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Vertically Aligned Growth and Characterization of III-Nitride Nanowires and Heterostructure Nanowires

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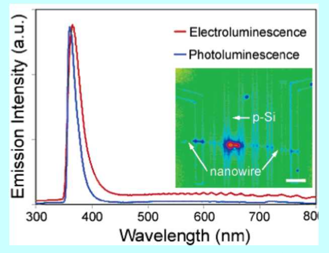
Semiconductor Nanowires

Reduced dimensionality and high atomic surface/bulk ratio can lead to enhanced or novel properties



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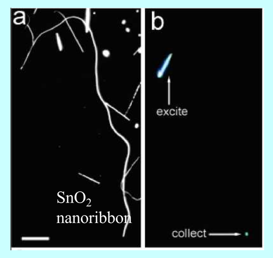
LEDs and microcavity lasers
- Nanosized light sources
- Higher efficiency due to lack of defects



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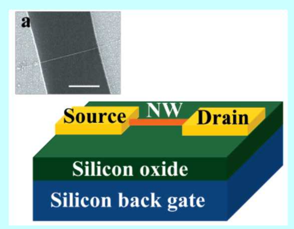
Waveguides and Filters
- coupled with nanowire light sources, building blocks for nanophotonics circuitry



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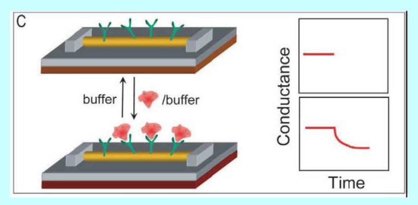
Transistors
- improved performance characteristics
- small size



Chem/bio-sensors
- large atomic surface/bulk ratio leads to depletion or accumulation in 'bulk' of nanowire
- resulting increased sensitivity may allow single-molecule detection

III-Nitride (AlGaInN) Nanowires

Attractive Properties of III-Nitrides

- Direct RT bandgaps spanning very wide energy range from ~0.7-6.2 eV (IR to deep UV)
- Form solid alloy system
- High breakdown field
- High mobility
- High thermal conductivity and temperature
- Radiation resistant and chemically inert
- Used in LEDs, laser diodes, UV photodetectors

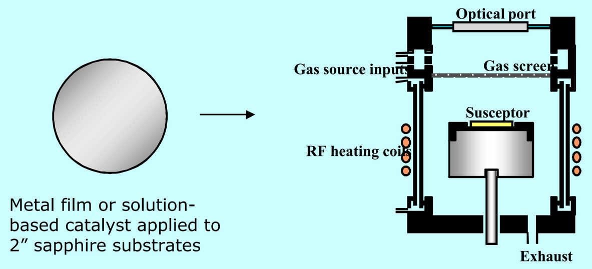
Project Goals

- Develop metal organic chemical vapor deposition (MOCVD) based growth techniques for the growth of III-nitride nanowires and heterostructure nanowires
- Develop control and understanding of nanowire alignment, density, quality, morphology, and properties
- Investigate electrical and optical properties of III-nitride nanowires as functions of growth parameters, size, morphology
- Use patterned templates for controlling placement, alignment
- Investigate surface effects and novel 1DEG/2DEG physics in core-shell heterostructure nanowires

Experimental Details

Catalysts: - Thin Ni films (2-5nm)
- $Ni(NO_3)_2$ in EtOH
- NiO nanoparticles in EtOH

MO Growth precursors:
Trimethylgallium (TMGa),
Trimethylaluminum (TMAl),
Trimethylindium (TMIn),
Ammonia (NH_3)



Metal film or solution-based catalyst applied to 2" sapphire substrates

Cold-wall rotating disk reactor

Advantages of MOCVD/OMVPE for III-Nitride Nanowire Growth
- Standard technique for III-nitride commercial growth
- Compositional control (alloys)/Doping
- *Ability to grow heterostructure nanowires in-situ*
- In-situ integration with films
- Scalability

Template-Free, Vertically Aligned Growth of GaN Nanowires on Sapphire

Represents simple pathway to inexpensive devices based on dense, vertically aligned III-nitride nanowires

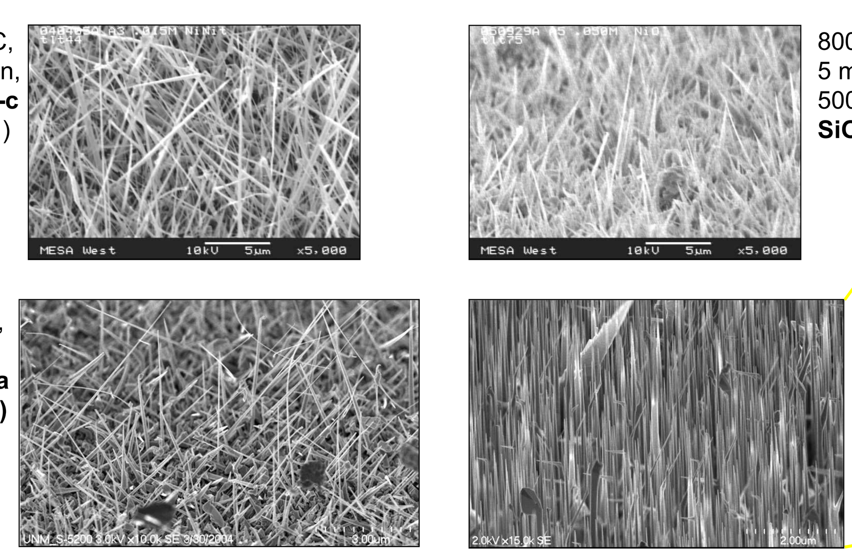
Role of Substrate Orientation on GaN Nanowire Growth

800°C, 15 min, **sapp-c (0001)**

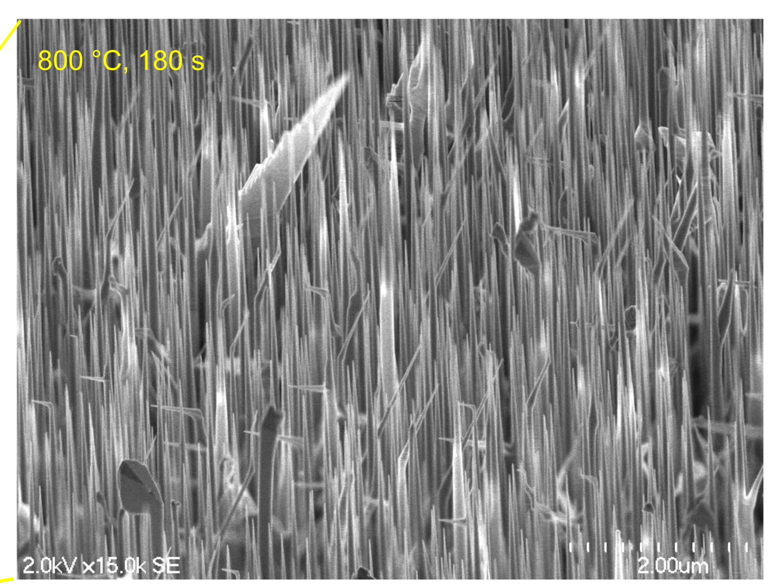
800°C, 5 min, 500nm **SiO_2 on Si**

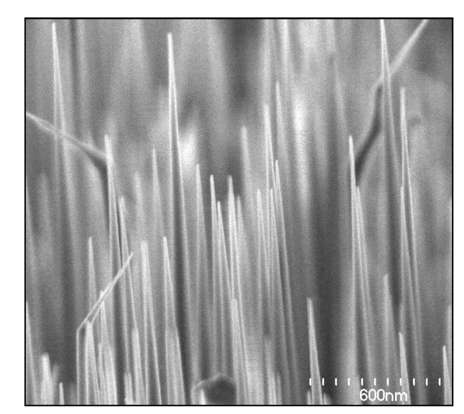
800°C, 5 min, **sapp-a (11-20)**

800°C, 3 min, **sapp-r (1-102)**

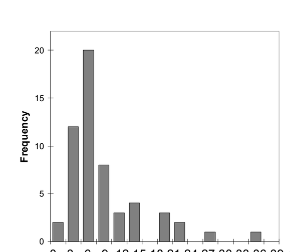


- Substrate plays important role in alignment
- Wires are triangular faceted on all substrates



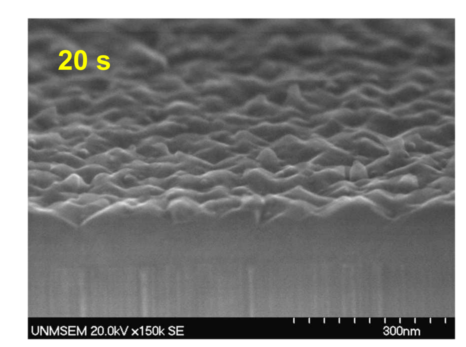


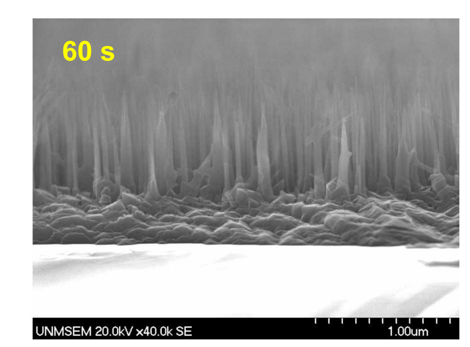
- Nanowires tapered and have sharp tips
- Nanowire facets all aligned in same direction, indicates common crystal orientation/direction

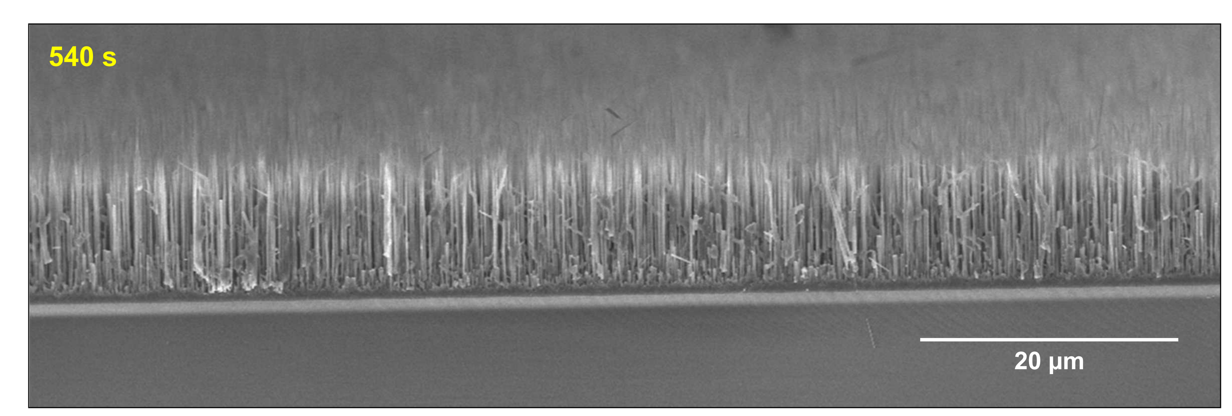


Nanowire tip diameter histogram, 180s growth

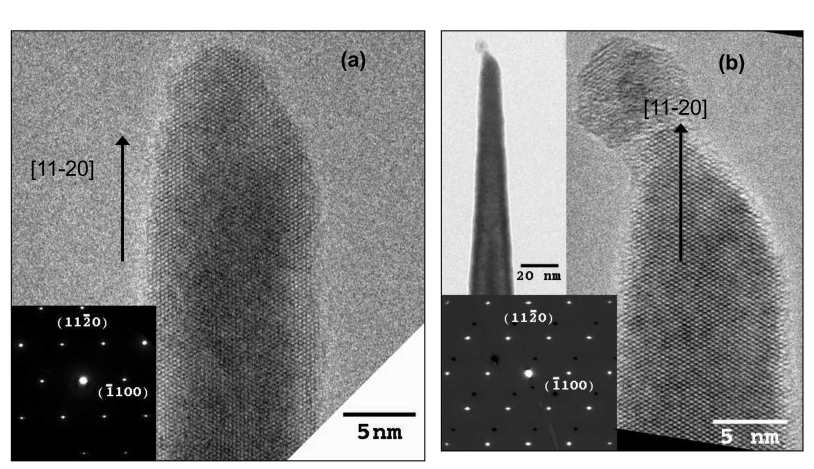
X-section view of GaN nanowire growth on (1-102) sapphire as a function of time





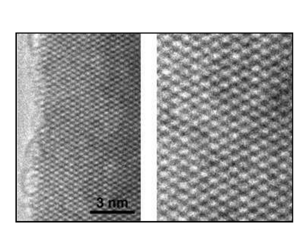


Vertically Aligned Nanowires – TEM Results and Growth Model

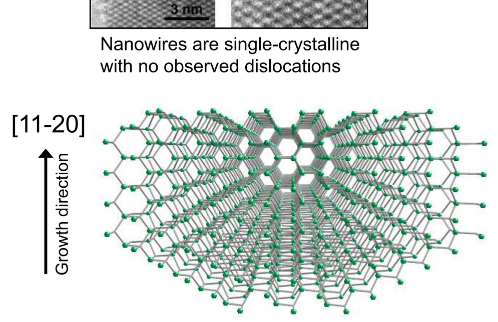


[11-20] oriented GaN nanowire
No catalyst tip

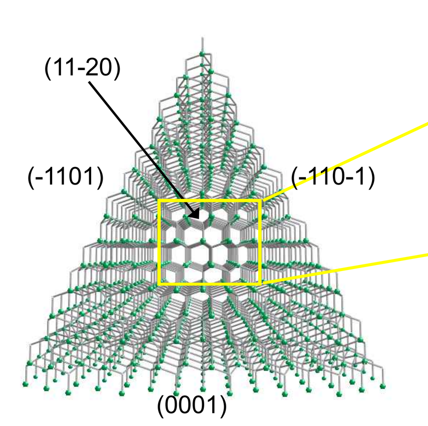
[11-20] oriented GaN nanowire
Ni catalyst tip



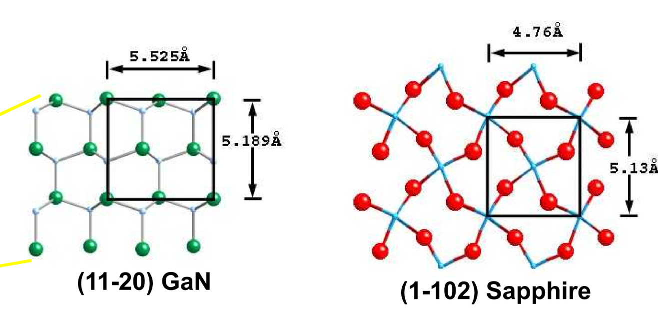
Nanowires are single-crystalline with no observed dislocations



[11-20] GaN Nanowire Side View

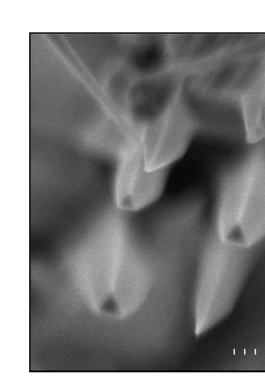


[11-20] GaN Nanowire Cross Section View Model Showing Side-Facet Planes

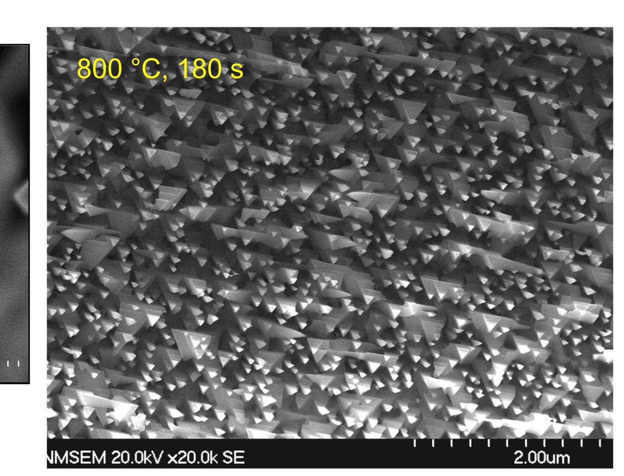


(11-20) GaN **(1-102) Sapphire**

- Nanowire growth direction same as (11-20) GaN film growth on r-plane sapphire – good crystallographic match explains alignment
  - [0001]GaN||[-1101]sapp = 1.3% mismatch
  - [-1100]GaN||[11-20]sapp = 15% mismatch



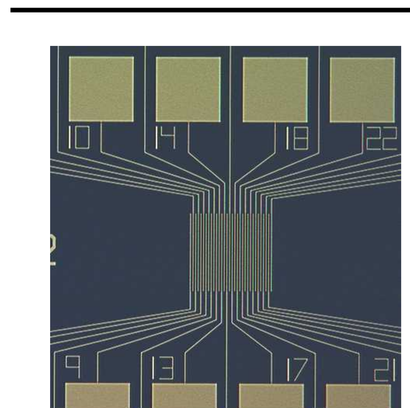
(Near plan view)



Plan view of GaN nanowire growth on (1-102) sapphire by MOCVD shows aligned facets & high density, along with nonvertical nanowires

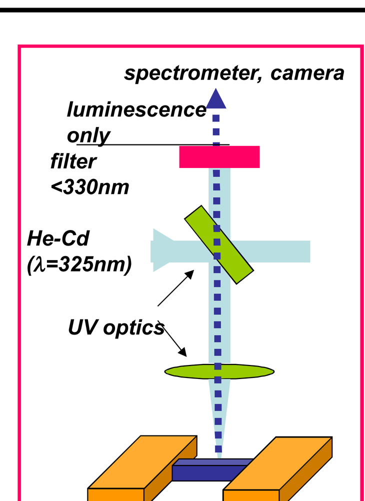
Wang, G. T., J. R. Creighton, A. Alec Talin, D. Werder, E. Lai, R. Anderson, I. Arslan. "Highly aligned growth and characterization of dense GaN nanowires on sapphire by metal-organic chemical vapor deposition." Nanotechnology 17 (2006) 5773-5780

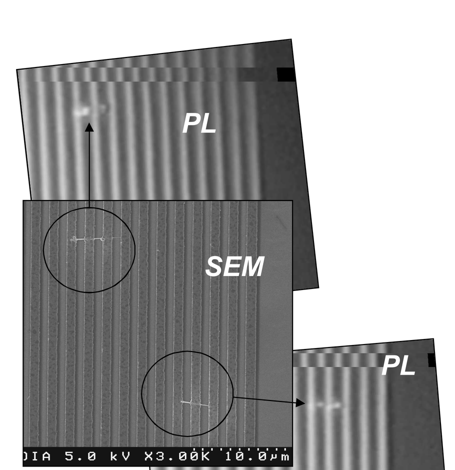
Sandia Platform for *Combined* Optical and Electrical Characterization



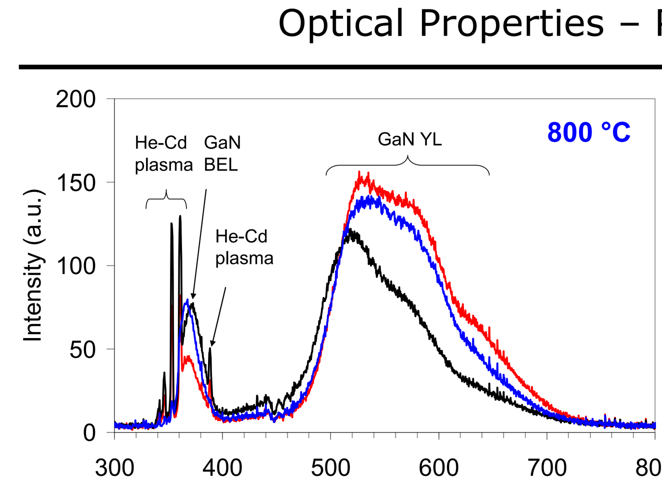
Nanowires dispersed onto Si/SiO_2; Addressable array of 32 top electrodes patterned

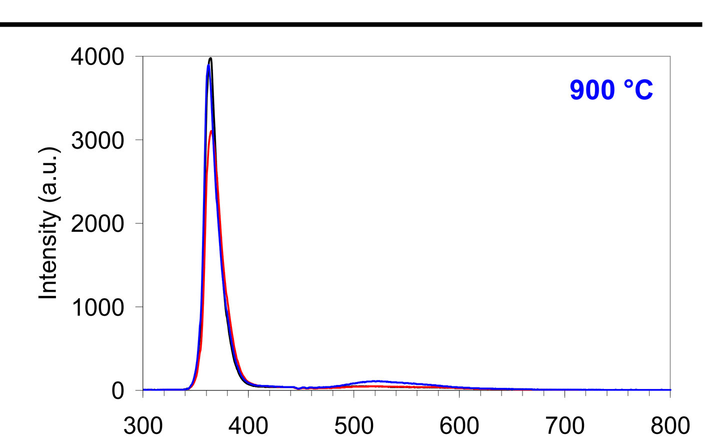
Each wafer -> ~100 individually addressable nanowire devices for statistically meaningful results





Optical Properties – Photoluminescence Studies

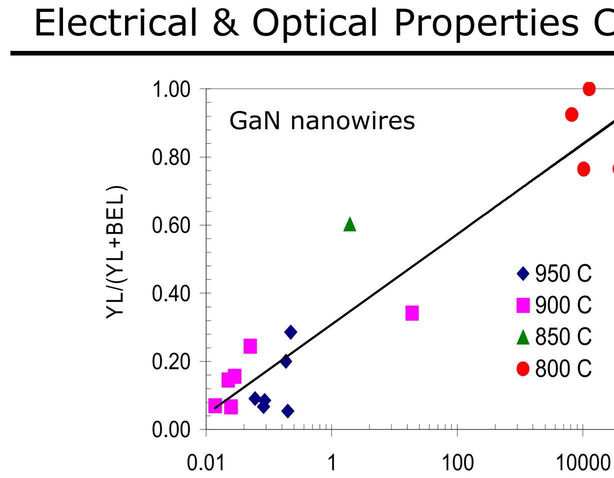




- Significant defect related yellow luminescence (YL) in nanowires grown at 800 °C
- **~50x increase in band-edge emission at 900 °C vs. 800 °C**, very good quality compared to undoped films
- YL linked to C incorporation in GaN films*

* Wickenden, A.E., Koleske, D.D., Henry, R.L., Twigg, M.E., Fatemi, M. *J. Crys. Growth* **2003**, 54

Electrical & Optical Properties Correlated



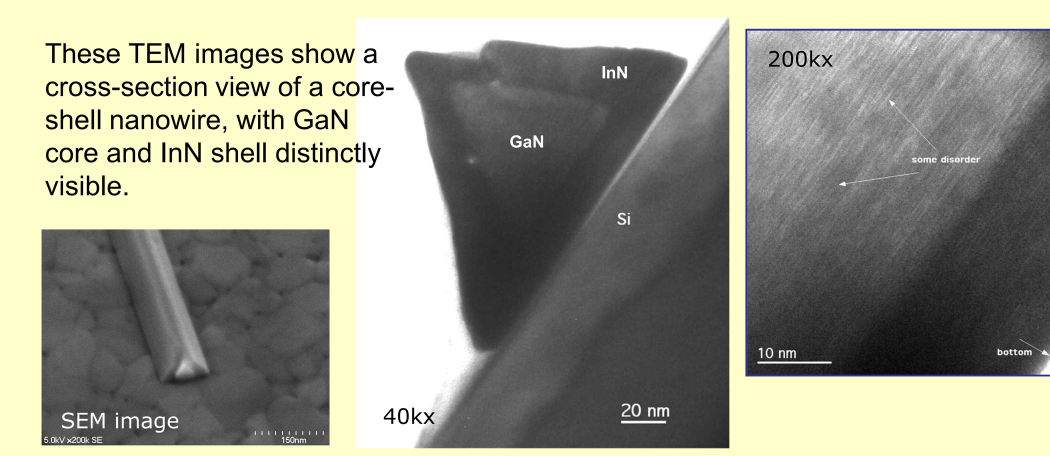
Growth T-Resistivity-PL Increase of growth temperature from 800°C to 900°C decreases nanowire resistivity by ~10^5, and significantly increases the band edge luminescence (BEL) compared to yellow luminescence (YL), generally associated with defects. Carbon, incorporated at 800°C from TMGa, may act as deep acceptor, compensating free carriers and quenching BEL.

Radial III-Nitride Heterostructure Nanowires

- Heterostructures are integral to modern compound semiconductor devices
- Heterostructure core-shell nanowires may have novel/enhanced properties

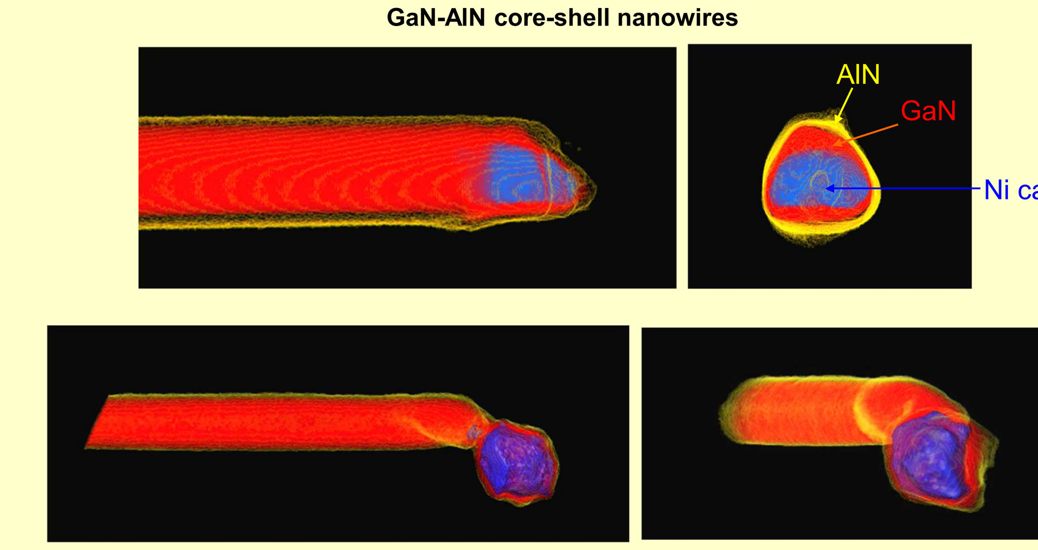
Cross-section of GaN core grown at 800°C, InN shell grown at 550°C

These TEM images show a cross-section view of a core-shell nanowire, with GaN core and InN shell distinctly visible.

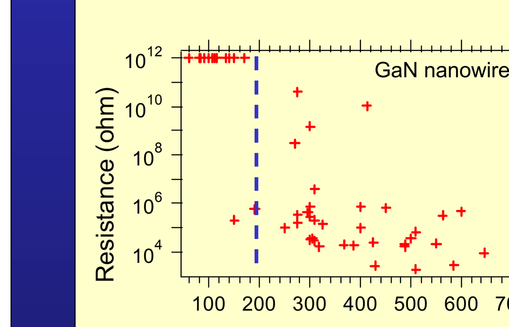


STEM tomography provides 3D visualization of nanowire, catalyst

GaN-AlN core-shell nanowires



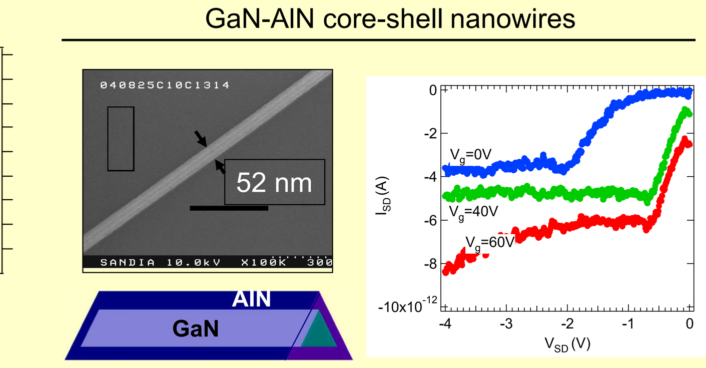
Passivation of surface states in GaN-AlN heterostructure nanowires?



Critical dimension
At GaN nanowire diameters less than ~200 nm, the resistance increases sharply. This is likely due to depletion of carriers by surface states.*

* Calarco, et.al., *Nanoletters* **5**, 981 (2005).

GaN-AlN core-shell nanowires



In contrast, for **GaN-AlN core-shell heterostructure nanowires**, conduction *is* observed in many nanowires at diameters ~50nm, indicating passivation of surface states.

Acknowledgments

- DOE Basic Energy Sciences
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