SAND2013-10556P

SSLS EFRC
Solid-State Lighting Science Energy Frontier Research Center

Sandia National Laboratories

III-nitride nanowires for visible optoelectronics

George T. Wang
Sandia National Laboratories, Albuquerque, NM
e-mail: gtwang@sandia.gov
http://www.sandia.gov/~gtwang

Sandia MESA Facility

Sandia Albuquerque

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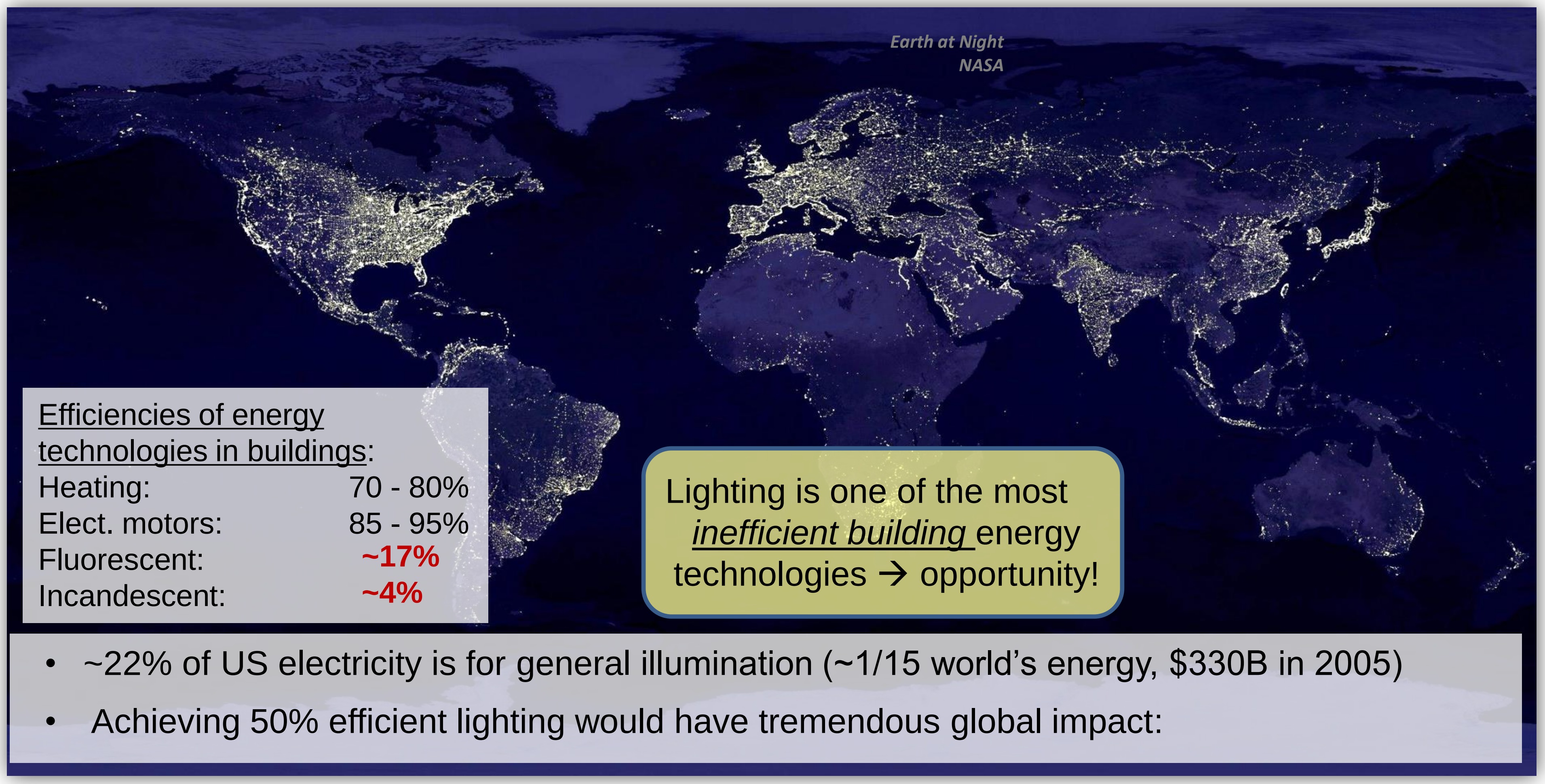
Lighting: large fraction of energy use and low efficiency



<u>Efficiencies of energy technologies in buildings</u>:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	**~17%**
Incandescent:	**~4%**

Lighting is one of the most *<u>inefficient building</u>* energy technologies → opportunity!

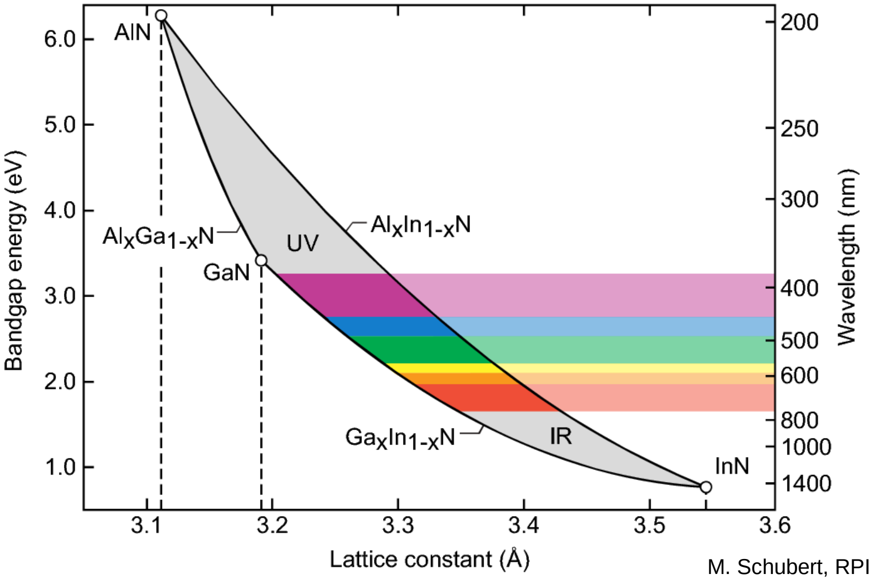
- ~22% of US electricity is for general illumination (~1/15 world's energy, $330B in 2005)
- Achieving 50% efficient lighting would have tremendous global impact:

US DOE target: 50% efficiency

- **decrease electricity consumed by lighting by > 50%**
- **decrease total electricity consumption by 10%**

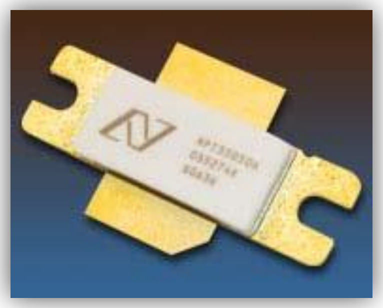
III-Nitride (AlGaInN) semiconductors – The Most Interesting Materials System in the World?

- **Direct RT bandgaps: ~0.7-6.2 ev**
- Solid alloy system (tuneable bandgaps)
- High breakdown field, mobility, thermal conductivity, melting temperature
- Radiation resistant and chemically inert
- InGaN covers entire visible & bulk of solar spectrum (PV material?)



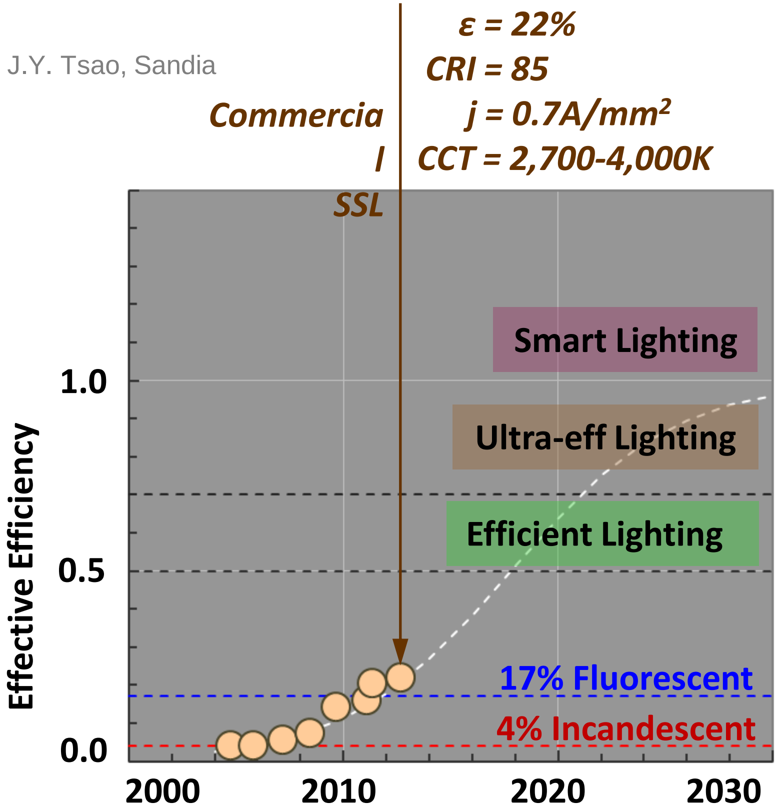
M. Schubert, RPI

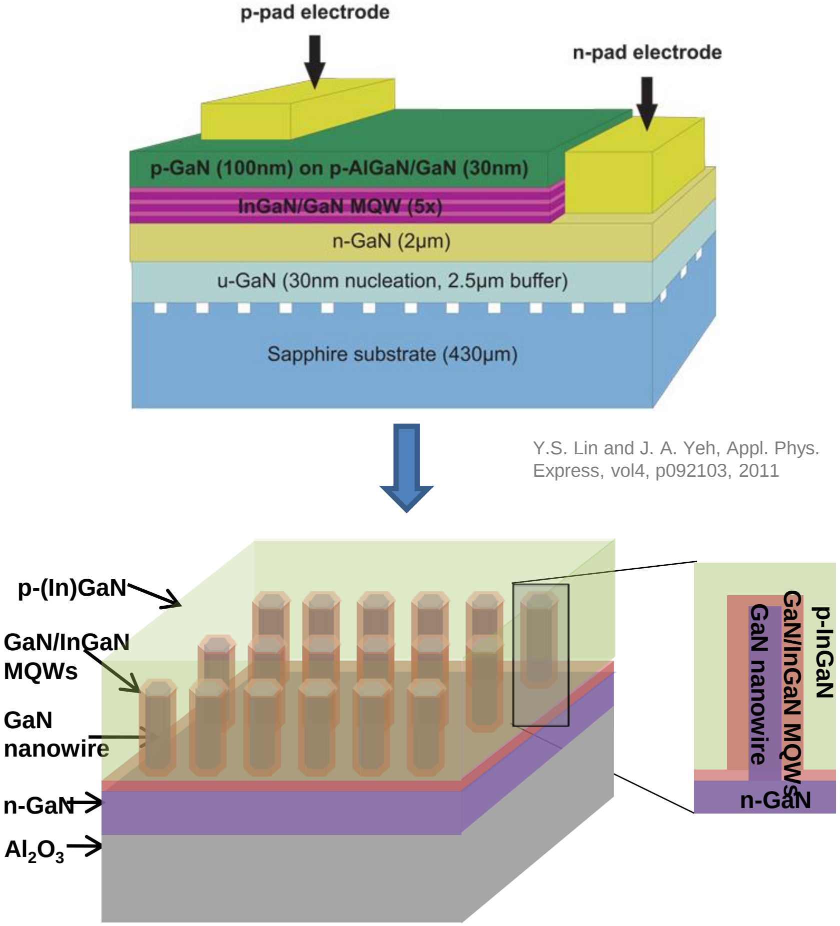
- *Commercially used in LEDs, blue laser diodes, high power electronics, HEMTs*



Nitronex GaN power transistor

Why III-nitride nanowires for optoelectronics?





"Ultra-efficient" SSL: > 70%

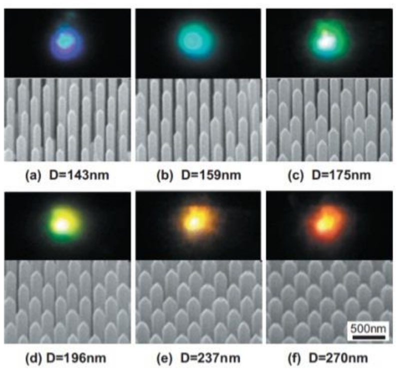
Requires *fundamentally new architectures* and understanding, *enabled* by basic research

Why III-nitride nanowires for SSL?

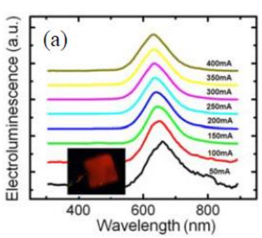
Advantages due to enhanced strain accommodation in nanowires

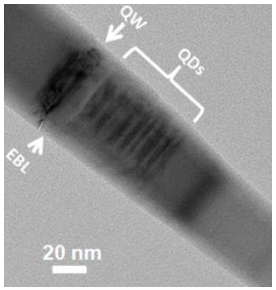
elastic strain relaxation at surface

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

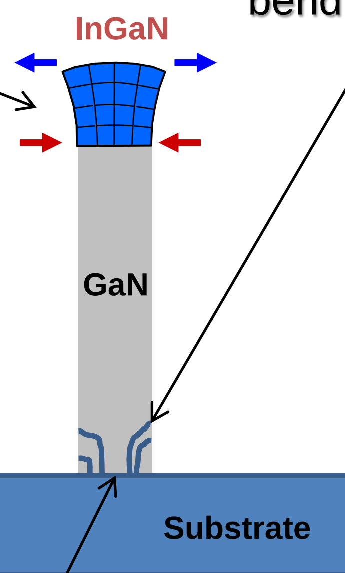


Sekiguchi et al., APL **96**, 231104 (2010) – Sophia U.



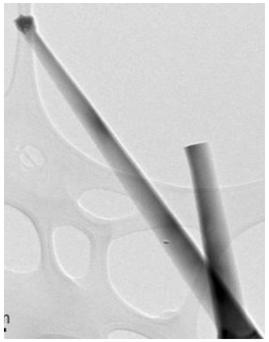


Nguyen et al., PTL IEEE **24**, 321 (2012) - McGill

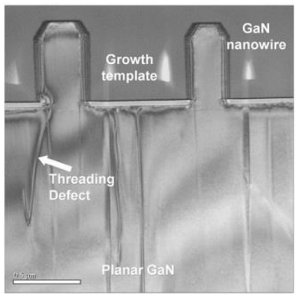


bending of dislocations (TDs) toward surface

benefit: reduced TDs, higher IQE



VLS-grown TD-free GaN NWs - Sandia

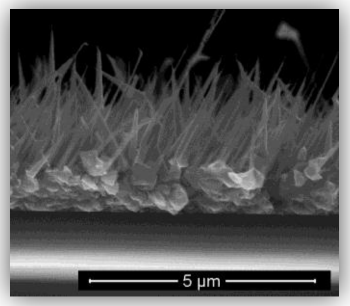


Hersee et al., J. Mat. Res. **17**, 2293 (2011) - UNM

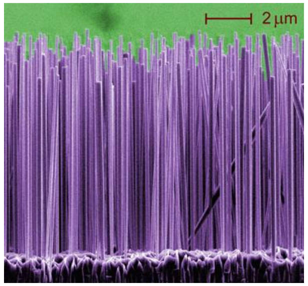
Bending & termination of TDs at nanowire base

small interfacial area

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



GaN NWs on tungsten foil - Sandia

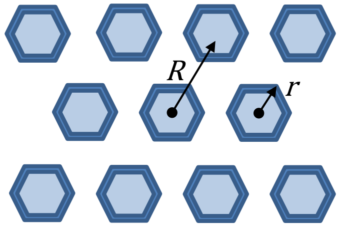


GaN NWs on Si - NIST

Why III-nitride nanowires for SSL?

vertical device integration

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

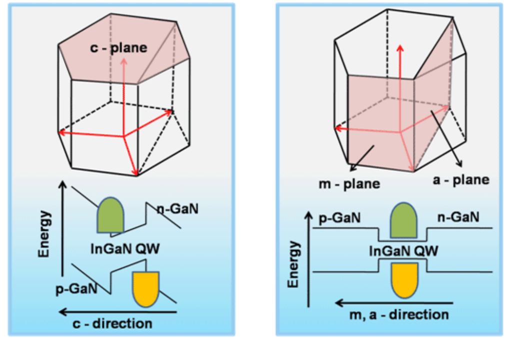


$$\frac{A_{sidewall}}{A_{substrate}} = \frac{6rh}{2.6R^2} \cong \mathbf{4.6F \cdot AR}$$

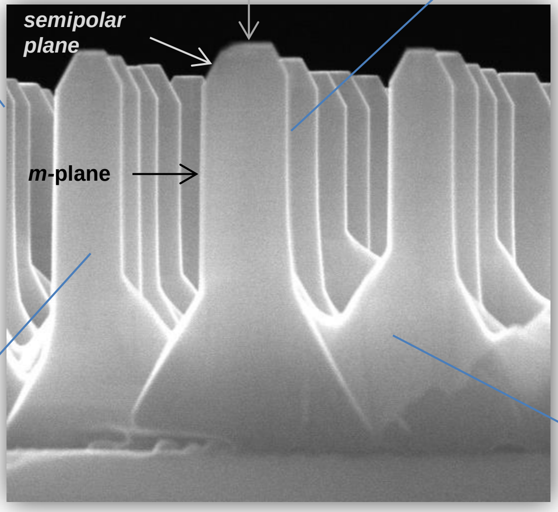
example: 4.6·0.5·3=**6.9× increase!**

access to nonpolar & semipolar planes

benefit: higher IQE, reduced wavelength shift



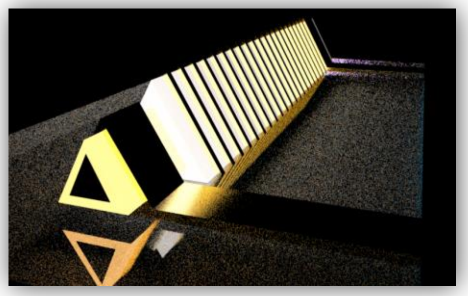
http://csel.snu.ac.kr/research/LED.php



Radial GaN/InGaN MQW NW (Sandia)

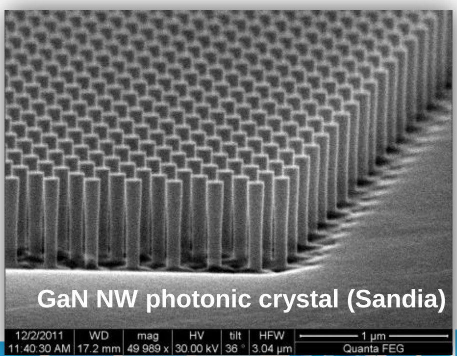
nanolasers

benefit: ultracompact, low power coherent light source



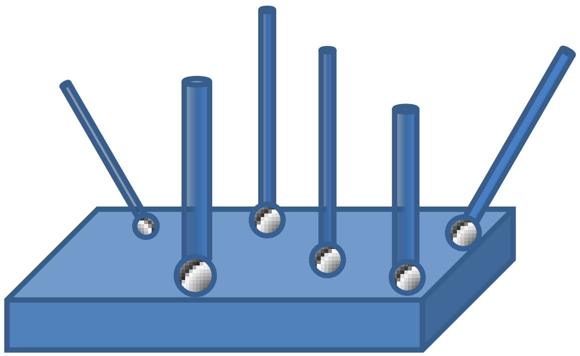
2D arrangements (photonic crystals)

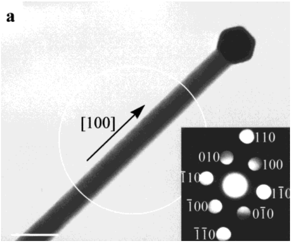
benefit: higher light extraction, IQE, wavelength tuning



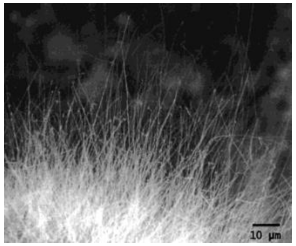
Bottom-up growth of GaN-based nanowires

Metal catalyzed (vapor-liquid-solid)





C. Lieber, 2000

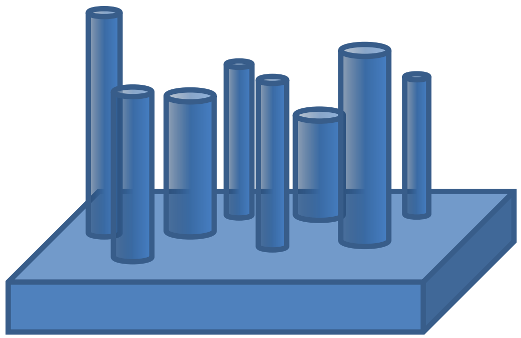


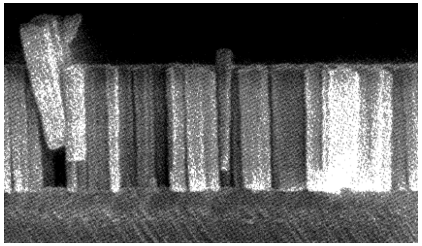
C.C. Chen, 2001

Methods: PLD, thermal evaporation, (MO)CVD

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

"Self-catalyzed"



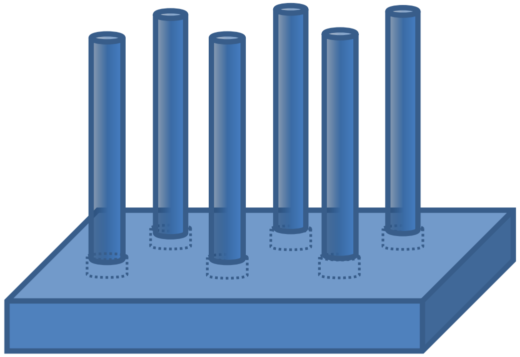


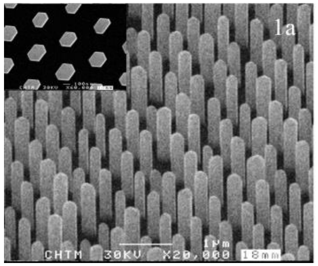
K. Kishino, 1997

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

Cons include slow growth rates and random ordering

Selective area growth (SAG)





S. Hersee, 2006

Methods: (PA)MBE, MOCVD

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

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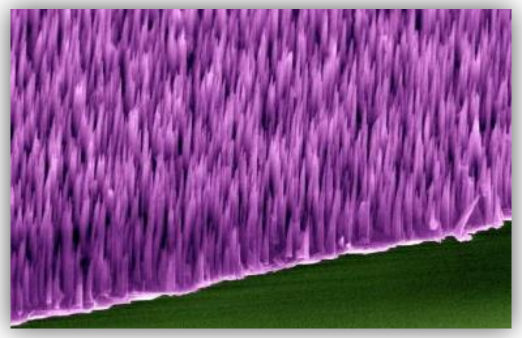
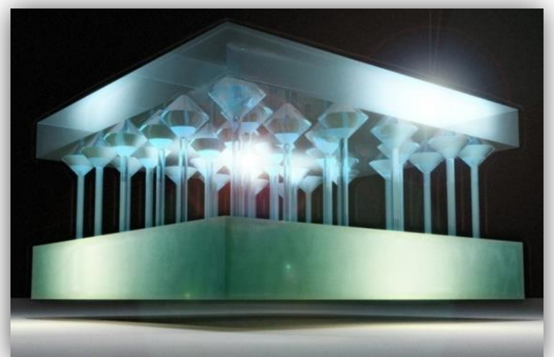
Sandia - Bottom-up III-nitride nanowires

Vertically-aligned growth



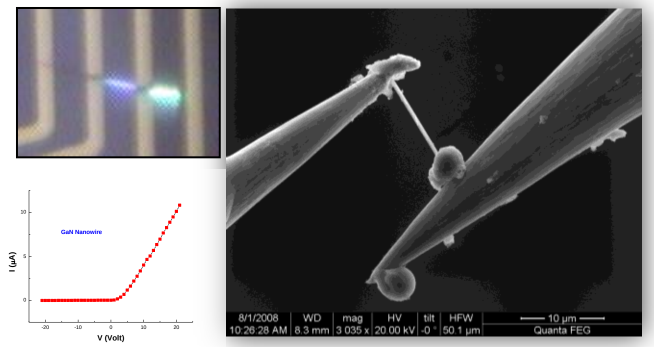
G. T. Wang et al., *Nanotechnology 17 5773-5780* (2006)
Q. Li, G. T. Wang, *Appl. Phys. Lett. 93, 043119* (2008)
Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth 310 3706-3709* (2008)

Nanowire-templated growth



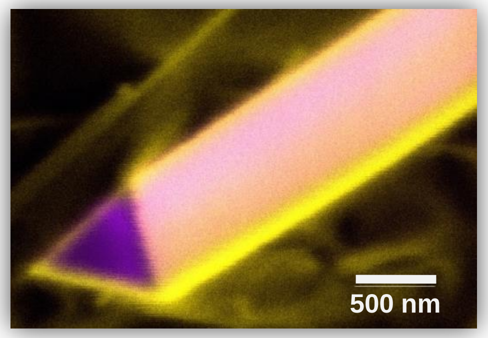
Q. Li, Y. Lin, J.R. Creighton, J. Figiel, G.T. Wang, *Adv. Mat.*, **21** 2416–2420 (2009)

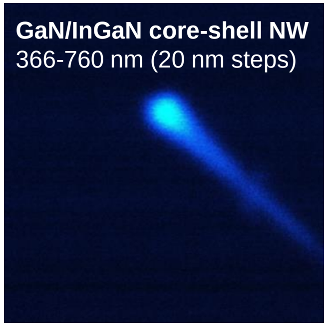
Electrical characterization



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

Optical imaging and spectroscopy



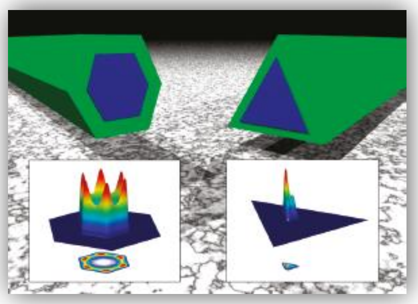


Q. Li, G. T. Wang, *Nano Lett.*, 2010, 10 (5), 1554 [GaN defect CL]
Q. M. Li, G. T. Wang, "*Appl. Phys. Lett.*, ***97***, 181107, 2010. [Gan/InGaN]
P.C. Uppadhya et al. *Semicond. Sci. Tech.* **25** 024017 (2010) [Ultrafast]
A. Armstrong, Q. Li, Y. Lin, A. A. Talin, G. T. Wang, APL **96**, 163106 (2010). [DLOS]

In-situ TEM

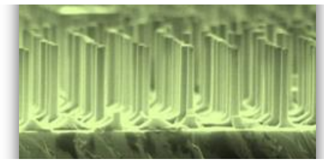
T. Westover et al., *Nano Lett.*, **9**, 257 (2009). [*in-situ* NW breakdown]
J. Y. Huang et al., *Nano Lett,* ***11 (4),*** *1618* ***(2011).*** [*in-situ* nanomechanics]

Theory

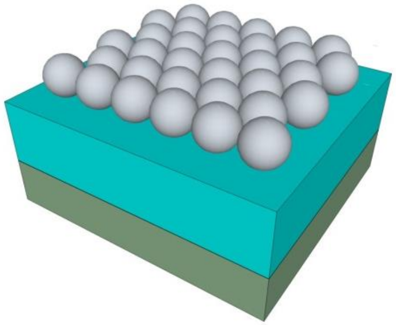


B. Wong et al., *Nano Lett* ***11 (8)****, 3074, 2011*

Bottom-up vs. Top-down III-N nanowires

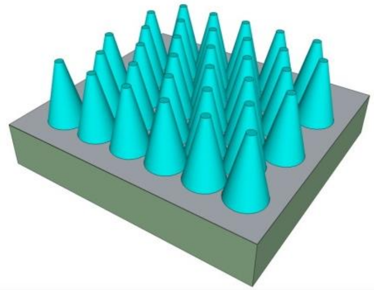
	Bottom-up 	Top-down (+ regrowth) 
Length	Up to hundreds of µm	Several µm
Diameter	~30 nm to microns	~10 nm to microns
Dislocations	Few or none	Depends on density in film
Radial architectures	Yes, typically by MOCVD	Yes, by MOCVD regrowth
Axial architectures	Yes, typically by MBE	Yes, but not strain relaxed
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

New dry + wet top-down ordered nanowire fabrication process

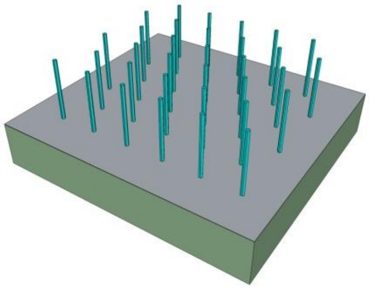


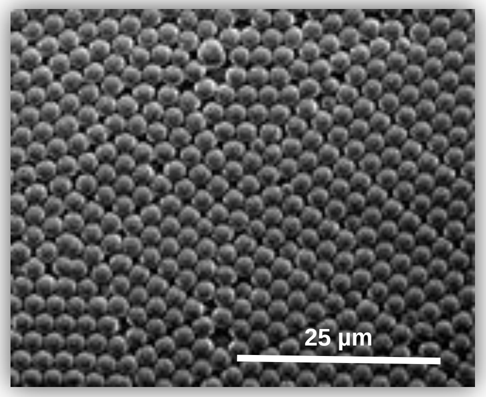
(0001) GaN on sapphire

ICP etch

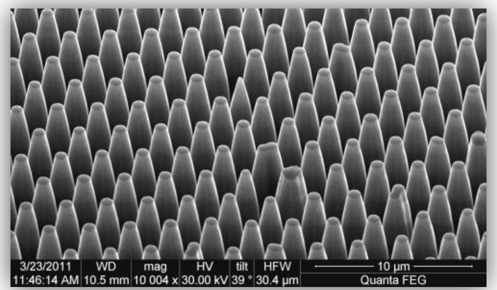


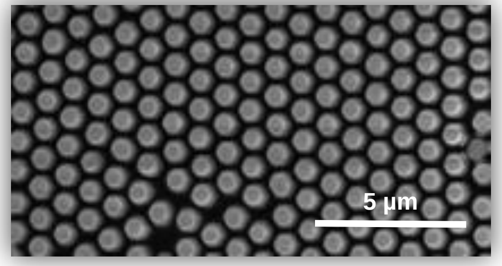
Selective wet etch
(AZ-400K developer)





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

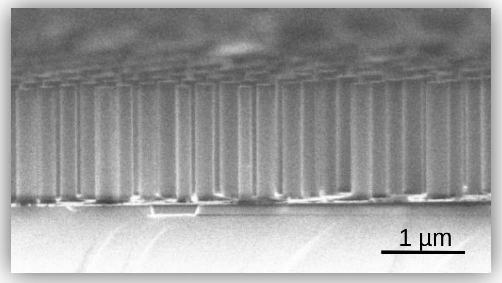


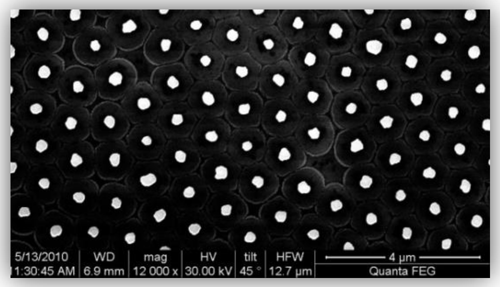


Plasma etch causes sidewall damage

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

Tapered; no well-defined facets



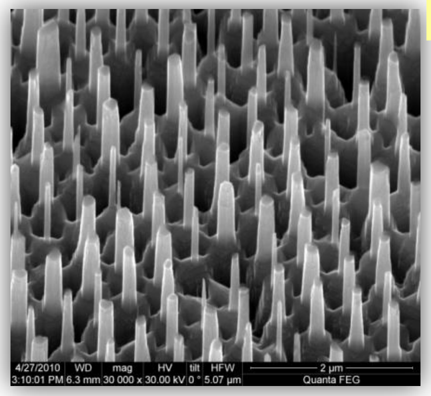


Wet etch: straight sidewalls, removes sidewall damage

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

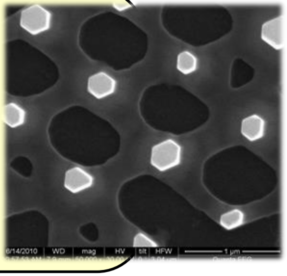


<u>*Superior and independent control of:*</u>

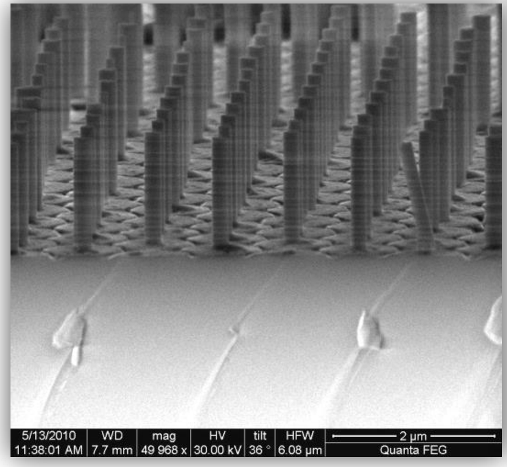
Height (dry etch depth)

Diameter (wet etch time)

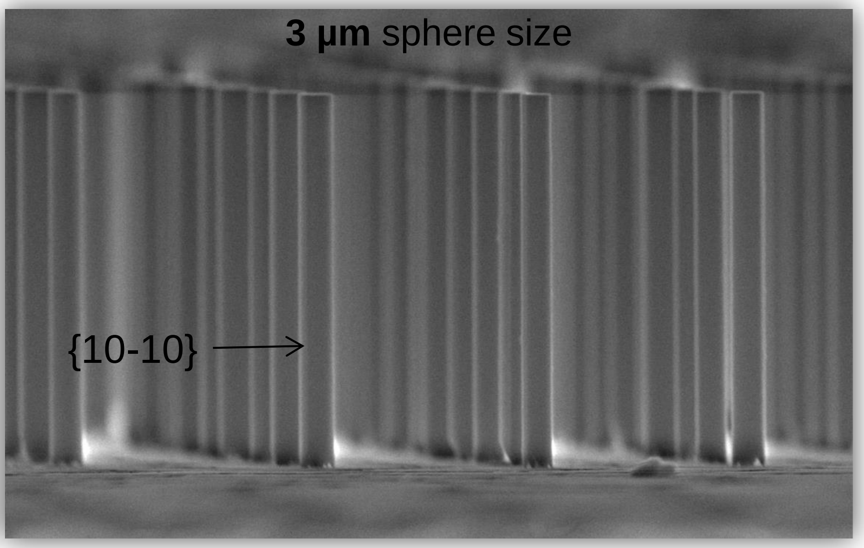
Pitch/arrangement (defined by masking template)

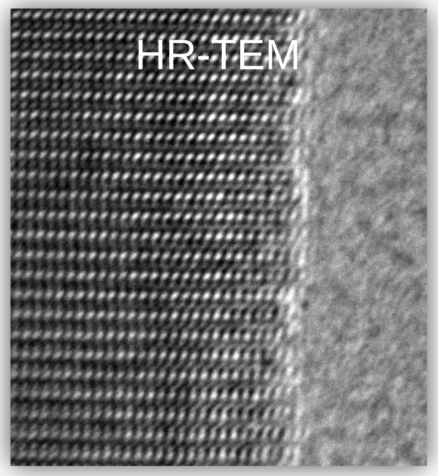


1 µm sphere size



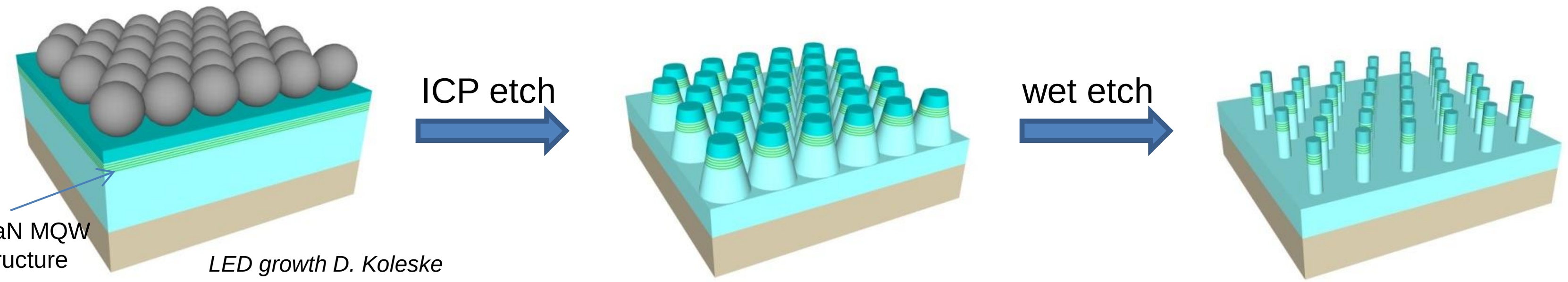
3 µm sphere size

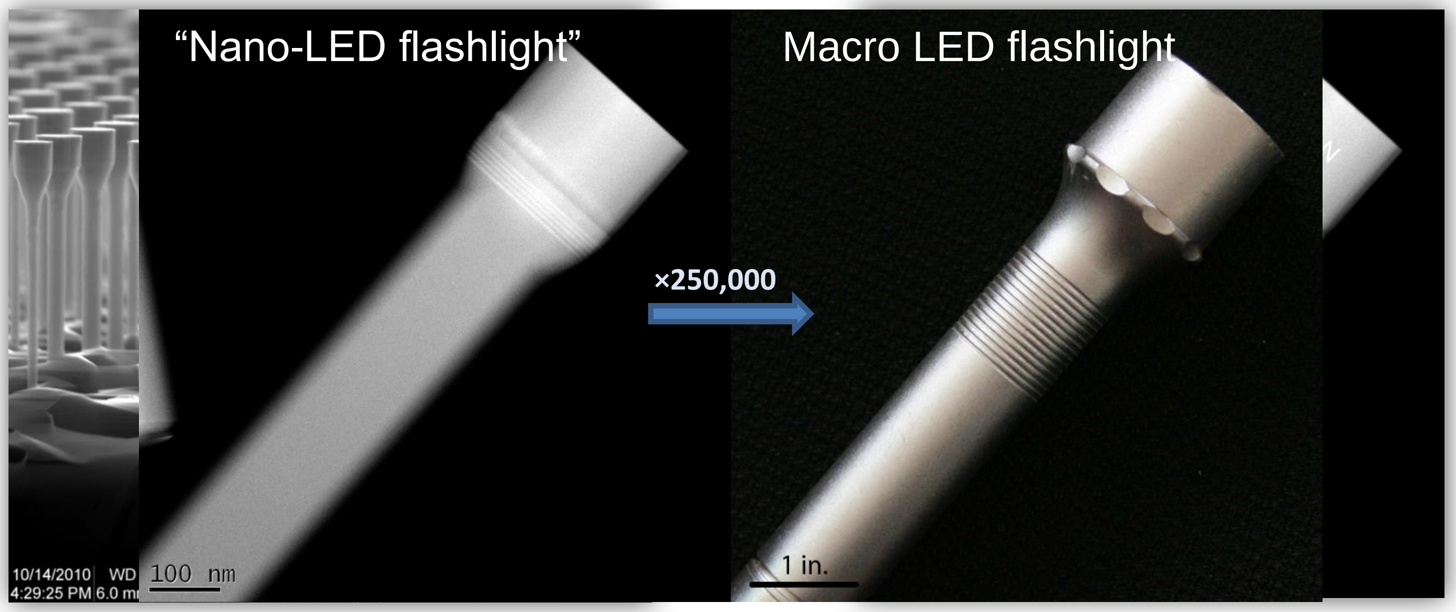




Smooth sidewall created by wet etch

Axial GaN/InGaN nanowire LEDs

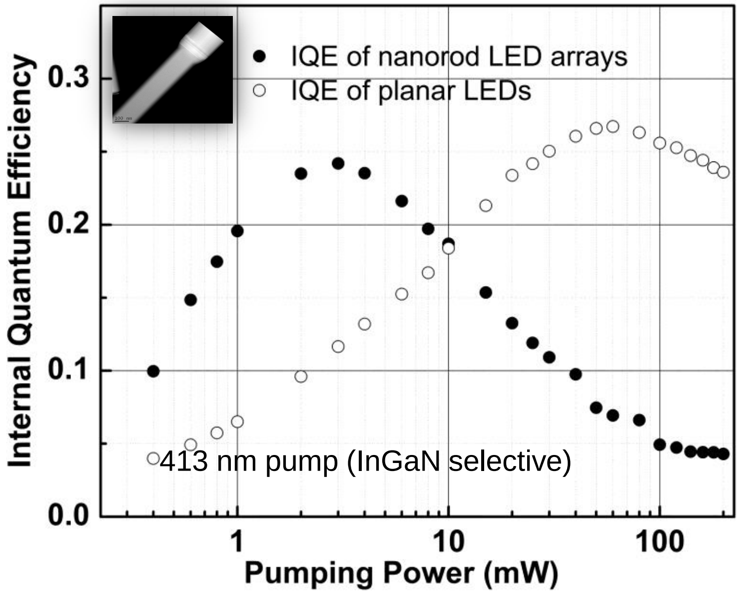




Q. Li et al., *Optics Express* **19**, 25528 (2011)

Optical performance – axial nanowire LEDs vs. planar LED

IQE – nanowire vs Film



PL, IQE: K. Westlake, M. Crawford

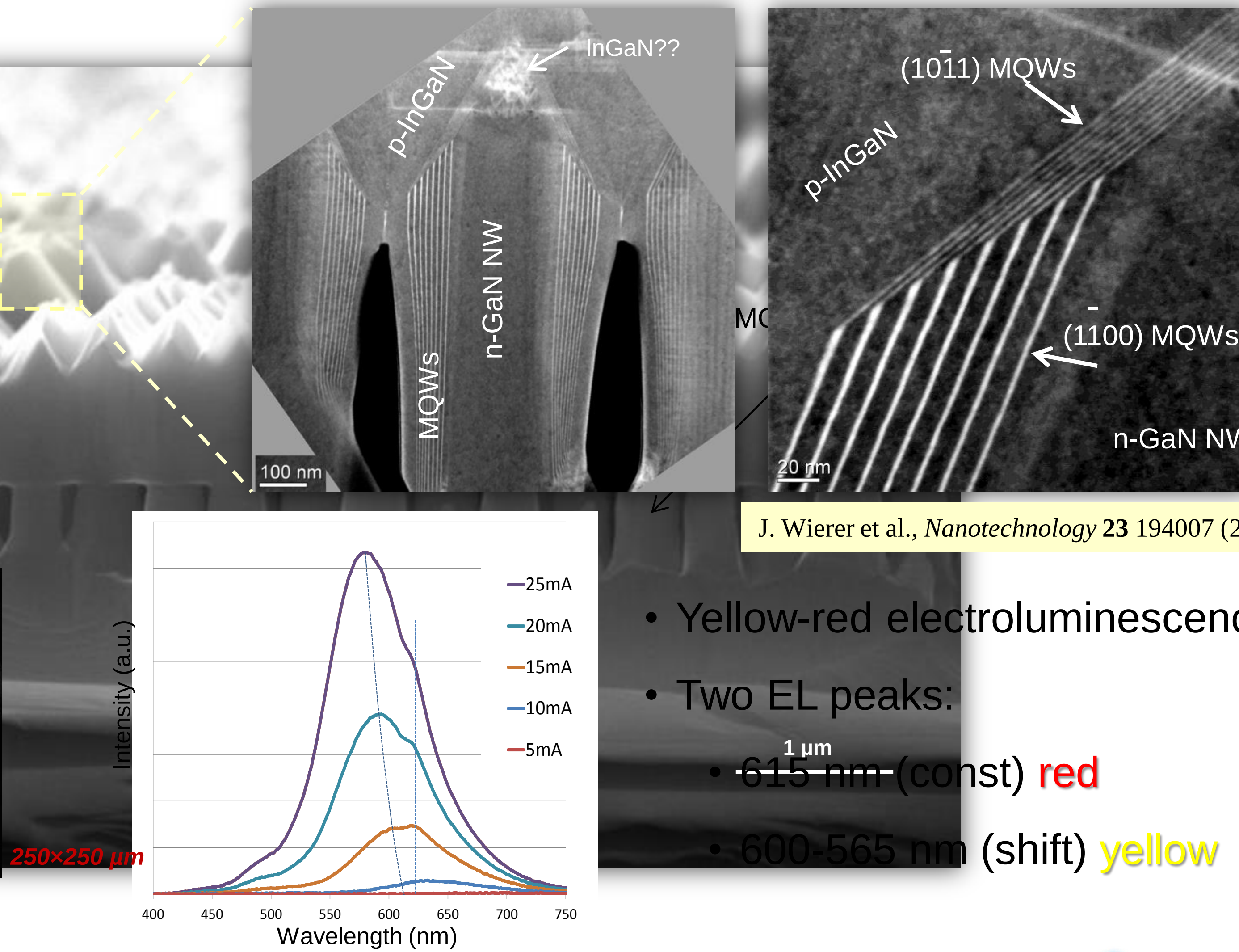
Q. Li et al., *Optics Express* **19**, 25528 (2011)

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

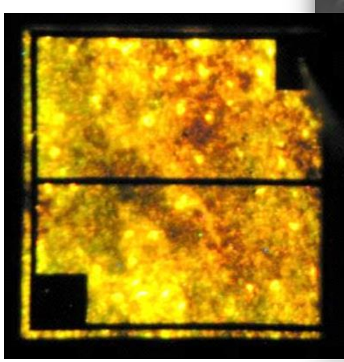
How much is surface passivation likely to improve IQE of NW LED?

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

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



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

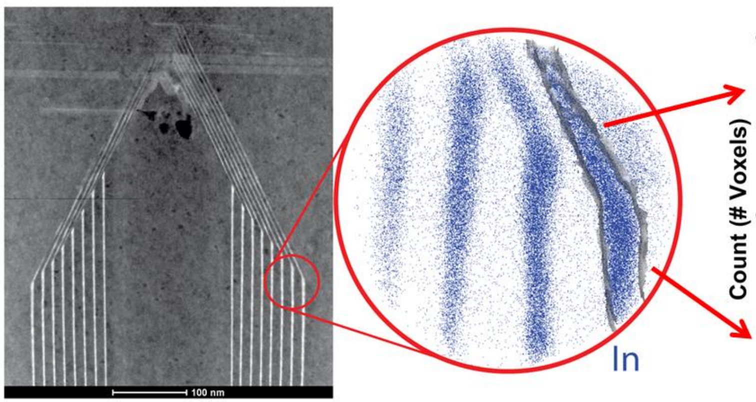


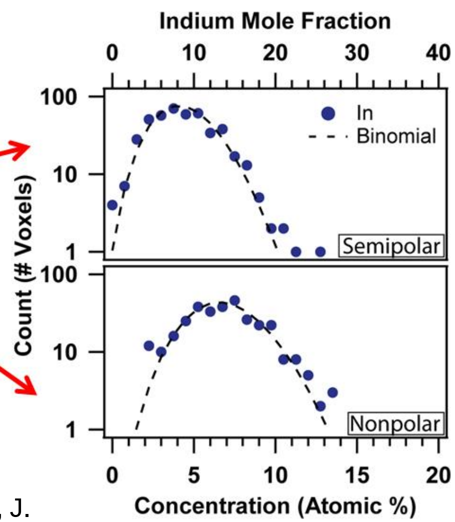
- Yellow-red electroluminescence!
- Two EL peaks:
  - 615 nm (const) red
  - 600-565 nm (shift) yellow

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

STEM-EDS

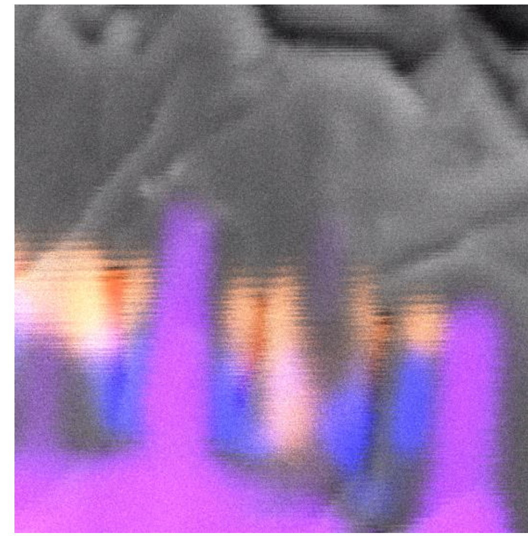
Atom probe tomography (APT)





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

Cathodoluminescence



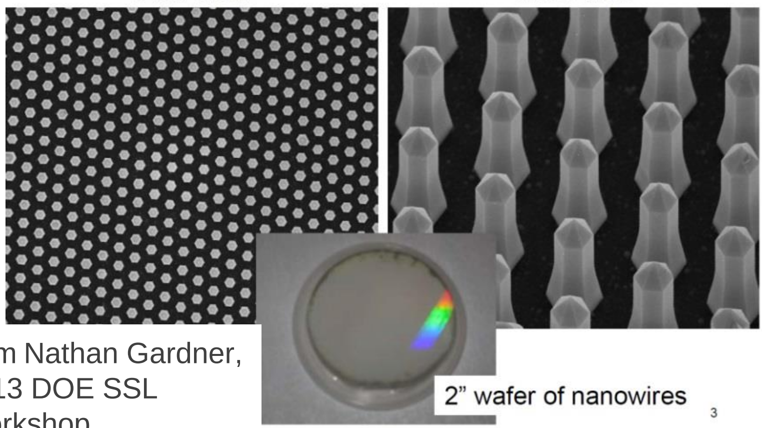
365 nm, 402 nm, 442 nm

- Nonpolar and semipolar QWs from radial NW LED were imaged by APT and correlated with scanning TEM and cathodoluminescence data
- Yellow-red emission likely originates from In-rich tip regions, not sidewalls, which emit blue, consistent with other reported core-shell nanowire InGaN QW structures.
- **If core-shell NWs are to solve the “green gap”, new advances are needed!**

Core-shell nanowire LED commercialization efforts

glō

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



from Nathan Gardner, 2013 DOE SSL Workshop

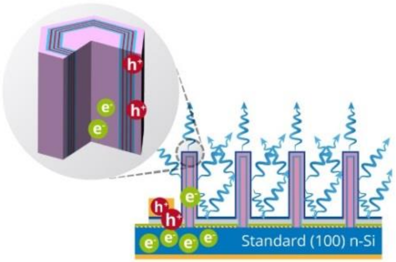
Bottom-up grown nanowires with *m*-plane MQWs

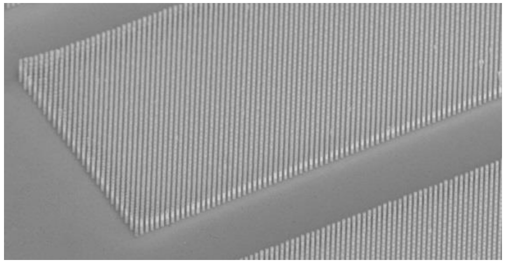
From ICNS-10 (Aug 2013):

- 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

SSLS EFRC

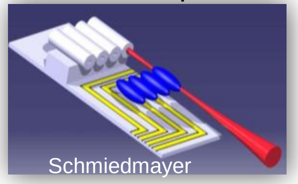
Nanowire Lasers

Why Nanowire Lasers?

- Nanowire forms a freestanding, low loss optical cavity
- Compact and low power due to small mode volume
- Possibility of high efficiency lasers at green and yellow wavelengths
- Potential applications including electronic/optical integration, sensing, imaging, lithography, lighting

Integrated nanophotonics, atom trapping, optical MEMS

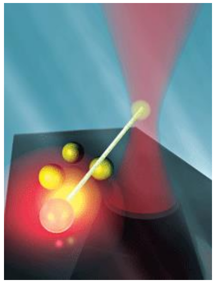
atom trap

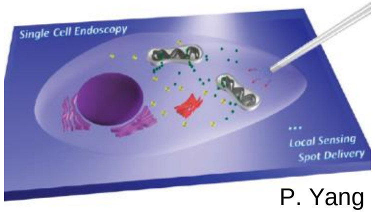


J. Ford, Lucent

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

Optical nanoprobes & chem/bio detection/sterilization





P. Yang

Sub-wavelength resolution probes for localized excitation, detection

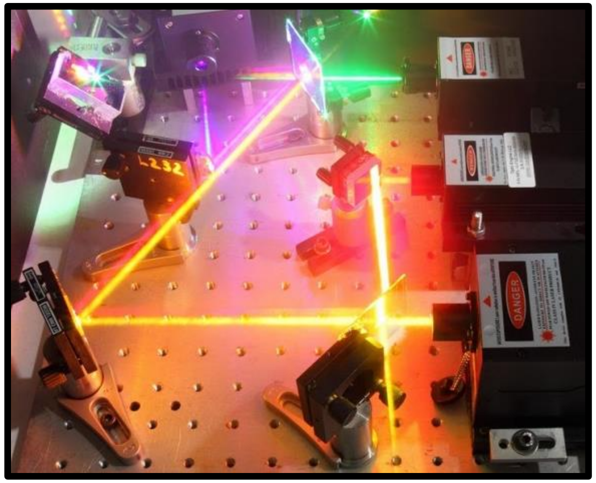
Lighting, projection, & holographic displays

Sony Crystal LED Display prototype

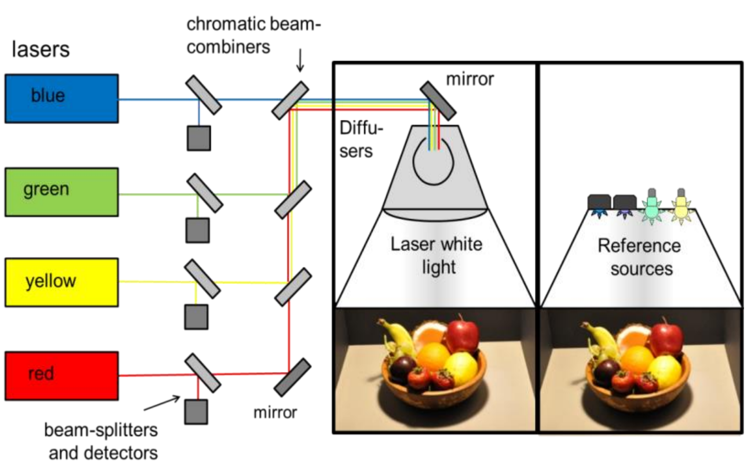
Low-power, speckle-free low coherence (random lasers)

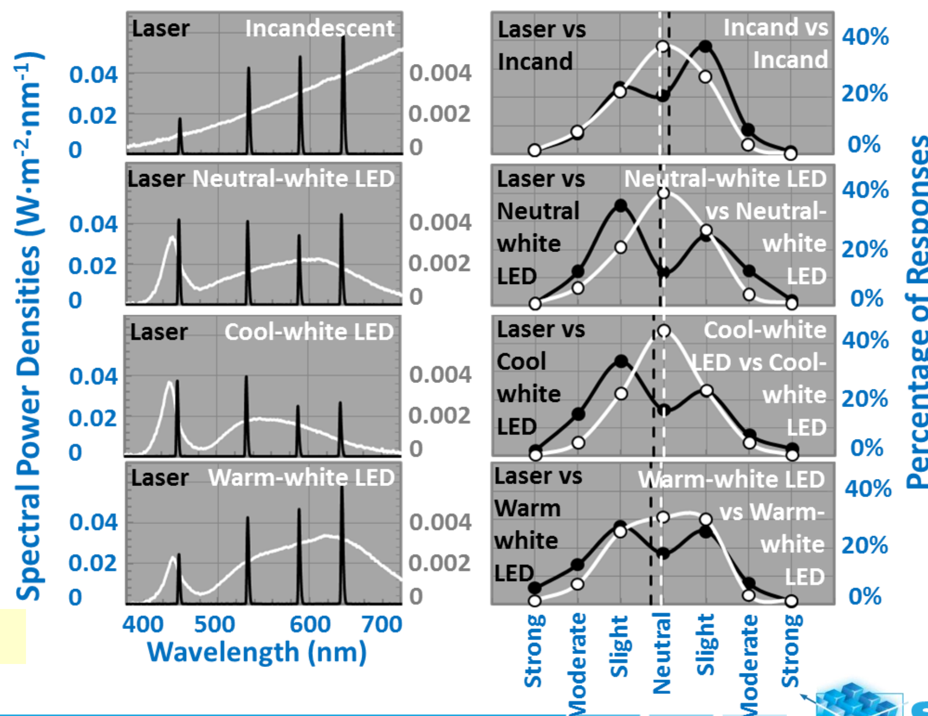
See also: S. Arafin, X. Liu, Z. Mi, "Review of recent progress of III-nitride nanowire lasers," *J. Nanophotonics* **7,** 074599-1

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**



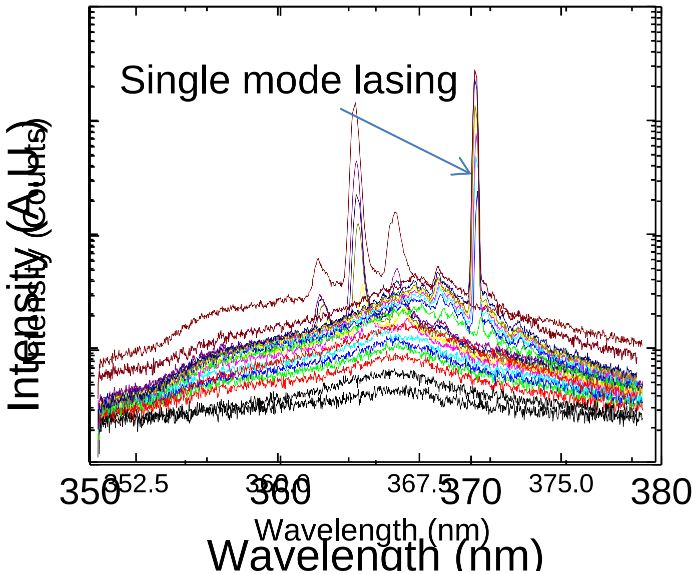


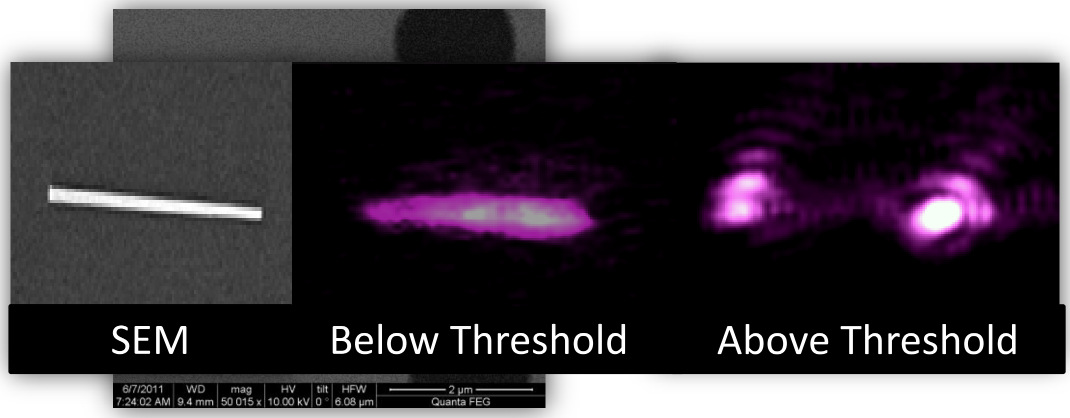
A. Neumann et al, *Optics Express*, **19**, A982-A990 (2011)

after A.J. Fischer

Method 1: Single-mode GaN nanowire laser via geometry control

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





Nanowire dimensions: ~**130nm** x 4.7µm
Nanowire dimensions: ~**500 nm** x 4.7µm

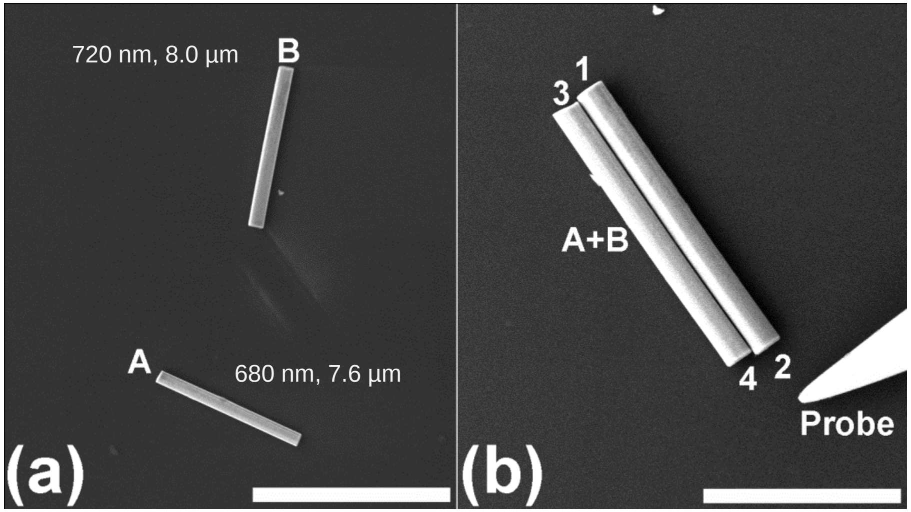
Q. Li et al., *Opt. Exp.* ***20*** *17873 (2012)*

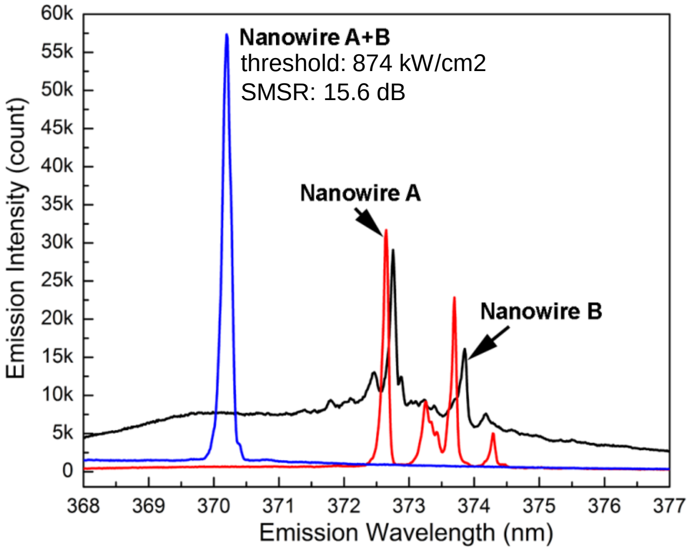
Single-mode: Narrow linewidth (<0.1 nm), 15dB Side Mode Suppression Ratio, and **Low Threshold** (~250 kW/cm^2)

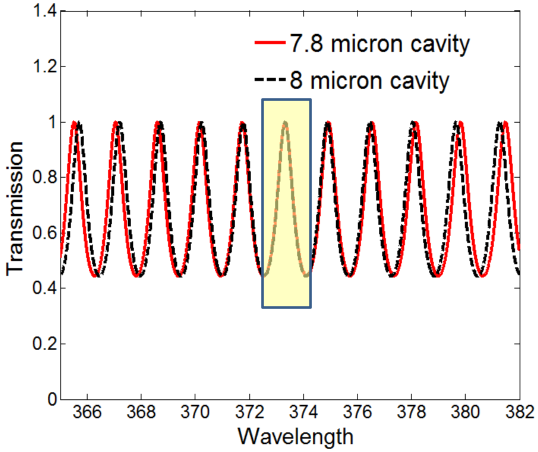
Multi-mode: Threshold ~500 kW/cm^2

Reducing the dimensionality of the wire (< ~130 nm diameter and < ~6 µm length) lowers the number of competing modes, leading to single-mode lasing.

Method 2: Single-mode lasing via coupled nanowire cavities





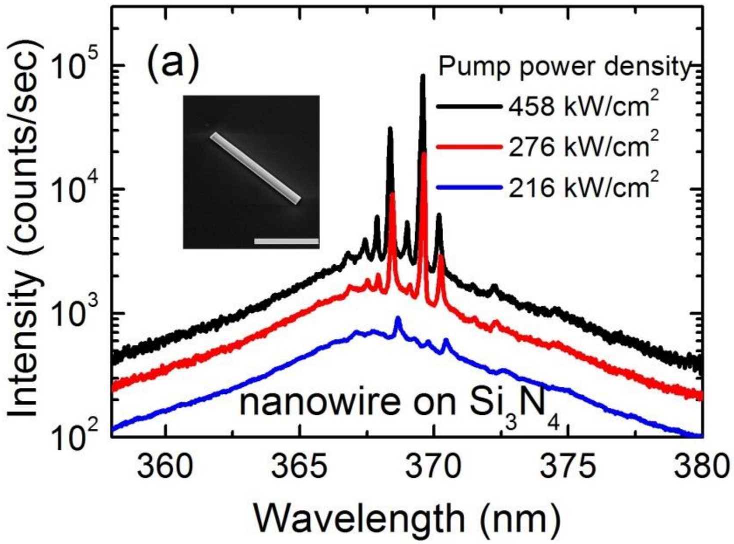


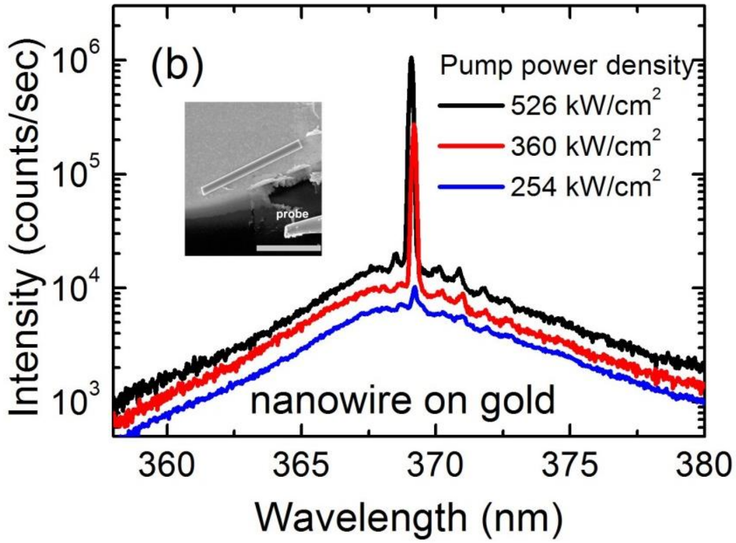
- GaN NWs need to be <~130 nm for single transverse mode behavior; larger single-mode NWs?
- Individual large NWs shows multiple modes.
- Coupled nanowires show single mode!
- Vernier effect – only resonant modes survive

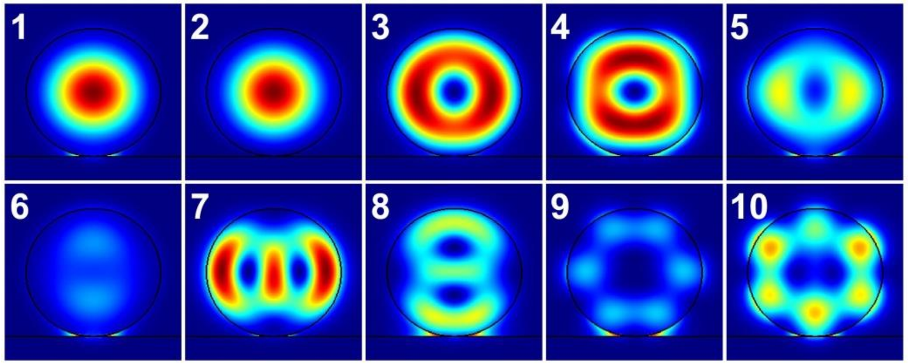
modeling: Huiwen Xu (UNM)

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

Method 3: Metal substrate induced single-mode nanowire lasing





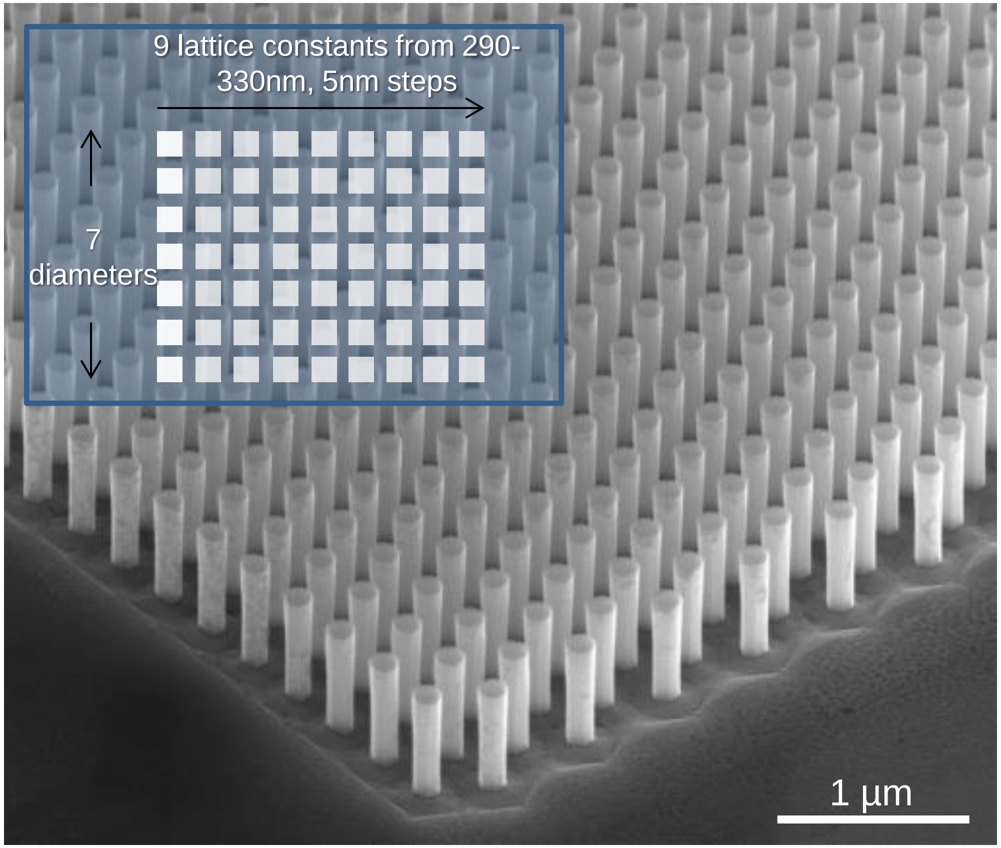


- NWs on Si_3N_4 show multi-mode lasing
- Same NWs moved onto gold-coated spot show single-mode lasing!
- Metal substrate induces mode-dependent loss mechanism

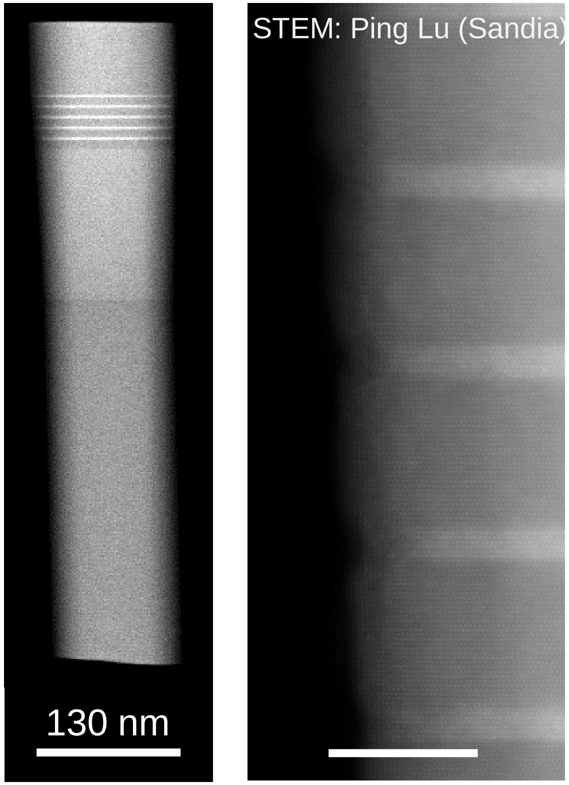
H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

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

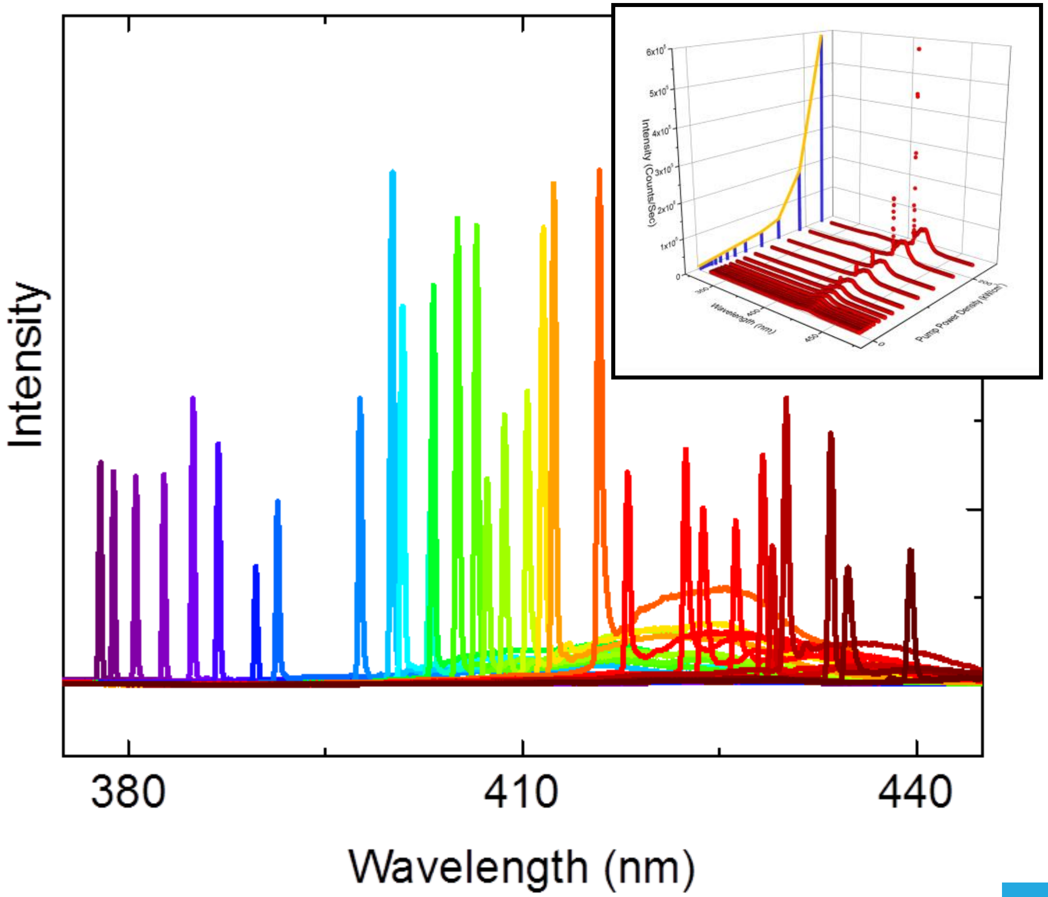


NW STEM images: 5x MQW InGaN emission centered at 420nm, $In_{0.02}GaN$ underlayer

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

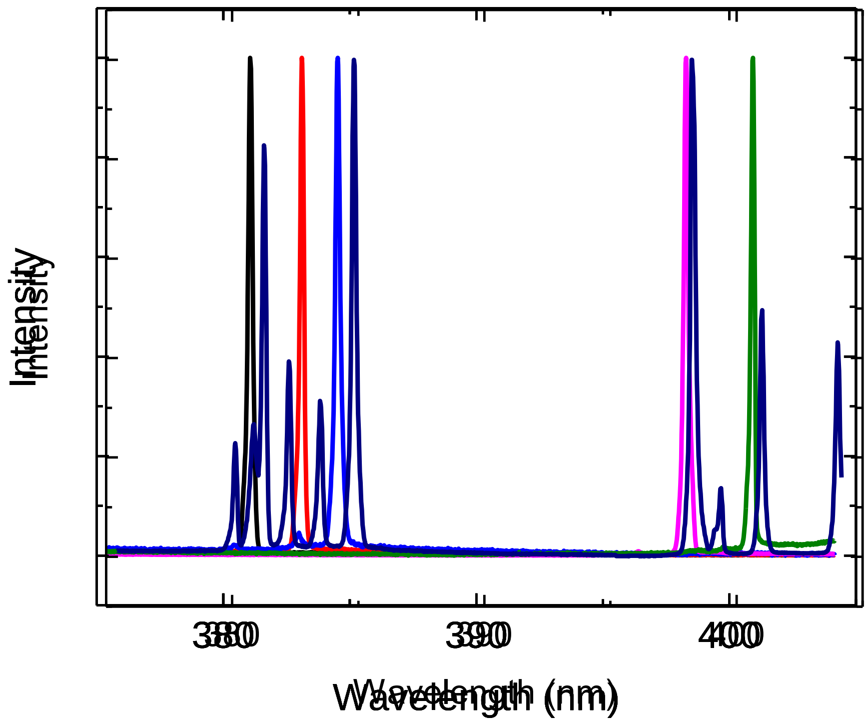
61 color nanowire laser array



- 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

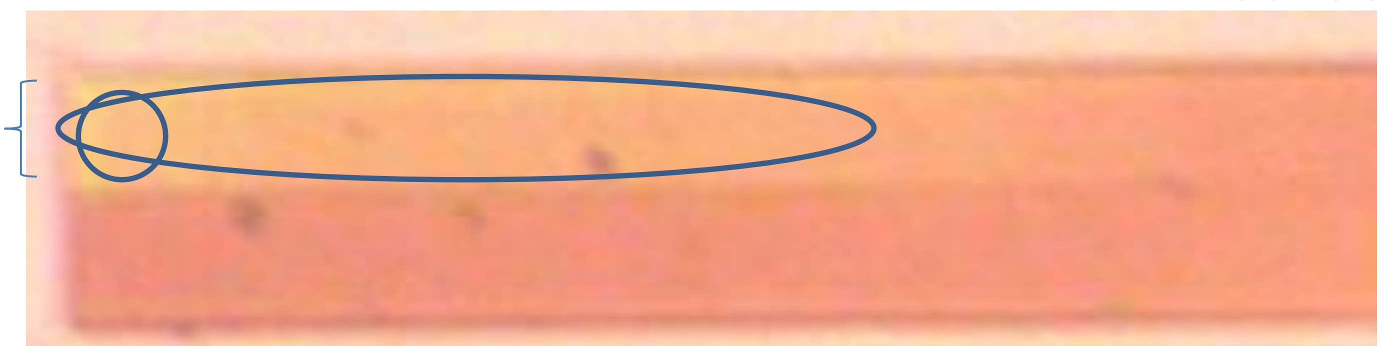
III-N Nanowire Photonic Crystal Lasers



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

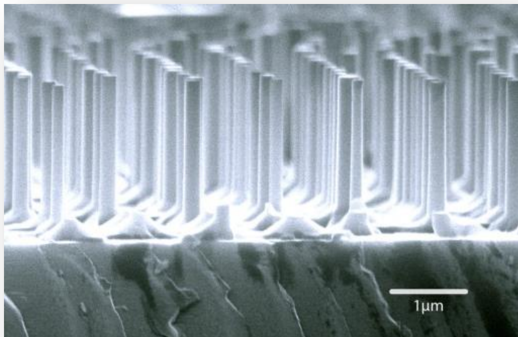
pitch: 320 nm
diameter: 130-140nm

10 um

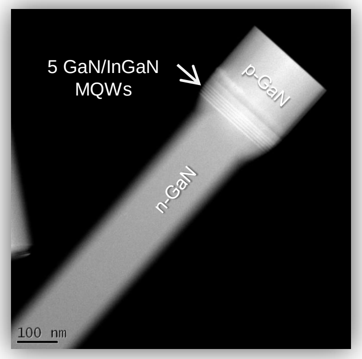


Summary – Top-down III-nitride nanowires

Top-down fabrication

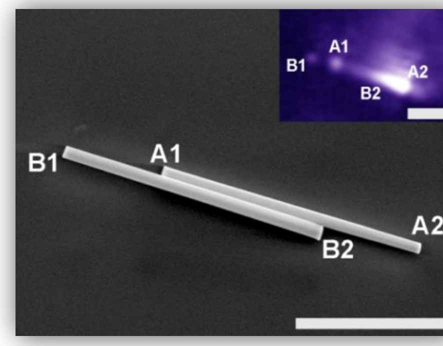


Axial nanowire LED "flashlight"



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

Single-mode GaN nanowire lasers

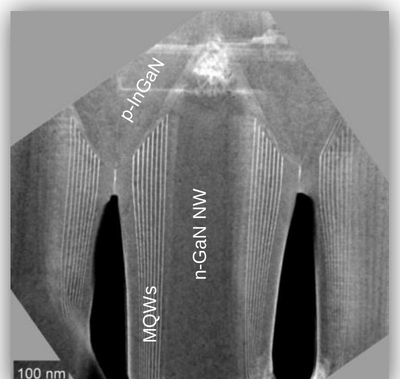


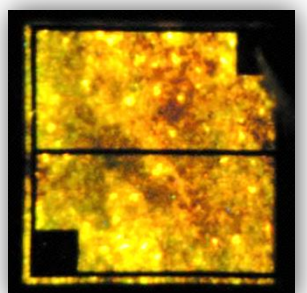
Q. Li et al., *Optics Express* **20** 17874 (2012)

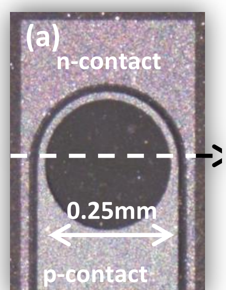
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

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

Vertically integrated radial nanowire LEDs and solar cells

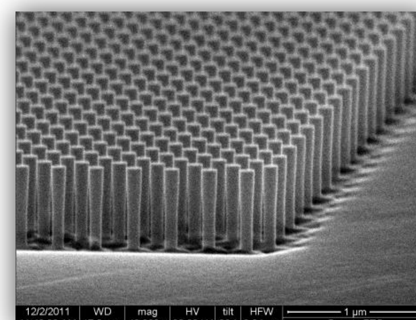


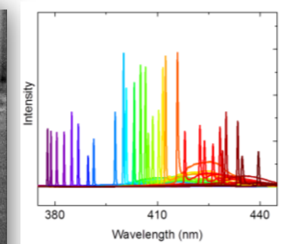




J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

Tunable nanowire photonic crystal lasers





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

Acknowledgments

Qiming Li - nanowire growth, nano-CL, TEM/EDXS, nanofabrication, strain-modeling

Jeffrey Figiel, Randy Creighton, Karen Cross –MOCVD growth, device processing & support

Jianyu Huang – In-situ SPM-TEM for correlated structure-property studies

Jonathan Wierer – LED/solar cell device fabrication/characterization

Karl Westlake, Mary Crawford – PL, IQE measurements

Daniel Koleske – LED growth

Igal Brener, Willie Luk, Weng Chow, Jeremy Wright, (Ph.D student), Huiwen Xu (Ph. D student), Ganesh Subramania – NW [PC] lasers

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

Funding Acknowledgment: DOE Basic Energy Sciences (BES) DMSE, Sandia's Solid-State-Lighting Science Energy Frontier Research Center (DOE BES), and Sandia's LDRD program

Contact: e-mail: gtwang@sandia.gov http://www.sandia.gov/~gtwang

SSLS EFRC

Backup/Extra Slides

Worldwide GaN-based nanowire SSL-related research

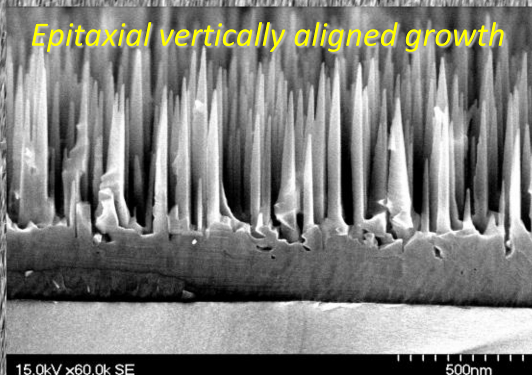
North America

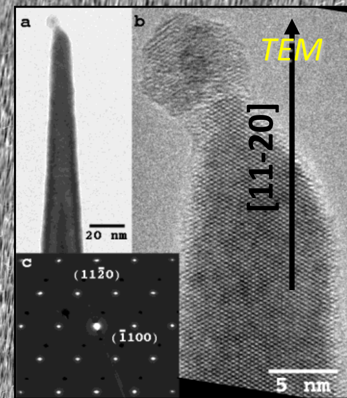
Europe

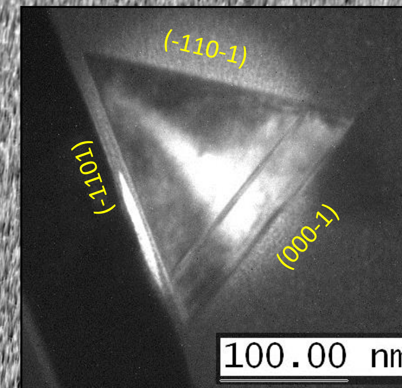
Asia

Sandia National Laboratories

"Bottom Up" aligned GaN nanowire growth



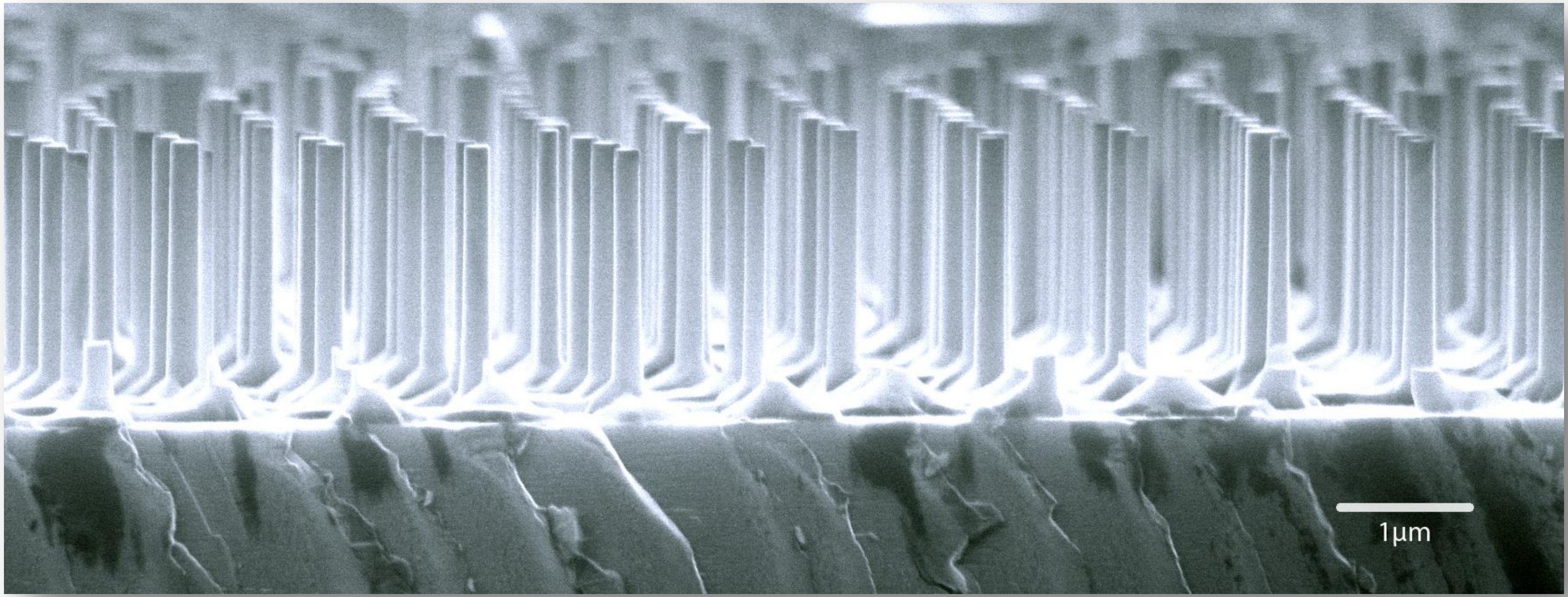




- Nanowires grown by Ni-catalyzed MOVPE/MOCVD (VLS)
- Highly-aligned vertical growth over large areas (2" r-sapphire wafer)
- Controllable densities as high as ~150 nanowires μm^{-2}
  Q. Li, G. T. Wang, *Appl. Phys. Lett. 93, 043119* (2008)
  Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth 310 3706-3709* (2008)
- Primary [11-20] growth orientation (⊥ to (11-20) *a*-plane)
- Triangular faceted -- (000-1) and equiv. (-1101) and (-110-1)
- TEM: Single crystal, dislocation free; *c*-plane stacking faults
  G. T. Wang et al., *Nanotechnology 17 5773-5780* (2006)

100 µm

Advantages of new top-down nanowire fabrication method



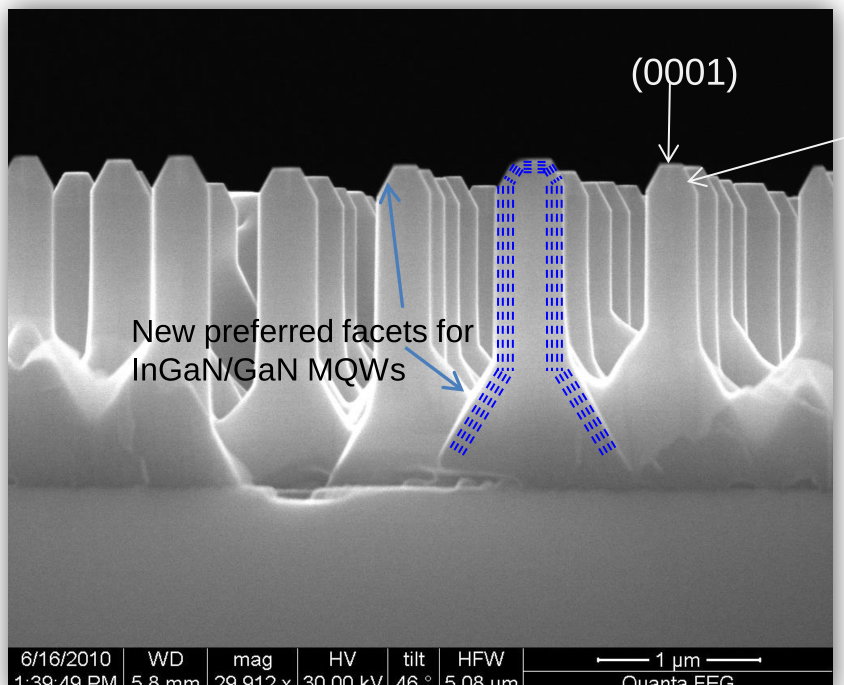
- Wider range of growth conditions, material tunability (1D growth cndns not needed)
- Lower point defect densities (higher growth temperature)
- Ordered/periodic arrays (difficult with catalyst/VLS-based methods)
- Axial III-nitride nanowire heterostructures possible by MOCVD
- Better control of geometry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

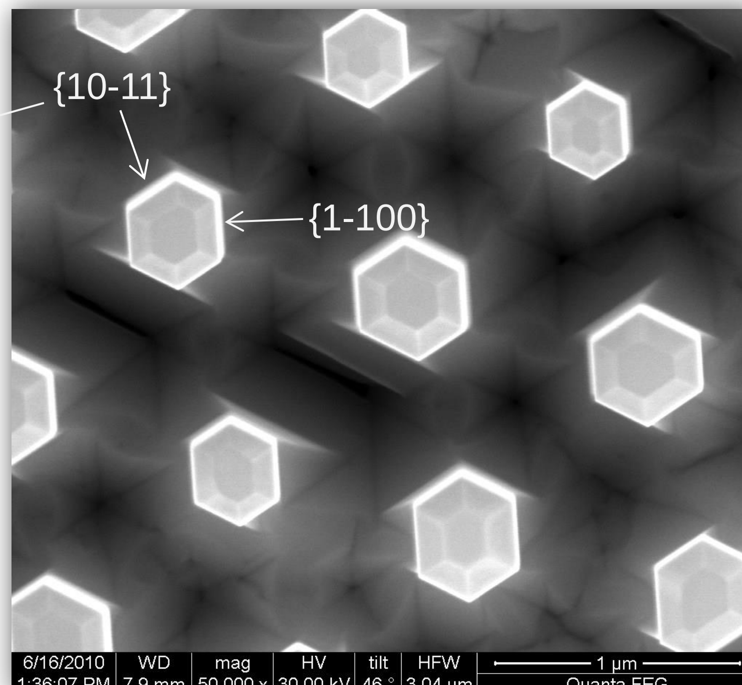
Radial core-shell InGaN/GaN MQWs on top-down NWs

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

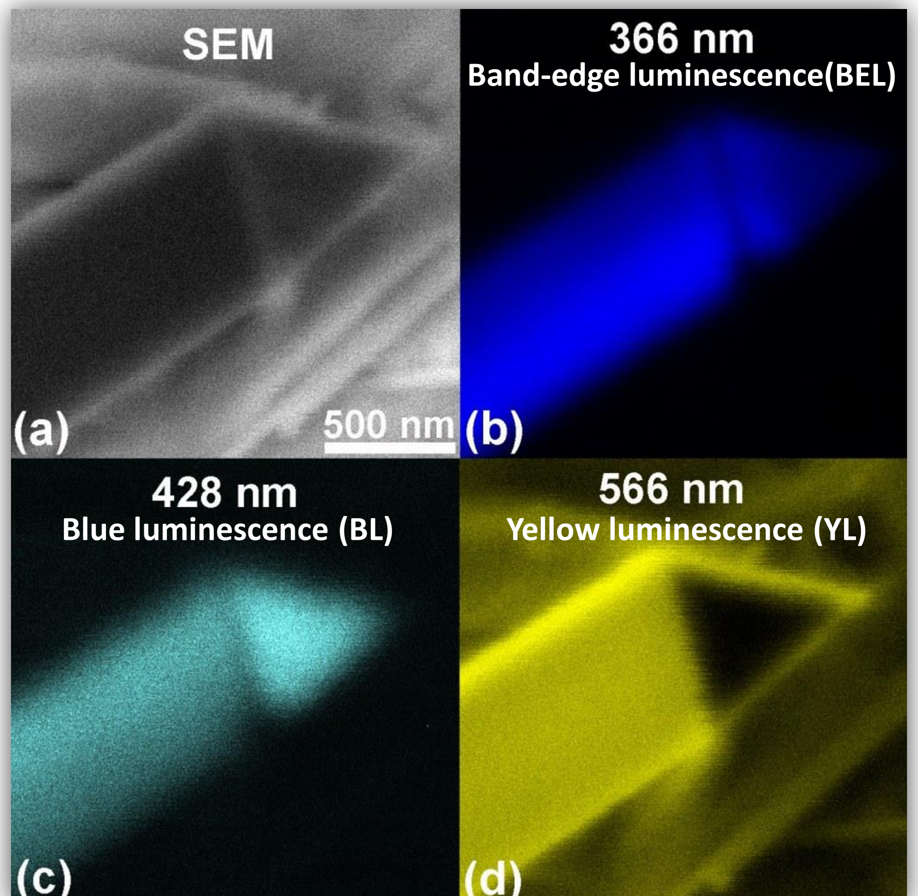
Sandia National Laboratories

Summary

- III-nitride nanowire based architectures have several potential advantages over planar-based devices for solid-state lighting, but numerous scientific & technical challenges in fabrication, performance, device contacts
- New top-down NW fabrication + regrowth: controlled geometries, high material quality, high uniformity, greater design flexibility
- Axial NW LEDs: won't replace commerical blue LEDs, but promising as high efficiency single nanowire light emitters for nanophotonics; in novel arrangements (e.g. photonic crystal), tunable wavelength devices possible
- Radial NW LEDs: most potential due to high surface area, but complicated by device growth on competing facets; advances needed if green-yellow-red wavelengths desired
- NW Lasers

SSLS EFRC

Spatial distribution of luminescence in GaN NWs



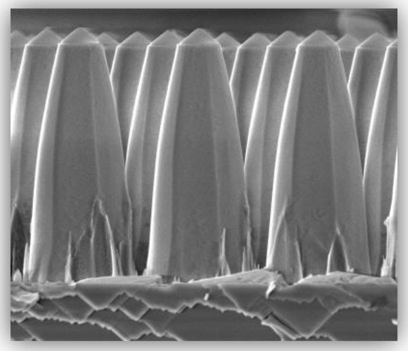
***Nanoscale Cathodoluminescence (CL) imaging:* Cross-section GaN NW**

- Band-edge luminescence (BEL) at ~366 nm and defect-related blue luminescence (BL) at ~428 nm observed in NW core/bulk
- **Defect-related yellow luminescence (YL) exhibits strong surface component** -- associated with surface states or concentrated near surface region
- YL in GaN attributed to many possible sources (C, O impurities, Ga vacancies, etc.)
- Isolated Ga vacancies have low diffusion barrier (~1.5 eV) & may migrate toward surface during growth
- BL linked to V_{Ga}-O_N (D ~2.2 eV), less mobile

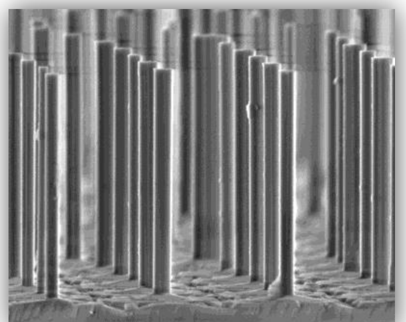
Q. Li, G. T. Wang, *Nano Lett.*, 2010, 10 (5), 1554

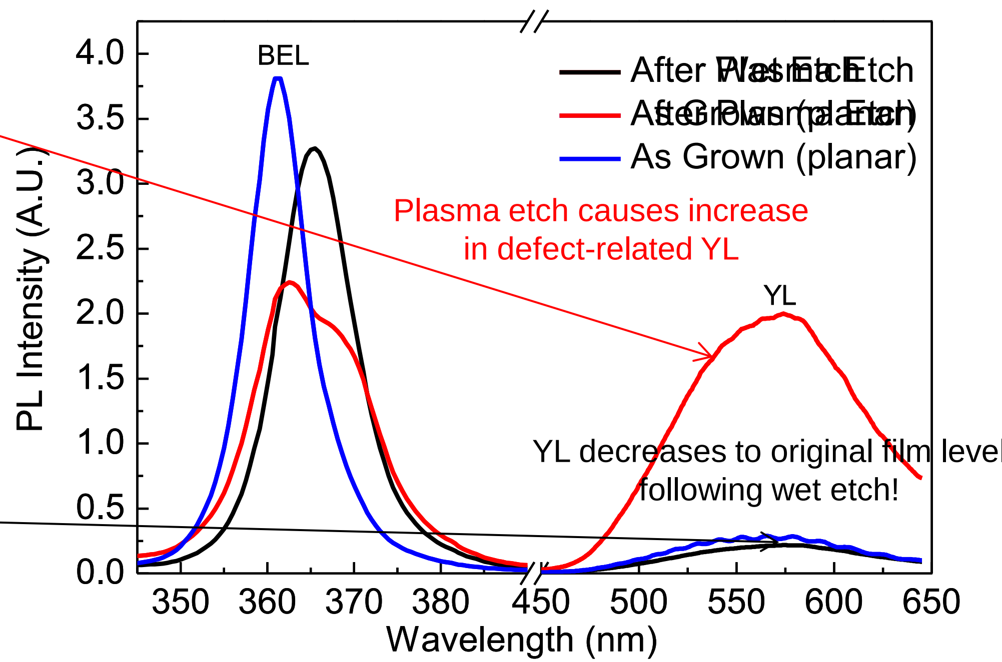
Wet etch step removes plasma etch damage

Plasma etch only

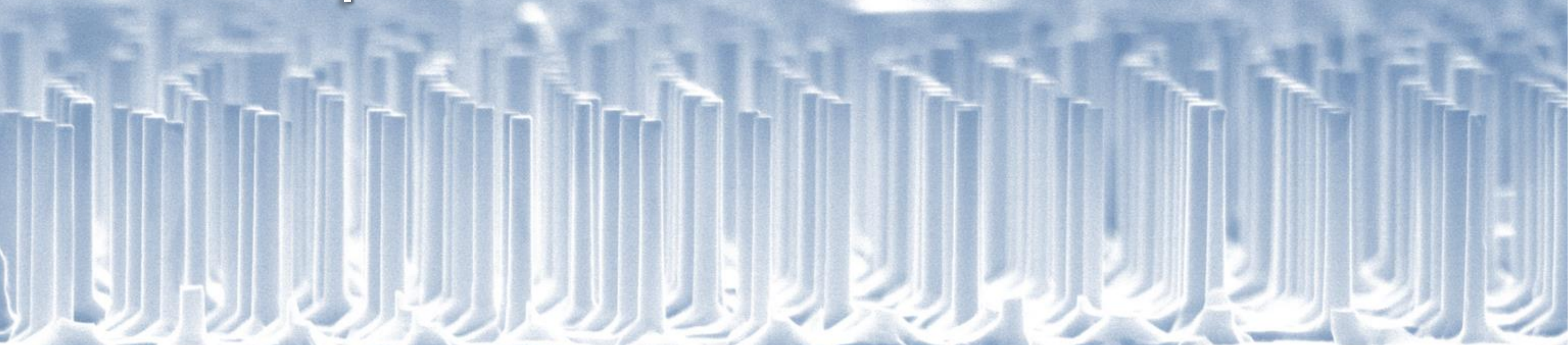


After wet etch





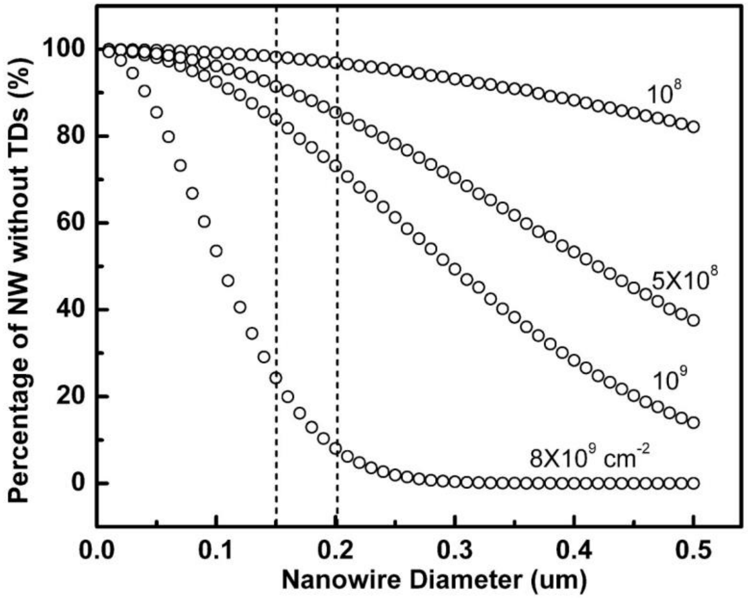
Top-down III-Nitride Nanowires



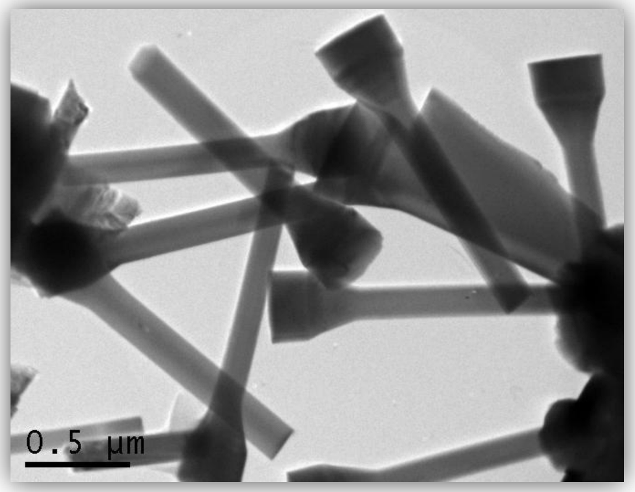
- Although dominant, bottom-up nanowire approaches suffer from some limitations
- Specific growth conditions needed for anisotropic growth which may not result in optimal material quality or desired material property
- Architectures may be limited depending on growth method (MBE vs. MOCVD)
- In response,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

Top-down nanowire threading dislocations

Monte Carlo simulation



Bright-field TEM



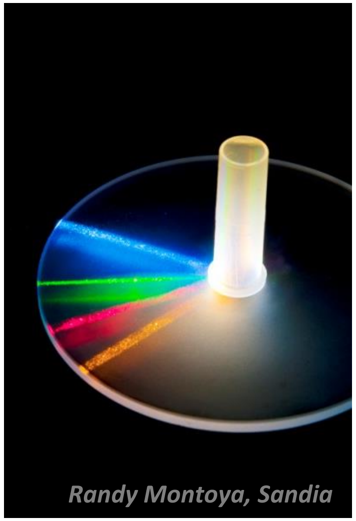
Nanowires etched from ~5e8 cm^{-2} planar LED

- 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

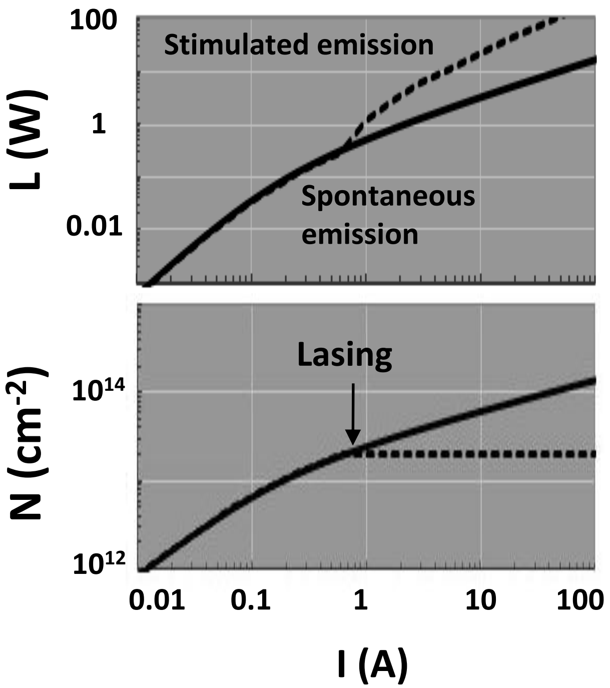
Advantages of lasers for lighting:

- 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

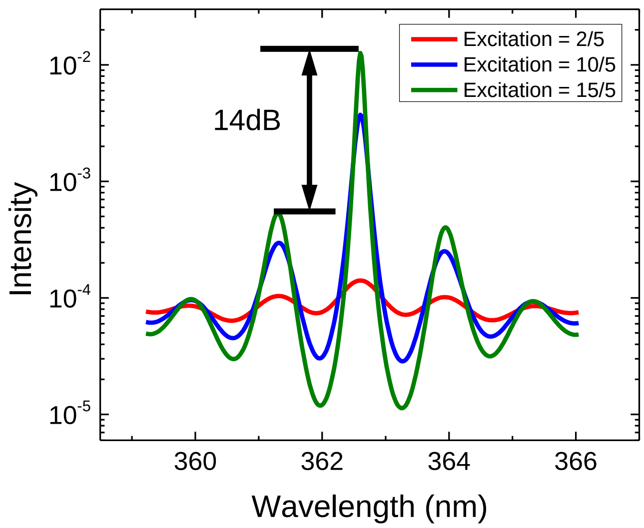


Are narrow linewidth sources acceptable?

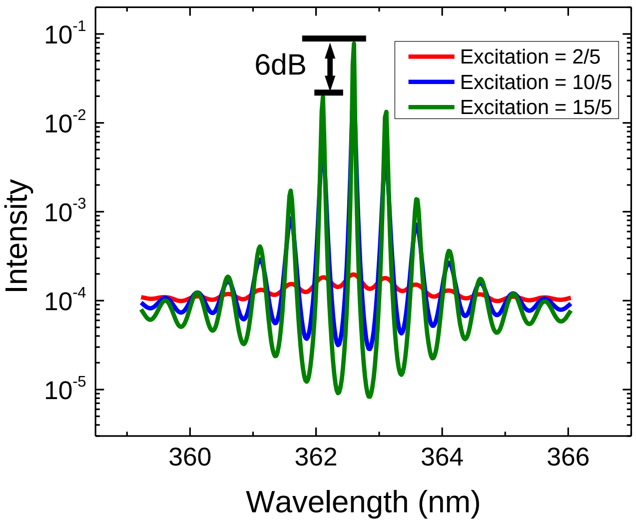
A.J. Fischer, Sandia

Single mode GaN nanowire laser

4 µm long, 140 nm dia. nanowire



12 µm long, 140 nm dia. wire



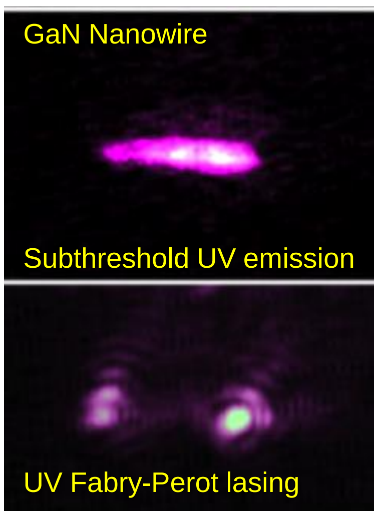
- Multimode laser theory calculations to determine which of the passive-cavity eigenmodes will be above lasing threshold for given experimental conditions.

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

Single-mode GaN Nanowire Lasers

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

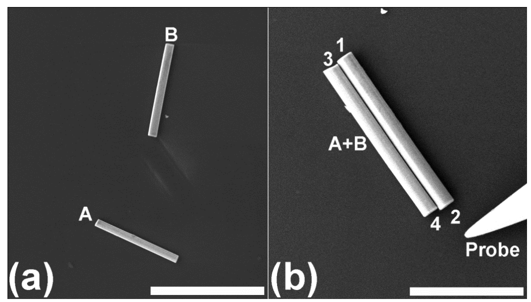
Mode control through geometry control

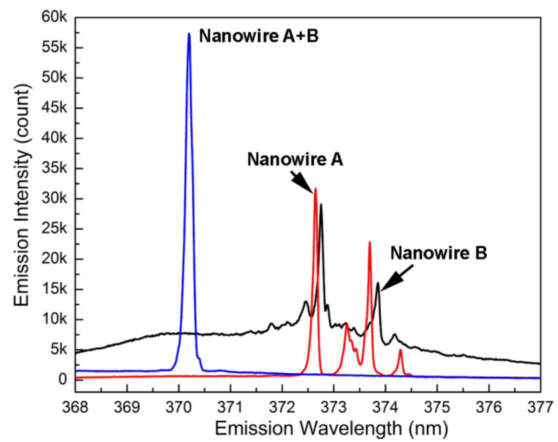


Reduction of diameter and length reduces # of competing modes

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

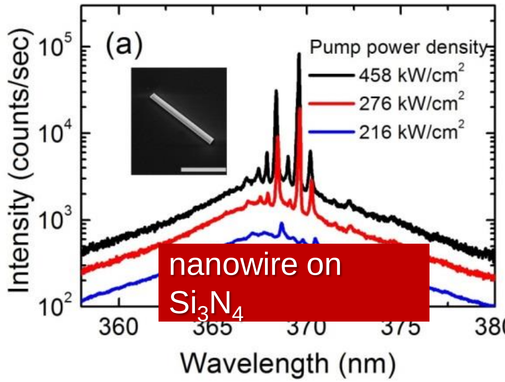
Mode control through coupled cavity

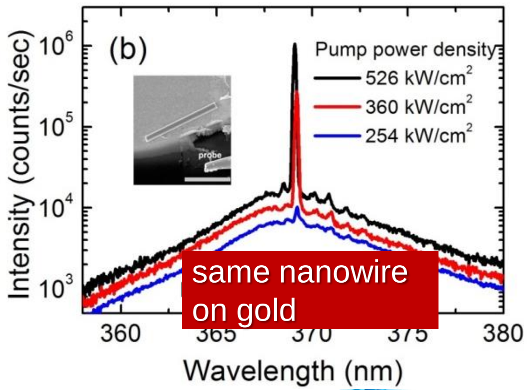




H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

Mode control through metal substrate coupling



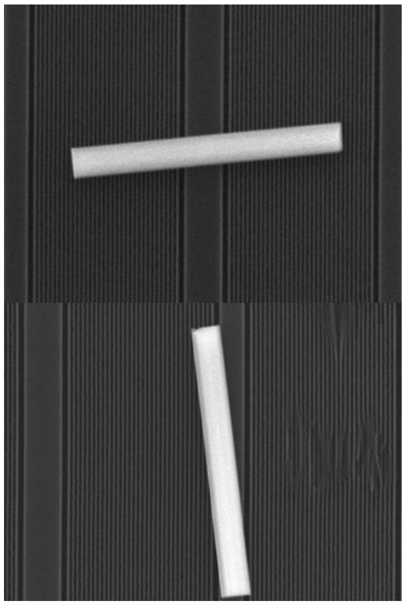


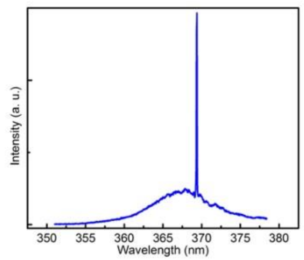
H. Xu et al., *Appl. Phys. Lett.* **101** 221114 (2012)

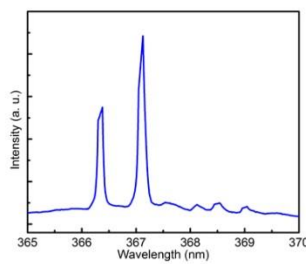
Sandia National Laboratories

Mode control in GaN nanowire lasers

Distributed feedback grating coupling



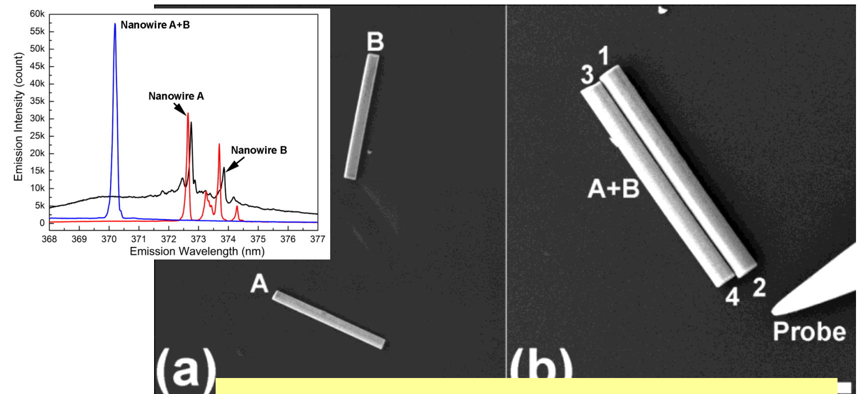




J. B. Wright et al., in preparation

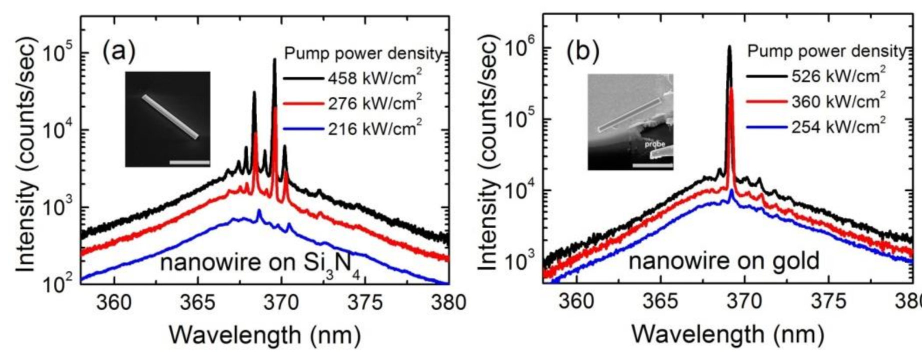
[8625-84] J. Wright et al., Wed. 6 Feb., poster

Coupled pair cavity



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

Metal substrate coupled



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

[8625-27] H. Xu et al., Tues. 5 Feb., 3:15p

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