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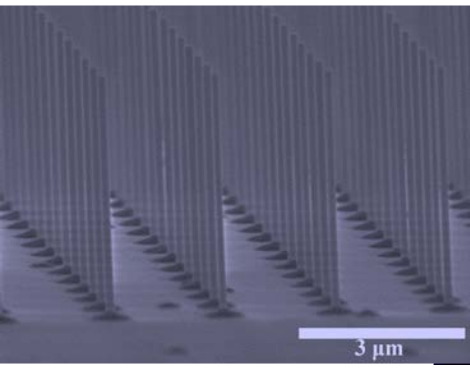

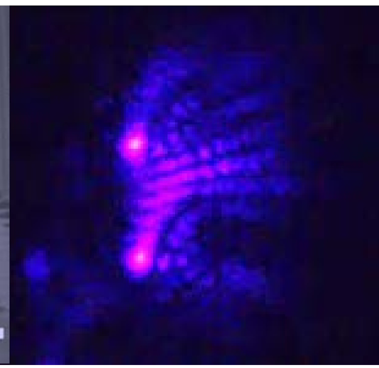
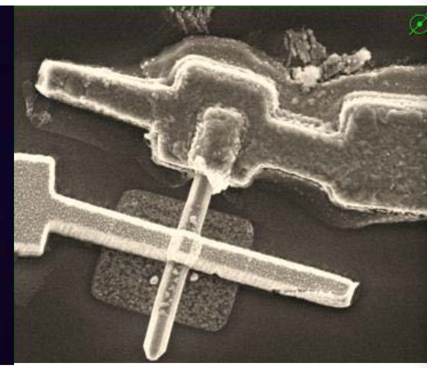
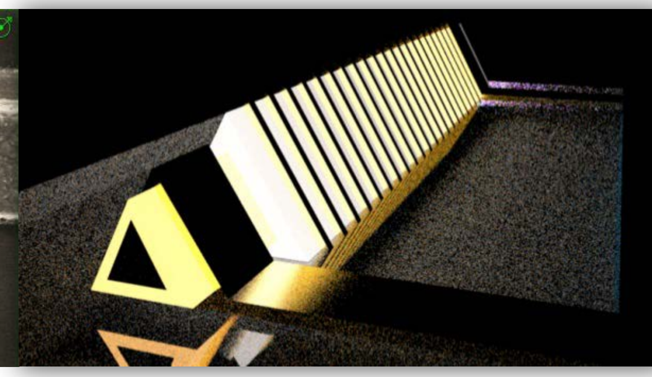

Electrically Injected UV-Visible Nanowire Lasers

Sandia Team: George T. Wang (PI), Jeremy B. Wright, Sheng Liu,, Qiming Li, Igal Brener, Benjamin Leung, Ting-Shan Luk, Weng Chow, Jeffrey. J. Figiel, Mary H. Crawford (PM)

University of New Mexico, Center for High Technology Materials (External Partner): Changyi Li (Ph.D student), Huiwen Xu (Ph.D student), Antonio Hurtado (visiting scholar), Luke F. Lester, Steven R. J. Brueck

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD Laboratory Directed Research & Development

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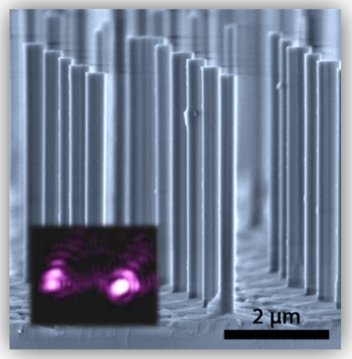
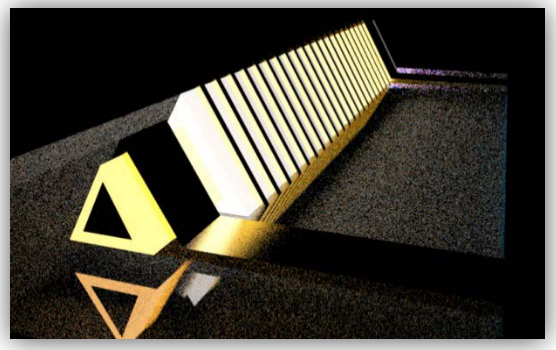
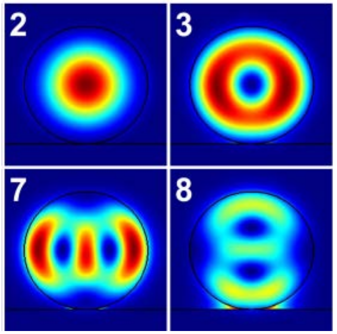
Electrically Injected UV-Visible Nanowire Lasers

Project Purpose







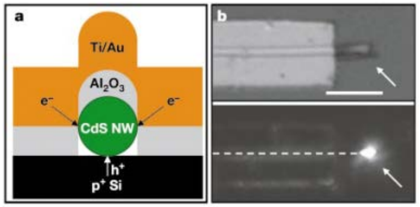
What? **Demonstrate electrically-injected UV-visible single nanowire (NW) lasers**

Why?

- *New ultracompact, low-threshold, low-power coherent light source due to tiny mode volume and high confinement*
- Nanowire forms a freestanding, low loss optical cavity
- Monolithic and integrable: platform for nanophotonic and electronic integration.
- Potential applications: nanoscale optical probes, nanolithography, optical MEMS/NEMS, lighting, displays, etc.
- New scientific understandings – generation, behavior, and manipulation of light and carriers at the nanoscale
- Allow SNL to build on a technical foundation in nano-optoelectronics

State-of-the art: Multiple challenges to creating electrically injected single nanowire lasers

- *<u>Background:</u> First reported electrically injected nanowire laser n-CdS on p-Si substrate[1] (2003)—1190 citations; not monolithic (requires p-Si substrate,) no follow-on electrically injected single nanowire lasers, none in technologically important III-nitride system*



1. Duan et al., *Nature* **421,** 241 (2003)

- In contrast to optical pumping, carriers are injected separately and need to efficiently transport and recombine radiatively in the active region
- Fabrication of complex p-n heterostructure nanowires. Current state-of-the-art nanowire synthesis techniques have critical limitations in these areas.
- Optical losses, including relatively low end facet reflectivities, increase thresholds
- Need good ohmic nanoscale contacts without creating losses
- Need predictive understanding of how nanowire design (geometry, architecture) impacts optical and lasing properties

Project R&D Approach

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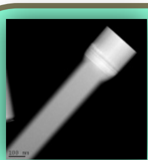
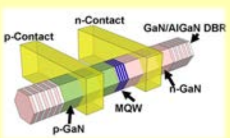


1. III-Nitride nanowire laser structure fabrication

Enabling capability: Recent Sandia-developed top-down fabrication

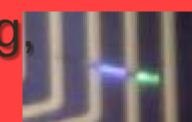
- **GaN/InGaN MQW p-n junction** nanowires with controlled geometries, doping
- **Explore axial** and **radial** heterostructure designs for maximum design flexibility



2. Threshold reduction & optical characterization

- **Built-in and coupled DBR** schemes to minimize facet losses
- **Modeling** nanowire designs to determine optimal placement of active region to maximize mode overlap
- **Characterization** via optical pumping for various nanowire laser designs

3. Device fabrication, modeling, and electrical injection



- **Develop ohmic nanowire contact metallization/schemes**
- **Study impact** of size and placement of metal contacts on optical properties
- **Demonstrate electroluminescence and electrically injected lasing** in optimized nanowire laser design

Team & Facilities

Modeling and theory

Optical characterization

Device fabrication & electrical injection

Management

Growth and nanowire fabrication


Mary Crawford
(Project Manager)


Jeffrey Figiel
Also: Daniel Koleske


Qiming Li


George T. Wang
(PI)

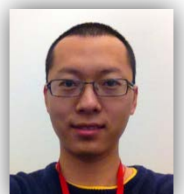

Jeremy Wright
(Ph.D Student)


Igal Brener

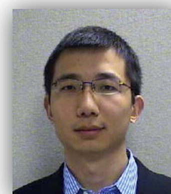

Willie Luk


Weng Chow


Benjamin Leung
(Post-doc)


Changyi Li
(Ph.D Student)


Huiwen Xu
(Ex-Ph.D Student)

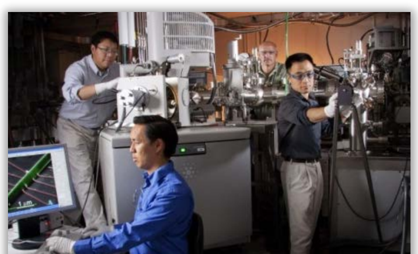

Sheng Liu
(Post-doc)


Antonio Hurtado
(Ex-visiting Scholar,
UNM/CHTM)

STEM: Ping Lu

Help with Electrical Contacts: Tzu-Ming Lu

Help with Nanostripe lasers: Miao-Chan Tsai

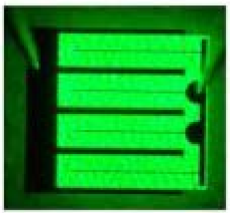


MESA Advanced Nanotechnology Tool (ANT)

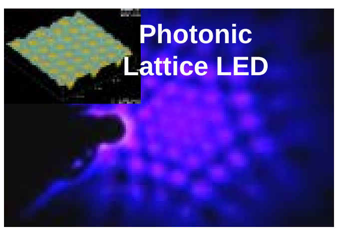
Sandia III-Nitride (AlGaInN) Materials and Device Research (1996-2014)

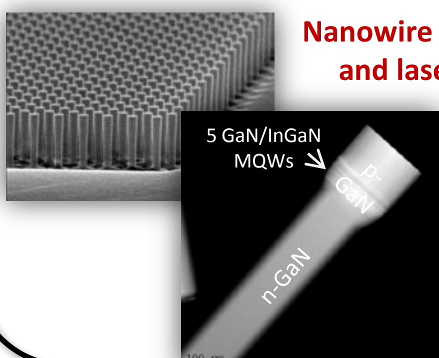
Visible Optoelectronics (Solid-State Lighting)

-GC LDRD 2000-2004; DOE EERE 2005-2013, EFRC 2010-2014



Filling the LED "green gap" in LED efficiency

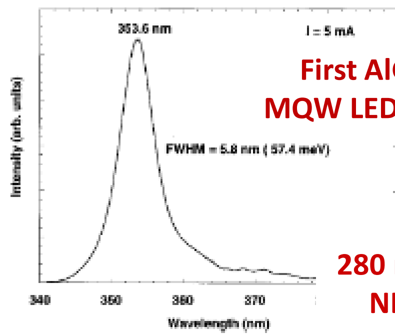




Nanowire LEDs and lasers

Ultraviolet Optoelectronics

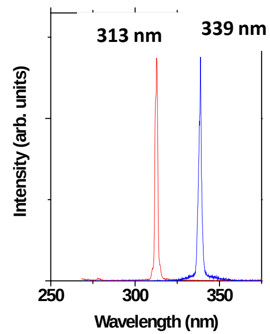
LDRD, DARPA, RTBF



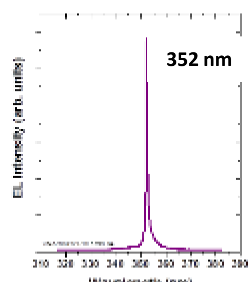
First AlGaN MQW LED (1998)

280 nm LED arrays for NLOS comm. link

Optically pumped Lasing

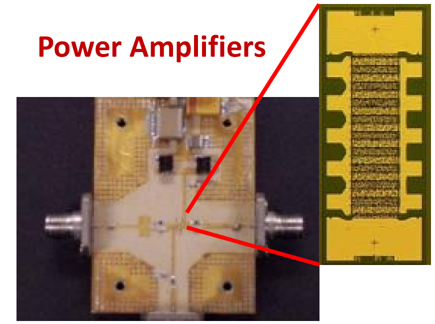


Electrically-injected AlGaN Laser Diode

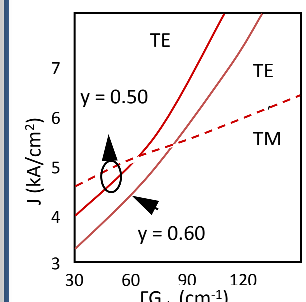


Power Electronics

Power Amplifiers

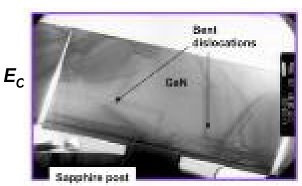


Advanced Modeling and Characterization

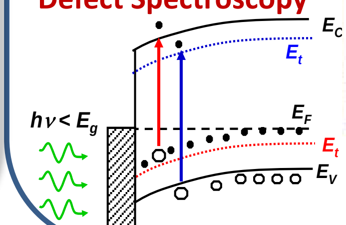


Gain modeling/many-body physics of of nitride lasers

Transmission electron microscopy



Defect Spectroscopy



Slide courtesy of Mary Crawford

Previous SNL research: bottom-up III-nitride nanowires

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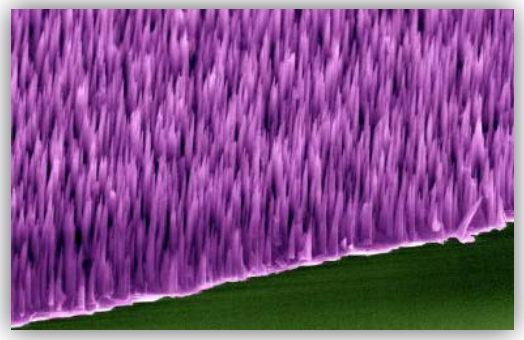
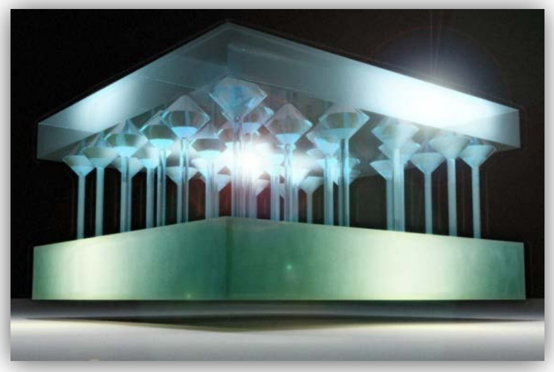
Vertically-aligned growth



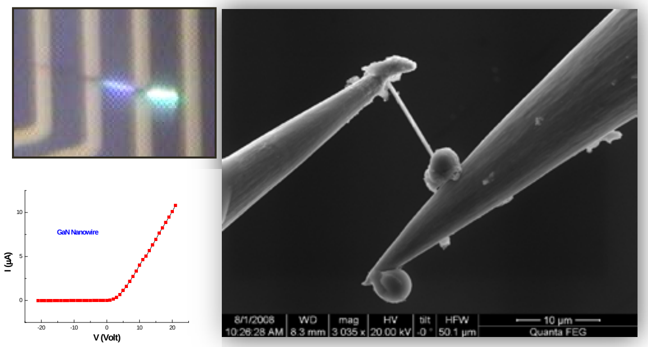
G. T. Wang et al., *Nanotechnology 17 5773-5780* (2006)
Q. Li, G. T. Wang, *Appl. Phys. Lett. 93, 043119* (2008)
Q. Li, J. R. Creighton, G.T. Wang. *J. Crys. Growth 310 3706-3709* (2008)

Nanowire-templated growth



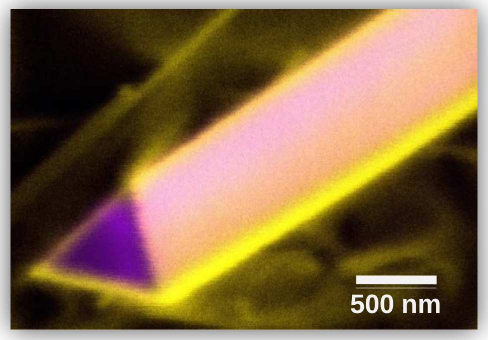
Q. Li, Y. Lin, J.R. Creighton, J. Figiel, G.T. Wang, *Adv. Mat.*, **21** 2416–2420 (2009)

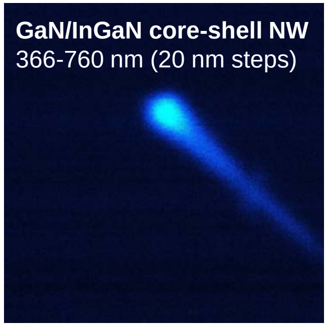
Electrical characterization



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



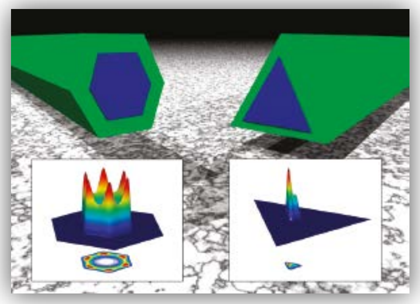


Q. Li, G. T. Wang, *Nano Lett.*, 2010, 10 (5), 1554 [GaN defect CL]
Q. M. Li, G. T. Wang, "*Appl. Phys. Lett.*, ***97***, 181107, 2010. [Gan/InGaN]
P.C. Uppadhya et al. *Semicond. Sci. Tech.* **25** 024017 (2010) [Ultrafast]
A. Armstrong, Q. Li, Y. Lin, A. A. Talin, G. T. Wang, APL **96**, 163106 (2010).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

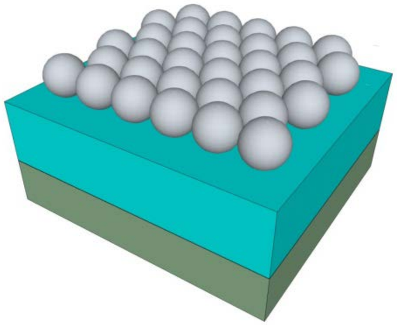
Theory



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

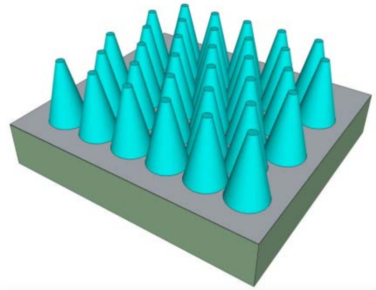
Enabling Capability:

Sandia developed dry + wet top-down ordered GaN nanowire fabrication process



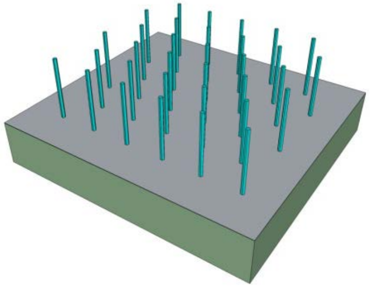
(0001) GaN on sapphire

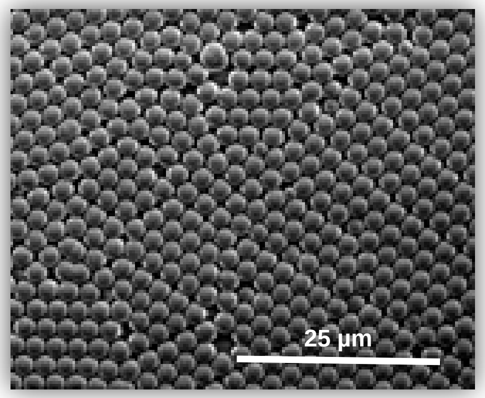
ICP etch



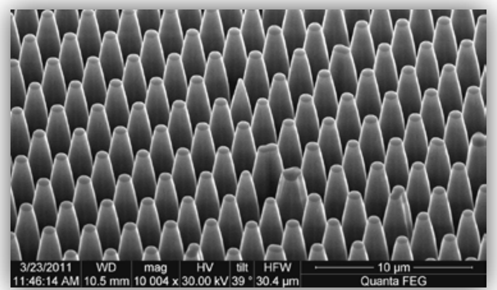
Selective KOH-based wet etch

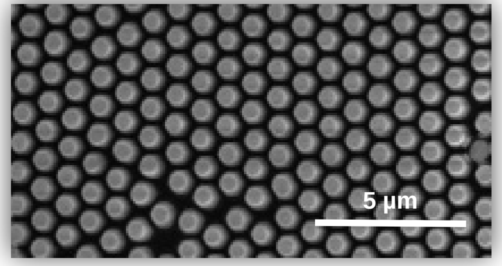
(AZ-400K developer)





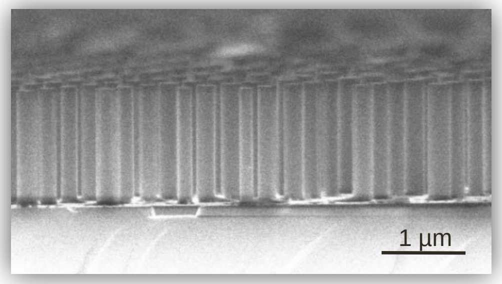
Q. Li, J. J. Figiel, G. T. Wang, Appl. Phys. Lett., **94**, 231105 (2009).

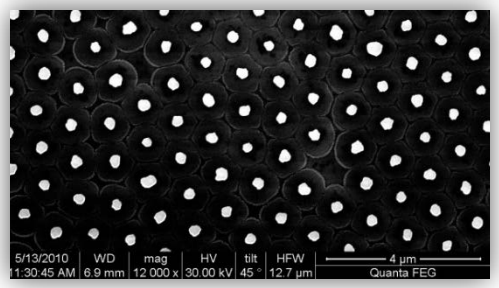




Plasma etch causes sidewall damage

Tapered; no well-defined facets





Wet etch: straight sidewalls, removes sidewall damage

Method enables straight and smooth GaN nanowires with controllable geometries

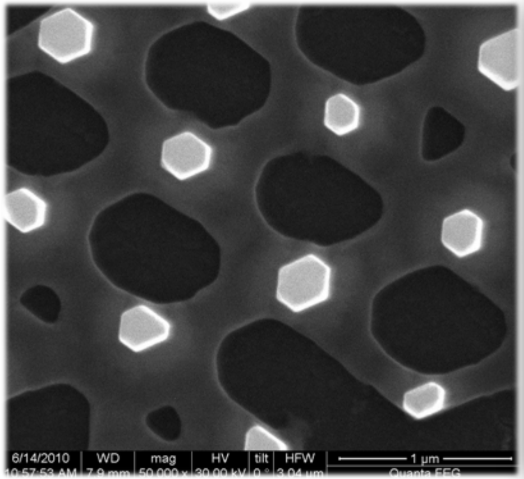
Wet etch rate negligible for top (Ga-polar) *c*-face & fast for semipolar planes, leads to nominally hexagonal NWs with **straight & smooth** *m*-facets

Superior and independent control of:

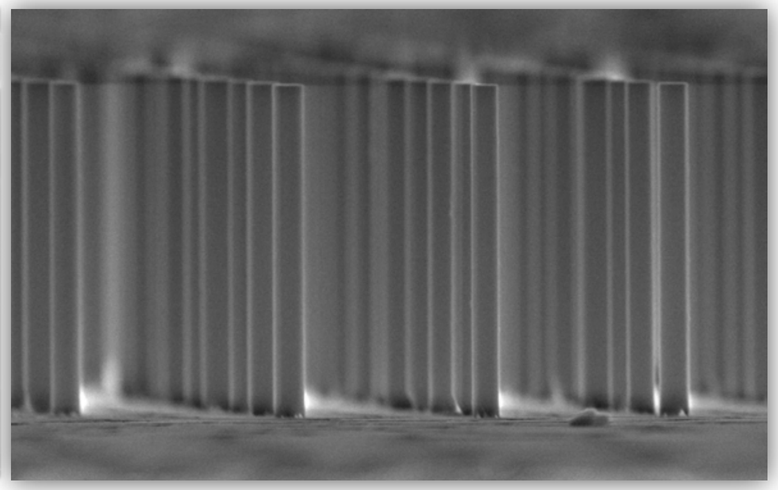
Height (dry etch depth)

Diameter (wet etch time)

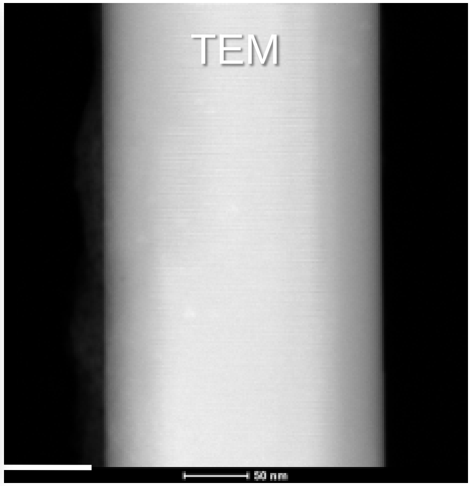
Pitch/arrangement (defined by masking template)



Following GaN regrowth



[0001] Oriented GaN nanowires via sphere lithography



Smooth sidewall created by wet etch

TEM: Ping Lu, SNL

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

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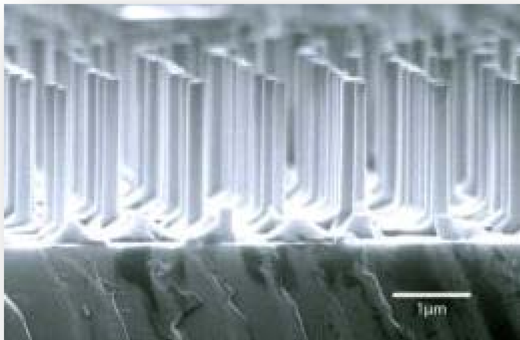
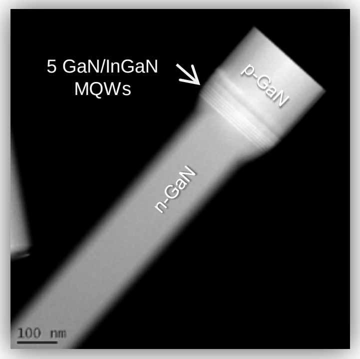
Top-down III-nitride nanowires: a platform for nanophotonics

Top-down fabrication

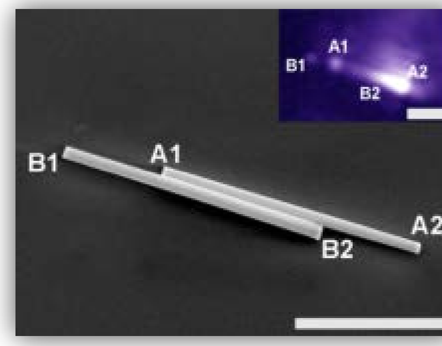


Axial nanowire LED "flashlight"



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

Single-mode GaN nanowire lasers

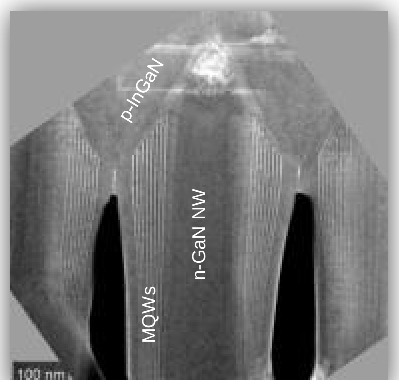


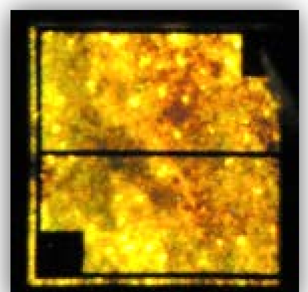
Q. Li et al., *Optics Express* **20** 17874 (2012)

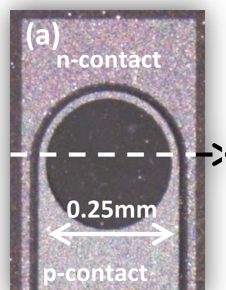
H. Xu et al., *Appl. Phys. Lett.* **101** 113106 (2012)

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

Vertically integrated radial nanowire LEDs and solar cells







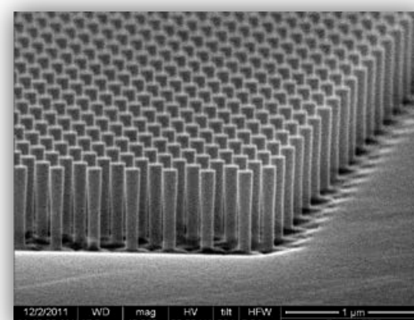
J. Wierer et al., *Nanotechnology* **23** 194007 (2012)

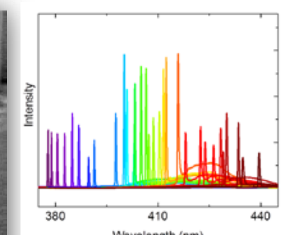
Riley, J.; *Nano Lett.* **14**, 4317 (2013)

S. L. Howell et al. "*Nano Lett.*, ***13***, 5123 (2013)

G. T. Wang et al., *Phys. Stat. Solidi A*, **211**, 748 (2014)

Tunable nanowire photonic crystal lasers





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

Technical Approach - Axial vs Radial Multiple Quantum Well (MQW) Heterostructure NW Architectures

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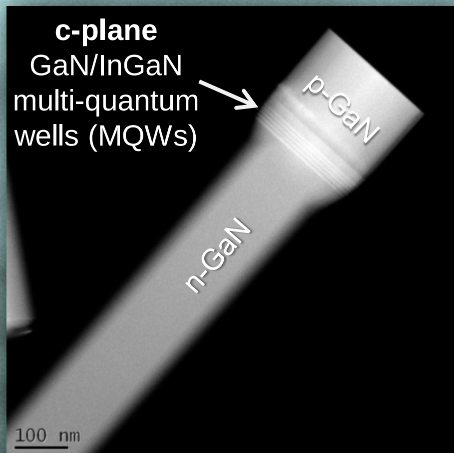


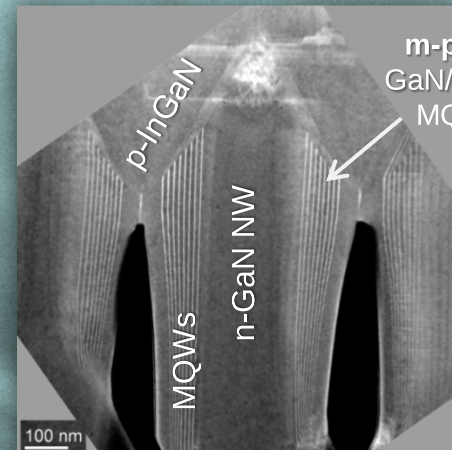
Mode overlap (maximize)

Threshold gain (minimize)

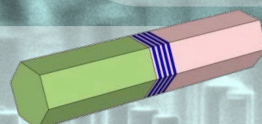
$$g_{th} = \alpha/\Gamma$$

Total optical losses (minimize)

$$\alpha_m \propto \ln(1/r_1 r_2)$$

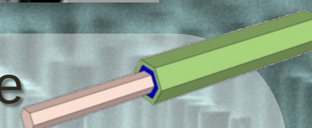


Axial NW diode



- easier to fabricate
- planar heterostructures can be optimized prior to etching
- contacts to exposed n- and p- regions easier to make
- carrier transport more straight-forward (no spreading layer)
- **small active region volume (c-plane disks)**

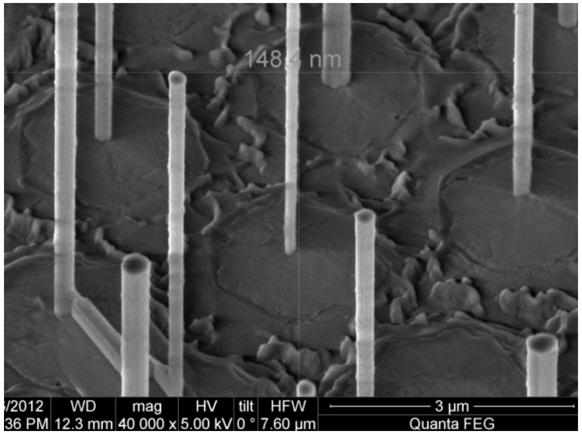
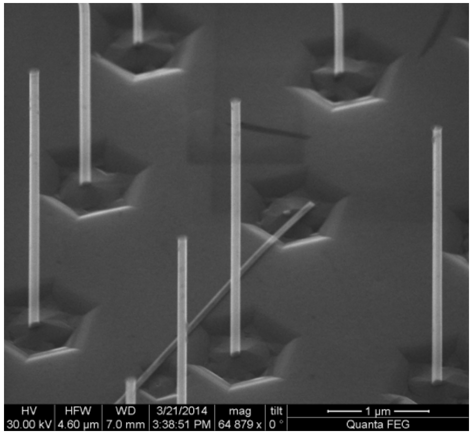
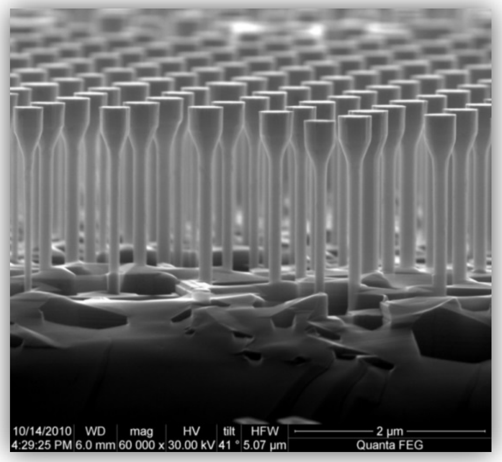
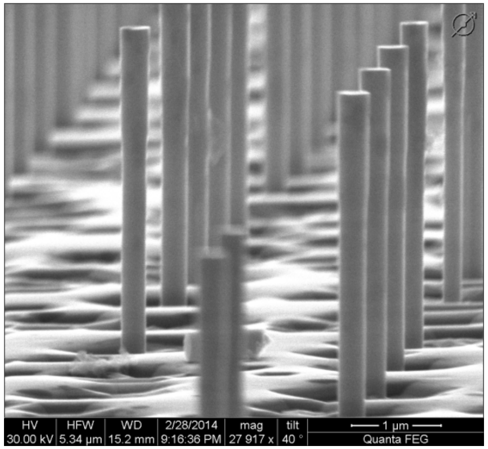
Radial NW diode



- **higher active region volume (m-plane shells)**
- active region not at surface
- **3D growth, characterization, optimization more challenging**
- **complex contacts: n-type core not exposed, spreading layer needed for p-contact**

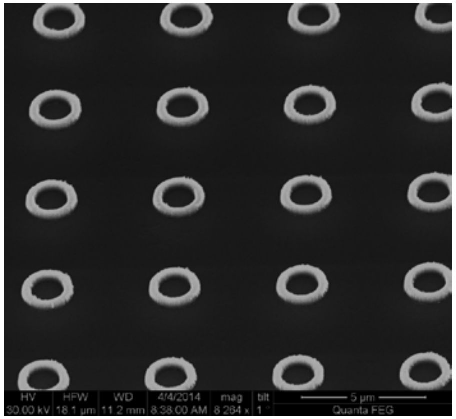
Key Accomplishments

Improved fabrication of size-controlled NWs via e-beam lithography

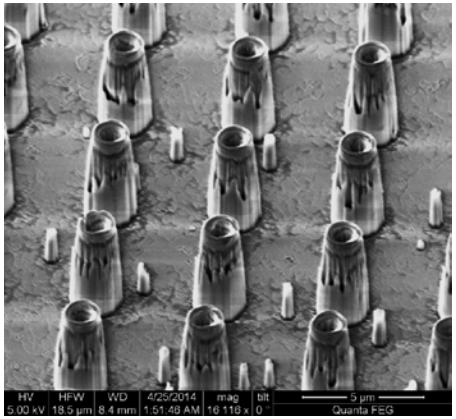
	Sphere lithography	e-beam lithography
GaN NWs	 NWs have larger diameter variation	 NWs have much smaller diameter variation
Axial InGaN/GaN MQW NW p-i-n diodes	 Tapered shape due to slower p-GaN wet etch rate **makes contact formation difficult and may increase optical losses**	 p-i-n Axial NWs have less taper since NWs dry etched close to desired diameter (short wet etch)

Key Accomplishments

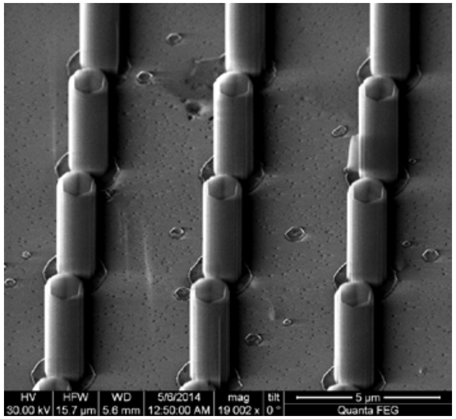
Fabrication of NWs with cross-sectional shape control, enabling control over nanolaser properties



EBL patterning

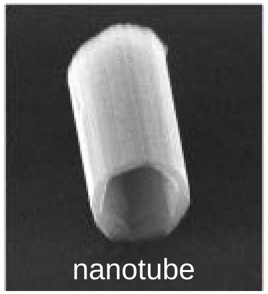


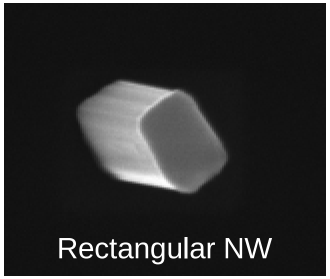
ICP Etch



AZ400K Wet Etch

- We extended our top-down nanowire fabrication method to include cross-sectional shape control
- *We showed that cross-sectional shape control allows for manipulating nanowire laser properties, including beam shaping (nanotube) and polarization control (rectangular wire)*



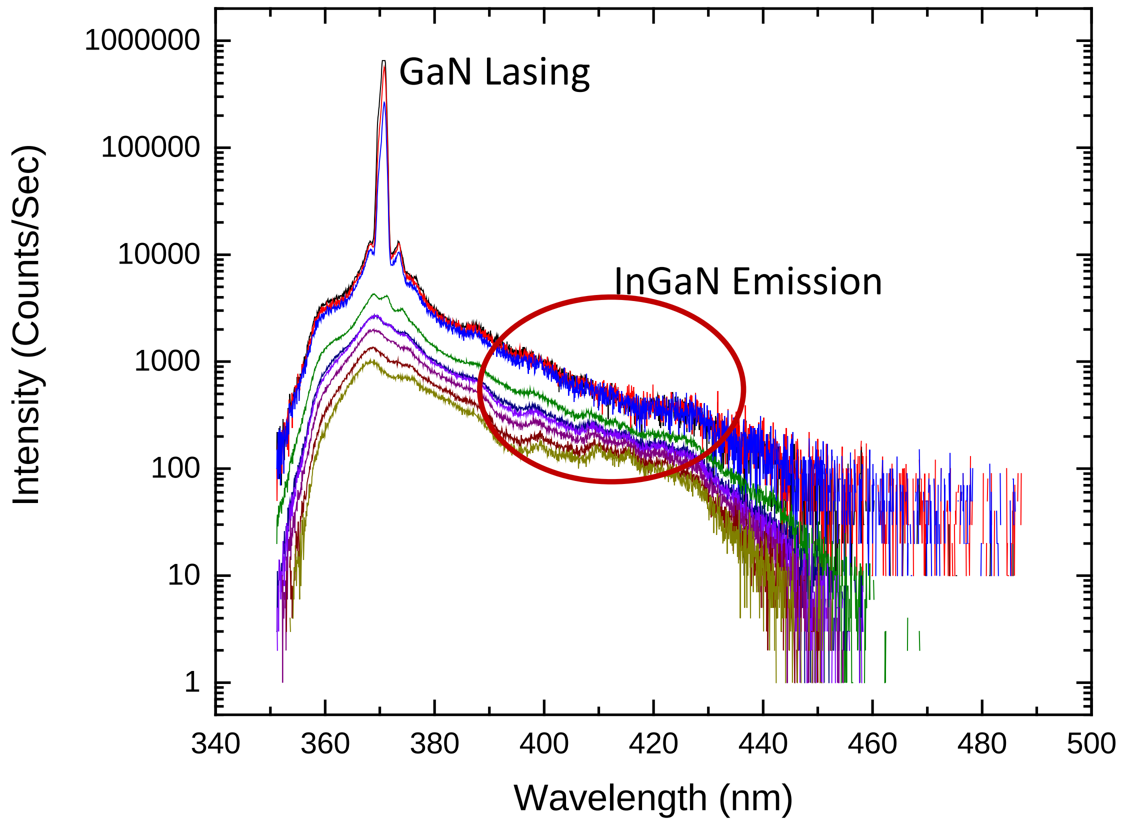


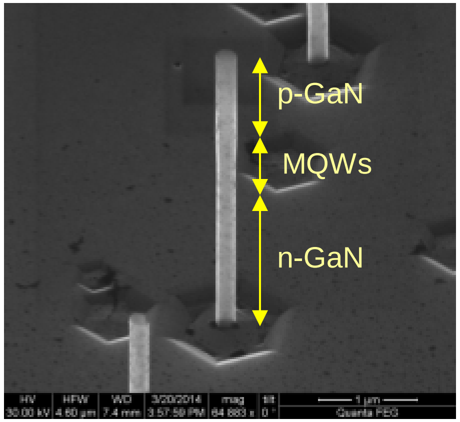
C. Li, S. Liu, A. Hurtado, J. B. Wright, H. Xu, T. S. Luk, J. J. Figiel, I. Brener, S. R. Brueck, G. T. Wang, "Annular-Shaped Emission from Gallium Nitride Nanotube Lasers", *ACS Photonics*, **2**, 1025 **(2015)**.

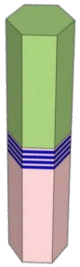
C. Li et al., "Linearly Polarized Emission from Single Rectangular Cross-sectional Gallium Nitride Nanowire Lasers," *submitted to Nanoscale*

Key Accomplishments

Fabrication and optical characterization of axial GaN/InGaN MQW NW p-i-n diode



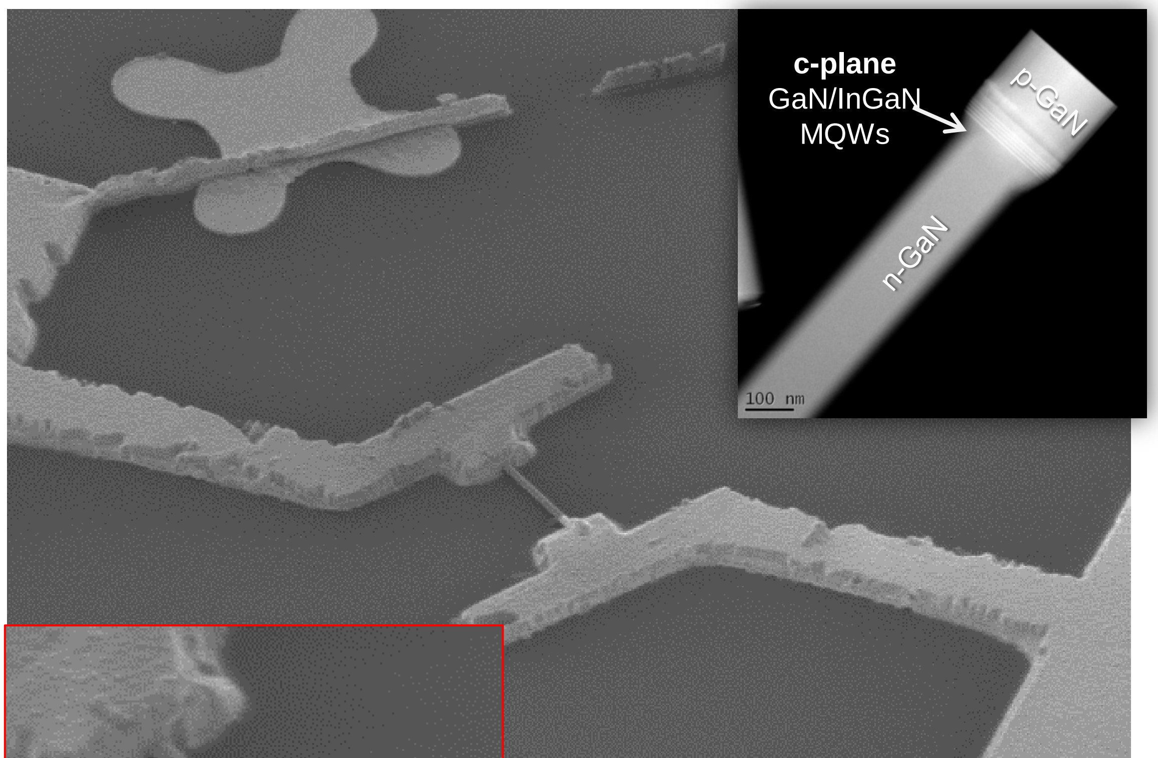


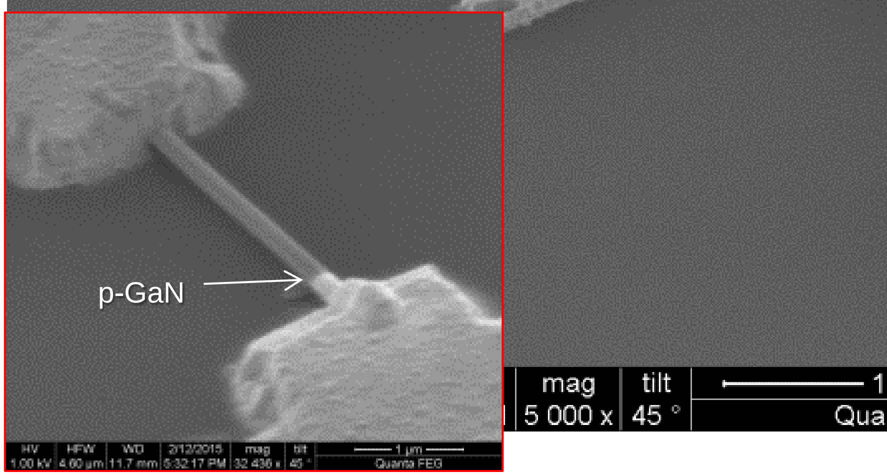


No InGaN lasing observed for axial NW laser diode structure

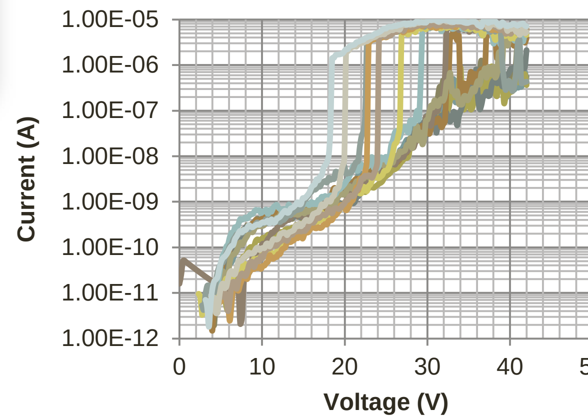
Key Accomplishments

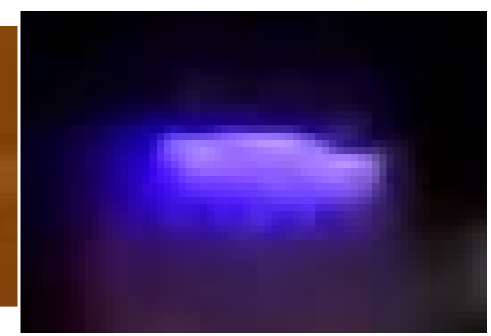
Electrically injected axial InGaN/GaN Nanowire LED





Axial nanowire LED (from LED0051, 1um p-GaN)
200 nm diameter, 3um length
Contacts: 400 nm Ni/200 nm Au, both sides
RTA: 500 C anneal, air, 2 min
After ebeam exposure, 30 kV, spot size 6.0 (~nA)
~25V, 5 μA





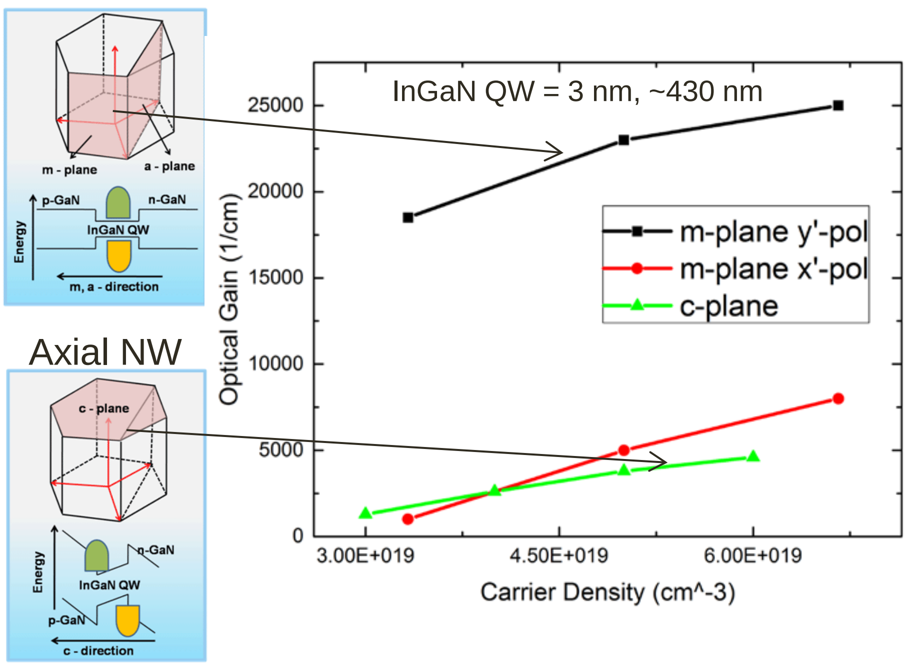
Blue electroluminescence from axial nanowire LED

Key Accomplishments

Analysis of expected optical gain for axial vs. radial NW designs

Optical Gain - Crystallographic Dependence

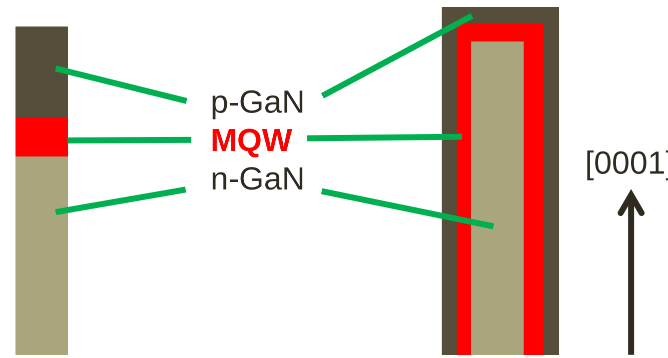
Radial NW



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

Optical Gain – Axial vs. Radial Geometry

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



Axial structure

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

Radial structure

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

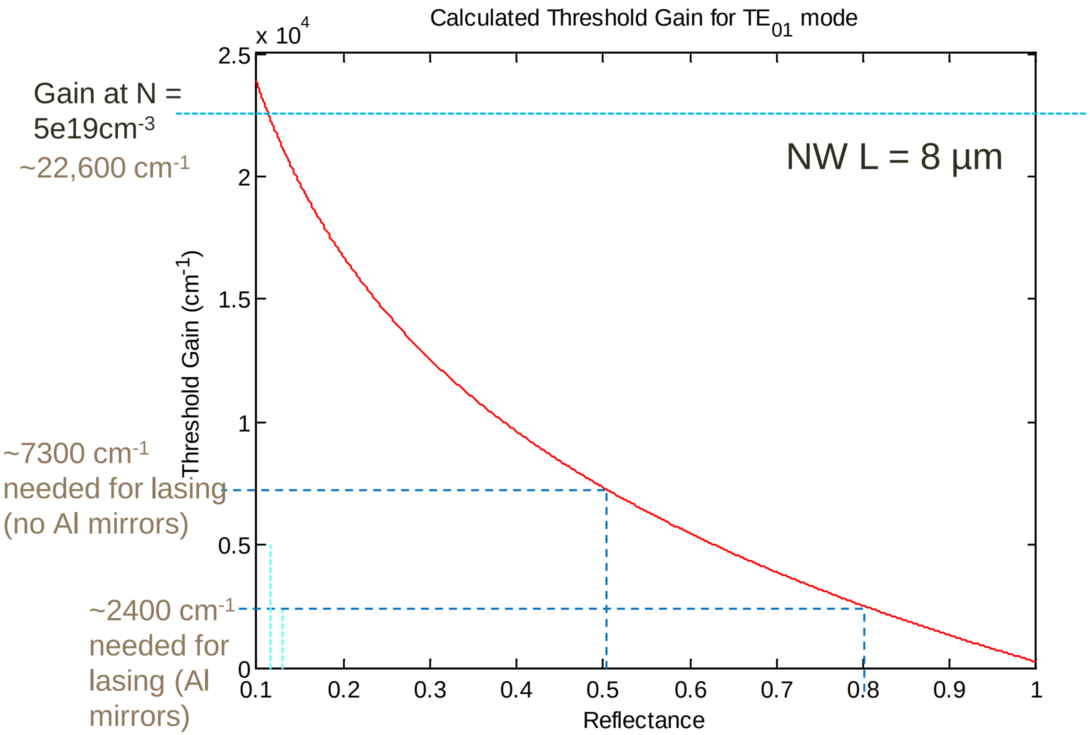
Radial: 48 times larger gain region compared to axial

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

J. Piprek, R. K. Sink, M. A. Hansen, J. E. Bowers, and S. P. DenBaars, "Simulation and optimization of 420-nm InGaN/GaN laser diodes," 2000, pp. 28-39.

Key Accomplishments

Analysis of expected optical gain for radial NW design

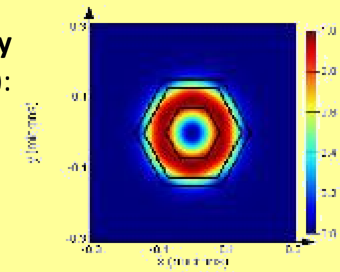


Optimal Geometry
(for T_cap >20nm):

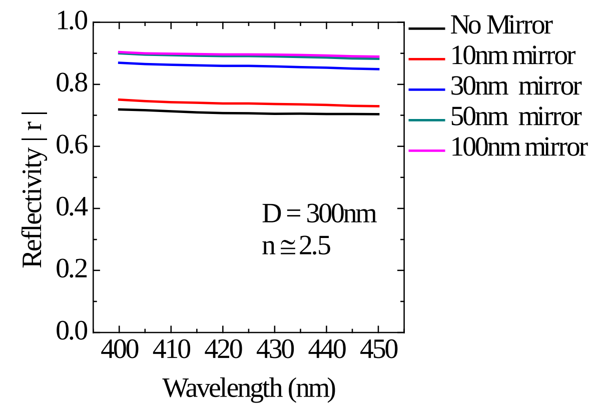
T_cap=23nm

D_core=140nm

$\Gamma_{xy} = 0.12199$



|r| of TE_{01} mode w/various Al mirror thickness

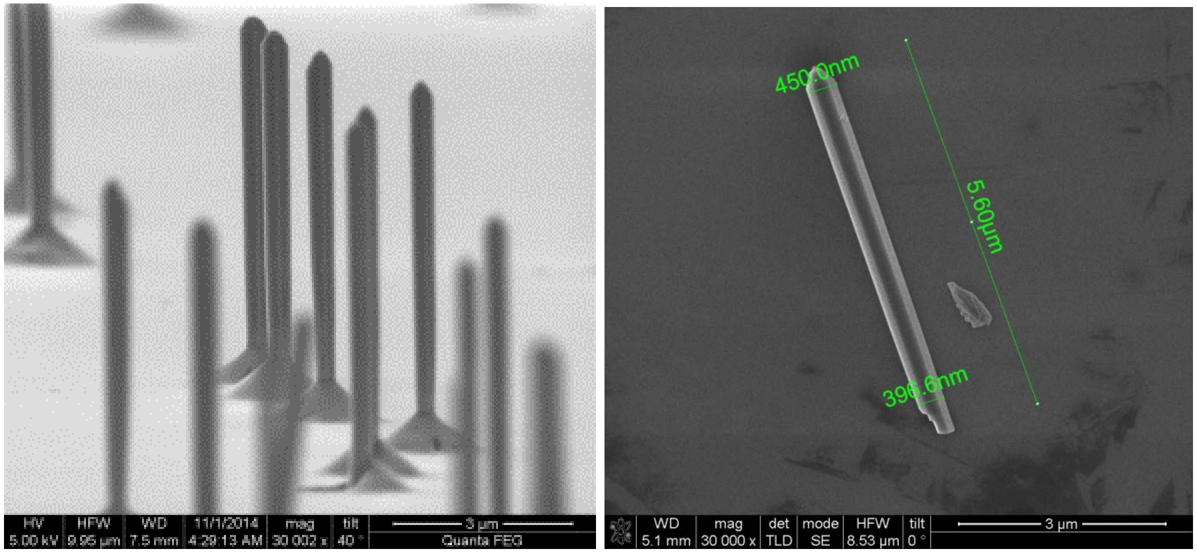


Models indicate sufficient gain available to achieve lasing in radial InGaN/GaN NWs!

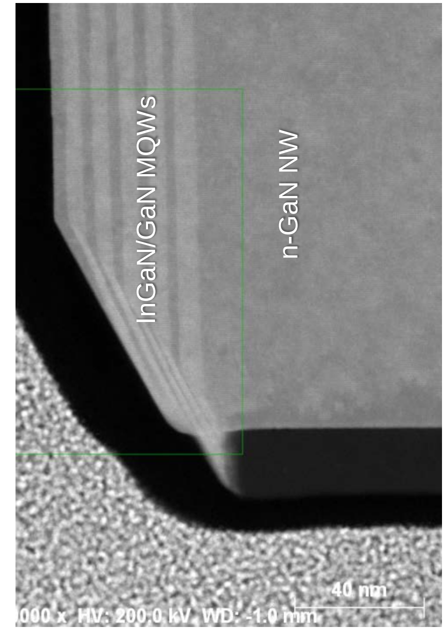
Reflectivity of up to ~90% for TE_{01} mode can be achieved in theory by adding 50nm Al mirror

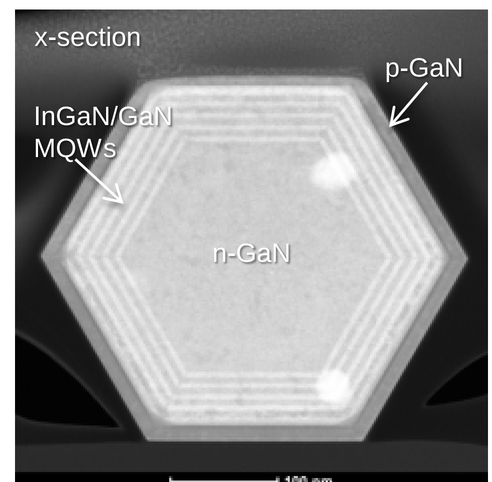
Key Accomplishments

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



Core-shell radial p-i-n InGaN/GaN MQW nanowires following MOCVD regrowth





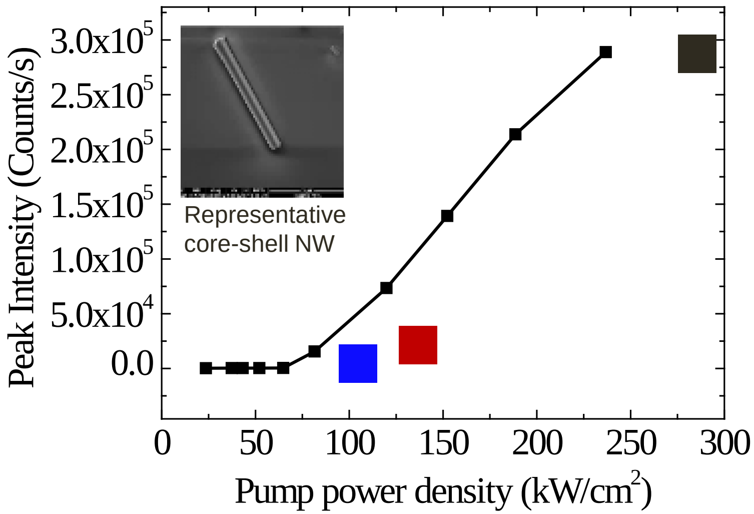
- Regrowth results in taper, with faster growth and wider QWs at tip. Growth of semipolar planes also results in non-flat tip, which may lower mirror reflectivity
- Growth conditions, layer thicknesses, varied over several runs, then nanowires tested by optical pumping for lasing

STEM by Ping Lu

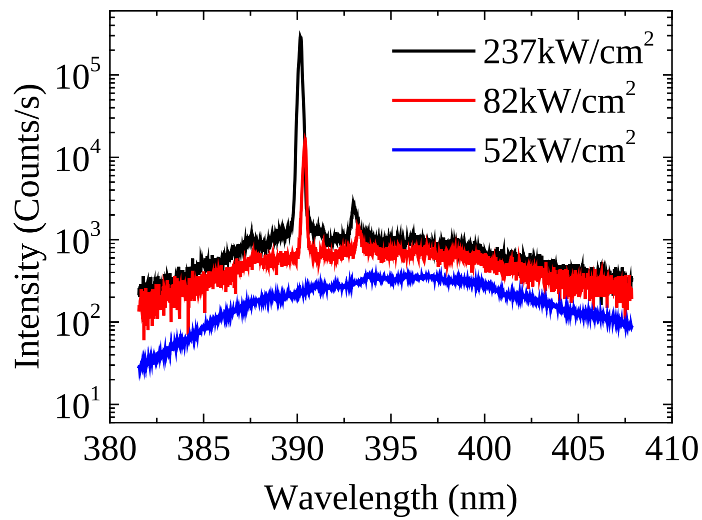
Key Accomplishments

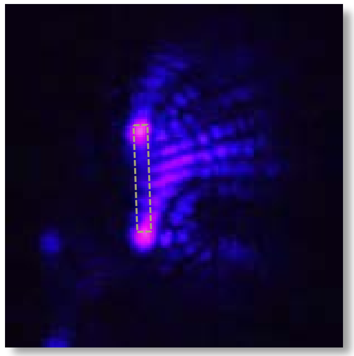
Optically pumped lasing from radial nonpolar p-i-n InGaN/GaN NW

L-L Curve



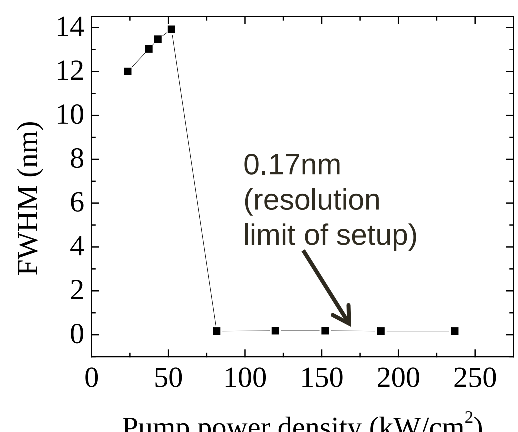
PL/Lasing spectra





CCD image of lasing NW

Threshold pump density = 75kW/cm^2
Lower than the threshold of GaN nanowire lasers in our group



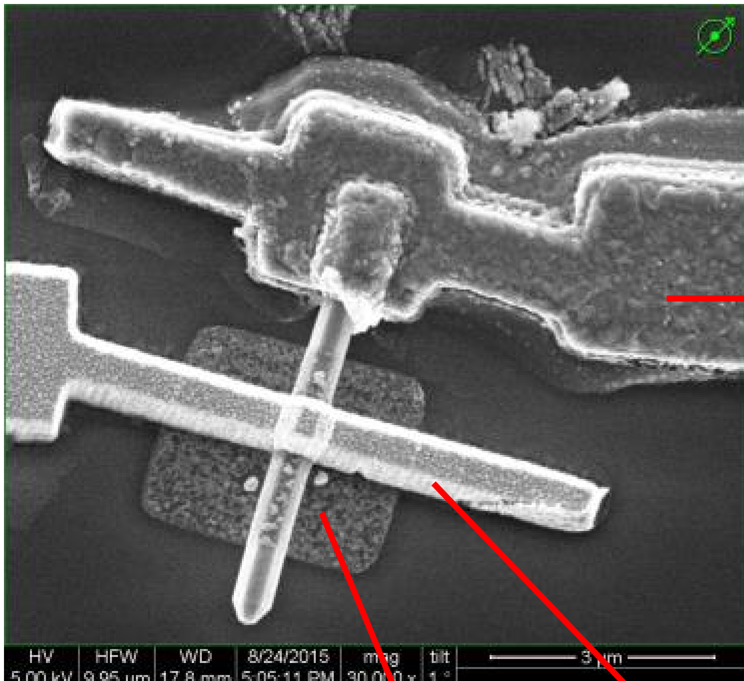
- First non-polar GaN/InGaN MQW core-shell NW laser
- Demonstrates feasibility of NW radial architecture as single NW laser

Manuscript under preparation

Key Accomplishments

Fabrication of p-i-n junction radial nanowire devices

Wire ID:	C0209 DBT
n-contact:	840 nm Ti
n-contact RTA:	Argon 30s 850C
Current spreading layer:	5nm Ni / 5nm Au
Current spreading layer RTA:	Air 550C 30sec
p-contact:	200nm Ni/ 500nm Au



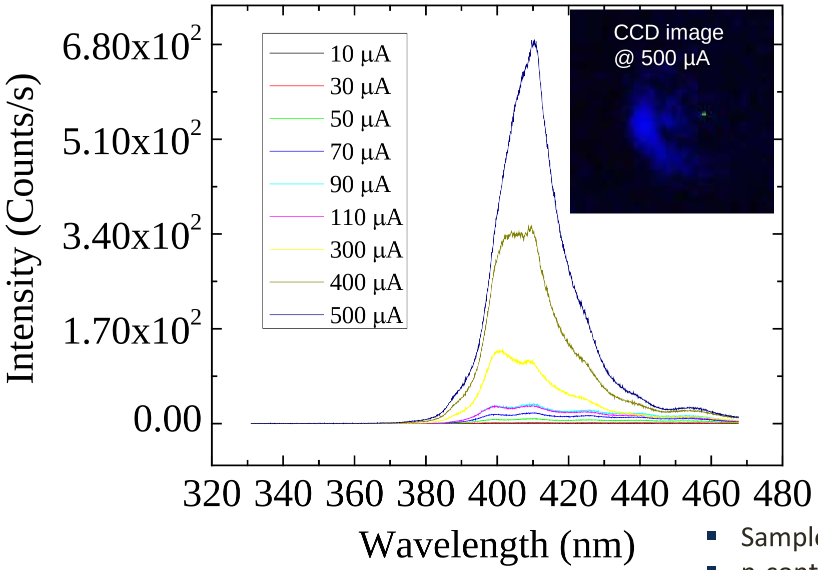
n-contact

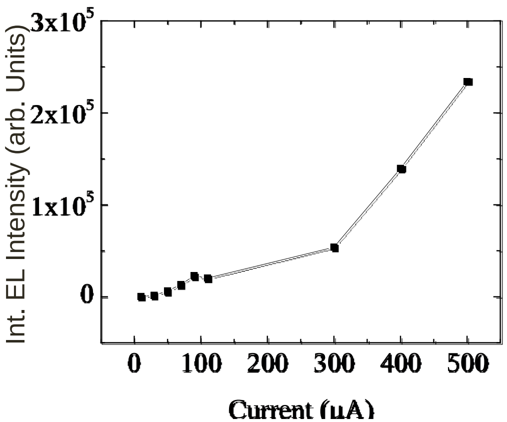
Current spreading layer

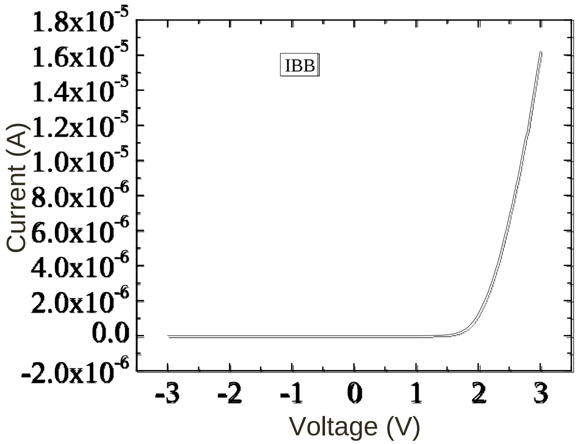
p-contact

Key Accomplishments

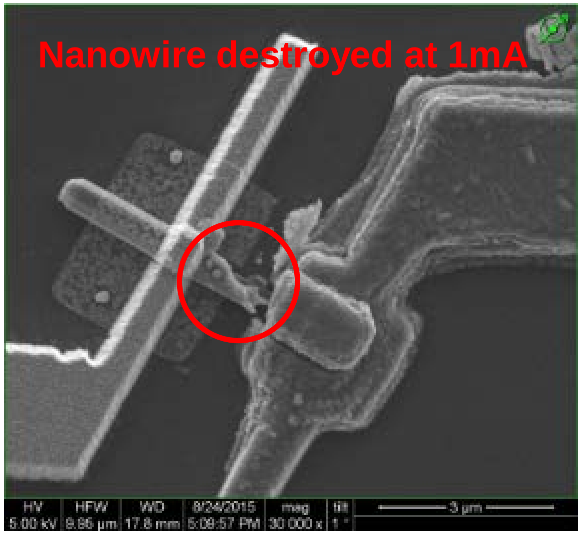
Electrically injected nonpolar radial InGaN/GaN nanowire LED







- Sample C0209 CW EL Wire IBB
- n-contact: 600 nm **Ti**
- Current spreading layer: **5nm Ni/ 5nm Au**
- p-contact: **Ni/Au**
- **Continuous** DC current

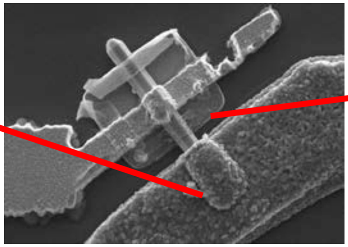


- Electroluminescence (EL) demonstrated from radial InGaN/GaN p-i-n nanowire
- No lasing observed before wire destroyed by Joule heating
- Pulsed EL measurements were subsequently performed, but still no lasing observed

Key Accomplishments

Studied impact of metal contacts on thresholds (optical pumping)

n-contact: 840nm Ti
RTA: Argon 850°C 30 sec



p-type current spreading layer (CSL):
5nm Ni/ 5nm Au
RTA: Air 550°C 30 sec

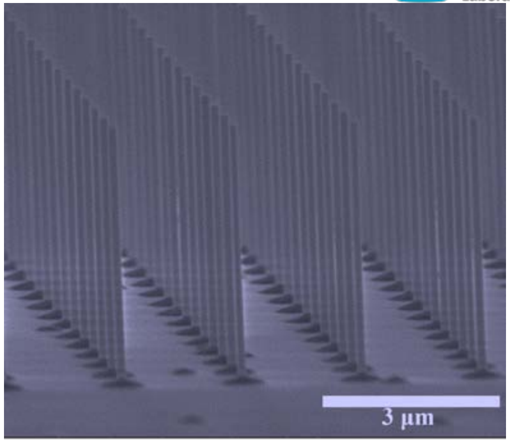
Note: contacts block pump light (not relevant for electrical injection)

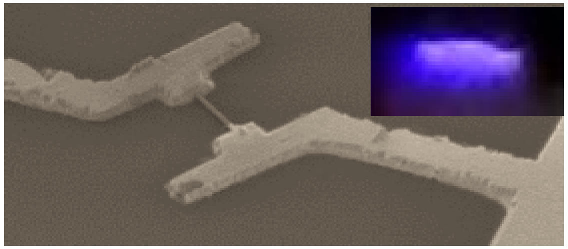
Wire number	Measured lasing threshold by optical pumping (kW/cm^2)				
	Bare Wire	Wire + Ti (n-contact)	Wire + Ti + RTA	Wire + Ti + RTA + CSL	Wire + Ti + RTA + CSL + RTA
BB5311	**593**	No lasing	No lasing	No lasing	No lasing
HB6132	**554**	1560	1417	No lasing	No lasing
JB5413	**451**	No lasing	No lasing	No lasing	No lasing
KB7332	**399**	No lasing	323	1178	No lasing
NB5322	**411**	No lasing	No lasing	No lasing	No lasing
OB2222	**506**	No lasing	643	No lasing	No lasing
OB9131	**532**	No lasing	No lasing	794	201
PB8222	**741**	743	432	818	1214

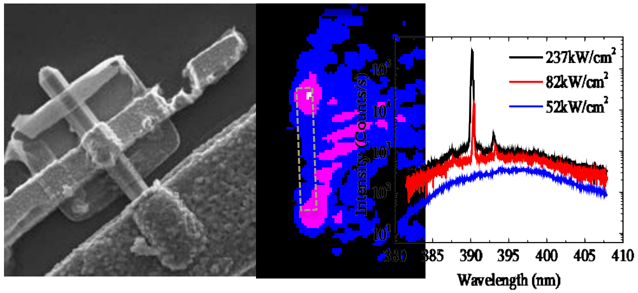
Conclusion: metal contacts have significant impact on lasing thresholds, need to optimize placement and design

Key Accomplishments: Summary

- **Our primary goal of electrically injected lasing from single nanowires was not achieved, however several notable achievements resulted from this project:**
- Advanced the *state-of-the art in controlled III-nitride nanowire fabrication* using e-beam patterning and optimized dry and wet etch processes
- Demonstrated process for *nanowire cross-sectional shape control and resulting ability to manipulate nanowire laser properties*, such as beam shape and polarization
- Analyzed axial versus radial nanowire laser designs
- Achieved *first optically pumping lasing from nonpolar core-shell III-N nanowires*
- Achieved *electrically injected axial and radial InGaN/GaN nanowire LEDs*
- Ten journal publications and 28 invited talks







Electrically Injected UV-Visible Nanowire Lasers (165704)

Publications

1. C. Li et al., “Nonpolar InGaN/GaN multi-quantum-well core-shell nanowire lasers,” *in preparation*
2. C. Li et al., “Linearly Polarized Emission from Single Rectangular Cross-sectional Gallium Nitride Nanowire Lasers,” *submitted*
3. C. Li, S. Liu, A. Hurtado, J. B. Wright, H. Xu, T. S. Luk, J. J. Figiel, I. Brener, S. R. Brueck, G. T. Wang, "Annular-Shaped Emission from Gallium Nitride Nanotube Lasers", *ACS Photonics*, **2**, 1025 **(2015)**.
4. S. Liu, C. Li, J. J. Figiel, S. R. Brueck, I. Brener, G. T. Wang, "Continuous and dynamic spectral tuning of single nanowire lasers with subnanometer resolution using hydrostatic pressure", *Nanoscale*, ***7***, 9581 **(2015)**.
5. J.B. Wright et al., “Gallium Nitride Distributed Feedback Nanowire Lasers” *Appl. Phys. Lett.* **104**, 041107 (2014); doi: 10.1063/1.4862193
6. C. Guclu, T. S. Luk, G. T. Wang, F. Capolino, "Radiative emission enhancement using nano-antennas made of hyperbolic metamaterial resonators", *Appl. Phys. Lett.*, ***105***, 123101 **(2014)**. **(COVER ARTICLE)**
7. H. Xu, A. Hurtado, J. B. Wright, C. Li, S. Liu, J. J. Figiel, T.-S. Luk, S. R. J. Brueck, I. Brener, G. Balakrishnan, Q. Li, G. T. Wang, "Polarization control in GaN nanowire lasers", *Optics Express*, 22, (2014)
8. Weng W. Chow, Frank Jahnke and Christopher Gies, “Emission properties of nanolasers during transition to lasing,” *Light: Science & Applications*, 3 (2014): e201 (2014)
9. A. Hurtado et al., “Transverse Mode and Polarization Switching in GaN Nanowire Lasers” *Appl. Phys. Lett.* **103**, 251107 (2013); doi: 10.1063/1.4835115
10. Wright et al. “Multi-Colour Nanowire Photonic Crystal Laser Pixels” *Scientific Reports* 3 : 2982 | DOI: 10.1038/srep02982

Electrically Injected UV-Visible Nanowire Lasers (165704)

External collaborations that have resulted from this project

- Ken Shih – UT Austin, study low threshold plasmonic GaN nanowire lasers
- Ganesh Balakrishnan – transfer top-down nanowire fabrication approach to III-Vs (e.g. GaAs, etc.)
- Daniel Gianola – in-situ TEM tensile strain piezoresistance experiments of GaN nanowires

IP resulting from this project

- J. B. Wright, I. Brener, G. S. Subramania, G. T. Wang, Q. Li, “Multicolor Photonic Crystal Laser Array” U.S. Patent 9,020,005 B2 (2015)
- G.T. Wang, Q. Li, “Method of fabricating vertically aligned Group III-V nanowires” U.S. Patent 8,895,337 B1 (2014)
- S. Liu, G. T. Wang, “Semiconductor Nano/Microlaser Tuning by Strain Engineering”, SD13375 Non Provisional Serial No. 14/737,222 filed 6/11/2015
- W. Chow, “Nanolasers as solution to efficiency droop in solid-state lighting” SD # *13362* 11/01/2014
- G. T. Wang, C. Li, S. Liu, “Cross-sectional shape controlled nanowires”, in preparation

Proposals submitted or in preparation that build on the results of this project

- U.S DOE BES, CINT User Proposal: *U2014B0089: Optoelectronic Properties of III-Nitride Nanostructures*, FY15-FY16, accepted (no funding allocated)
- U.S DOE BES, *Energy Frontier Research Center for Solid-State Lighting (renewal)*, $20M, FY15-19, not funded
- DARPA SCOUT, *UV-Visible Frequency Comb Sources based on Nitride Materials*, $5.3M, FY14-17, not funded
- U.S. DOE EERE, *Polarization and Strain Engineering for Green InGaN LEDs with over 40% Efficiency*, $1.9M, FY15-16, not funded
- U.S. Army Research Office (ARO) STIR Program, *Two-step etch process for fabrication of III-V Nanolasers,* $50K, FY16, **accepted** (funding goes to UNM/CHTM)

Significance/Impact of Results

PMU impact, potential follow-on opportunities, and intellectual property opportunities/concerns

- Significantly advanced our expertise and capabilities in III-nitride nanophotonics. Investments have made Sandia the leader in top-down fabricated III-N nanowires.
- This will allow us to pursue future opportunities in nanophotonics from internal and external (DOE BES, ARPA-E, DOD, ARO, DARPA, etc.)
- Recently granted seed money ($50K, ARO) to fund UNM/CHTM student/postdoc at to transfer top-down approach to create III-V (e.g. GaAs-based) nanolasers. Success could lead to larger programs.
- Three Ph.D students and three post-docs have had the opportunity to work on this project, advancing the state-of-the-art in nanostructure fabrication, optical characterization, and modeling of nanowire lasers.
- Project has contributed to a number of invited talks (28), journal publications (10), and IP, positioning us as a leading group in III-nitride nanowire optoelectronics.

Electrically Injected UV-Visible Nanowire Lasers (165704)

PM: George Wang (01126), FY13-15, $1.53M

PMU Benefit & Timeframe

- Near-Term (next 1-2 years): Publish papers, file TAs/Patents resulting from project
- Near-to-Mid-Term (next 2-5 years): Look for follow-on opportunies relevant to E&C PMU Research Foundations and Research Challenges

Impact and S&E Legacy

- Project has led to fundamental advances in understanding and control of single nanowire lasers
- Substantially enhanced our expertise and capabilities in III-nitride nanophotonics, making Sandia the leader in III-nitride nanowires fabricated by top-down approaches

Efforts to Leverage R&D

- File TAs and patents resulting from work
- New collaborations resulting from this project
- Use science and technology know-how to explore new concepts and impact mission-relevant problems
- New LDRD on Quantum Nanophotonics will leverage advances and capabilities from this project

What's Next

- Pursue future opportunities in nanophotonics from internal and external (DOE BES, ARPA-E, DOD, DARPA, etc.)
- Recently granted seed money ($50K) to fund UNM/CHTM student/postdoc at to transfer top-down approach to create III-V (e.g. GaAs-based) nanolasers. Success could lead to larger follow-on programs.

Electrically Injected UV-Visible Nanowire Lasers (165704)

Invited Presentations (28)

1. G.T. Wang, "III-Nitride Nanowires for Solid-State Lighting," McGill Workshop Emerging Lighting Solutions, Montreal, Canada, 1/10/2013 (keynote)
2. G.T. Wang, "Nanowires: A New Architecture for Solid-State Lighting," USC Invited Seminar, USC, Los Angeles, CA, 3/6/2013 (invited)
3. G.T Wang, "Nanowires as an Architecture for Solid-State Lighting," Taiwan SSL Conference, Taipei, Taiwan, 3/26-27/2013 (invited)
4. Wang, G. T., *Nanowires for Solid-State Lighting*, EFRC PI Meeting, 7/18/13, Washington, DC.
5. G.T. Wang, *Nanowires: A Future Architecture for Solid-State Lighting*, Fall 2013 National ACS Meeting, 9/8-12/13, Indianapolis, IN.
6. Wright, J. B.,…, G. T. Wang, *Characterization of III-Nitride Nanowires*,Triennal CINT Review, 9/10-11/13, Los Alamos, NM **(invited)**.
7. G.T. Wang, III-Nitride Nanowires: New Materials for Light Emission, Nanowires 2013, 11/11-15/13, Rehovot, Israel
8. G. T. Wang, III-nitride nanowires for visible optoelectronics, 8th Workshop on Frontiers in Electronics, 12/17-20/13, San Juan, Puerto Rico.
9. Chow, W. W., *Emission properties from nanolasers during transition to lasing*, 44rd Winter Colloquium on the Physics of Quantum Electronics, 1/6-9/14, Snowbird, UT.
10. G. T. Wang, III-nitride nanowires for future optoelectronics, Arizona State University, 3/27/14, Tempe, AZ
11. I. Brener, Waves, Light and Artificial Lighting, Science Bowl 2014, 4/25/14, Washington D.C.
12. Chow, W. W., *Emission properties from nanolasers during transition to lasing*, University of Texas Arlington, EECE Department Seminar, March 21, 2014, Arlington, TX.
13. Chow, W. W., *Emission properties from nanolasers during transition to lasing*, SPIE Photonics Europe Conference, 4/14-17/14, Brussels, Belgium.
14. Chow, W. W., *Nanolaser*, Workshop in Honor of Dr. Stephen F. Jacobs (co-inventor, Cesium laser, 1962), 1/14-15/2014, Texas A&M University, College Station, TX
15. Wang, G. T., *III-Nitride Nanowire Heterostructures by Top-Down and Combined Top-Down Bottom-Up Approaches*, North American Molecular Beam Epitaxy Conference (NAMBE 2013), 10/5-11/13, Banff, Canada
16. Wang, G. T., *III-Nitride Nanowires: Novel Materials for Light Emission*, AVS 60th International Symposium and Exhibition, 10/27-11/1/13, Long Beach, CA
17. Wang, G. T., *III-Nitride Nanowires: New Materials for Light Emission*, Nanowires 2013, 11/11-15/13, Rehovot, Israel
18. Wang, G. T., *III-Nitride Nanowires for Visible Optoelectronics*, 8th Workshop on Frontiers in Electronics (WOFE 2013), 12/17-20/13, San Juan, Puerto Rico
19. Wang, G. T., *III-Nitride Nanowires for Future Optoelectronics*, Seminar at Arizona State University, 3/27/14, Tempe, AZ
20. Wang, G. T., et al., *Top-Down III-Nitride Nanowires: from LEDs to Lasers*, SPIE Optics+Photonics Meeting, 8/18-21/14, San Diego, CA

Invited Presentations Con't

21. Fischer, A. J., et al., *Fabrication of InGaN Quantum Dots for Use as Active Photonic Emitters,* SPIE Optics+Photonics 2014 Conference, 8/17-21/14, San Diego, CA
22. Wang, G. T., J. B. Wright, H. Xu, A. Hurtado, C. Li, S. R. J. Brueck, Q. Li, T.-S. Luk, J. J. Figiel, I. Brener, *Mode and Polarization Control in Gallium Nitride Nanowire Lasers*, 2014 Progress in Electromagnetics Research Symposium (PIERS 2014), 8/25-28/2014, Guangzhou, China
23. Wang, G. T., *III-Nitride Nanowires for Future Optoelectronics,* International Symposium on Materials for Enabling Nanodevices (ISMEN2014), 9/3-5/14, Tainan, Taiwan
24. Wang, G.T., *III-Nitride Nanowires: Novel Materials for Future Optoelectronics*, International Symposium on Semiconductor Light Emitting Devices (ISSLED 2014), 12/14-19/15, Kaohsiung, Taiwan
25. Wang, G. T. , *III-Nitride Nanowires for UV-Visible Optoelectronics*, 2015 IEEE Photonics Society Summer Topicals Meeting Series, 7/13-15/15, Nassau, Bahamas
26. Chow, W. W., F. Jahnke, C. Gies, *Nanolaser Emission under Few-Emitter or Unity-Spontaneous-Emission-Factor Conditions*, 12th Conference on Nonlinear Optics and Excitation Kinetics in Semiconductors (NOEKS), 9/22-25/14, Bremen, Germany
27. Chow, W. W., F. Jahnke, C. Gies, *First Principle Study of Nanolasers: Photon Statistics and Laser Threshold,* Asia Communications and Photonics Conference (ACP 2014), 11/11-14/14, Shanghai, China
28. Chow, W. W., *Correlations and Photon Statistics in Nanocavity Emitters,* Nanoscience Seminar Series, Department of Physics, ASU, 4/24/15, Tempe, AZ

Electrically Injected UV-Visible Nanowire Lasers (165704)

Contributed Presentations

1. H. Xu et al., "Single-Mode Lasing in Gallium Nitride Nanowires," SPIE Photonics West, San Francisco, CA, 2/5/2013
2. Wang, G. T., Q. Li, J. J. Wierer, D. D. Koleske, J. J. Figiel, *Top-Down Fabricated III-Nitride Nanowire LEDs and Solar Cells*, 2013 Photonics West, 2/2-7/13, San Francisco, CA.
3. Wright, J. B., G. Subramania, Q. Li, I. Brener, T. S. Luk, G. T. Wang, S. Sheng, H. Xu, L. F. Lester, *Photonic Crystal II-Nitride Nanowire Lasers*, Photonics West 2013, 2/2-7/13, San Francisco, CA.
4. Xu, H., J. B. Wright, A. Hurtado, G. T. Wang, T. S. Luk, J. J. Figiel, K. C. Cross, G. Balakrishnan, L. F. Lester, I. Brener, Q. Li, *Mode Control in Gallium Nitride Nanowire Lasers*, 55th Electronic Materials Conference, 6/26-28/13, South Bend, IN.
5. Xu, H., A. Hurtado, J. B. Wright, G. T. Wang, T. S. Luk, J. J. Figiel, K. C. Cross, G. Balakrishnan, L. F. Lester, I. Brener, Q. Li, *Manipulation of Lasing Polarization in GaN Nanowires*, 55th Electronic Materials Conference, 6/26-28/13, South Bend, IN.
6. Li, Q., H. Xu, J. B. Wright, G. T. Wang, I. Brener, T. S. Luk, W. W. Chow, J. J. Figiel, K. C. Cross, *Controlled Lasing in GaN Nanowires*, SPIE Optics + Photonics Conference, 8/25-29/13, San Diego, CA.
7. Xu, H., J. B. Wright, A. Hurtado, T. S. Luk, J. J. Figiel, L. F. Lester, I. Brener, Q. Li, G. T. Wang, *Mode and Polarization Control in Gallium Nitride Nanowire Lasers*, , ICNS 13 Conference, 8/25-30/13, Washington, DC.
8. Wright, J. B., S. Liu, G. T. Wang, Q. Li, D.D. Koleske, P. Lu, H. Xu, T. S. Luk, I. Brener, G. S. Subramania, L. F. Lester, *Monolithic III-Nitride Multi-Color Laser Arrays*, Electronic Materials Conference, 6/26-28/13, South Bend, IN.
9. Xu, H., A. Hurtado, G. Balakrishnan, L. F. Lester, Q. Li, Wright, J. B., G. T. Wang, T. S. Luk, I. Brener, J. J. Figiel, K. C. Cross, *Polarization and Modal Control of GaN Nanowire Lasers*, International Conference for Nitride Semiconductors (ICNS), 8/25/-30/13, Washington, DC.
10. Wright, J. B., S. Liu, G. T. Wang, Q. Li, D.D. Koleske, P. Lu, H. Xu, T. S. Luk, I. Brener, G. S. Subramania, L. F. Lester, A. Benz, *Tunable Blue-Violet III-Nitride Nanowire Photonic Crystal Lasers*, CLEO 2013, 6/9-14/13, San Jose, CA.
11. Xu, H., A. Hurtado, Q. Li, J. B. Wright, G. T. Wang, I. Brener, J. J. Figiel, T. S. Luk, C. Li,, *Controlled Lasing in GaN Nanowires*, CINT User Conference 9/25/2013, Santa Fe, NM.
12. Programmatic Review - Coltrin, M. E., **J. Y. Tsao**, G. T. Wang, M. H. Crawford, J. J. Wierer, *Idea Sketch for an EFRC 2 for Ultra-Efficient Solid-State Lighting*, Webex EFRC 2 Planning Meeting, 10/1/13.
13. Wang, G. T., Xu, H., J. B. Wright, A. Hurtado, T. S. Luk, J. J. Figiel, L. F. Lester, I. Brener, Q. Li, *Mode and Polarization Control in Gallium Nitride Nanowire Lasers*, SPIE Photonics West 2014, 2/1-6/14, San Francisco, CA.
14. Subramania, G., J. B. Wright, S. Liu, G. T. Wang, Q. Li, A. Benz, D. D. Koleske, P. Lu, H. Xu, L. Lester, T. S. Luk, I. Brener, *Multi-Color Nanowire Photonic Crystal Laser Pixels*, American Physical Society March Meeting 2014, 3/3/-7/14, Denver, CO.
15. Li, C., A. Hurtado, J. B. Wright, S. Liu, T. S. Luk, I. Brener, S. R. J. Brueck, G. T. Wang, *Gallium Nitride Nanotube Lasers*, CLEO 2014, 6/8-13/14, San Jose, CA.
16. Wright, J. B., S. Campione, S. Liu, J. A. Martinez, H. Xu, Q. Li, T. S. Luk, G. T. Wang, B. S. Swartzentruber, I. Brener, *Gallium Nitride Nanowire Distributed Feedback Lasers*, CLEO 2014, 6/8-13/14, San Jose, CA.
17. Fischer, A. J., X. Xiao, J. Y. Tsao, D. D. Koleske, P. Lu, G. Subramania, M. E. Coltrin, J. B. Wright, S. Liu, I. Brener, G. T. Wang, *InGaN Quantum Dots for High Efficiency Blue and Green Light Emitters*, CLEO 2014, 6/8-13/14, San Jose, CA.

Electrically Injected UV-Visible Nanowire Lasers (165704)

Contributed Presentations continued

18. Wang, G. T., Q. Li, J. B. Wright, H. Xu, J. J. Wierer, D. D. Koleske, J. J. Figiel, A. Hurtado, L. F. Lester, G. Subramania, T. S. Luk, I. Brener, *Top-Down III-Nitride Nanowire LEDs and Lasers*, 56th Electronic Materials Conference, 6/25-27/14, Santa Barbara, CA.
19. **Li, C.**, A. Hurtado, J. Wright, H. Xu, S. Liu, T. Luk, I. Brener, S. R. J. Brueck, G. T. Wang, *Top-Down III-Nitride Nanotube Lasers*, 56th Electronic Materials Conference, 6/25-27/14, Santa Barbara, CA.
20. **Liu, S.**, C. Li, J. Wright, G. T. Wang, T. Luk, M. B. Sinclair, I. Brener, *Spectral tuning $>$ 25 nm from GaN nanowire lasers using hydrostatic pressure*, 56th Electronic Materials Conference, 6/25-27/14, Santa Barbara, CA.
21. Wang, G. T., H. Xu, J. B. Wright, A. Hurtado, T.S. Luk, J. J. Figiel, S. Liu, C. Li, S. Brueck, L. Lester, Q. Li, I. Brener, *Mode and Polarization Control in Gallium Nitride Nanowire Lasers*, 2014 IEEE Photonics Society Summer Topicals Meeting Series, 7/14-16/14, Montreal, Canada.
22. **Li, C.**, S. Liu, A. Hurtado, J. B. Wright, H. Xu, T. S. Luk, I. Brener, S. R. J. Brueck, G. T. Wang, Cross-Sectional Controlled GaN Nanowire Lasers, 2014 CINT User Meeting, 9/22-23/14, Santa Fe, NM.
23. **Li, C.**, J. B. Wright, S. Liu, P. Lu, J. J. Figiel, B. Leung, T. S. Luk, I. Brener, S. R. J. Brueck, G. T. Wang, *Nonpolar InGaN/GaN Multi-Quantum-Well Core-Shell Nanowire Lasers*, 2015 CLEO Conference, 5/10/15/15, San Jose, CA.

Backup Slides

Thoughts on significant remaining challenges and potential roadblocks

Sandia National Laboratories

- For radial NW laser, optimization of growth and structure difficult due to 3D structure and small size. Basic details such as layer thickness require complex scanning TEM experiments, and doping levels cannot be determined from Hall measurements
- Non-uniform growth on nanowire sidewalls from top-to-bottom results in reduced gain and additional losses
- For the above reasons, the nanostripe architecture with *c*-plane MQWs may be easier to achieve electrically injected lasing than radial NW, if liftoff of stripe can be achieved by selective wet etching
- Contact formation leads to significant optical losses. However, a fraction of the wires maintained optically pumped lasing after contact formation. Further study and new schemes and potentially different metals need to be considered.
- Nanoscale 3D Ohmic contacts significantly more challenging than bulk 2D contact, particularly the p-contact. Further work needed to solve this challenge.

R&D Goals and Milestones

Sandia National Laboratories

Goal	Milestone	Completion Date	Status 9/3/15
1. Fabricate nanowire (NW) laser structures	Axial p-n junction MQW NWs	FY13 Q1	Completed; straight axial NW LEDs via e-beam lithography
	Radial p-n junction MQW NWs (exposed core)	FY13 Q3	
	NWs with built-in GaN/AlN DBR structure	FY13 Q4	Achieved, but poor morphology
	Fabricate optimized NW laser design	FY14 Q4	
2. Threshold reduction via novel design strategies	Model NW laser modes (optimize gain overlap)	FY13 Q2	Initial designs completed
	Calculate gain-current relation of laser active region	FY13 Q3	
	Model built-in and coupled DBR NW laser designs	FY13 Q3	Coupled and built-in modeling completed; Exploring Al mirrors
	Characterize lasing from p-n junction MQW NWs	FY14 Q1	Axial NWs do not show lasing; Radial NWs show lasing
	Characterize lasing from NWs with intra-cavity (built-in) DBR	FY14 Q2	Difficulties with fabrication
	Characterize lasing from NWs coupled to DBR	FY14 Q3	Completed; single-mode, small threshold reduction.
3. Electrically-injected NW laser in UV-visible range	Ohmic n- and p-contacts to NW n- and p- regions	FY13 Q3	n-contact demonstrated; p-contact still in progress
	Electrically injected axial p-n junction NW LED	FY13 Q4	High turn-on voltage likely from non-optimized contacts
	Model carrier transport in NW lasers	FY14 Q1	
	Electrically injected radial p-n junction NW LED	FY14 Q2	p-contact likely not Ohmic
	Study impact of contacts on NW lasing properties	FY14 Q3	We can try on pure GaN wires first; same wires before and after metal contact deposition. Data from Al-coated ends.
	Select optimized NW laser/contact design for device fabrication	FY14 Q4	
	Horizontal geometry electrically injected NW laser	FY15 Q2	
	Explore etched horizontal nanostripe laser geometry.	FY15 Q4	
Communicate results	LDRD reports & presentations	Annual	
Final SAND report	Submit SAND report	FY15 Q4	

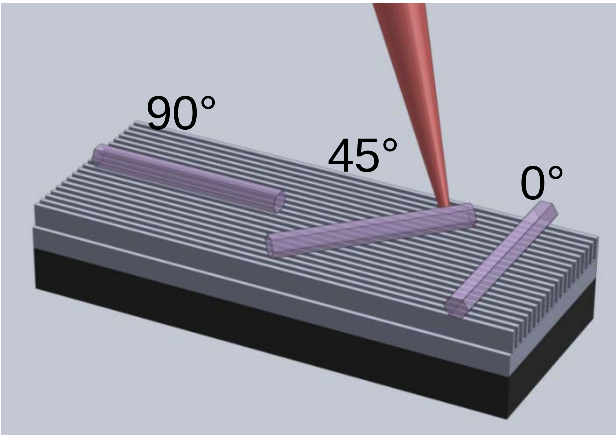
completed

in progress

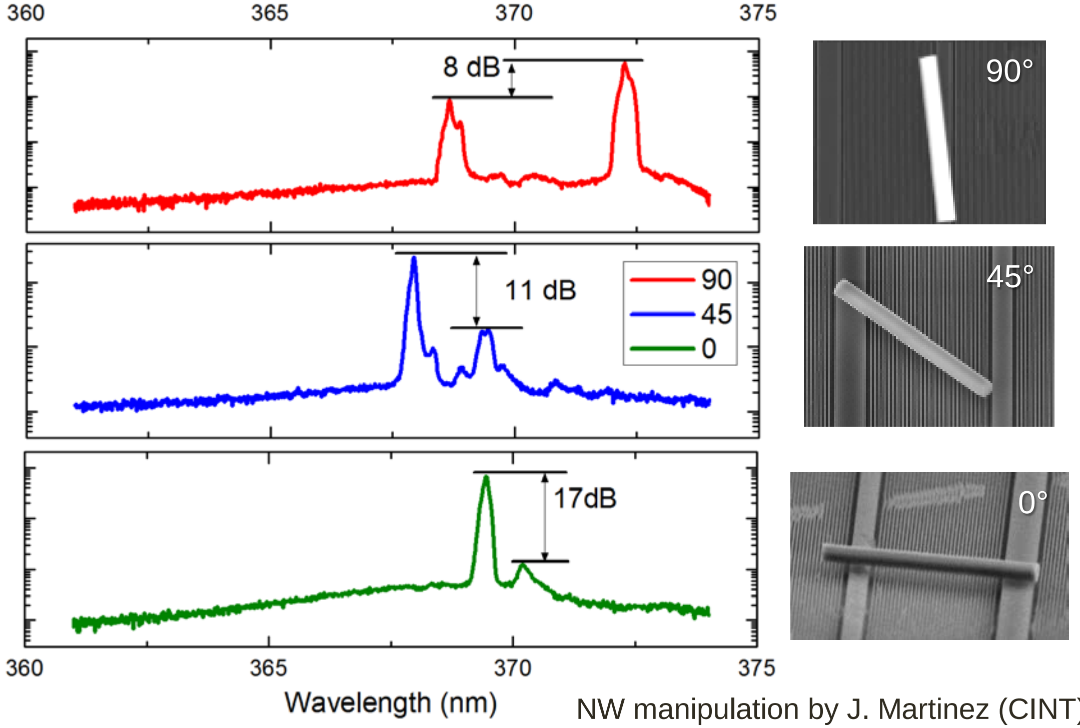
dropped/ unsuccessful

Key Accomplishments

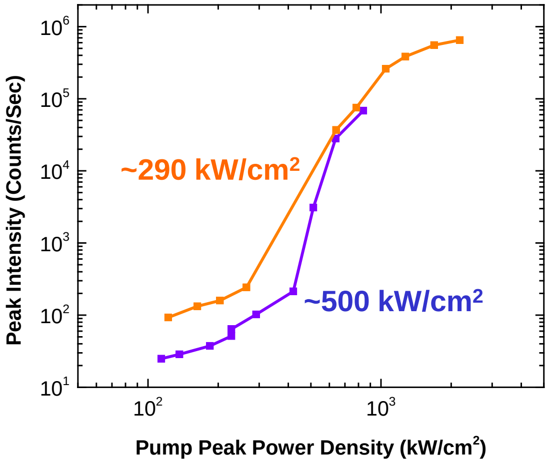
Nanowire Laser Coupled to External Dielectric Grating (DFB)



The effective index of the waveguide is periodically altered by the grating substrate.



NW manipulation by J. Martinez (CINT)



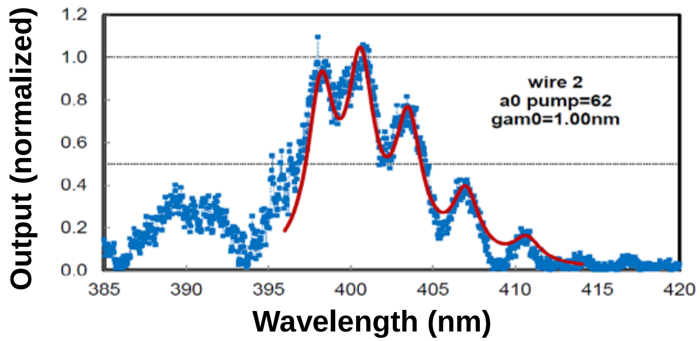
- At the designed alignment single-mode lasing was achieved with a 17dB mode suppression ratio.
- Observed reduction in the lasing threshold

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, *Appl. Phys. Lett.* **104** (4), 041107 (2014).

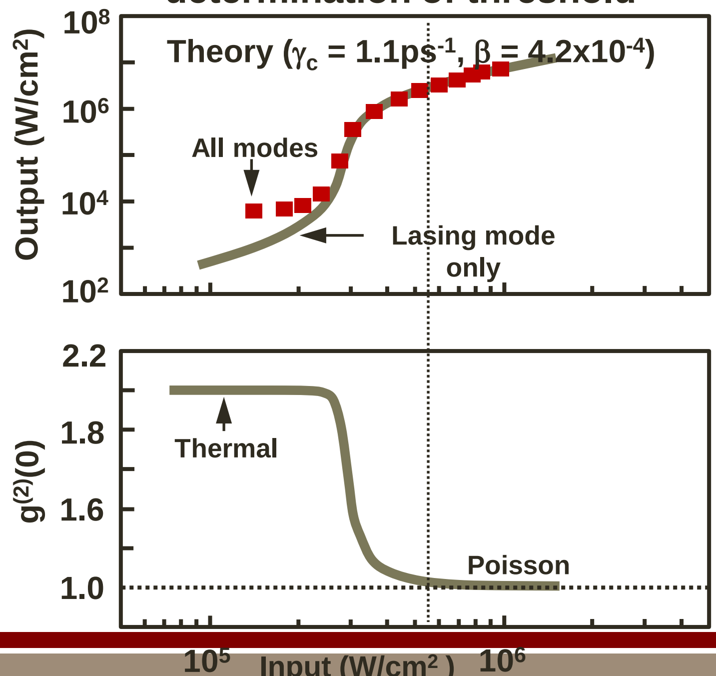
Key Accomplishments

Modelling to elucidate nanowire laser properties

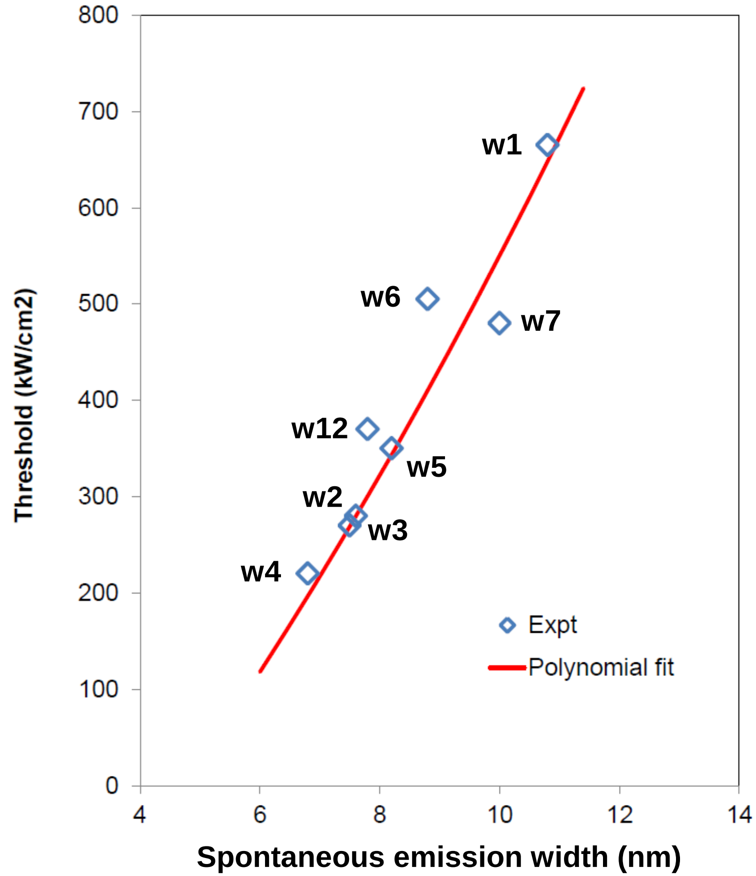
Extraction of linewidth



Verification of lasing and determination of threshold



All wires



Fit suggests lasing threshold related to inhomogeneous broadening

Key Accomplishments

Analysis of axial nanowire laser design requirements

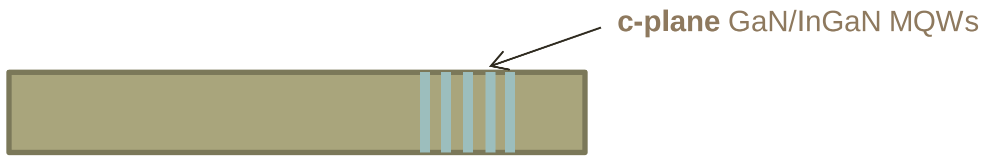
Nanowire Constants

$$\lambda := 420\text{nm}$$

$$\text{Length} := 5\mu\text{m}$$

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

$$\Gamma_{xy} := 1$$



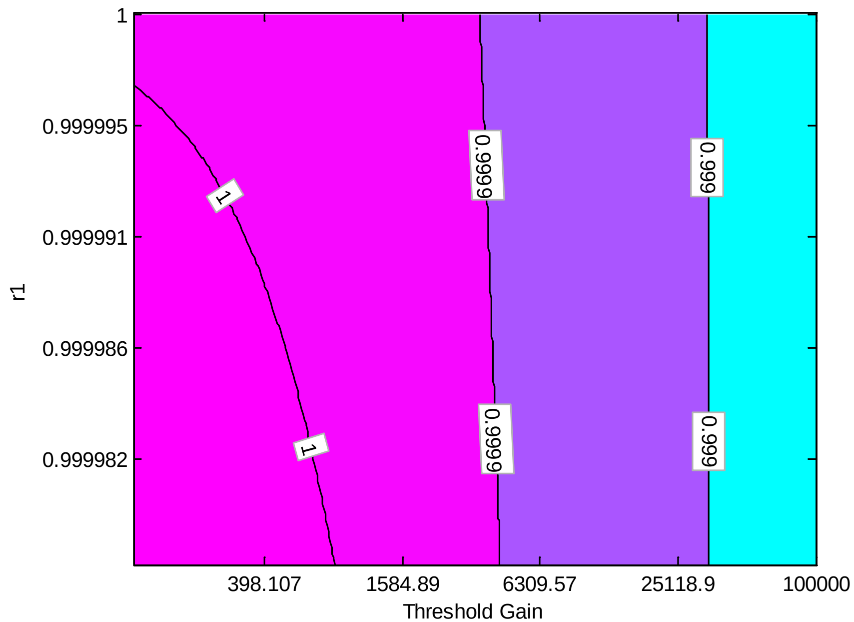
Overlap Calculation

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

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

Threshold Gain

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



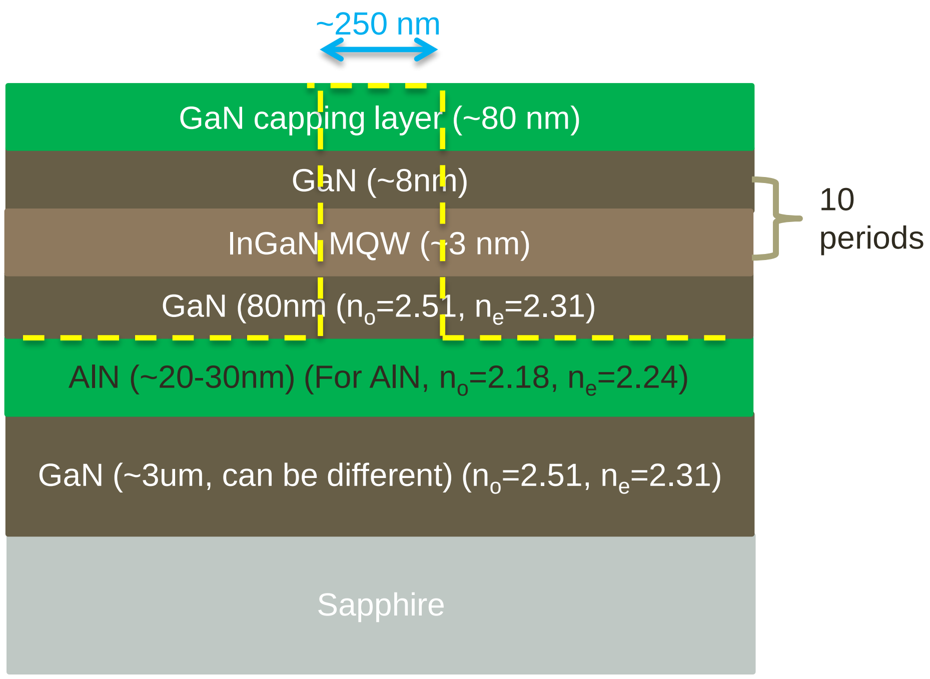
- Need unrealistically high mirror reflectivities for axial NW design!
- **Therefore shift focus to radial NW design**

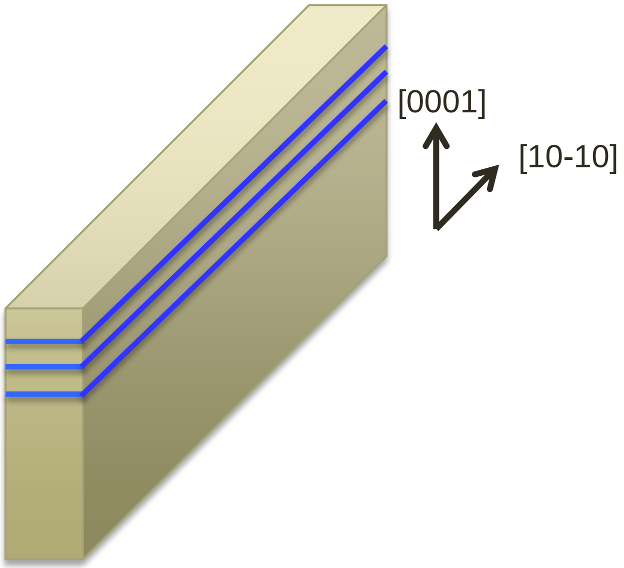
Key Accomplishments

Fabrication and Characterization of Nanostripe Laser

Advantages: optimized c-plane device growth, long cavity and gain lengths possible

Proposed structure (with AlGaN lower index for mode confinement)

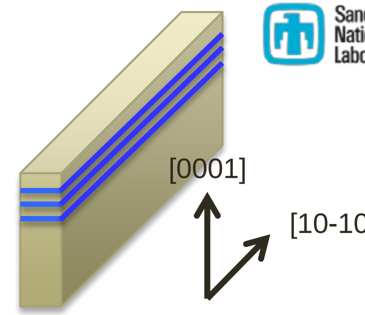


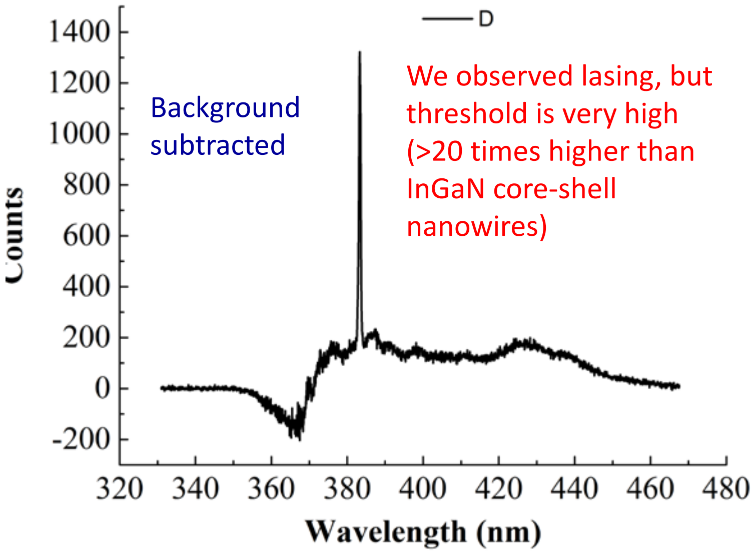


Due to growth difficulties, leaving out the Al(Ga)N layer may work.

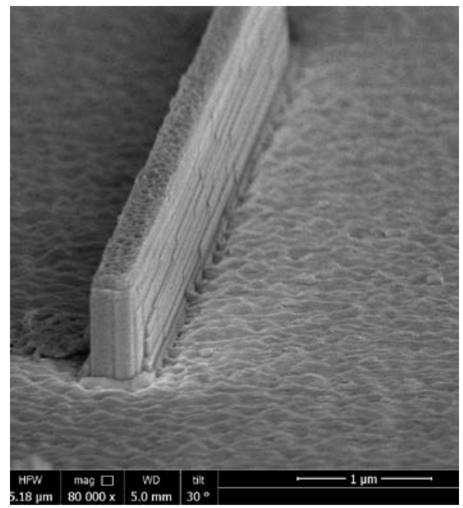
Key Accomplishments

Fabrication and Characterization of Nanostripe Laser



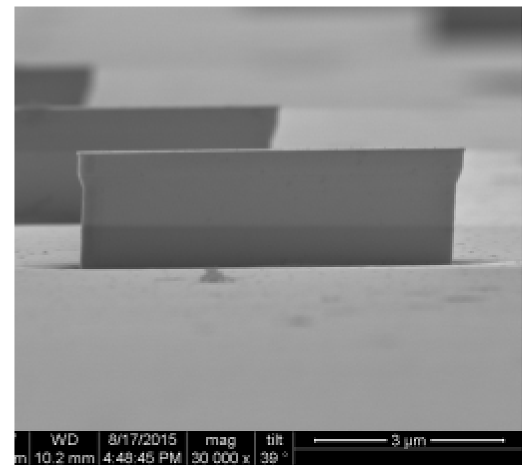


8 minutes AZ400k @ 65C



Ni stripe mask

2 hrs AZ400k @ 90C



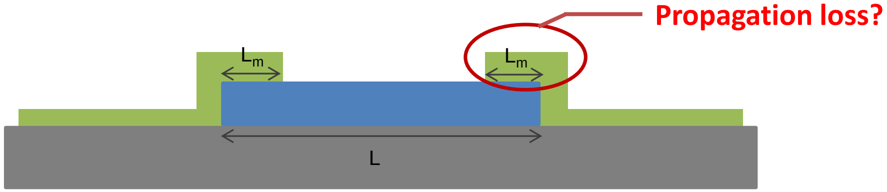
HSQ mask – improved sidewall smoothness

Lasing observed in a few nanostripe samples, **but threshold is very high** (>20 times higher than InGaN core-shell nanowires)

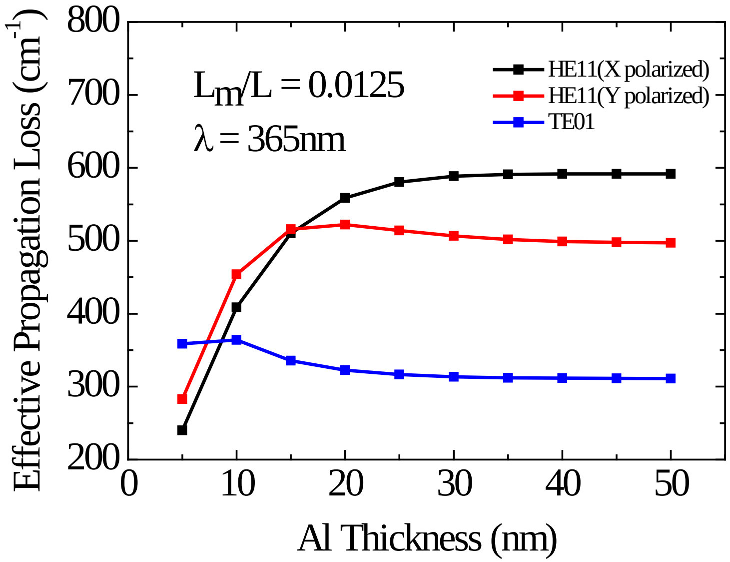
Different mask materials (Ni, SiO_2, HSQ) and dry and wet etch conditions tested to improve sidewall smoothness. However, no improvement in lasing thresholds were observed with smoother sidewalls. A lower refractive index cladding Al(Ga)N layer may be required at the bottom of the stripe.

Key Accomplishments

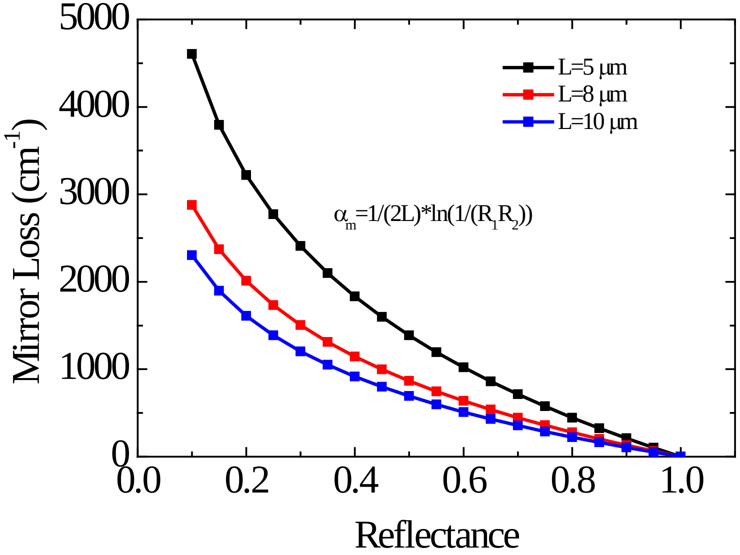
Explored Al end facet mirrors to increase end facet reflectivities



Al on the **sidewall** increases the propagation loss



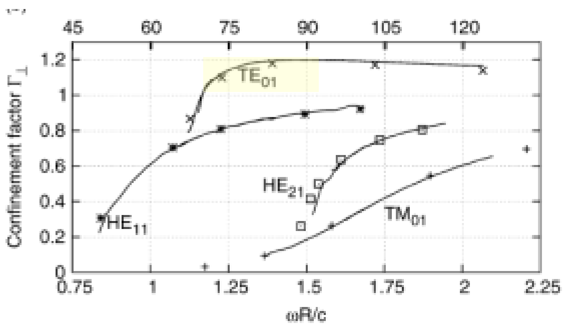
Al on the **end-facet** decreases the mirror loss

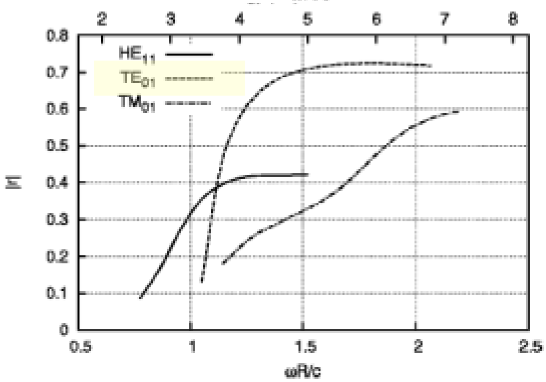


Need to minimize Al deposition on NW sidewall (reduce L_m)

Key Accomplishments

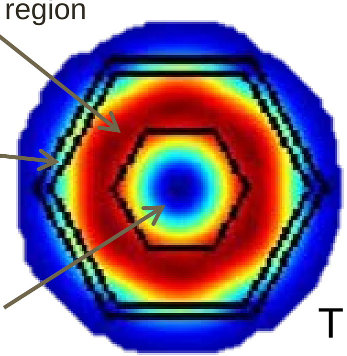
Model optimal radial NW laser geometry





A. V. Maslov & C. Z. Ning, *Quantum Electronics, IEEE J. of,* **40**, 1389-1397 (2004); A. V. Maslov and C. Z. Ning, *Appl. Phys. Lett.*, **83**, 1237-1239 (2003)

- TE_{01} mode predicted to have highest reflectivity and confinement
- "Donut" shape of TE_{01} mode intuitively good fit for core-shell geometry



TE_{01} Mode

Quantum well thickness = 3nm
Barrier thickness = 7nm
5x InGaN QWs & 6 GaN barriers
In mol fraction in the QW = 15%
Lasing wavelength = 420nm

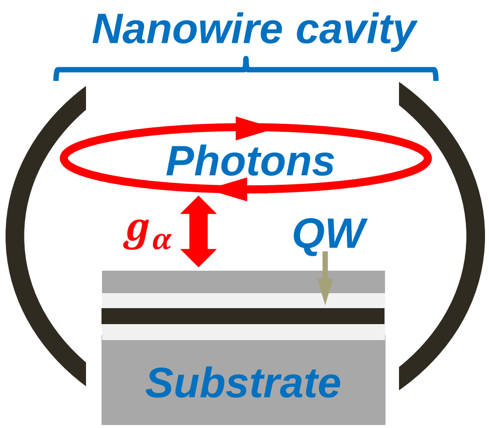
Methodology

- Define hexagonal NW geometry
- Solve for Eigen Modes
- Calculate Confinement Factor Γ_{xy}

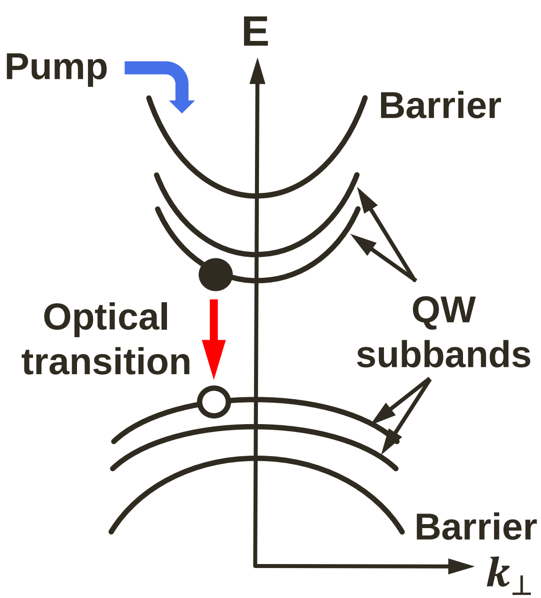
$$\Gamma_{xy} = \frac{\int |E| dS_{qw}}{\int |E| dS_{total}}$$

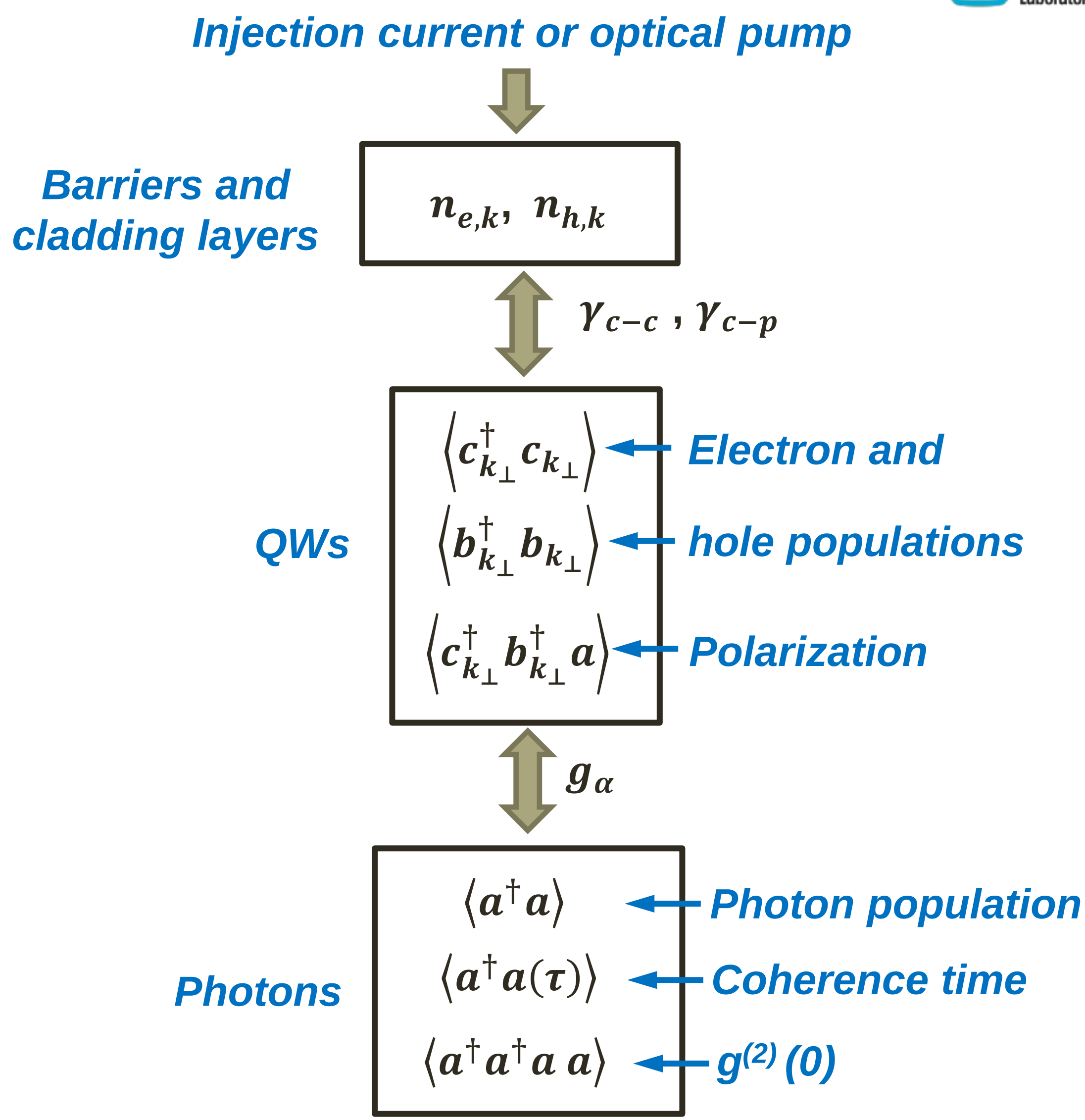
- Repeat for range of NW core diameter and cap (p-GaN) thickness (fixed active region geometry)
- Determine optimal geometries with highest Γ_{xy}

Model: population dynamics and correlations



Electronic structure

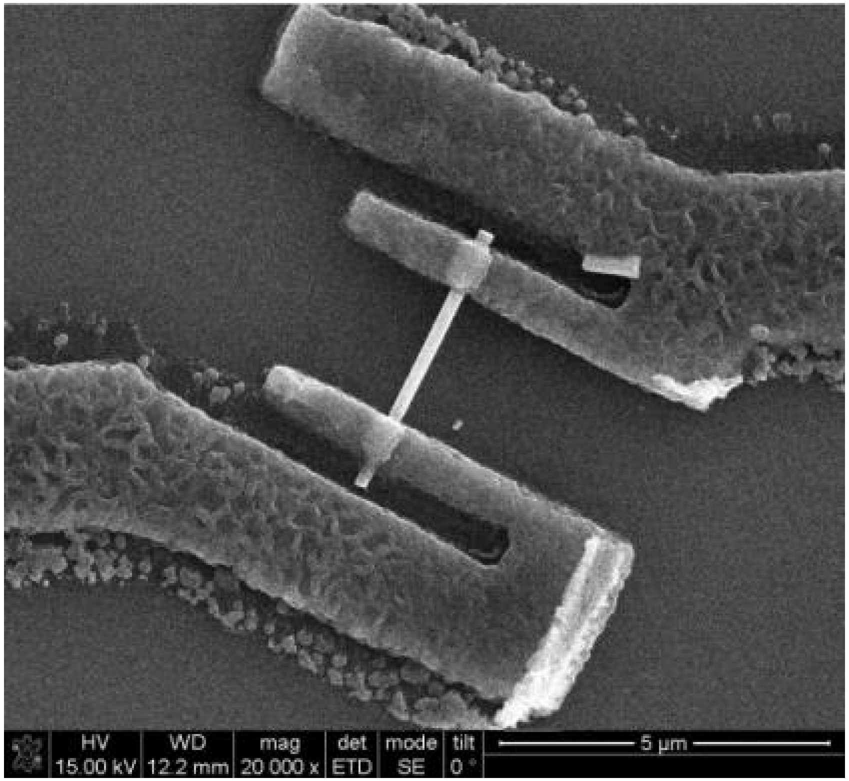


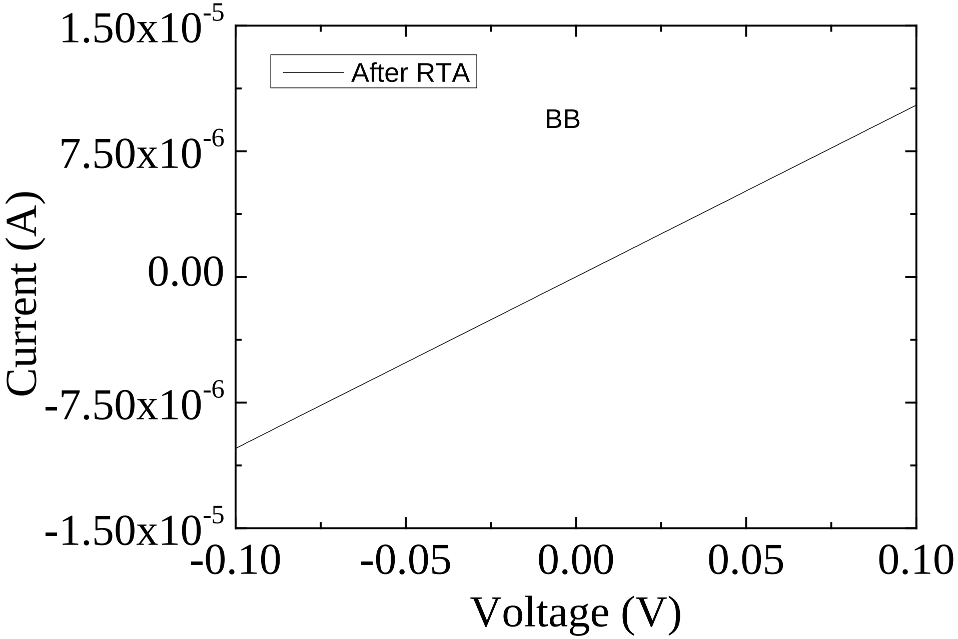


Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)
Chow, Gies & Jahnke, Light: Science & Applications3, e201 (2014)
Chow & Crawford (submitted APL)

Key Accomplishments

Ti Ohmic contact to n-type GaN nanowires





Sample: BN729

- Q0001 Si-doped GaN nanowires
- E-beam lithography
- 5 min UVO3 de-scum
- 2% HF dip before metallization
- **400nm Ti** e-beam deposition
- 50W 5min oxygen plasma de-scum
- RTA
  - o 850C 30 sec in forming gas

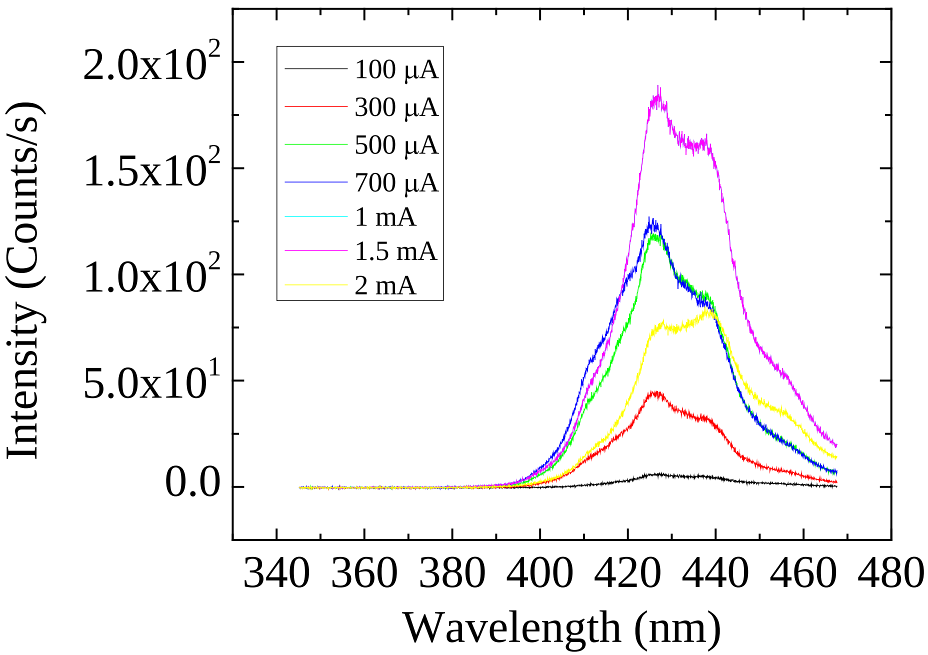
With help from Tzu-Ming Lu

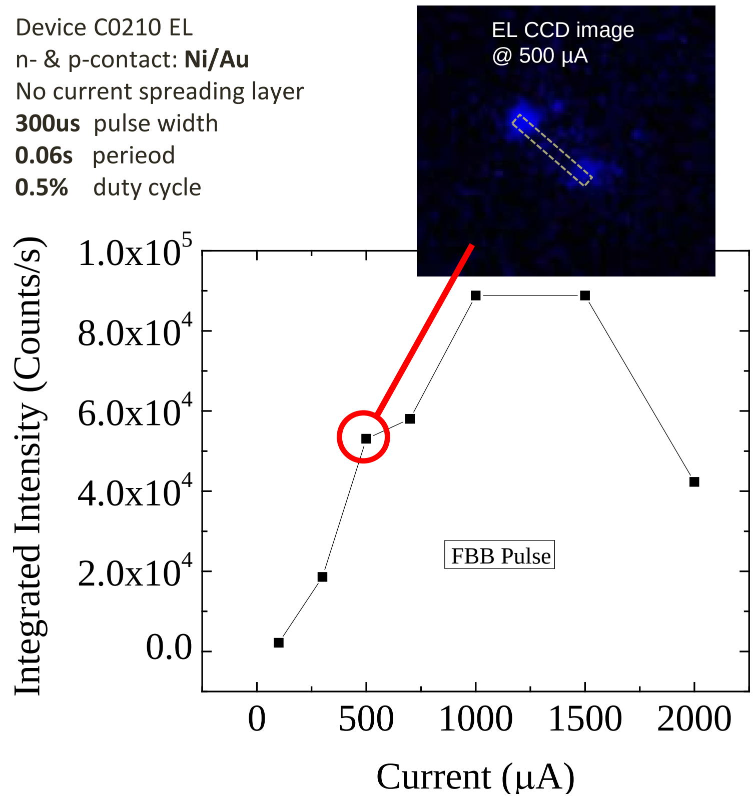
Key Accomplishments

Pulsed Measurement: Electrically injected nonpolar radial InGaN/GaN nanowire LED

- Device C0210 EL
- n- & p-contact: **Ni/Au**
- No current spreading layer
- **300us** pulse width
- **0.06s** perieod
- **0.5%** duty cycle

EL spectra of pulsed operation





- Stronger EL observed (accounting for duty cycle) from pulsed injection compared to continuous injection, but still no lasing observed
- Likely non-Ohmic p-contact reduces injection efficiency