nanoHub 501 Tutorial
Purdue University
16 January 2008

Multiphase Gallium Nitride Nanowires and Nanocircuits

Professor Virginia M. Ayres
Electronic and Biological Nanostructures Laboratory
Department of Electrical & Computer Engineering
Michigan State University, USA

ayresv@msu.edu

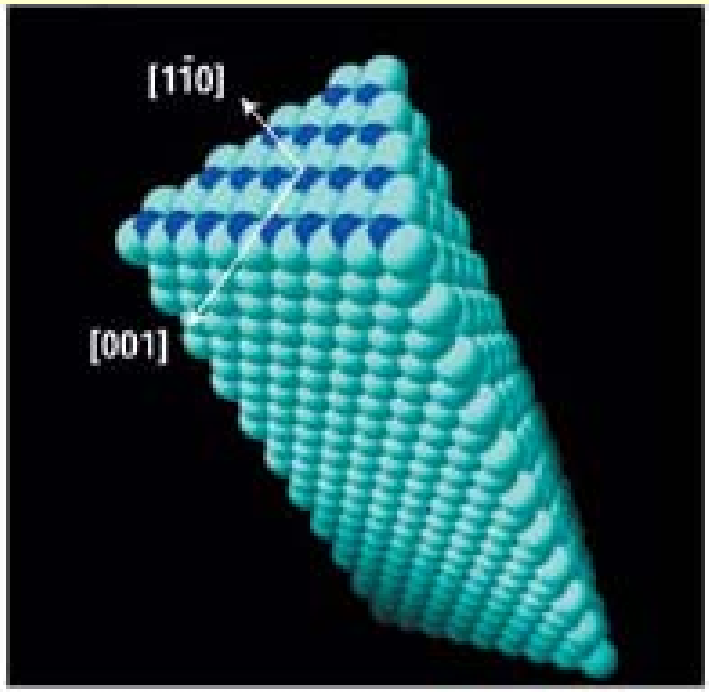
http://www.egr.msu.edu/ebnl

Andrew Baczewski
NSF REU
Dr. Reg Ronningen
NSCL
Prof Marty Crimp
Dr. Ben Jacobs
HRTEM
Kaylee McElroy
SEM
Prof. Josh Halpern
Dr. Maoqi He
Multiphase GaN NWs
Wood shop
First Aid Kit
PEPSI

Outline:

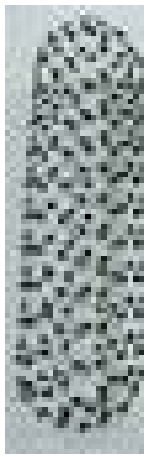
- Multiphase GaN Nanowires
  - Single-Phase Nanowires
  - Multiphase Nanowires
    - Plain-View HRTEM
    - SAED, EDS, EELS, CL, SEM
    - Cross-Section HRTEM
  - Where NWs Come From: Matrix
    - SEM
    - HRTEM
  - How Multiphase NWs Form
- Novel Nanoelectronics
  - 2 and 4-Point Probe
  - GaNFETs
- Radiation Experiments
  - Space Radiation Environment
  - Electronics in Space
  - Simulated Space at the NSCL
  - Radiation Experiments
    - GaN Nanowires
    - GaN Nanocircuits

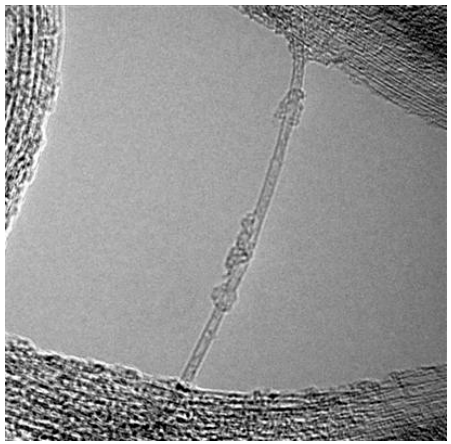
VLS Growth of Single Phase GaN Nanowires

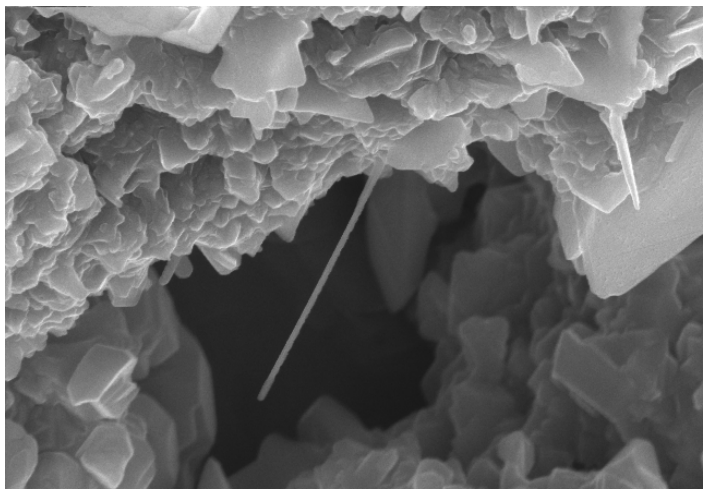


Nature Materials 3, 524 - 528 (2004)

Single Phase GaN Nanowires



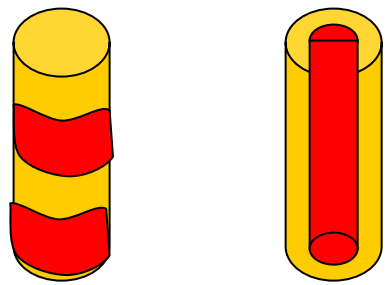




Carbon Nanotubes:
S. Iijima, early 1990's

Homostructure Nanowires:
Si: C. Lieber, mid 1990's
Ge, III-V (GaN), II-VI (ZnSe)

Heterostructure Nanowires:
Lieber, Yang, Cui: mid 1990's ->
GaAs-AlGaAs
GaP-AlGaP
GaN-InGaN



Vapor-Liquid-Solid Growth

GaN Quantum Well Lasers: 1990s ->

Adele C. Tamboli, Elaine D. Haberer, Rajat Sharma, Kwan H. Lee, Shuji Nakamura and Evelyn L. Hu, Room-temperature continuous-wave lasing in GaN/InGaN microdisks, Nature Photonics 1, 61 - 64 (2006)

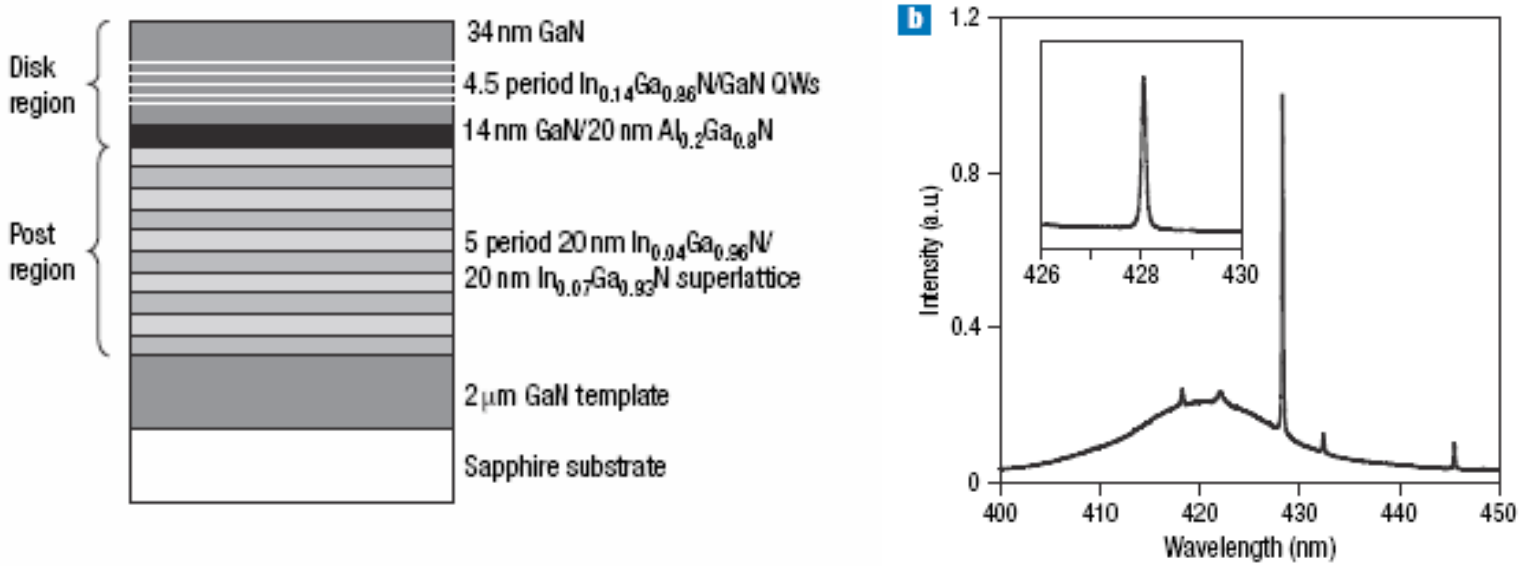
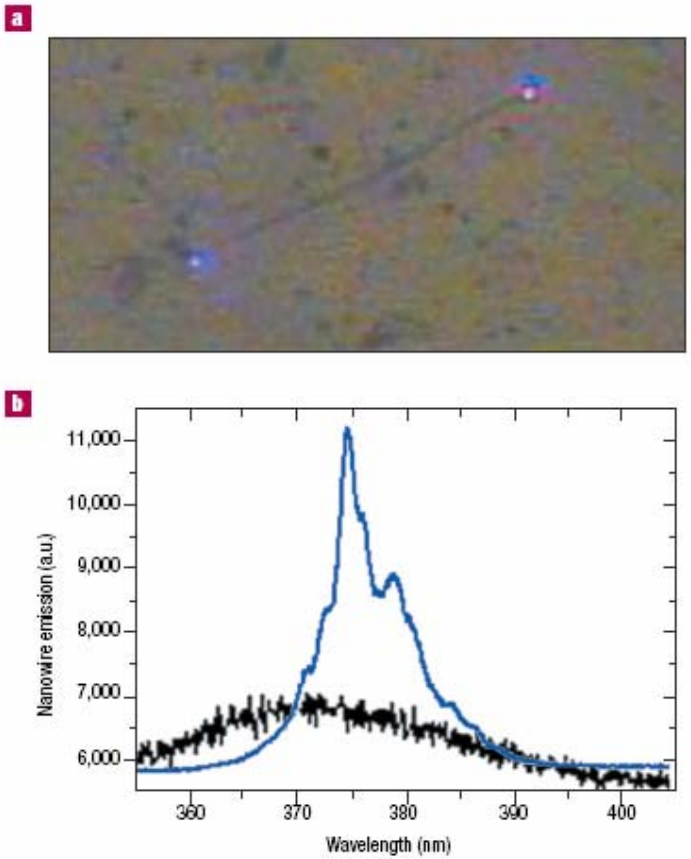


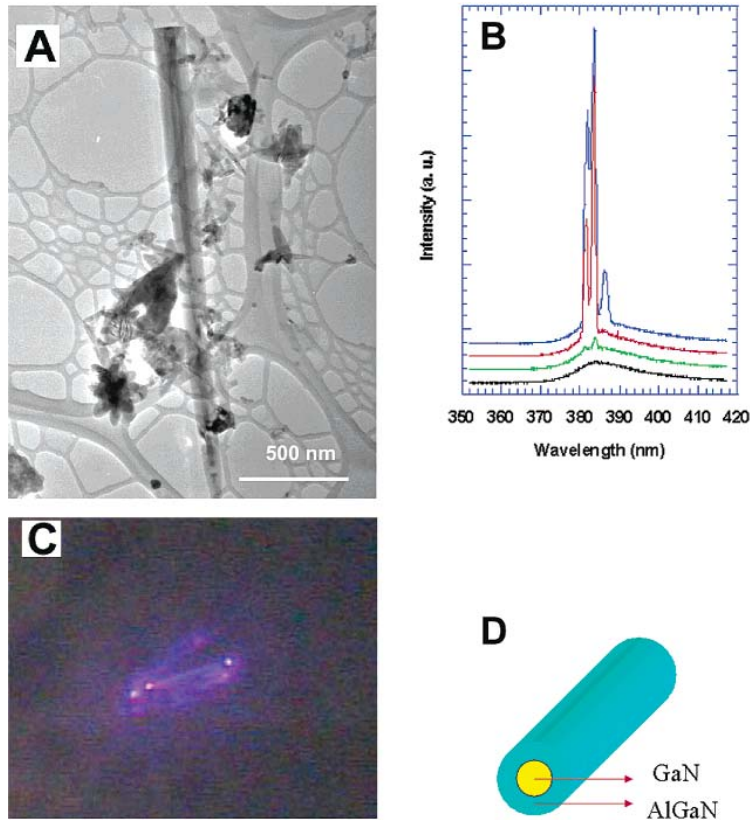
Figure 1 Epitaxial structure of material used to make microdisks. Light is confined to the disk region, and the post region is selectively etched to form an undercut structure.

Single Phase GaN Nanowires

JC Johnson, HJ Choi, KP Knutsen, RD Schaller, P Yang and R Saykally, Single gallium nitride nanowire lasers Nature Materials, 106-109, 2002

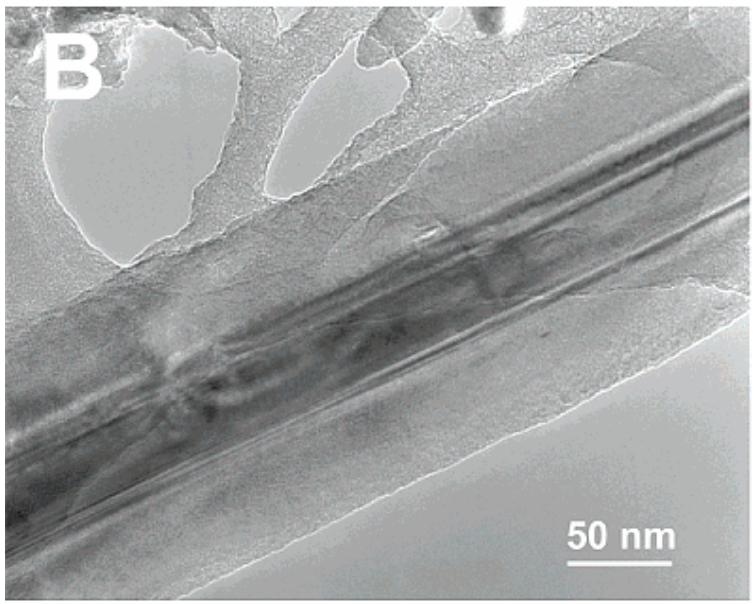


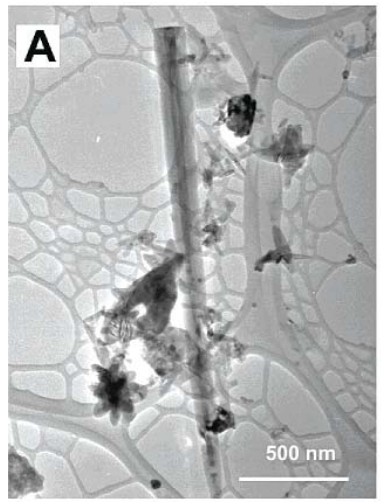
Heon-Jin Choi, Justin C. Johnson, Rongrui He, Sang-Kwon Lee, Franklin Kim, Self-Organized GaN Quantum Wire UV Lasers, J. Phys. Chem. B, 107, 8721-8725, 2003

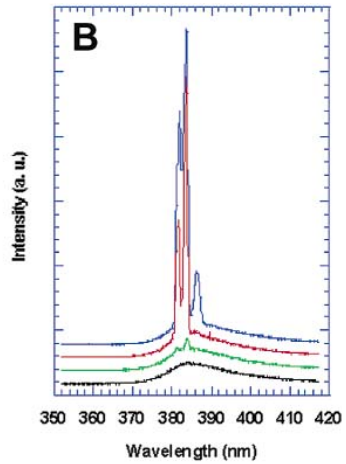


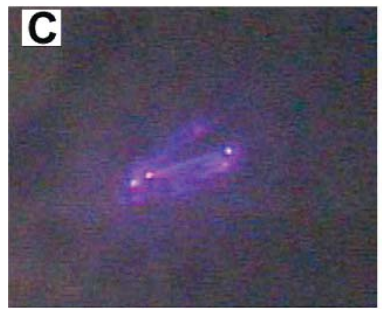
Single Phase GaN Nanowires

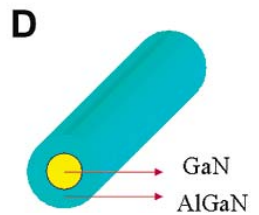
Heon-Jin Choi, Justin C. Johnson, Rongrui He, Sang-Kwon Lee, Franklin Kim, Self-Organized GaN Quantum Wire UV Lasers, J. Phys. Chem. B, 107, 8721-8725, 2003









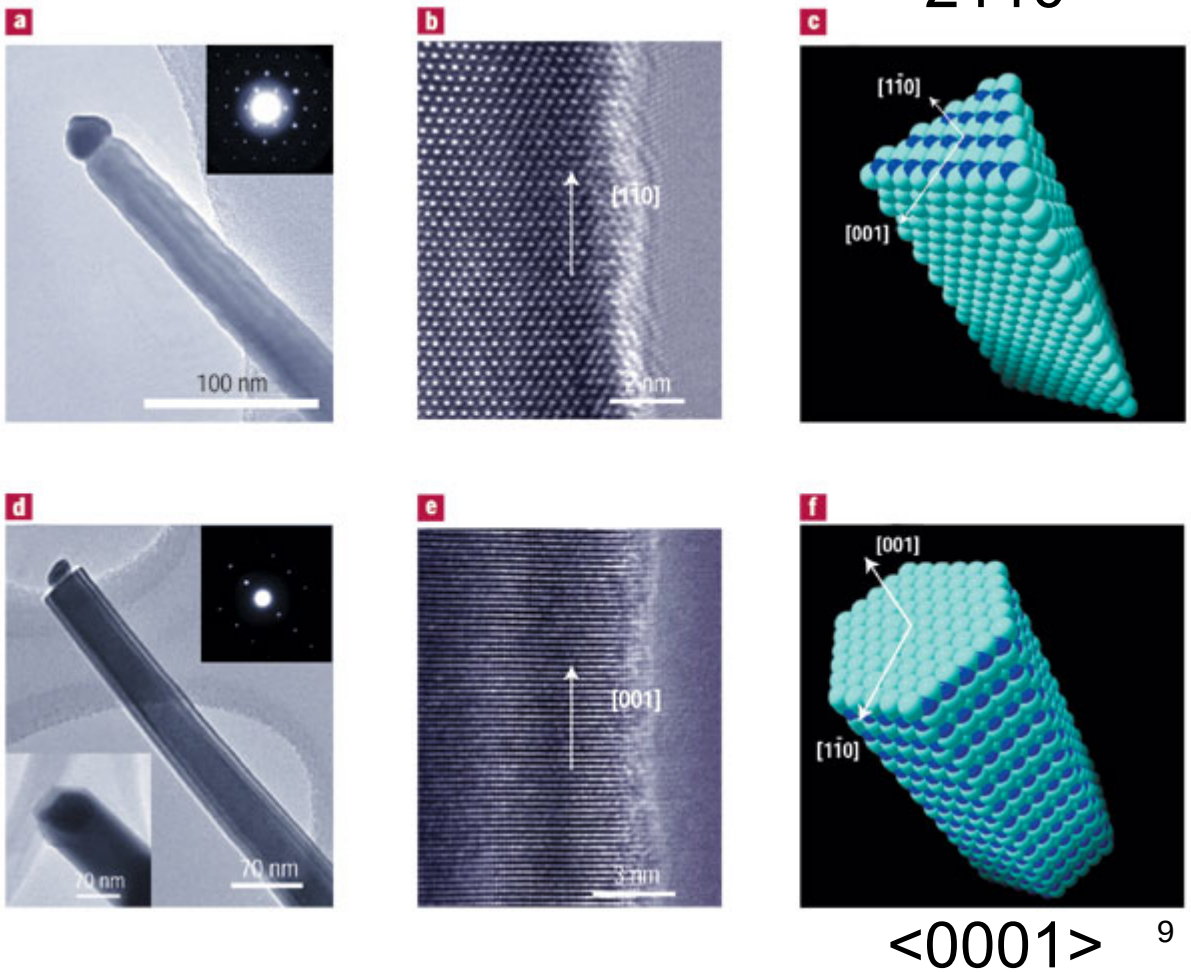


Single Phase GaN Nanowires

Tevye Kuykendall, Peter J. Pauzauskie, Yanfeng Zhang, Joshua Goldberger, Donald Sirbuly, Jonathan Denlinger and Peidong Yang, Crystallographic alignment of high-density gallium nitride nanowire arrays, Nature Materials 3, 524 - 528 (2004)

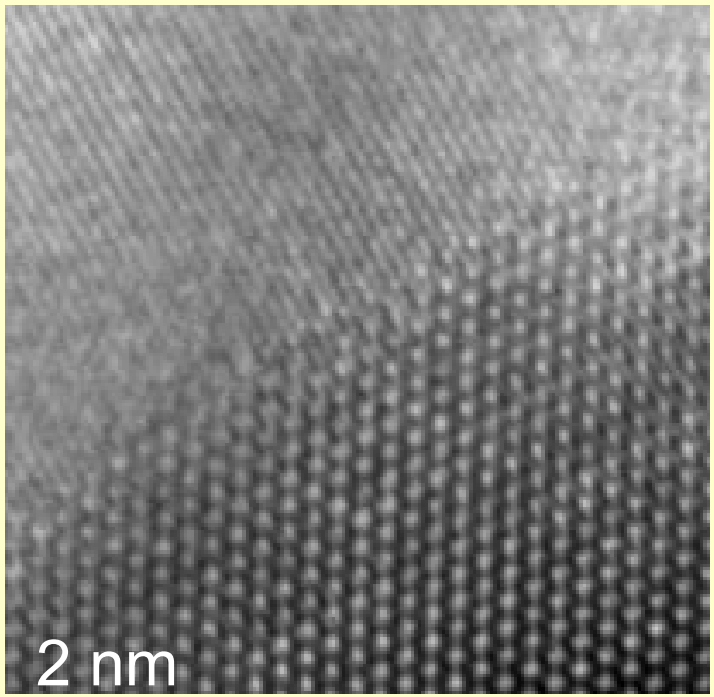
<$2\bar{1}\bar{1}0$>

Vapor-liquid-solid (VLS) growth



<0001>

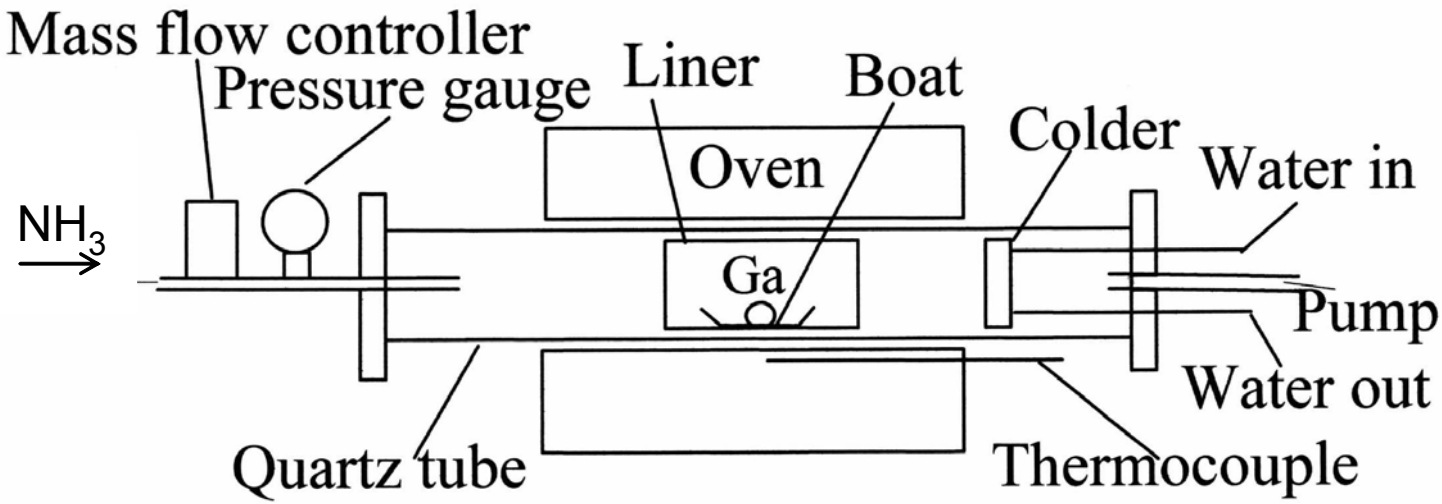
VS Growth of Multiphase GaN Nanowires



Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)

Multiphase GaN Nanowires:

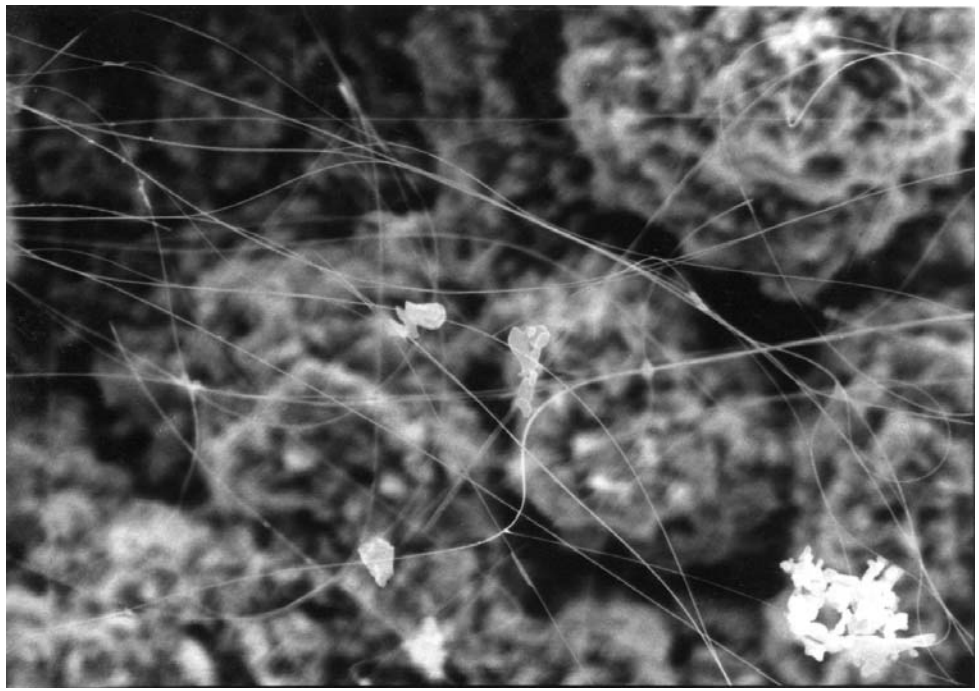
- Catalyst free
- Direct reaction NH_3 with Ga



M. He, P. Zhou, S.N. Mohammad, G.L. Harris, J.B. Halpern, R. Jacobs, W.L. Sarney, L Salamanca-Riba, "Growth of GaN nanowires by direct reaction of Ga with NH3", *J. of Crystal Growth* Vol. 231 (2001) 357.

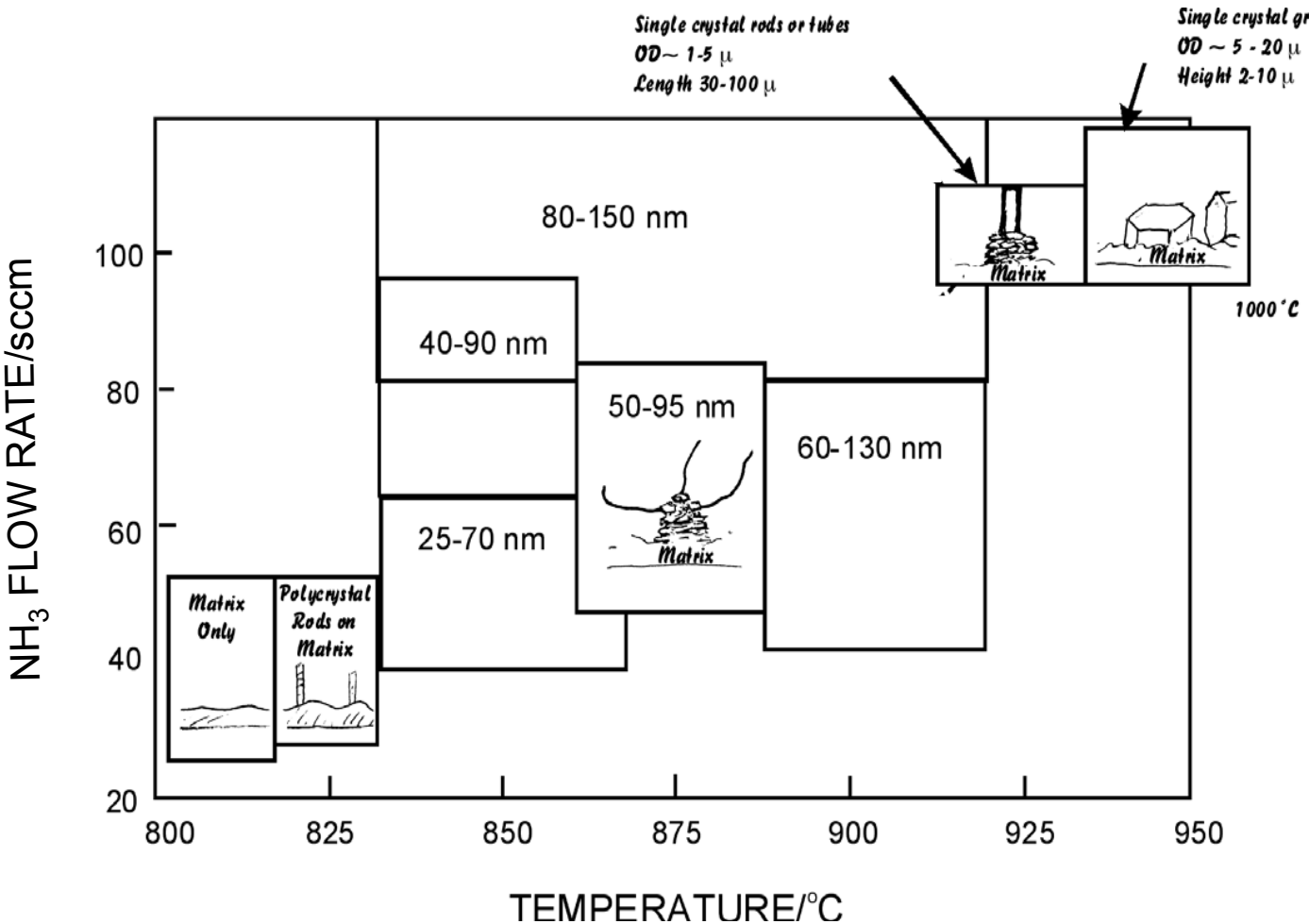
Multiphase GaN Nanowires:

- Catalyst free
- Direct reaction NH_3 with Ga
- Oxygen-free starting materials



M. He, P. Zhou, S.N. Mohammad, G.L. Harris, J.B. Halpern, R. Jacobs, W.L. Sarney, L Salamanca-Riba, "Growth of GaN nanowires by direct reaction of Ga with NH3", *J. of Crystal Growth* Vol. 231 (2001) 357.

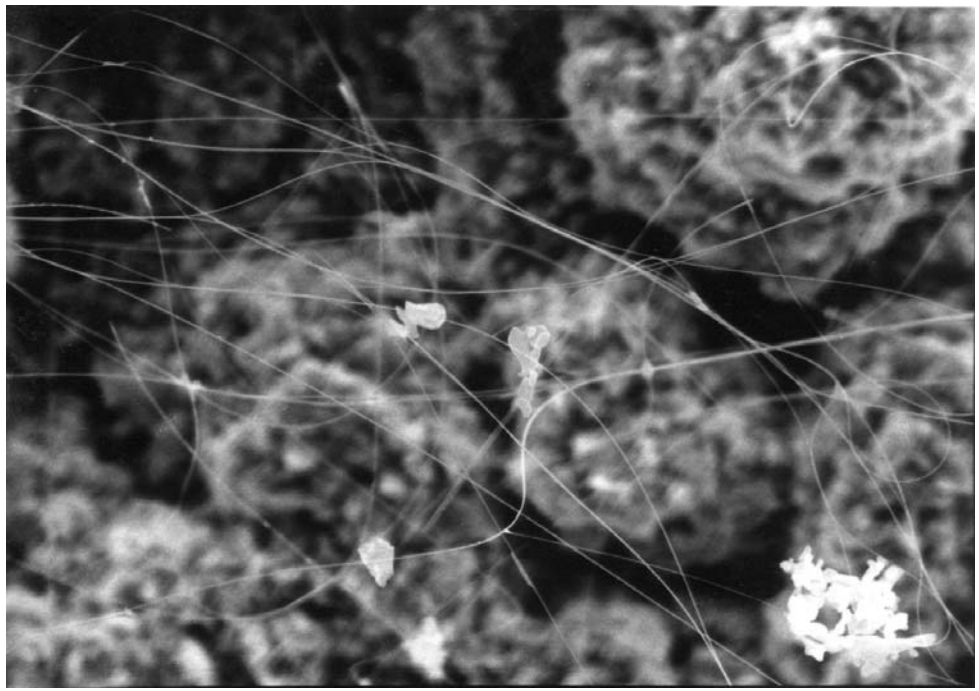
Multiphase GaN Nanowires: Growth Matrix



1. Self-catalyzed VLS
2. Vapor-Solid

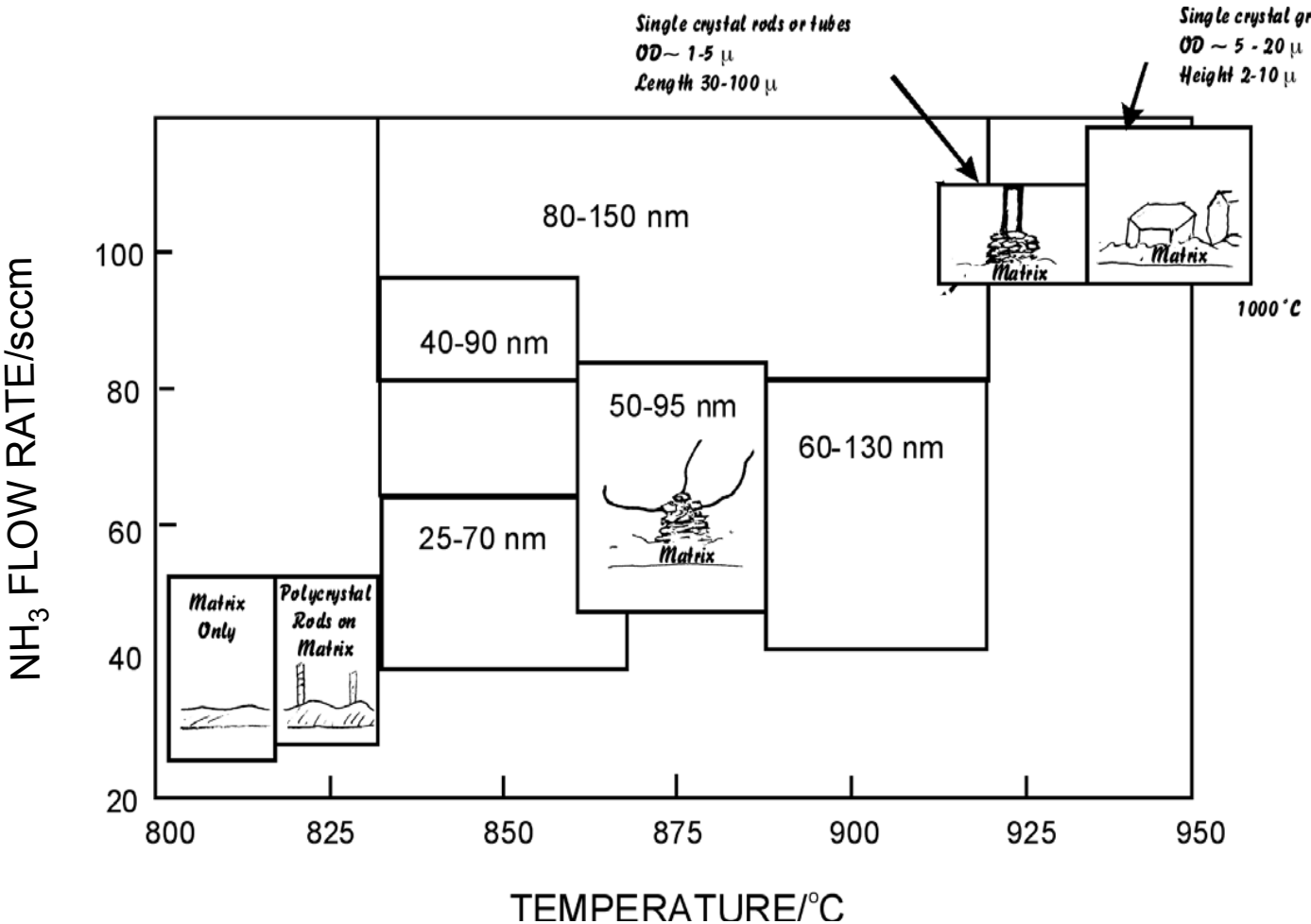
Multiphase GaN Nanowires:

- Catalyst free
- Direct reaction NH_3 with Ga
- Oxygen-free starting materials



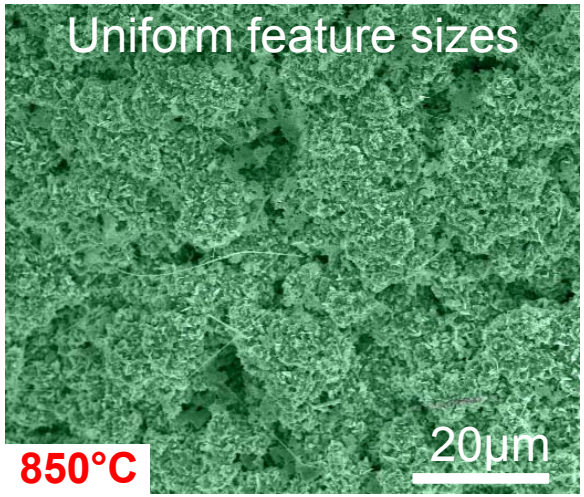
M. He, P. Zhou, S.N. Mohammad, G.L. Harris, J.B. Halpern, R. Jacobs, W.L. Sarney, L Salamanca-Riba, "Growth of GaN nanowires by direct reaction of Ga with NH3", *J. of Crystal Growth* Vol. 231 (2001) 357.

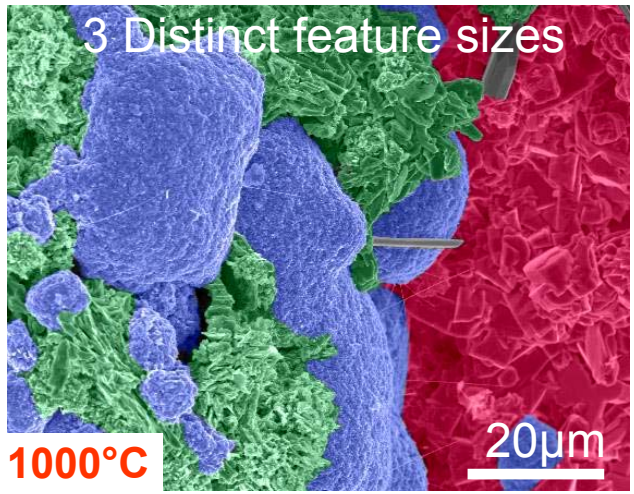
Multiphase GaN Nanowires: Growth Matrix



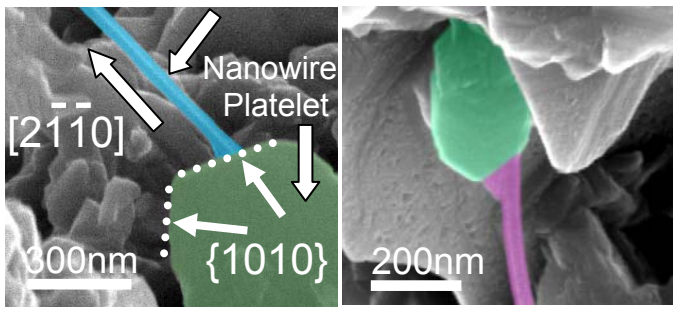
1. Self-catalyzed VLS
2. Vapor-Solid

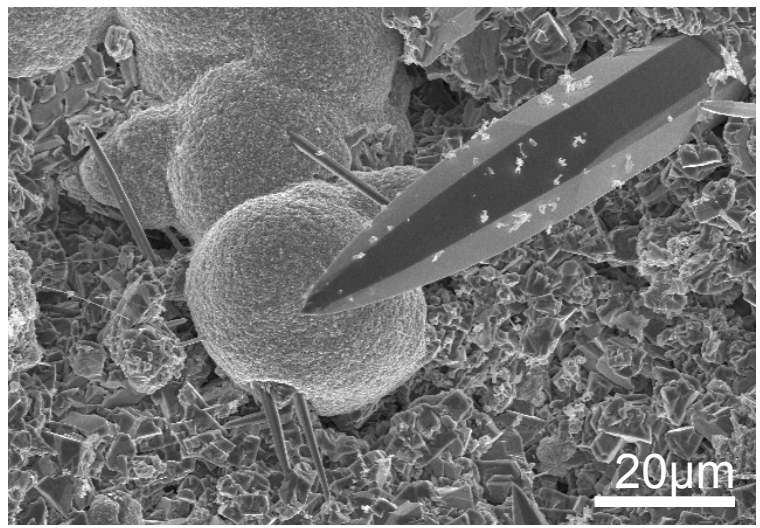
The Growth Matrix





- Blue region - 100 nm to 200 nm. Green region - 200 nm to 1 µm. Red region - 1 µm to 5 µm.

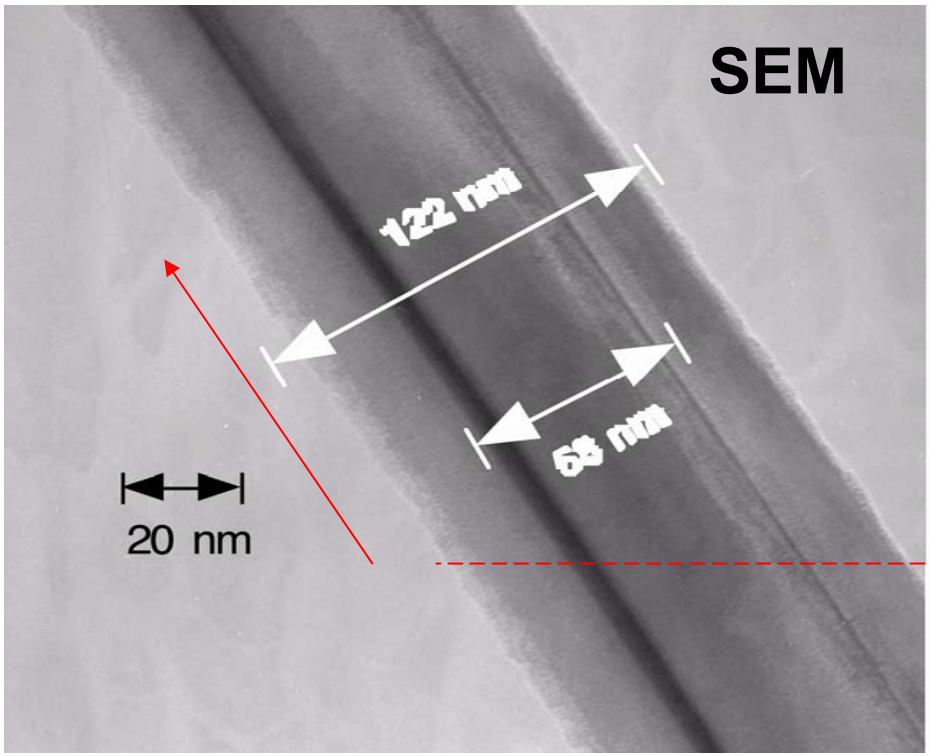


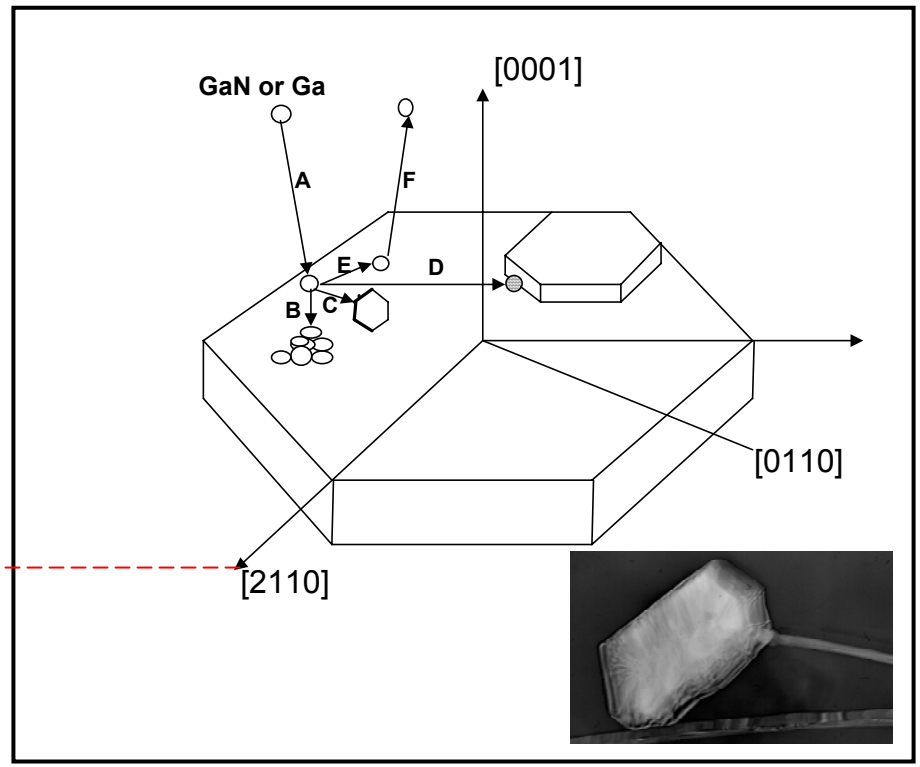


- Nanowires grow from hexagonal platelet sides
- Based on previous nanowire growth directions and shape of the platelet sides, looking down on the platelet top (0001) planes

Multiphase GaN Nanowires:

Vapor-Solid (VS) Growth



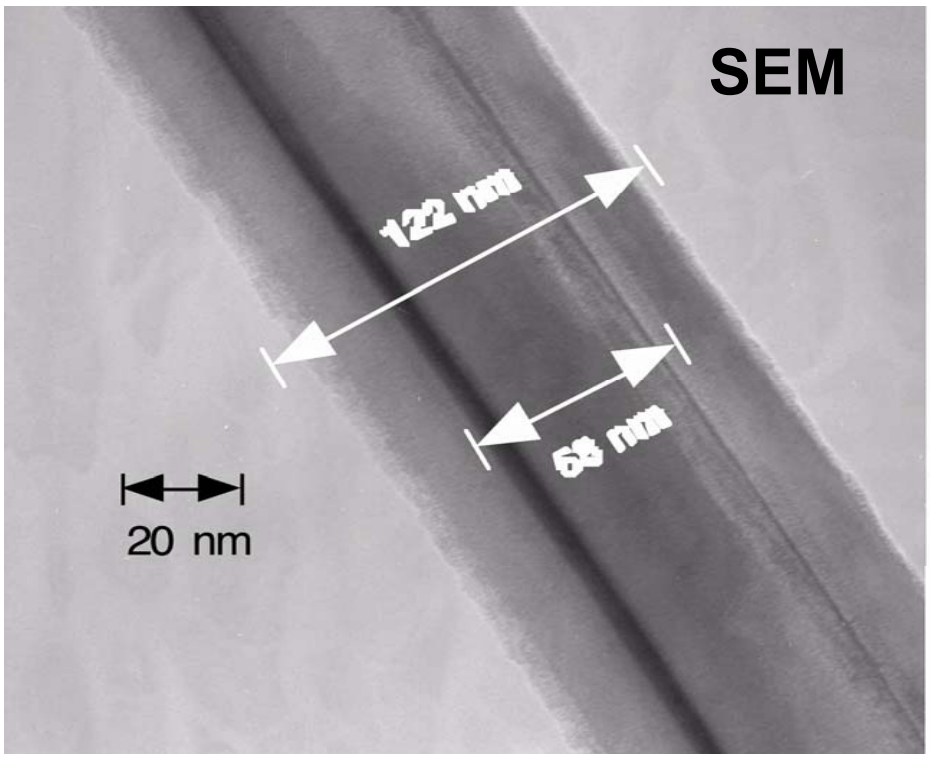


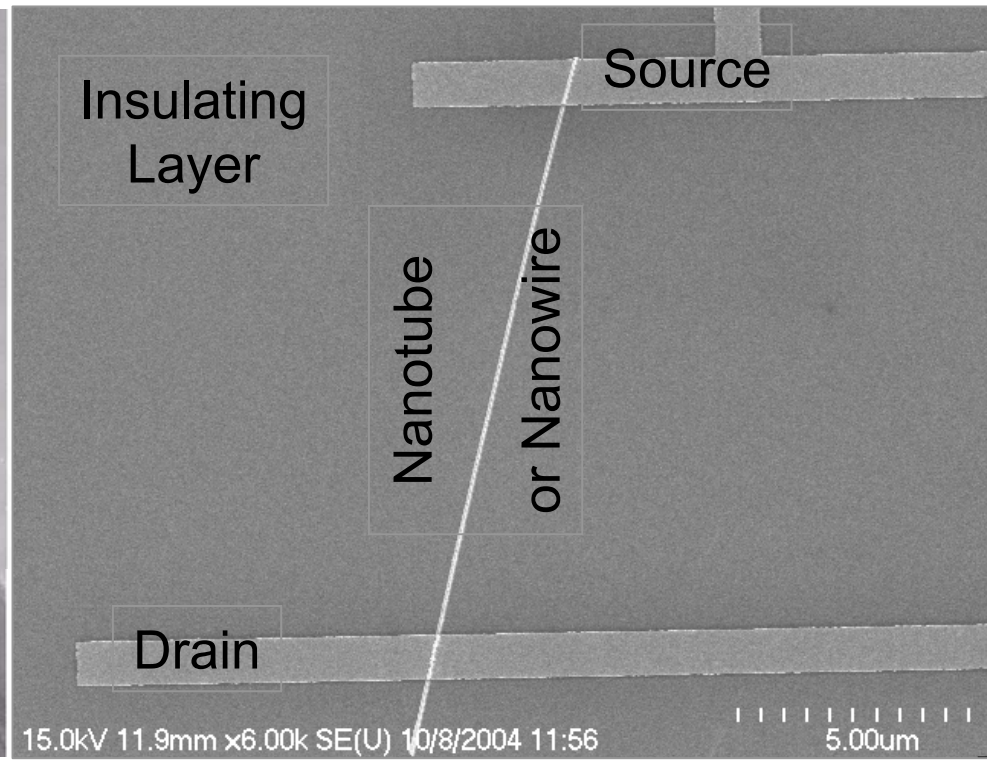
Single Phase Wurtzite GaN Nanowires **X**

M. He, P. Zhou, S.N. Mohammad, G.L. Harris, J.B. Halpern, R. Jacobs, W.L. Sarney, L Salamanca-Riba, "Growth of GaN nanowires by direct reaction of Ga with NH3", *J. of Crystal Growth* Vol. 231 (2001) 357

Original goal: nanoFET by Electron Beam Lithography

nanoFET by EBL

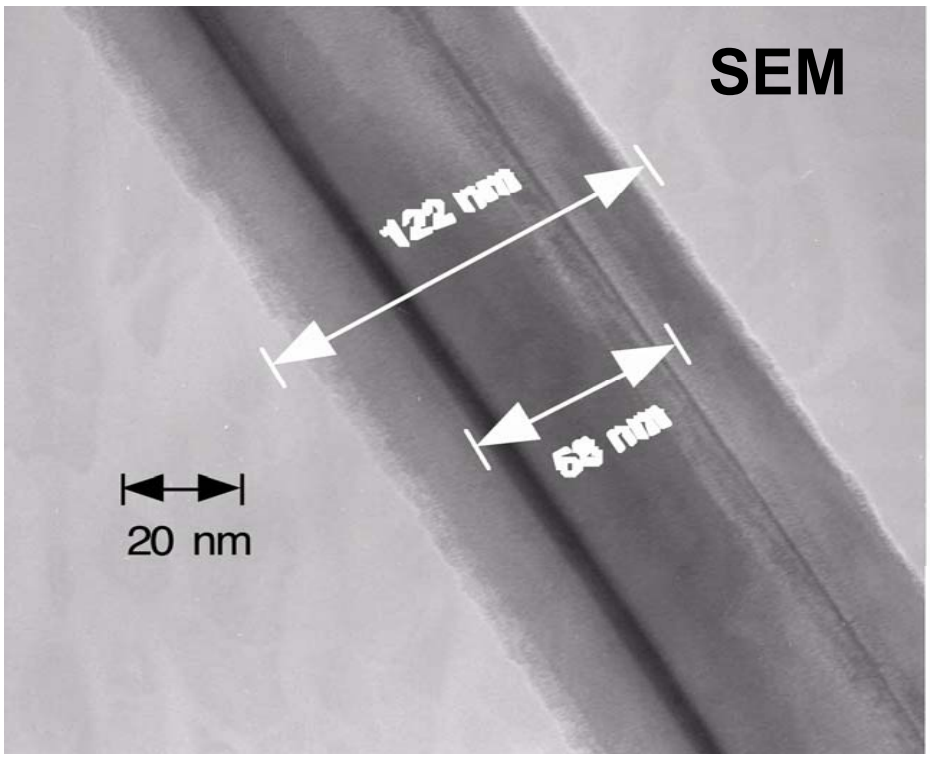


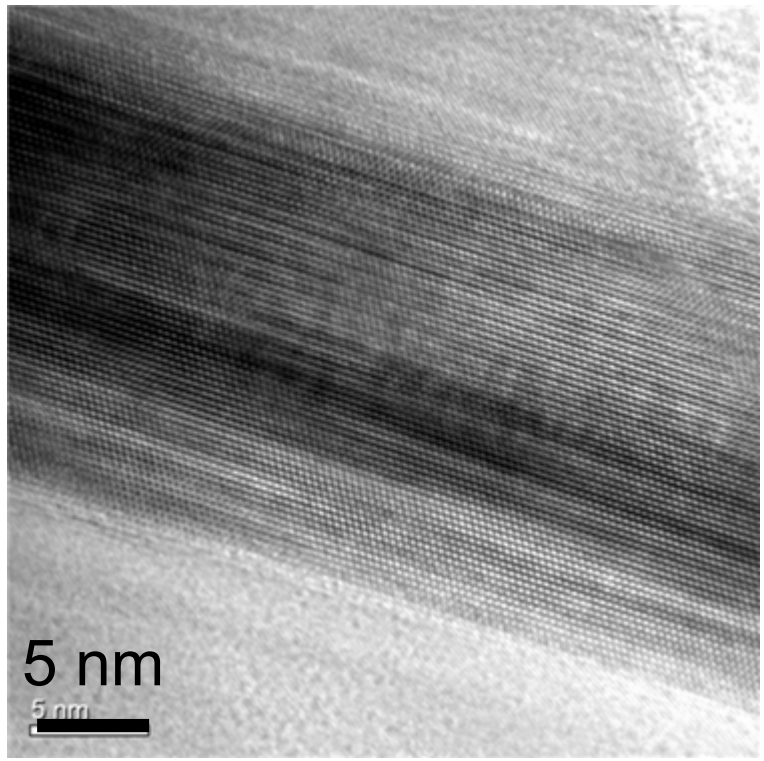


nanoFET by EBL
W. M. Keck Foundation
Microelectonics Center

Multiphase GaN Nanowires:

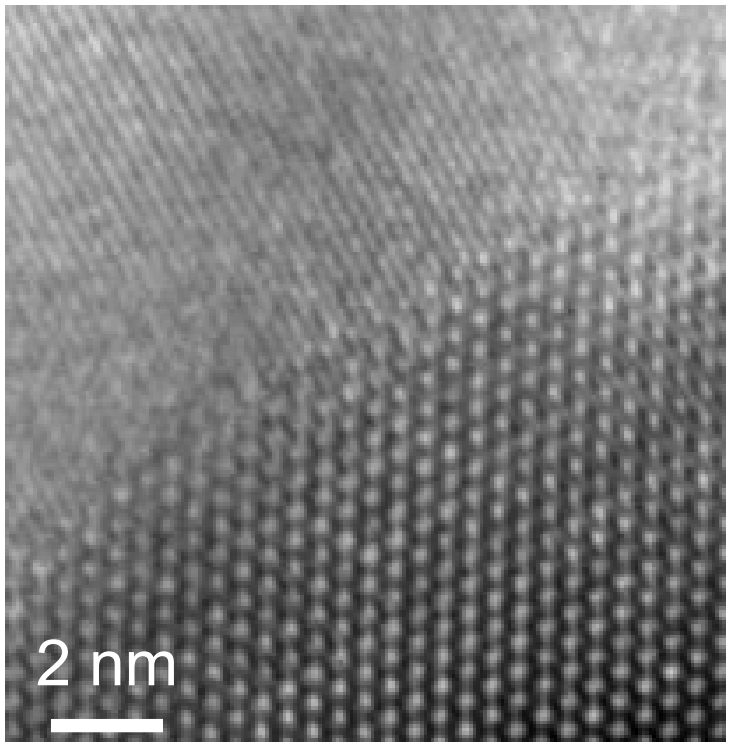
TEM: JEOL 2200FS



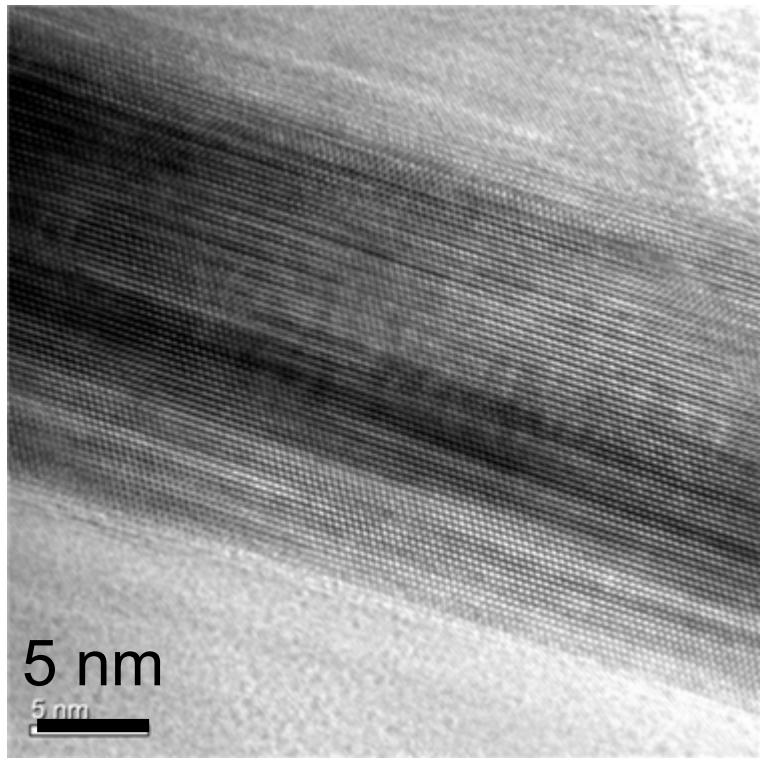


Multiphase GaN Nanowires:

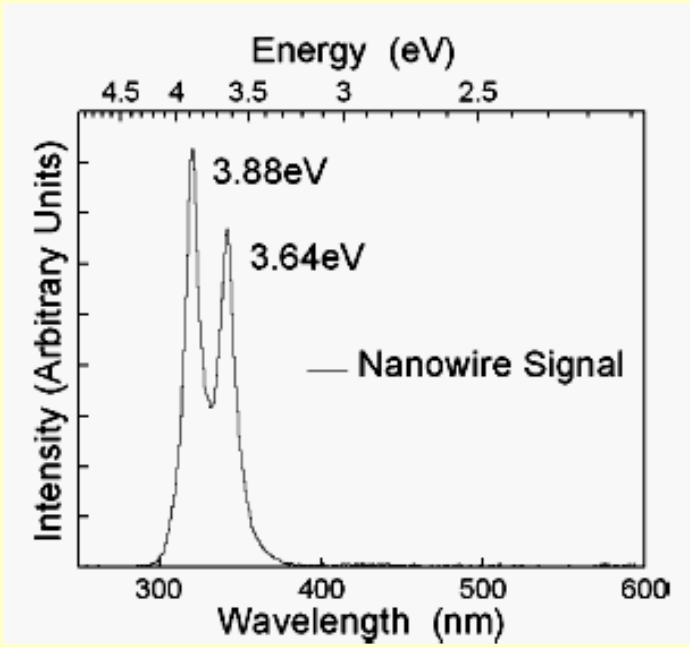
HRTEM: JEOL FE 2200



TEM: JEOL 2200FS

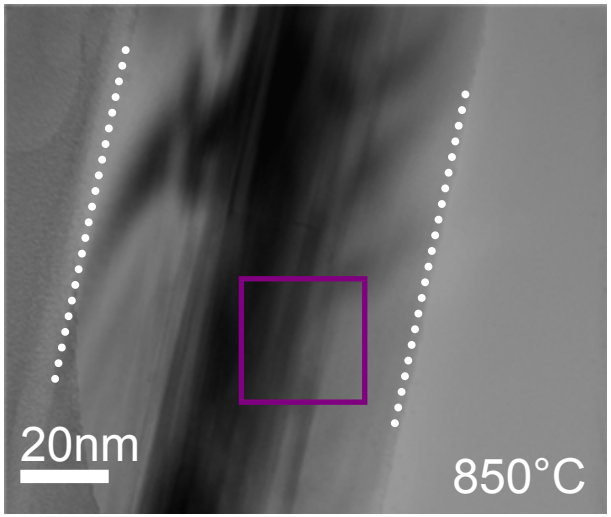


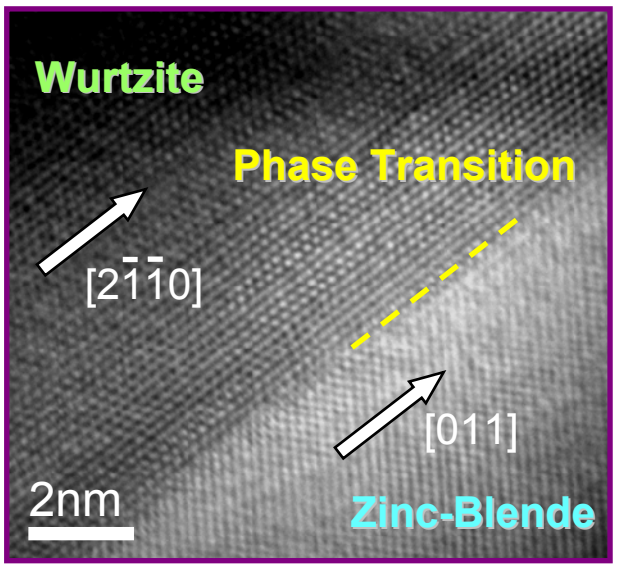
Multiphase GaN Nanowires: the Proofs

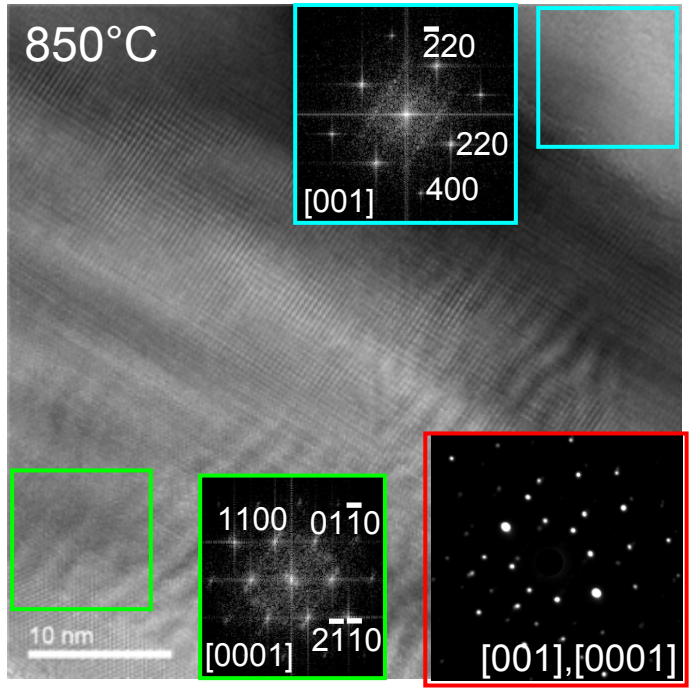


Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)

Plain-view TEM and HRTEM NWs @ 850°C







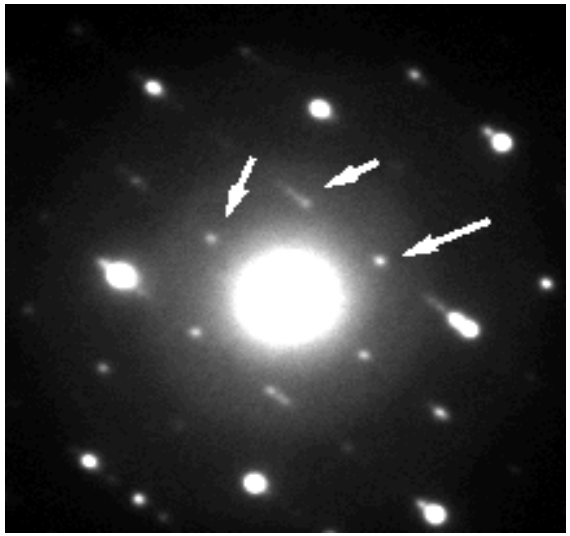
Both the zinc-blende and wurtzite phases grew longitudinally and simultaneously

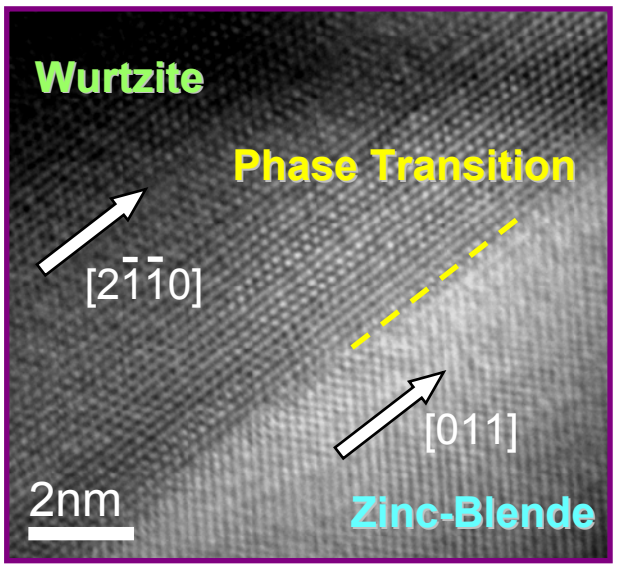
This is the first time this phenomenon was observed in nanowires!

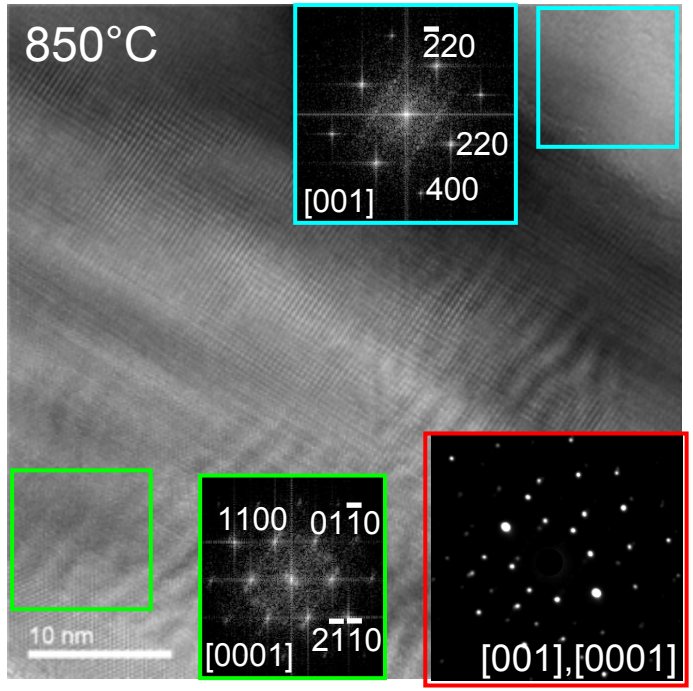
Complicated structure - see the diffraction pattern, both phases show up

The details of this nanowire structure were well worth pursuing, could lead to important nanowire applications

Selected Area Electron Diffraction (SAED)







Both the zinc-blende and wurtzite phases grew longitudinally and simultaneously

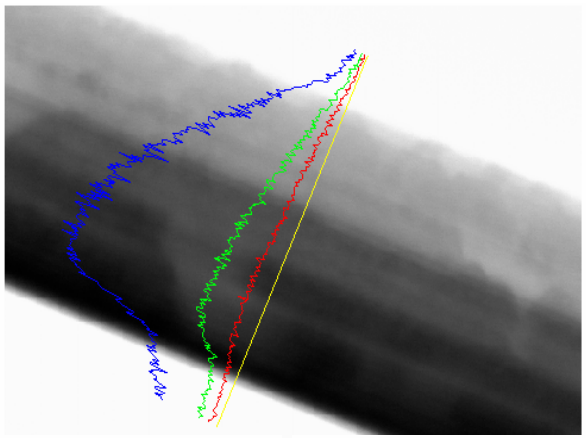
This is the first time this phenomenon was observed in nanowires!

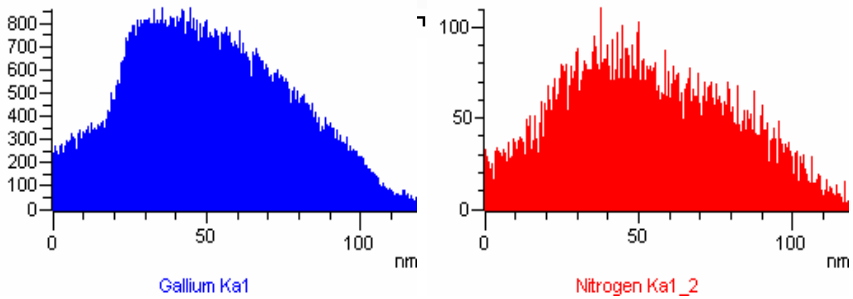
Complicated structure - see the diffraction pattern, both phases show up

JAVA Electron Microscopy Simulation (JEMS) to multiple orders of diffraction spots

Quantitative Energy Dispersive X-ray Spectroscopy (EDS)

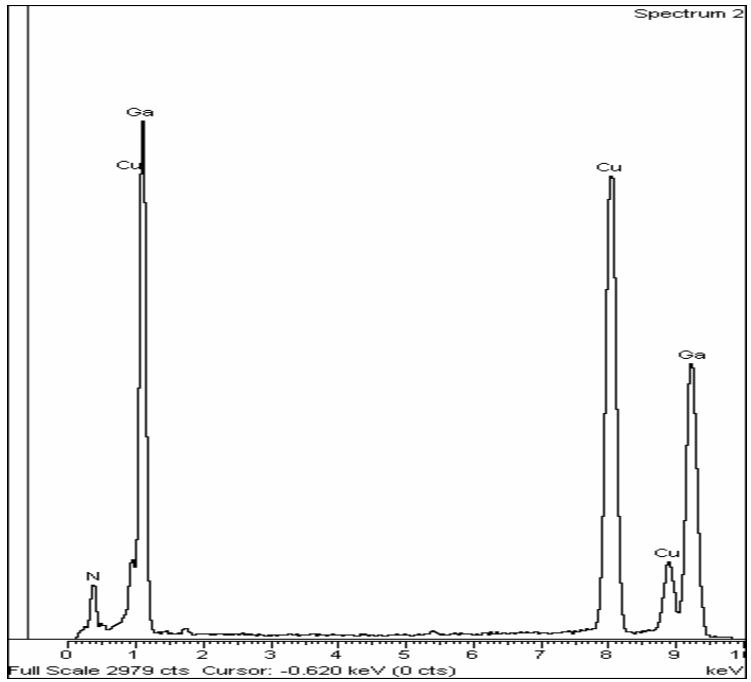
The nanowire diameter where the cross section was taken for the Energy dispersive X-ray spectroscopy (EDS).





Relative intensities of gallium and nitrogen. Gallium is higher due to its higher atomic weight.

Gallium and nitrogen peaks at each energy.

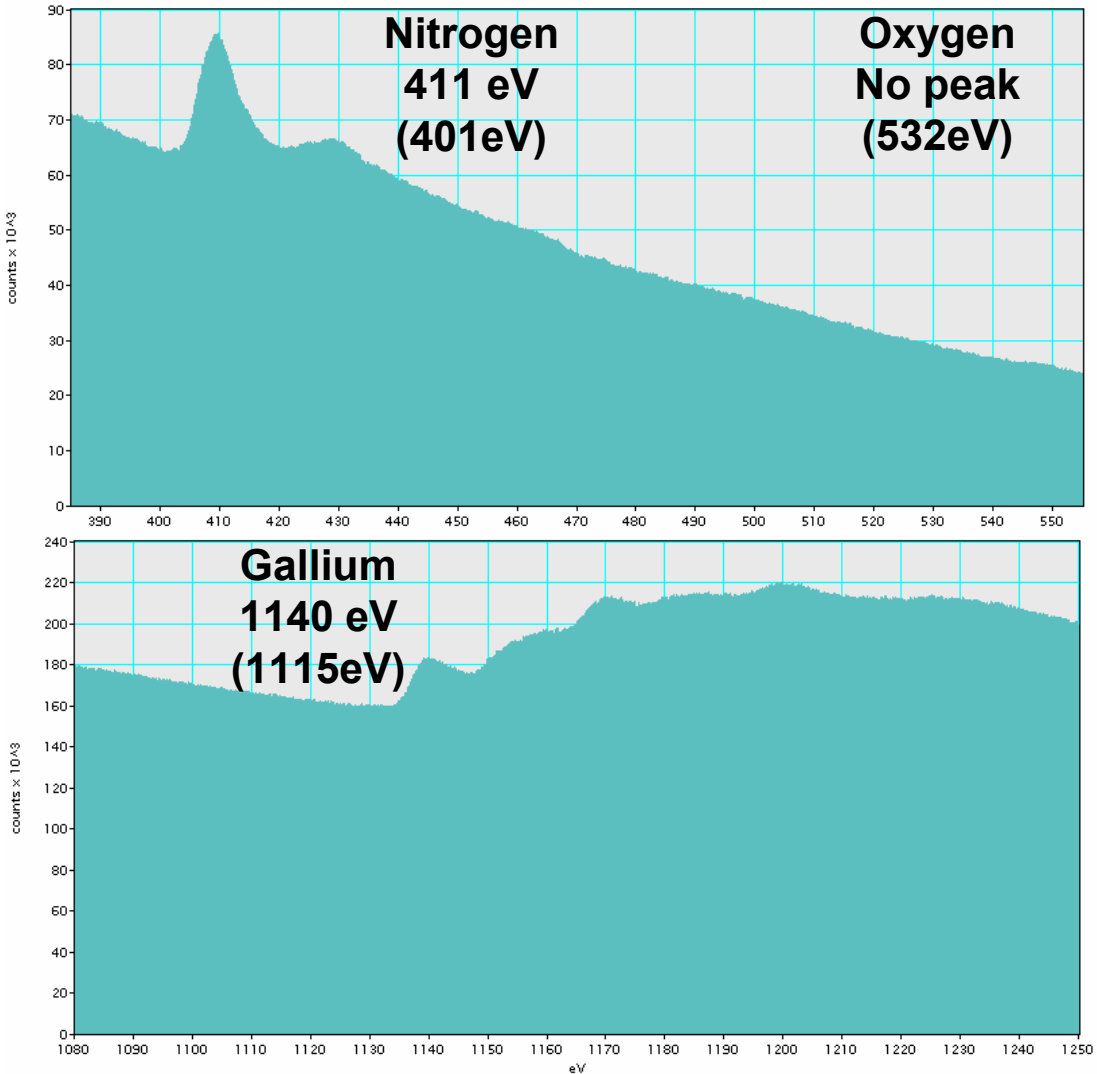


Quantitation method : Cliff Lorimer thin ratio section.
Processing option : All elements analyzed (Normalised)
Number of iterations = 5

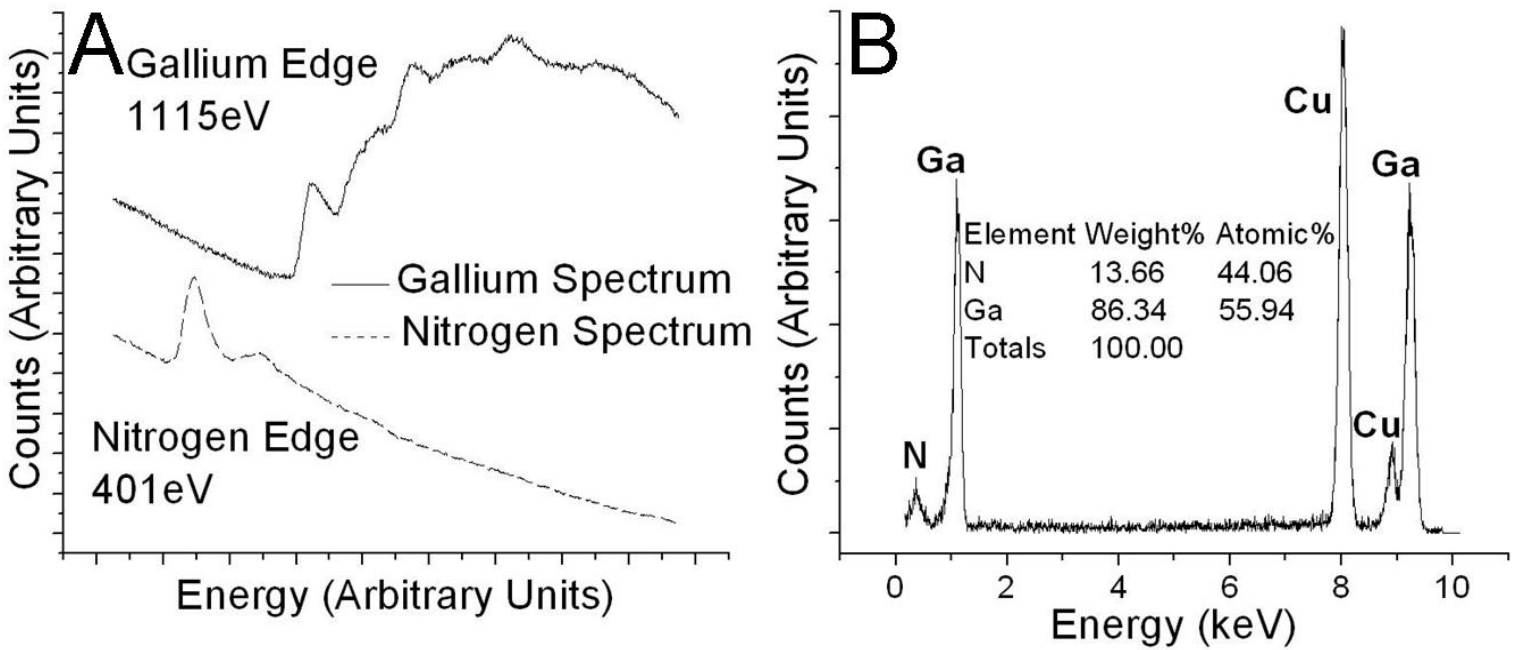
Element	Weight%	Atomic%
N K	17.27	50.96
Ga K	82.73	49.04
Totals		100.00

Electron Energy Loss Spectroscopy (EELS)

Checking for Ga_2O_3

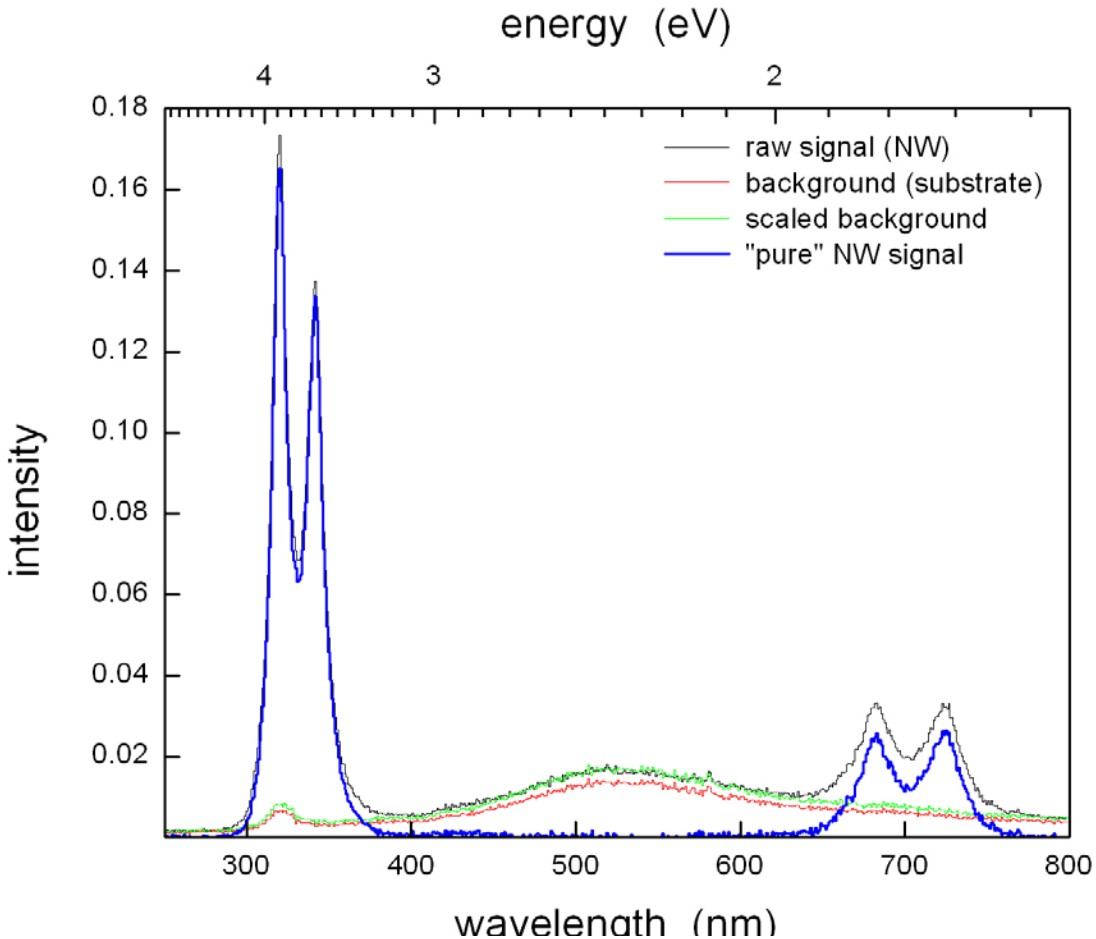


EDS and EELS: Stoichiometric GaN



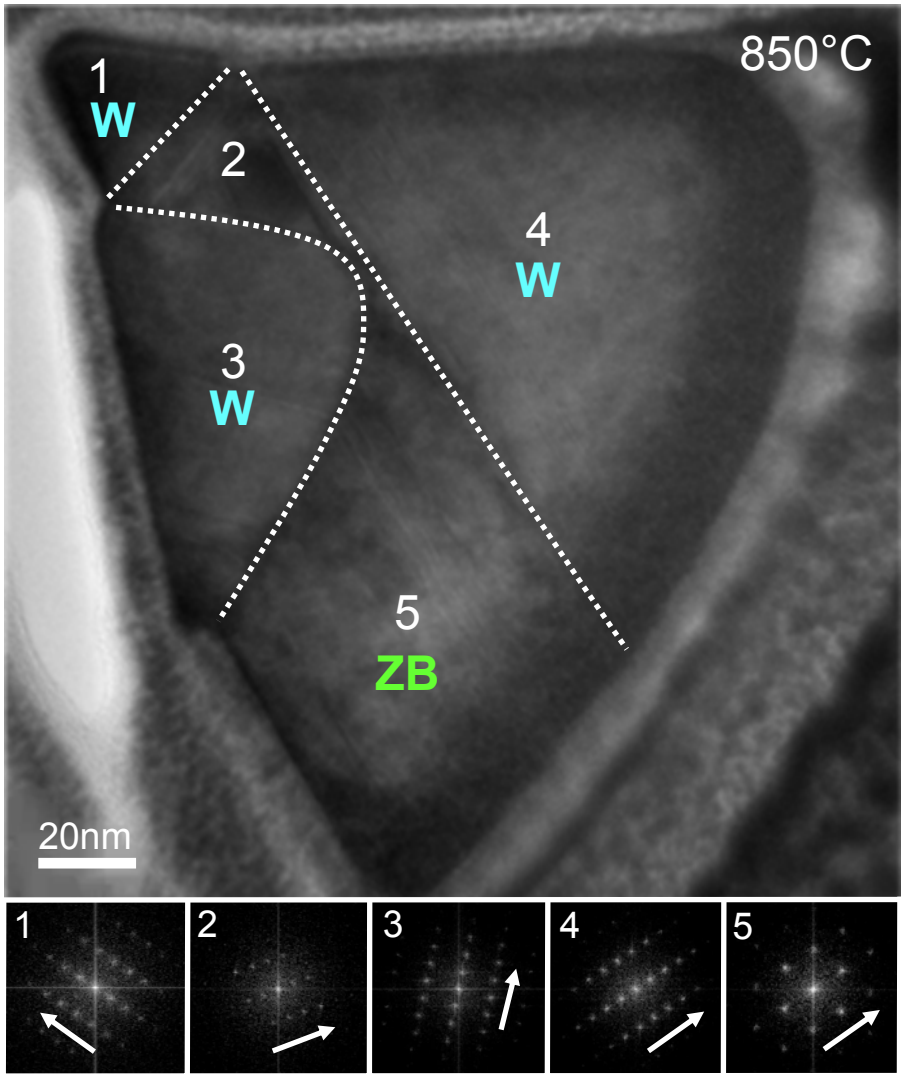
Benjamin W. Jacobs ,et al , “Electronic and Structural Characteristics of Zinc-Blende Wurtzite Biphasic Homostructure GaN Nanowires”, Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)

Cathodoluminescence: 2 bandgaps

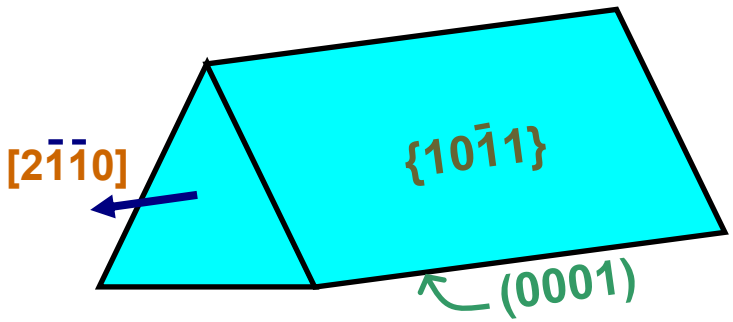


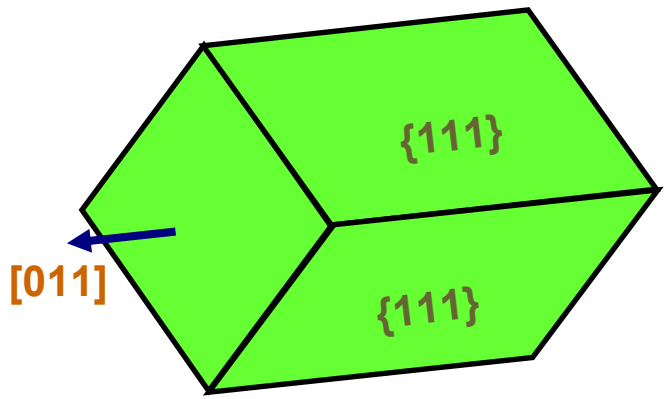
Benjamin W. Jacobs ,et al , “Electronic and Structural Characteristics of Zinc-Blende Wurtzite Biphasic Homostructure GaN Nanowires”, Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)

Nanowire Cross-Sections

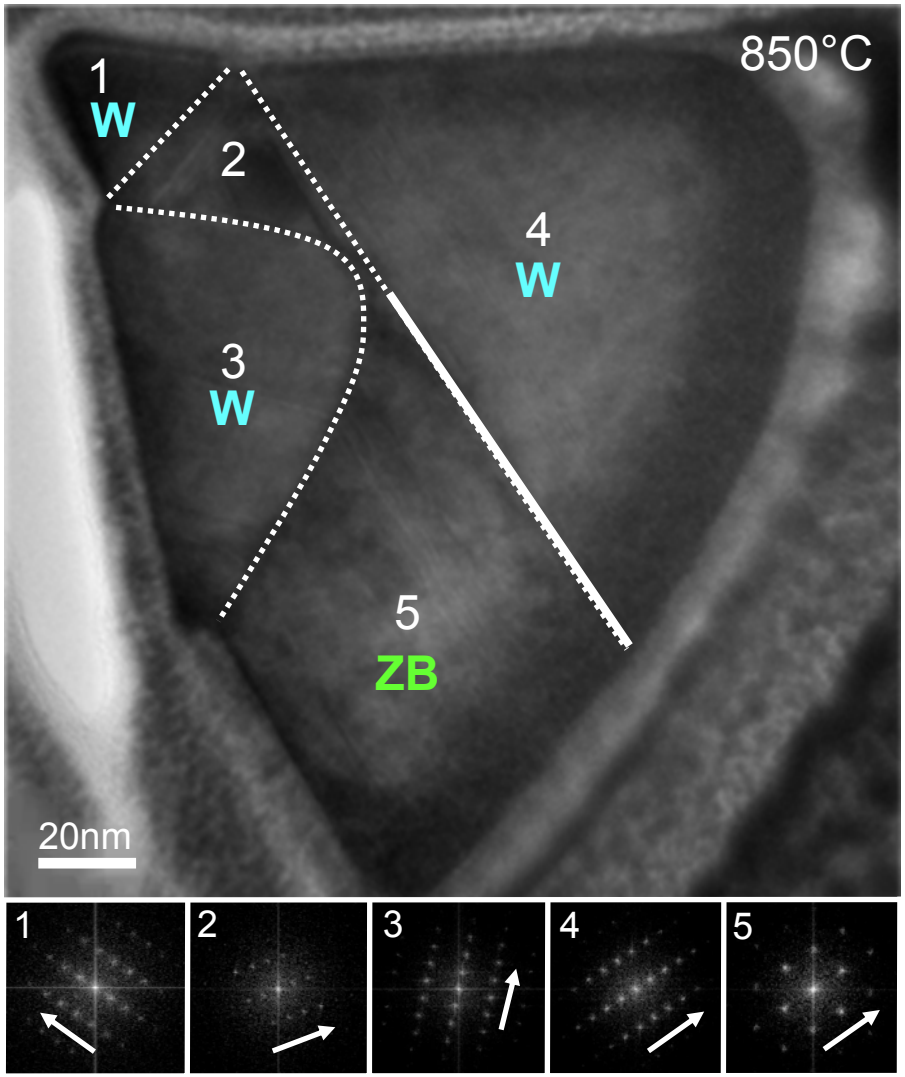


- Complicated structure, so how can it form?
- Nanowire cross-sections shed light on how its possible
- Several distinct crystalline domains

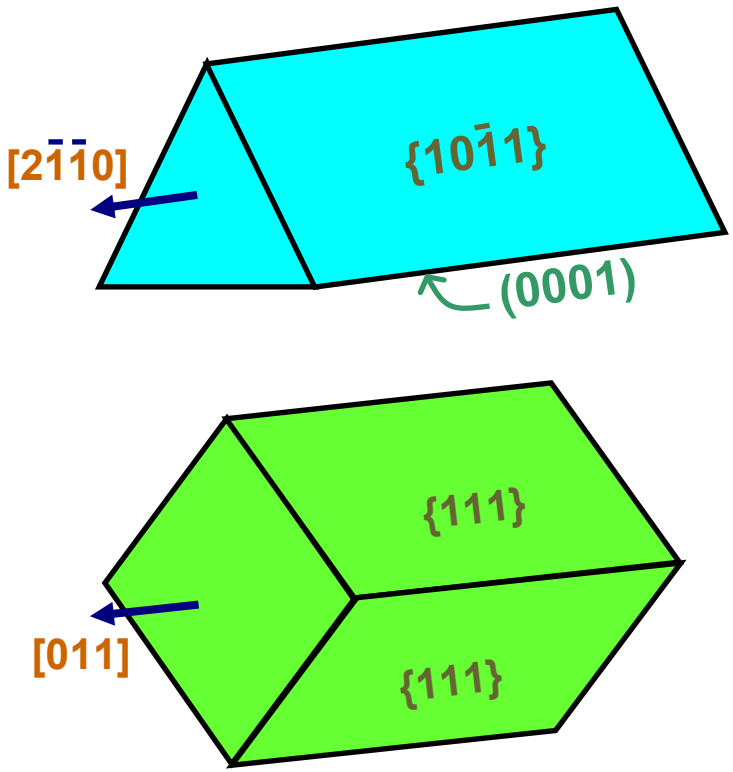




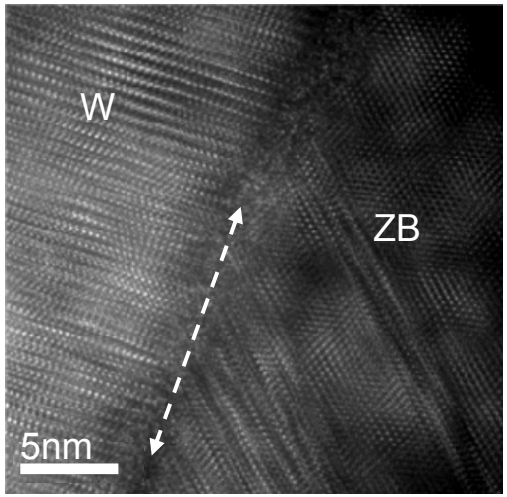
Nanowire Cross-Sections

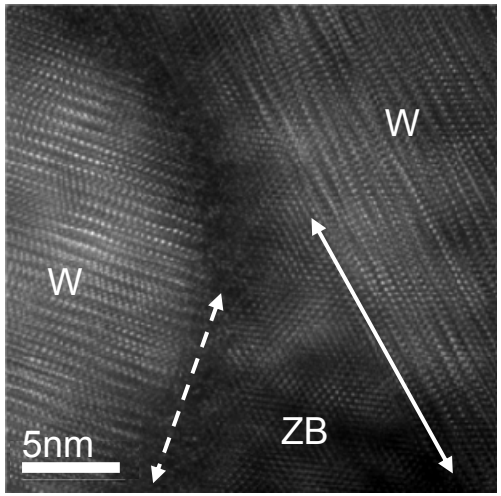


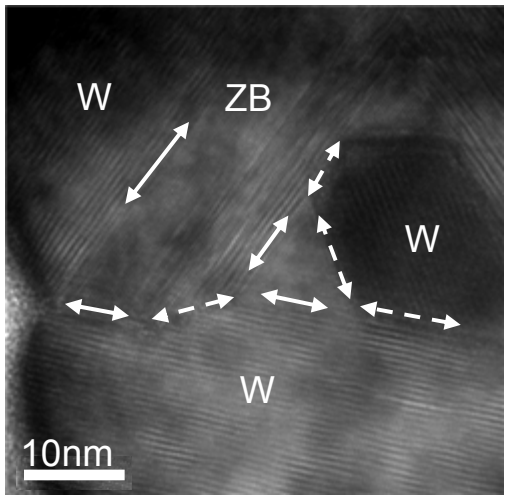
- Long ~80 nm coherent interface 111/0001.
- Nanowire cross-sections shed light on how its possible
- Several distinct crystalline domains

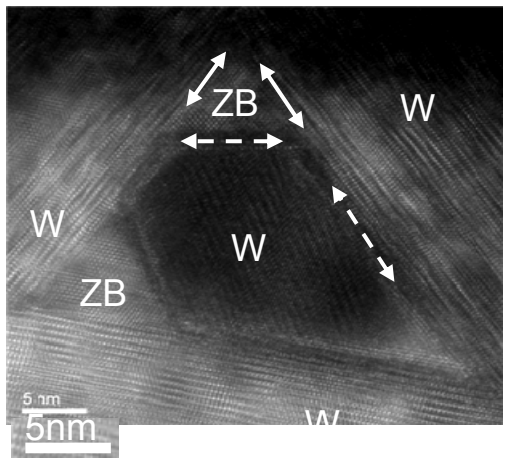


Nanowire Cross-Sections

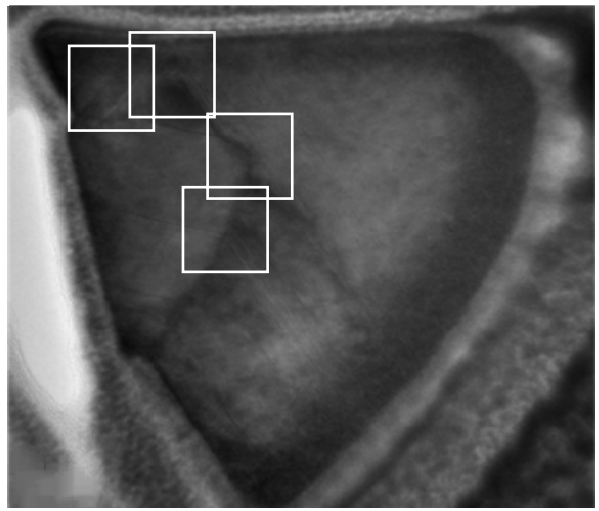




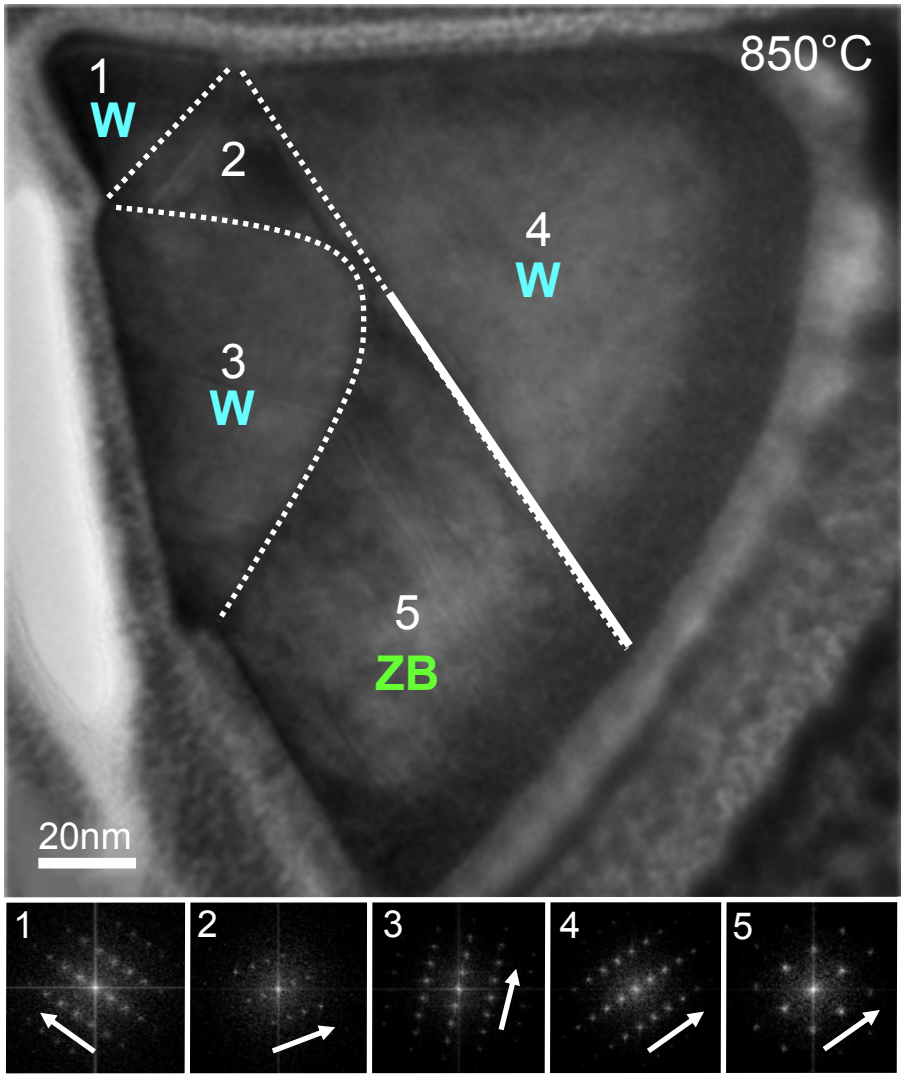




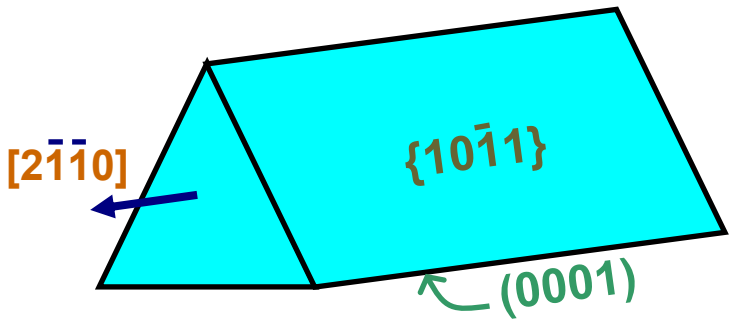
- Several **distinct crystalline domains** with **coherent** (solid lines) and **incoherent** (dotted lines) interfaces
- First report of this type of structure

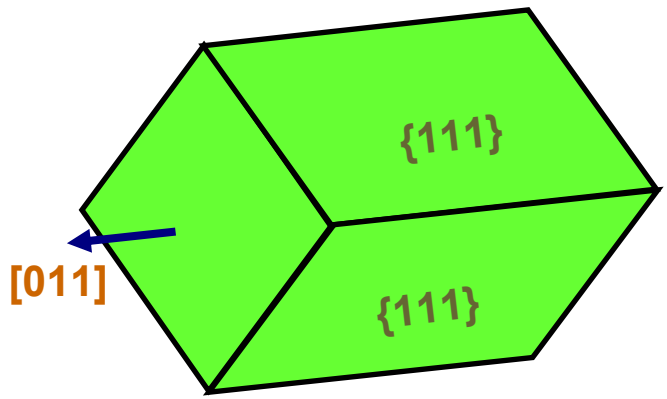


Nanowire Cross-Sections

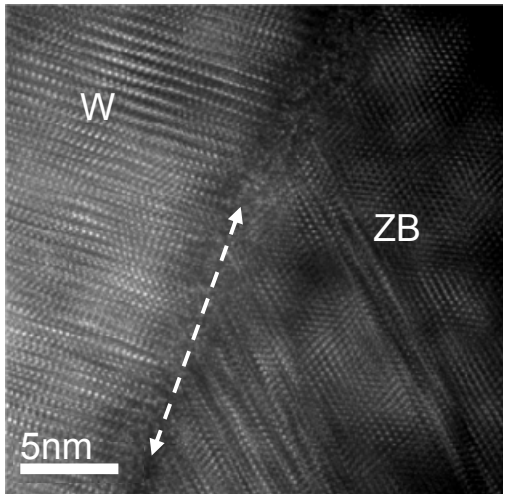


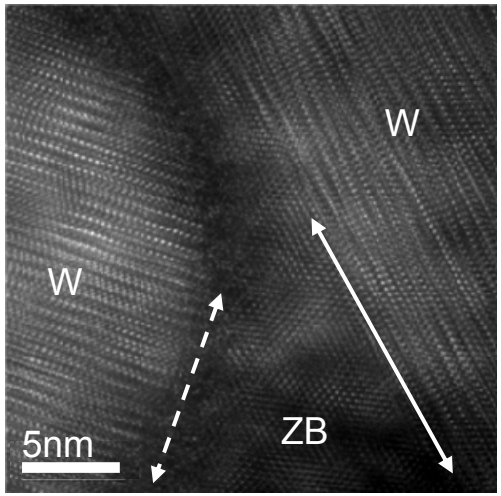
- Long ~80 nm coherent interface 111/0001.
- Nanowire cross-sections shed light on how its possible
- Several distinct crystalline domains

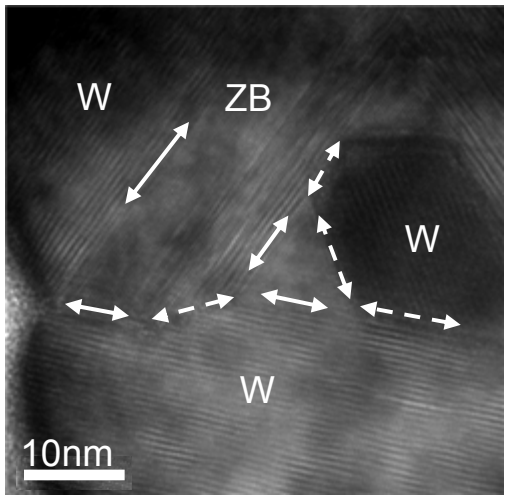


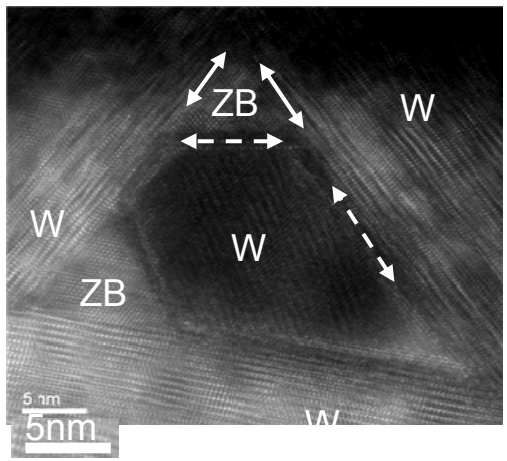


Nanowire Cross-Sections

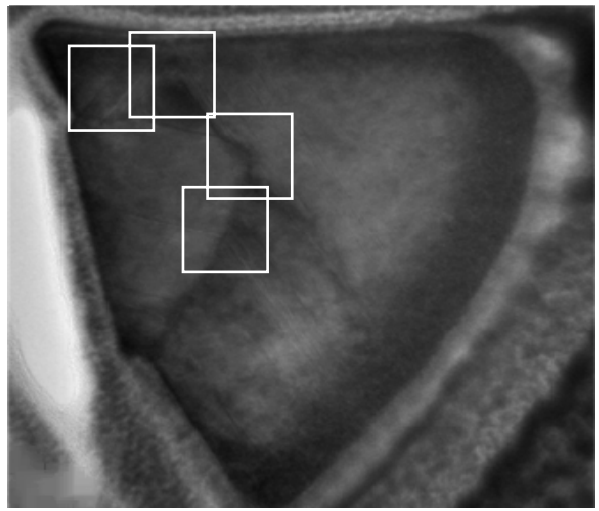




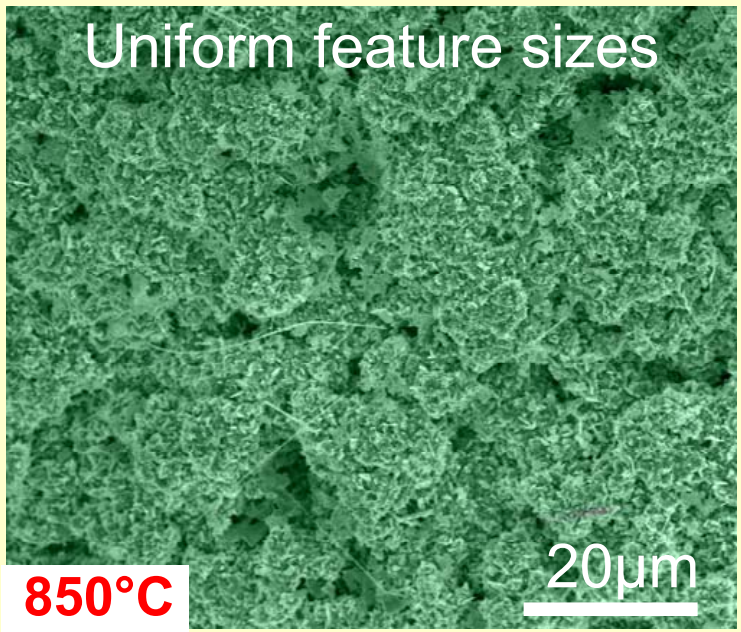




- Several **distinct crystalline domains** with **coherent** (solid lines) and **incoherent** (dotted lines) interfaces
- First report of this type of structure

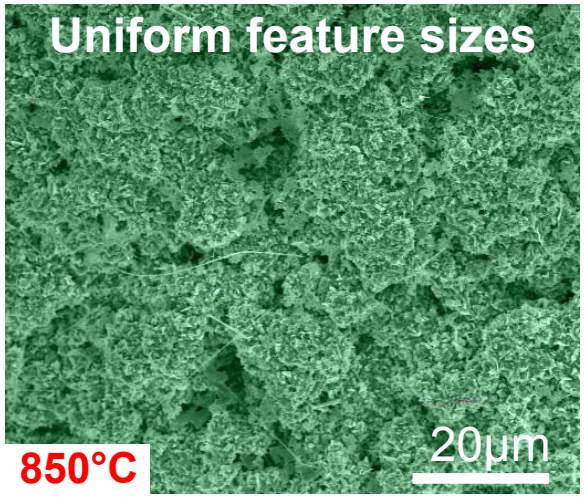


VS Growth of Multiphase Phase GaN Nanowires: the Growth Matrix

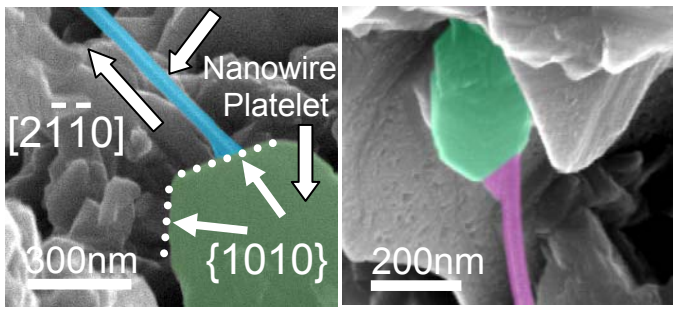


Submitted, Nano Lett.,

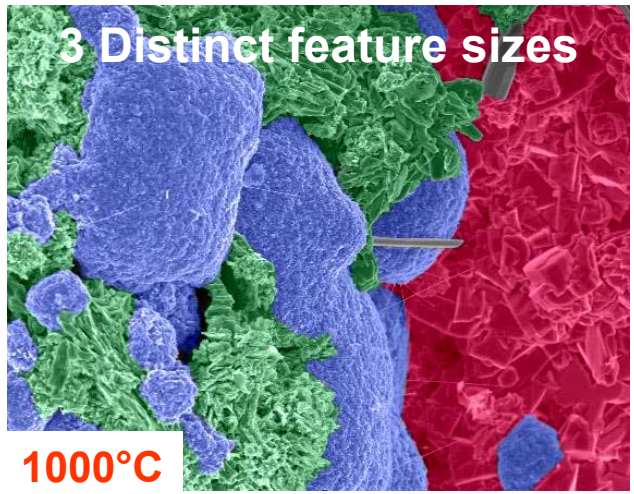
The Growth Matrix



850°C

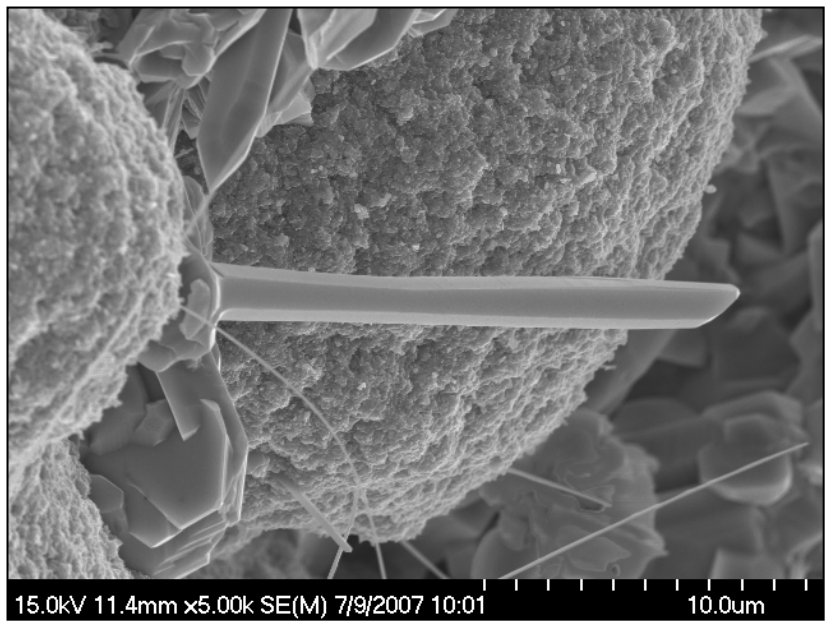


- Nanowires grow from hexagonal platelet sides
- Based on previous nanowire growth directions and shape of the platelet sides, looking down on the platelet top (0001) planes

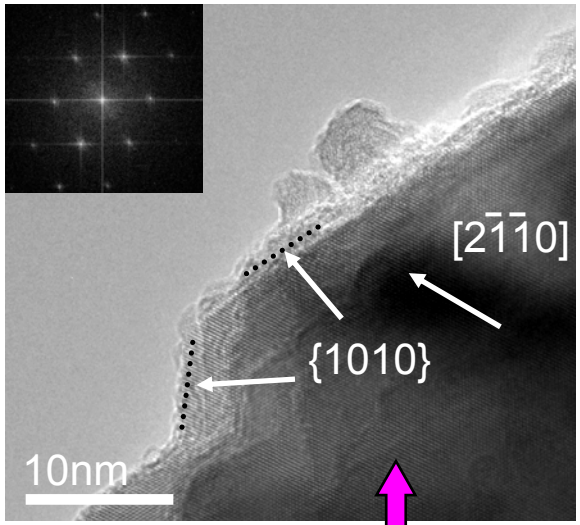


1000°C

- Blue region - 100 nm to 200 nm.
- Green region - 200 nm to 1 μm.
- Red region - 1 μm to 5 μm.

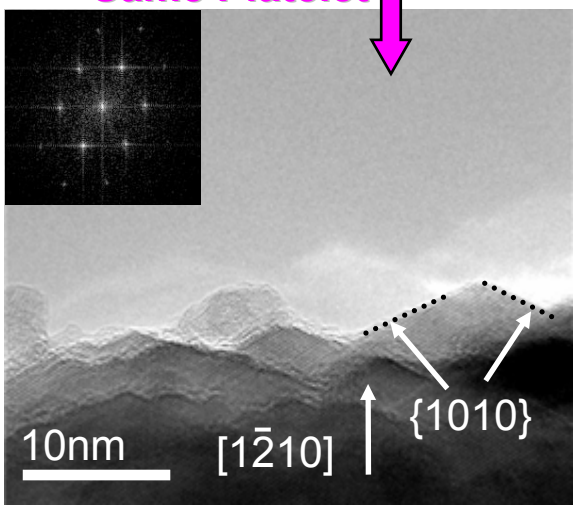


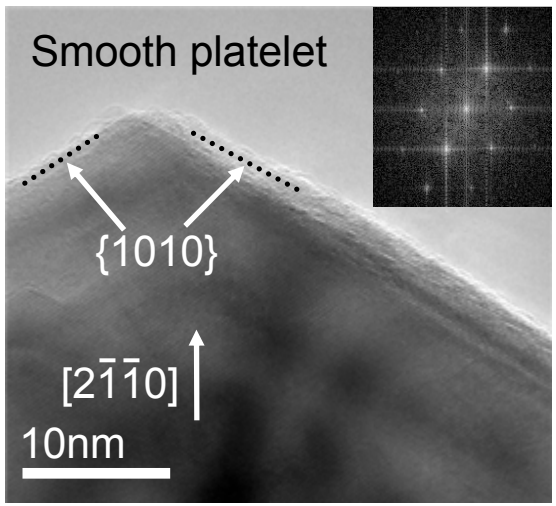
The Growth Matrix

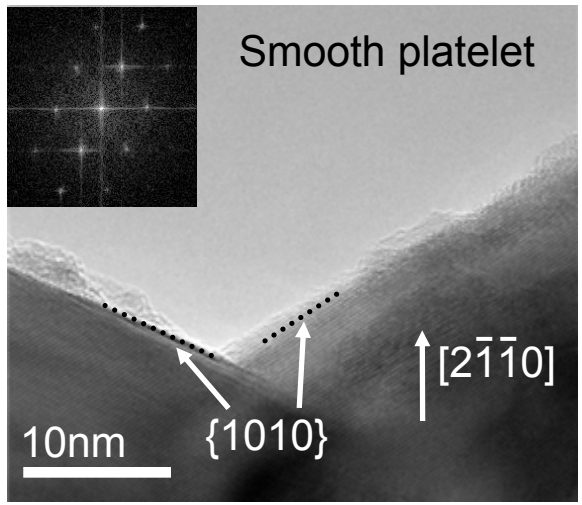


- A closer HRTEM look at the hexagonal platelets revealed interesting features
- A network of nanoscale ledges
- In the same orientation and coherent with the hexagonal platelets

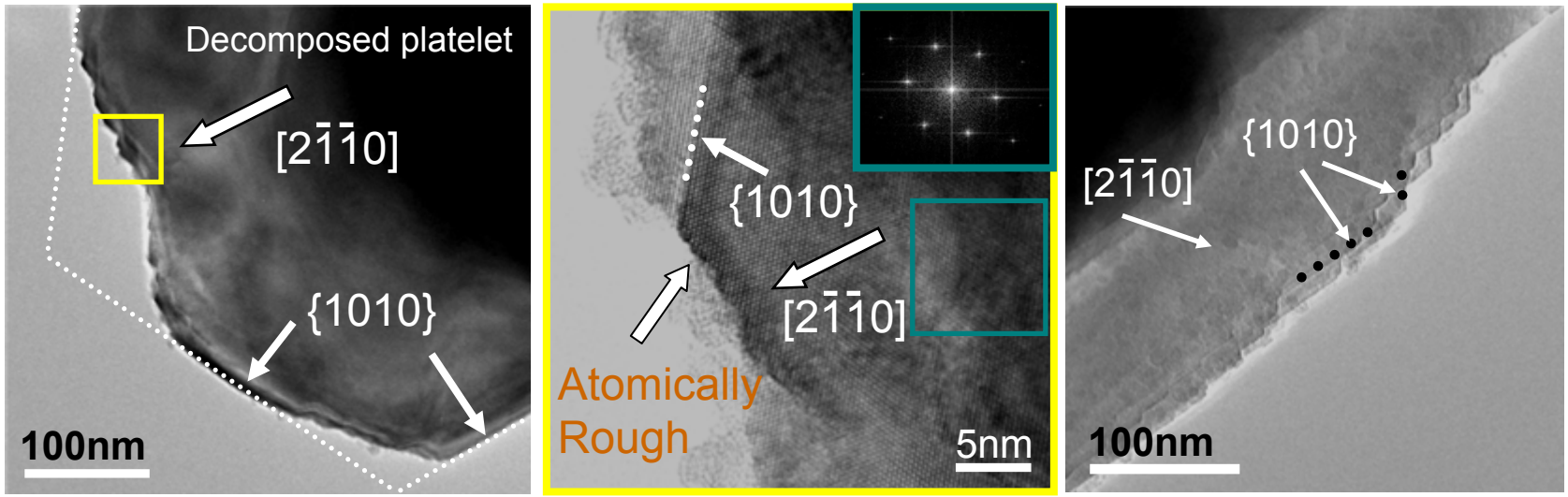
Same Platelet





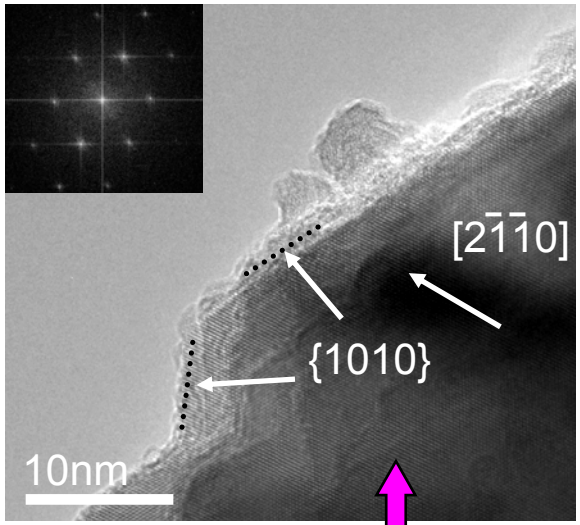


How Multiphase GaN can form @ 850°C



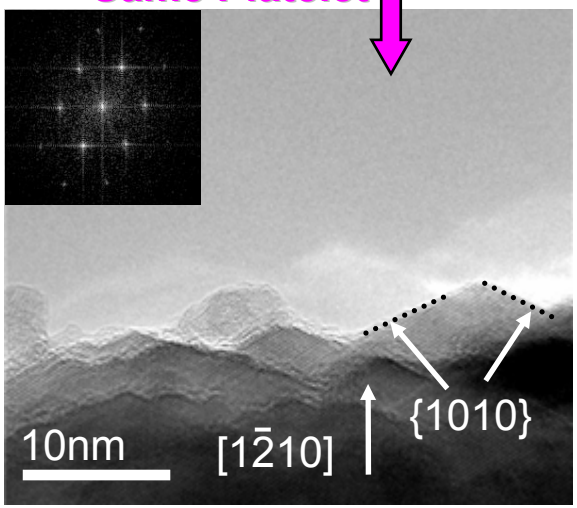
- Decomposed platelet leading to nanoscale platelet formation – N_2 formation
- An HRTEM image of the platelet shows the features and orientation of the ledges and atomic scale roughness on the side of the ledge
- A TEM image of a different platelet showed that nanoscale ledge formation could occur on the sides of platelets leading to a saw-like roughened edge
- These ledges are thought to be active sites where nanowire nucleation can occur

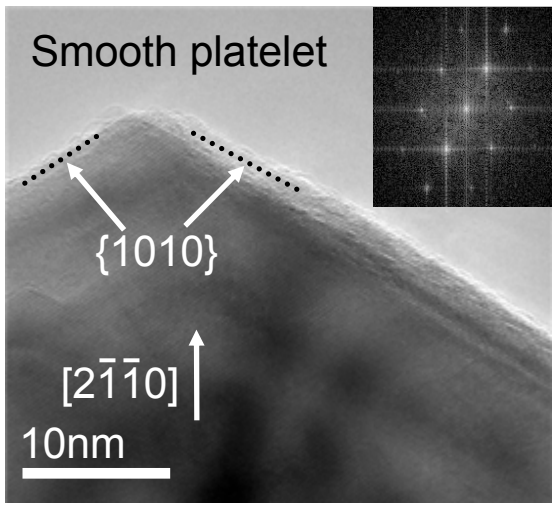
The Growth Matrix

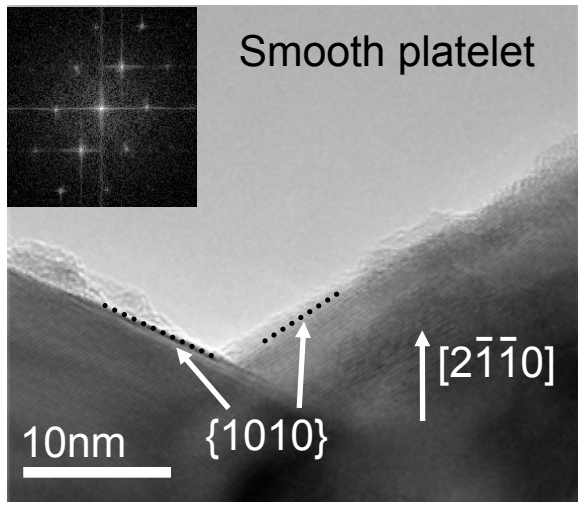


- A closer HRTEM look at the hexagonal platelets revealed interesting features
- A network of nanoscale ledges
- In the same orientation and coherent with the hexagonal platelets

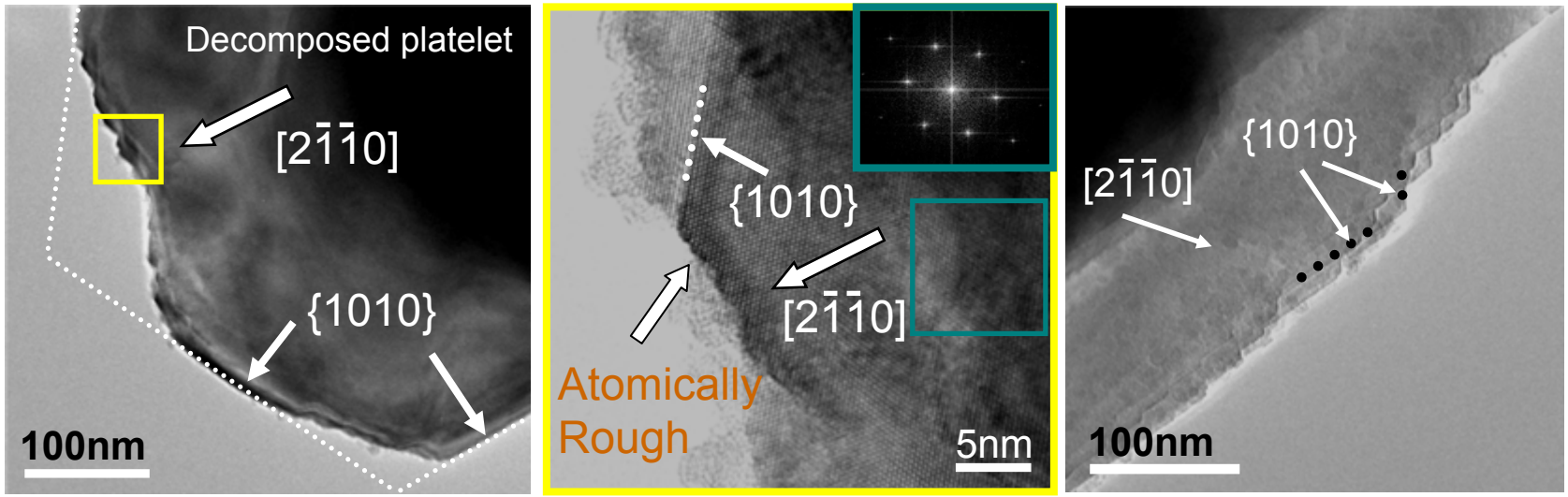
Same Platelet





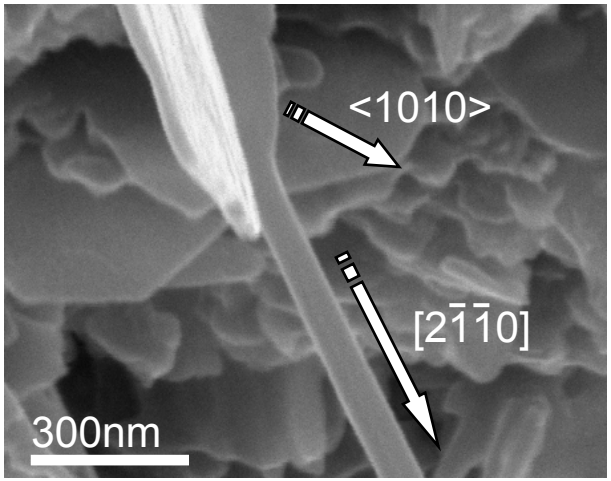


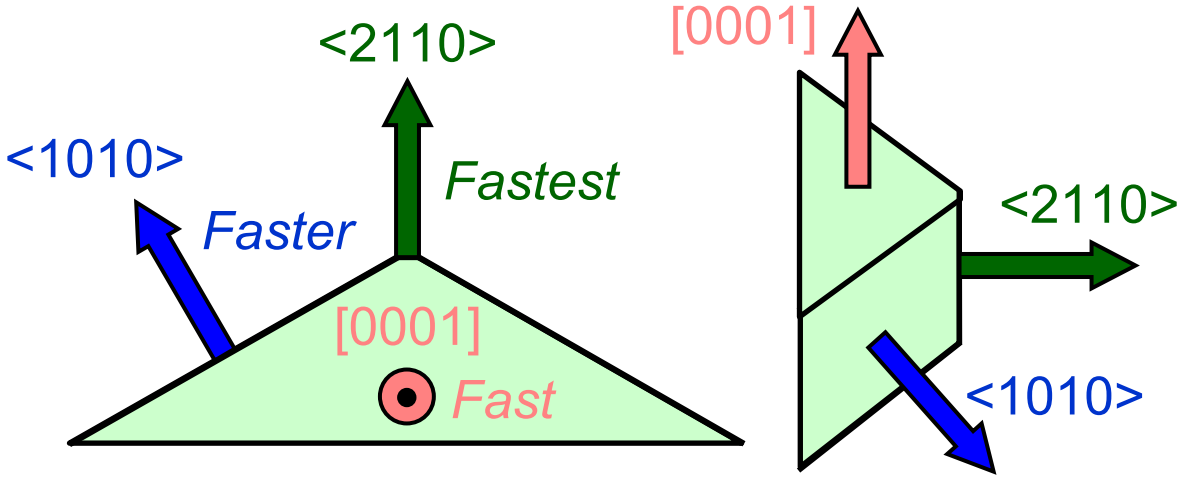
How Multiphase GaN can form @ 850°C

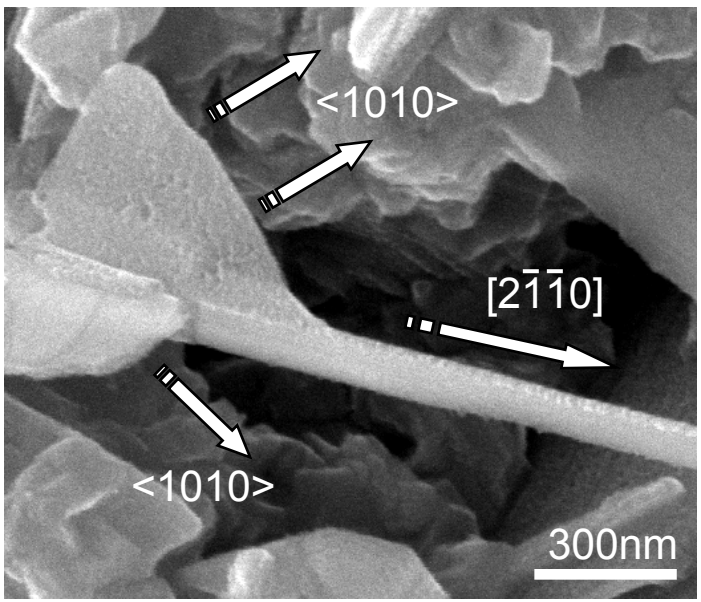


- Decomposed platelet leading to nanoscale platelet formation – N_2 formation
- An HRTEM image of the platelet shows the features and orientation of the ledges and atomic scale roughness on the side of the ledge
- A TEM image of a different platelet showed that nanoscale ledge formation could occur on the sides of platelets leading to a saw-like roughened edge
- These ledges are thought to be active sites where nanowire nucleation can occur

How Multiphase GaN can form @ 850°C

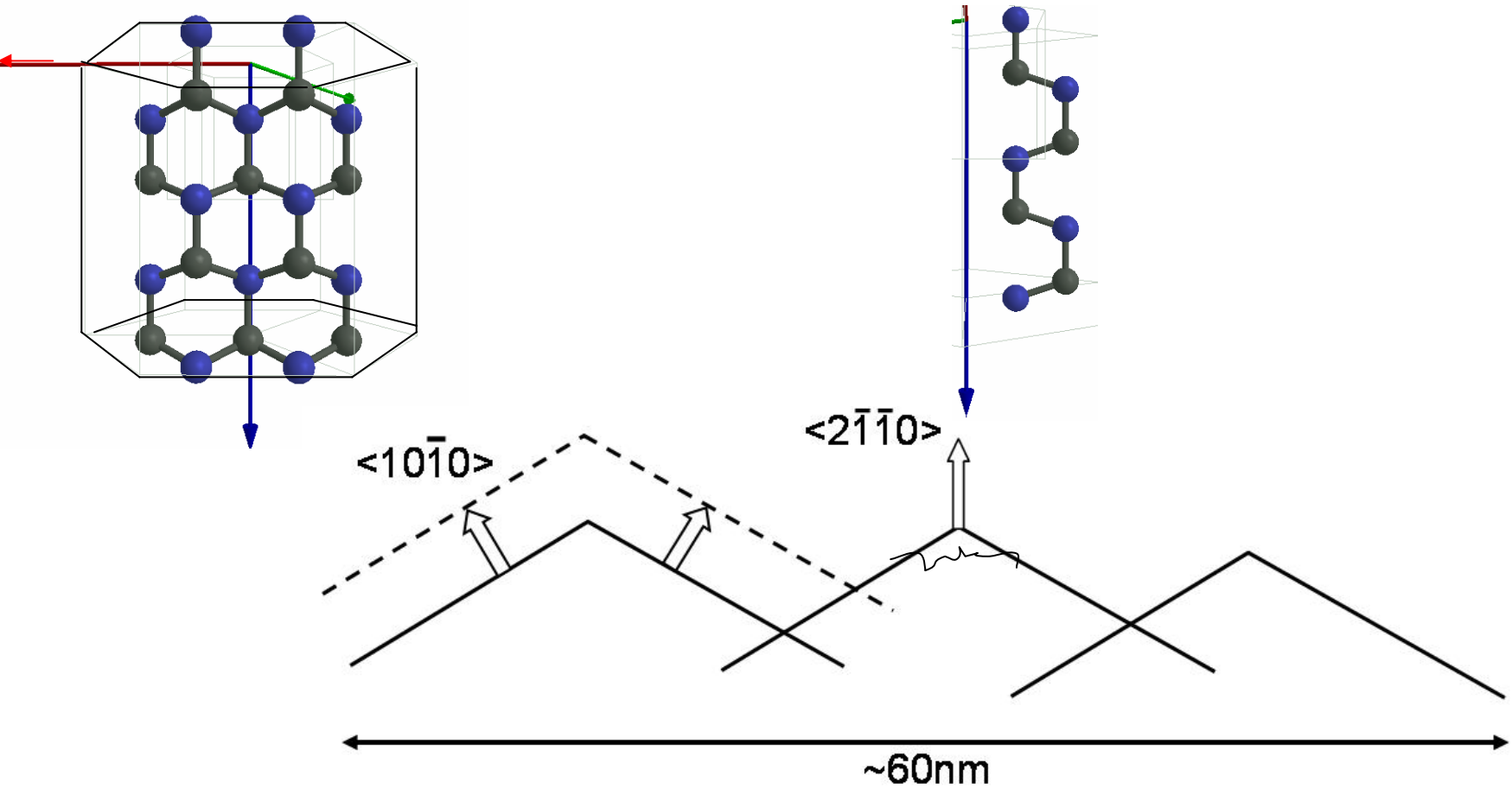






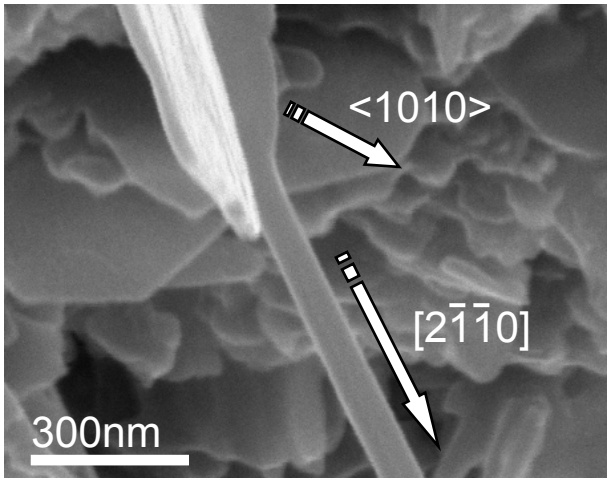
- Multiple **competitive growth processes** occur during nanowire nucleation and growth
- Gives rise to 'blade' formations at the nanowire base
- Can persist for 10 to 100 nm
- The <2110> direction is the fastest so it eventually dominates growth

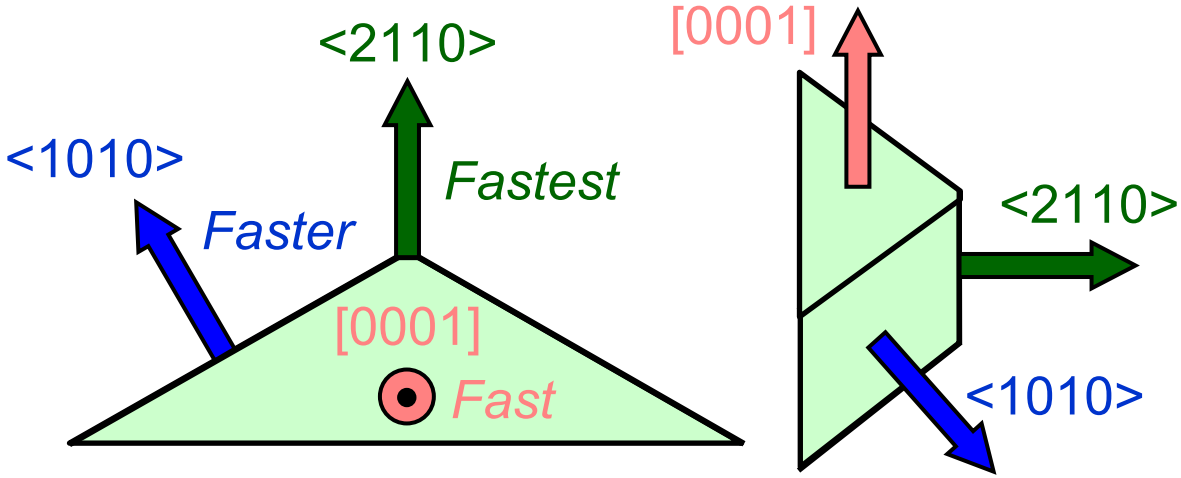
How Multiphase GaN can form @ 850°C

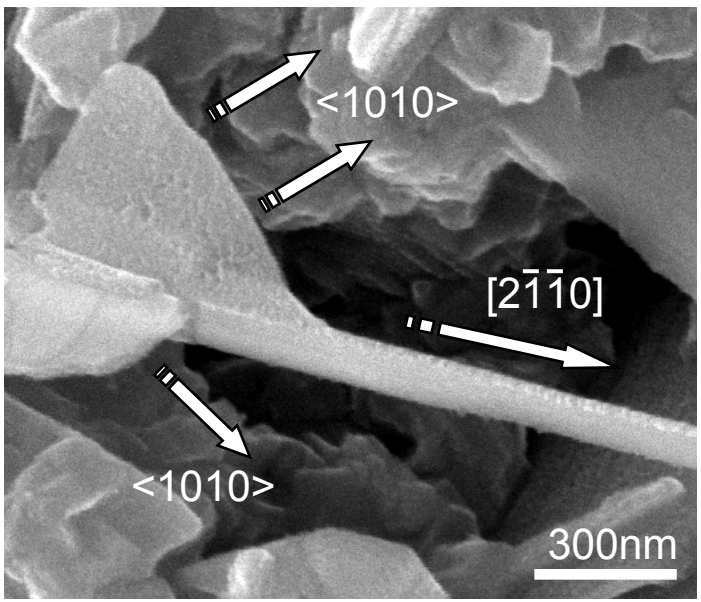


Model showing the nanoscale ledges. The edges are the {1010} planes and the peaks point in the <2110> direction. Step edge growth can occur on the {1010} planes and nanowire growth along the <2110> direction. there is a rough correlation with domain size.

How Multiphase GaN can form @ 850°C

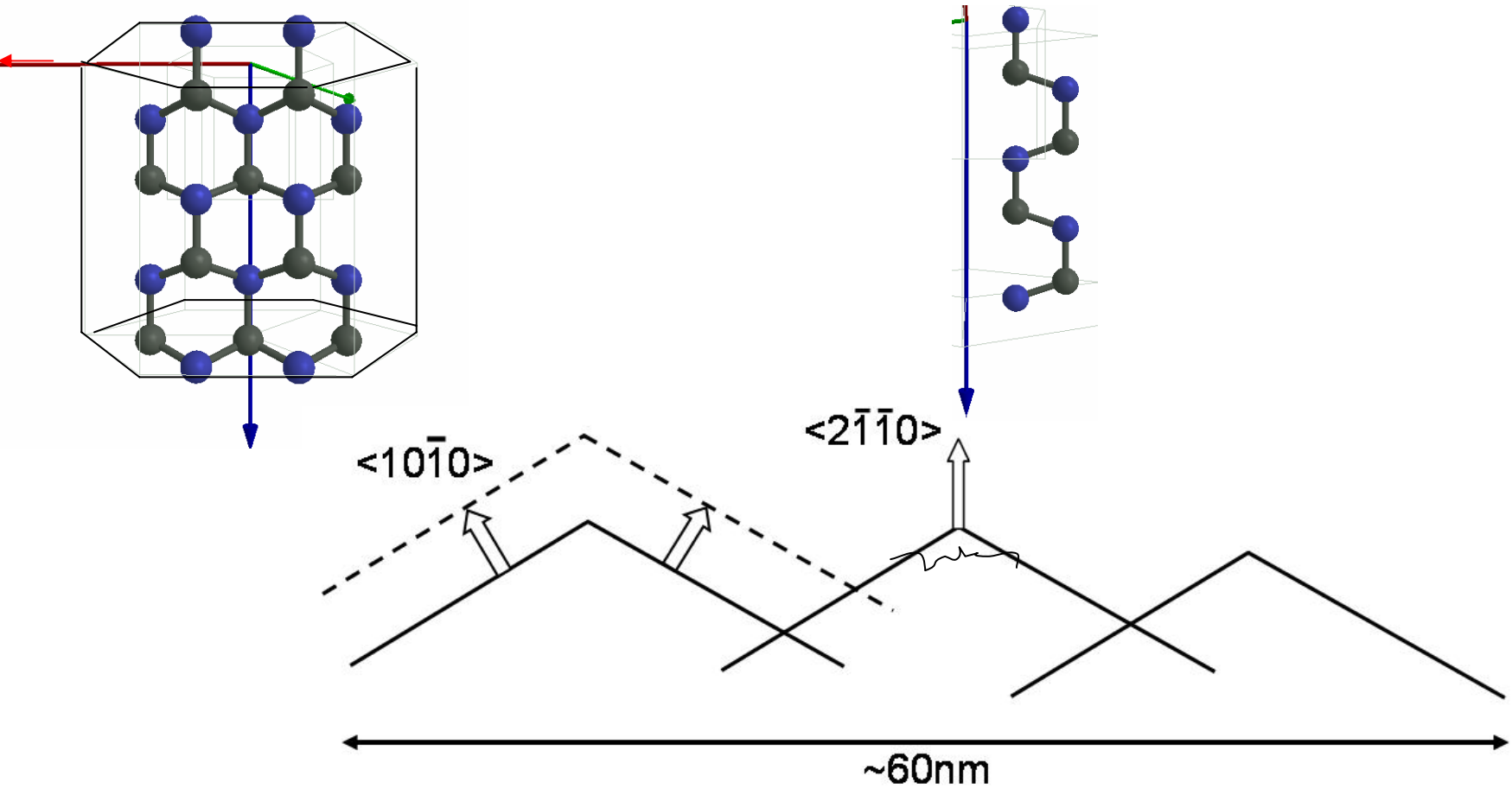






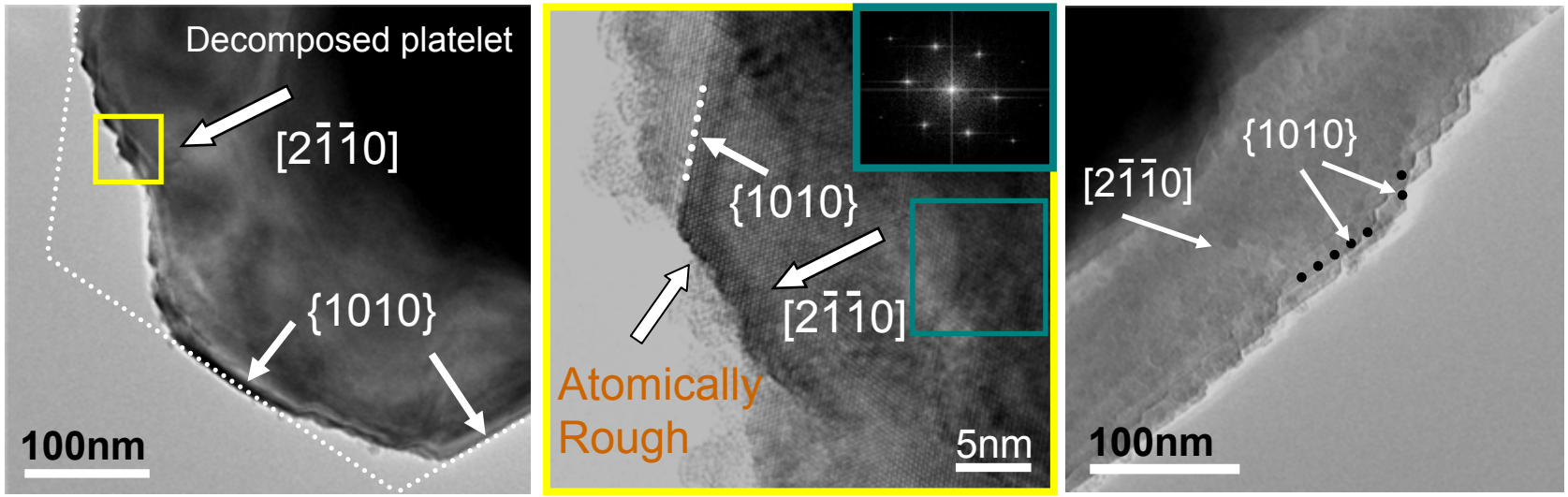
- Multiple **competitive growth processes** occur during nanowire nucleation and growth
- Gives rise to 'blade' formations at the nanowire base
- Can persist for 10 to 100 nm
- The <2110> direction is the fastest so it eventually dominates growth

How Multiphase GaN can form @ 850°C



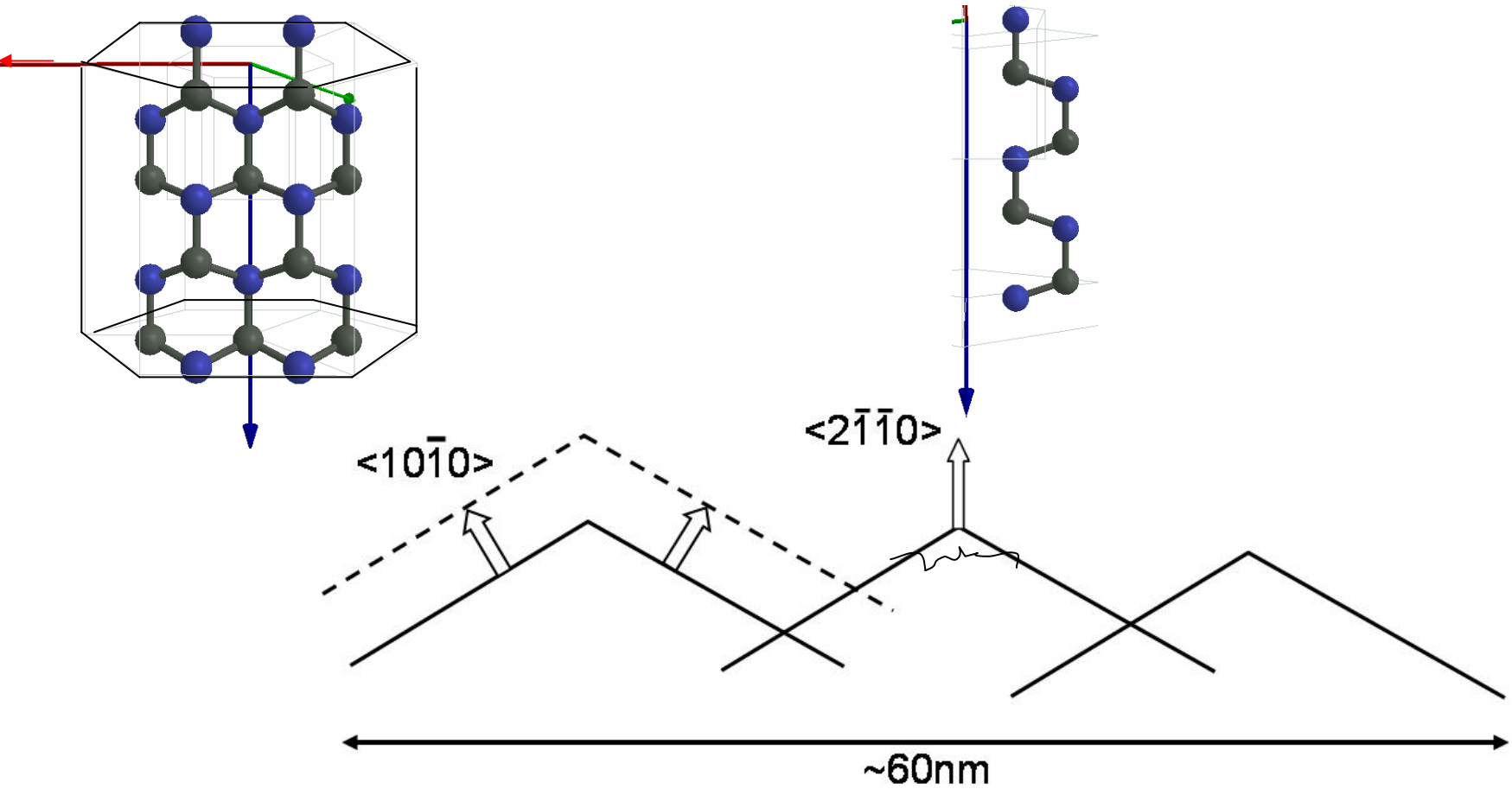
Model showing the nanoscale ledges. The edges are the {1010} planes and the peaks point in the <2110> direction. Step edge growth can occur on the {1010} planes and nanowire growth along the <2110> direction. there is a rough correlation with domain size.

How Multiphase GaN can form @ 850°C



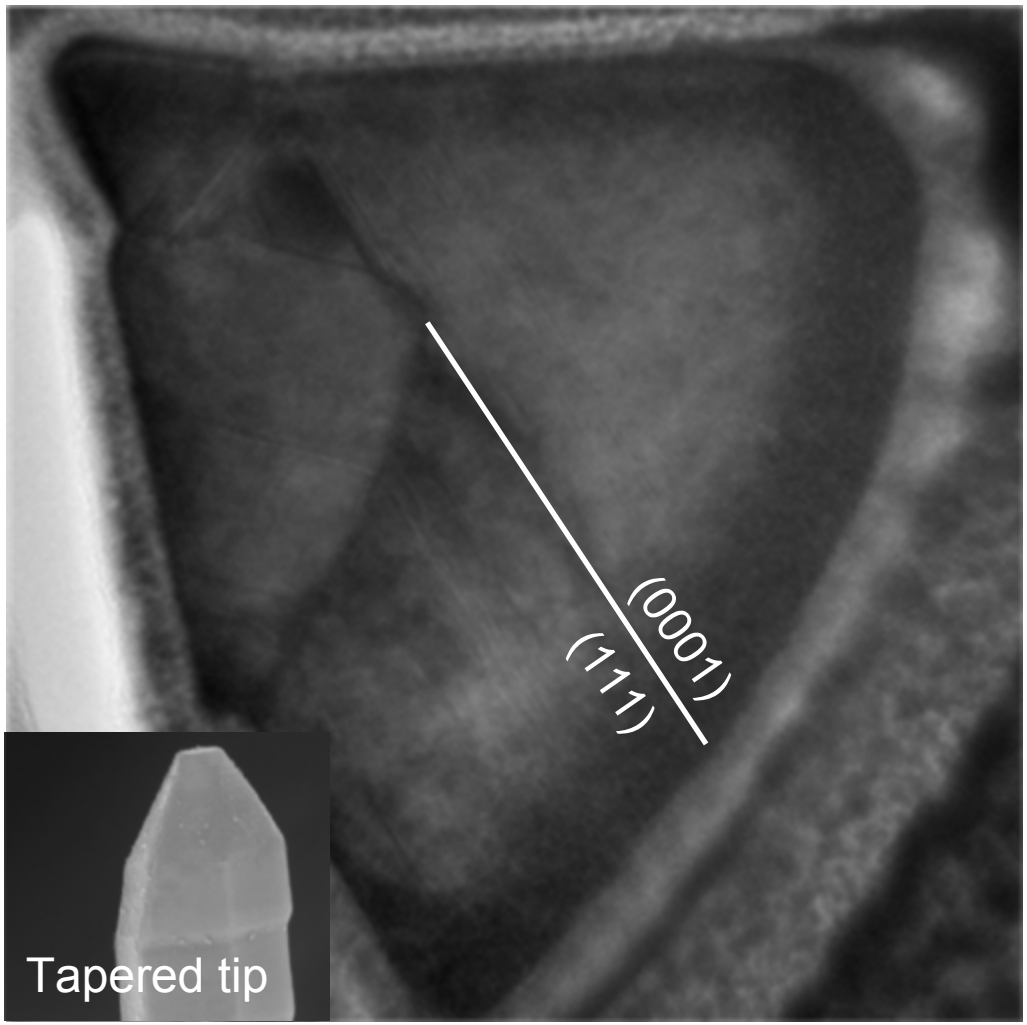
- Decomposed platelet leading to nanoscale platelet formation – N_2 formation
- An HRTEM image of the platelet shows the features and orientation of the ledges and atomic scale roughness on the side of the ledge
- A TEM image of a different platelet showed that nanoscale ledge formation could occur on the sides of platelets leading to a saw-like roughened edge
- These ledges are thought to be active sites where nanowire nucleation can occur

How Multiphase GaN can form @ 850°C



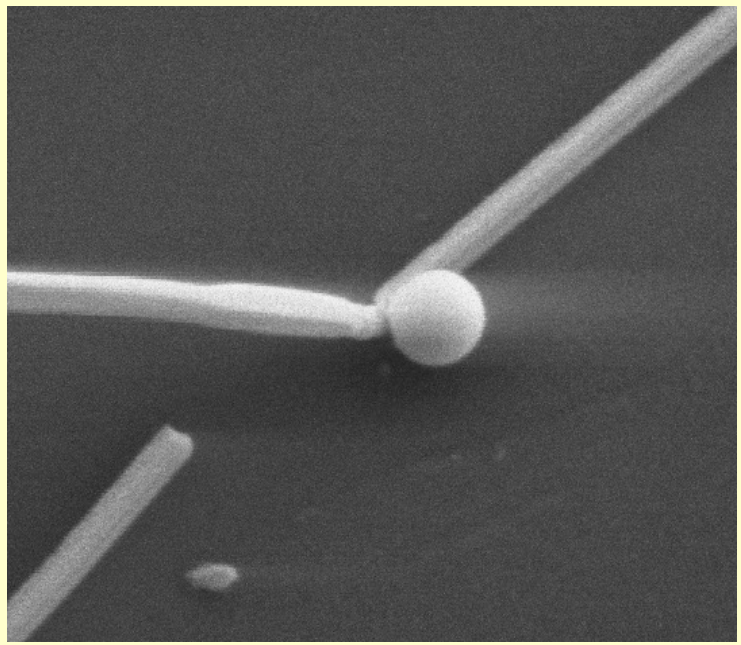
Model showing the nanoscale ledges. The edges are the {1010} planes and the peaks point in the <2110> direction. Step edge growth can occur on the {1010} planes and nanowire growth along the <2110> direction. there is a rough correlation with domain size.

How Multiphase GaN can form @ 850°C



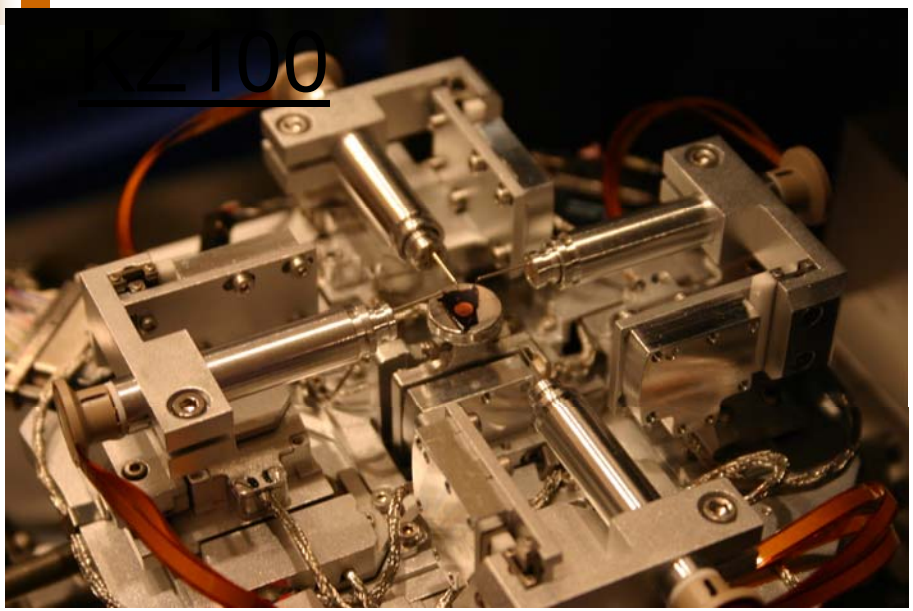
- The (0001) planes have typically been observed to **terminate within the internal nanowire volume**.
- Instability of the (0001) planes may be compensated through the incorporation of the **zinc-blende phase**, as a **stabilizing aspect** of the multiphase configuration – a second option
- Theory has shown that the (0001) plane in GaN thin films is not stable – Bernholc *PRB* **56** 12725

Novel Nanoelectronics of Multiphase GaN Nanowires



Nanotech., Vol. 18, 475710 (6 pp) (2007)

KZ100



@ Zyvex Laboratories, Richardson TX

zyvex

KEITHLEY

KZ100:

Ultra low noise SCS4200

+

30 nm W Nanoprobes

+

Real-time SEM

+

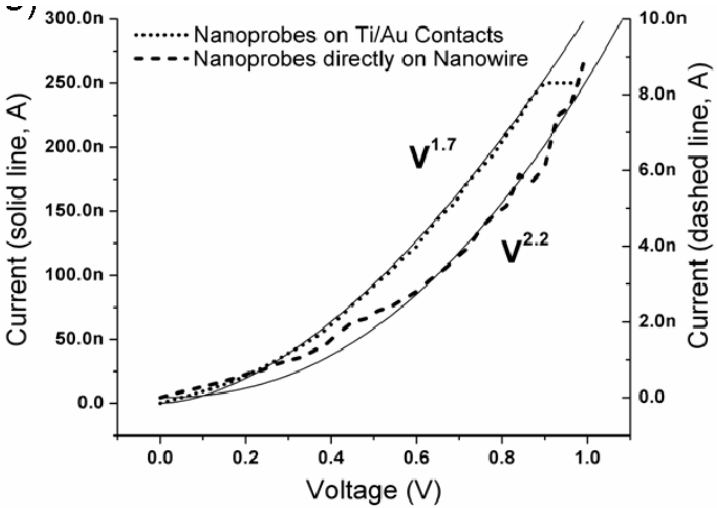
R.E. Stallcup, Zyvex

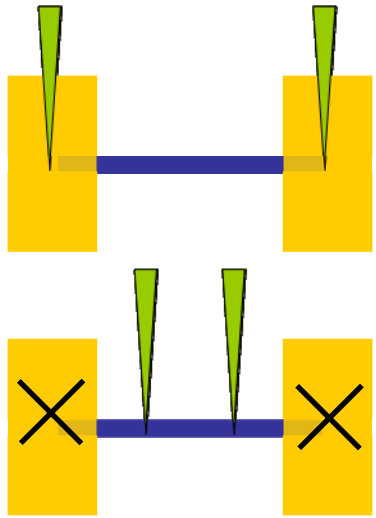
A.B. McDougall, Zyvex

M.A. Tupta, Keithley

Novel Nano Electronics - 2-Point Probe

- Studied the dynamic resistance, $R = \Delta V/\Delta I$





Ti/Au-Nanowire contact

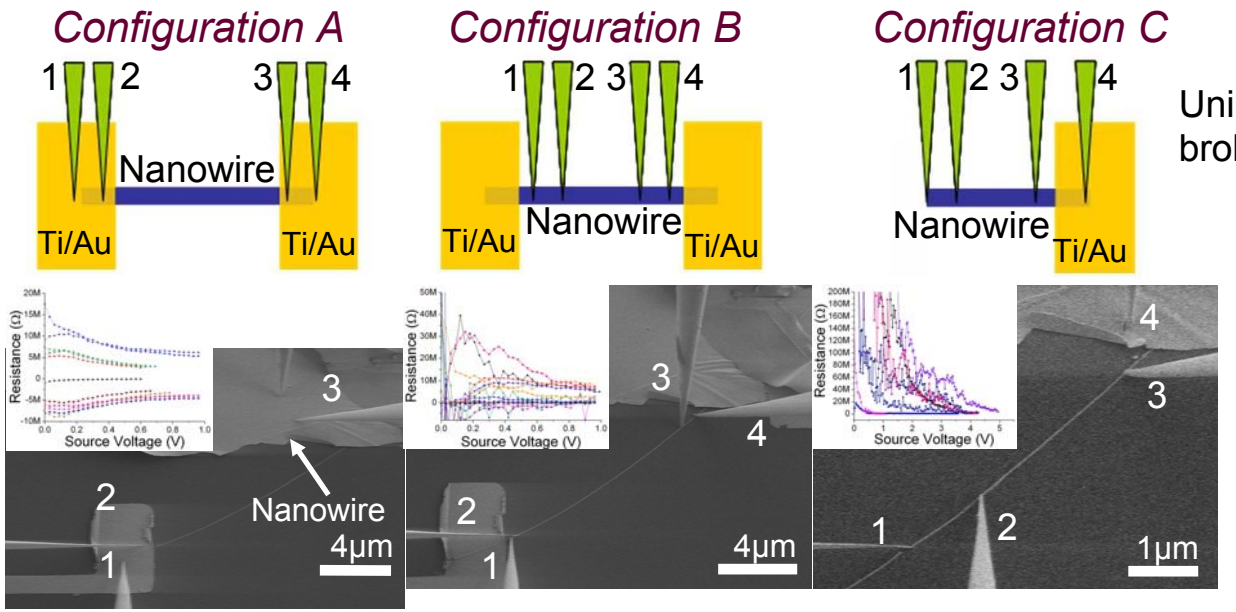
Configuration A - $I(V) \propto V^{1.7}$

Probe-Nanowire contact

Configuration B - $I(V) \propto V^{2.2}$

- Formation of a **Schottky barrier** at the probe–nanowire contact as well as at the Ti/Au–nanowire contact.
- Different exponents
  - Variations in coupling indicate **different barriers** between the probe–nanowire and Ti/Au–nanowire interfaces
  - Smaller metal contact area concentrates the electric field at the junction – Avouris *PRL* **87** 256805
  - Electron conduction channel variations through the contact may also play a role, where **microscopic to microscopic contacts may increase the carrier injection efficiency** – Datta *Electronic Transport in Mesoscopic Systems*

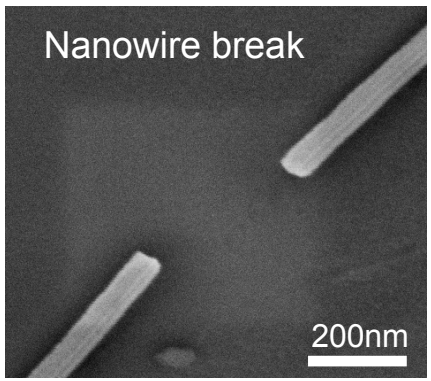
Novel Nano Electronics - 4-Point Probe

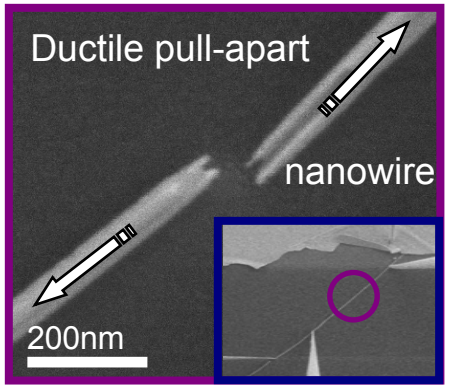


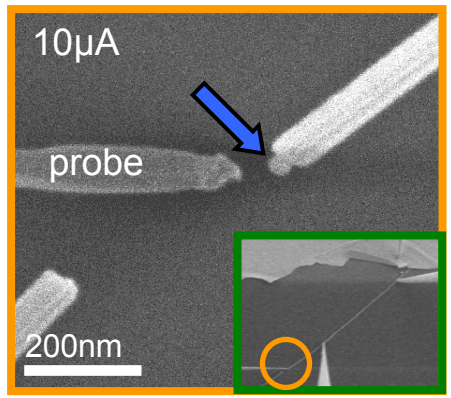
- Why 4-point probe?
  - Accurate resistance measurements, know source current, high impedance voltage probes omit contact resistance (Zyvex KZ100 Nanomanipulator)
  - Really small probes are noninvasive (or much less invasive), reduction in probe induced scattering
- Configuration A - measure the total system resistance **4.5MΩ**
- Configuration B - measure the nanowire resistance (noninvasive) **500kΩ 15.6mΩ-cm**
- Configuration C – measure the nanowire resistance **375kΩ**
- Noisy variations in the resistance may be due to inconsistencies in probe coupling in the respective configurations - Establishing a good contact was difficult

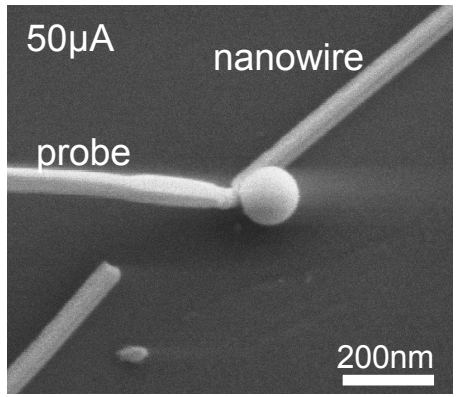
Novel Nano Electronics - Breakdown:

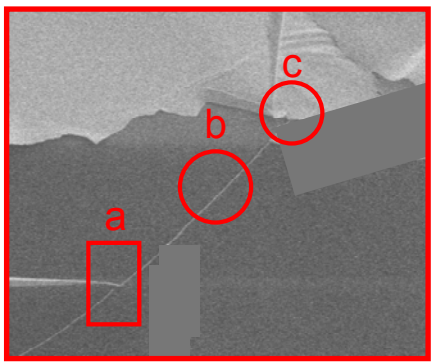
2-point with one probe direct to NW







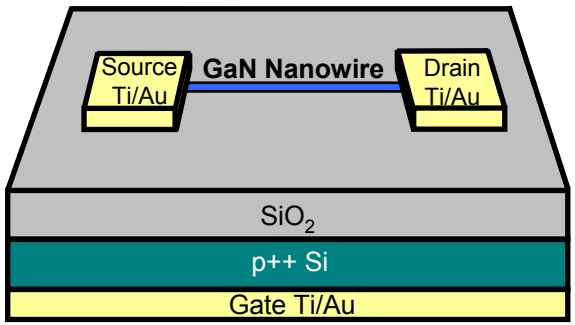


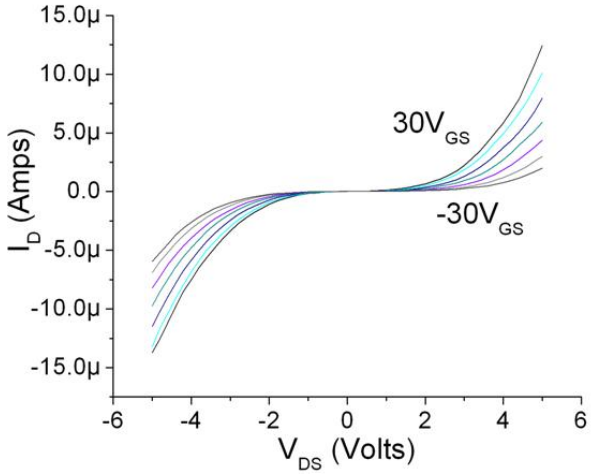


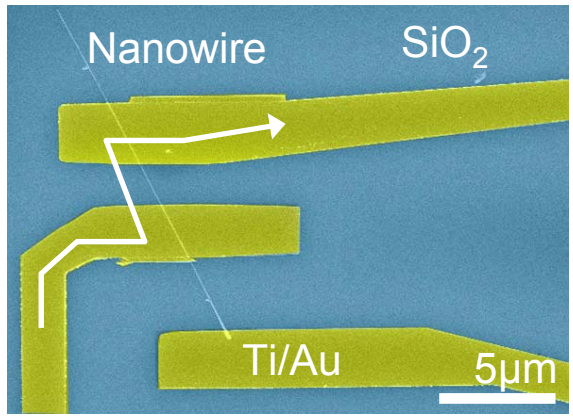
- Breakdown – how much current can we pass?
- A new phenomenon was observed prior to breakdown – a liquid protrusion (the nanowire melted!)
- Large current density – 10×10^5 A/cm^2 whole nanowire 5×10^6 A/cm^2 one wurtzite phase

- **Phase-specific transport?** *Where* is the current actually flowing?
  - Is the difference in phase band gaps large enough to effectively confine electrons? Longitudinal quantum well? See this in nanowire heterostructures, increase in electron mobilities >10,000 cm^2/Vs (nanowire HEMT Leiber *NL* **7** 3214 2007)
  - What is the barrier between the interfaces?

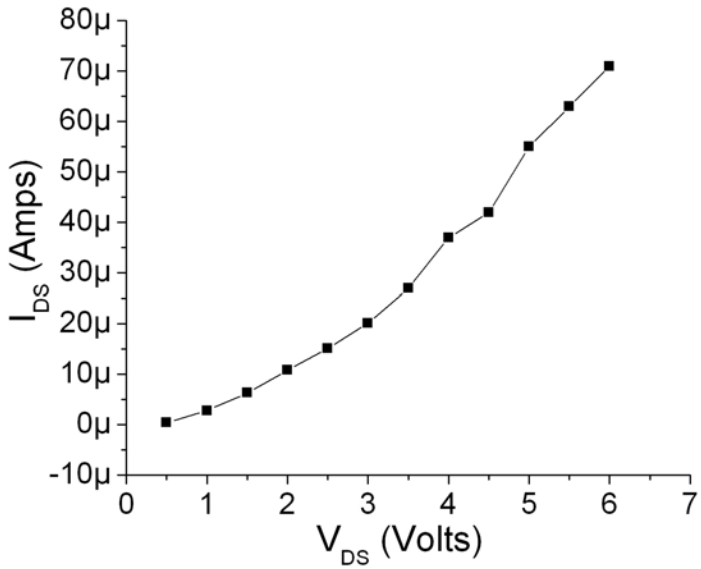
Novel Nano Electronics - GaNFET



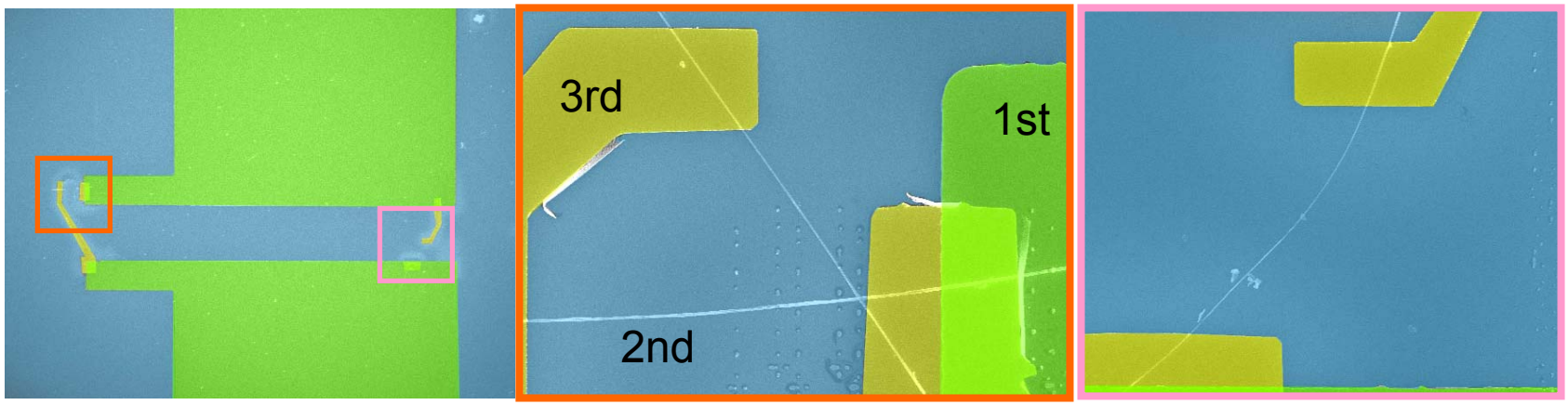




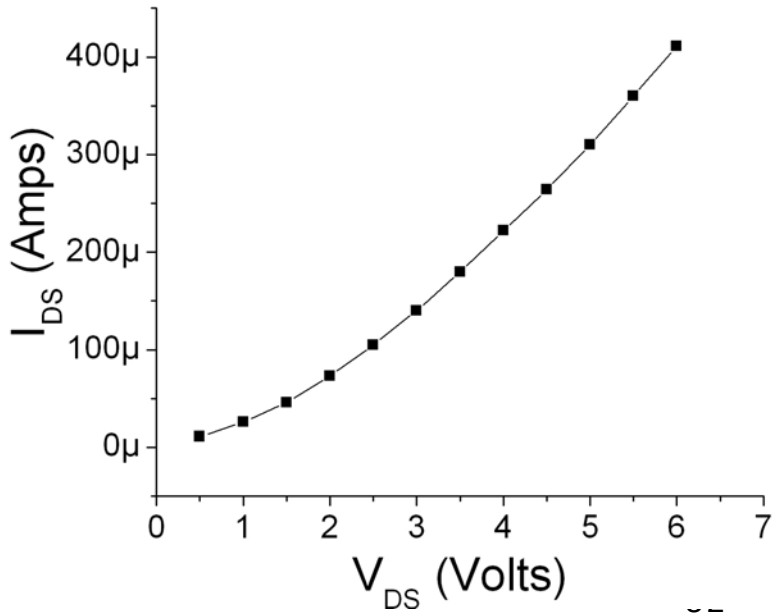
- Three-terminal GaNFET
  - Back gate configuration
  - I-V traces, indicated Schottky barrier behavior since the current changed non-linearly as V_{DS} was swept and V_{GS} stepped.
  - **n-type device**
  - **High current densities**



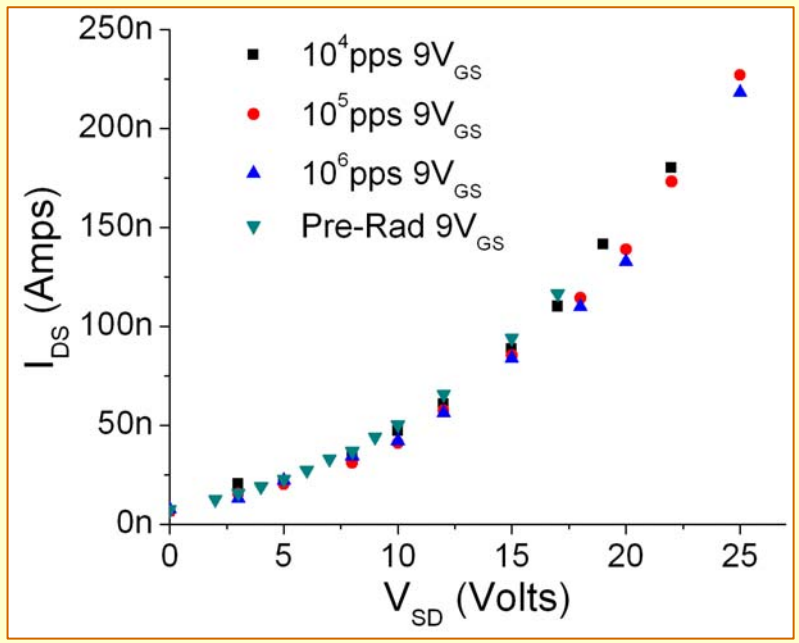
Novel Nano Electronics - GaNFET



- Circuit with three nanowires contacted in parallel
- Over 400 μA was measured at 6 V_{DS}
- Overall picture of how the circuit was fabricated
  - 1st the large Ti/Au pads were patterned with optical lithography (OL).
  - 2nd the nanowires deposited on the surface
  - 3rd Ti/Au contacts were patterned with EBL

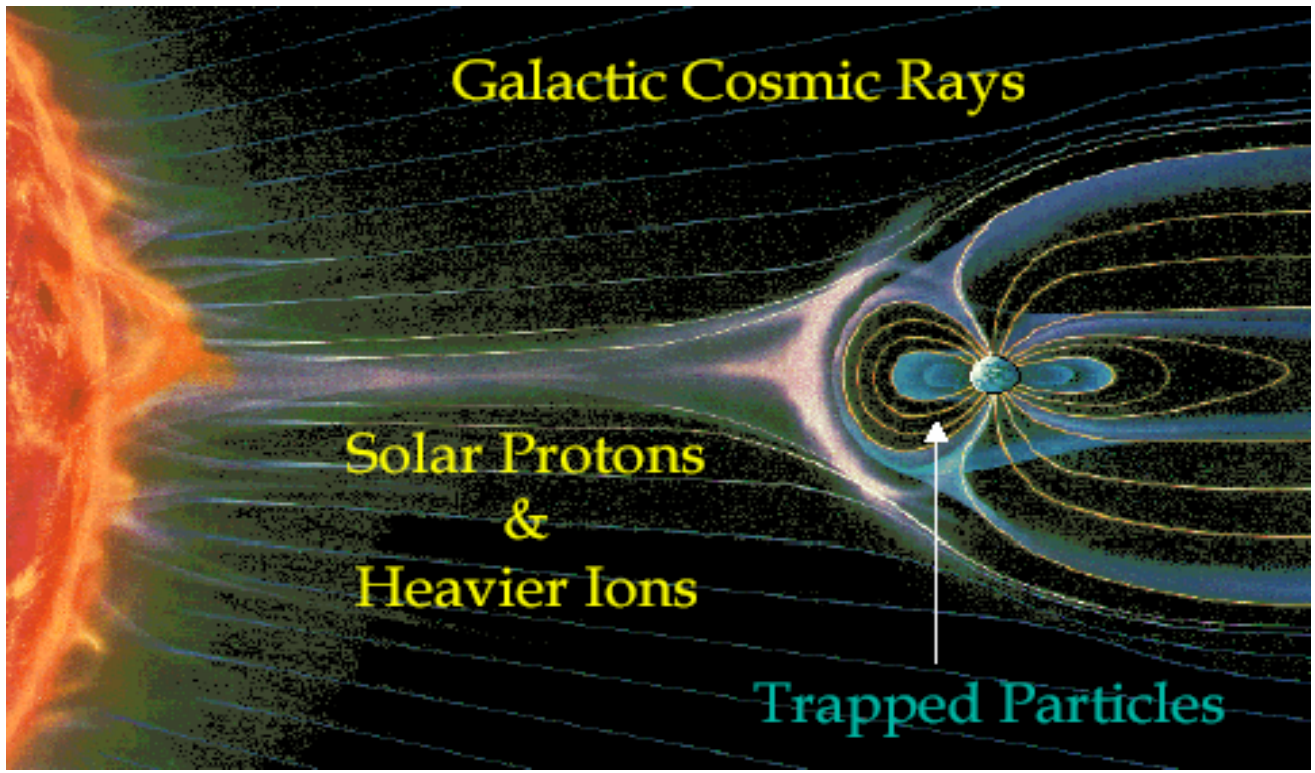


Multiphase GaN Nanowires and Nanocircuits in Space

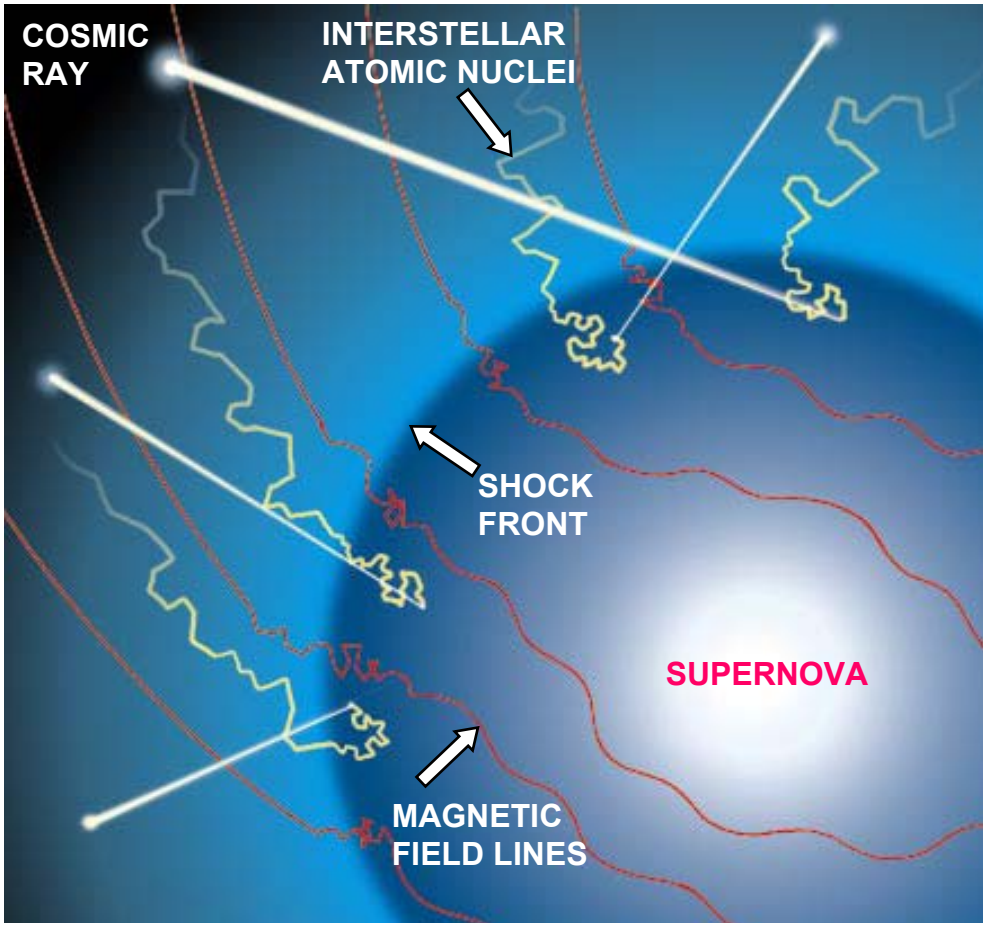


Diamond and Relat. Mater., Vol. 15, 1117-(2006)

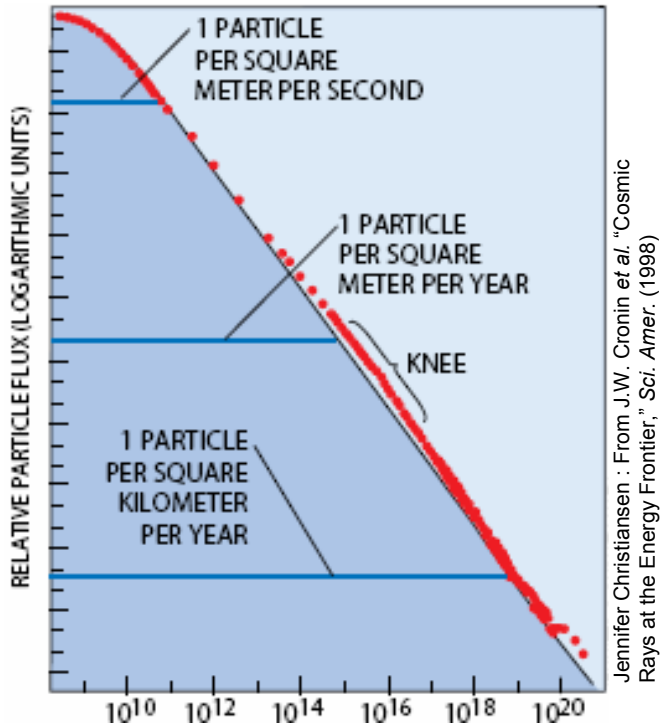
Space Radiation Environment:
Close to Home



Space Radiation Environment:
Outer Space



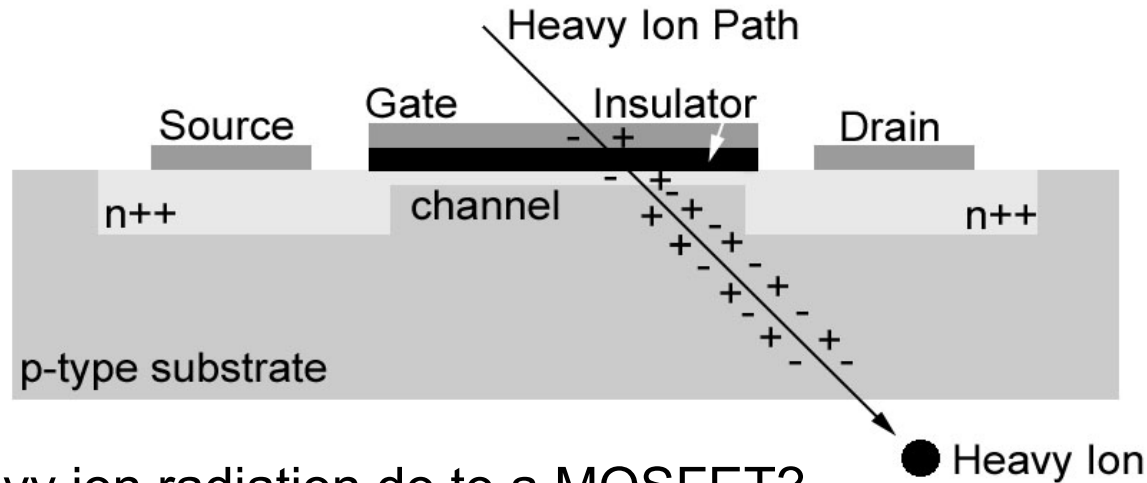
George Kelvin: From J.W. Cronin *et al.* "Cosmic Rays at the Energy Frontier," *Sci. Amer.* (1998)



Supernova and other sources account for particle energies to about 10^{16} eV, the range of energies to the "knee", above that the source is not as yet known

Electronics in Space - MOSFET

- Sensitive Areas
  - Gate
  - Conduction Channel
  - Junctions



What does heavy ion radiation do to a MOSFET?

Changes the **threshold voltage**, V_t, and lower the **transconductance**, g_m, (how well the gate voltage modulates the current)

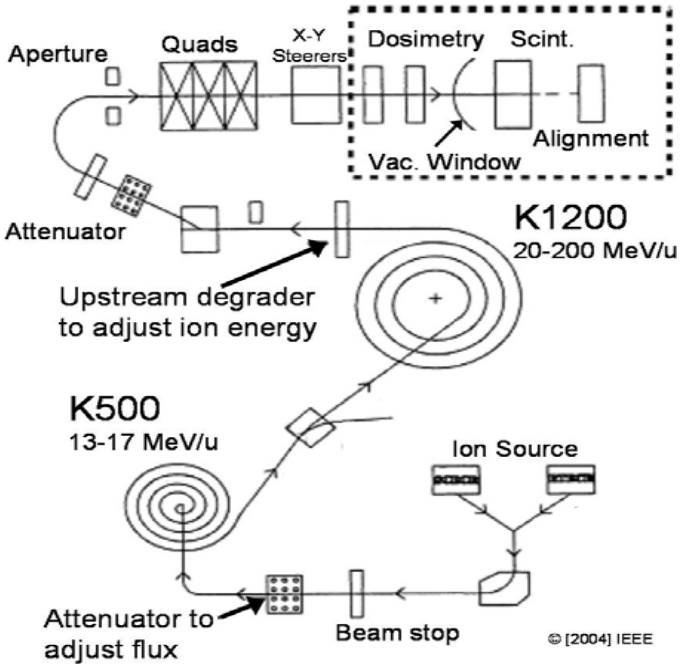
$$V_t = 2\phi_b + \frac{2\sqrt{qN_A\varepsilon_s\phi_b}}{C_{ox}} + \phi_{ms} - \frac{Q'_{ox}}{C_{ox}} - \frac{Q_{it}}{C_{ox}}$$

In CMOS technology a reduction in V_t makes n-type transistors harder to turn off and p-type transistors harder to turn on - this is very bad for business

Heavy ion radiation could also render the transistor completely **inoperable**

National Superconducting Cyclotron Laboratory

Energies that match heavy ion space radiation

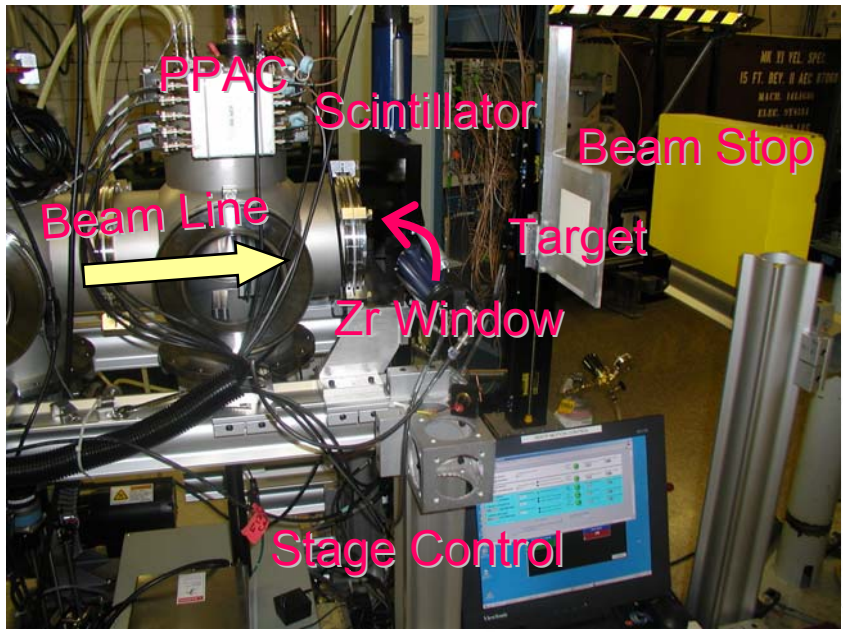


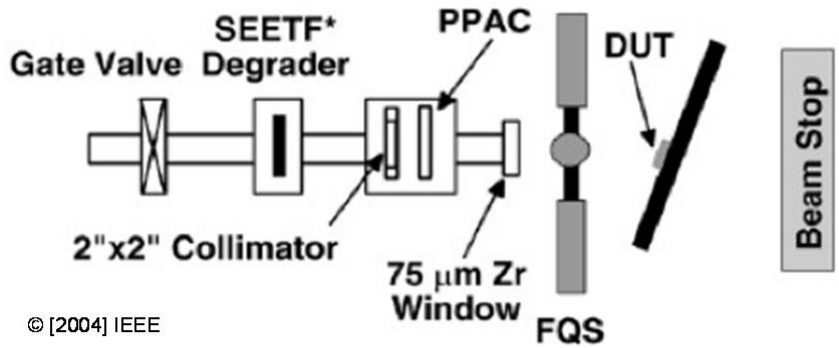
R. Ladbury *et al. IEEE T. Nucl. Sci.* **51,** 3664 (2004)

- Can accelerate any ion in the periodic table
- Coupled Cyclotron accelerates ions from a ionized gas source
- Strong magnets prepare and steer the beam to various vaults where experiments take place
- The Single Event Effect Test Facility (SEETF) is the primary vault we use for testing

Single Event Effect Test Facility (SEETF

- Remote controlled testing system
  - X-Y stage control
  - Laser cross-hair and camera device for precise target positioning
  - Ethernet enables flexibility for a wide variety of user supplied testing and characterization equipment
- Beam characteristics such as fluence can be measured and tracked – important for accurate dose calculation



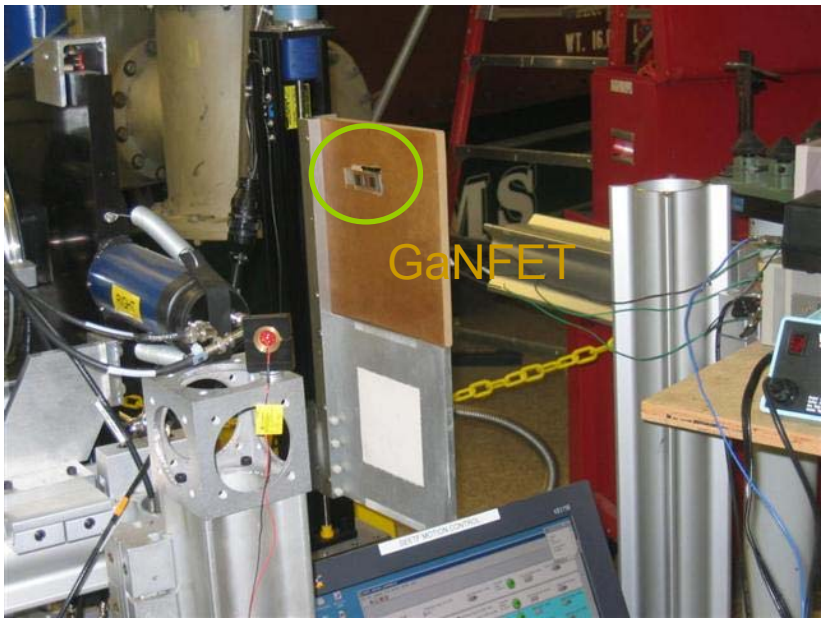


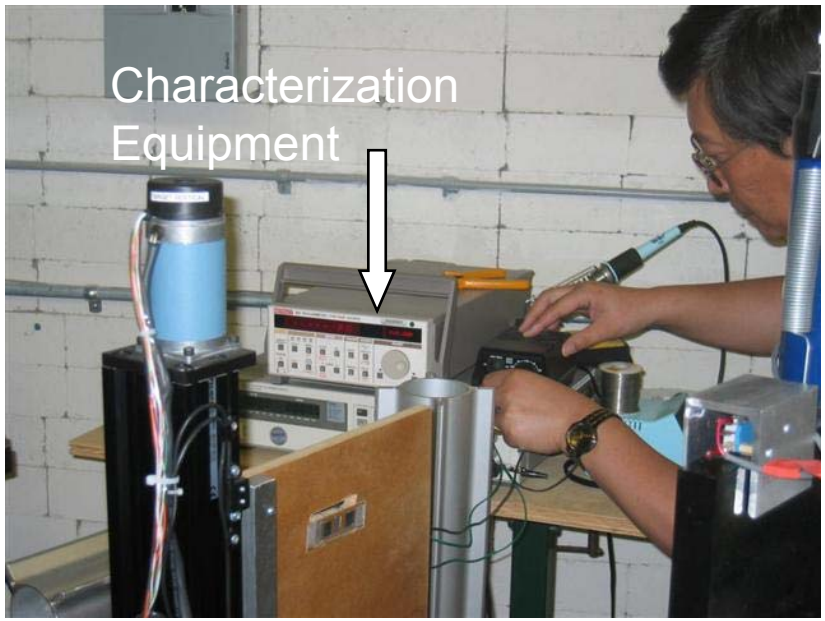
© [2004] IEEE

R. Ladbury *et al. IEEE T. Nucl. Sci.* **51,** 3664 (2004)

Radiation Experiments: ^{78}Kr @ 140 (128) MeV/u

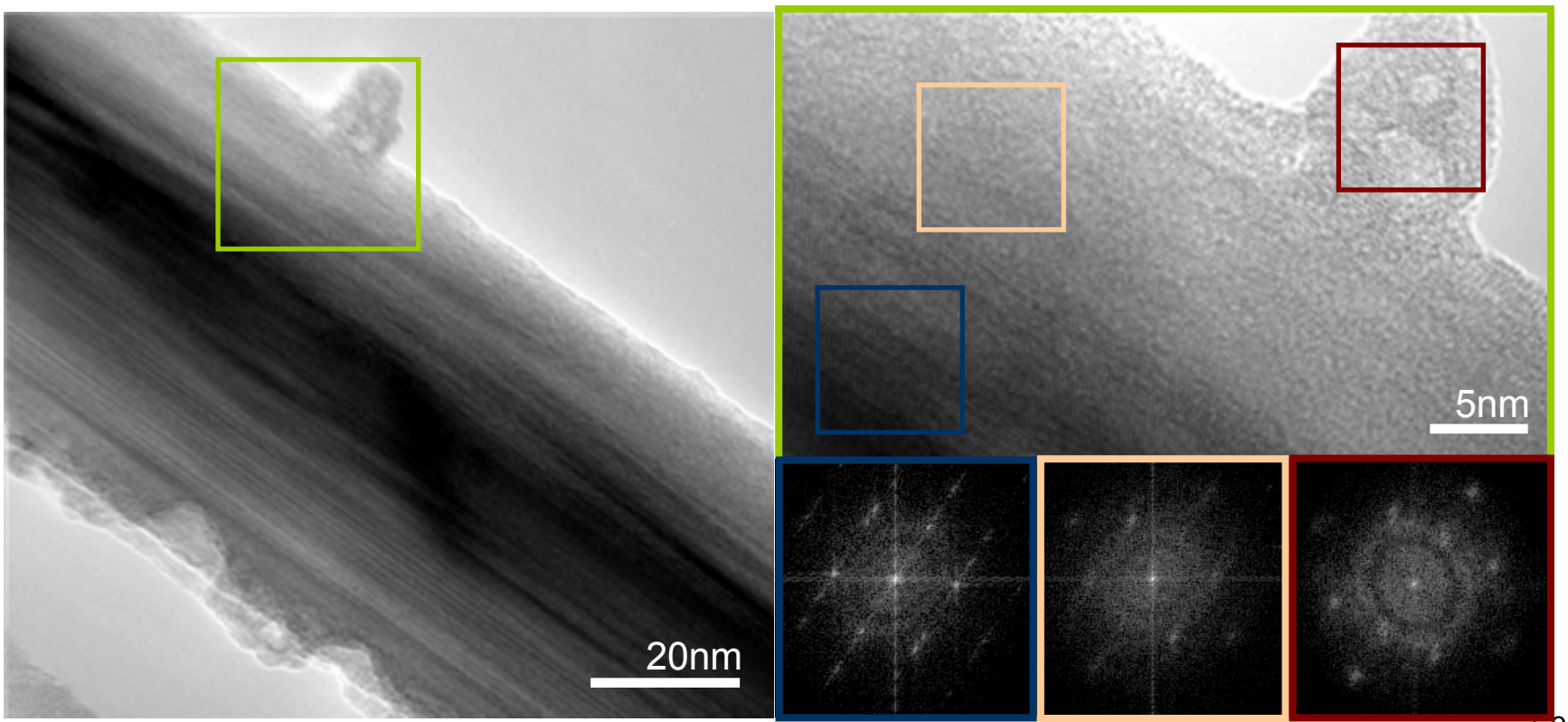
- Multiphase GaN nanowires
- Multiphase GaN nanowire-based field effect transistors





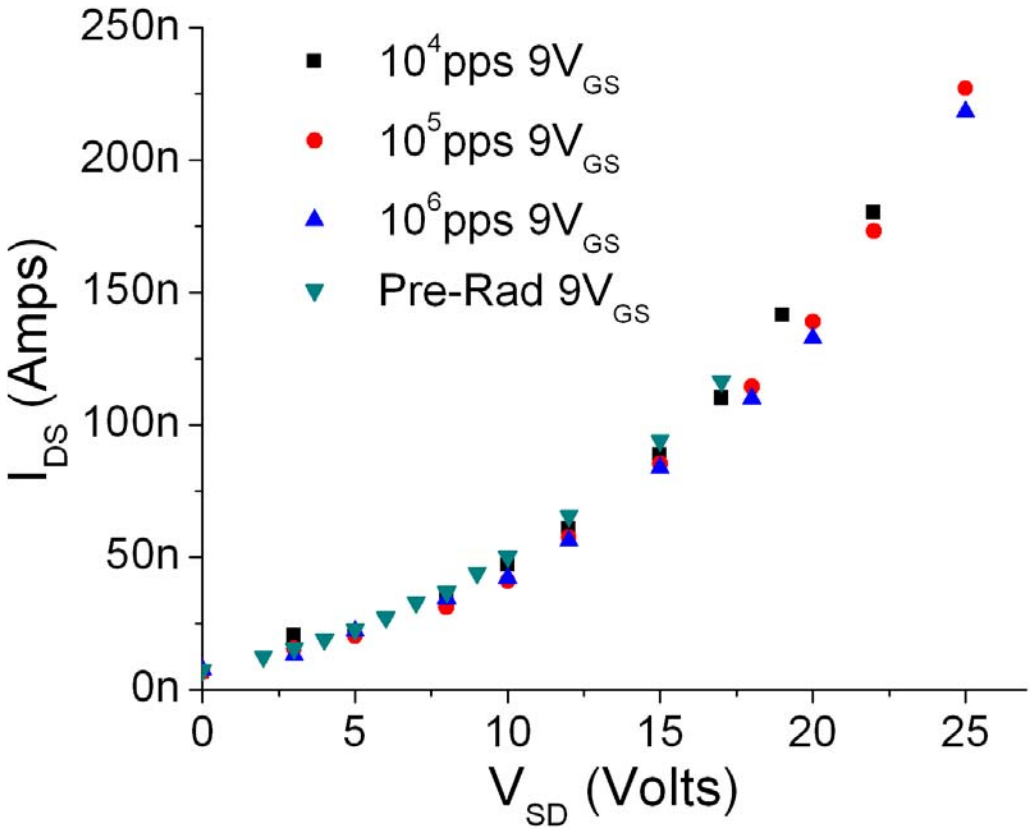
Experimental Results: Multiphase GaN Nanowires

- No ionization tracks observed
- Plumes of material - FFTs show ring patterns and spot patterns
- The zinc-blende/wurtzite interface did not seem to be affected, a pristine interface remained after radiation



Experimental Results: Multiphase GaN nanoFET

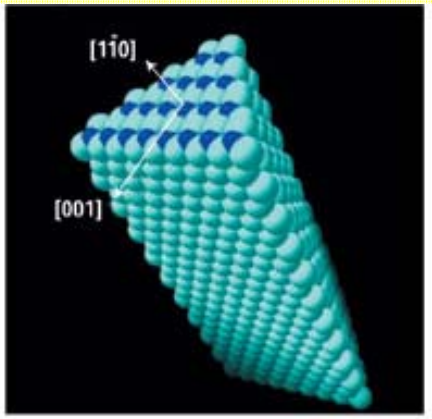
- **10^2** pps over a beam area of 200 mm^2 and was gradually increased to **10^4** pps, **10^5** pps and finally **10^6** pps, **600** sec corresponding to **$3x10^4$** to **$3x10^7$** particles/cm^2
- V_{GS} increased 3, 6, 9 Volts
- Normal function



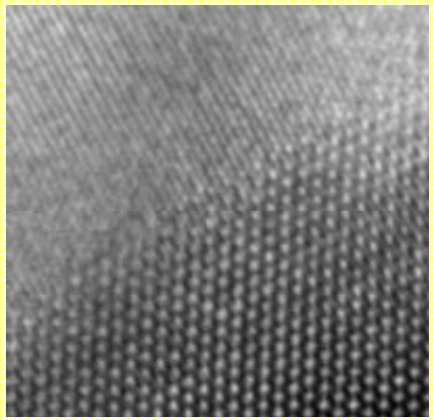
V.M. Ayres *et al. Diam. Relat. Mater.* **15**, 1117-1121 (2006)

V.M. Ayres, B.W. Jacobs, M.E. Englund, E.H. Carey, M.A. Crimp, R.M. Ronningen, A.F. Zeller, J.B. Halpern, M.-Q. He, G.L. Harris, D. Liu, H.C. Shaw and M.P. Petkov, "Investigation of Heavy Ion Irradiation of Gallium Nitride Nanowires and Nanocircuits", Diamond and Relat. Mater., Vol. 15, pp. 1117-1123 (2006)

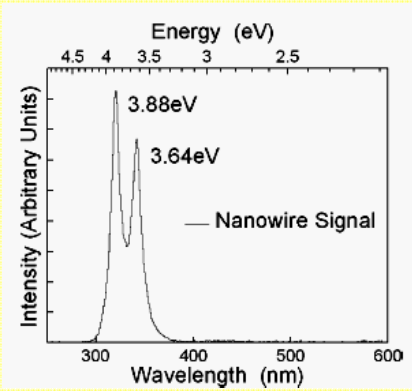
Summary:
Multiphase GaN Nanowires and Nanocircuits



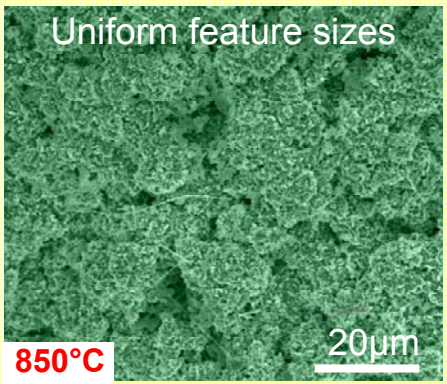
Nature Materials 3, 524 - 528 (2004)



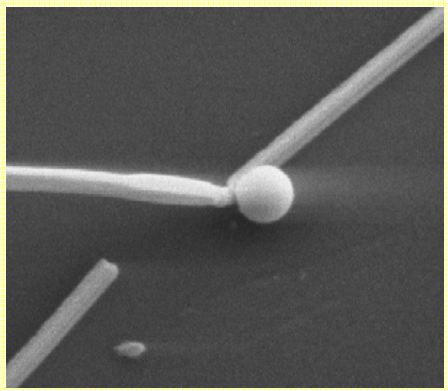
Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)



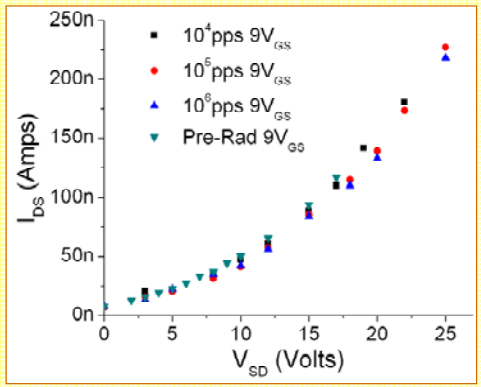
Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)



Submitted, Nano Lett.,



Nanotech., Vol. 18, 475710 (6 pp) (2007)



Diamond and Relat. Mater., Vol. 15, 1117-(2006)

Acknowledgements:

The support of NASA Goddard Space Flight Center and the National Science Foundation IREE, PREM, CREST and REU programs are gratefully acknowledged. B.W.J would like to thank the NASA Goddard Graduate Student Researchers Program. All nanocircuits were fabricated at the W. M. Keck Microfabrication Facility at Michigan State University.

References:

Benjamin W. Jacobs, Virginia M. Ayres, Mihail P. Petkov, Joshua B. Halpern, MaoQe He, Andrew D. Baczewski, Kaylee McElroy, Martin A. Crimp, Jiaming Zhang, Harry C. Shaw, "Electronic and Structural Characteristics of Zinc-Blende Wurtzite Biphasic Homostructure GaN Nanowires", Nano Lett., Vol. 7, No. 5, pp. 1435-1438 (2007)

B W Jacobs, V M Ayres, R E Stallcup, A Hartman, M A Tupta, A D Baczewski, M A Crimp, J B Halpern, M He and H C Shaw, "Electron Transport in Zinc-Blende Wurtzite Biphasic Gallium Nitride Nanowires and GaNFETs", Nanotech., Vol. 18, 475710 (6 pp) (2007)

V.M. Ayres, B.W. Jacobs, M.E. Englund, E.H. Carey, M.A. Crimp, R.M. Ronningen, A.F. Zeller, J.B. Halpern, M.-Q. He, G.L. Harris, D. Liu, H.C. Shaw and M.P. Petkov, "Investigation of Heavy Ion Irradiation of Gallium Nitride Nanowires and Nanocircuits", Diamond and Relat. Mater., Vol. 15, pp. 1117-1123 (2006)

M. He, P. Zhou, S.N. Mohammad, G.L. Harris, J.B. Halpern, R. Jacobs, W.L. Sarney, L Salamanca-Riba, "Growth of GaN nanowires by direct reaction of Ga with NH3", J. of Crystal Growth Vol. 231 (2001) 357.

Thank you for your attention. Any questions?

ayresv@msu.edu