Title: Nanowire Templated Lateral Epitaxial Growth (NTLEG) of Low Dislocation Density GaN

SAND2007-3629P

Prime Recipient: Sandia National Laboratories
Agreement Number (M6643034)

Technology Focus: Nanotechnology (Core)
Relevant Subtask Priority Area: Improvement of internal efficiency of nitride LEDs by reduction of defect density

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Outline

- Objective of project
- Schedule/Budget Overview
- Project Objective
- Technical Background
- Technical Approach & Work Plan
- Progress to Date
- Technical Barriers/Problems
- Milestones/Deliverables
- Project Team/Capabilities
- Commercialization Plan

Schedule/Budget Overview

The table shows, by budget period, the amount of government funding going to Sandia National Laboratories. Since Sandia National Laboratories is a prime contactor to DOE there is no cost sharing in this project.

	Start Date	End Date	Government Share	Performer Share	Total
Budget Period 1	(10/01/06)	(9/30/07)	397K$	$	397K$
Budget Period 2	(10/01/07)	(3/31/08)	220K$	$	220K$
Total	**(10/01/06)**	**(3/31/08)**	**617K$**	**$**	**617K$**

Total Spent + Committed Funding (as of end of 5/25/2007): $269K (44% of budget) (roughly linear spending so far)

Detailed Cost Analysis

(Taken from the proposal)

	Manpower (FTE)	Manpower costs ($K)	Equipment / Supplies ($K)	Travel ($K)	Total Costs ($K)
Year 1	1.68	360	25	12	397
Mos. 13-18	.88	206	7	6	219

Costs include all applicable indirect burdens and represent full-cost-recovery. Sandia's specific overhead cost recovery rates and individual salary rates are proprietary information.

Project Objective

To develop a novel, **low-cost** technique (Nanowire Templated Lateral Epitaxial Growth, **NTLEG**) employing vertically aligned GaN nanowire arrays grown by metal-catalyzed metal-organic chemical vapor deposition (MOCVD) as high quality templates for the lateral growth and coalescence of low dislocation density, non-polar GaN films (target ≤ 10^8 cm^{-2} range for first eighteen months of project, eventual target ≤ 10^7 cm^{-2} range dislocations).

Technical Background

Background - Benefits of Solid-State Lighting

Targets from the 2006 EERE Multi-Year Program Plan and analysis from the report on the 2006 BES Workshop on Basic Research Needs for SSL

Could reduce global electricity used for lighting by 50%. (by 2025)

Substantial reductions in carbon-related pollution.

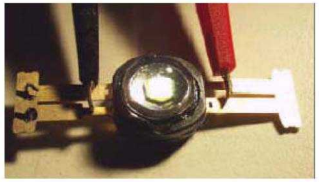
Annual potential benefits in US alone projected for 2025:

- Saving 620 terawatt hours / yr of electric energy
- Eliminating 100 million metric tons / yr of carbon emission
- Alleviating the need for 71 new power stations (1000 MW each)
- Financial savings to consumers of $42 Billion / yr

Creation of a new lighting industry, with many new, high quality jobs.

New flexibility on how general purpose lighting is achieved.

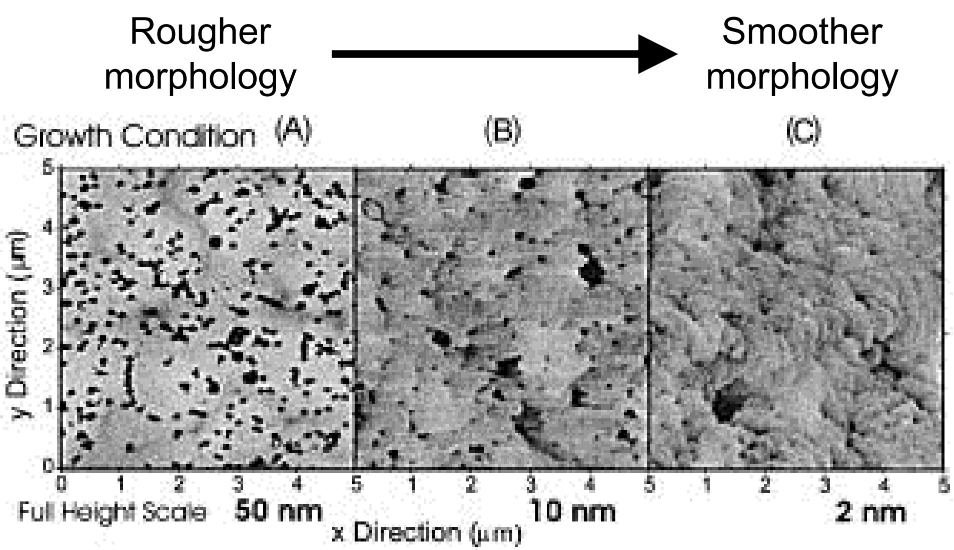


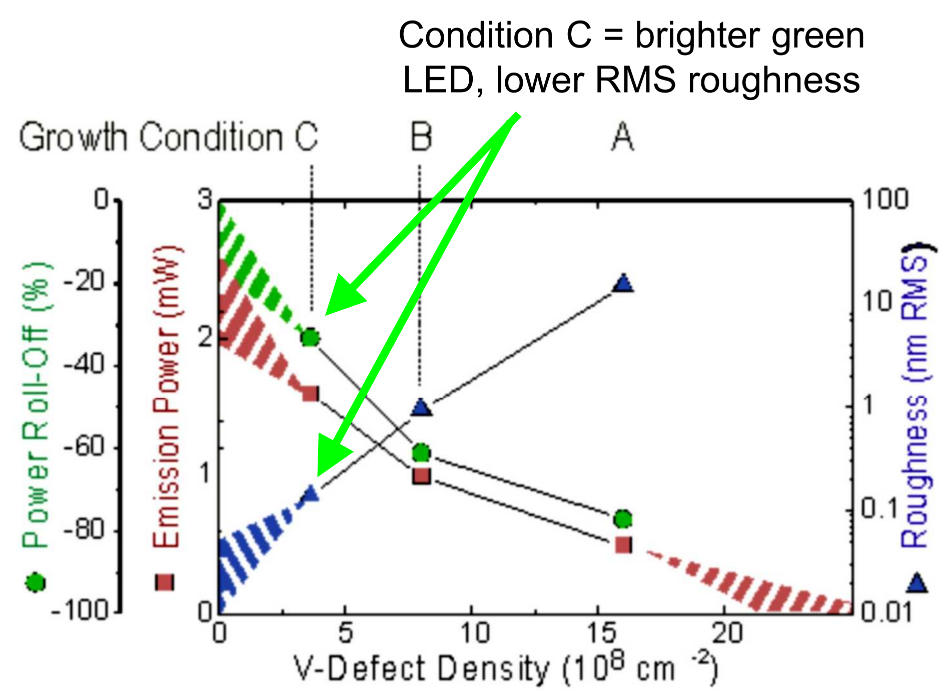


Background - Potential Benefits to SSL – Improved Green LEDs

Red-Green-Blue SSL approach should be most energy efficient, however green LEDs efficacy is substantially lower than red or blue LEDs.

Possible correlation between reduced V-defect formation, smoother surface morphology, and brighter green LEDs.



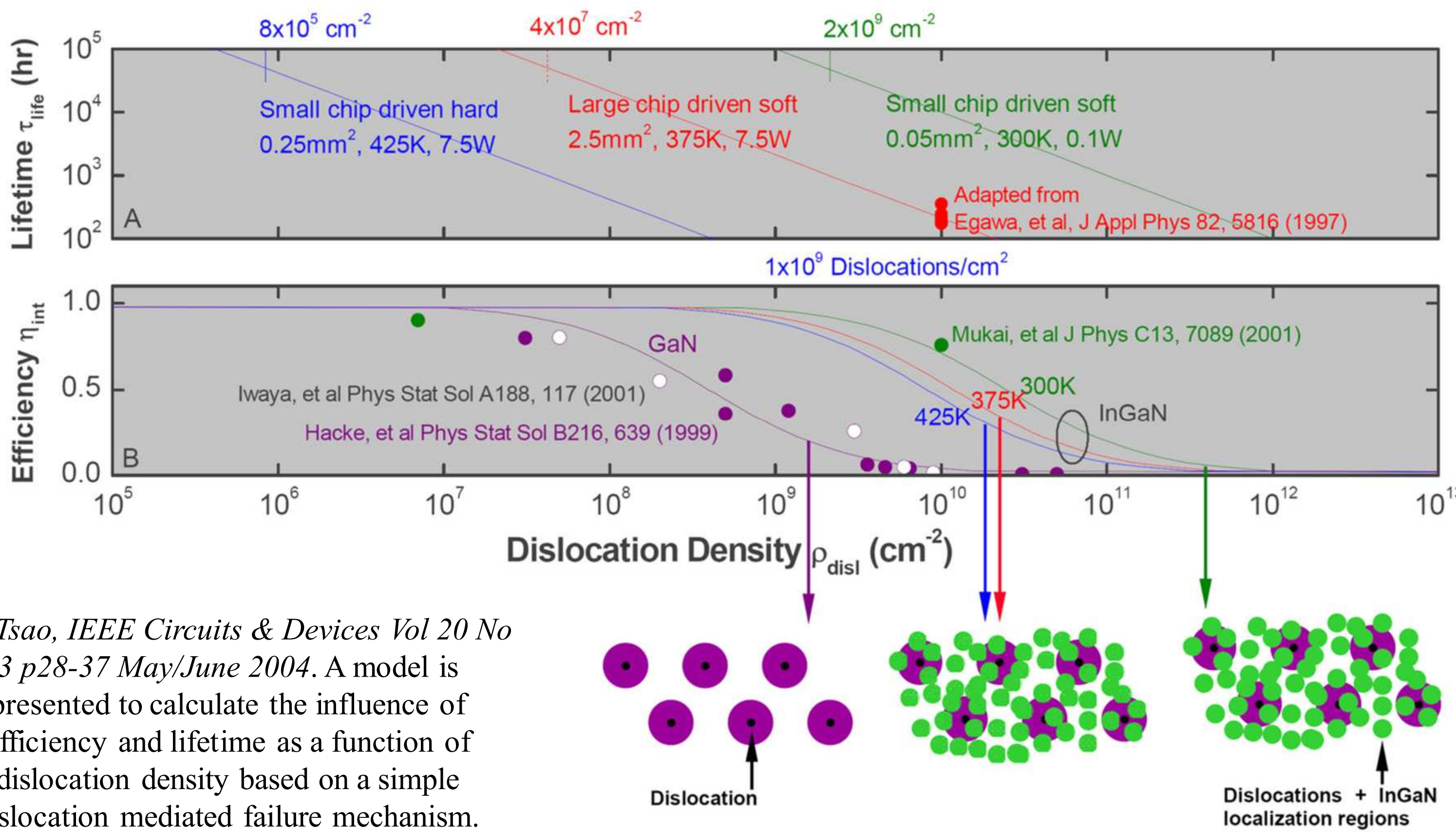


Wetzel, et al., Appl. Phys. Lett. 85, 866 (2004).

Brighter green LEDs when grown on lower dislocation density GaN.

Background - Potential Benefits to SSL – Improved LED lifetime

For high current opto-electronic applications, devices might degrade through common dislocation induced failure mechanism observed in other III-V semiconductor devices. *At future, higher input power densities, dislocations ≤ 10^7 cm^{-2} may be required for acceptable lifetimes*



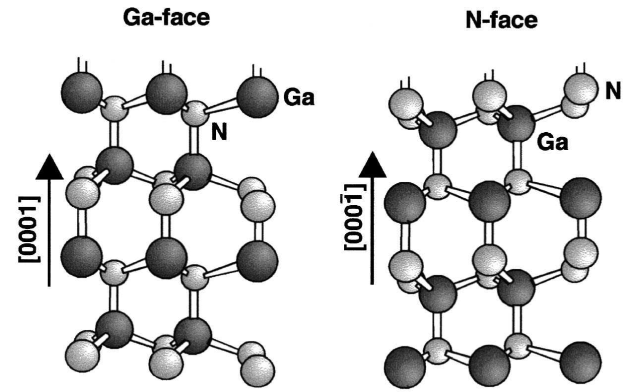
J.Y. Tsao, IEEE Circuits & Devices Vol 20 No 3 p28-37 May/June 2004. A model is presented to calculate the influence of efficiency and lifetime as a function of dislocation density based on a simple dislocation mediated failure mechanism.

Device lifetime increased on lower dislocation density GaN.

The Problem with Polar GaN

- Wurtzite GaN has spontaneous and piezoelectric polarization fields aligned along the c-axis (standard growth direction for GaN technology)
- This causes a spatial separation of electrons and holes in LED quantum wells and reduces quantum efficiency and can produce a shift in the emission wavelength at different drive currents (quantum confined Stark effect).
- This effect is increased as In content increases, making efficient green LEDs challenging

GaN lattice

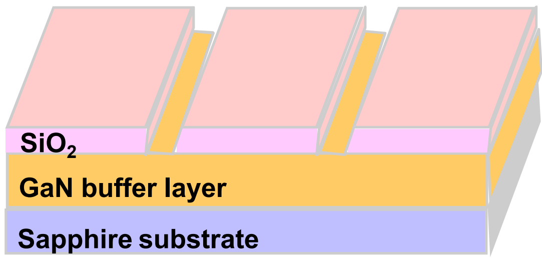


- Non-polar a-plane and m-plane GaN have a surface plane with equal numbers of gallium and nitrogen atoms, which eliminate deleterious polarization effects. **Thus, green LEDs grown on non-polar GaN could have greatly increased efficiency.**
- Ni et al. (APL, **89,** 262105, 2006) have demonstrated (11-20) a-plane GaN with dislocation densities in 10^8 cm^{-2} range in window areas (10^{10} cm^{-2} range bare sapphire) via epitaxial lateral overgrowth (ELO).

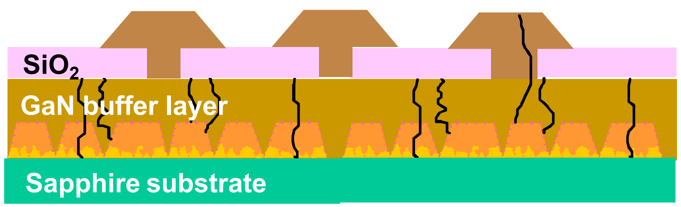
Background – Current Technology

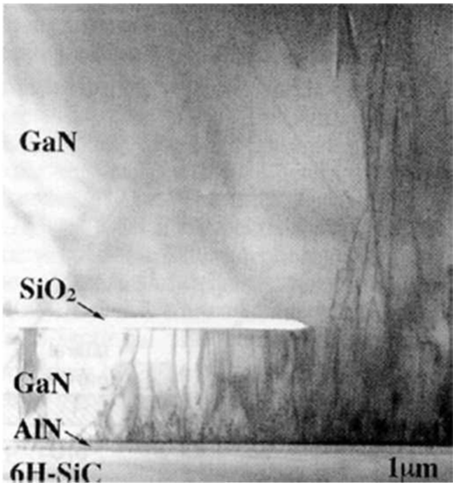
Epitaxial lateral overgrowth (ELO) techniques currently employed reduce the dislocation densities of heteroepitaxial GaN. With lateral overgrowth techniques, typical dislocation densities in the mid-high 10^7 cm^{-2} range can be achieved.

Dielectric mask pattern defines new growth zone



GaN grows only from exposed regions;
Threading dislocations density greatly decreased.





Defect density decreased from $10^9/cm^2$ to less than $10^7/cm^2$ above the masked regions*

*** Ref: T. Zheleva, O-H Nam, J. D. Griffin, M. D. Bremser, R. F. Davis, Mat. Res. Soc. Symp. Proc., 482, 393 (1998).**

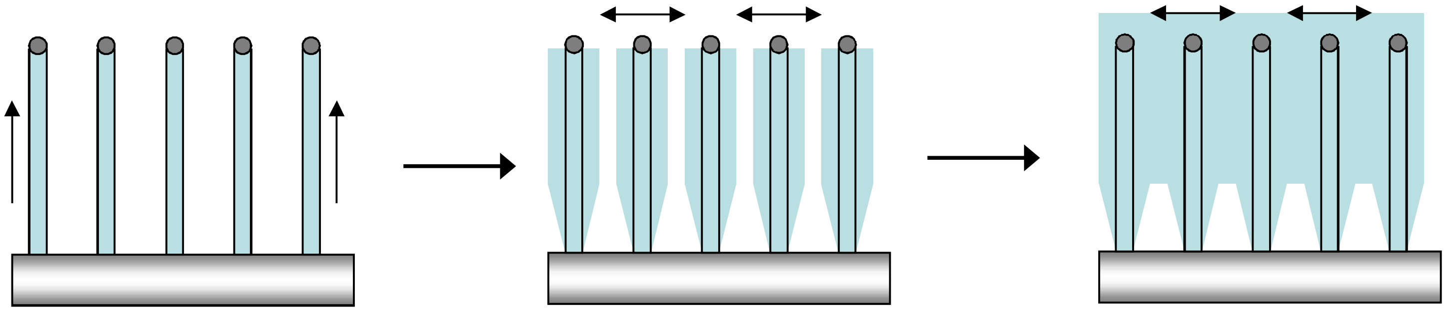
Main disadvantage of ELO techniques is cost. Due to process complexity, epitaxial cost is tripled or more, limiting use to more costly devices like blue laser diodes. Recent quote (late 2005) for ELO GaN material on 2-inch sapphire ~$1200 per wafer, compared to ~$300 for conventionally grown GaN.

Potential Benefits to SSL -- Cost

In order to achieve targeted efficiency and device lifetime goals, it will be necessary to provide low dislocation density GaN substrates and buffers that will allow fabrication of high power density, efficient LEDs with long lifetimes. Additionally, the costs of these substrates and buffers must be low enough to allow LEDs to be cost-competitive with other lighting technologies.

*This proposal will impact **all aspects of the DOE SSL mission** by providing a novel technique (NTLEG) that will enable growth of high quality (eventual target ≤ 10^7 cm^{-2} range dislocations) GaN buffers at a cost **substantially lower** than current lateral overgrowth techniques. Additionally, the GaN films produced using this technique will be **non-polar** a-plane GaN. This will enable **cost-competitive, high power density, high efficiency LEDs with long lifetimes** to be developed.*

Overview & Advantages of NTLEG Approach

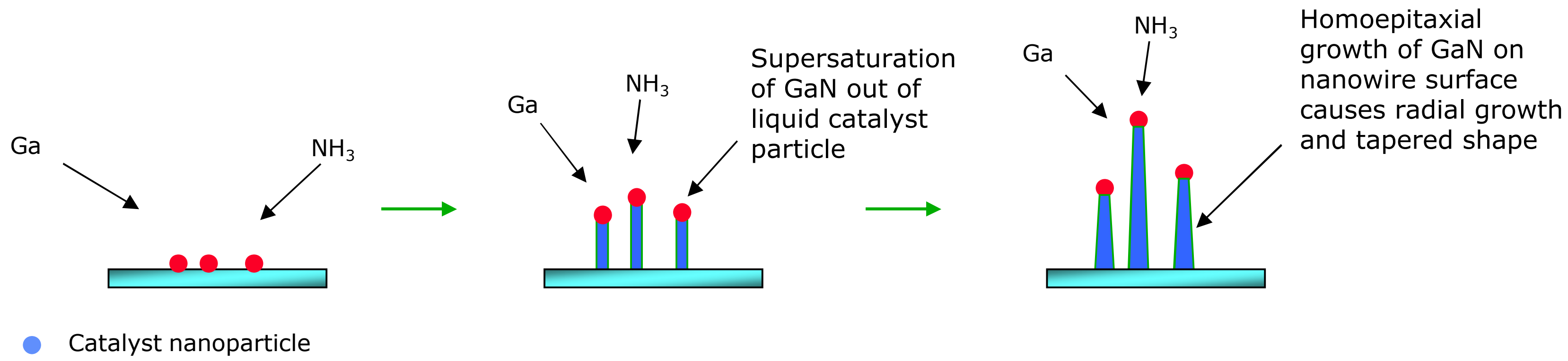


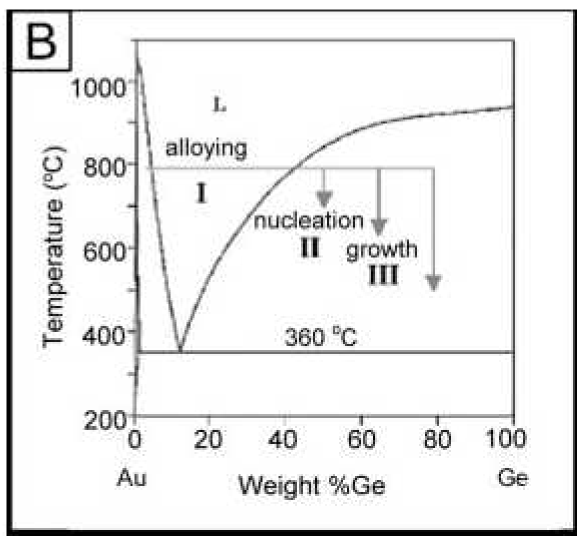
Advantages of NTLEG approach over ELO

- High quality, low dislocation or dislocation-free nanowires as growth template
- **Nanowires serve as 3D-compliant nanoscale bridges connecting film and substrate, relieving strain in the film & reducing defects (nanoheteroepitaxy)**
- No unusable “stripe” areas
- Low cost
  - Sapphire can be used (potentially even Si)
  - Requires no patterning or interruption of growth
  - Cost is comparable to standard GaN growth on sapphire
- Film takes on nanowire orientation (**non-polar orientations available**)

Background: VLS-Based Synthesis of GaN Nanowires

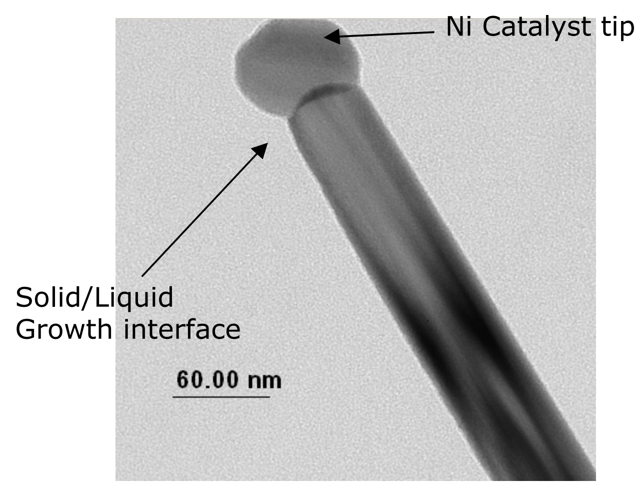
Vapor-liquid-solid (VLS) mechanism





From Xia et al. *Adv. Mater.* ***2003,*** *15, 353.*

Single crystal GaN Nanowire

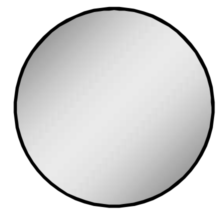


G.T. Wang

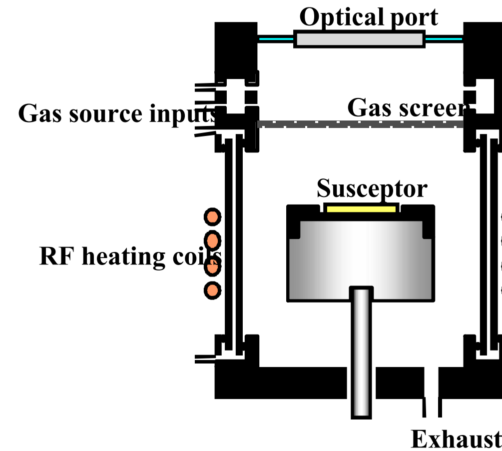
Sandia GaN Nanowire Growth Experimental Details

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

<u>MO Growth precursors</u>:
Trimethylgallium (TMGa),
Trimethylaluminum (TMAl),
Trimethylindium (TMIn),
Ammonia (NH_3)



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



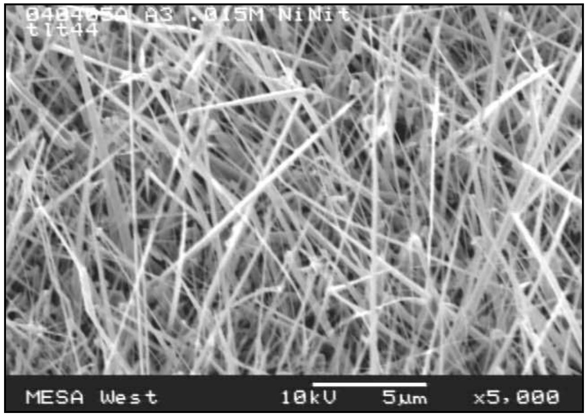
Cold-wall rotating disk reactor

<u>Advantages of MOCVD/OMVPE for III-Nitride Nanowire Growth</u>

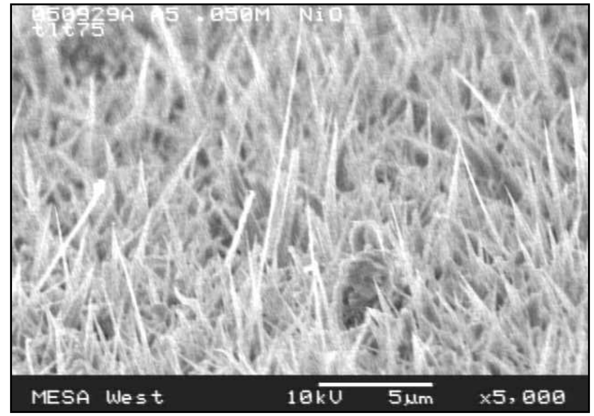
- Standard technique for III-nitride commercial growth
- Precursor control (flow, modulation)
- Compositional control (alloys)
- In-situ n-type and p-type doping
- *Ability to grow heterostructure nanowires in-situ*
- In-situ integration with films
- Scalability

Vertically aligned GaN nanowires possible by careful selection of substrate orientation

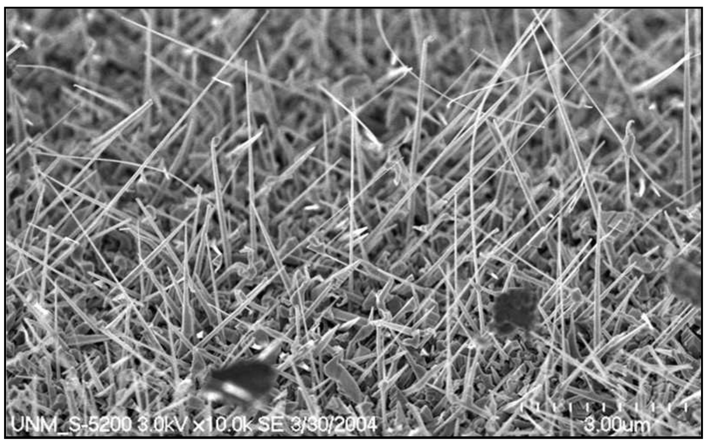
800°C, 15 min, sapp-c (0001)



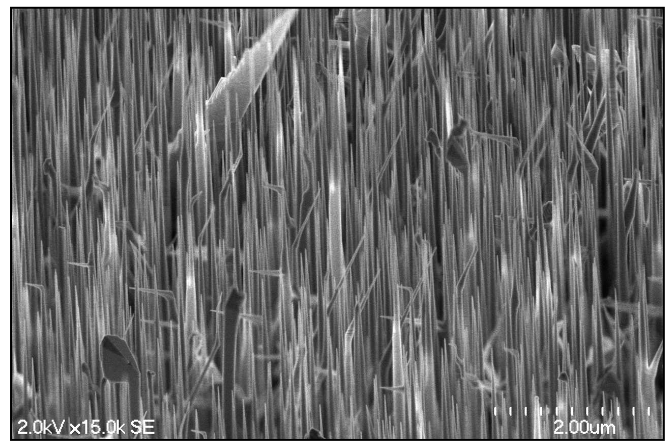
800°C, 5 min, 500nm SiO2 on Si



800°C, 5 min, sapp-a (11-20)



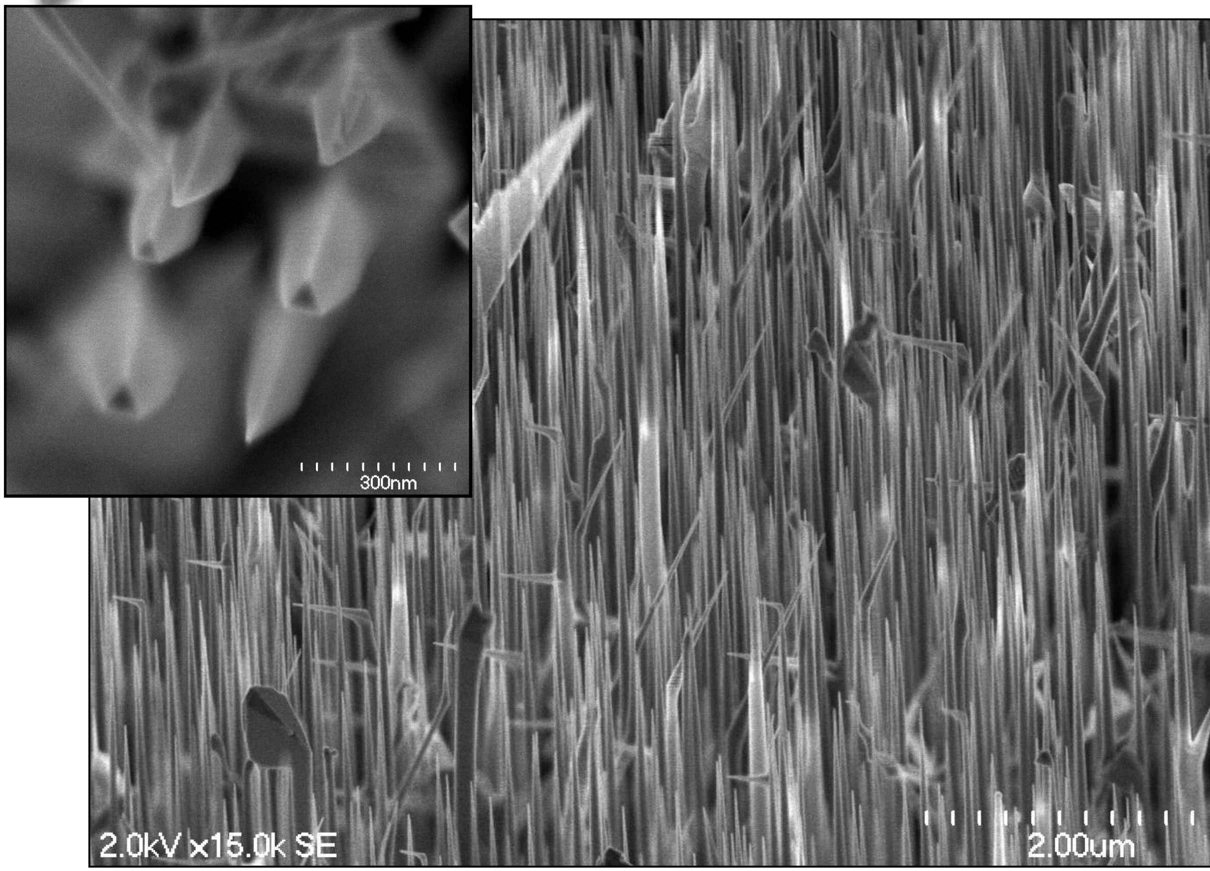
800°C, 3 min, sapp-r (1-102)

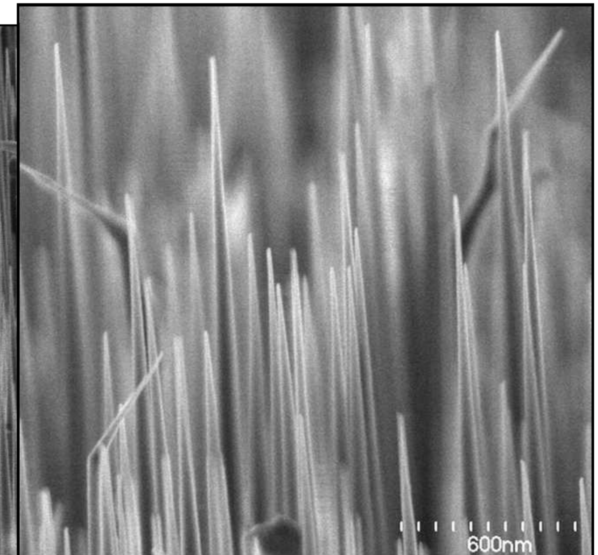


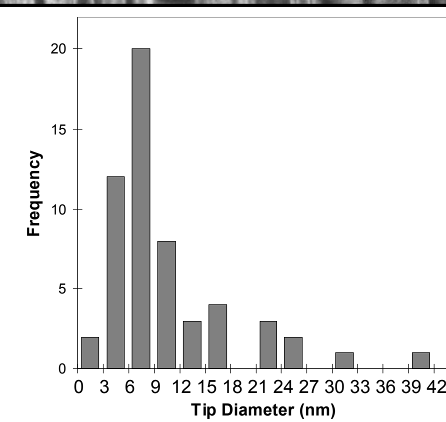
- Substrate plays important role in alignment
  - Crystallographic alignment of GaN nanowires on (100) γ-$LiAlO_2$ and (111) MgO[1]

[1] Kuykendall, T.; Pauzauskie, PJ; Yanfeng Zhang; Goldberger, J.; Sirbuly, D.; Denlinger, J.; Peidong Yang *Nature Mat.* **2004,** 3, 524.

Vertically aligned nanowire growth on r-plane sapphire



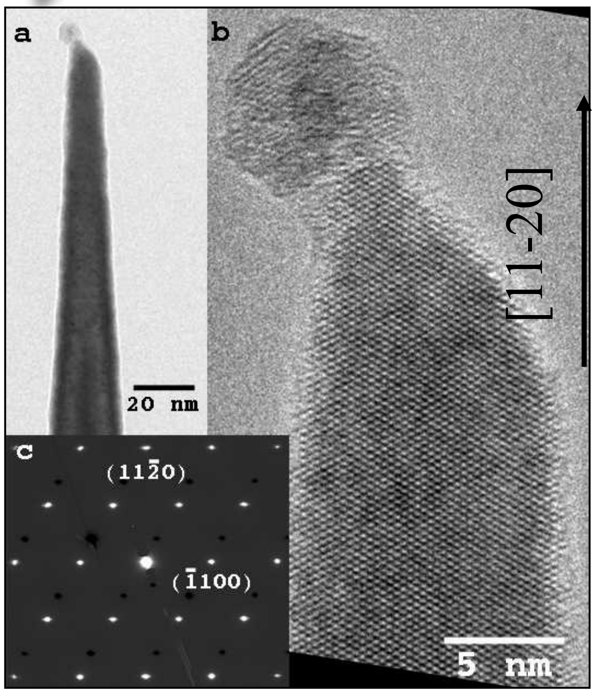


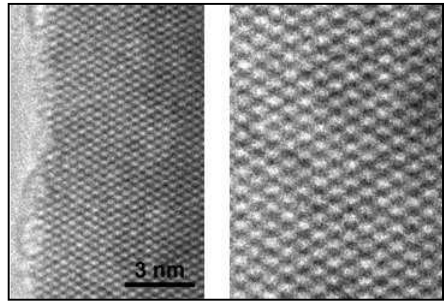


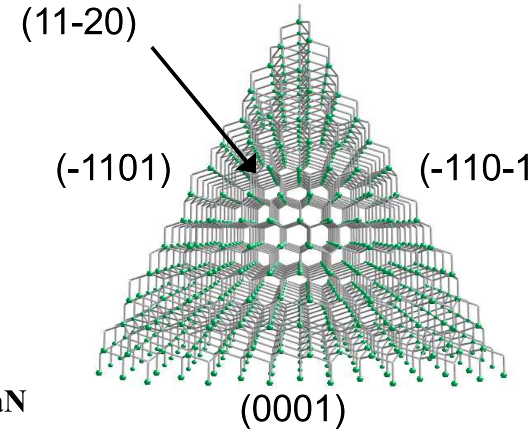
- Catalyst: $Ni(NO_3)_2$ in EtOH
- Regions of highly aligned, vertical nanowires
- **Nanowire facets all aligned in same direction** – indicates common crystal orientation – ***ideal (and necessary) for NTLEG film nucleation***

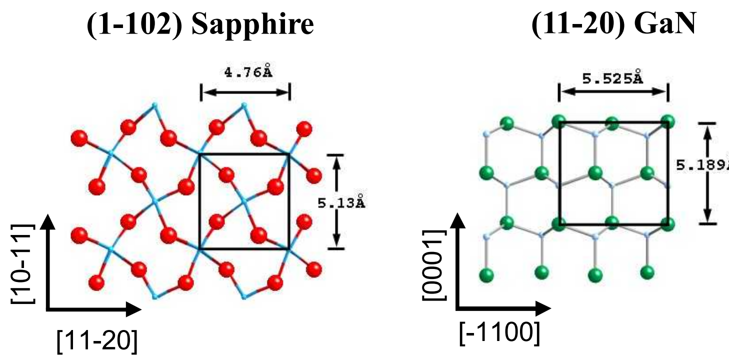
Wang, G. T. et al., Nanotechnology 17 (2006) 5773-5780

TEM - Structure & Orientation of Nanowires









- Nanowires are single crystal (wurtzite) and **dislocation-free**
- [11-20] growth direction same as (11-20) a-plane GaN film growth on r-plane sapphire – explains crystallographic alignment of nanowires
  - [0001]GaN||[-1101]sapp = 1.3% mismatch
  - [-1100]GaN||[11-20]sapp = 15% mismatch (near match every 7 spacings)
- **Note: Due to nanowire orientation, NTLEG film will be non-polar (11-20) a-plane GaN !**

Wang, G. T. et al., Nanotechnology 17 (2006) 5773-5780

Technical Approach and Work Plan

- **Task 1 -– Growth, characterization, and optimization of GaN nanowire templates**
  - **Goal:** Template-free growth and characterization of dense, highly uniform and highly aligned vertical arrays of single crystal GaN nanowires across 2" r-plane sapphire.

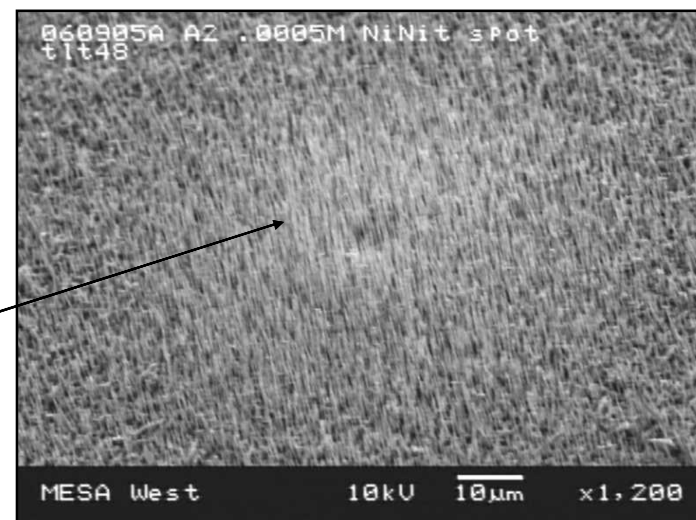
- **Task 2 -- Growth, characterization, modeling, and optimization of GaN NTLEG films**
  - **Goal:** Growth, characterization, and modeling of GaN NTLEG films using template-free GaN nanowire arrays. Optimize and demonstrate a-plane non-polar GaN NTLEG films with dislocation densities ≤10^8 cm^{-2} range.

Task 1. Growth, characterization, and optimization of GaN nanowire templates

Goal: *Template-free growth and characterization of high quality, vertical arrays of single crystal GaN nanowires across 2” r-plane sapphire*

- We will work towards the *uniform* growth of highly aligned, vertical GaN nanowires across the area of 2-inch unpatterned *r*-plane sapphire wafers
- These aligned nanowire arrays will serve as the growth template for lateral growth of the NTLEG films (Task 2)

- We have previously demonstrated *regions* of vertically aligned GaN nanowires on unpatterned (1-102) *r*-plane sapphire substrates
- However, the exact conditions leading to the highest degree of uniformity, density, and alignment are still not well understood (related to non-uniform drying of solution)
- The result is poor coverage and reproducibility of these highly aligned regions



Spot with highly aligned nanowires

Task 1. Growth, characterization, and optimization of GaN nanowire templates

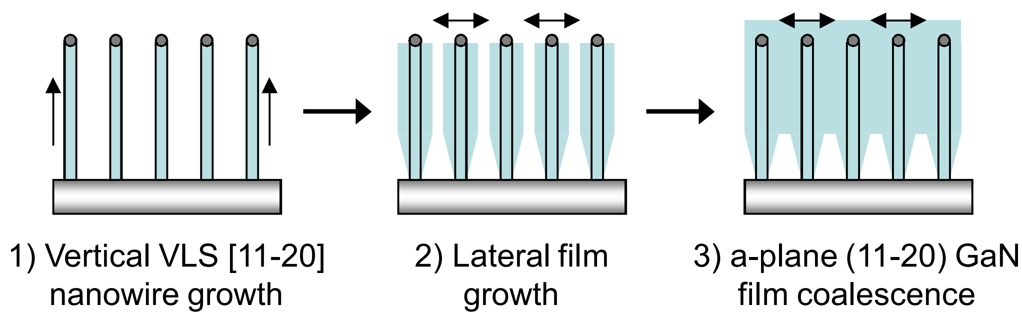
Approaches we will initially try to achieve *reproducible, uniform, wide-area* aligned growth:

- Application of catalyst in different forms (film vs. solution vs. nanoparticles)
- More controlled application of catalyst (e.g. spin-coating)
- More careful study of catalyst nanoparticle formation and distribution
- Experiment with substrate surface preparation (e.g. preannealing)
- Examine effect of miscut angle on growth
- Vary process conditions (flows, V-III ratio, pressure, temperature)

- The alignment, density, uniformity, orientation, morphology, and structural quality of the nanowires will be characterized using SEM and TEM
- The optical & electrical properties of the nanowires will be probed with I-V and photoluminescence and cathodoluminescence measurements

Task 2. Growth, characterization, modeling, and optimization of GaN NTLEG films

Goal: *Growth and characterization of* ***non-polar*** *a-plane GaN NTLEG films using template-free GaN nanowire arrays. Optimize and demonstrate NTLEG films with dislocation densities ≤10^8 cm^{-2} range.*



- **Subtask 2.1. Growth and optimization of NTLEG GaN films from vertical nanowire arrays grown without the use of a template**
- **Subtask 2.2. Characterization of NTLEG GaN films**
- **Subtask 2.3. Modeling of NTLEG process**

Subtask 2.1. Growth and optimization of NTLEG GaN films from vertical nanowire arrays grown without the use of a template

- Following growth of a uniform, vertical nanowire array, the growth conditions will be altered *in-situ* such that vertical VLS-based nanowire growth is quenched and lateral growth from the side facets of the nanowires is accelerated.

- Lateral growth will continue until coalescence of the lateral growth fronts into a continuous film. Pinch off will result in a suspended film not connected to the sapphire substrate, which will relieve strain energy and reduce the number of defects in the NTLEG film.

- We will experiment with different growth conditions (e.g. temperature, V/III ratio, pressure) to see the effect on lateral growth rates and film morphology and dislocation density.

- We will vary the *density* and *height* of the vertical nanowire arrays and study the effect on coalescence, film morphology and dislocation density

- Based on characterization studies (subtask 2.2) and modeling studies (subtask 2.3), we will refine our growth processes.

Subtask 2.2. Characterization of NTLEG GaN films

To establish the overall quality of the NTLEG GaN layers and to help refine the NTLEG growth process, we will use a combination of structural, optical, and electrical characterization tools:

- SEM – uniformity, density, morphology, and growth rates

- Dislocation density measurements:
  - Electron-beam induced current (EBIC) imaging of dislocations
  - Etch pit density (EPD) will be measured using acid etching, followed by optical and SEM imaging of the resulting pits.
  - TEM will be carried out to ensure accurate threading dislocation counts.

- X-ray diffraction (XRD)

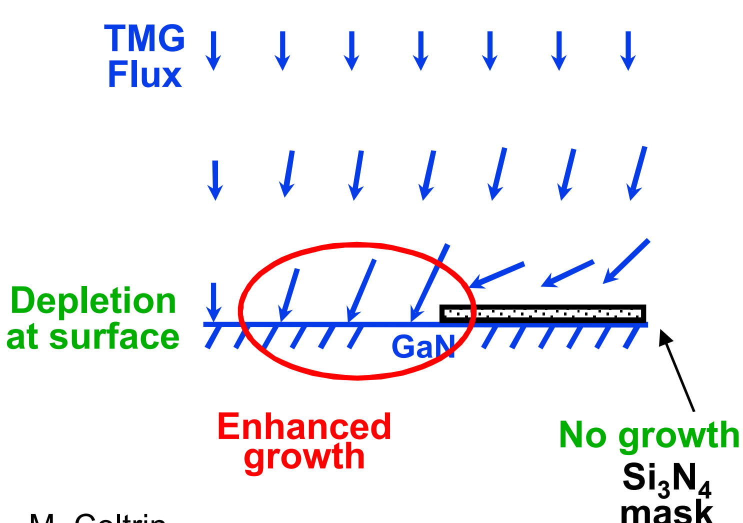
- Optical characterization: photoluminescence and nano-cathodoluminescence with image mapping

- Carrier concentrations and mobility determined by Hall & 4-pt. measurements

Subtask 2.3. Modeling of NTLEG process

- Details of the lateral growth and coalescence will depend on the GaN nanowire facet growth rates, which in turn are controlled by growth temperature, pressure, and III/V ratio.
- We will simulate the lateral growth up through coalescence of the planar GaN using capabilities from our previous work on GaN ELO kinetics and transport & our models of GaN crystal-facet evolution. These calculations will be used to optimize the process parameters

Epitaxial Lateral Overgrowth



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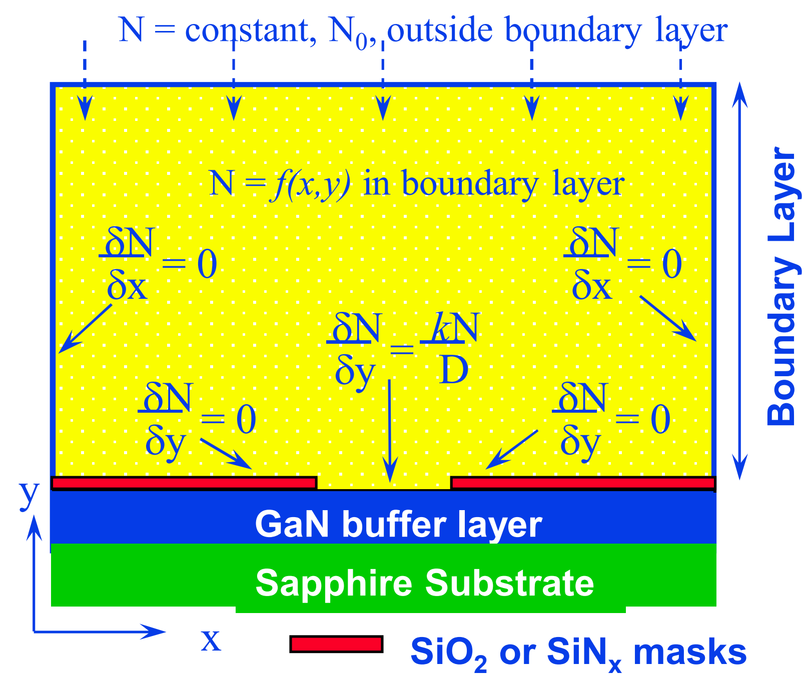
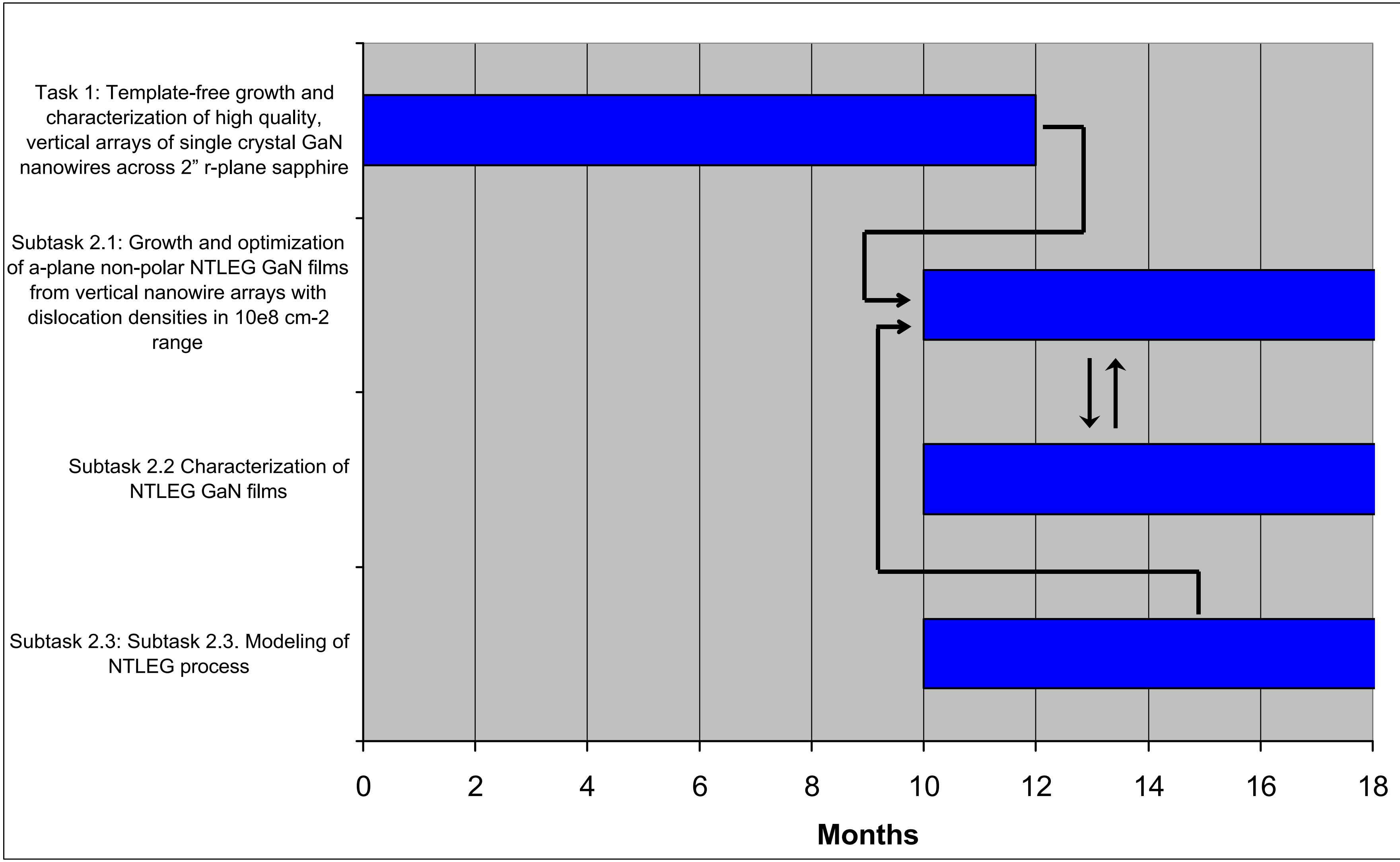


Finite-element calculations quantitatively model mass transport onto ELO features

Project Gantt Chart



Progress to Date (Month 8)

Task 1. Growth, characterization, and optimization of GaN nanowire templates

Proposed completion milestone: Month 12
Current Status: **Successfully completed ahead of schedule**

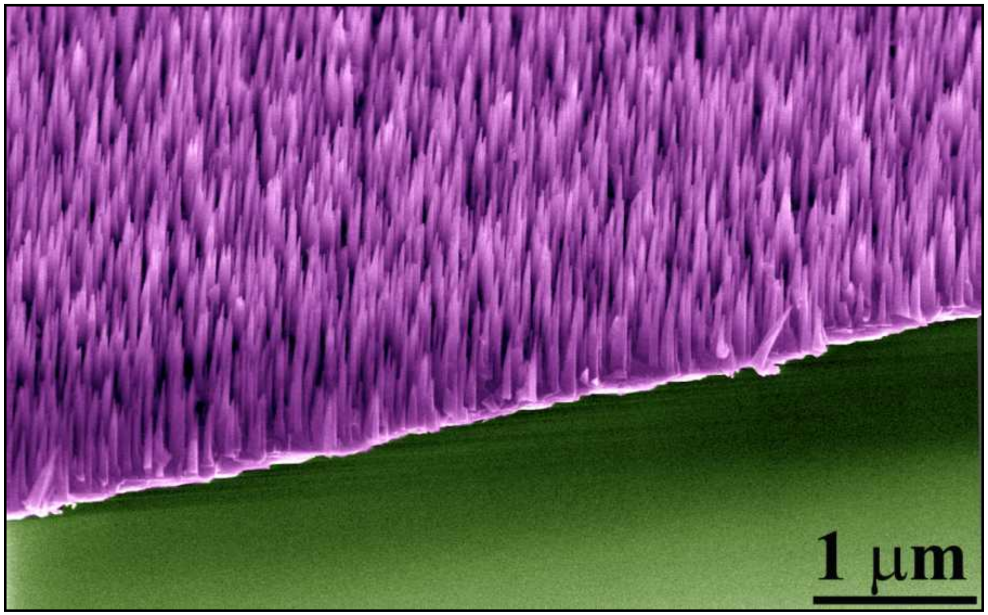
Approaches attempted to achieve controlled, highly aligned and highly uniform growth of vertical GaN nanowires on sapphire:

- Varying V-III ratio
  - *Result:* *An optimal V-III ratio was found which greatly improved nanowire alignment, density, and uniformity. Small circular spots with poor nanowire alignment observed (using nickel nitrate solution).*
- Spin-coating solution-based nickel nitrate solution
  - *Result:* *Large-area uniformity improved; entire wafer could be evenly coated*
- Use of Pt catalyst
  - *Result:* *No success at getting nanowire growth*
- Varying growth temperature
  - *Result:* *Strong effect on nanowire density and degree of alignment*
- Use of e-beam evaporated thin Ni films as catalyst to improve uniformity
  - ***Result:*** ***Highly uniform, highly aligned nanowire growth obtained across entire area. No spots with poor alignment observed.***

Progress to Date (Month 8)

Task 1. Growth, characterization, and optimization of GaN nanowire templates

Using thin Ni films evaporated onto r-plane sapphire and optimized growth conditions, we can achieve very highly aligned nanowire growth with excellent uniformity across the wafer, along with control of nanowire density and height.



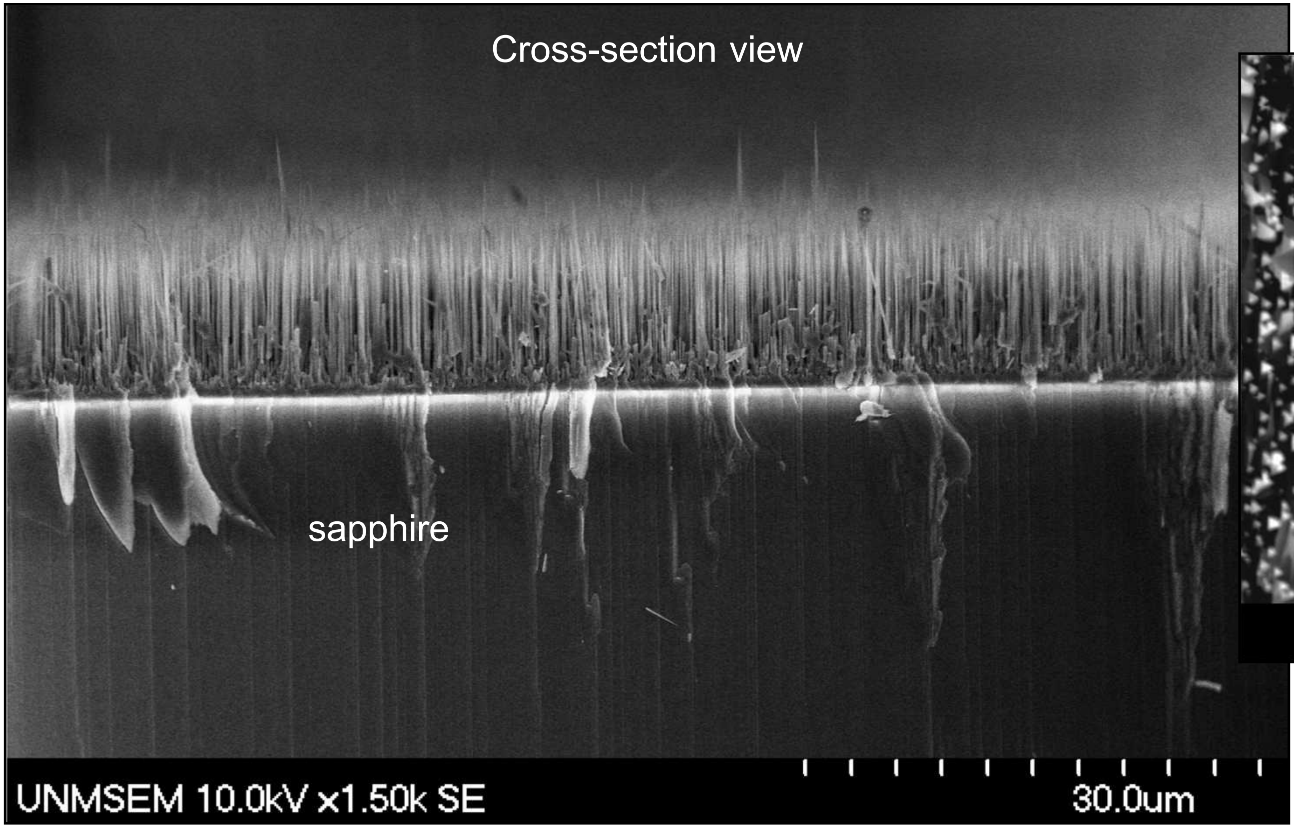
60 s growth

Progress to Date (Month 8)

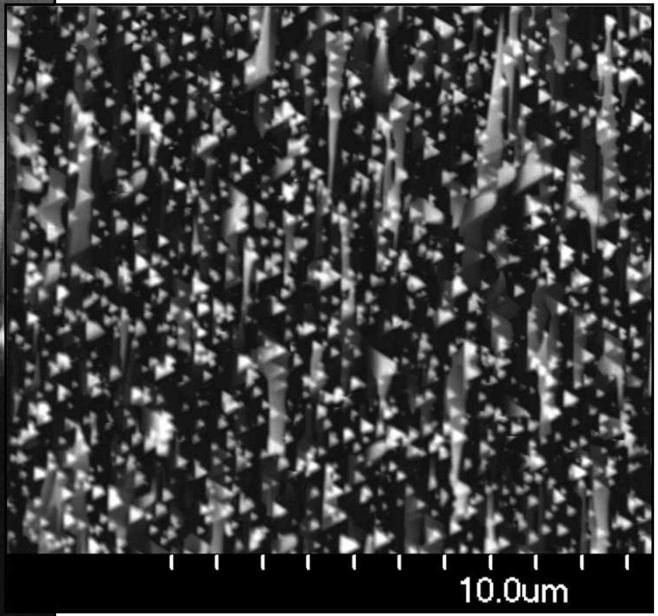
Task 1. Growth, characterization, and optimization of GaN nanowire templates

- Nanowire length is controlled by growth time
- Plan view image confirms aligned facets

"Mission Accomplished" – Task 1 achieved 4 months early



Plan view

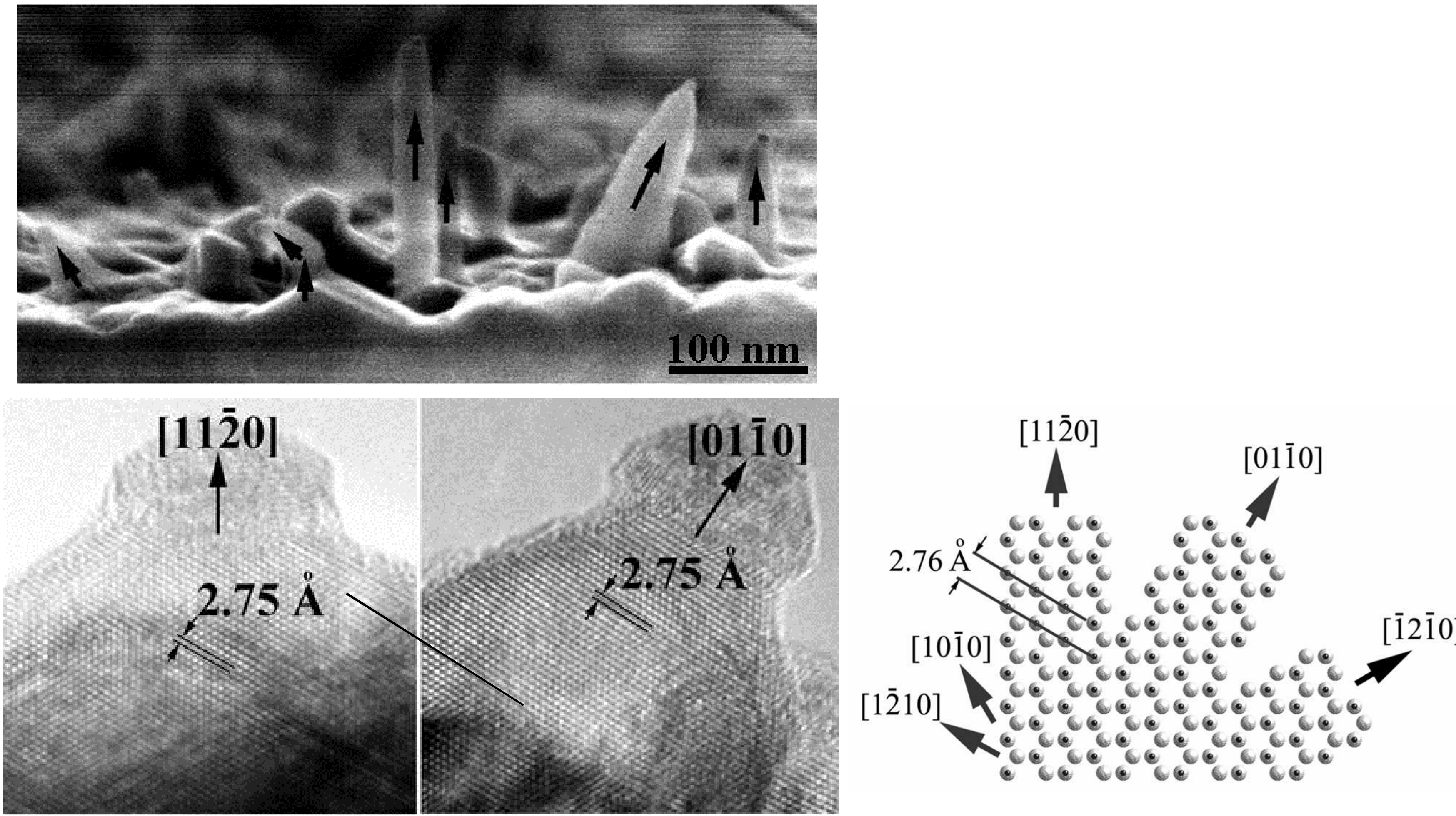


540 s growth

Growth rate ~ 1 μm/min

Progress to Date (Month 8)

Task 1. Growth, characterization, and optimization of GaN nanowire templates



Tilted nanowires have same crystal orientation relative to the substrate as vertical nanowires and thus should not be an issue during film coalescence

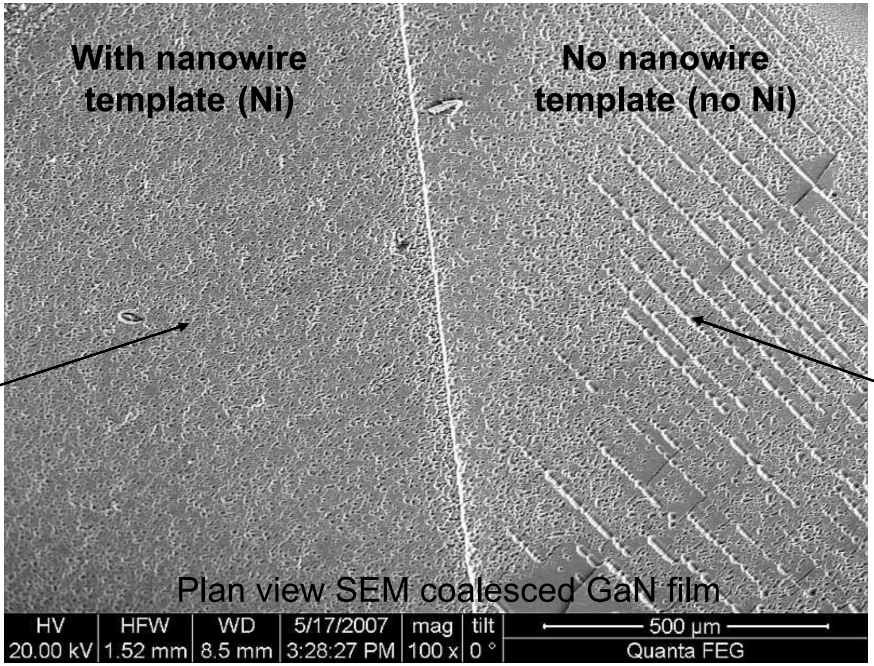
Progress to Date (Month 8)

Task 2. Growth, characterization, modeling, & optimization of GaN NTLEG films

Task 1 completed ahead of schedule, Task 2 started early (preliminary results promising)

Comparison of GaN film grown using vertical nanowire array and film grown without

No cracks in NTLEG film



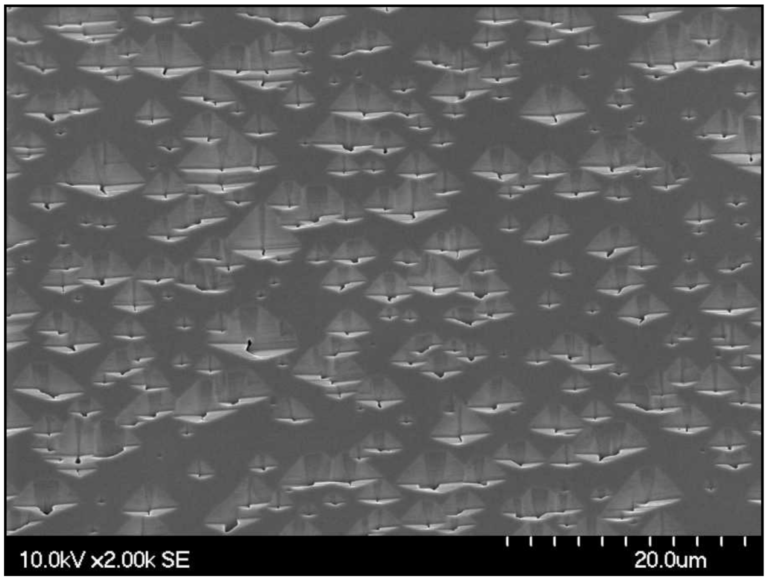
Cracks/grooves

- **Complete coalescence of a-plan GaN film achieved from vertical nanowires.**
- SEM images shows **strain relief of NTLEG GaN** compared with GaN film grown on sapphire, as evidenced by the lack of cracks.
- **Demonstrates proof of concept of NTLEG technique.**

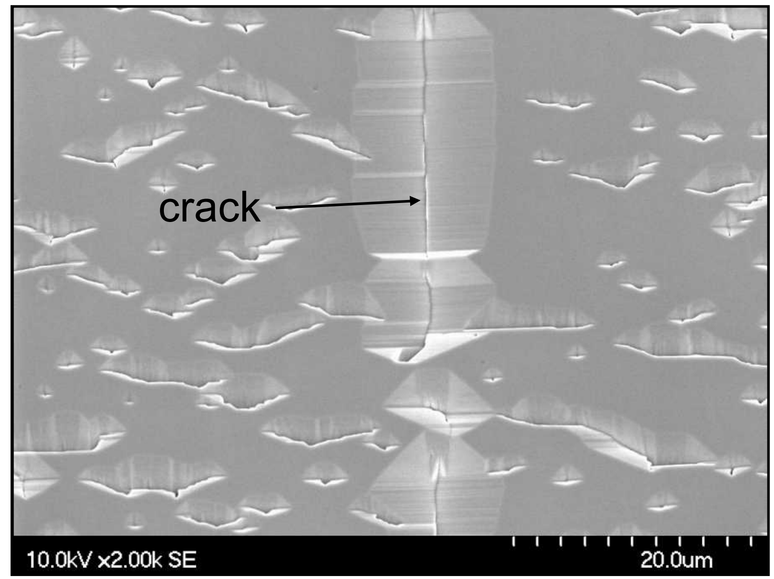
Progress to Date (Month 8)

Task 2. Growth, characterization, modeling, & optimization of GaN NTLEG films

Plan view SEM images of fully coalesced GaN



NTLEG GaN on sapphire covered with thin Ni (vertical nanowire template)



GaN on blank sapphire (no Ni)

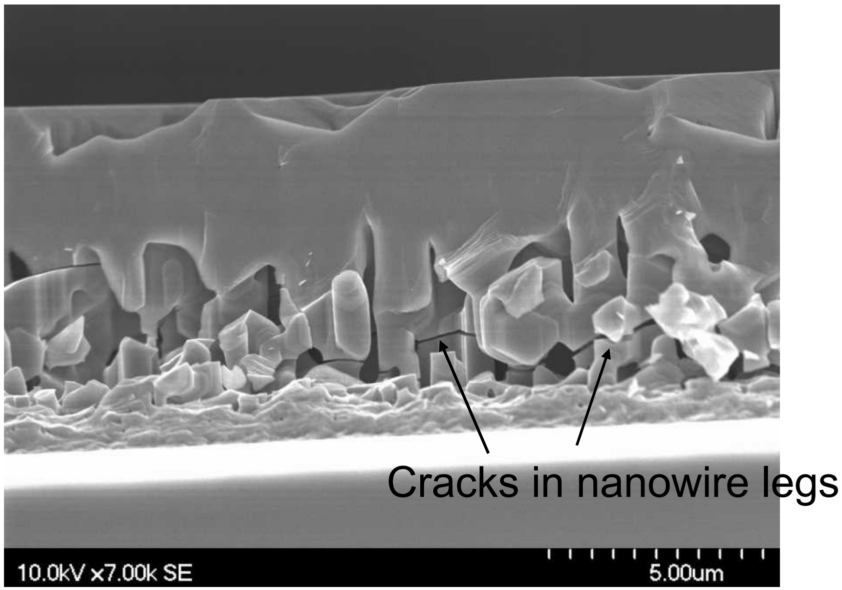
- Free of cracks
- Regular pit faceting
- Small pits, density ~10^7 cm^{-2}

- Cracks present throughout film
- Irregular pit faceting
- Large pits, low number density

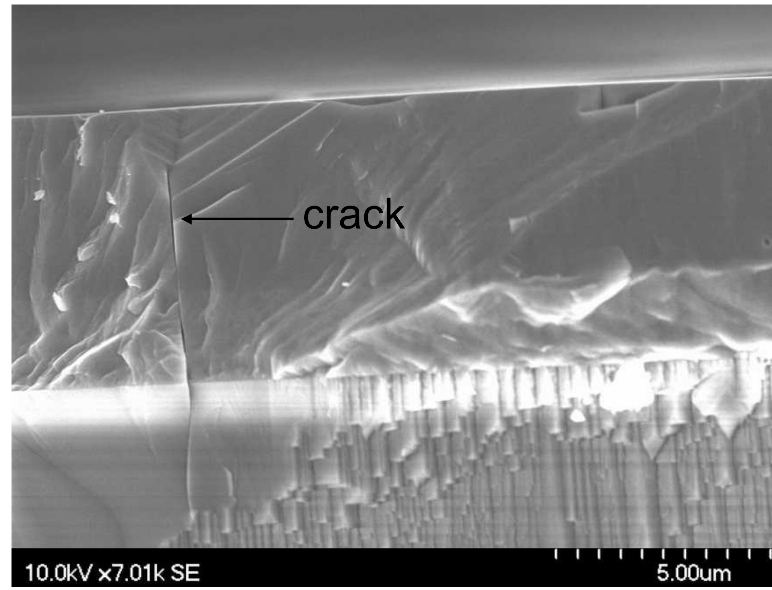
Progress to Date (Month 8)

Task 2. Growth, characterization, modeling, & optimization of GaN NTLEG films

Cross-section SEM images of fully coalesced GaN



NTLEG GaN on sapphire covered with thin Ni (vertical nanowire template)



GaN on blank sapphire (no Ni)

- **Strain is relieved in NTLEG GaN** by nanowire template as shown by cracks in 'legs'. In contrast, cracks propagate to surface in GaN grown directly on sapphire .
- **Future experiments** – adjust nanowire length and density; adjust film growth conditions; study time series of nucleation process; optimize to reduce dislocation density and surface pit density

Technical Barriers/Problems

- **Transition from current research reactor to commercial Veeco D-125 reactor**
  - Due to different reactor characteristics, process conditions will have to be re-optimized for controlled, uniform nanowire growth.

- **Formation of "suspended" NTLEG film**
  - Currently have lateral growth along the length of the nanowires during film nucleation, causing them to grow fatter and nucleate together
  - We want to reduce transport down the nanowires to create a pinch-off effect

- **Reduction of surface pit density**
  - Vary process conditions
  - Potential two-step film growth process: first step that favors lateral nucleation of film from nanowire array, second step that smooths out surface

- **Mechanical stability of suspended NTLEG film may be weak**
  - Thickness will be varied to achieve mechanically stable film

Budget Period Milestones

Current Month (May 07): Month 8 of project

Milestones	Description	Completion Time	Current Status (month 8)
Milestone 1	Growth, characterization, and optimization of GaN nanowire templates. Demonstration of high quality, vertical array of single crystal GaN nanowires across 2" r-plane sapphire.	Month 12	**Completed** (but will have to be re-optimized in new reactor)
Milestone 2.1	Growth and optimization of NTLEG GaN films from vertical nanowire arrays grown without the use of a template. Optimize and demonstrate a-plane non-polar NTLEG films with dislocation densities ≤10^8 cm^{-2} range.	Month 18	Complete coalescence of a-plane GaN film achieved. Proof of concept demonstrated.
Milestone 2.2	Characterization of NTLEG grown GaN films using template-free GaN nanowire arrays.	Month 18	Currently underway.
Milestone 2.3	Develop model for growth of NTLEG GaN films	Month 18	Waiting on further results from lateral growth experiments

Deliverables

- We will document the findings of our research in a set of two reports submitted to the DOE Project Manager on both of the Tasks listed in Section C:
  - *Task 1: Growth, characterization, and optimization of GaN nanowire templates*
  - *Task 2: Growth, characterization, modeling, and optimization of GaN NTLEG films*
- The reports will give detailed descriptions of the activities, results, and implications for Solid-State Lighting in each of the tasks described in the previous section.
- Submit to the DOE Project Manager annual technical reports.
- Monthly Highlight Communications of developments, achievements, changes, and problems.
- Present poster/presentations at annual SSL Workshops
- Prepare detailed briefings for presentation to the DOE Project Manager to explain the plans, progress, and results of our technical effort.
- We will also provide and present a technical paper(s) at the DOE / NETL Annual SSL Review Meeting.

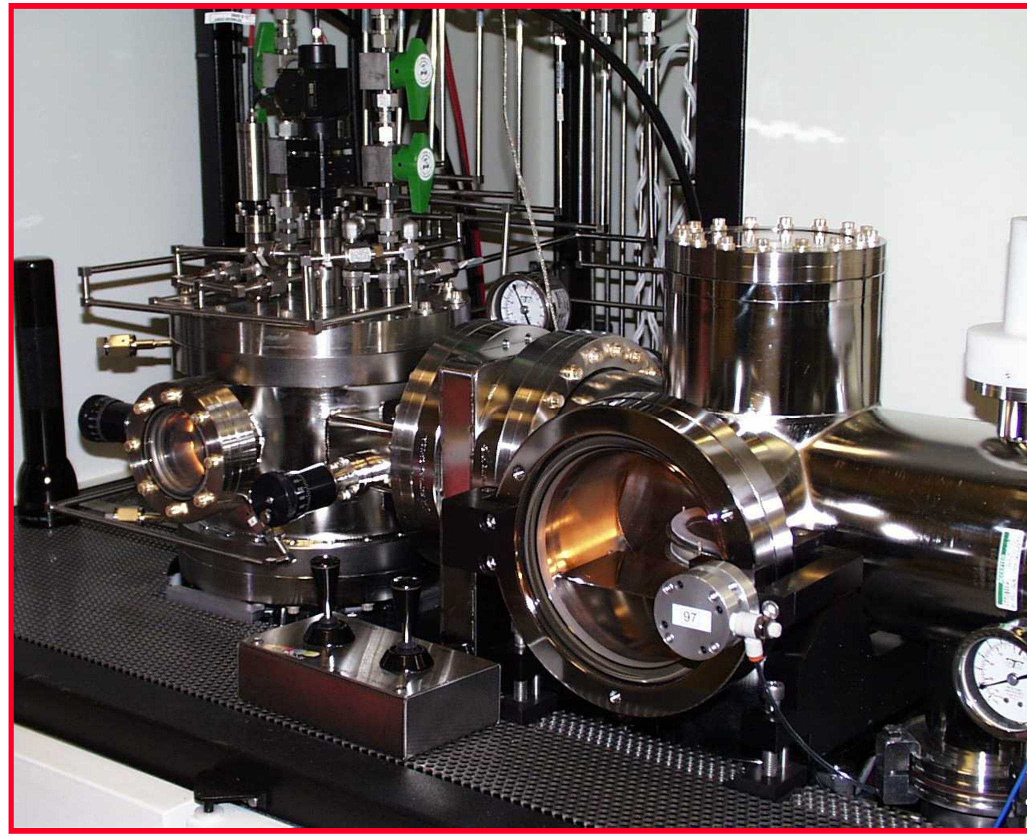
Project Team/Capabilities

Project Researchers and Roles (FY07)

Name	Responsibilities	Fraction of time*
Robert M. Biefeld (PM)	Project Manager	-----
George T. Wang (PI)	Project direction, growth & characterization, reports	0.35
Qiming Li (post-doc)	Growth, processing, characterization	0.95
J. Randall Creighton	MOCVD growth & equipment support	0.10
A. Alec Talin	Electrical and optical measurements (nanowire)	0.10
Michael E. Coltrin	Modeling	0.10
Stephen R. Lee	XRD analysis	0.04
Arthur Fischer	Optical characterization (film)	0.04

- Sandia involved in the growth and characterization of the III-nitrides since 1997.
- This work has been supported both internally (LDRD) and externally (BES, NETL, and DARPA) for many years.
- The PI, George T. Wang, has extensive experience in the synthesis and characterization of III-nitride nanowires. He has experience leading several programs involving nitride nanowire research, and is the owner of the new $3.5M Advanced Nanotechnology Tool (ANT).

Availability of Facilities and Equipment



Growth chamber through ~5/07

→ And afterward transition to this 3 wafer D125 Veeco reactor (currently being installed).

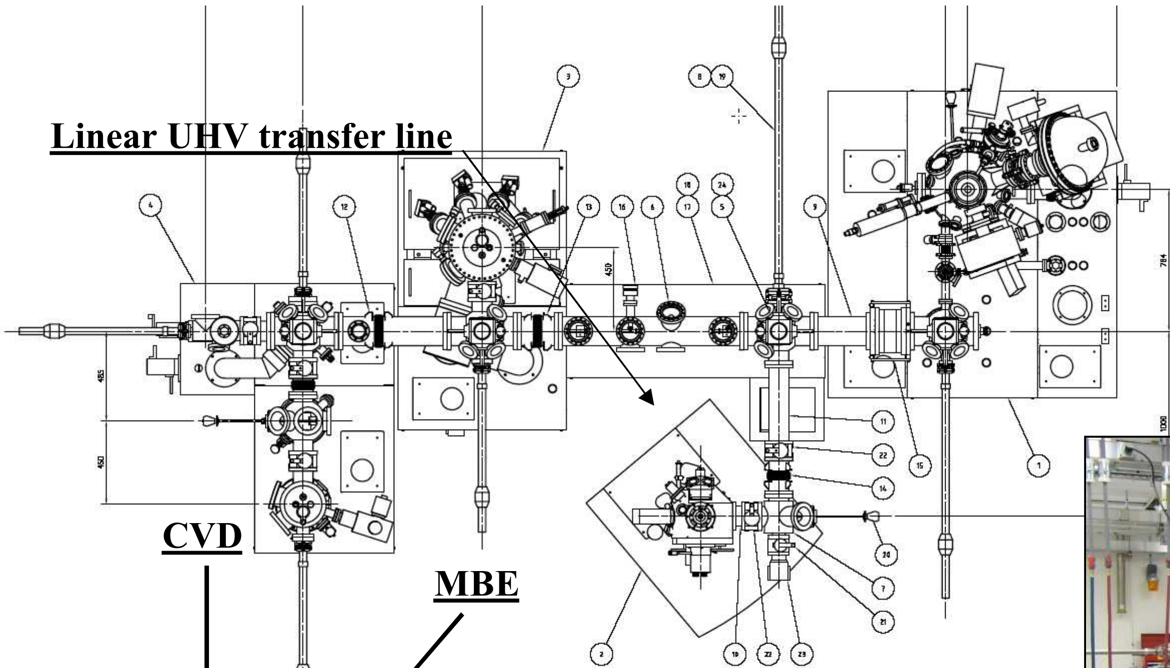
Availability of Facilities and Equipment

- This project will make extensive use of the Center for Compound Semiconductor Science and Technology (CCSST) at Sandia, with over 6500 square feet of clean room space. The CCSST contains an electron beam lithography system (JEOL JBX-5FE), 3 Karl Suss MJB-3 aligners with one operating in deep UV, 2 Karl Suss MA-6 aligners with backside alignment capabilities, a full array of wet benches, 4 e-beam metal evaporators, metal plating baths, two rapid thermal annealing systems (one devoted exclusively to nitride systems), FE and filament scanning electron microscopes (SEMs), atomic force microscope (AFM), several sputtering systems for metals and dielectrics, 2 oxidation furnaces, 6 MOCVD systems, 2 new coupled electron cyclotron resonance (ECR)/inductively coupled plasma (ICP)-reactive ion etching (RIE) etch/deposition systems (one for Ga-based materials and one for In-based materials), a Bosch ICP etch system, several smaller reactive ion etch systems and a full array of characterization and packaging tools.
- Other characterization facilities at Sandia include Rutherford backscattering (RBS), nuclear reaction analysis system, Ion implantation for modification of composition, and ion irradiation for production of lattice defects, Auger spectrometers, in-situ ultra-high-vacuum (UHV) ion, photon, and electron beam irradiation, UHV facility combining surface analysis by low-energy electron diffraction (LEED) and Auger electron spectroscopy, with ion-beam analysis/channeling, a unique deep level transient spectroscopy system (DLTS), cathodoluminescence spectrometer (CL), photoluminescence systems (PL), photoluminescence excitation (PLE), time-resolved photoluminescence (TRPL), Fourier-transform infrared spectroscopy (FTIR), photothermal deflection, Capacitance/Voltage-profiling, Hall effect and 4-terminal dc and ac conductivity measurements, a dopant profiling Polaron, transmission electron micro-scopes (TEM), a Philips X'PERT x-ray diffractometer and abundant optical/electrical measurement capabilities.
- Sandia's compound semiconductor clean room operations and associated characterization laboratories will be moving into new facilities starting in 2006. These facilities are part of the new, $450 million MESA (Microsystems and Engineering Sciences Applications) complex that is currently under construction. Part of the MESA project includes a budget for upgrading equipment as well as new facilities and new, enhanced capabilities. This complex when completed will enable a quick turnaround for innovative compound semiconductor device prototypes at Sandia. The arrangement of this facility will also encourage collaboration among diverse organizations to enable a more efficient working environment.

MESA Advanced Nanotechnology Tool (ANT)

- *$3.5M custom tool ~3 years in the making providing advanced deposition, growth, and characterization capabilities for nanoscience research and development*

Linear UHV transfer line

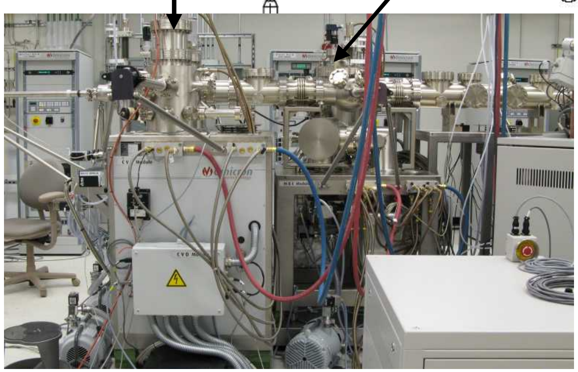


Surface Characterization

- UHV Gemini FE-SEM
- VT-STM + AFM
- Scanning Auger Microscopy
- UHV VT Cathodoluminescence w/mapping
- XPS
- Ion gun for depth profiling

CVD

MBE



FEI FE-ESEM

- 1.2 nm resolution
- 4.5e-6 to 30 Torr
- Imaging of insulating substrates
- Heating stage to 1500°C
- < 2nm @ 30kV resolution
- EBIC with nanomanipulators ?

Anticipated use of ANT for this project: SEM, EBIC, CL

Sandia National Laboratories

Final Product/Commercialization

- **Our final product will be**
  - Demonstration of NTLEG non-polar a-plane GaN on unpatterned sapphire with dislocation densities in the 10^8 cm^{-2} range.
- **Commercialization**
  - Technology transfer - our applied research findings to Solid-State Lighting Industrial Product Development members by the mechanisms outlined in Section II, Part 7 (Exceptional Circumstances).
  - Product Demonstration – by providing our best performing material to industrial partners to evaluate commercial potential for LED technology.
  - Licensing strategy - includes aggressively seeking patents of the IP arising from this research. Such protection of the IP makes it more attractive to industry for licensing and use in commercial products. Sandia has an Intellectual Property Center devoted to patenting and licensing our technology. We have a good track record in licensing our compound semiconductor technologies to companies, e.g., VCSEL patents, in situ growth rate monitor, in situ stress monitor, Chemkin software. We have applied for 2 U.S. patents and have filed another 12 patent disclosures as a result of our recent Grand Challenge LDRD project.
  - License agreements - Sandia can negotiate exclusive or non-exclusive license agreements for its IP. A potential barrier that could arise would be if more than one company should desire to obtain exclusive license to this technology. We will engage in good-faith negotiation with all potential licensees and will also be guided by rules of the modified intellectual property arrangements of the Determination.