SAND2012-1584P

Boeing Visit to Sandia – February 22, 2012

Solid-State Lighting and Related Efforts at Sandia

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Outline of Presentation

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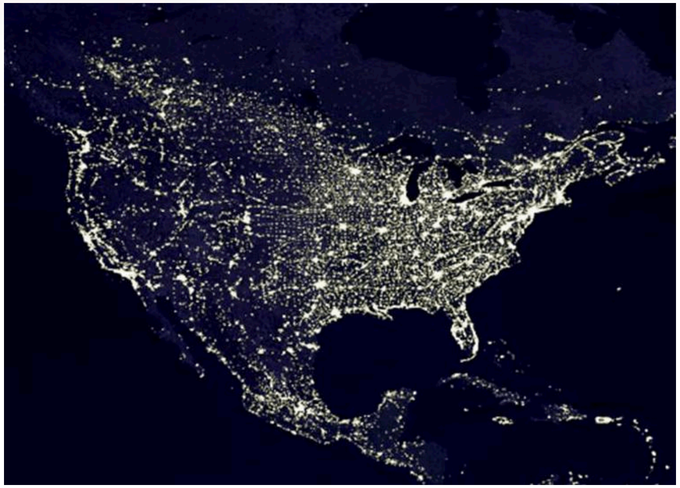
Why Solid-State Lighting Matters



- ~22% of electricity consumption is used for lighting
- Lighting is one of the most ***inefficient*** energy technologies in buildings → opportunity!
- 2012 DOE projections:
  - 36% adoption by 2020
  - 74% adoption by 2030

➢ **decrease electricity consumed by lighting by ~46%**

Efficiencies of energy technologies in buildings:

Heating: 70 - 80%
Elect. motors: 85 - 95%
Fluorescent: 20-25%
Incandescent: ~3-5%

US DOE target: 50%
"Ultra-efficient" SSL*: ≥ 70%

Projected Year 2030 Savings	US
Electricity used (TW-hr)	300/year
$ spent on Electricity	$30B/year
Electricity generating capacity (GW)	50
Carbon emissions (Mtons/year)	210

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Some Current SSL Research Efforts

- **Energy Frontier Research Center**
  - Solid State Lighting Science center team is exploring energy conversion in tailored photonic structures.
  - Understand the efficiency limiting factors for semiconductor materials
  - Investigate radically new designs, such as nanowires and quantum dots, and lasers
  - Study energy conversion processes in low dimension structures
- **EERE Advanced SSL Manufacturing Project "Implementation of Process-Simulation Tools and Temperature-Control Methods for High-Yield MOCVD Growth" with Veeco and Philips Lumileds**
  - Goal: *A complementary set of high-resolution short-wavelength and infrared in-situ monitoring tools for accurate substrate temperature measurement and growth rate monitoring*
- **EERE SSL Core Technology Project on "Semi-polar GaN Materials Technology for High IQE Green LEDs"**
  - Goal: *540 nm LED with 50% IQE*
  - Investigate In incorporation on different orientations of GaN substrates

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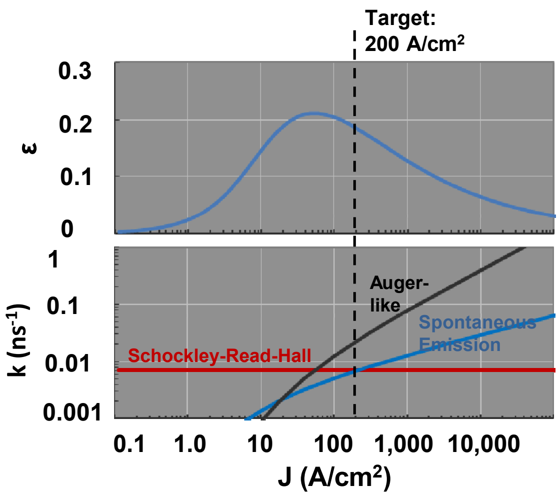
Three Challenges for SSL

① *Flatten the ε(J) curve (droop)*



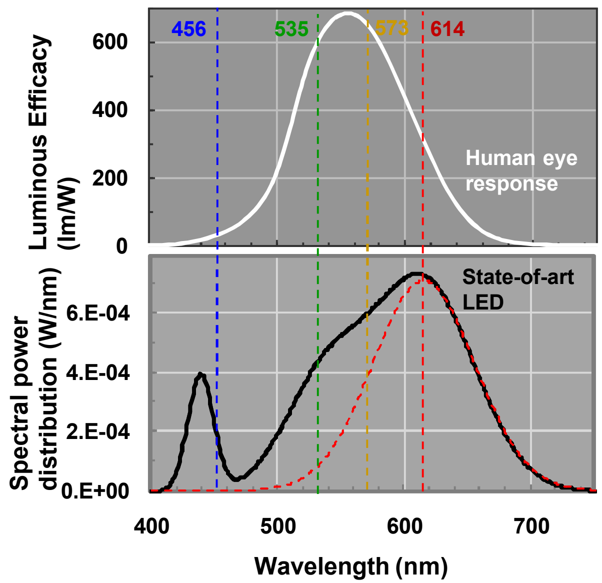
$$\varepsilon = \left(\frac{V_{ph}}{V}\right) \cdot \varepsilon_{INJ} \cdot \frac{Bn}{A + Bn + Cn^2} \cdot \varepsilon_{EXT}$$

Shockley-Read-Hall

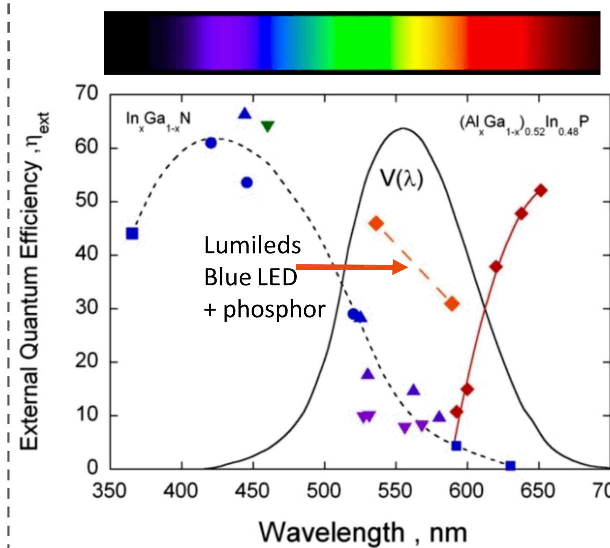
Spontaneous Emission

Auger-like

② *Narrow-linewidth shallow-red color conversion*



③ *Fill the red-yellow-green EL gap*



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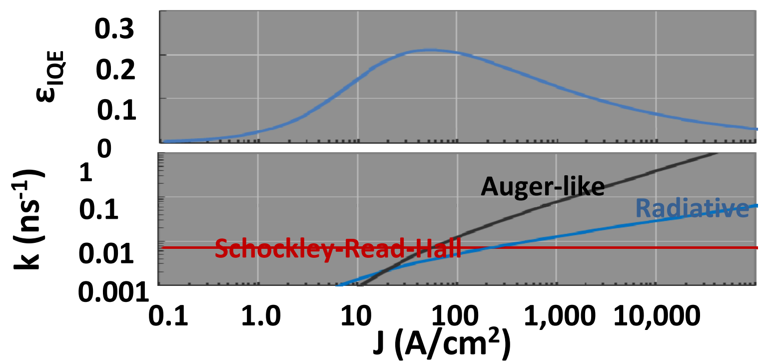
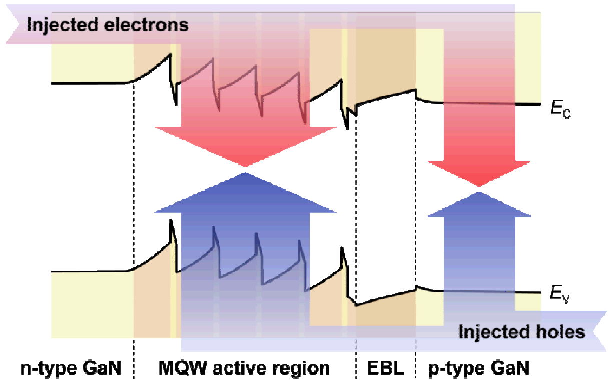
EFRC Thrust 1: Competing Energy Conversion Routes in Light-Emitting InGaN

Recombination pathways: Radiative and Non-Radiative

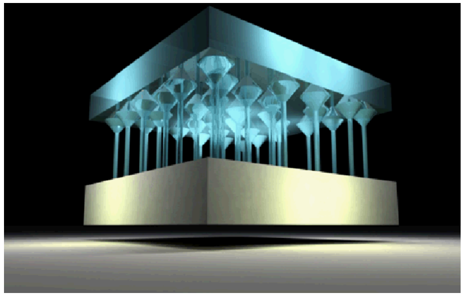


Carrier injection and transport pathways



EFRC Thrust 2: Beyond 2-D

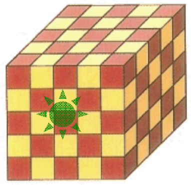
InGaN Nanowires

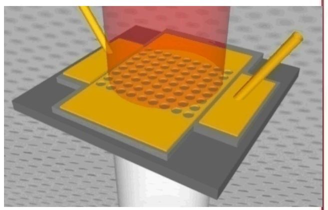


Quantum Dots

EFRC Thrust 3:

Beyond Spontaneous Emission





Lasers, Photonic Crystals, Polaritons, and Plasmonics

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Efficiency droop has traditionally been analyzed using a macroscopic “ABC” approximation

ε_{Joule} Joule efficiency (resistive losses)

ε_{IQE} Internal quantum efficiency

Extraction efficiency (photon trapping and absorption)

$$\varepsilon = \left(\frac{V_{ph}}{V_{ph}+IR}\right)\cdot \varepsilon_{inj}\cdot \frac{BN^2}{AN+BN^2+CN^3+\ldots}\cdot \varepsilon_{ext}$$

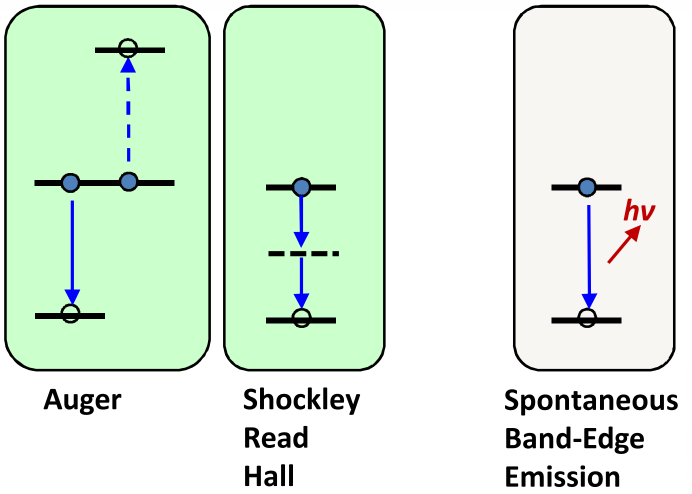
Auger-like

Spontaneous Emission

Shockley-Read-Hall (defect-mediated)

Injection efficiency (carrier overshoot or escape)

Power conversion efficiency



Problems:

1. *Carrier density “N” is treated identically for all three terms*
2. *Possibility that coefficients A,B,C can vary is typically ignored*

The traditional view may be too simple.

No single explanation for droop is accepted

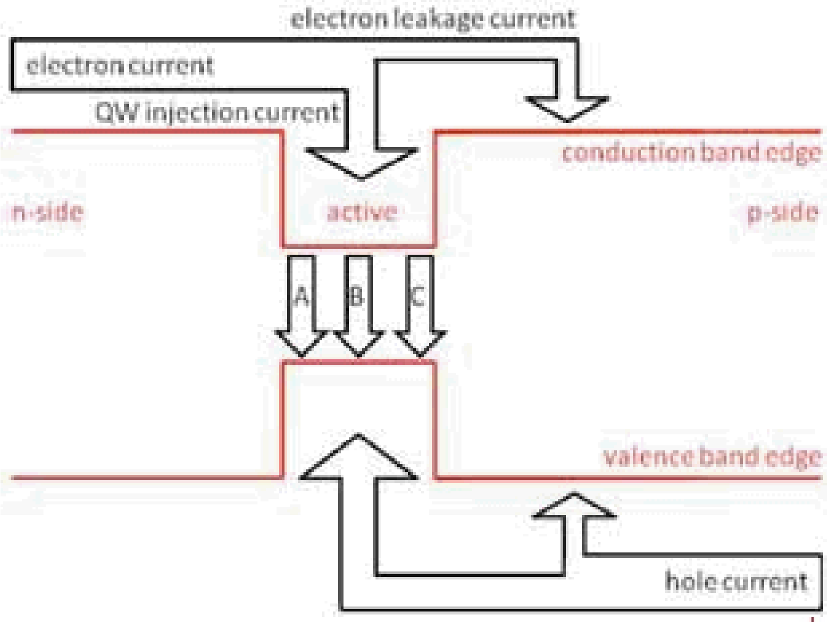
(At least) two camps arguing about droop:

1. *Auger is the dominant effect*
2. *Carrier leakage out of the QWs is the dominant effect*

Either model can be used to fit the data.

A more accurate treatment would perhaps

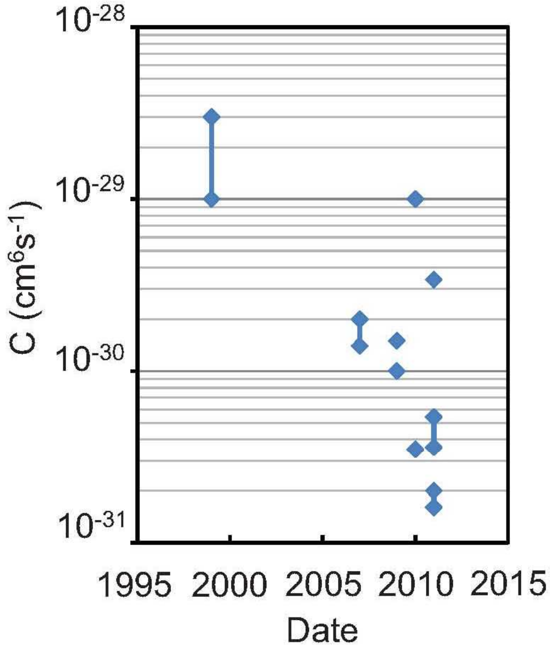
- *Use different definitions for the "N" in each of the A, B, and C terms, and*
- *Allow the coefficients A, B, and C to vary with N*



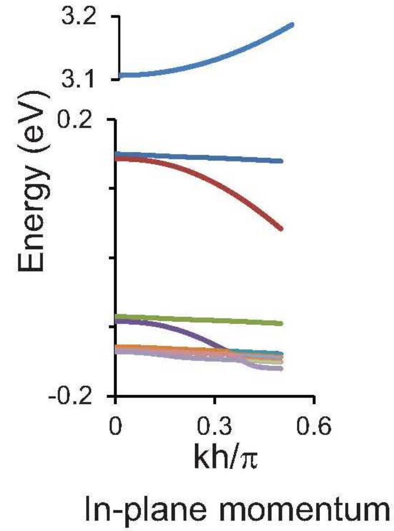
J. Piprek, Phys. Status Solidi A **207**, 2217 (2010)

Motivations for a more detailed model

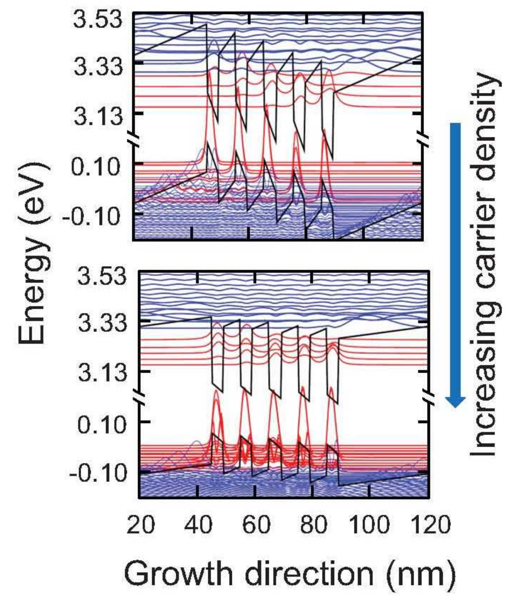
Variation in Auger coefficient from IQE curve fitting with ABC model

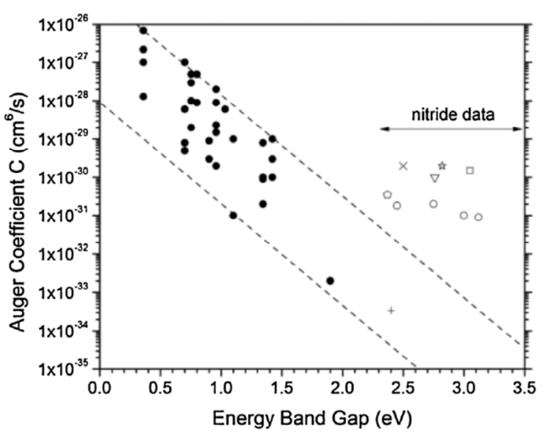


Energy dispersions



Carrier density dependent band structure changes





J. Piprek, Phys. Status Solidi A **207**, 2217 (2010)

Variations in radiative recombination with carrier density are predicted by a more detailed microscopic model

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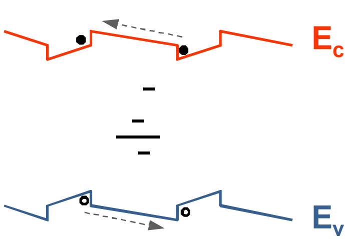
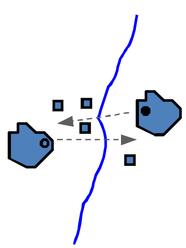
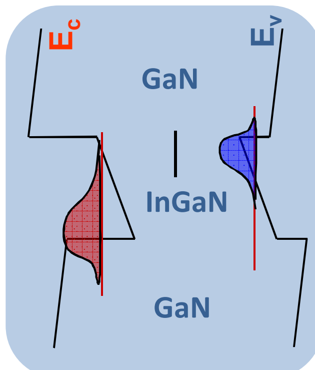
Microscopic View:
Carriers aren't identical, but are distributed

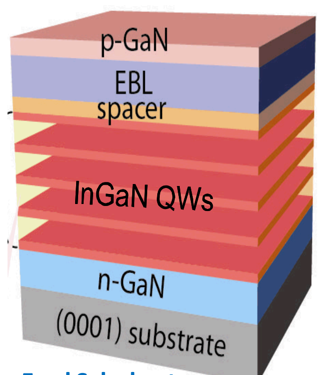
over xy-plane (bandgap inhomogeneities)





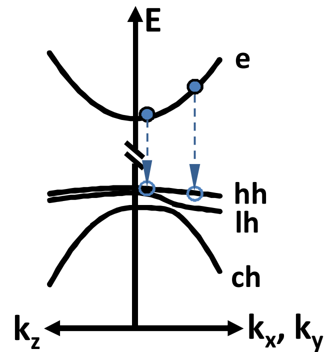
along z-axis (polarization fields and imperfect transport)

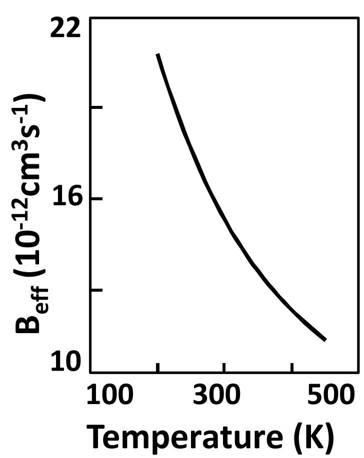




Fred Schubert
Mary Crawford

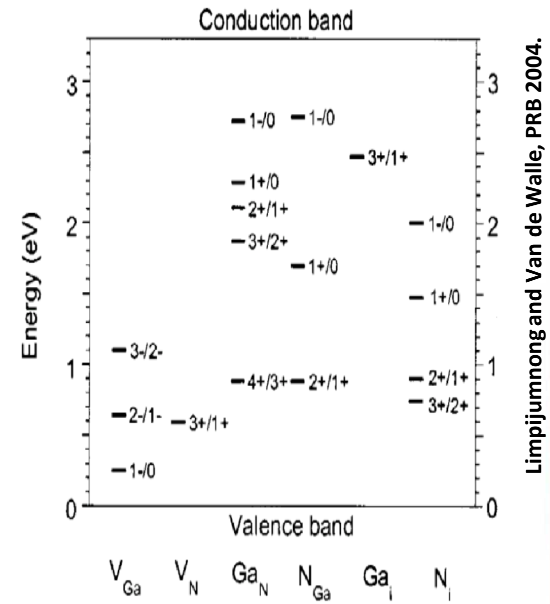
in k-space (plasma heating)





Weng Chow

over deep-level charge states (Fermi level changes)



Andy Armstrong
Normand Modine
Weng Chow
Mary Crawford

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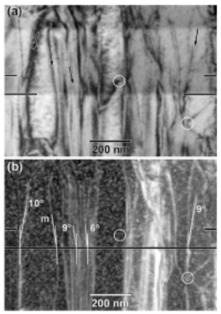
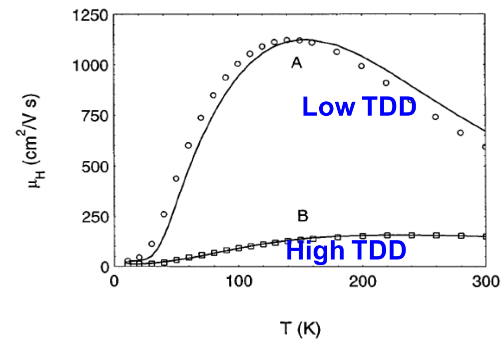
Sources of Defects in III-Nitrides

Types of Defects in Semiconductors

Extended Defects

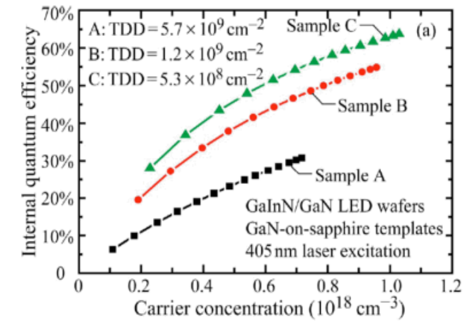


D. M. Follstaedt et. al. JAP 105, 083507 2009



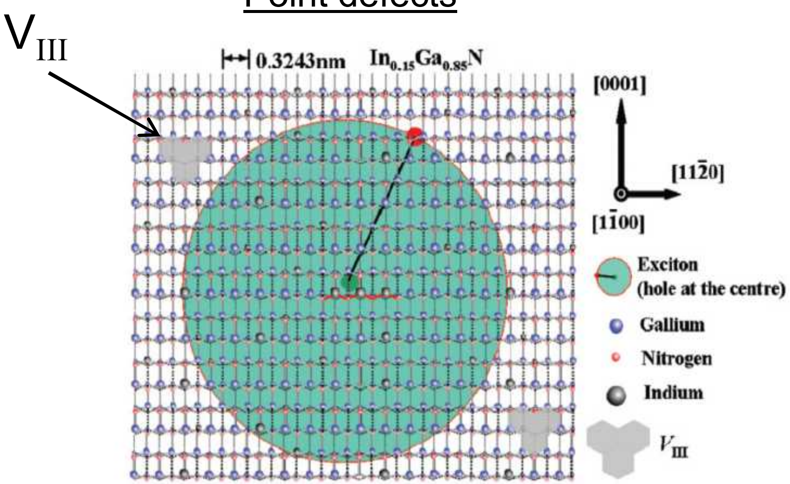
Look and Sizelove, PRL 82 1237 (1999)

Defects affect the radiative efficiency of III-Nitrides



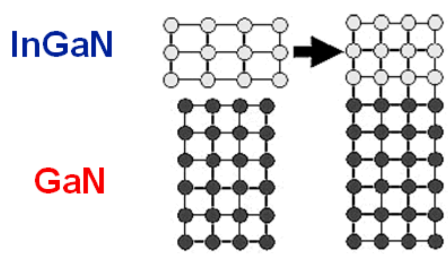
Q. Dai et. al., Appl. Phys. Lett. 94, 111109 (2009)

Point defects

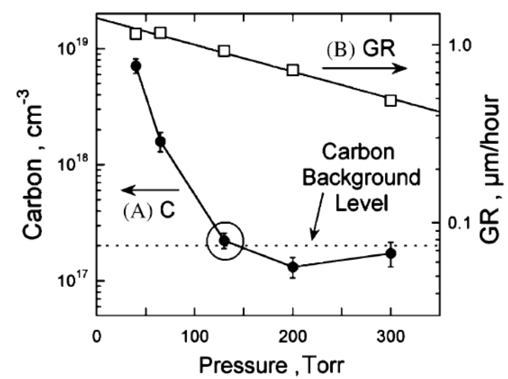


Chichibu et al., Philos. Mag. 87, 2019 (2007)

Growth conditions and strain



Lack of native substrates



Koleske et al., JCG 242 55 (2002)

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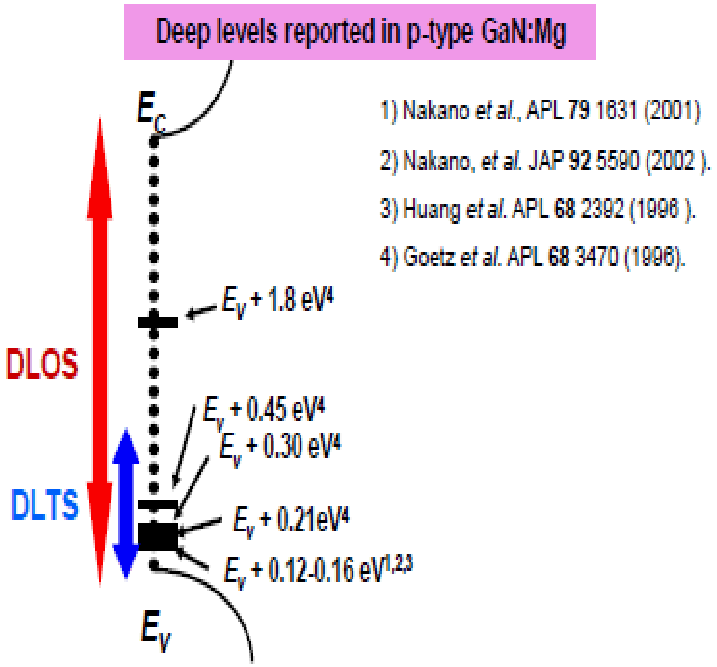
Challenges related to probing point defects

- **Wide band-gap in III-Nitrides**
  0.8 eV for InN, 3.4 eV for GaN, 6.2 eV for AlN

- **Thermal techniques do not allow the entire bandgap to be probed**
  Deep level transient spectroscopy only probes a portion of the bandgap (In, Al, Ga)N

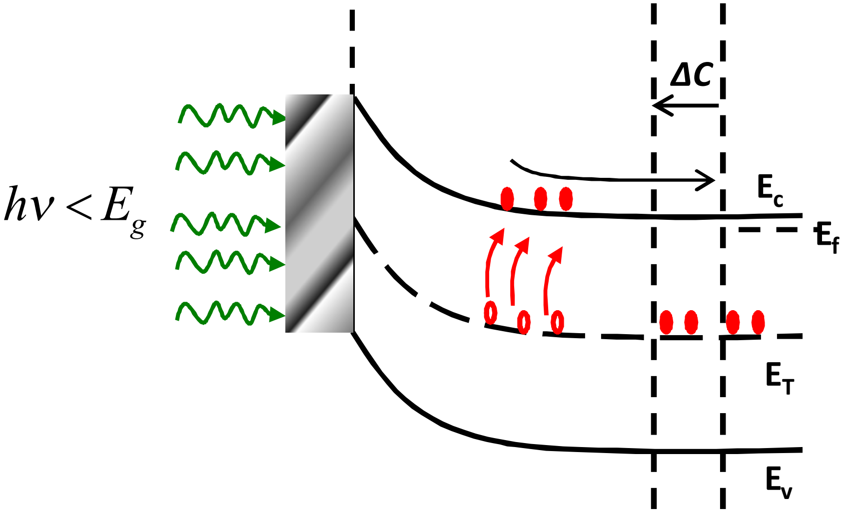
- **Luminescence does not quantify defects**
  Cannot quantify defect densities

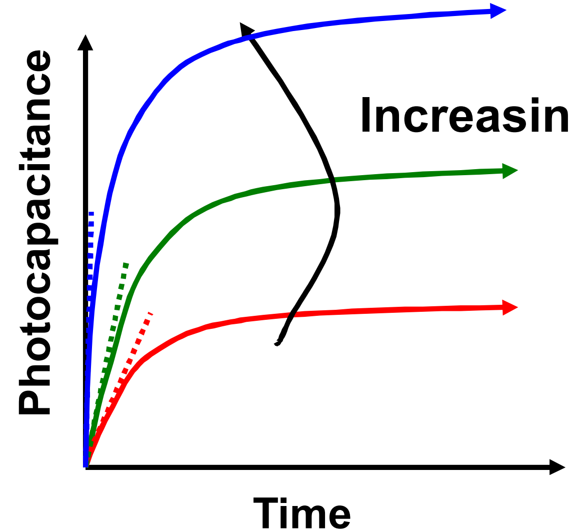


Deep level optical spectroscopy (DLOS); a differential photocapacitance technique

<u>Deep Level Optical Spectroscopy (DLOS)</u>[1]

- **Only sensitive to depletion regions**
- ***<u>Sub-band gap</u>*** **illumination to photoionize defect levels (reverse of PL)**
- ***<u>Quantify</u>*** **energy level and density of** ***<u>radiative and non-radiative</u>*** **defects**





replace

- $dC(t)/dt|_{t=0} \propto \sigma^o(h\nu)$
- **Optical cross-section** $\sigma^o = e^o/\Phi(h\nu)$
- **Fitting the optical cross-section σ(hν) to a theoretical model[2] extracts**
  - **Optical ionization** (E^O)
  - ***Frank Condon Energy (dFC)***
- **Defect density** N_t **from steady-state photocapacitance**

1. Chantre *et al.* PRB 23, 5335 (1981). 2. Paessler JAP 96, 715 (2004).

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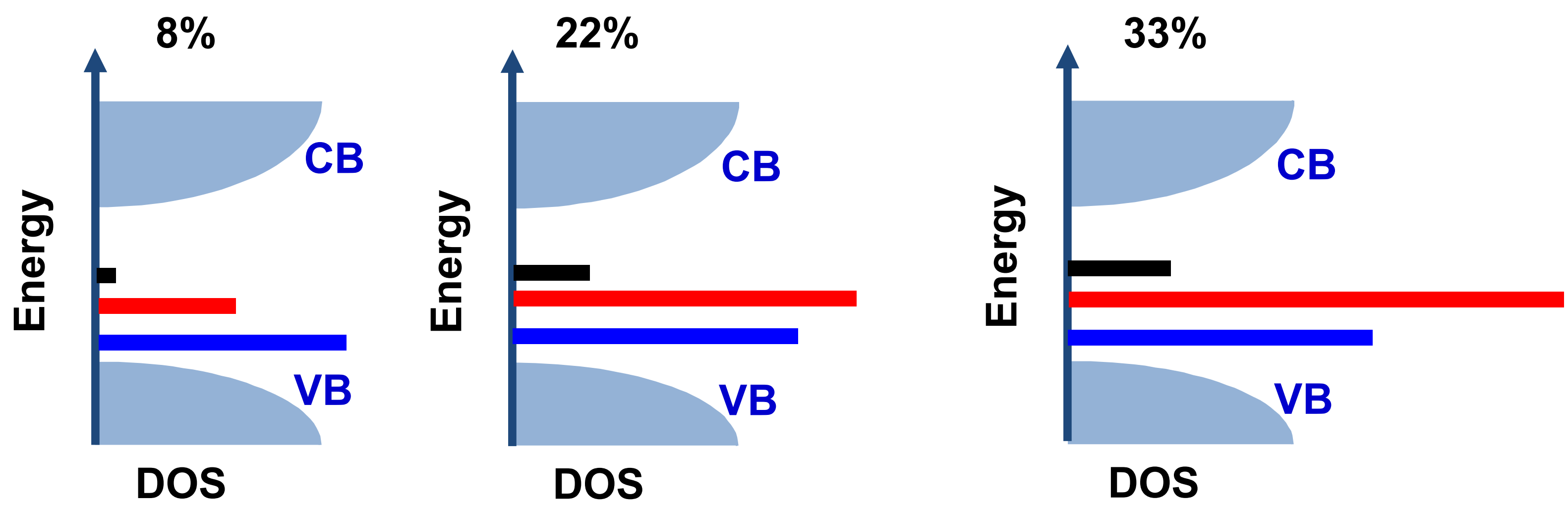
Summary of DLOS Studies of AlGaN

Dominant defect in AlGaN related to *($V_{III\text{-}cation}$) / ($V_{III\text{-}cation}$-complex)….*



- ***Defect optical ionization energies blue shift and defect densities increase with Al mole fraction***
- ***L2 defect has highest defect density for*** $Al_{0.22}Ga_{0.78}N$ **and** $Al_{0.33}Ga_{0.67}N$
  - ***near mid-gap defect level may be detrimental to LD operation***
- ***L2, suspected*** **($V_{III\text{-}cation}$)/($V_{III\text{-}cation}$-complex)**[1] ***level appears to track the vacuum level***
- ***L3 seems to deepen with respect to Ev***

1. K.B. Nam et. al, Appl. Phys. Lett., 86, 222108 (2005).

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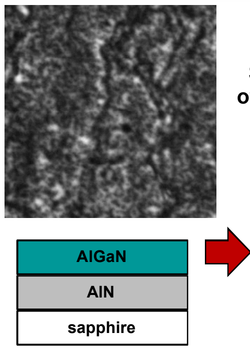
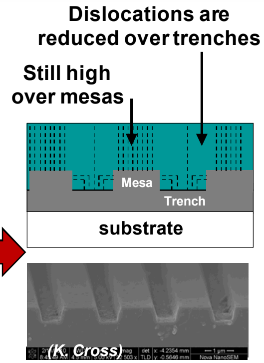
AlGaN Growth

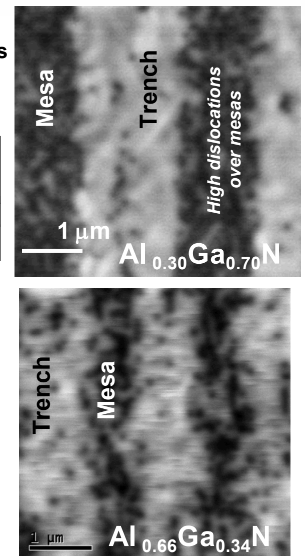
Developed method for dislocation reduction in 30% and 60% AlGaN epilayers

CL from planar epilayer

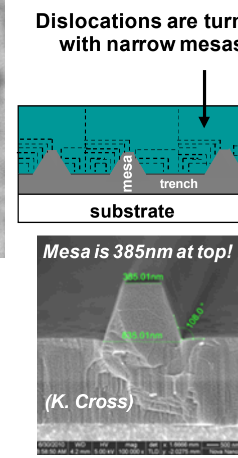


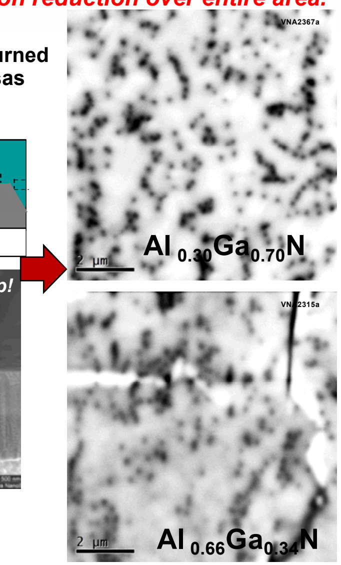
Dislocation reduction over trench areas.





Dislocation reduction over entire area.



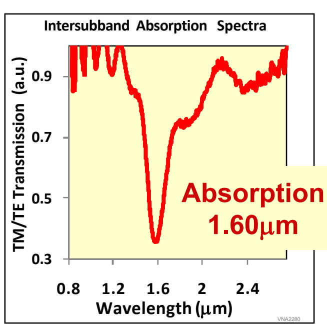


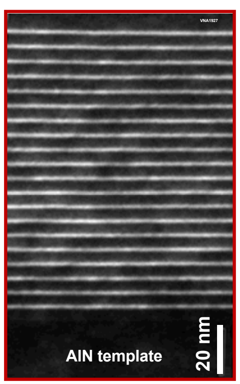
Cathodoluminescence reveals dislocations as dark spots

Identified Impurity-Induced Layer Disordering in Nitrides for the 1st time.

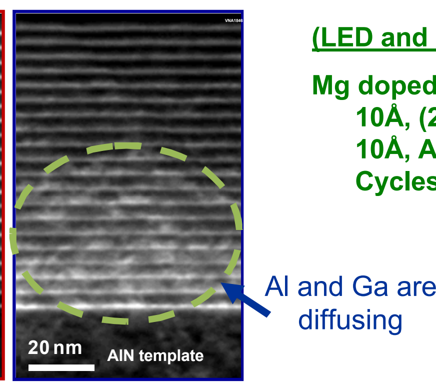
(Inter-subband Project)

Si doped superlattice:
15Å, (10%)AlGaN
50Å, AlN
Cycles: 20x





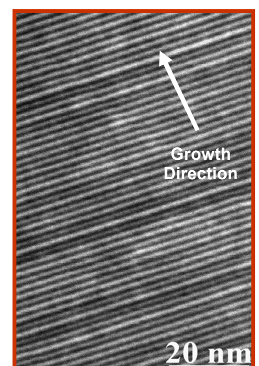
Undoped
Sharp interfaces



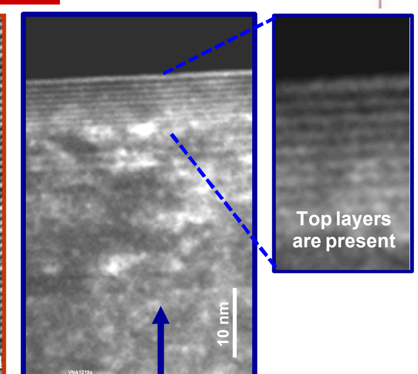
Si – Doped
Intermixed layers

(LED and Lasers)

Mg doped superlattice
10Å, (23%)AlGaN
10Å, AlN
Cycles: 200x



Undoped
Sharp interfaces



Mg-Doped
Intermixed layers

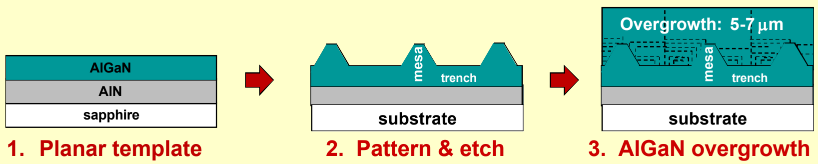
➡ Doping with Si or Mg leads to strong intermixing of superlattice layers grown at 1000 C
➡ Suppressing Al, Ga diffusion is key to growing state-of-the-art ISB structures and Mg-SL

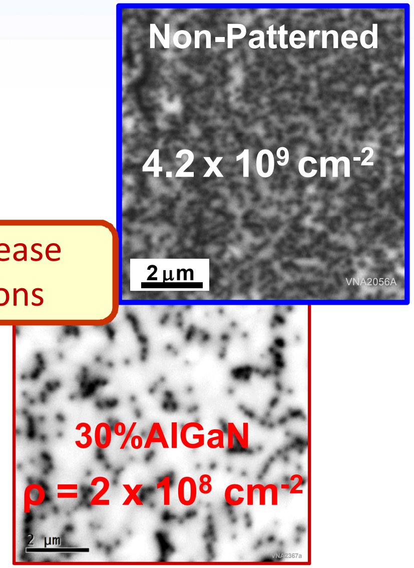
AlGaN Growth

Developed (30%)AlGaN based UV-Laser diodes (LD)

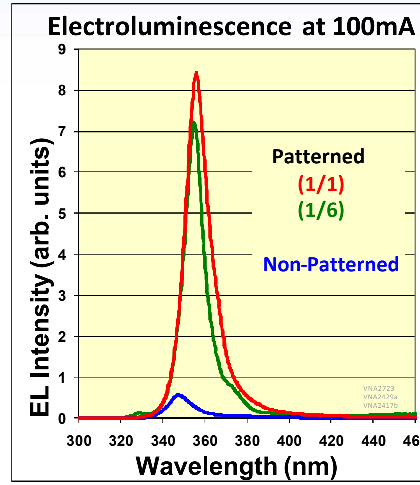
- Established low dislocation growth process
- LD structures reached 28kA/cm^2

➡ Liminus Devices interested in power LEDs (320-370nm)





➡ 20x decrease in dislocations



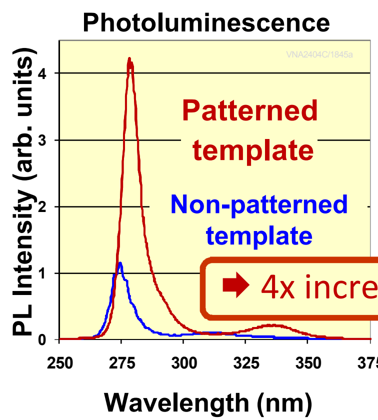
➡ 15x increase in EL

GaN HEMTs for high voltage applications

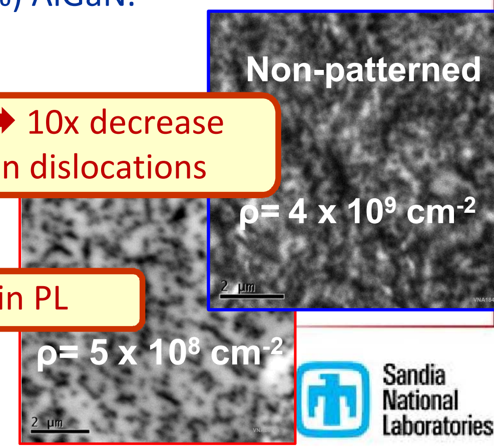
- Carbon doped GaN enable +500V HEMT operation. (air-breakdown limited)

Developed (60%) AlGaN based UV-LEDs

- 1st low dislocation overgrowth process for high Al composition (~60%) AlGaN.



➡ 4x increase in PL



➡ 10x decrease in dislocations

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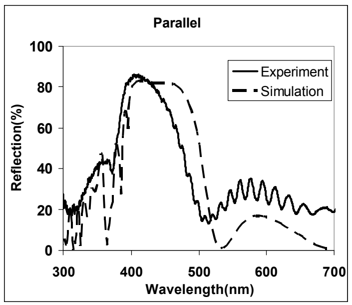
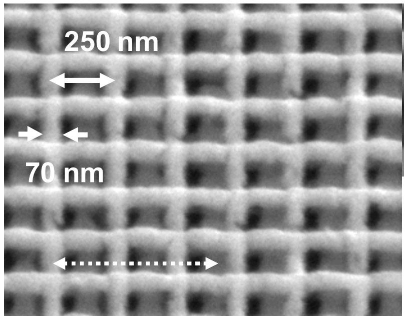
Photonic Lattice/ Meta-materials Investigations

UV-Vis TiO_2 logpile 3DPC (LDRD/EFRC)

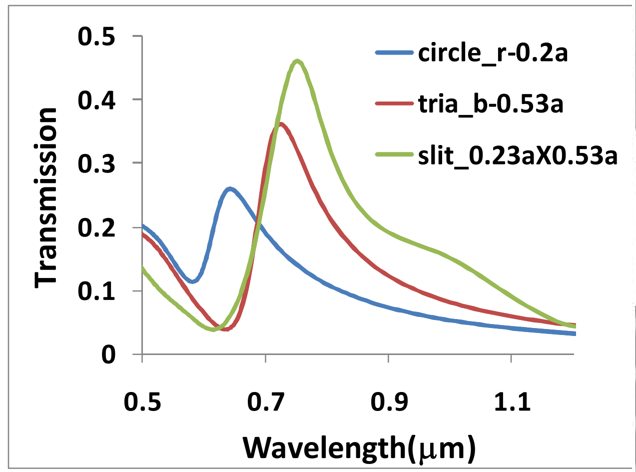
- Photonic bandgap spanning the near-UV and visible wavelengths that can enhance radiative emission of nitride emitters in the blue green regime

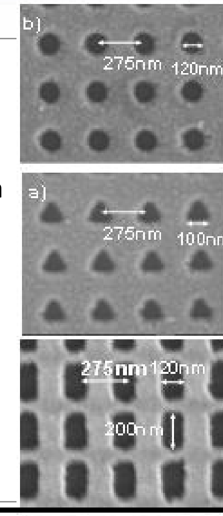




Metallic Nanohole Array Sensors (LDRD)

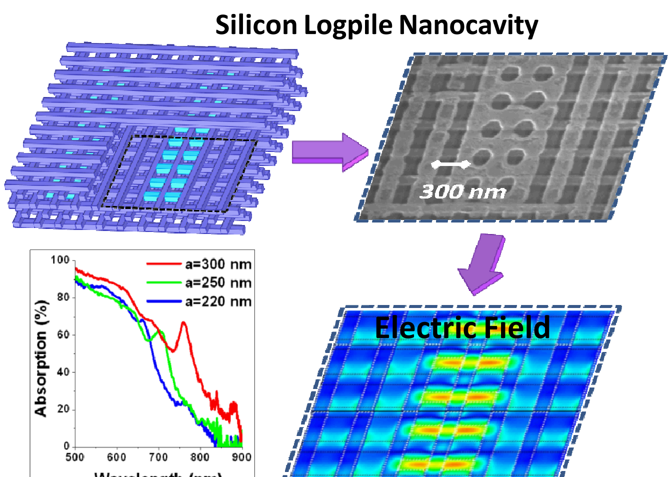
- Design, modeling and fabrication of metal nanohole structures for optimal extraordinary visible transmission for chemical sensing





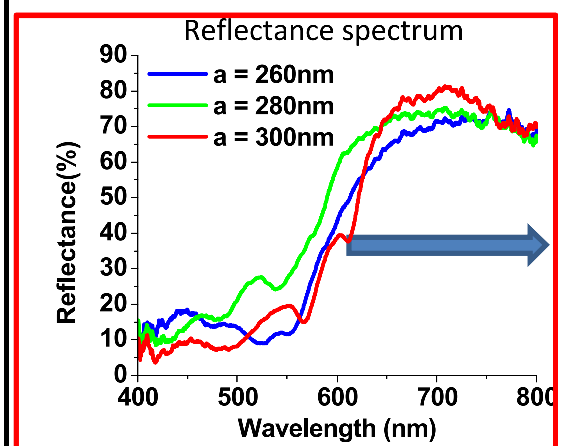
Near-Visible Si logpile 3DPC (LDRD/EFRC)

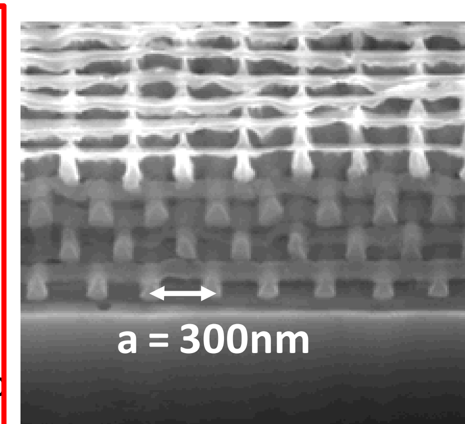
- Silicon logpile with embedded cavities that can operate in the visible well beyond silicon's absorption edge
- Large refractive index of Si will enable wider photonic bandgap in the visible regime for emission control



Visible GaN logpile 3DPC (LDRD/EFRC)

- All GaN logpile PC can enable a three dimensional, scalable, higher brightness LED

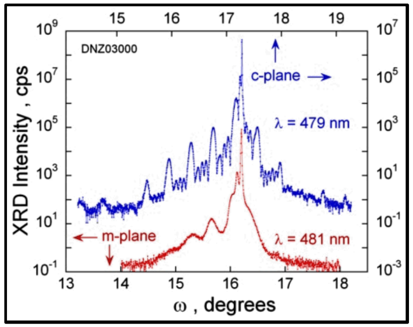




InGaN and GaN materials development

NETL program to develop long wavelength LEDs on non-polar and semi-polar bulk GaN

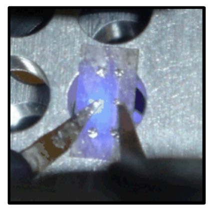
With Mary Crawford (PL), Steve Lee (XRD), and Mike Coltrin (modeling)



XRD scans of InGaN MQWs on c-plane and m-plane GaN substrates

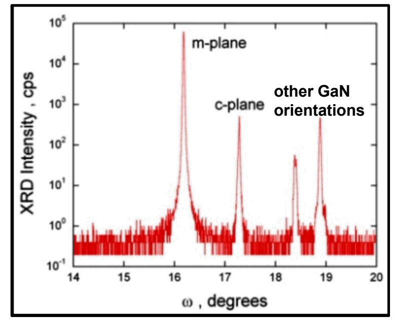
Despite numerous stacking faults, the PL intensity from MQWs on bulk m-plane GaN were ~ 50% as intense as on c-plane GaN depending on laser power.

LED quicktest of first m-plane InGaN LEDs grown at Sandia

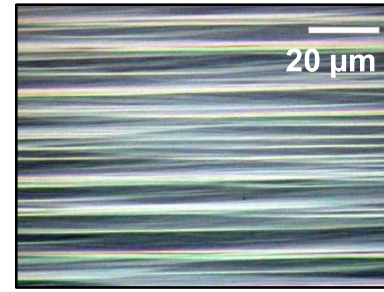


Development of higher indium concentration InGaN for Solar PV on m-plane GaN

With Jon Wierer (sapphire etching) and Steve Lee (XRD analysis)



XRD measurement of GaN growth on trenched a-plane sapphire

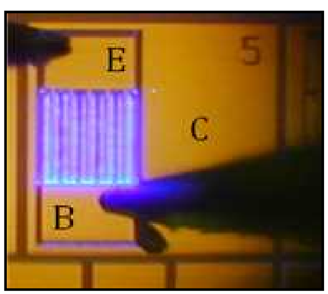


m-plane GaN grown on m-plane SiC

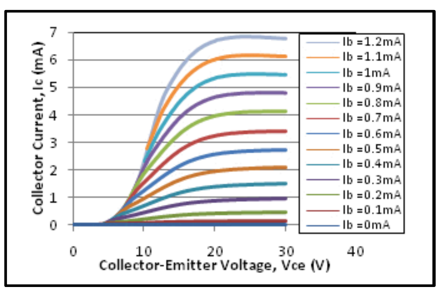
Achieved fully coalesced m-plane GaN by enhancing GaN nucleation.

Study of light emission from HBTs to understand current droop mechanisms for SSL

With Jon Wierer (device design and testing)



Lit HBT design with interdigitated emitter fingers



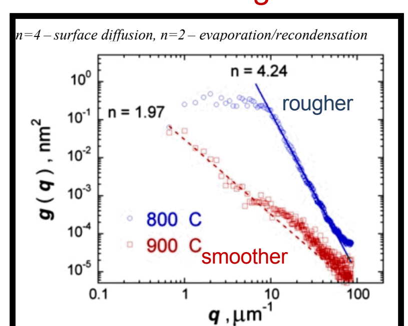
Common-emitter current vs. voltage characteristics with base current steps of 0.1 mA

First nitride-based HBT at Sandia with a current gain of 5.

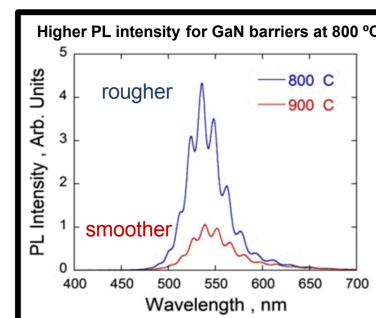
Studies of InGaN morphology and possible relationship to luminescence -

With Steve Lee (XRD) and Mary Crawford (PL)

PSD analysis → smoothing mechanism and length scale



PSD of green MQWs with GaN barriers grown at 800 C and 900 C

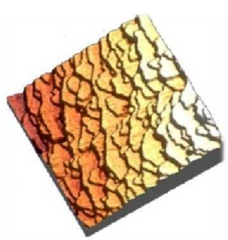


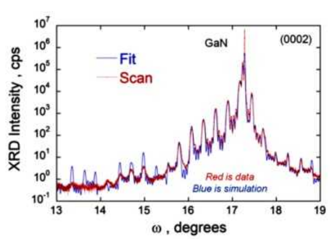
Brighter MQWs on rougher GaN barriers – suggests localization?

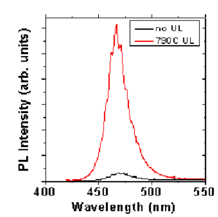
"Semi-polar GaN Materials Technology for High IQE Green LEDs"

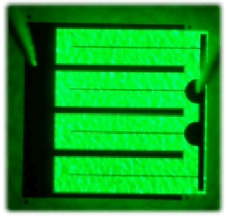
<u>Overall *Goal*</u>*: Use m-plane and Semipolar GaN Substrates to Fabricate Highly Efficient 540 nm LED with an IQE of 50% with Inlustra*.

<u>Process</u>: Explore m-plane and semipolar GaN orientations to determine which orientations produce the highest indium incorporation (longest wavelength) and highest IQE.



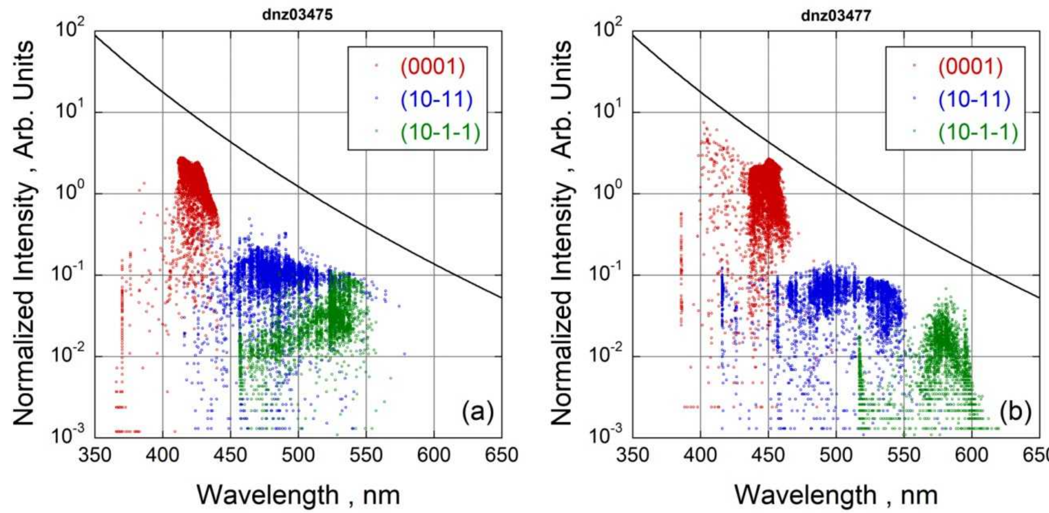




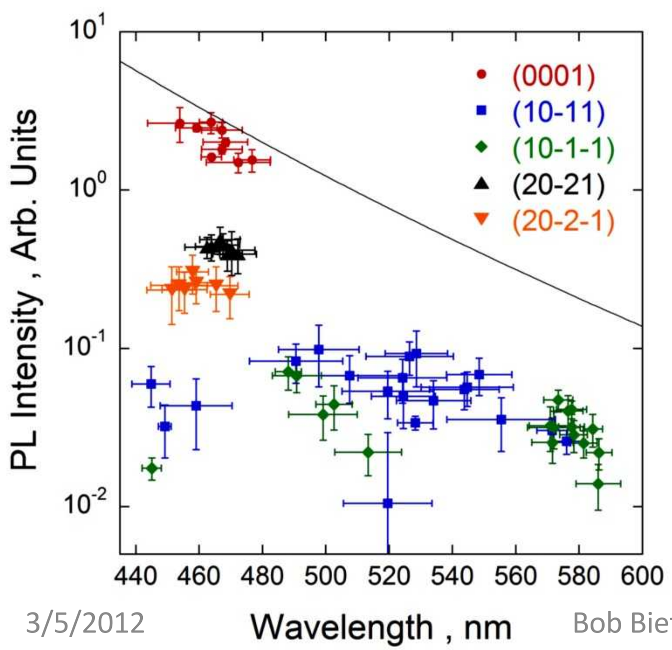


Same MQW growth on (0001), (10-11), and (20-21)

- From photoluminescence maps determine maximum wavelength and intensity for each substrate.
- Examples of two different growth conditions shown on the right.
  - DNZ03475 – QW Temp = 760



- The PL intensity of MQWs on c-plane decreases more as the wavelength increases compared to m-plane.



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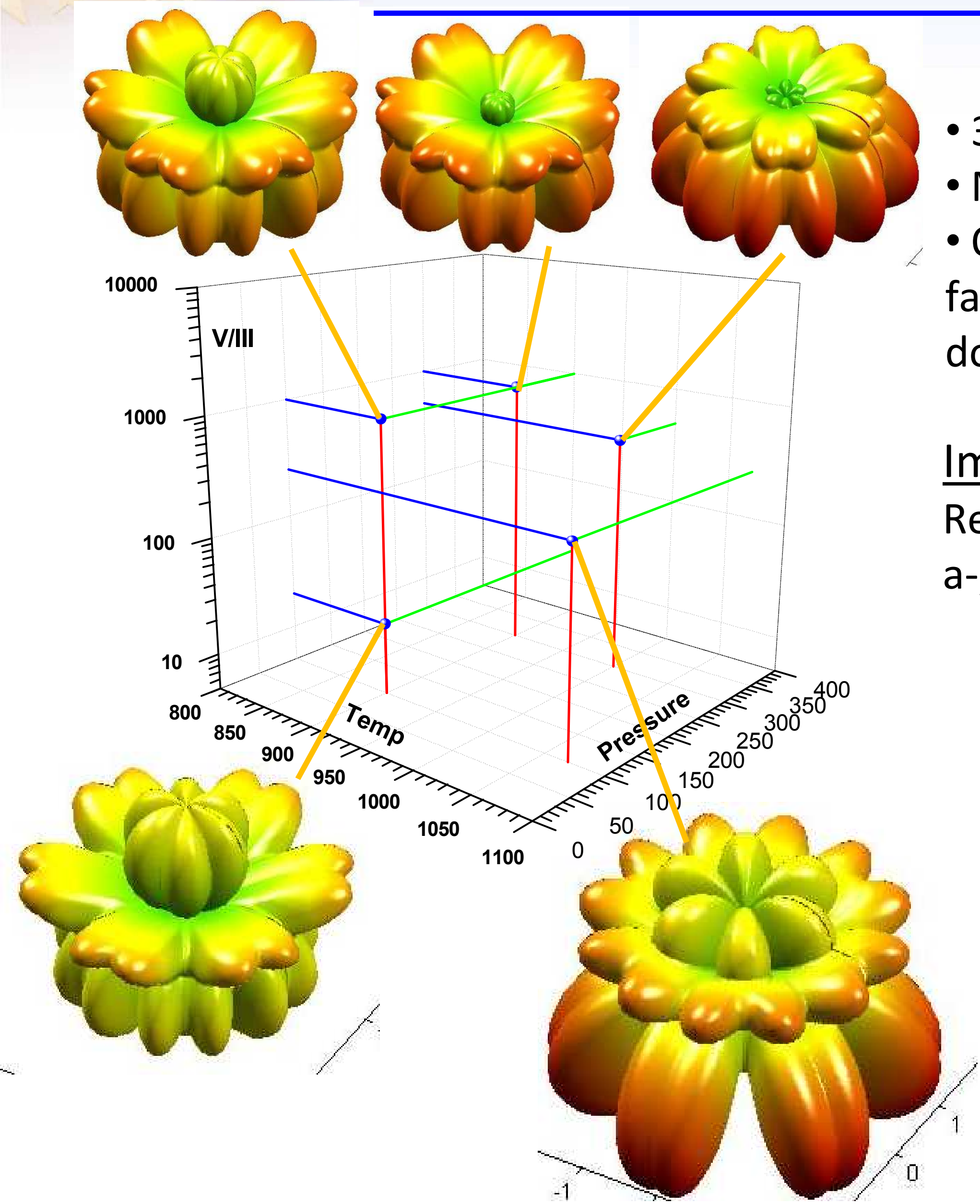
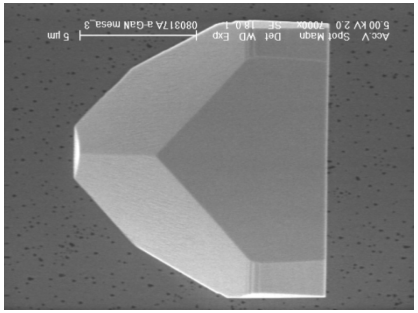
Kinetics of Semi-Polar GaN Morphology Evolution

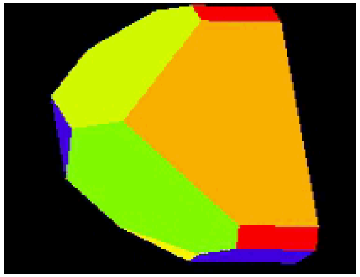


- 3-D v-plots mapped for 5 growth conditions
- Model of convex, a-GaN SAG island shape.
- Observed growth rates of concave facets: facets speed up with increased T and slow down with increasing P, and V/III ratio

Impact:

Results give insight into planar epitaxy of c-, a-, m-, and (11$\bar{2}$2)-plane GaN





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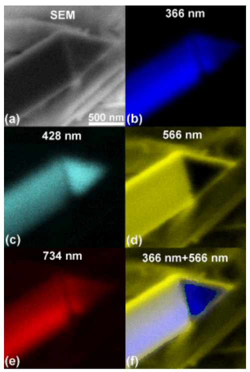
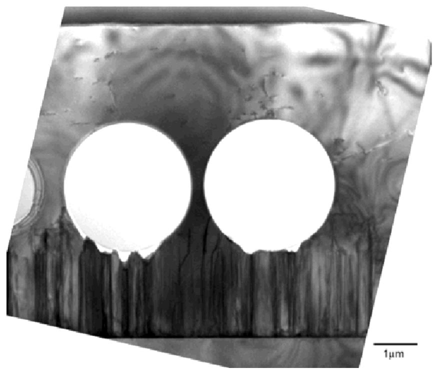
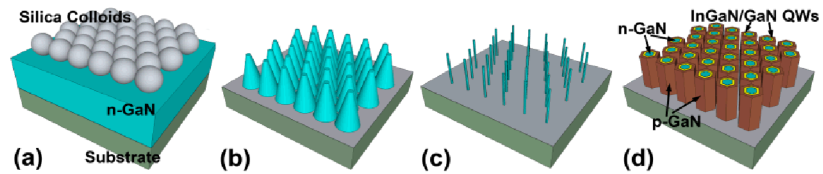
InGaN Nanowire Growth and Characterization

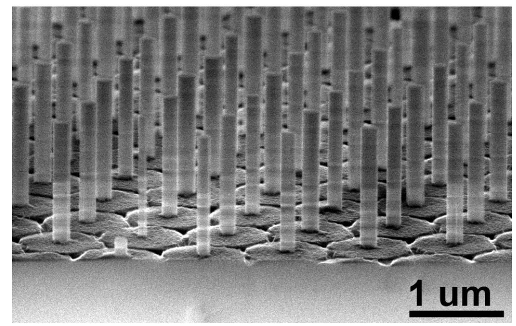


Studied the distribution of point defect related luminescence by CL imaging. Q. Li, etal, NanoLetter, 2010

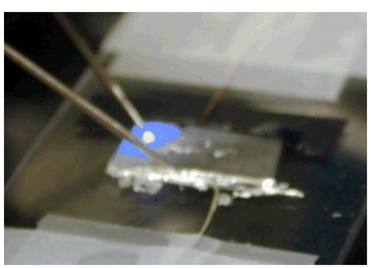


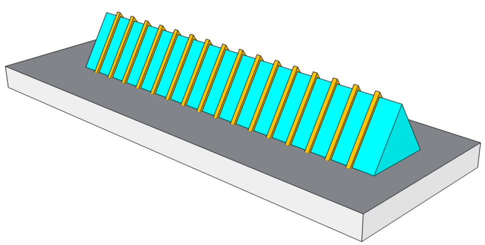
Threading dislocation in GaN epilayers can be reduced to 10^7 cm-2 range by using monolayers of silica colloids. This technique attracted attention from industry. Collaboration with Phillips/Lumileds is being established.



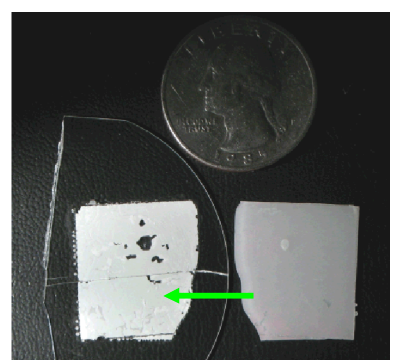


Developed new nanowire synthesis techniques. Materials quality and nanowire device performance was improved. Nanowire based LEDs shows their potential in SSL.





Single mode DFB nanowire Lasers



Liftoff GaN epilayers from substrates using monolayers of silica colloids. Teamed up with Oxford Instrument in developing free-standing HVPE GaN substrates using this techniques.

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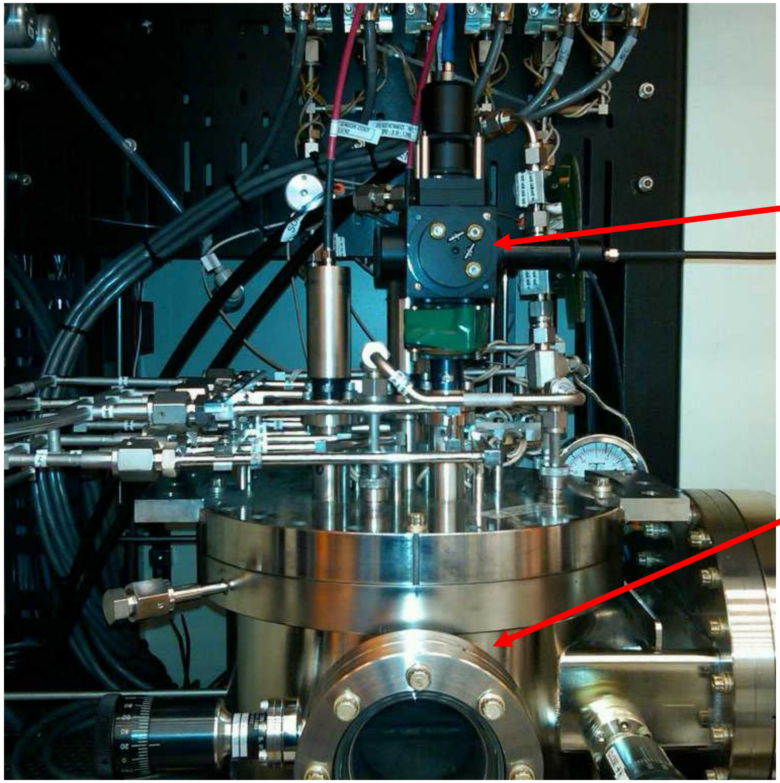
Measure GaN Temperature Directly: Design and install UV-ECP for multiwafer InGaN MOCVD system.

Measures R and T_{ecp} at 405 nm and 550* nm for each wafer



UVV ECP collection/injection optics

Veeco D-125 chamber

[radiation shield added around heater filaments]

*at 550 nm the wafer is transparent but this wavelength is useful for growth rate measurements

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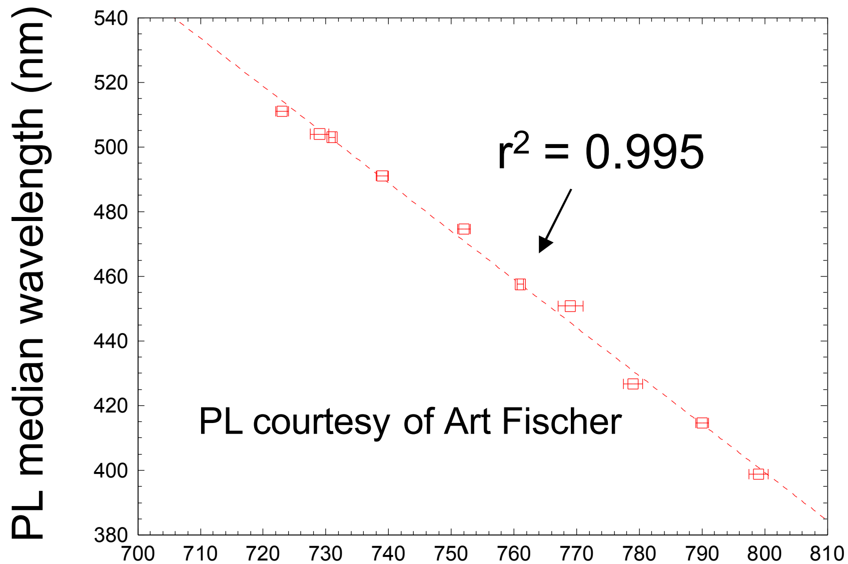
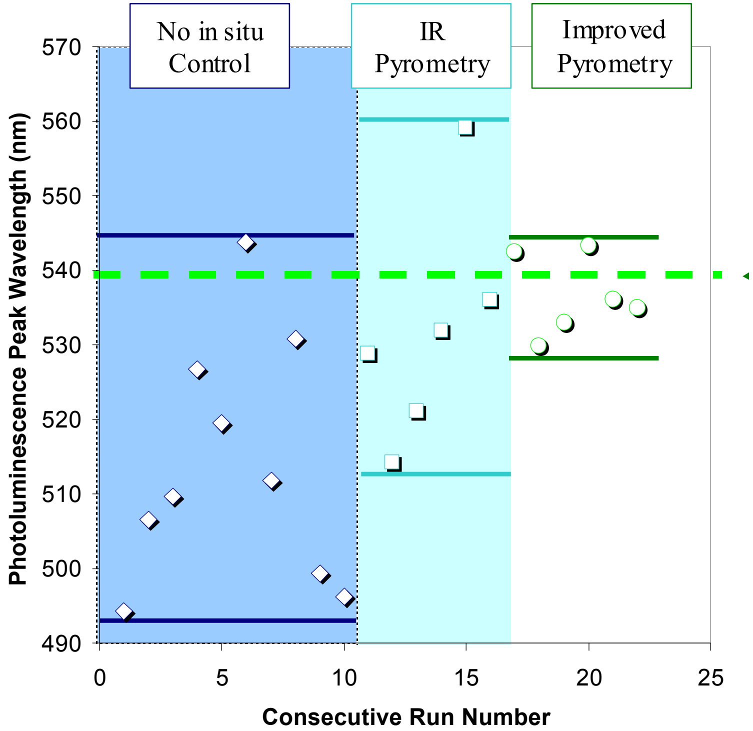
Reproducible and Controllable Growth with UV Pyrometer



UVV-ECP Temperature (°C)



Variation of composition (wavelength) of InGaN with temperature

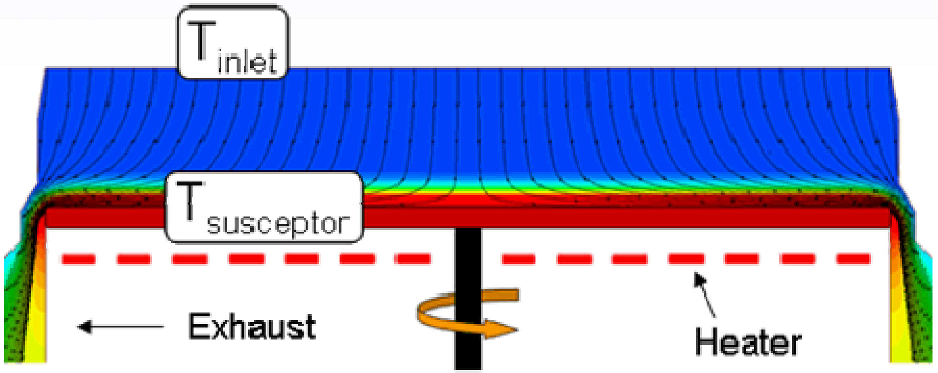
UV Pyrometer improves yield

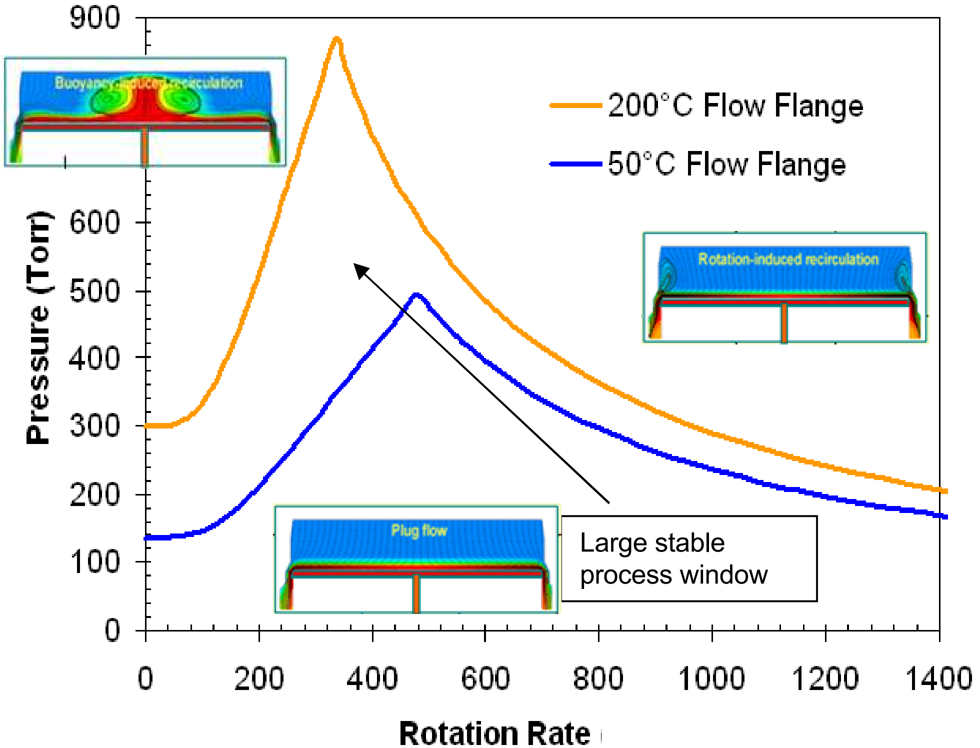
Benefits for Manufacturing - Heated Flow Flange

Fluid Flow Coupled to Chemistry (Fluent+Chemkin)

Greater gas inlet temperature (T_{inlet}):

- Reduces buoyancy forces
  - *Smaller vertical temperature gradients*
- Increases the stable process window
  - Higher pressure / lower rotation rate capability
  - Improved hydride efficiency
- Reduced parasitic particulate formation (?)
  - Contrary to technical understanding
- More uniform wafer temperatures
  - Improved PL wavelength uniformity





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Chemistry of group-III nitride MOCVD is complex at every stage

~10 cm | **wafer surface**

~1 cm

Reactor Inlet chemistry (20-100°C)

<u>All reactants</u> form adducts with NH_3

$$Al(CH_3)_3 + NH_3$$
$$\downarrow\uparrow$$
$$(CH_3)_3Al{:}NH_3(g)$$
condensation $\downarrow\uparrow$
$$(CH_3)_3Al{:}NH_3(s)$$

boundary-layer chemistry (100-1000°C)

Pyrolysis

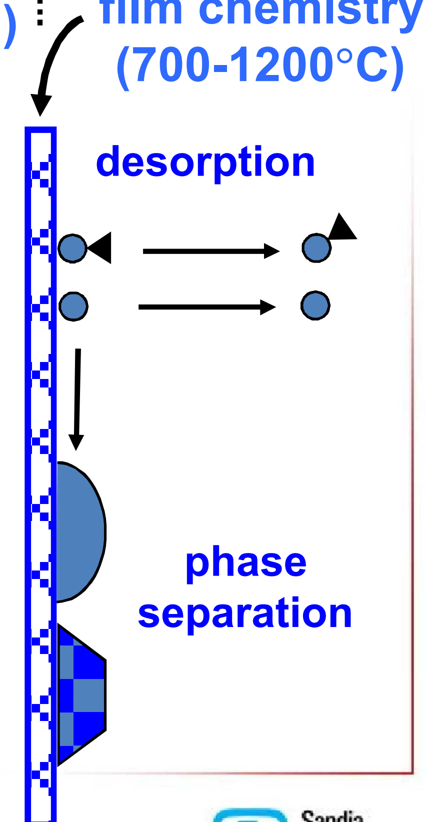
$$Ga(CH_3)_3 \rightarrow Ga + 3\ CH_3$$

Adduct based Rxns

$$(CH_3)_3Al{:}NH_3 \rightarrow (CH_3)_2AlNH_2 \rightarrow \text{"cluster"}$$

nanoparticle nucleation and growth (CVD)

surface & thin film chemistry (700-1200°C)



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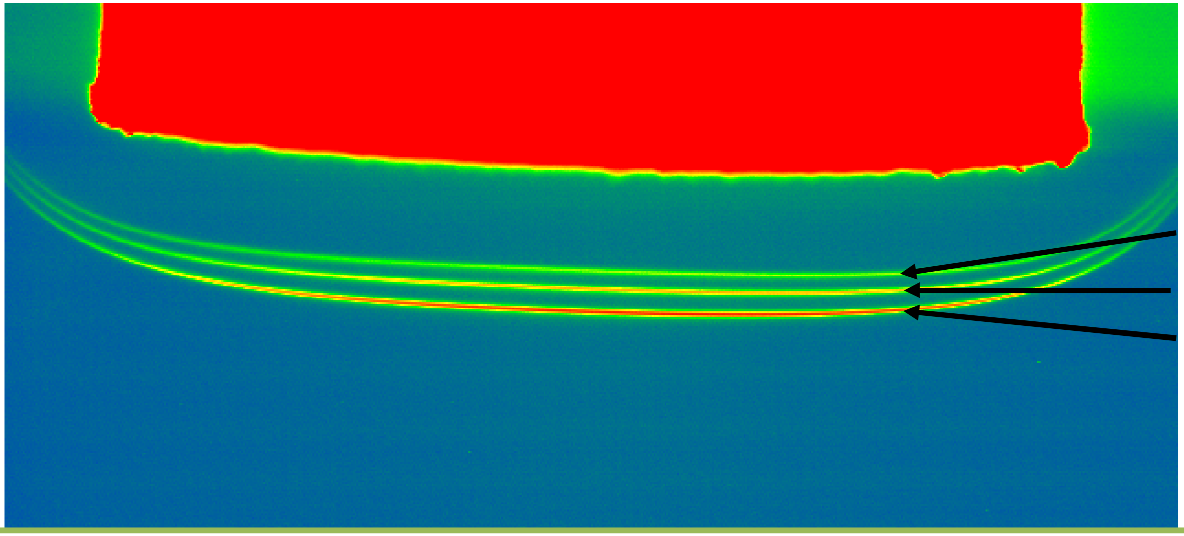
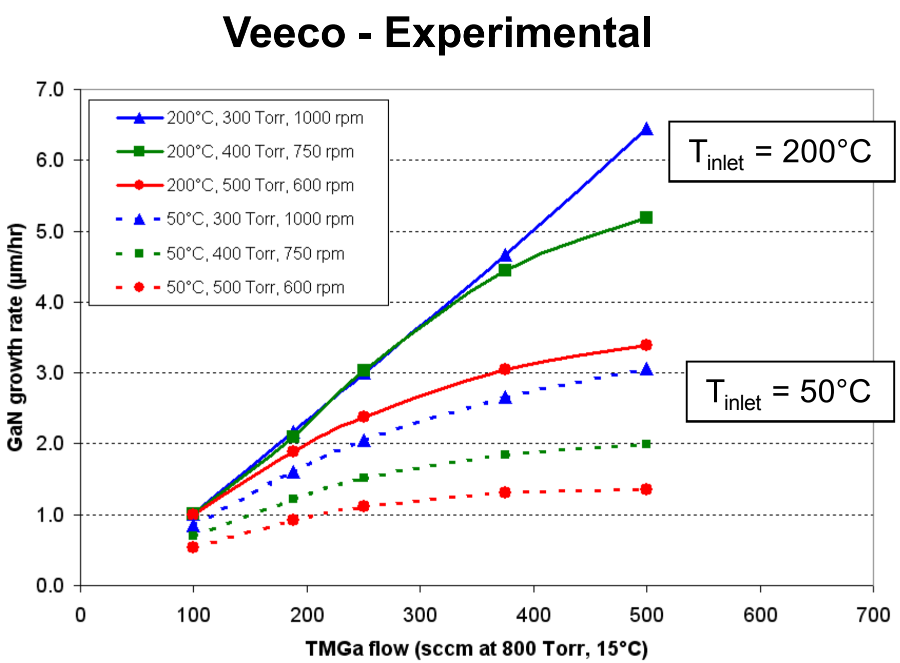
As inlet Temperature is raised, layer of particles gets closer to hot surface and scattering intensity drops

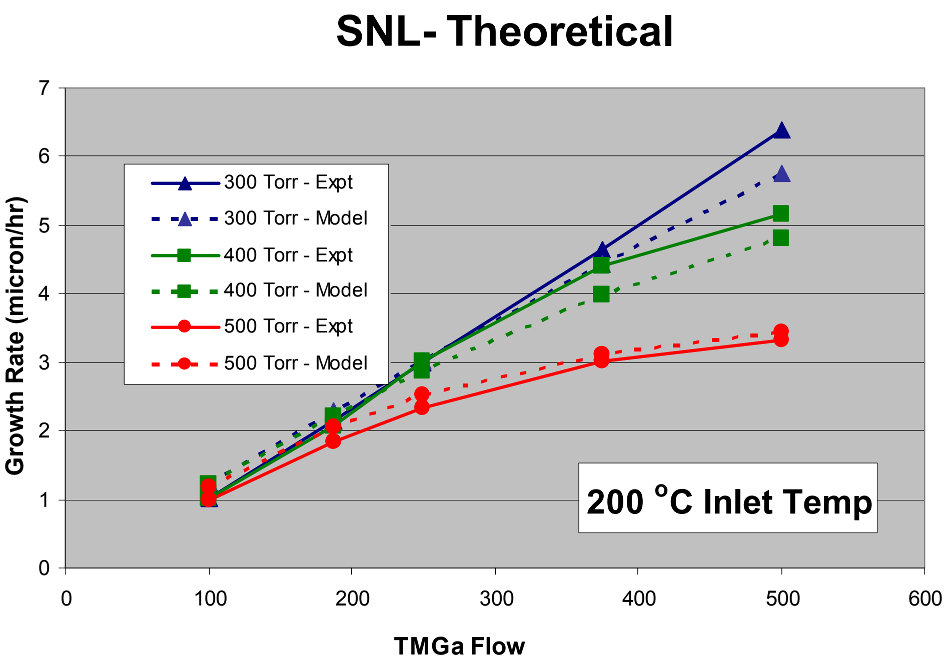


1) Shift in position towards hot surface expected from reduction in thermophoretic force
2) The intensity trend agrees qualitatively with Veeco MOCVD growth rate results

Fewer particles = higher growth rate

Heated Flow Flange – Experiment vs. Model





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Related, Current LDRDs

- Efficient, High-Voltage, High-Impedance GaN/AlGaN Power FET and Diode Switches
- Exploring Energy Transfer Processes in Semiconductor Light Emitters
- Science-based Solutions to Achieve High Performance Deep UV Laser Diodes
- Extension of Semiconductor Laser Diodes to New Wavelengths for Novel Applications