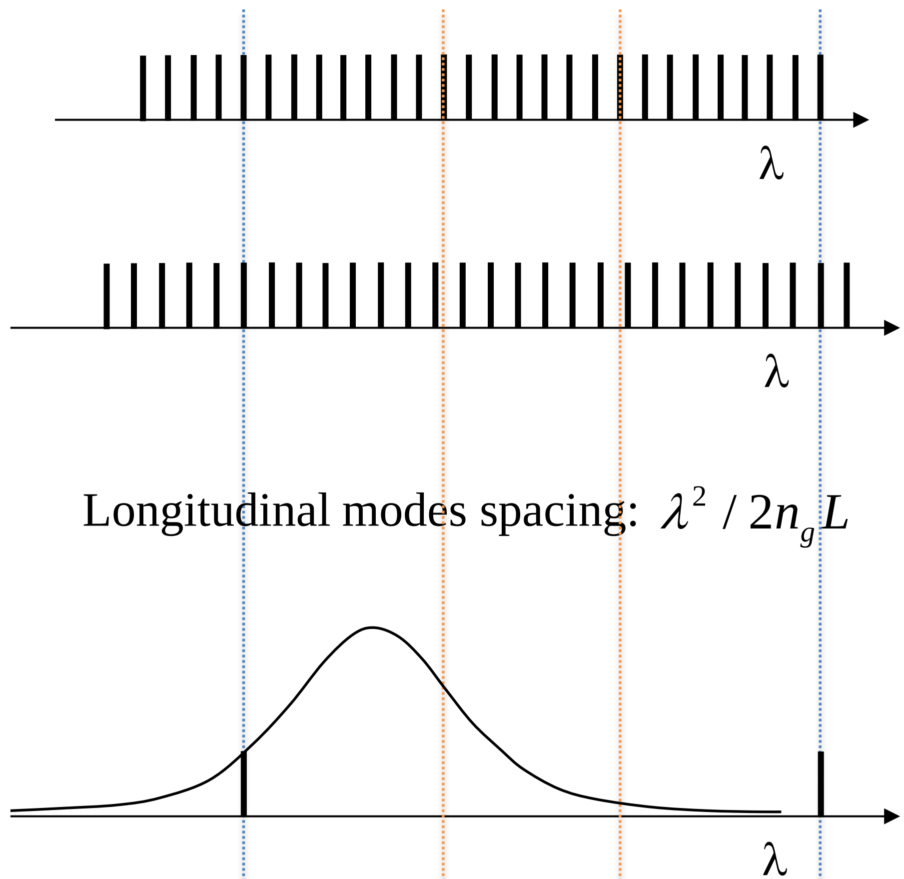
Q. Li et al., *Opt. Exp.* ***20*** *17873 (2012)*

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: Vernier Effect From a Coupled Cavity





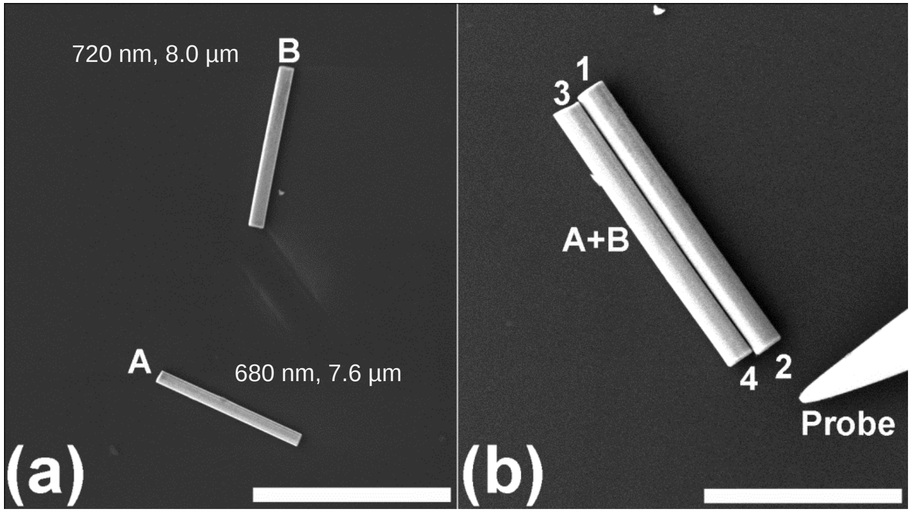
Longitudinal modes of Nanowire A

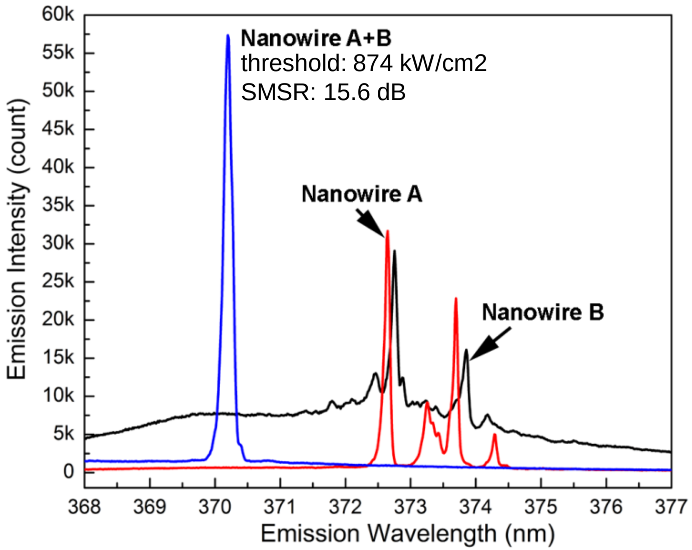
Longitudinal modes of Nanowire B

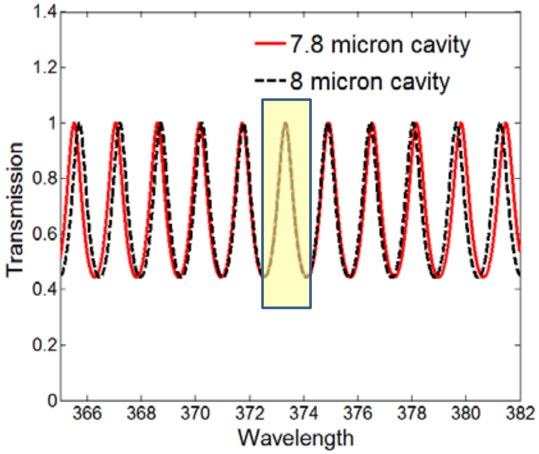
Longitudinal modes of Nanowire A+B

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

Method 2: Single-mode lasing via coupled nanowire cavities







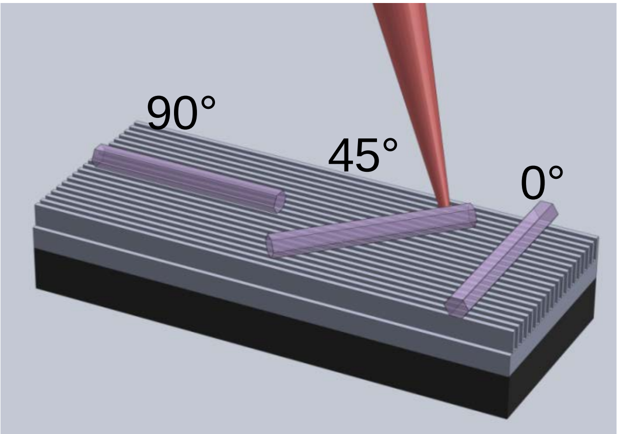
- GaN NWs need to be <~130 nm for single transverse mode behavior; larger single-mode NWs?
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

modeling: Huiwen Xu (UNM)

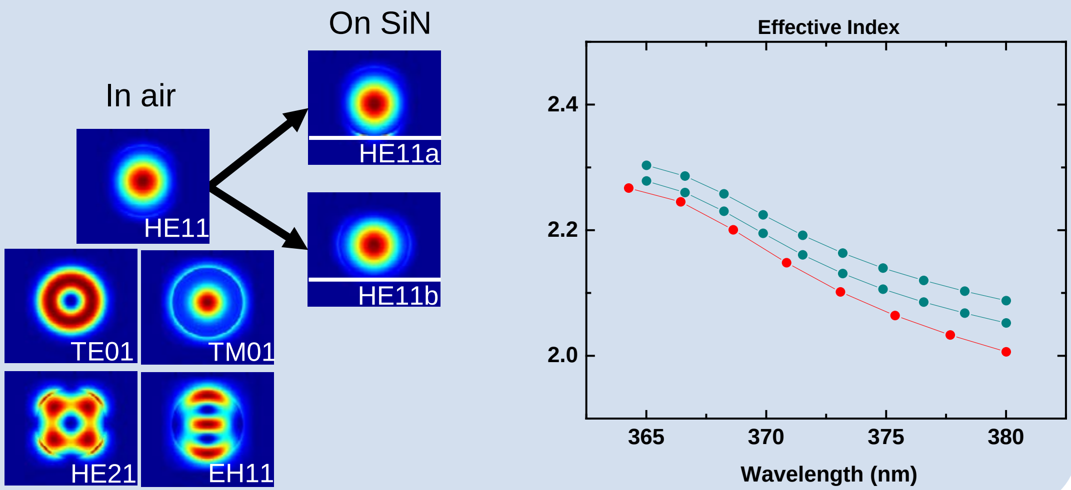
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

Method 3: Distributed Feedback (DFB) Nanowire Laser

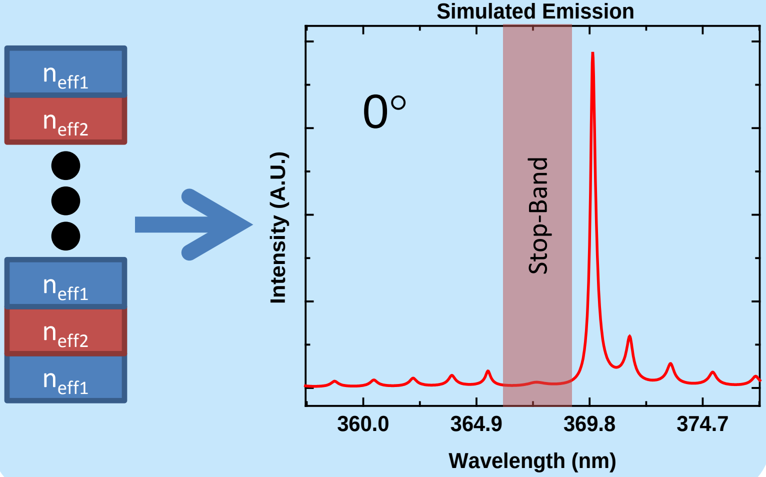
- Standard method for mode control in semiconductor lasers
- Here, single nanowires are coupled to grating substrate to achieve distributed feedback
- Stop-band position and width tuning via nanomanipulation of the angular alignment



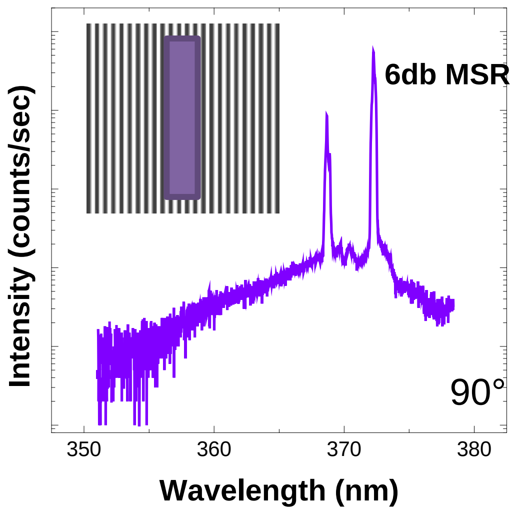
Mode Calculations

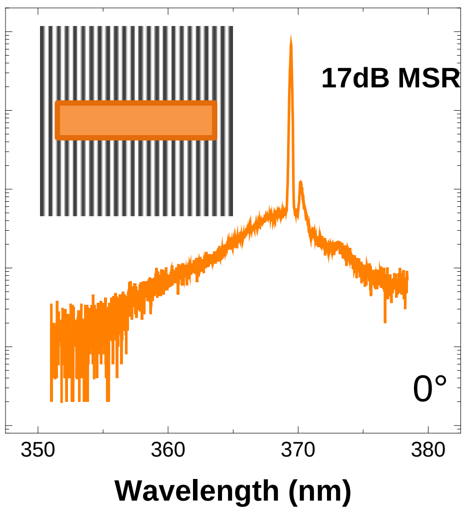


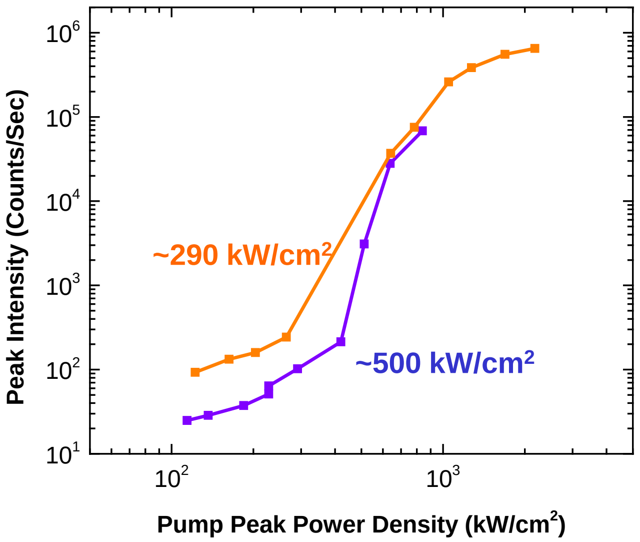
Transfer Matrix Method

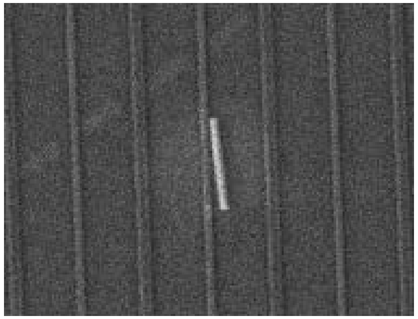


Method 3: DFB Nanowire - Optical Results

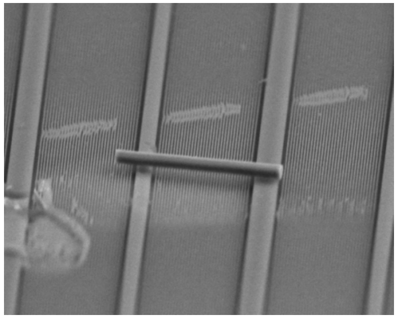








NW diameter ~180 nm

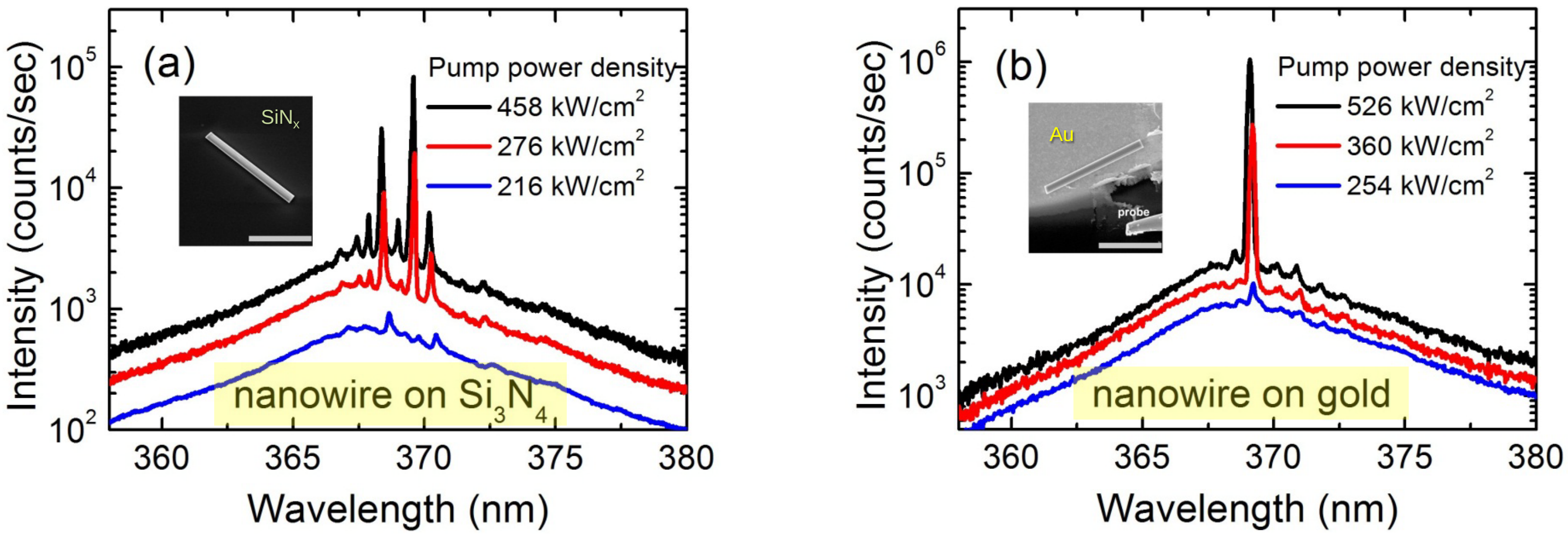


- At the designed alignment single-mode lasing was achieved with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

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

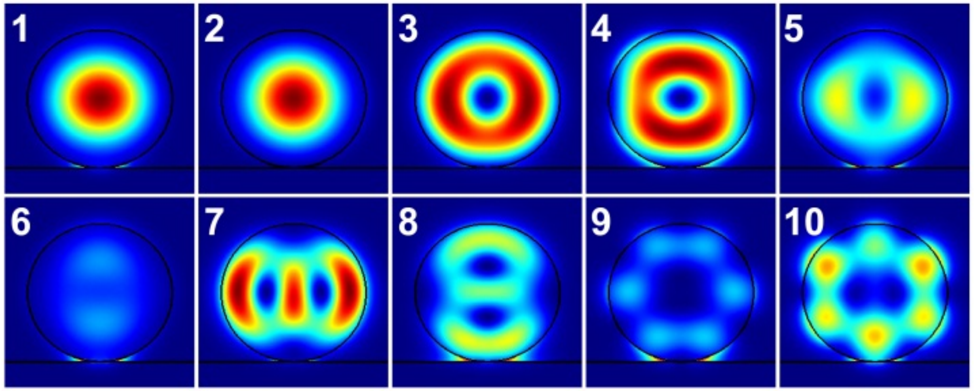
diameter~350 nm, length ~5.3 µm



- 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.

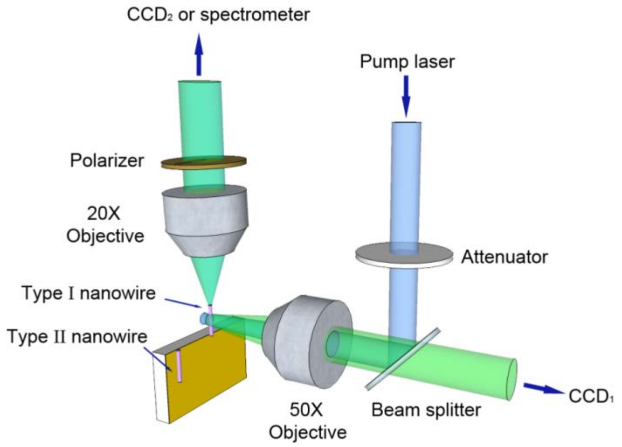
Only surviving mode (Mode 2)

	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

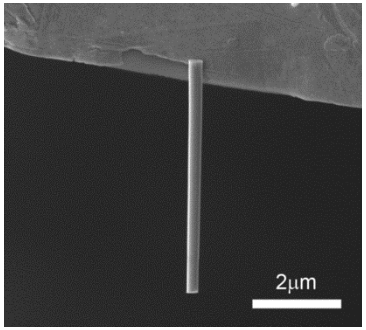
Propagation loss of different transverse modes.

Metal substrate generates a mode-dependent propagation loss

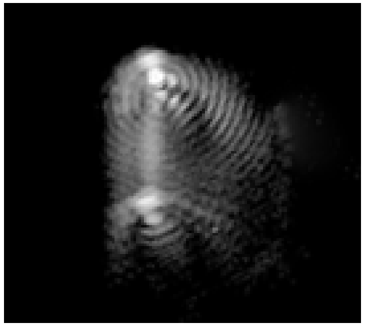
Lasing Polarization Properties of Freestanding GaN NWs



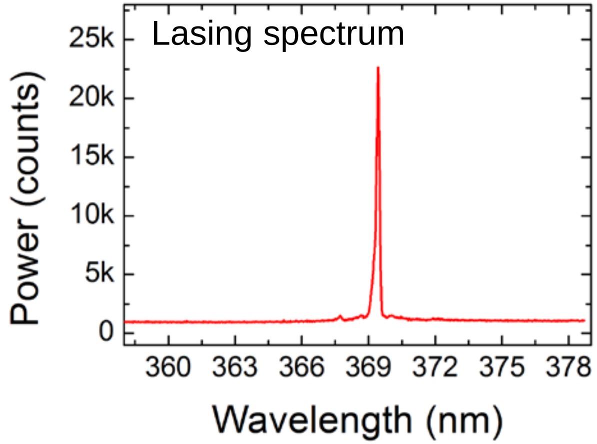
End-facet optical characterization setup

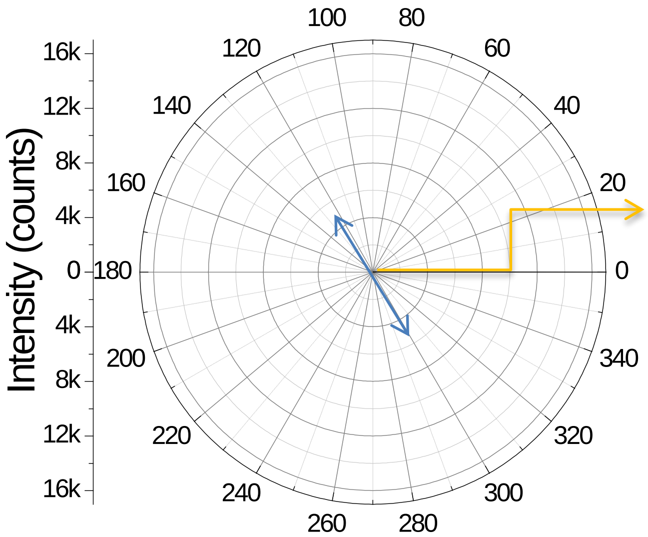


SEM image of a nanowire hanging off substrate



CCD image of lasing nanowire hanging off substrate





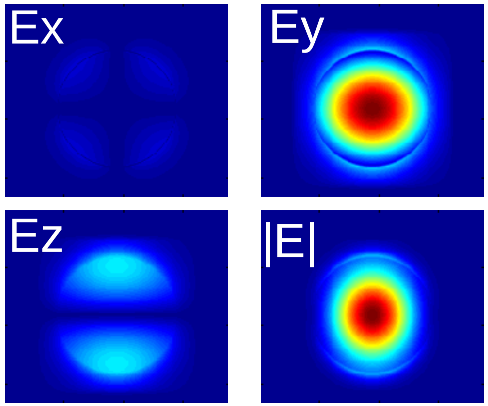
Indicative of elliptical polarization

Polarization angle random wrt surface

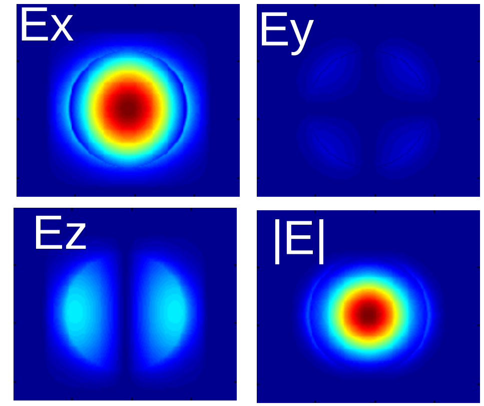
Intensity vs. the rotation of the polarizer

Why nanowire laser elliptically polarized?

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



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

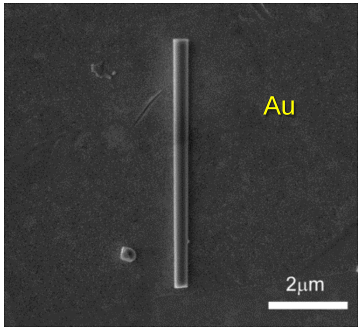


Two orthogonal polarized fundamental modes supported by a 200 nm diameter nanowire in air

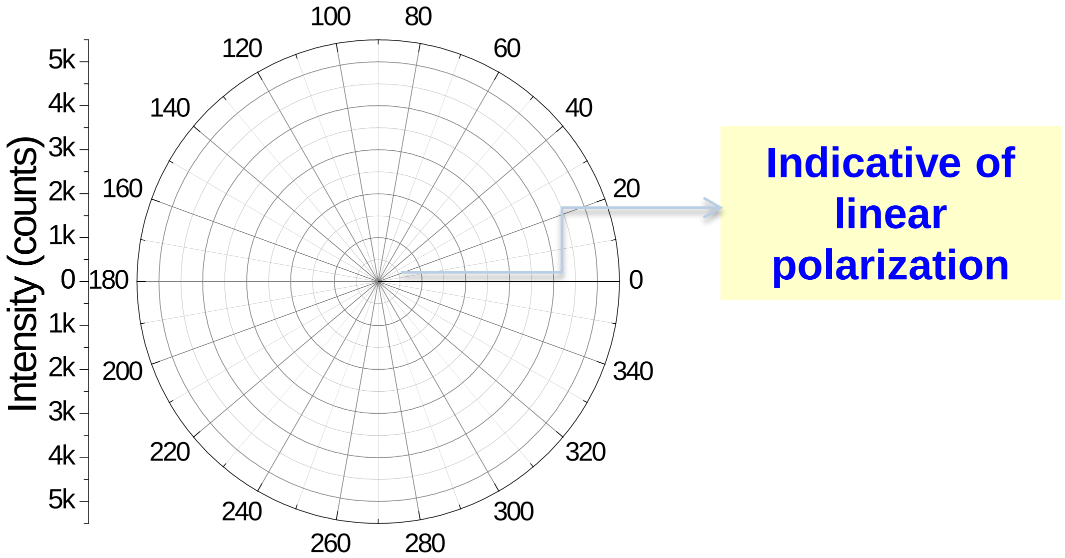
- ✓ Both fundamental transverse modes
- ✓ Same electric field intensity
- ✓ **Two degenerate modes superimpose resulting in elliptical polarization**

Polarization Control: Nanowire on Gold Substrate

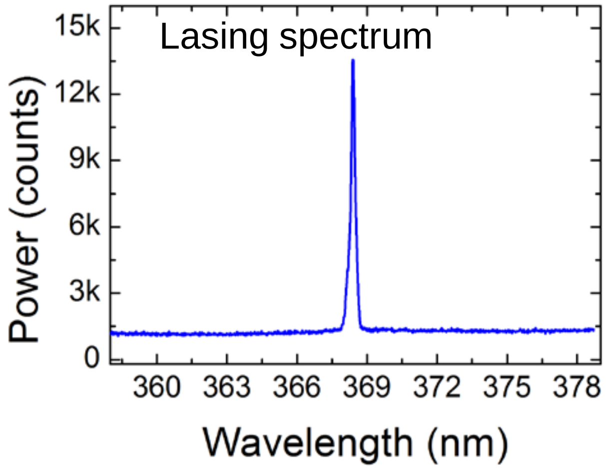
Polarization control (linear polarization) desired for many applications



nanowire on **gold**

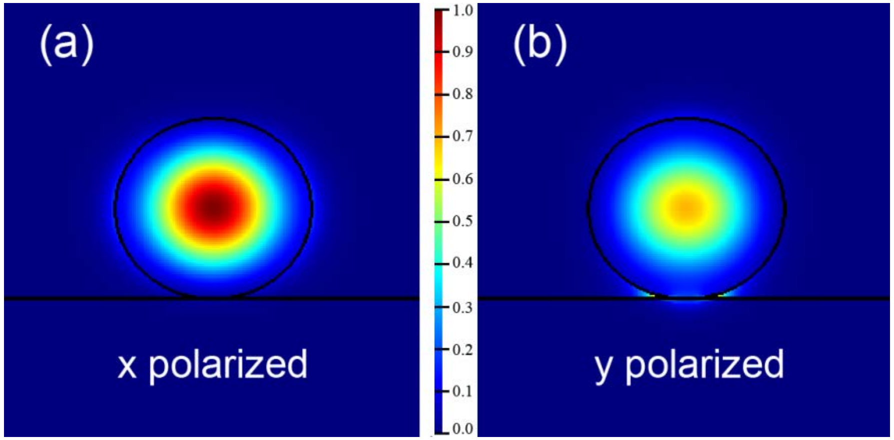


Intensity vs. the rotation of the polarizer



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

Why Does Linear Polarization Happen on Gold?

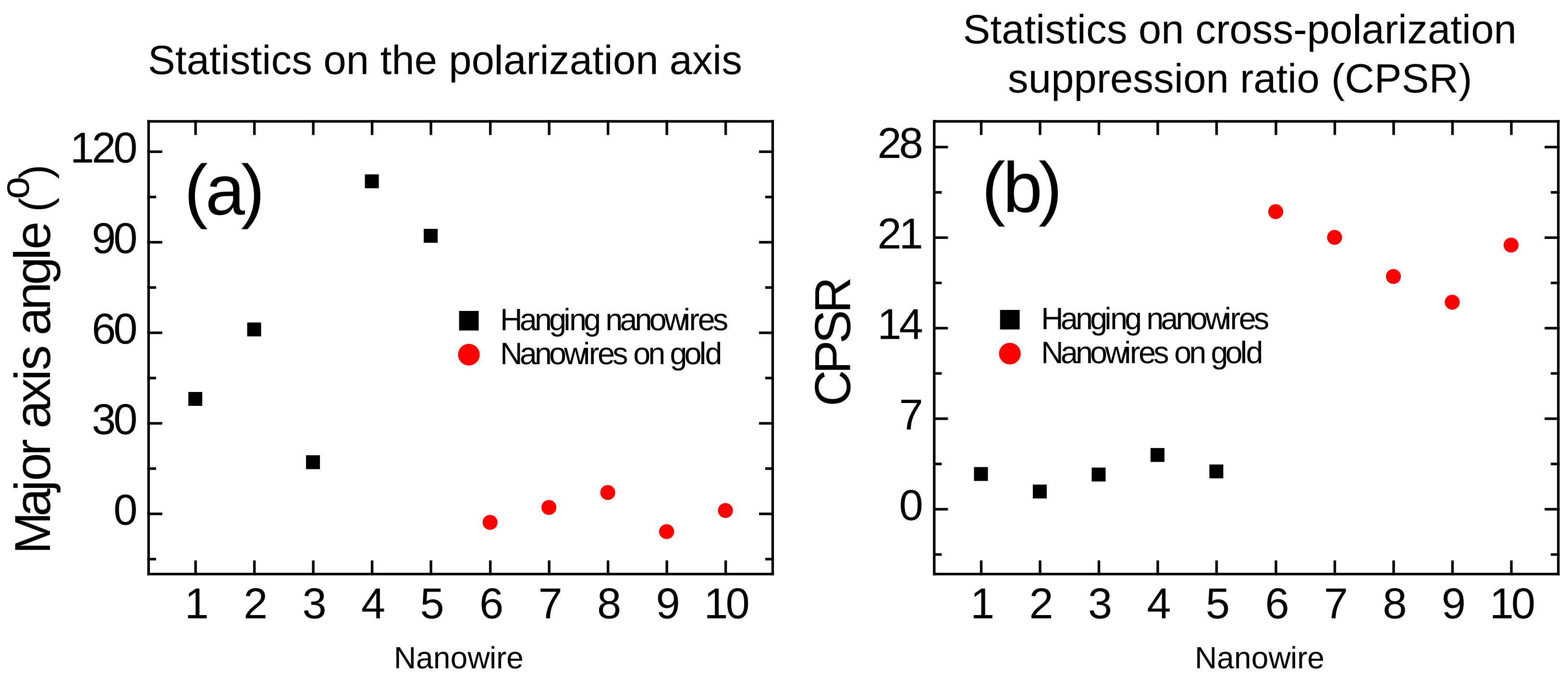


Fundamental modes supported by the nanowire-gold geometry

- ✓ 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

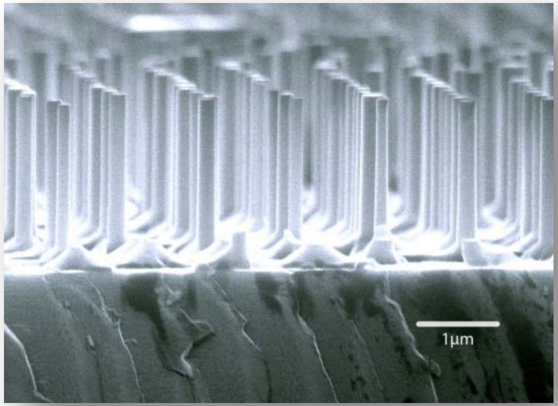
Lasing Polarization Statistics of Free Standing and on-Gold Nanowires



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

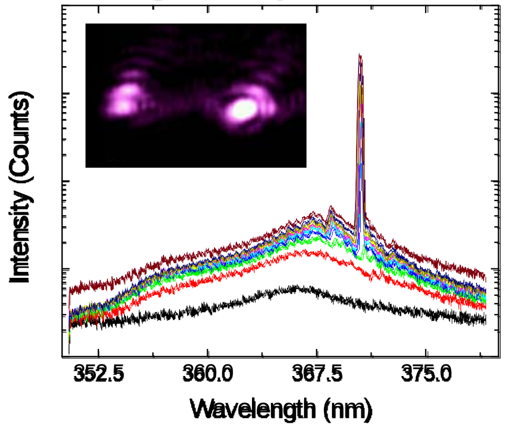
Summary – Mode & Polarization Control

Top-down fabrication



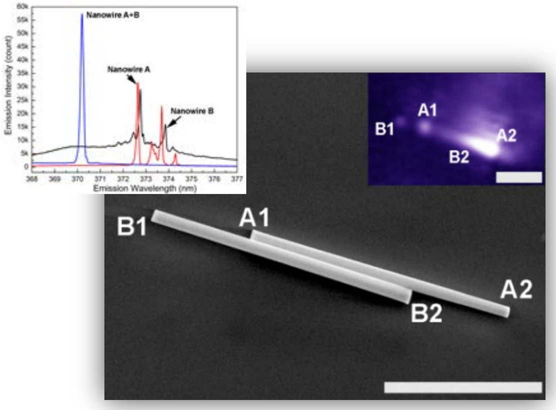
Q. Li et al., *Optics Express* **19**, 25528 (2011)

Single-mode NW lasers by geometry control



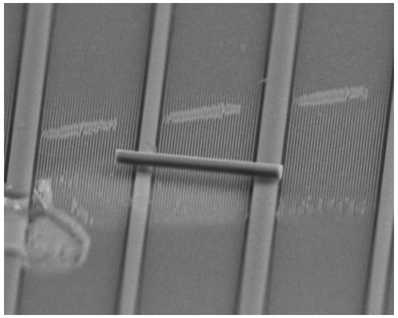
Q. Li et al., *Optics Express* **20** 17874 (2012)

Single-mode coupled nanowire laser



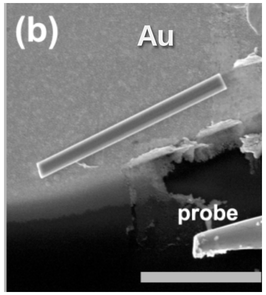
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

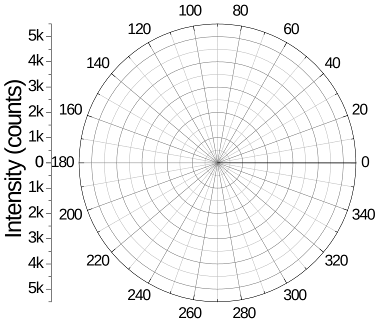
Distributed feedback NW lasers

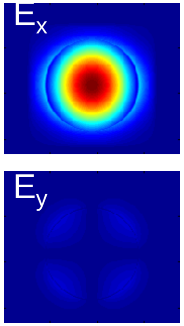


J.B. Wright et al., *App. Phys. Lett.* **104** 041107 (2014)

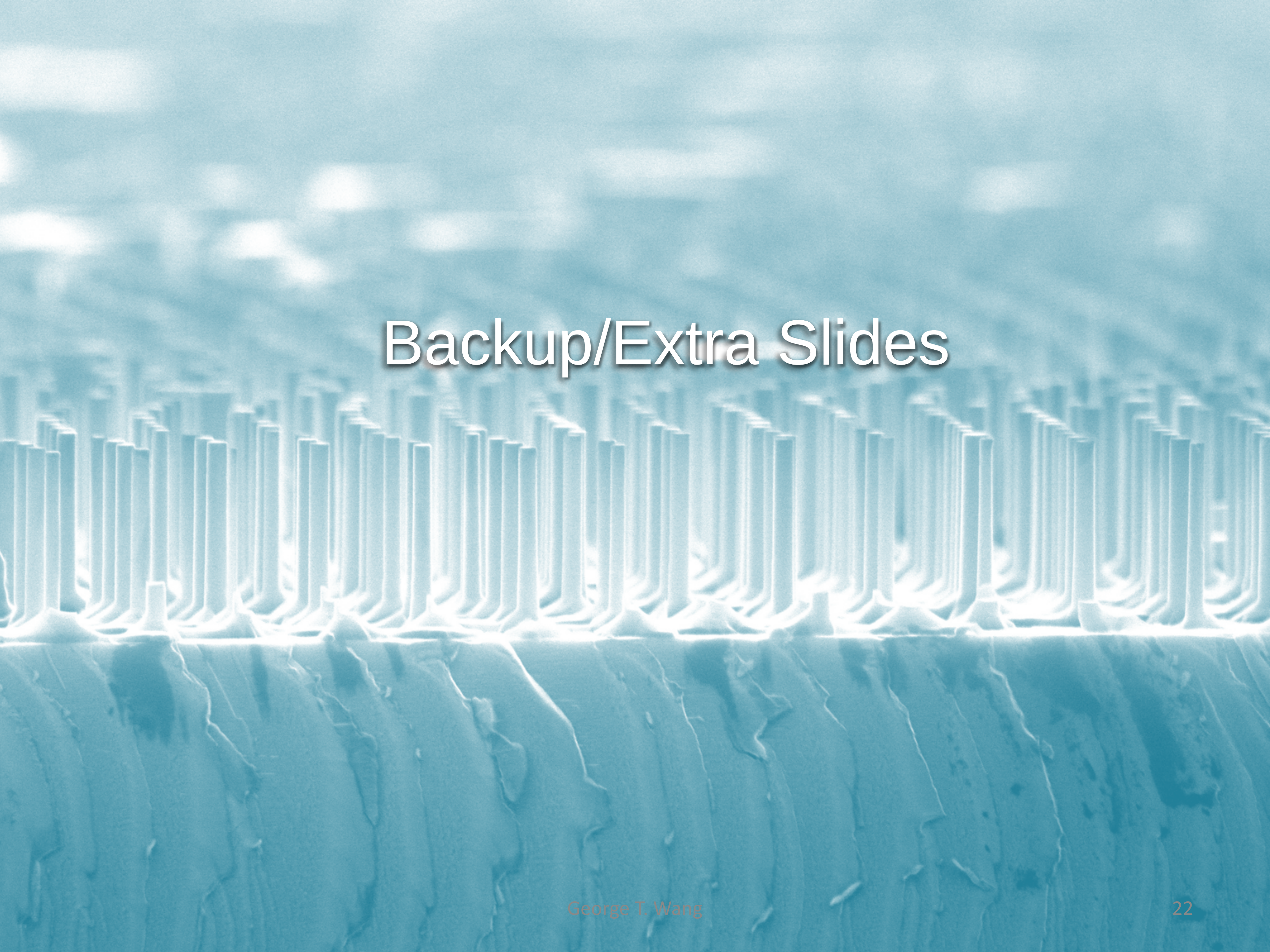
Single-mode and linearly polarized gold NW lasers coupled to gold substrate







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

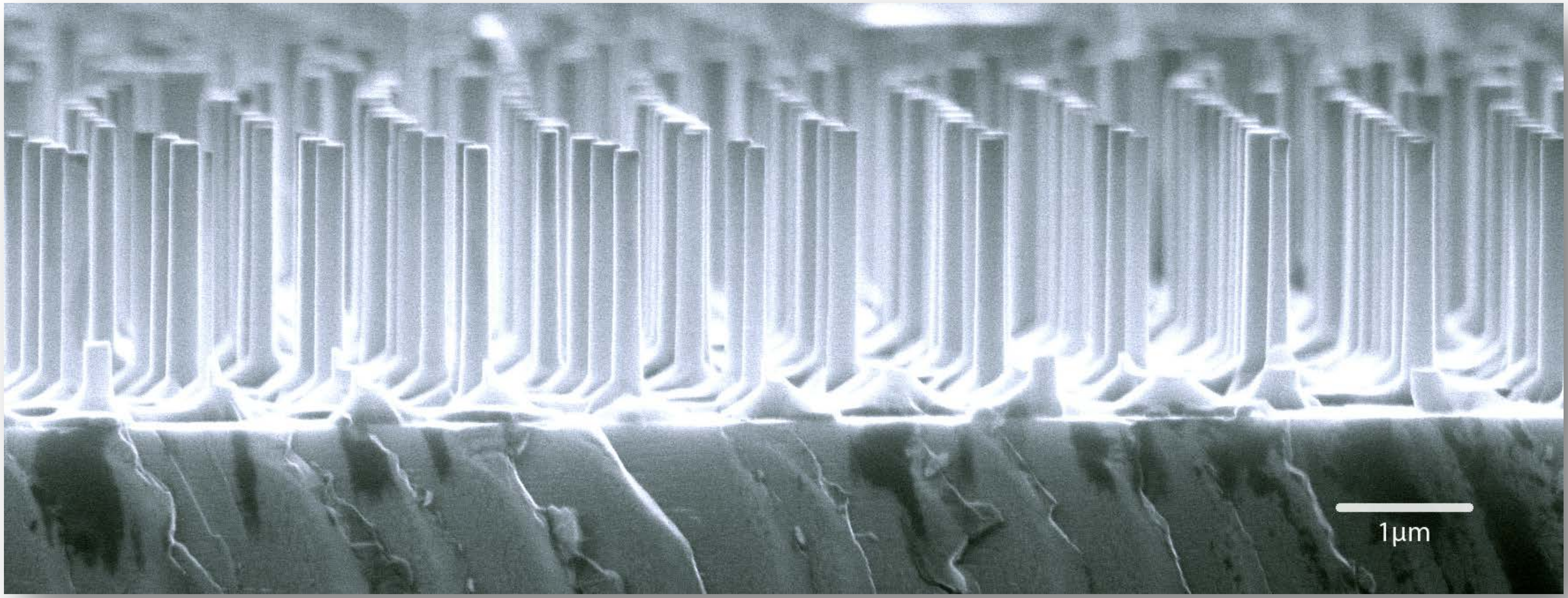


Backup/Extra Slides

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

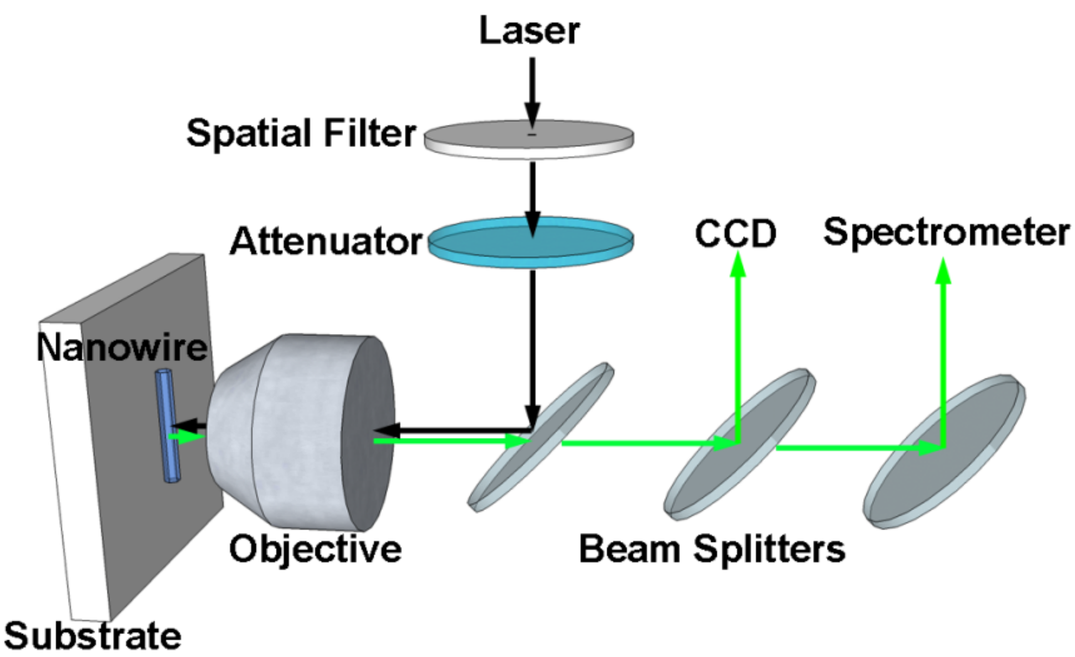
- Nanowire lasers generally exhibit *multiple modes*
- *Single mode* behavior desired for highest resolution and beam quality

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)

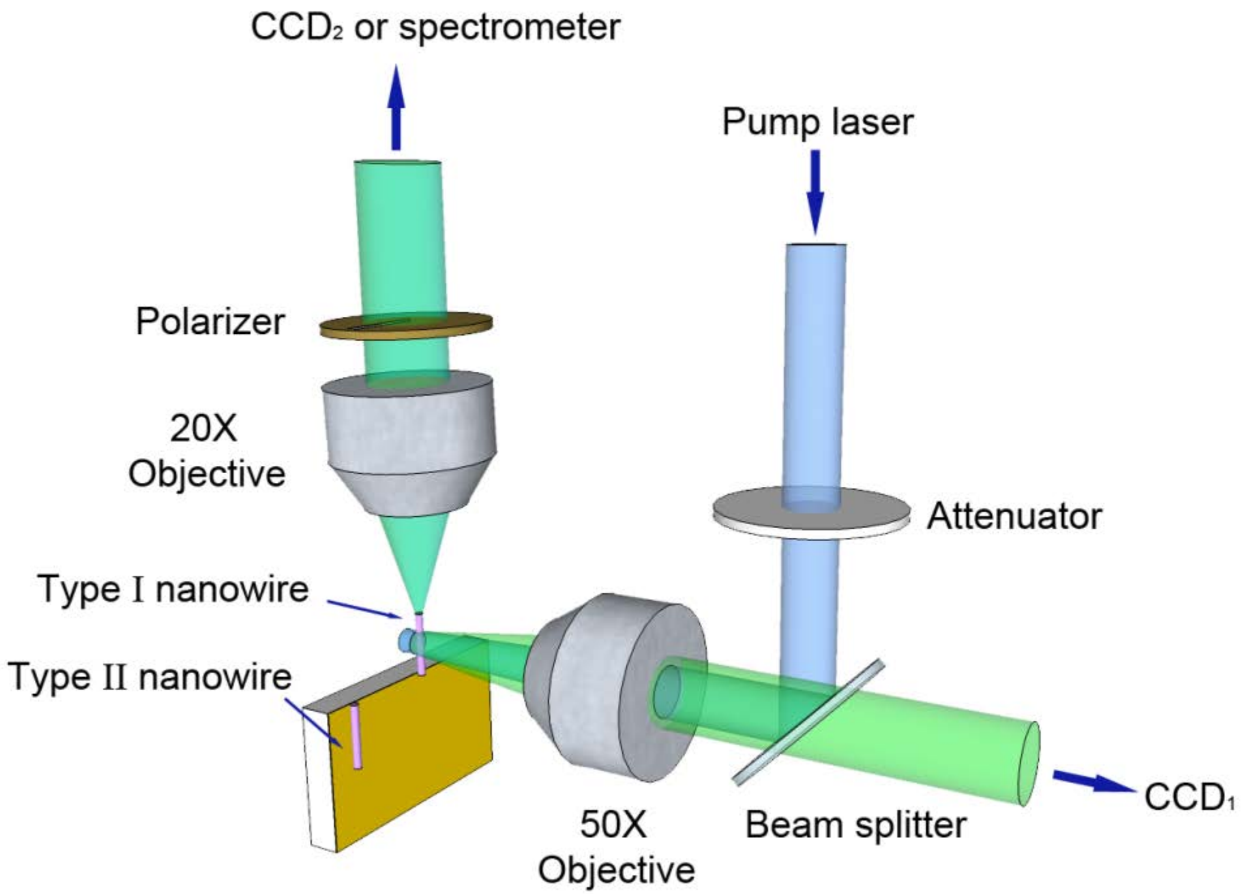
Nanowire Optical Characterization



- ✓ Pump: pulsed quadrupled Nd:YAG laser
- ✓ 266nm, 400ps, 10kHz, 5.2mW
- ✓ Spot size: 1~5 μm
- ✓ Room temperature operation

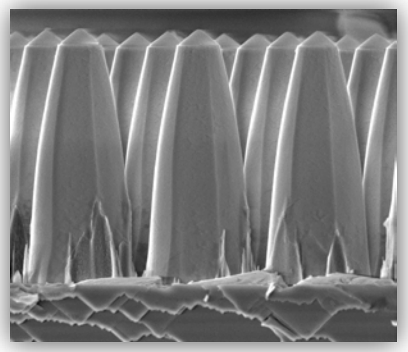
Q. Li, et al. Opt. Express 20, 17873 (2012)

End-Facet Optical Characterization

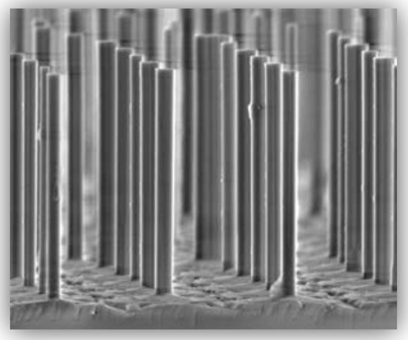


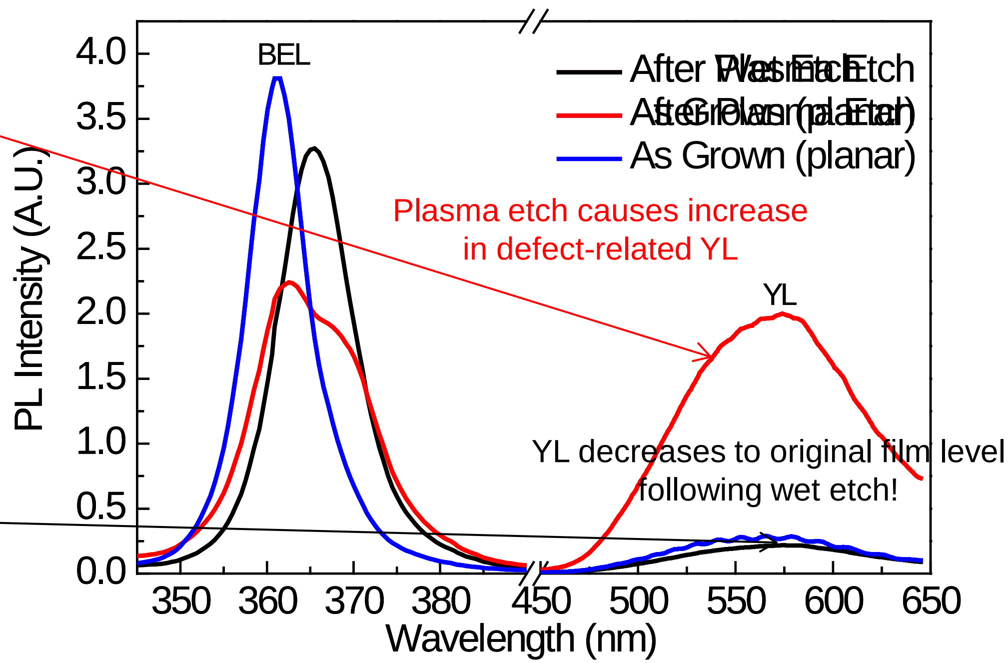
Wet etch step removes plasma etch damage

Plasma etch only



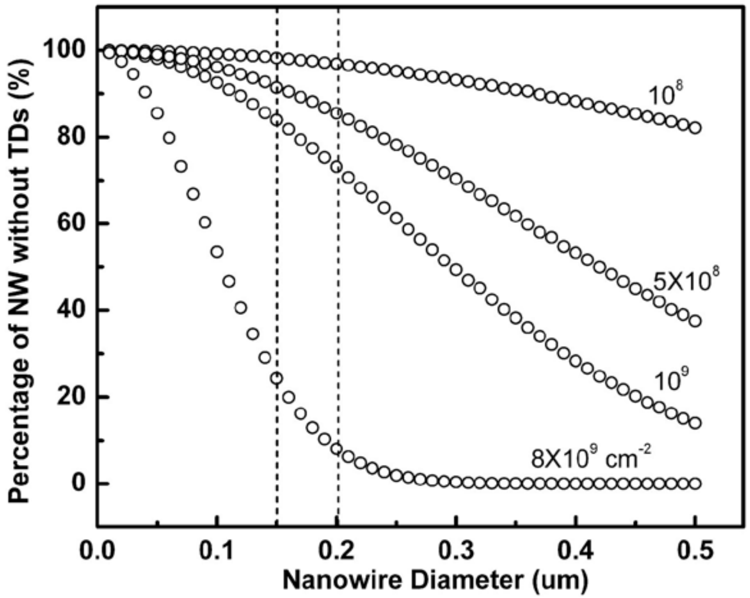
After wet etch



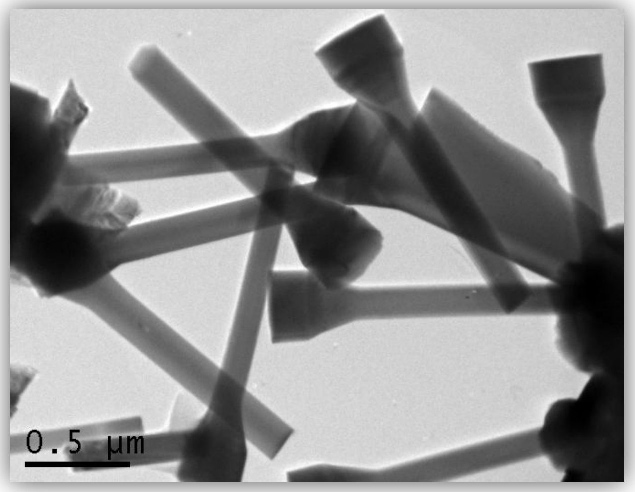


Top-down nanowire threading dislocations

Monte Carlo simulation



Bright-field TEM



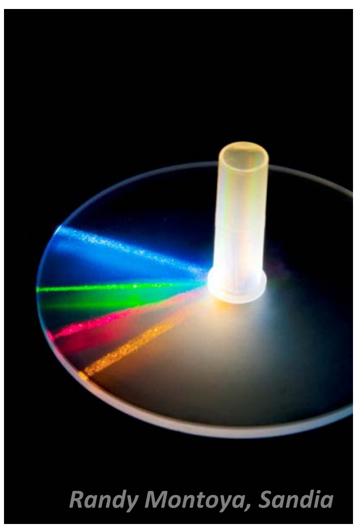
Nanowires etched from ~5e8 cm^{-2} planar LED

- 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

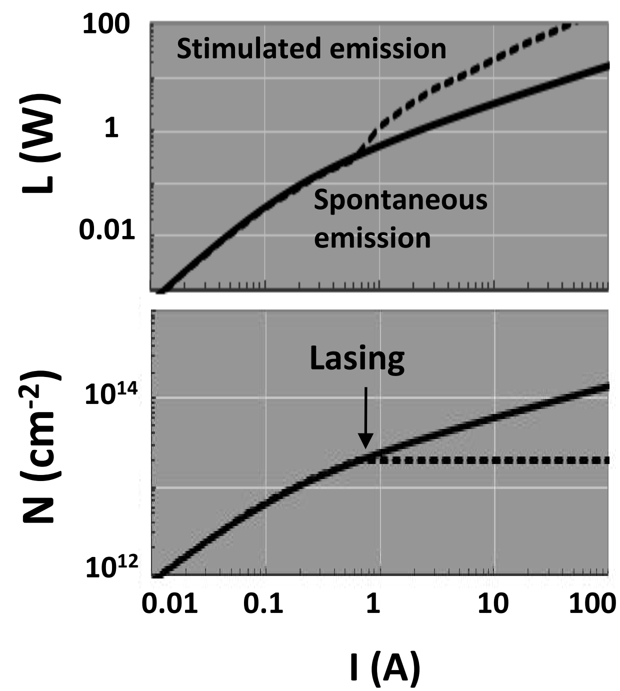


Randy Montoya, Sandia

Laser Sources For SSL:

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

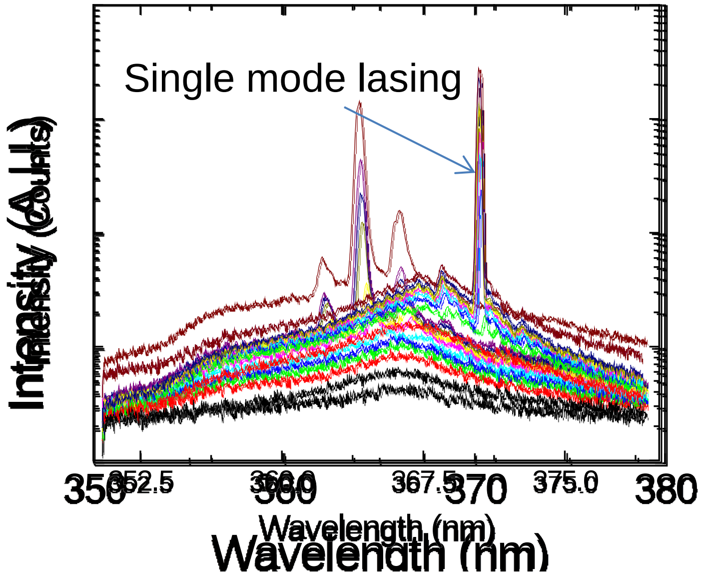
Clamped carrier density

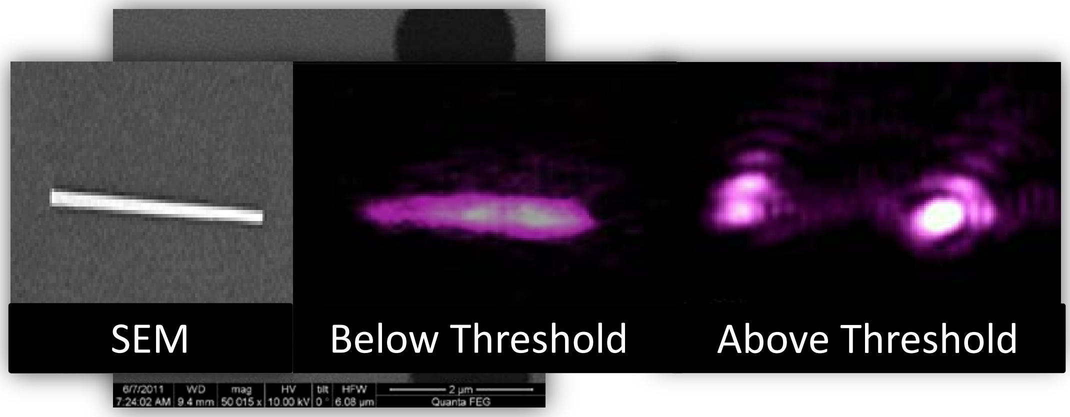


Are narrow linewidth sources acceptable?

A.J. Fischer, Sandia

Method 1: Single-mode NW laser via geometry control





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

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

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

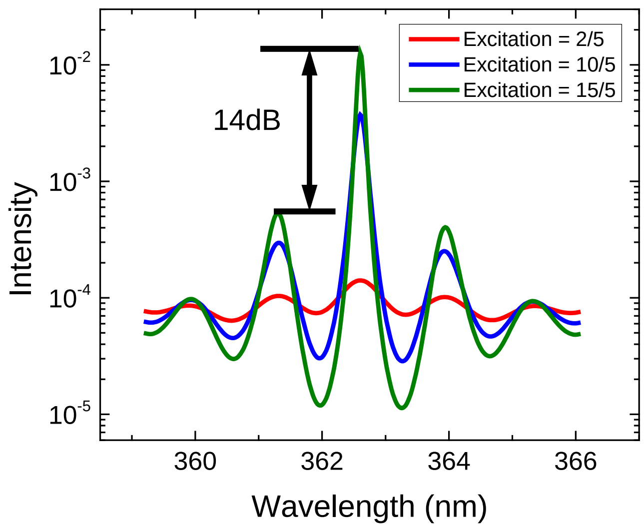
Single-mode: Narrow linewidth (<0.1 nm), 15dB Side Mode Suppression Ratio, and **Low Threshold** (~250 kW/cm^2)

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

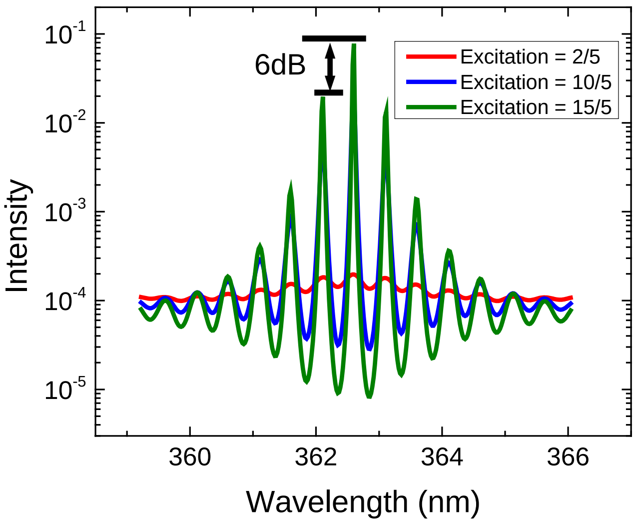
- Reduction of diameter (<~130 nm): reduction of transverse modes
- Reduction of length: (<~6 µm length): reduction of longitudinal modes
- **Reduced dimensionality leads to single mode lasing**

Single mode GaN nanowire laser

4 µm long, 140 nm dia. nanowire



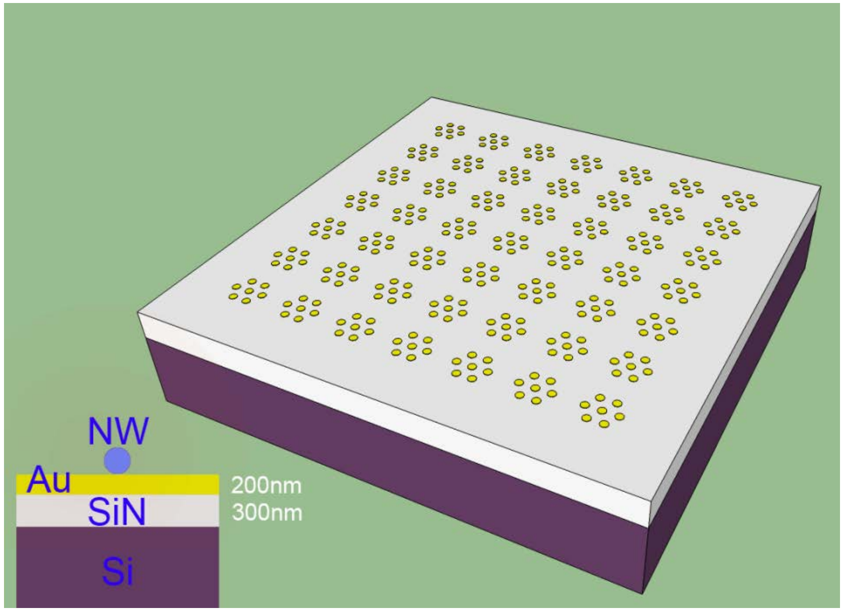
12 µm long, 140 nm dia. wire



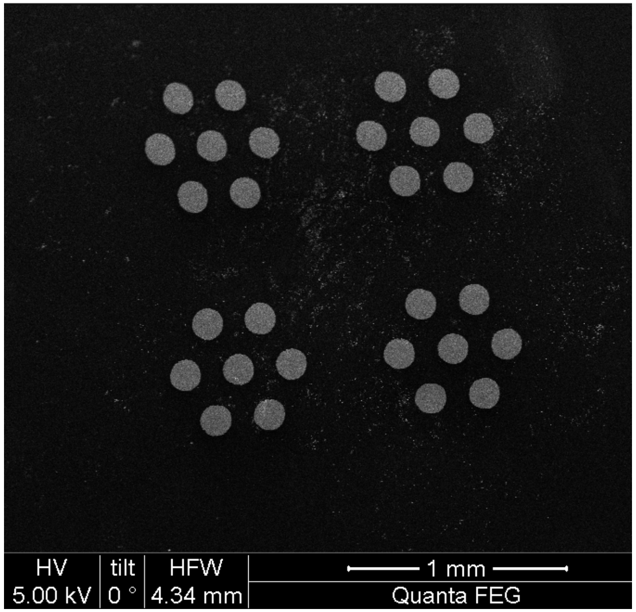
- Multimode laser theory calculations to determine which of the passive-cavity eigenmodes will be above lasing threshold for given experimental conditions.

- Modeling shows that by reducing the dimensionality of the wire we can reduce the number of competing modes, leading to single-mode lasing.

Gold substrate preparation



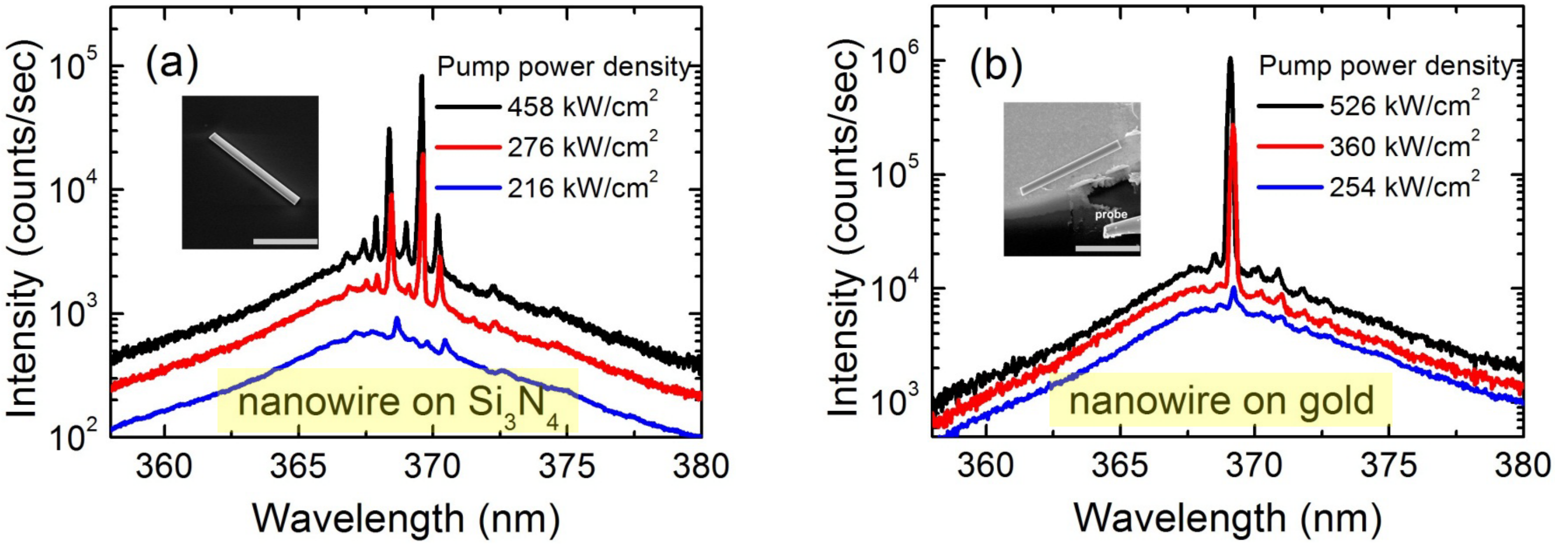
Schematic of the substrate design



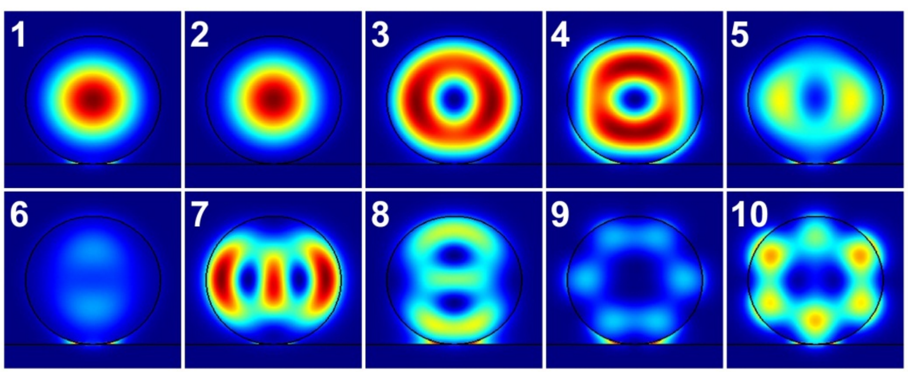
SEM image of prepared Au on SiN substrate

Nanowires can be transferred between SiN and Au regions for lasing behavior comparison

Method 4: Metal substrate induced single-mode nanowire lasing



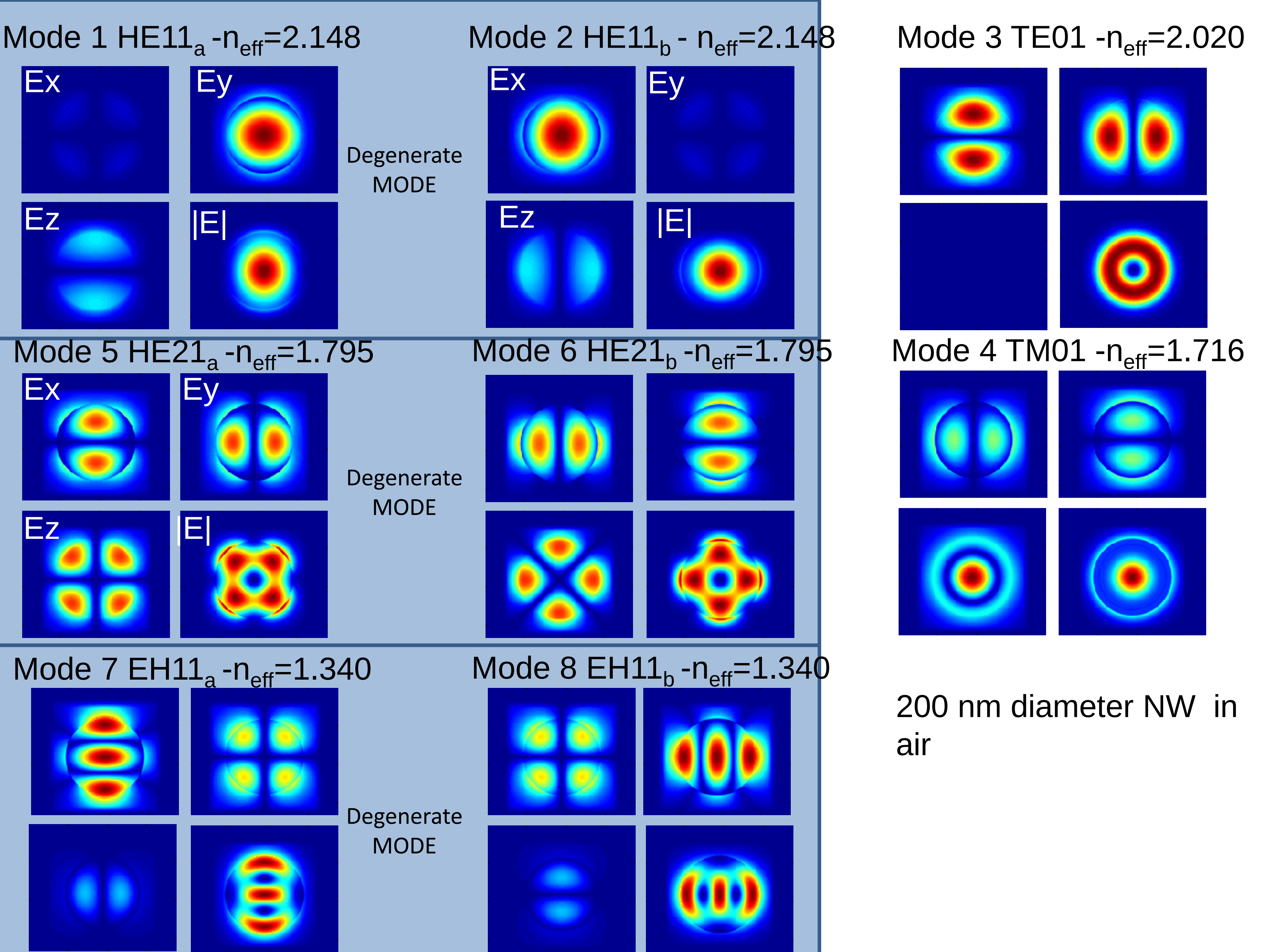
iameter~350 nm
length ~5.3 µm



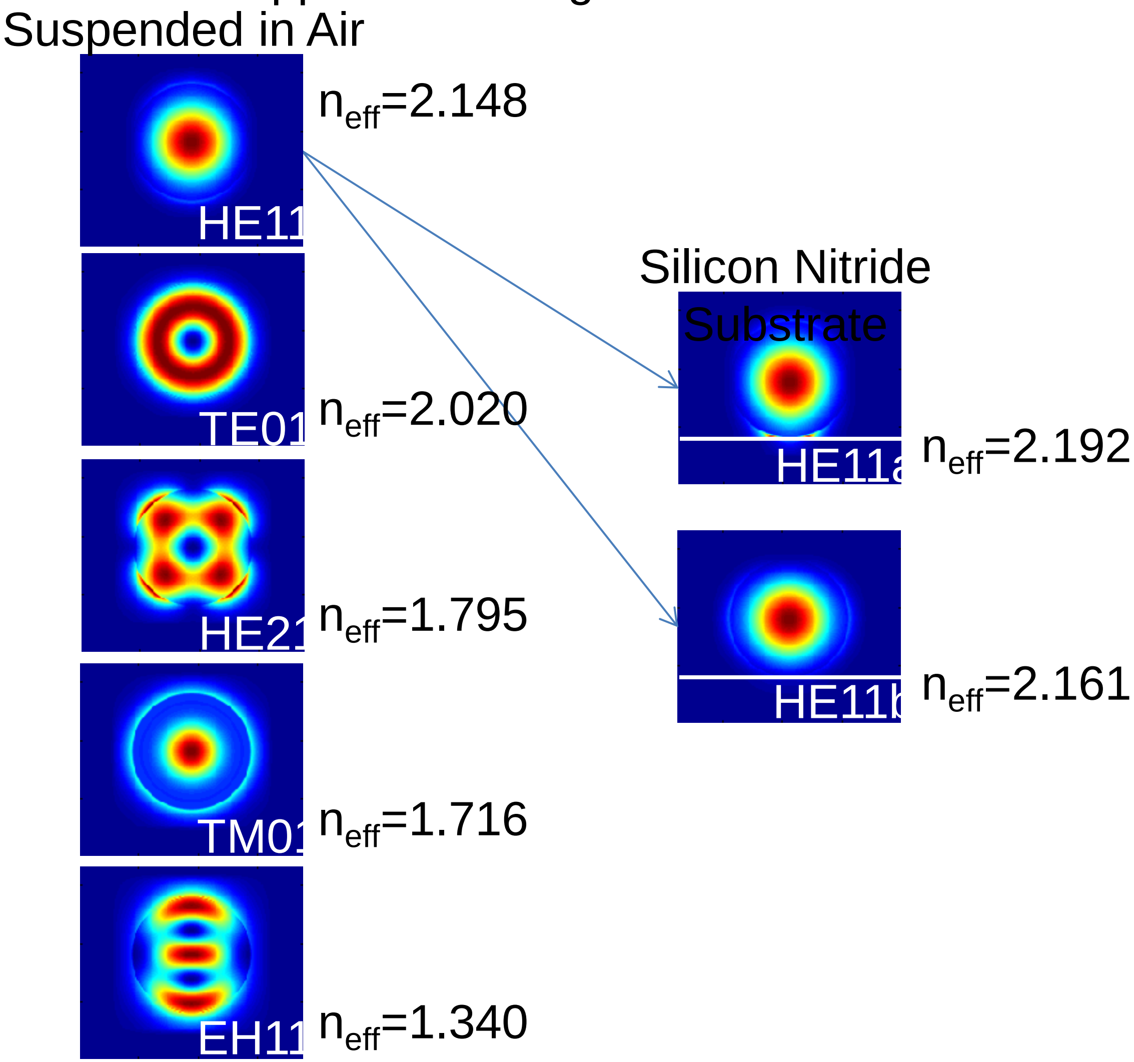
Calculated mode profiles

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

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

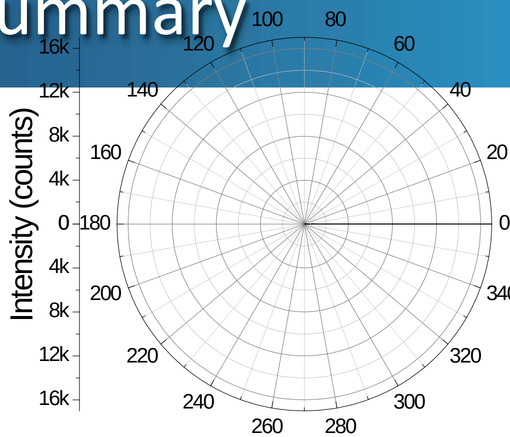

Mode 1 HE11a -neff=2.148
Ex
Ey
Ez
|E|
Degenerate MODE
Mode 2 HE11b - neff=2.148
Ex
Ey
Ez
|E|
Mode 3 TE01 -neff=2.020
Mode 5 HE21a -neff=1.795
Ex
Ey
Ez
|E|
Degenerate MODE
Mode 6 HE21b -neff=1.795
Mode 4 TM01 -neff=1.716
Mode 7 EH11a -neff=1.340
Degenerate MODE
Mode 8 EH11b -neff=1.340
200 nm diameter NW in air

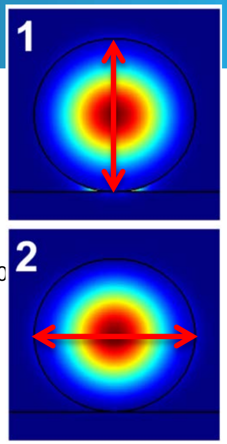
Supported Waveguide Modes



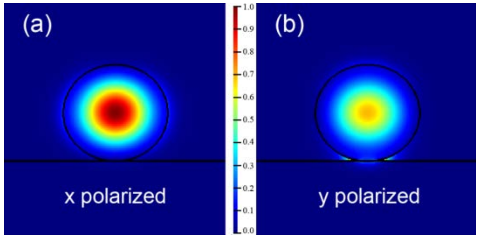
Polarization Control Summary

- A free-standing GaN nanowire laser is typically elliptically polarized with random orientation

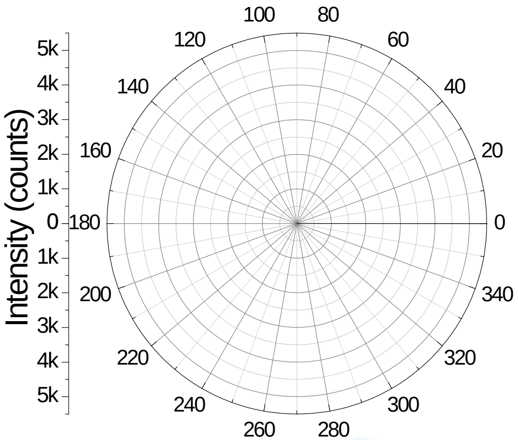




- The elliptical polarization originates from the mode degeneracy of the nanowire



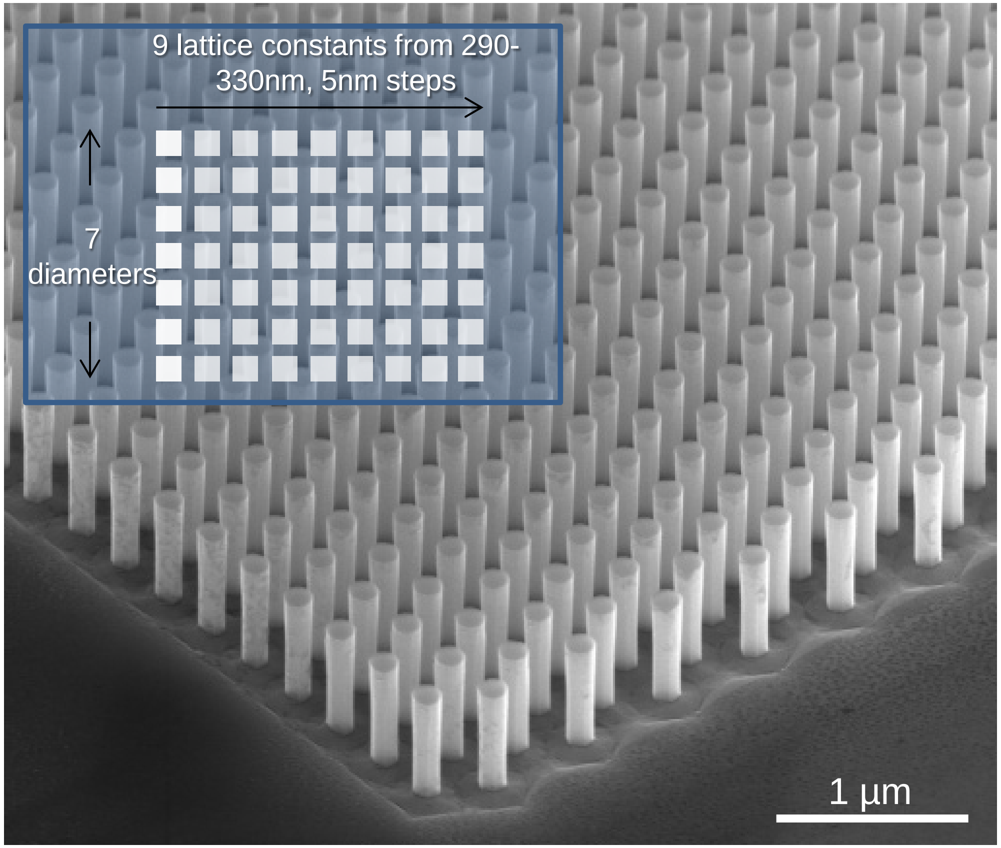
- A on-gold nanowire generates a larger cavity loss for the perpendicularly polarized mode



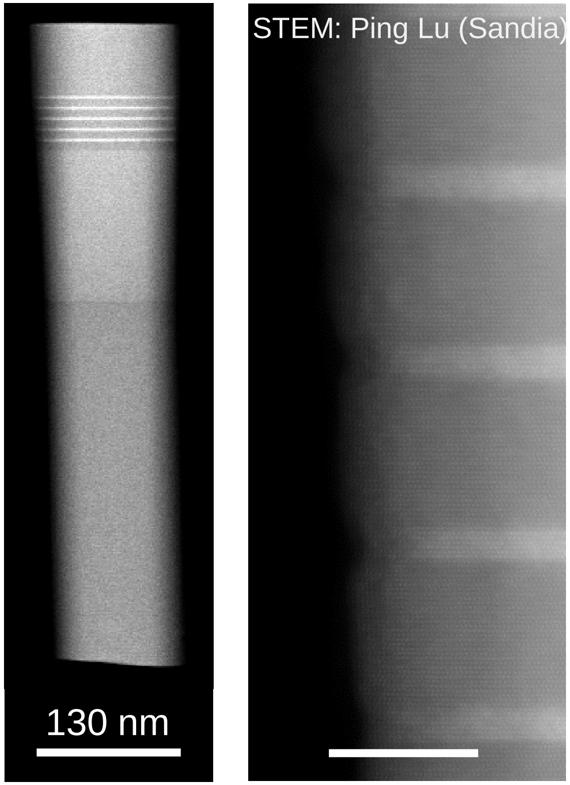
- Linear polarization is achieved with a fixed polarization parallel to the substrate

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

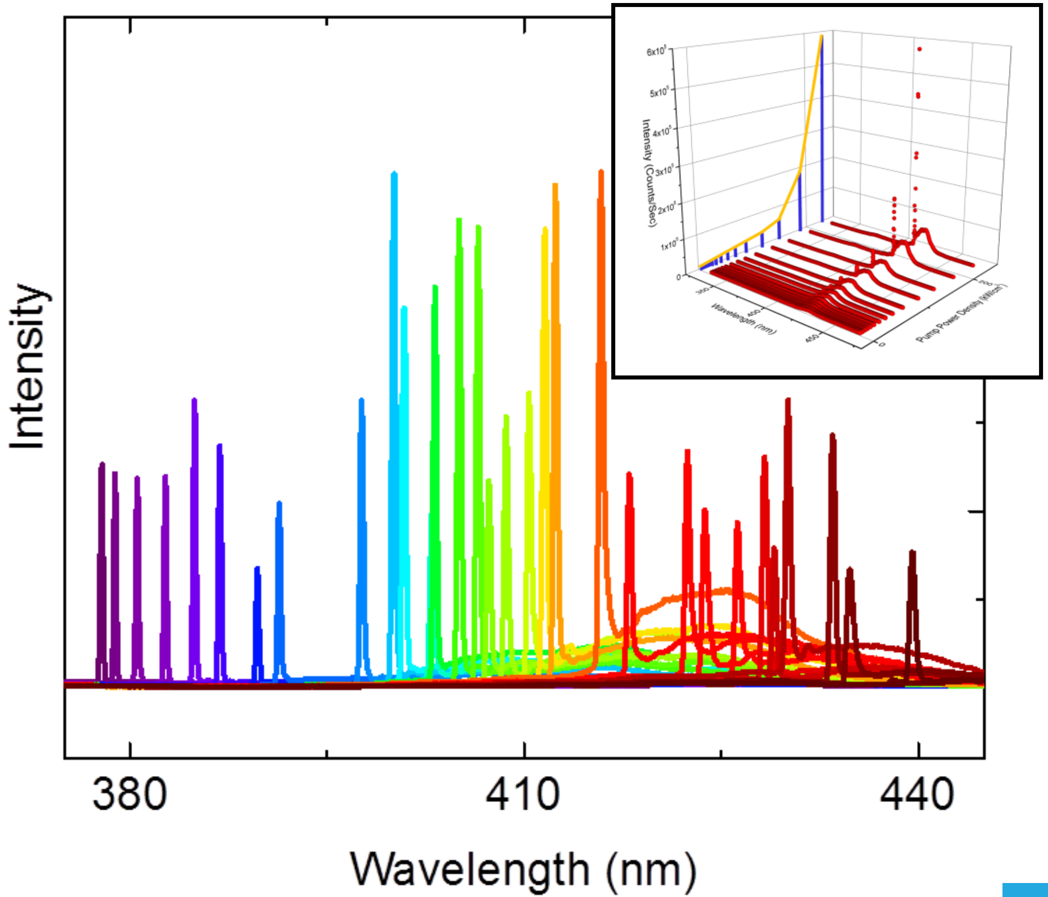


NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

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

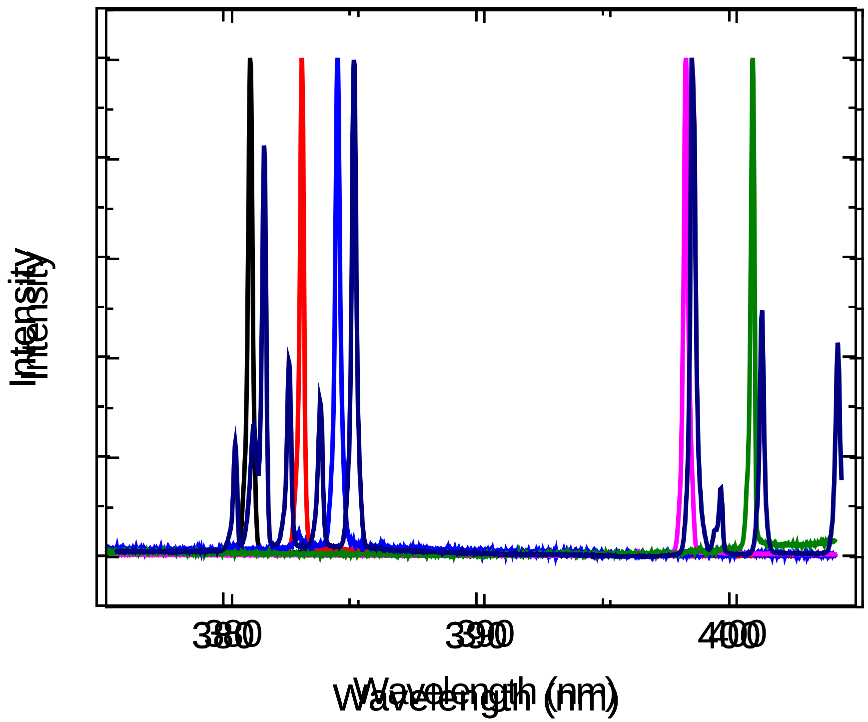
61 color nanowire laser array



- 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)

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

III-N Nanowire Photonic Crystal Lasers

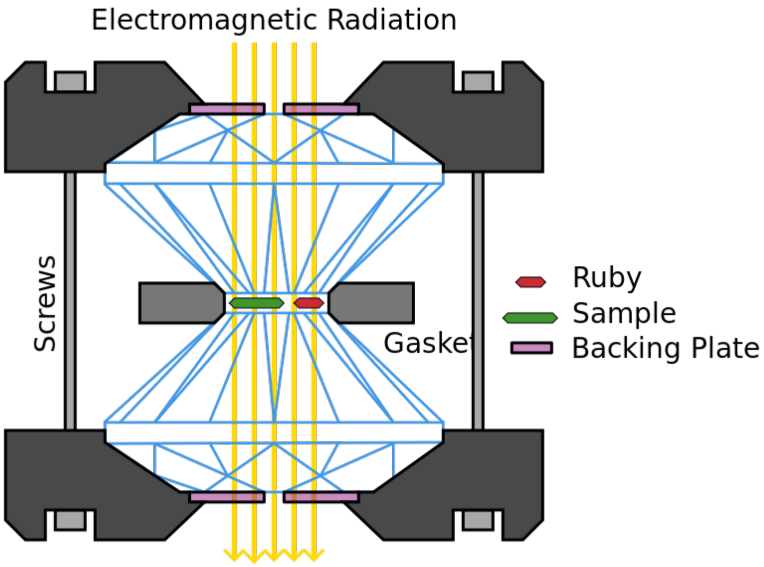


J.B. Wright et al., Scientific Reports 3, Article number: 2982 (2013) doi:10.1038/srep02982

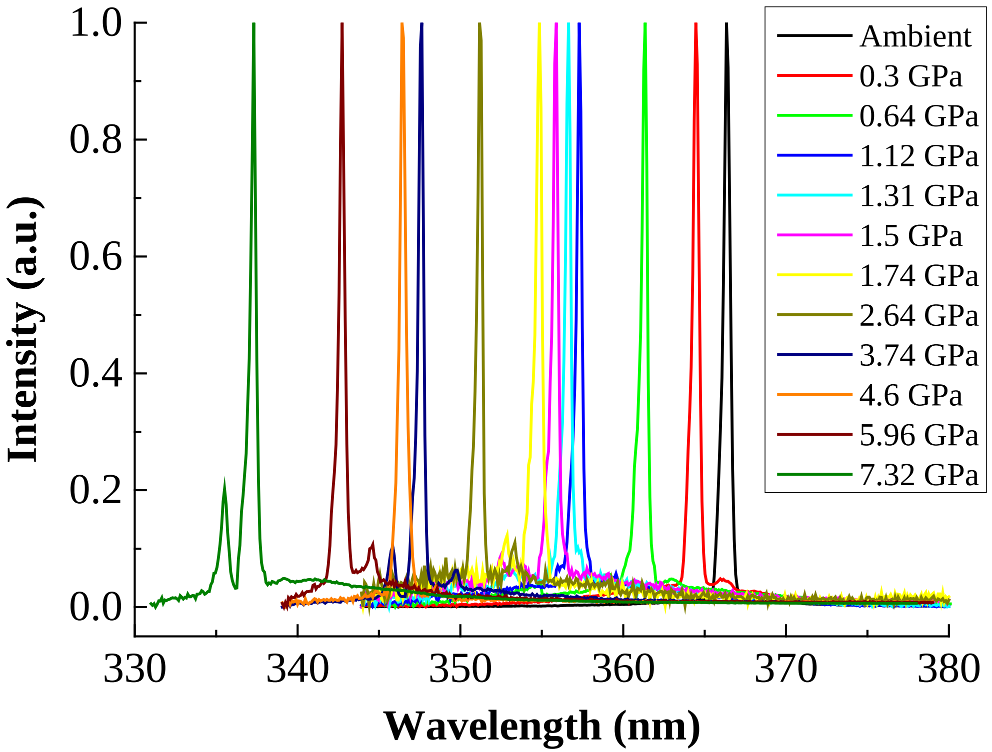
pitch: 320 nm
diameter: 130-140nm

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

Hydrostatic pressure medium (silicone oil) transmits pressure isotropically

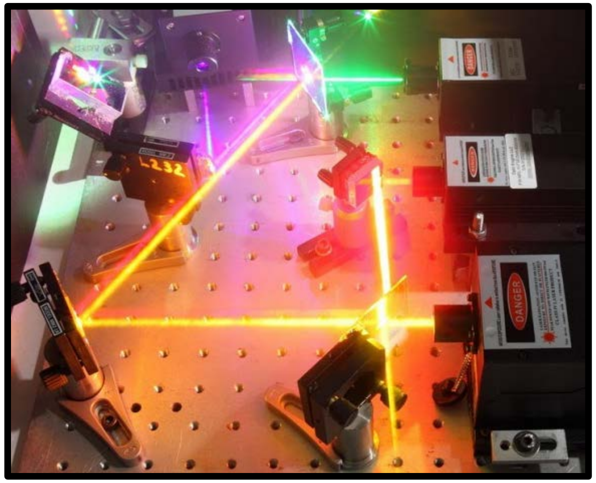


http://en.wikipedia.org/wiki/Diamond_anvil_cell

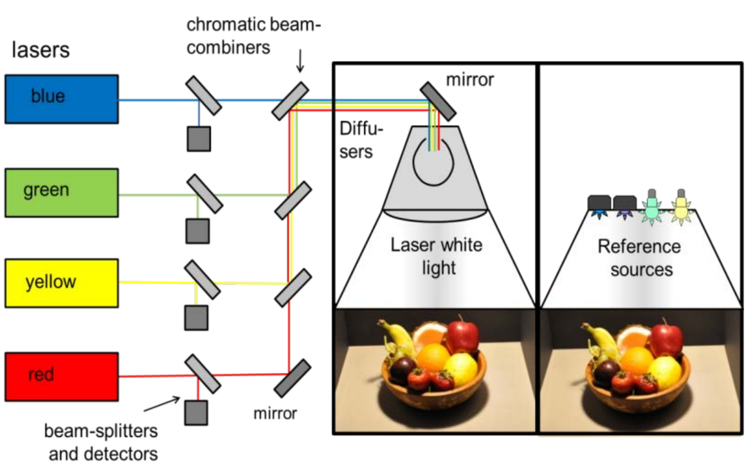


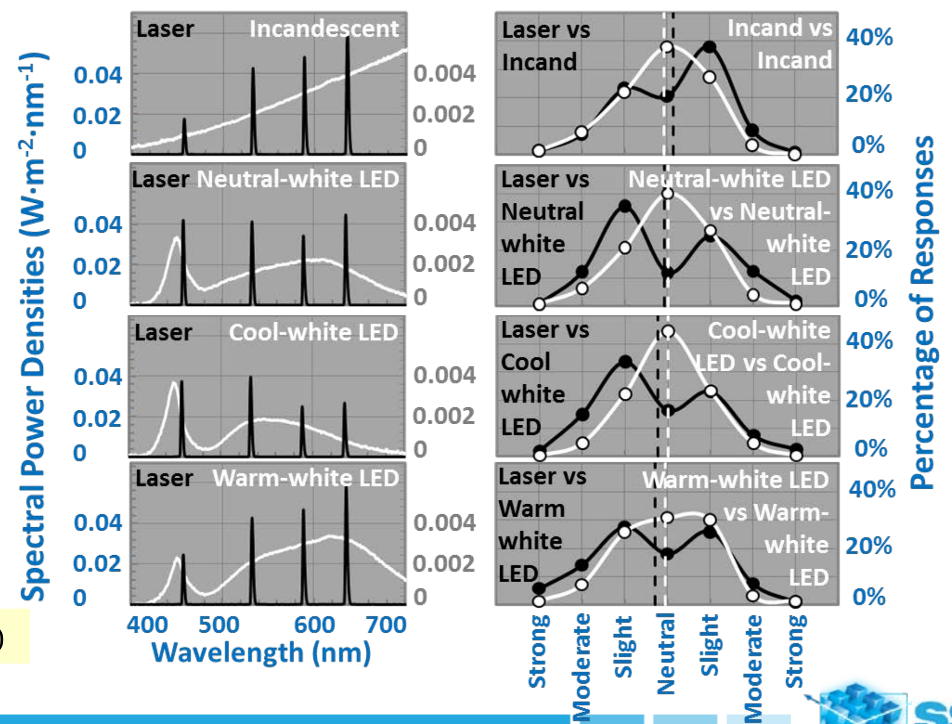
- Applied pressure induces bandgap increase
- ~30nm lasing tuning demonstrated over ~7.3 GPa
- Continuous and reversible tuning possible
- Well defined fine tuning (<0.1nm) possible with current setup

Lasers for Solid-State Lighting?
A Human Factors Study: RYGB Laser Illuminant



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





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

after A.J. Fischer