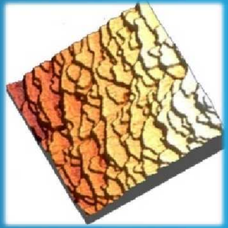
Applied Materials Meeting, August 29, 2011

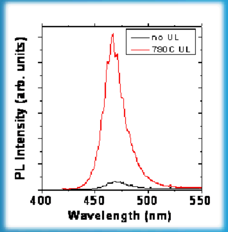
SAND2011-7368P

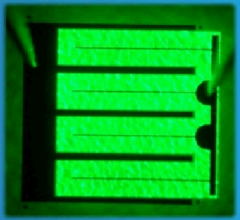
SSLS EFRC

SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Group III-Nitride Growth for Solid State Lighting







Daniel D. Koleske, J. Randall Creighton, Michael E. Coltrin, Mary H. Crawford, Stephen R. Lee, and Andrew Armstrong

Work supported by the US Department of Energy, Office of Basic Energy Sciences

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Sandia National Laboratories, a multiprogram laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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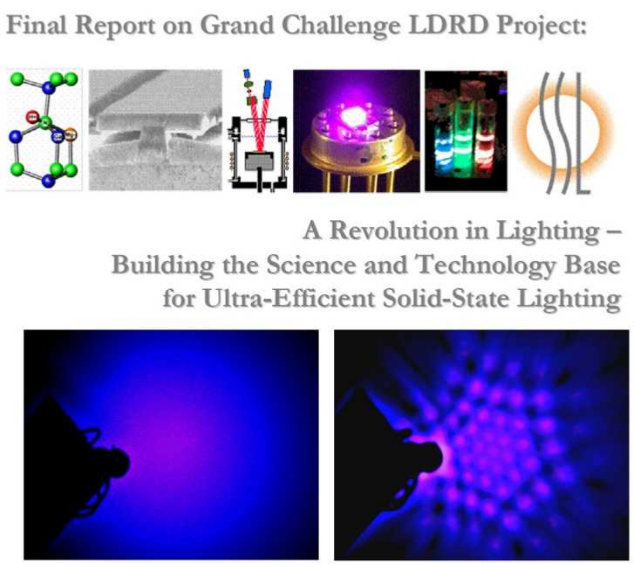
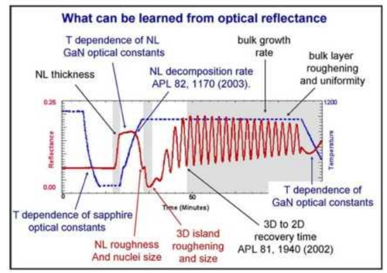
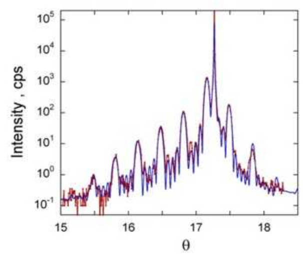
Topics for Discussion

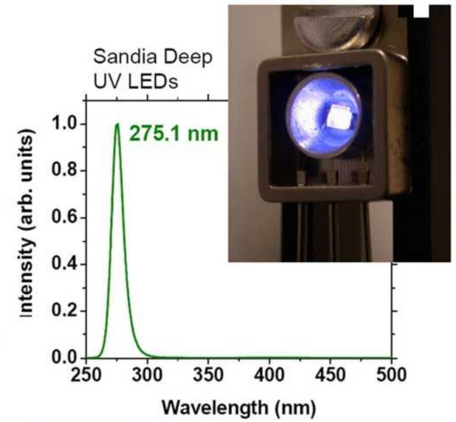
- Current SSL programs at Sandia
- Heteroepitaxy studies – GaN on sapphire
- MOCVD reactor chemistry
- InGaN growth related to improving LED brightness
- Semipolar GaN growth – brighter green?

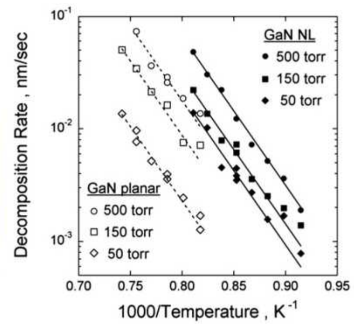
Long Legacy of R & D in SSL and Group III - Nitrides

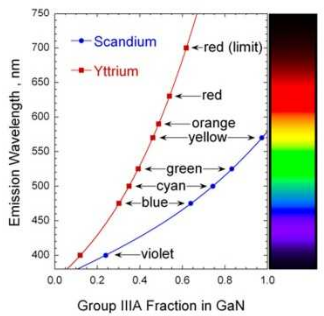


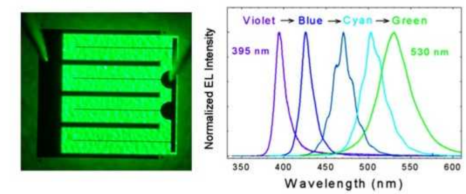










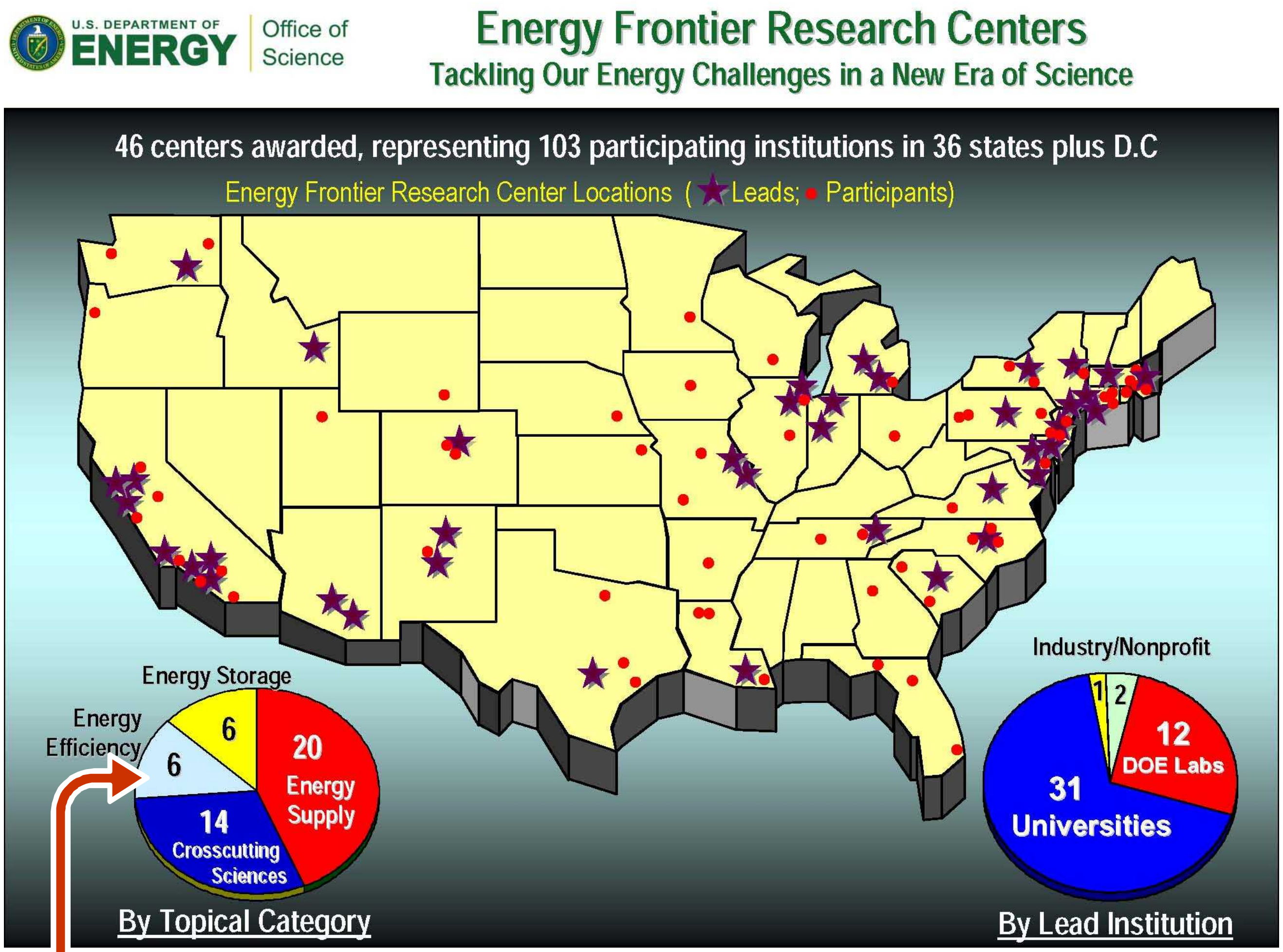


- Sandia has been involved in group III nitride research since 1997.
- Sandia was there from the start. In 1999, Jeff Tsao, Jeff Nelson, Roland Haitz (HP) and Fred Kish (HP) wrote a “white paper” to DOE for increased support for LED development for SSL.
- Sandia has been supported both internally (LDRD) and externally (BES, NETL, and DARPA) for many years. From 2001 to 2004 it was supported by a 8 M$ grand challenge LDRD at Sandia. More recently, support has been provided by DOE basic energy sciences (BES), and additional LDRDs, and EERE/NETL.

Current SSL related programs at Sandia

- **SSL Science (SSLS) Energy Frontier Research Center (EFRC) – (DOE/BES) - 2010 - 2015**
- Semi-polar GaN Materials Technology for High IQE Green LEDs – (EERE/NETL) – 1/15/2010 to 1/15/2013.
- Driving Down HB-LED Costs: Implementation of Process Simulation Tools and Temperature Control Methods for High Yield MOCVD - with Veeco - (EERE/NETL) - 5/1/2010 - 4/30/2012
- Novel Defect Spectroscopy of InGaN Materials for Improved Green LEDs (EERE/NETL) 04/01/08 - 03/31/11 – just finished.
- Ten previous EERE/NETL funded programs and internal LDRD programs on SSL, including Grand Challenge LDRD (2001-2004).

We are one of 46 Department of Energy Office of Science EFRCs



- Goal: To establish the scientific foundation for a fundamentally new U.S. energy economy
- Overall Budget: $777M over 5 years beginning Aug 2009
- Our Budget: $18M over 5 years

We are one of 6 EFRCs focused on efficiency, and the only one focused on SSL

People & Resources: 2011 Snapshot (33+20)

Management Team
Jerry Simmons
Mike Coltrin
Jeff Tsao

Thrust Leaders
Mary Crawford
Art Fischer
George Wang

Senior Staff
Andy Armstrong
Bob Biefeld
Igal Brener
Weng Chow
Jianyu Huang
Dan Koleske
Francois Leonard
Qiming Li
Willie Luk
Jim Martin
Normand Modine
May Nyman
Lauren Rohwer
Eric Shaner
Ganesh Subramania
Jon Wierer

Post-Docs & Students
Tania Henry
Emil Kadlec
Jeremy Wright

Business & Administrative
Rene Sells
Alyssa Christy
Chris Monroe
Katelynn Florentino

Technical Support
Jeff Figiel
Tony Coley
Kris Fulmer
Karl Westlake

Integrated Materials Research Lab

Center for Integrated Nanotechnologies

Microsystems Engineering Sciences & Applications Complex

University of New Mexico
Professor Steve Brueck
Sasha Neumann

Yale University
Professor Jung Han
Chris Yerino
Ben Leung

Northwestern University
Professor Lincoln Lauhon
Sonal Padalkar (PD)
Jim Riley

Los Alamos National Lab
Rohit Prasankumar
Prashanth Upadhya
Rohan Kekatpure (PD)
Minah Seo (PD)

Rensselaer Polytechnic Univ
Professor Fred Schubert
Di Zhu
Ahmed Noemaun
Qi Dai

University of Massachusetts
Professor Dan Wasserman
Troy Ribaudo

UC Merced
Professor David Kelley

Philips Lumileds
Mike Craven

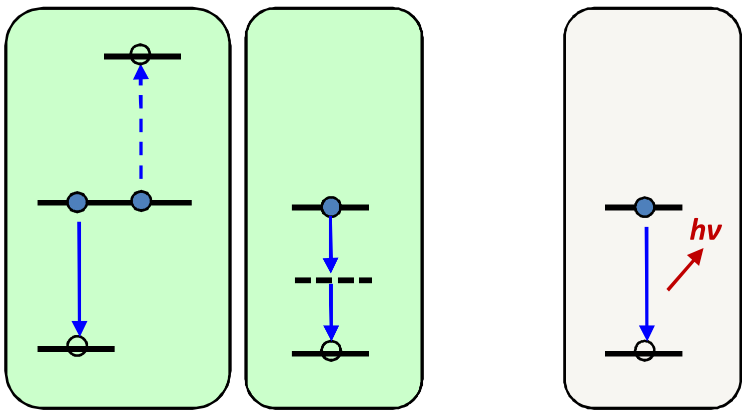
Our EFRC's Scientific Thrusts

1 Competing Radiative and Non-Radiative Processes

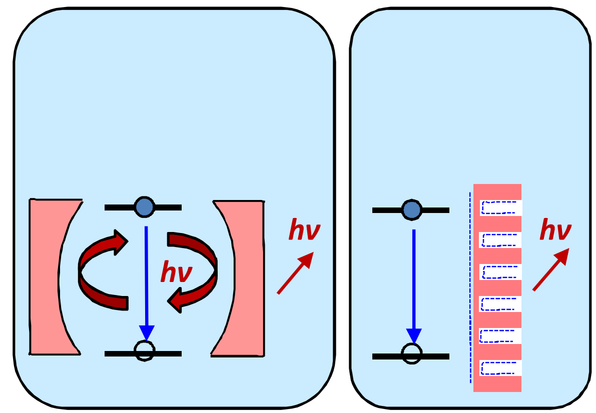
Develop a microscopic understanding of the competition between radiative and non-radiative e-h recombination: spontaneous emission from planar structures.

2 Beyond Free-Space Spontaneous Emission

Explore energy conversion routes that short-circuit conventional spontaneous emission but end in free-space photons.



Auger | **Shockley Read Hall** | **Spontaneous Band-Edge Emission**



Stimulated Emission and Strong Coupling | **Plasmonic Intermediaries**

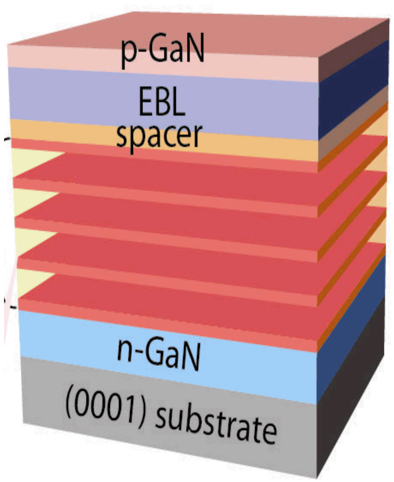
3 Beyond-2D

Explore the use of non-planar nanoscale structures to modify energy conversion routes so that they may be (a) isolated and better understood, and (b) engineered and optimized.

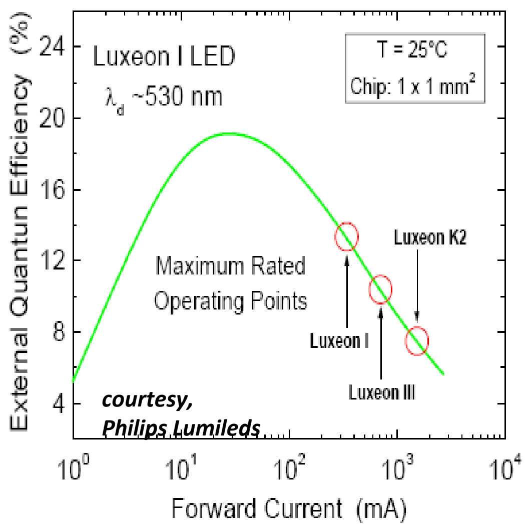
Mary Crawford (PI)
Weng Chow,
Dan Koleske,
Andy Armstrong,
Normand Modine,
Fred Schubert (RPI)

1.1 Origin of Efficiency Droop: Beyond the A,B,C Approximation

Typical Device Heterostructure



Macroscopic observable



Usual A,B,C Approximation

Extraction efficiency (photon trapping and absorption)

ε_{Joule} Joule efficiency (resistive losses)

ε_{IQE} Internal quantum efficiency

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

2.8V 0.6Ω

Injection efficiency (carrier overshoot/escape)

Shockley-Read-Hall (defect-mediated)

Spontaneous Emission

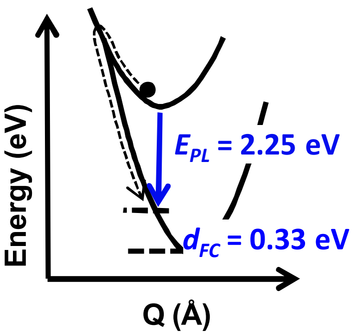
Auger-like

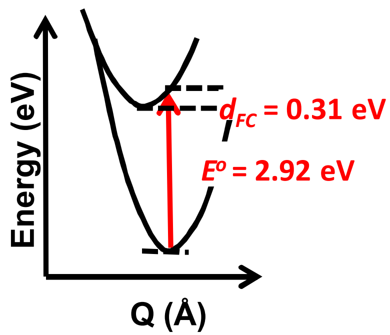
1.2 Deeper into Point Defects: Fundamental Properties of V_{Ga}

Deep Level Optical Spectroscopy: Measure deep-level densities, cross-sections, Franck-Condon shifts

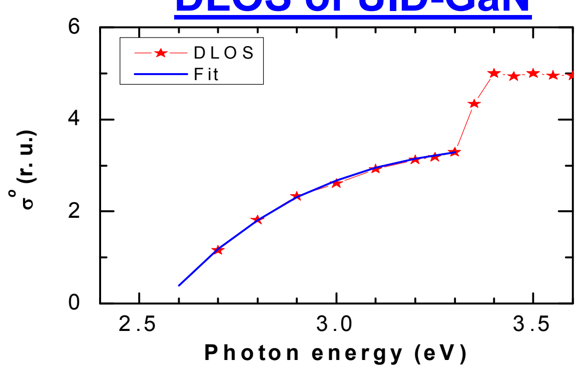
Andy Armstrong (PI)
Normand Modine
Dan Koleske
Mary Crawford

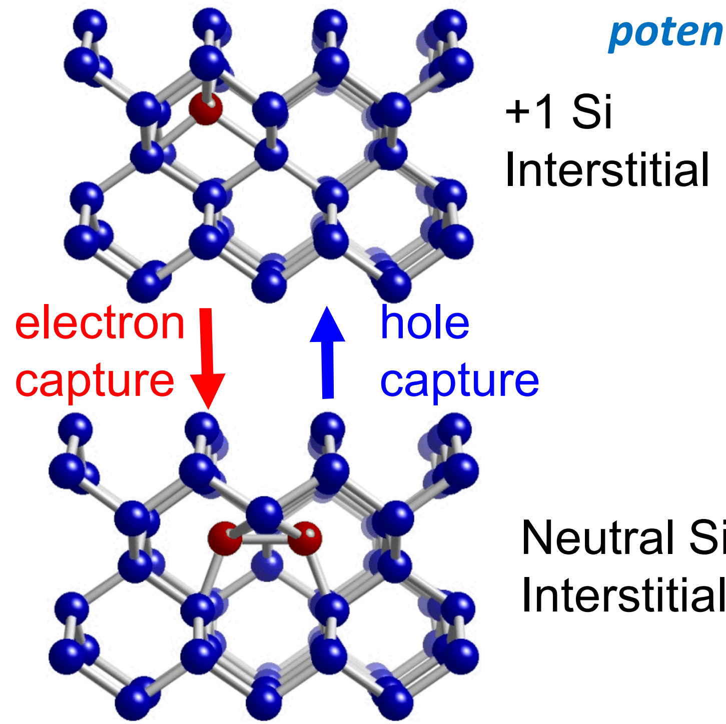
Density Functional Theory: Ab initio calculations of Eo, hw, S using realistic multi-dimensional anharmonic potentials





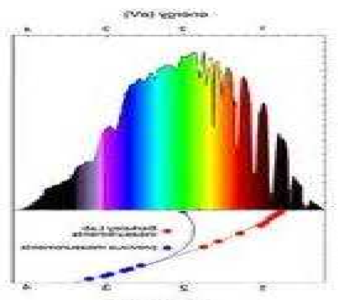
DLOS of UID-GaN

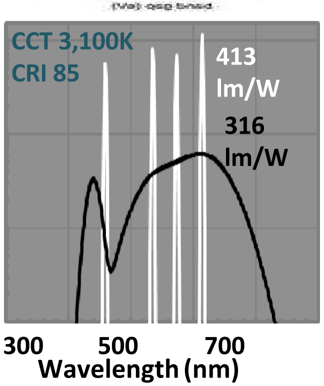




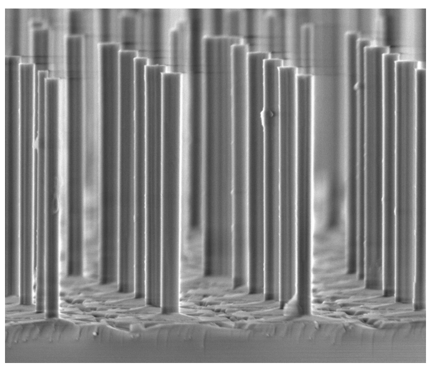
3.1 Beyond 2D: 1D Nanowire Synthesis, Properties, Architectures

High InGaN compositions needed to span the desired SSL wavelengths



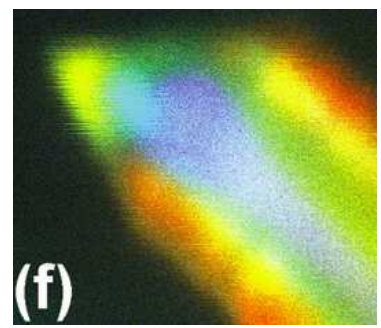


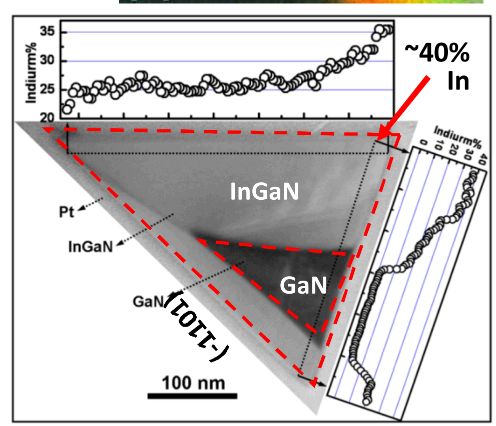
High aspect ratio enables strain accomodation



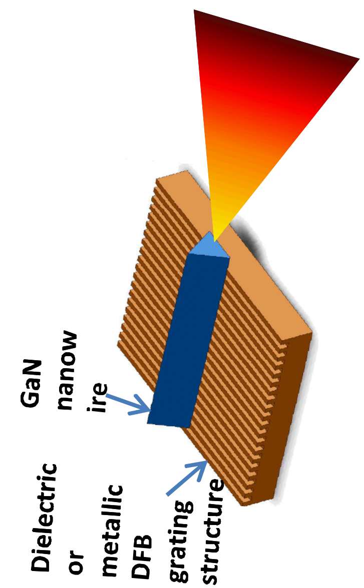
George Wang (PI)
Qiming Li,
Jianyu Huang
Igal Brener,
Francois Leonard
Rohit Prasankumar
Lincoln Lauhon

Measurements verify 40% InGaN, with anisotropies





Future work: InGaN nanowire lasing!



Topics for Discussion

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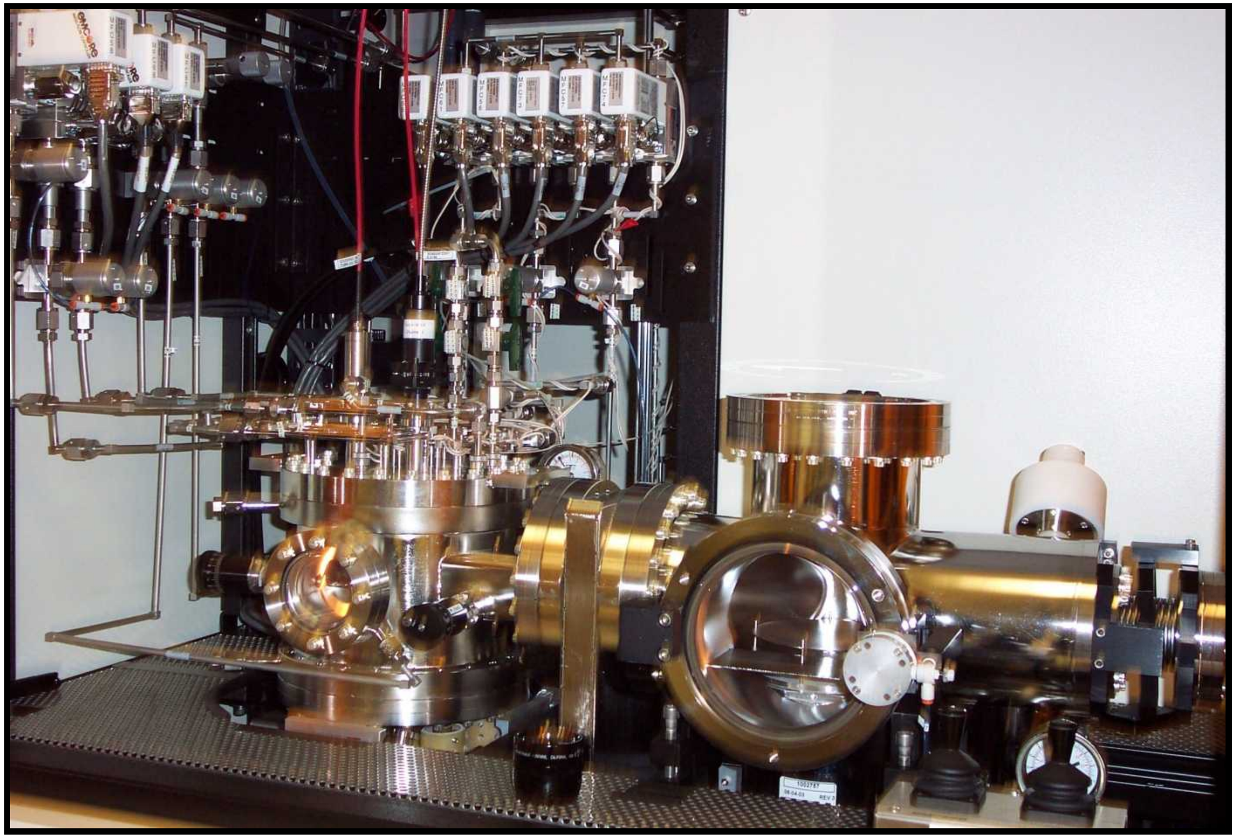
Three D-125 Veeco short-jar MOCVD systems at Sandia



- **MOCVD reactor** – Veeco D125 short-jar - 3-2” wafers simultaneously.
- **Precursors –** trimethyl sources of In, Al, and Ga, and $Mecp_2Mg$ and SiH_4 for p- and n-type doping.
- **Gases –** NH_3, N_2, H_2 (no H_2 for InGaN)
- **Temperature –** GaN at 1050 °C, InGaN at 680 – 880 °C.

Growth differences between InGaN and GaN are:
lower temperature, higher NH_3, no H_2, slower growth rate (less total MO).

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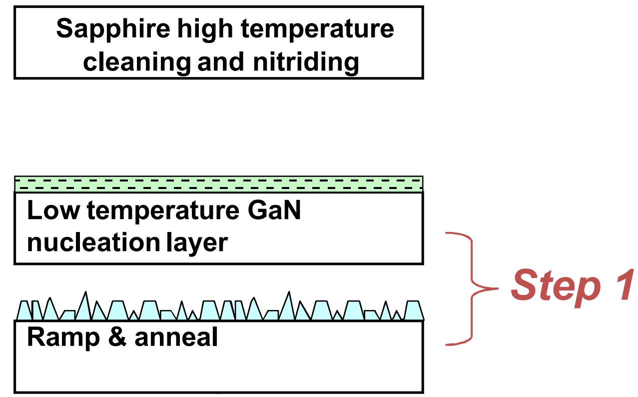
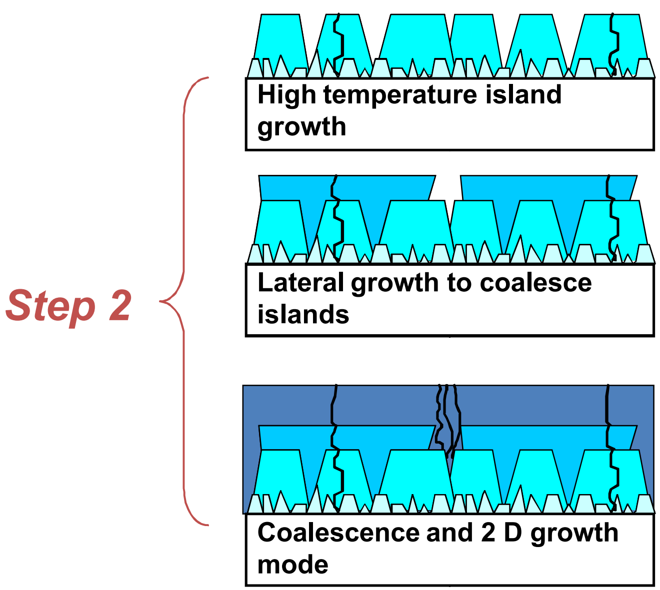
Typical "two step" heteroepitaxy of GaN on sapphire

1) Sapphire heated to high temperature (1050 – 1100 ºC) in H_2 to "clean" the surface; surface sometimes exposed to NH_3 at high temperature.

2) Grow 20 – 30 Å GaN NL at 500 – 600 ºC; as grown NL contains "cubic" material with stacking faults.

3) Heat GaN NL to 1000 – 1080 ºC in flowing H_2, N_2, and NH_3. Wurtzite GaN nuclei form.





4) At high temperature, Ga source is turned on. Isolated GaN grains grow on the GaN nuclei from the decomposition of the GaN NL. Some dislocations propagate up from the GaN grains.

5) Islands grow laterally / vertically; grains begin to coalesce. Growth conditions can be tuned to increase / decrease lateral growth rate.

6) When grains have coalesced, growth becomes 2-D. Dislocations are formed as GaN grains coalesce to accommodate grain twist / tilt.

Based on work from K. Hiramatsu, et al., Journal of Crystal Growth 115, 628 (1991).

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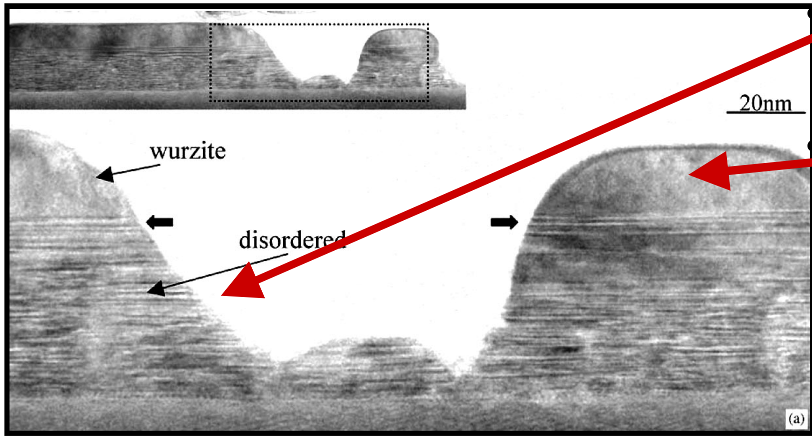
GaN morphology evolution on sapphire

Figure from Lada et al., J. Crystal Growth 258, 89 (2003).

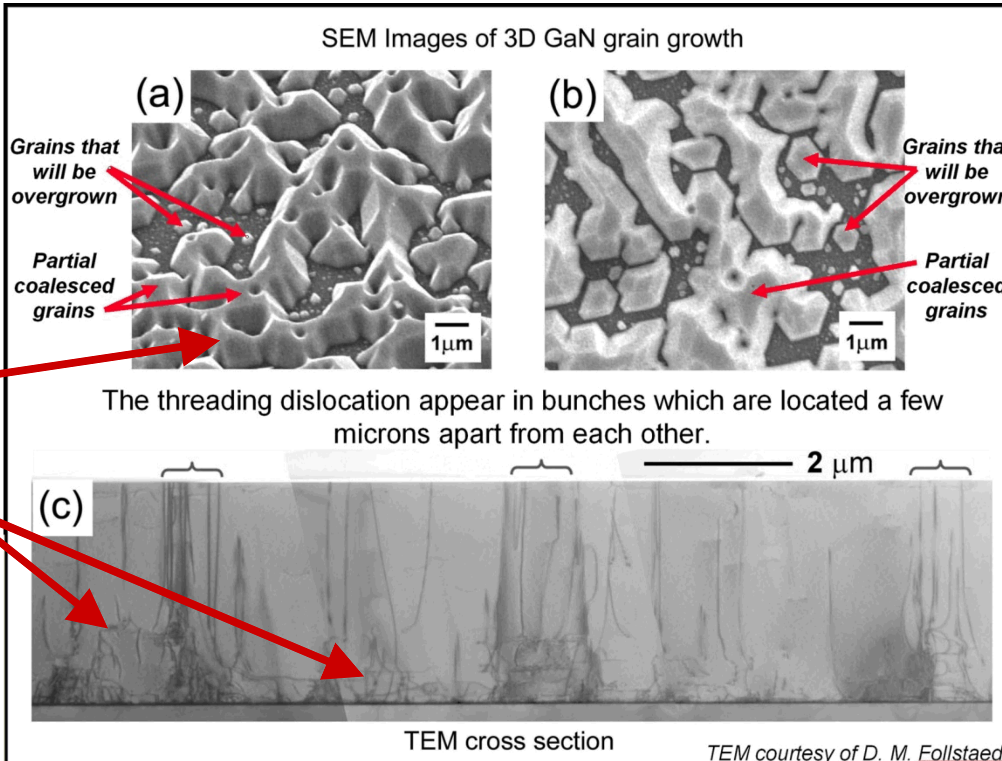


As grown GaN nucleation layers contain disordered GaN with many stacking faults.

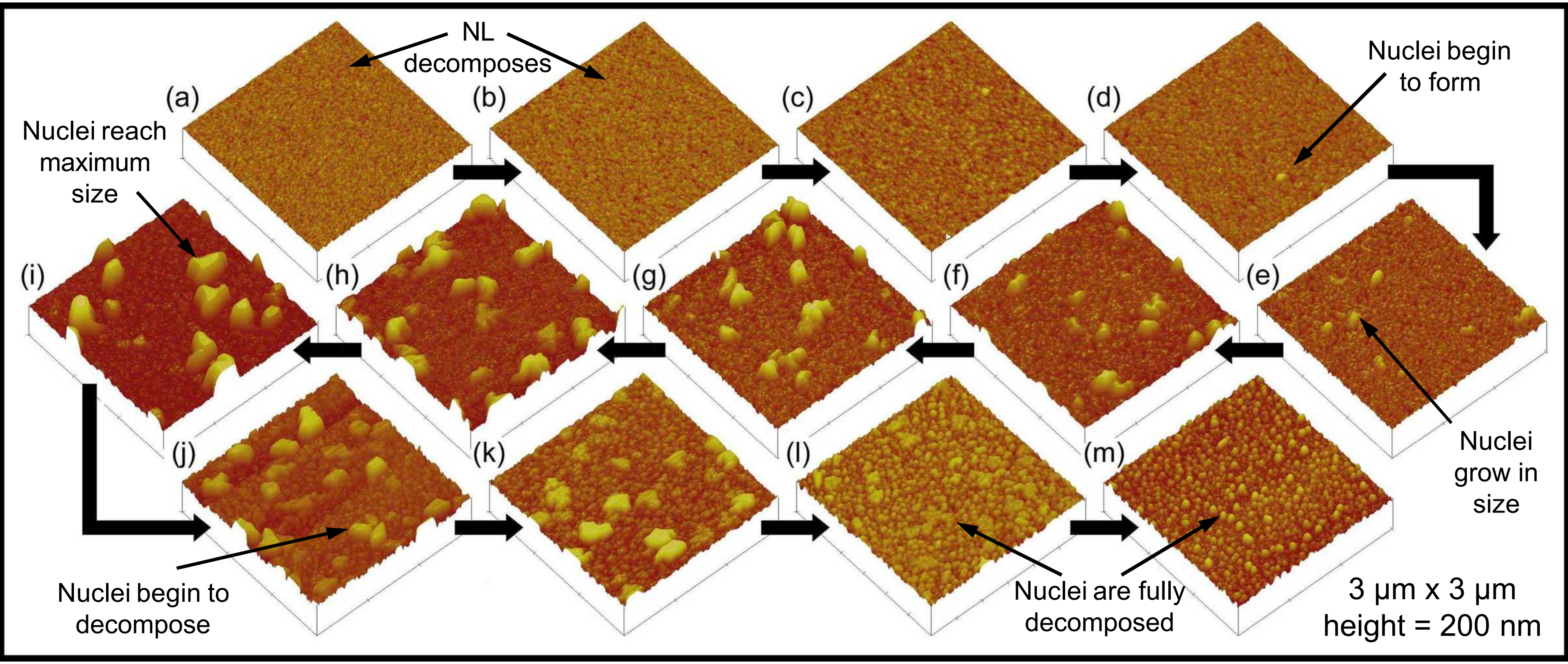
Once annealed, wurtzite GaN forms on top of GaN NL, forming nano-sized GaN nuclei from which further high temperature GaN growth occurs.

- High temperature growth on the GaN nuclei produces GaN grains.
- Growth conditions can be varied to enhance the pyramidal growth mode delaying coalescence. Dislocations are bent laterally on pyramidal facets
- Dislocations are concentrated in bunches located microns apart.

Works! But not Ideal!



Mechanism for GaN nuclei formation as the nucleation layer is annealed.



Arrows indicate increasing annealing temperature + time in H_2, N_2, and NH_3. *Koleske et al., J. Crystal Growth 273, 86 (2004).*

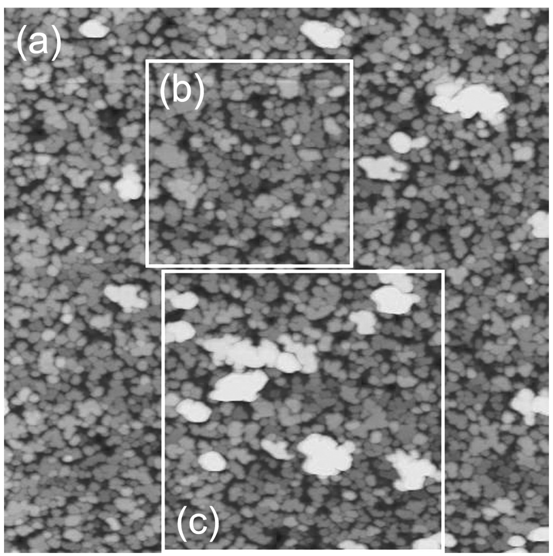
Mechanism for GaN nuclei formation → NL decomposes during annealing, Ga atoms desorb into the gas phase and reincorporate with NH_3 to form GaN nuclei.

Key mechanism: Gas phase desorption and reincorporation not surface diffusion.

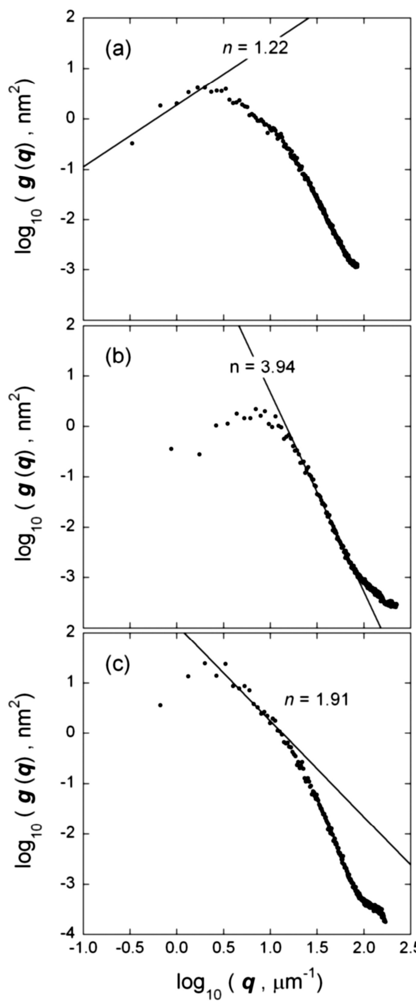
PSD analysis of GaN nucleation layer evolution

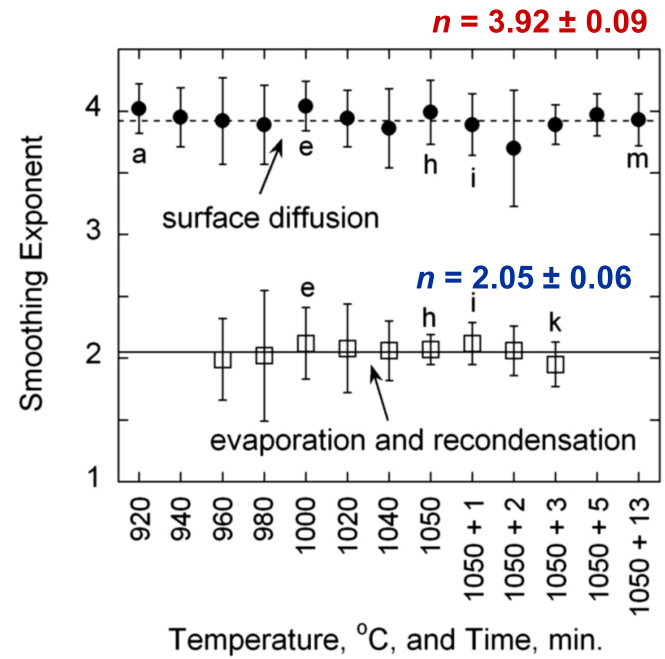
AFM scan of NL at 1000 °C

Low temperature deposited GaN NL is smoothed via surface diffusion, *n* = 4.



GaN nuclei form out of deposited GaN NL via evaporation and reconden-sation mechanism, *n* = 2.





Consistent with gas phase transport model of Mitchell, *et al.*, J. Crystal Growth 222, 144 (2001).

Koleske et al., J. Crystal Growth 273, 86 (2004).

LED growth on wafer-bonded sapphire-on-polycrystalline AlN substrate

Worked with Aonex Technologies Inc. to develop LED structures on wafer bonded sapphire to polycrystalline AlN substrates.

Coefficient of Thermal Expansion matched.

We conclude that the 2-step growth process on the composite substrates proceeds in a similar way to growth on sapphire – similar dislocation density.

T. Pinnington, et al., J. Crystal Growth 310, 2514 (2008).

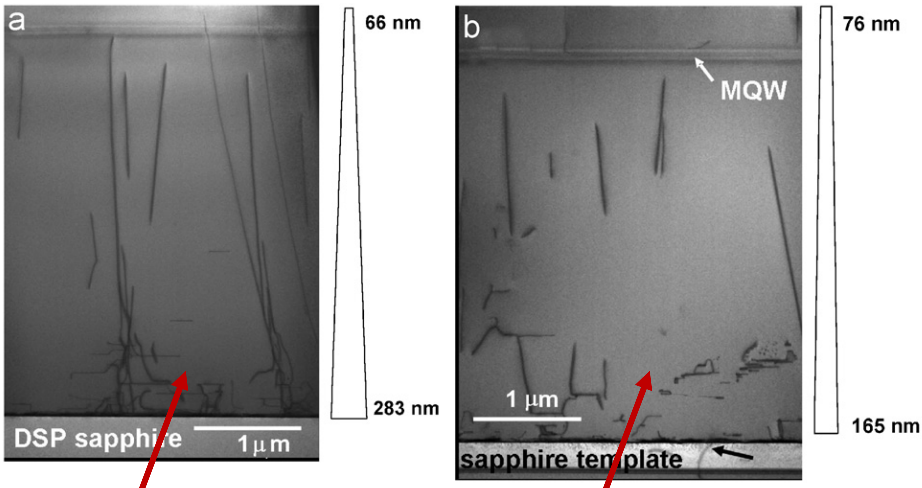


Fig 5. (a) DSP sapphire and (b) sapphire/P-AlN composite substrate. Foil thickness as determined by SEM is shown at the right of each image.

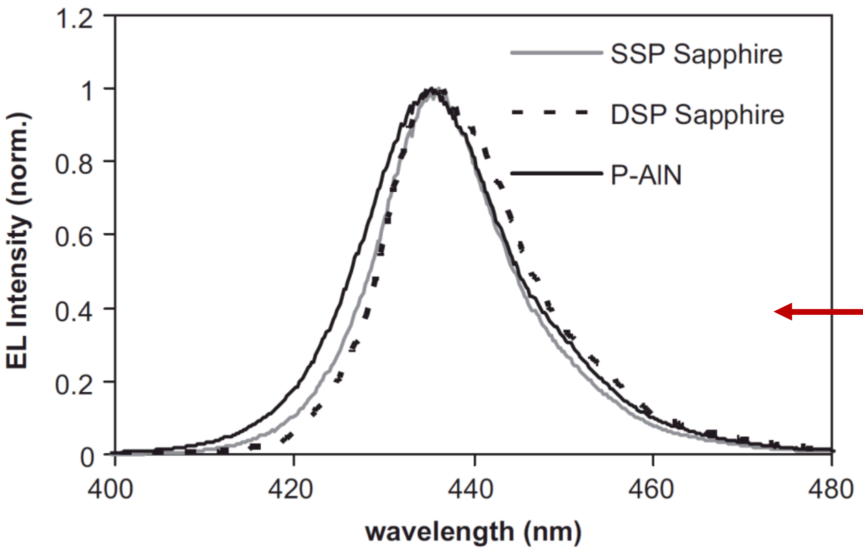


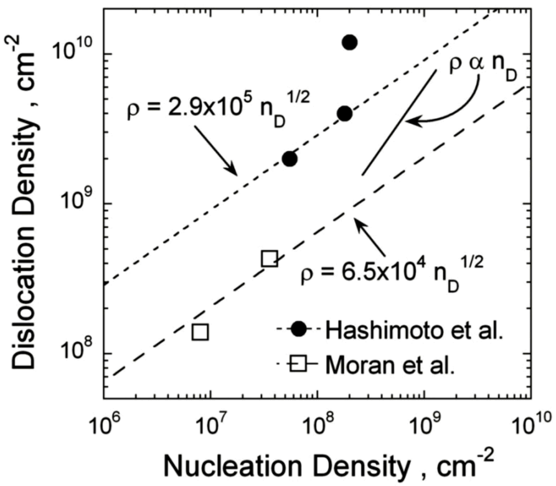
Fig. 6. Normalized electroluminescence spectra of LED structures grown on a composite sapphire/P-AlN substrate and bulk sapphire substrates show similar wavelengths near 440 nm.

Later confirmed GaN growth on GaN wafer bonded to poly-AlN – maintained low dislocation density ~ 10^6 cm^{-2}.

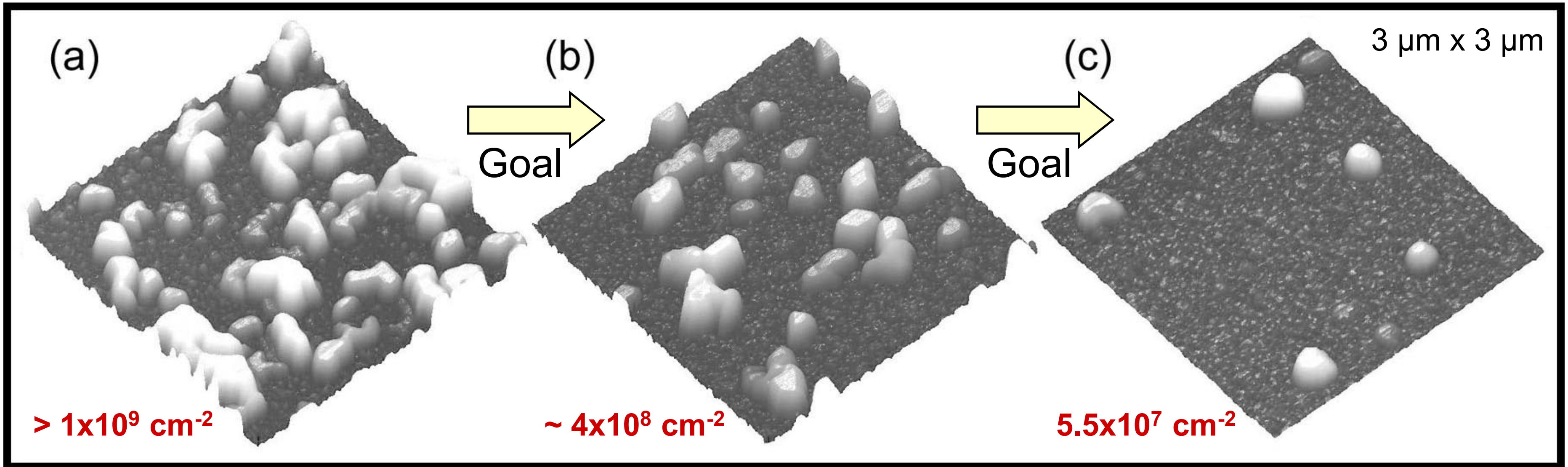
EERE/NETL program on GaN dislocation reduction on sapphire (2007 - 18 month)

- If dislocations form to accommodate grain twist and tilt, then the GaN nuclei density, n_D, should correlate with the dislocation density, ρ.

$$\rho = \text{const} \times n_D^{1/2}$$



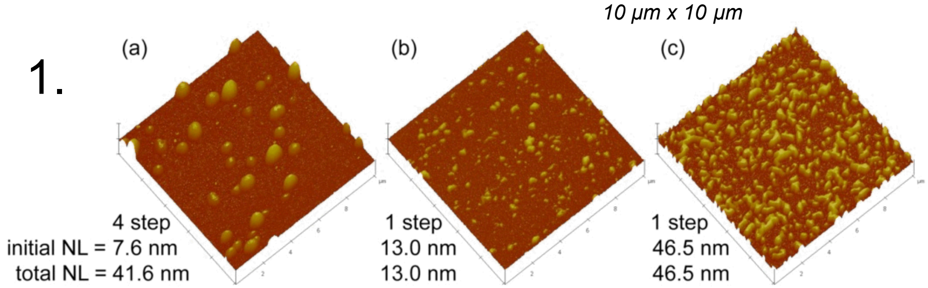
- Goal is to reduce the dislocation density of GaN films on sapphire from 5×10^8 cm^{-2} to 1×10^8 cm^{-2} by limiting the nuclei density while maintaining high lateral growth rate.



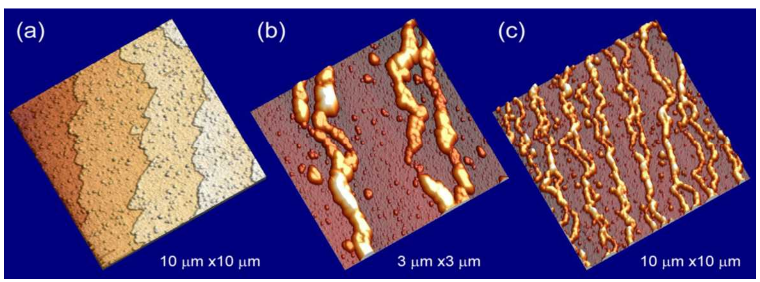
Steps taken to reduce dislocation density

1. Reduce initial NL thickness – can use multiple NL growth and annealing sequences to build up GaN grains.
2. Anneal sapphire wafers – nucleation enhanced along the step edges.
3. Silicon nitride was necessary on annealed sapphire wafers.
4. AFM used to count dislocations – achieved total dislocation densities < 1×10^{8} cm^{-2} .
5. Some issues with incomplete coalescence.

1.



2.



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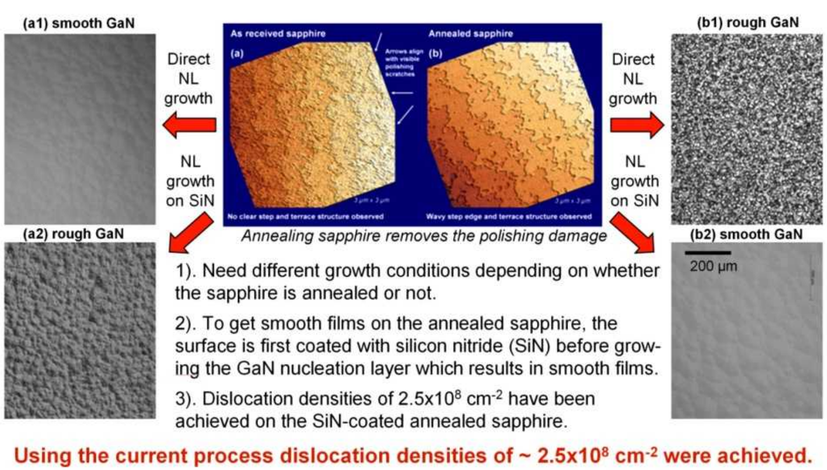
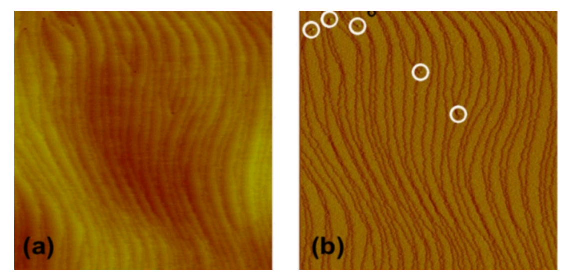
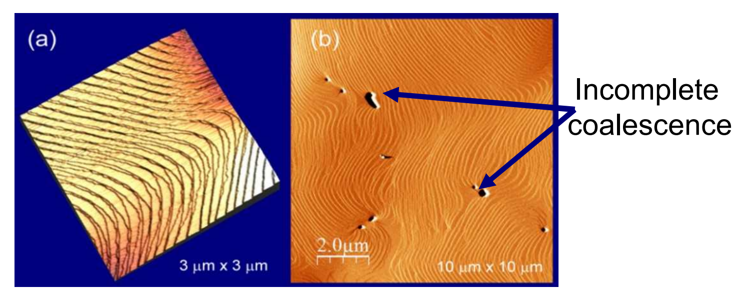


4.



3 µm x 3 µm

5.



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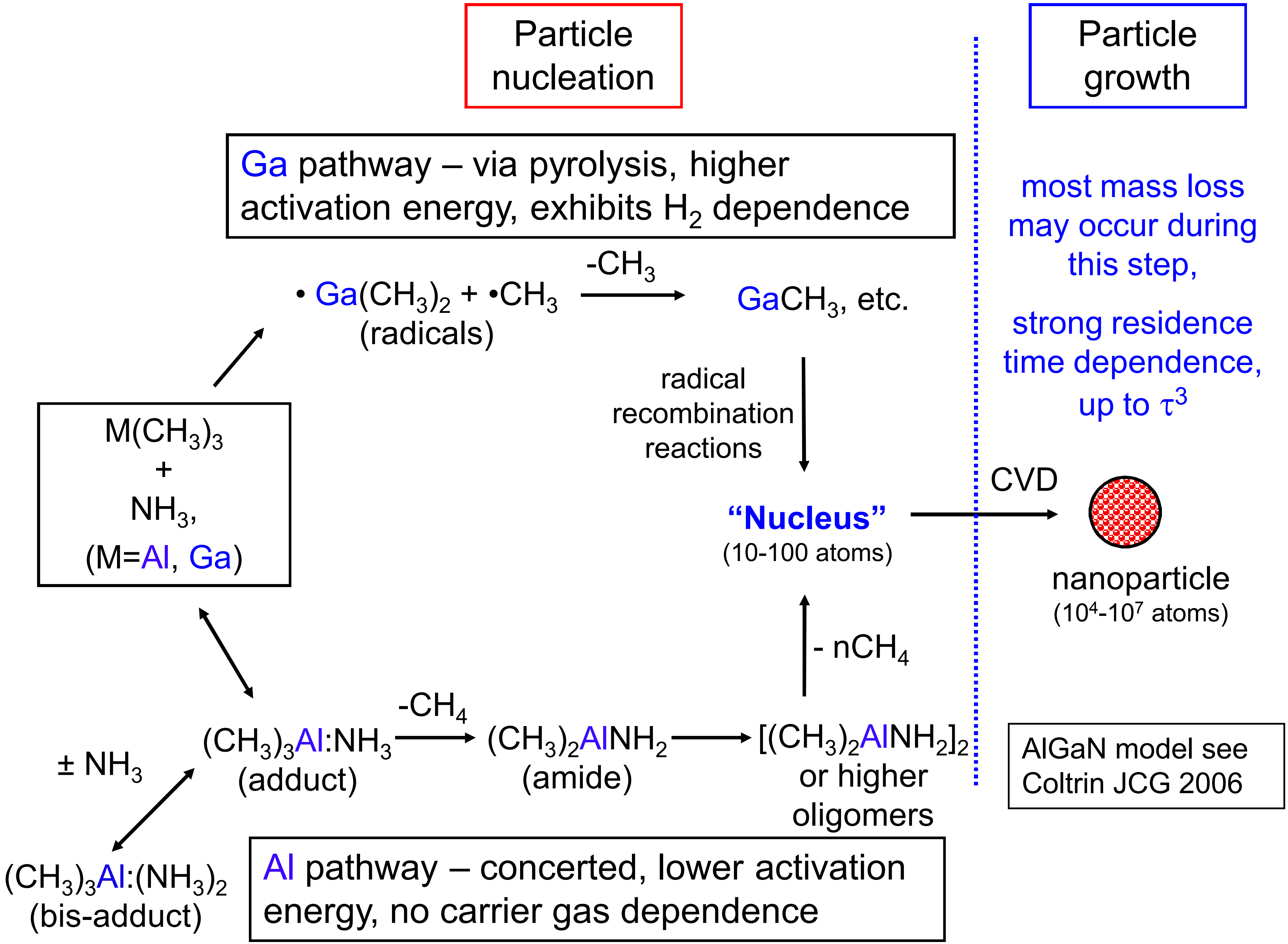
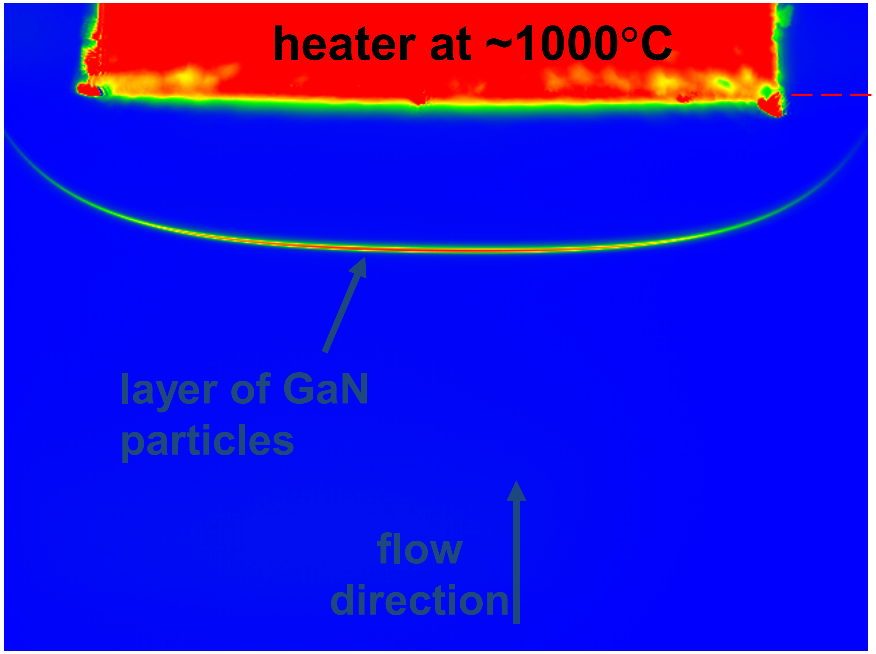


Particle nucleation
Particle growth
Ga pathway – via pyrolysis, higher activation energy, exhibits H_2 dependence
• $Ga(CH_3)_2$ + •CH_3
(radicals)
$-CH_3$
$GaCH_3$, etc.
radical recombination reactions
most mass loss may occur during this step,
strong residence time dependence, up to τ^3
$M(CH_3)_3$
+
NH_3,
(M=Al, Ga)
"Nucleus"
(10-100 atoms)
CVD
nanoparticle
(10^4-10^7 atoms)
- nCH_4
± NH_3
$(CH_3)_3Al:NH_3$
(adduct)
$-CH_4$
$(CH_3)_2AlNH_2$
(amide)
$[(CH_3)_2AlNH_2]_2$
or higher oligomers
AlGaN model see Coltrin JCG 2006
$(CH_3)_3Al:(NH_3)_2$
(bis-adduct)
Al pathway – concerted, lower activation energy, no carrier gas dependence

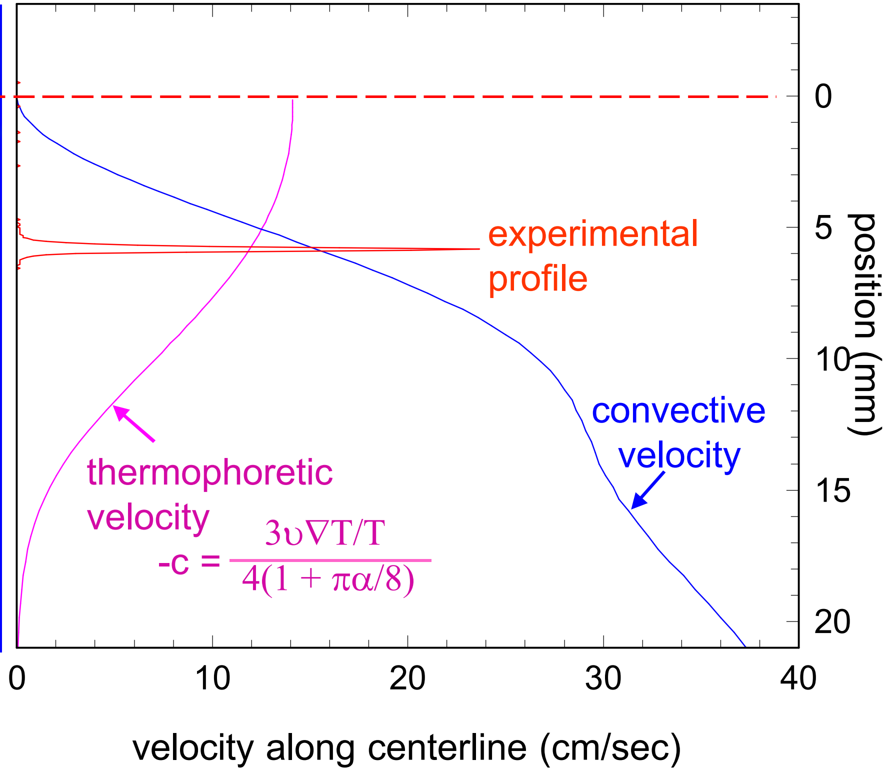
In situ laser light scattering reveals nanoparticles during GaN, AlN, and InN MOCVD

Inverted stagnation point flow (SPF) reactor



Nanoparticles are well within the thermal boundary layer, residing at temperatures of 600-700°C

The calculated particle position (thermophoretic force = -viscous force) agrees well with experiment



AlN particles are 35-50 nm in diameter (APL 2002)

Summary/Significance of III-N chemistry studies

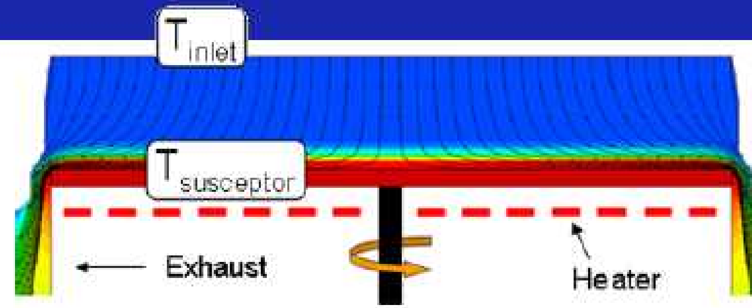
- Nucleation and growth of nanoparticles is the fundamental mechanism for loss of group-III flux during GaN, AlN, and AlGaN MOCVD
- Most parasitic chemistry requires high temperatures, occurs in the boundary layer
- Our MOCVD model with a particle nucleation and growth mechanism (via approximations) reproduces most experimental observations for GaN/AlGaN (Coltrin JCG2006)

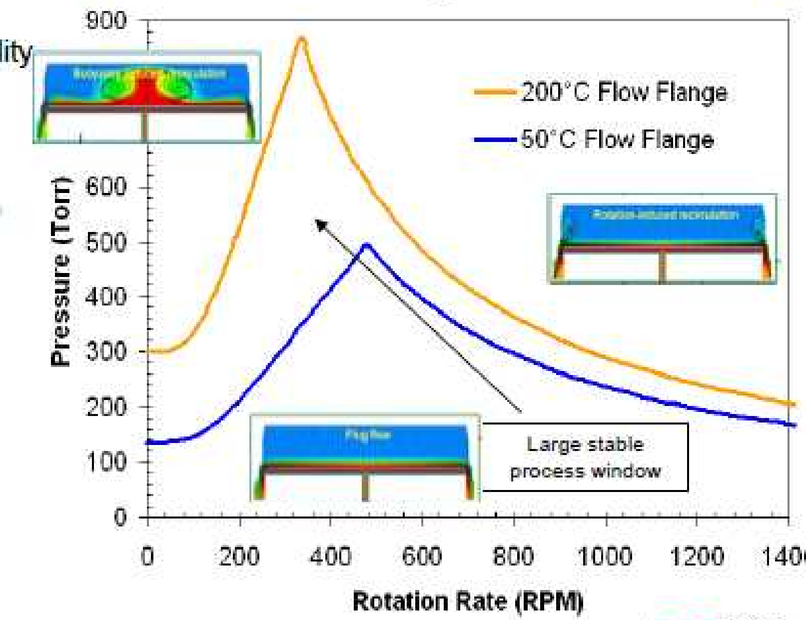
(mostly for flow stability reasons) Veeco has developed a heated flow flange (T_{inlet} ~200°C) for their K465i system

10.0 Heated Flow Flange – Benefits

Greater gas inlet temperature (T_{inlet}):

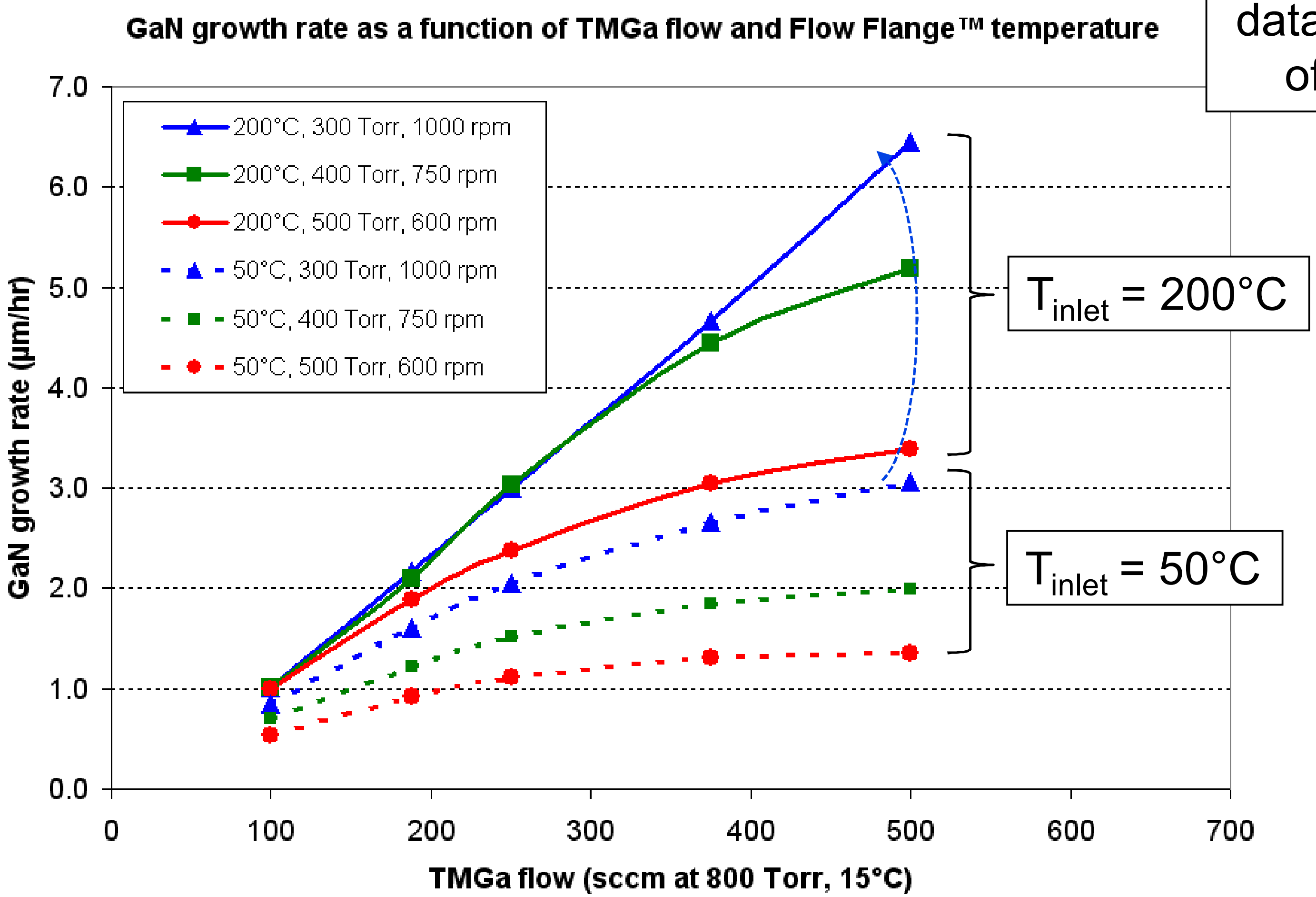
- Reduces buoyancy forces
  - *Smaller vertical temperature gradients*
- Increases the stable process window
  - Higher pressure / lower rotation rate capability
  - Improved hydride efficiency
- Reduced parasitic particulate formation (?)
  - Contrary to technical understanding
- More uniform wafer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



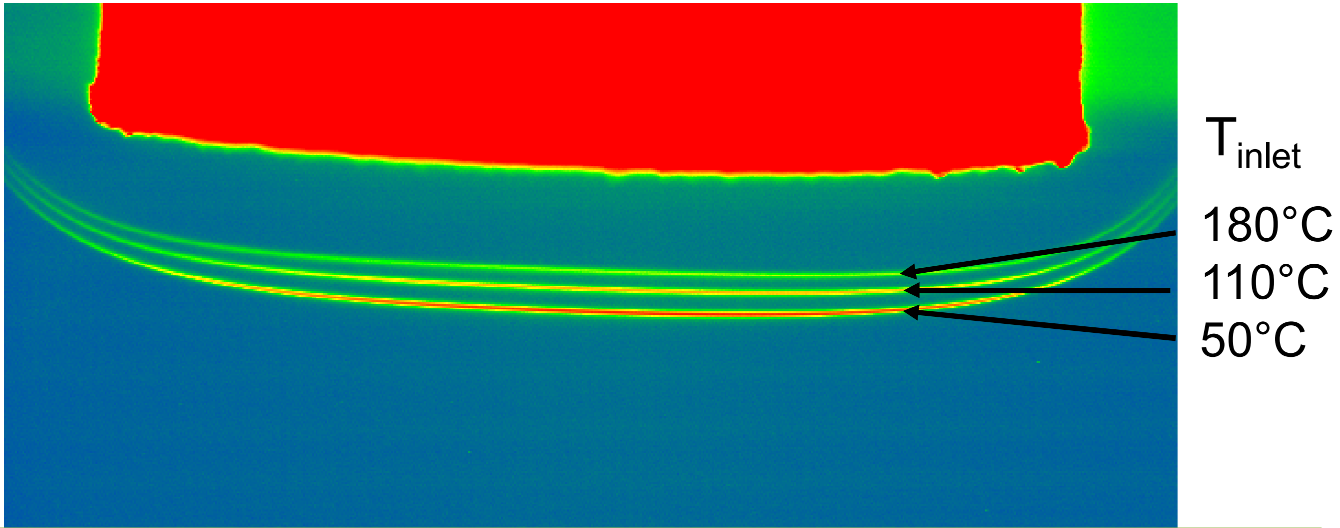


Growth rates exhibit an unexpected dependence on inlet temperature

data courtesy of Veeco



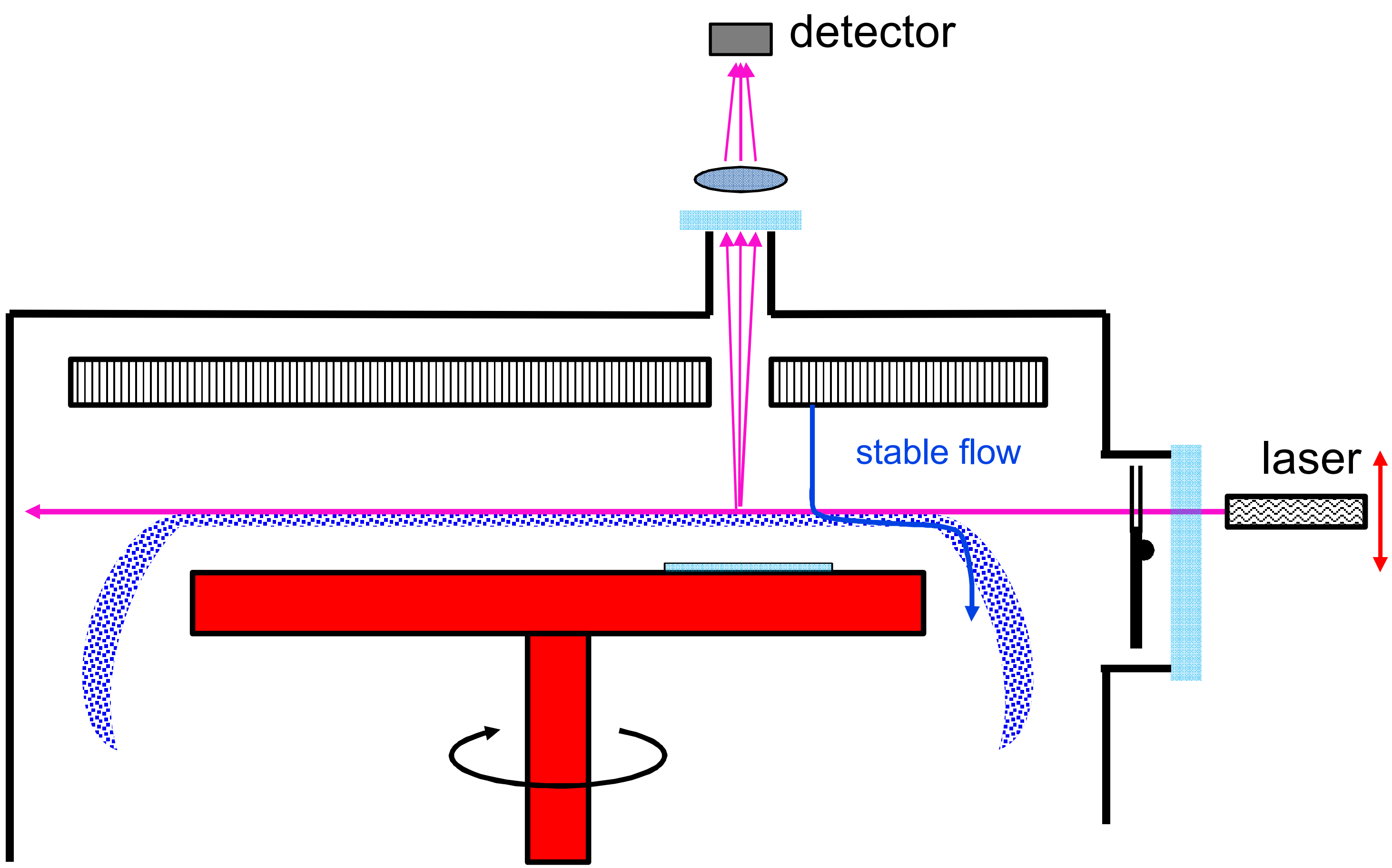
As inlet Temperature is raised, layer of particles gets closer to hot surface and scattering intensity drops



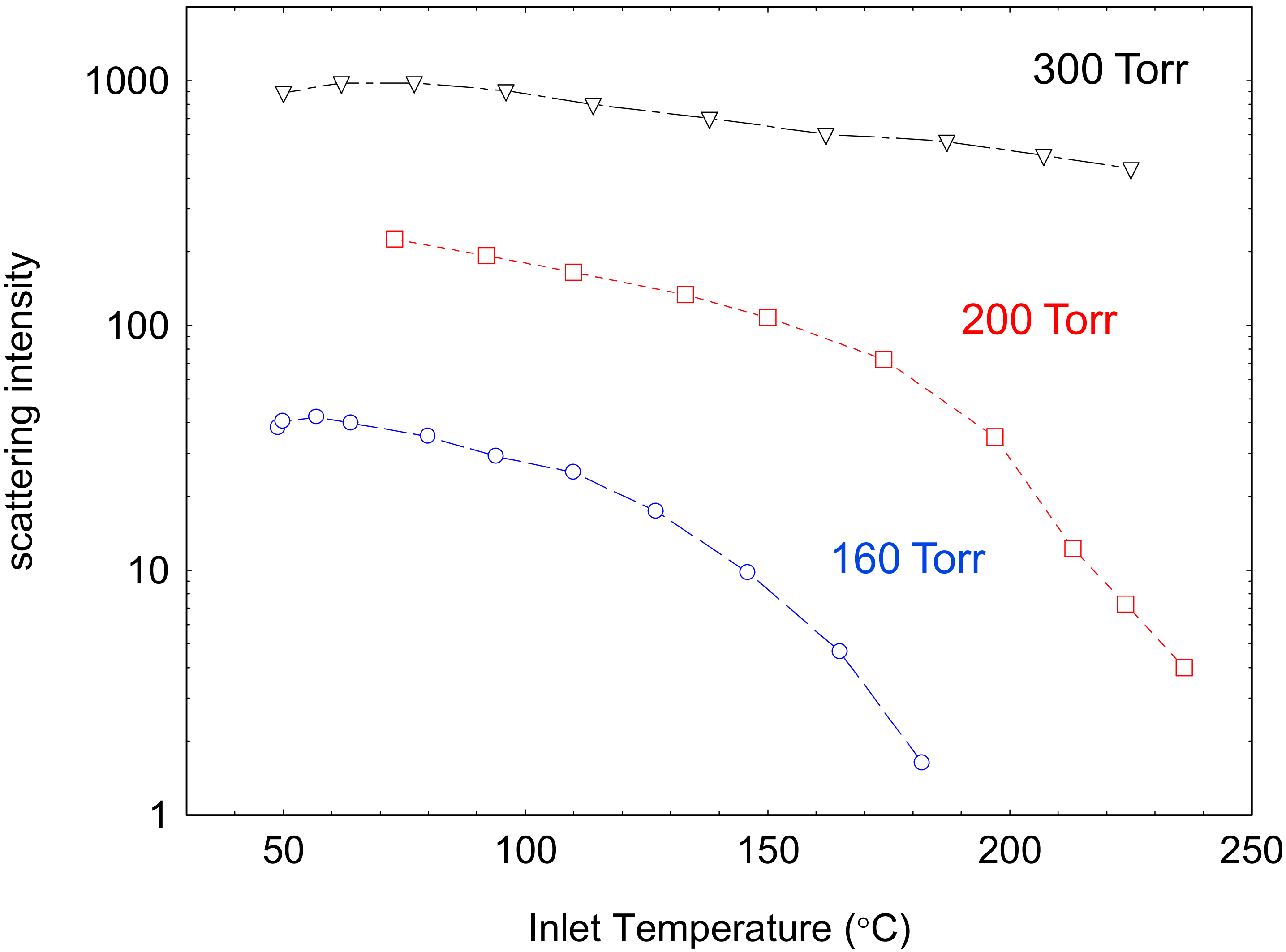
1) Shift in position towards hot surface expected from reduction in thermophoretic force
2) The intensity trend agrees qualitatively with Veeco MOCVD growth rate results

Fewer particles = higher growth rate

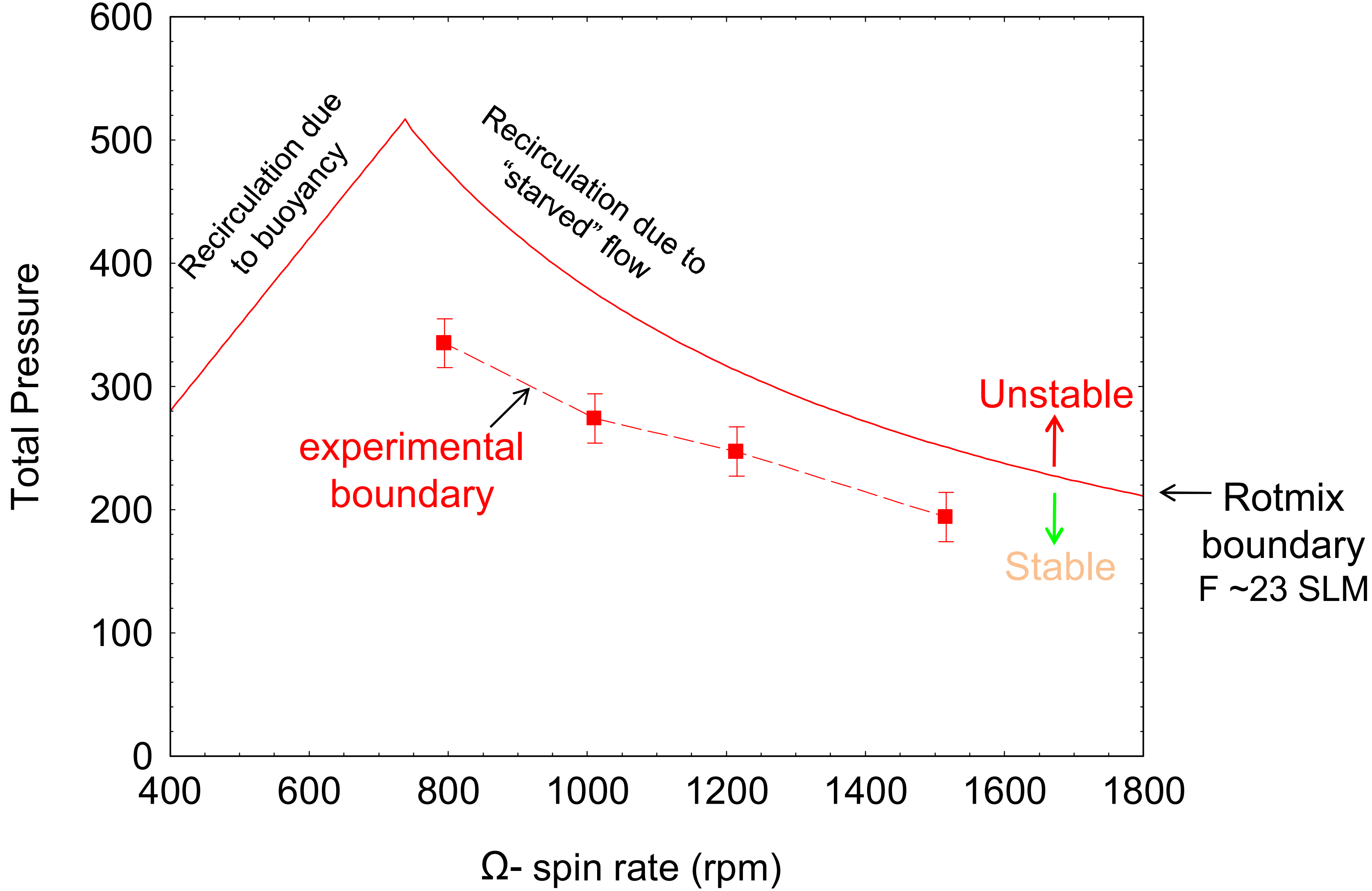
Schematic of light scattering in Veeco D-125 RDR at stable flow conditions



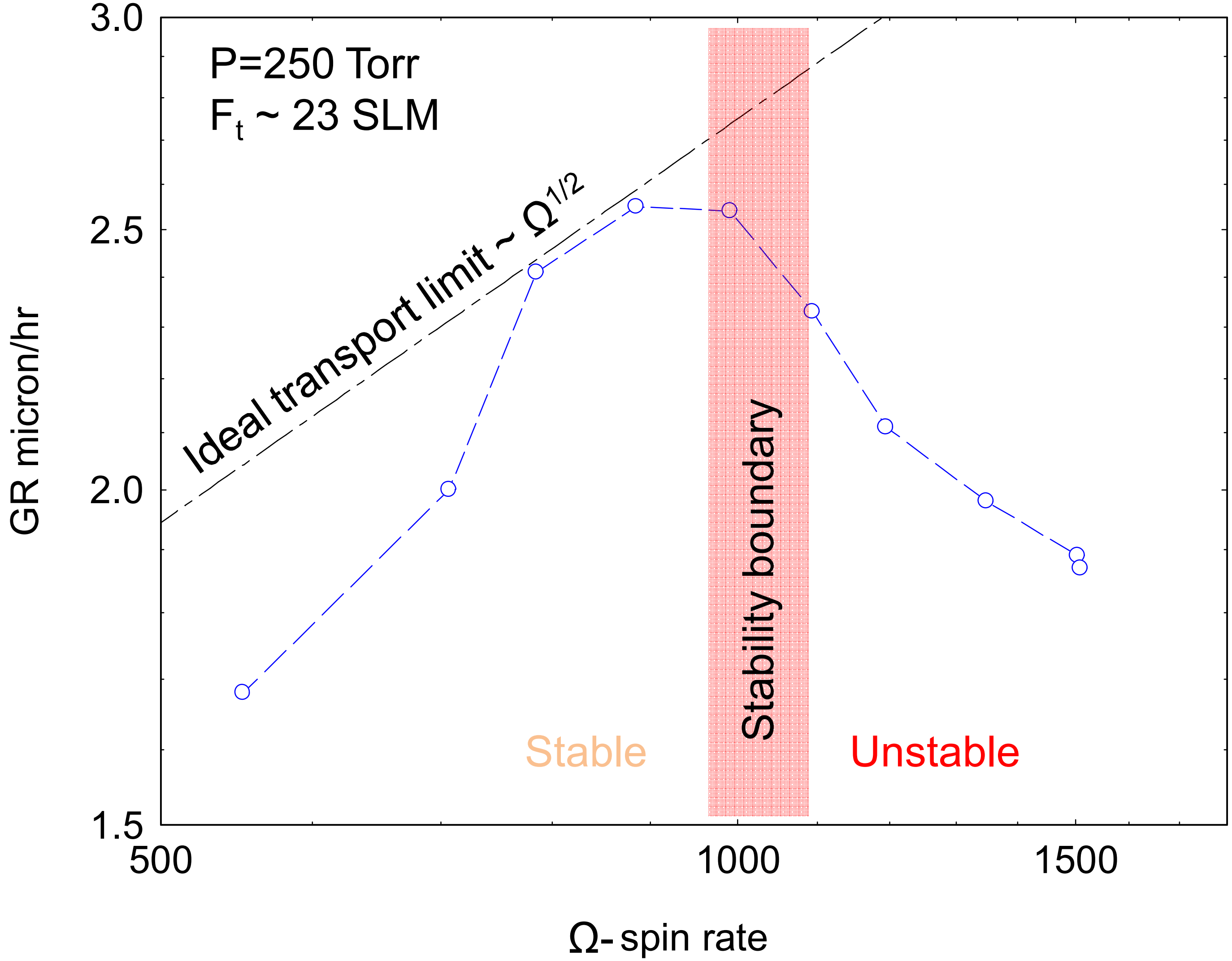
Depending on conditions, the response to a 200ºC rise in inlet temperature can be modest (~3X) or significant (>50X)



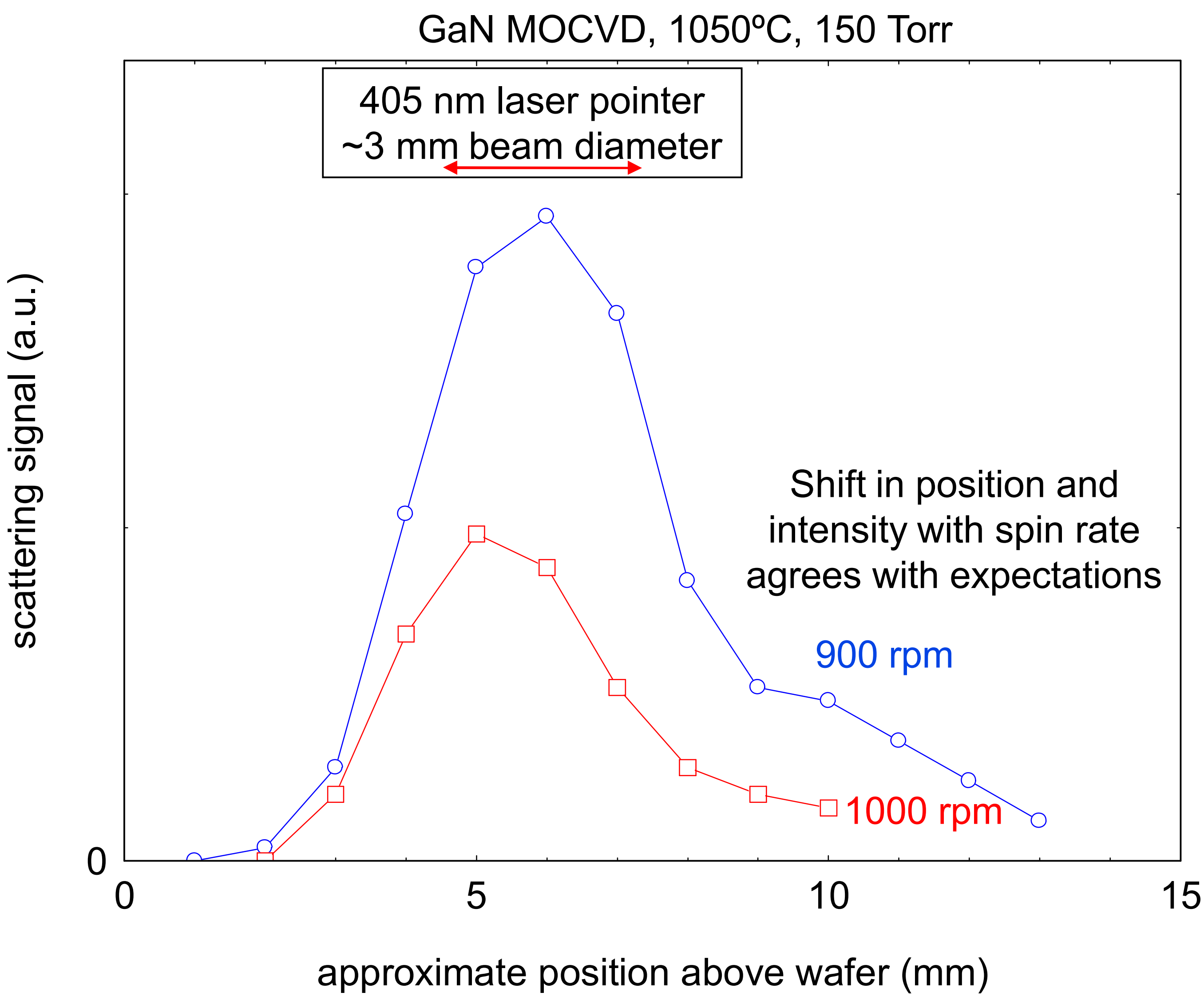
Experimental stability boundary exhibits approximate ~1/Ω dependence, but occurs at pressures somewhat lower than predicted



GaN MOCVD growth rate peaks near the stability boundary, drops rapidly at unstable conditions



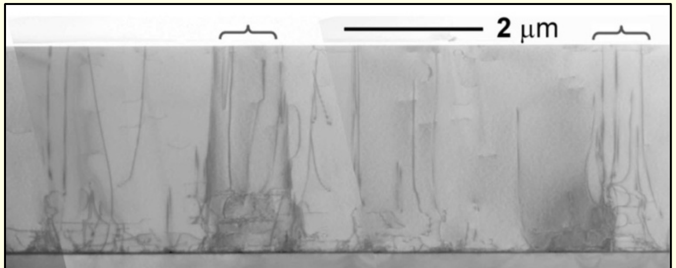
“Proof-of-concept” results; light-scattering from particles under “stable” flow conditions



Topics for Discussion

- Current SSL programs at Sandia
- Heteroepitaxy studies – GaN on …
- MOCVD reactor chemistry
- InGaN growth related to improving LED brightness
- Semipolar GaN growth – brighter green?

With high dislocation density, how can InGaN LEDs be so bright?



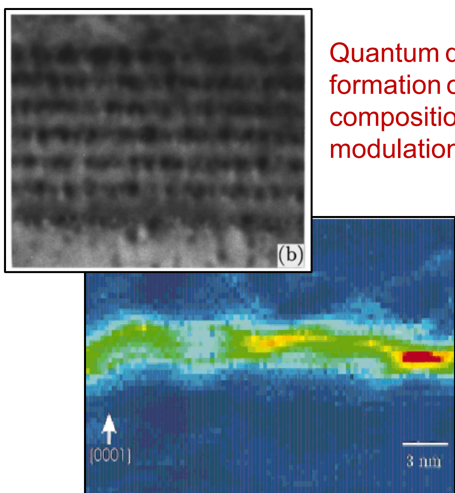
TEM courtesy of D. M. Follstaedt

- High brightness LEDs are typically grown on high dislocation density GaN (10^9 cm^{-2}).
- With this large dislocation density LEDs in the other III-V materials would not work.

Are dislocations nonradiative recombination sites?

High efficiency suggests some type of carrier localization; the exact nature of which is unknown!

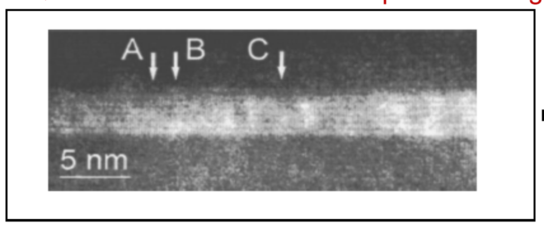
Narukawa, APL 70, 981 (1997)

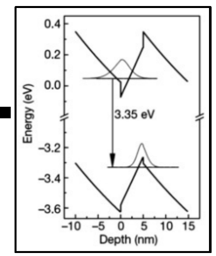


Quantum dot formation or compositional modulation

Gerthsen, Phys. Stat. A Sol. 177, 145 (2000).

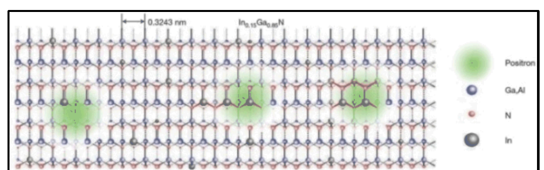
QW thickness fluctuations coupled to strong piezoelectric fields



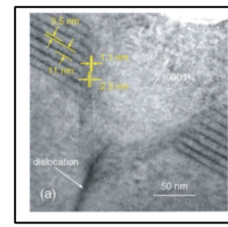


Graham, JAP 97, 103508 (2005)

Holes localized at In-N valence states, followed by exciton formation and light emission.

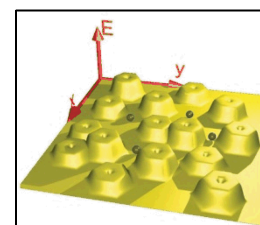


Chichibu, Nat. Mat. 5, 810 (2006)



Thinner QWs around v-defects

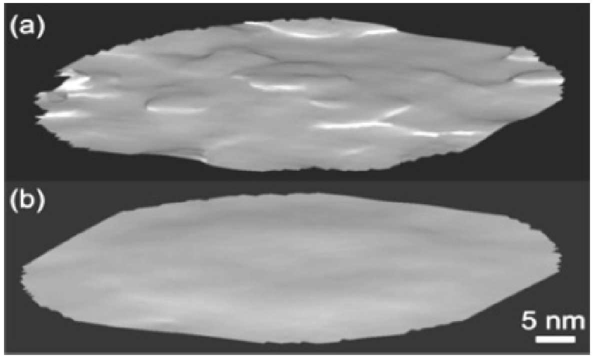
Energetic screening around dislocations



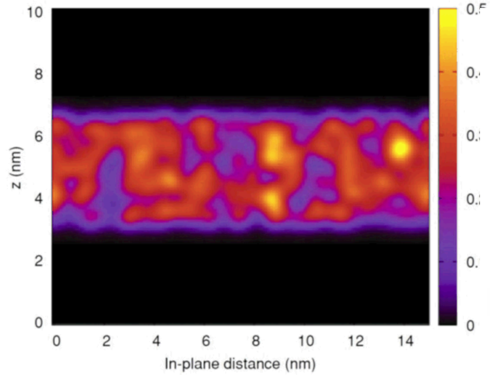
Hangleiter, PRL 95, 127402 (2005).

InGaN morphology may influence localization

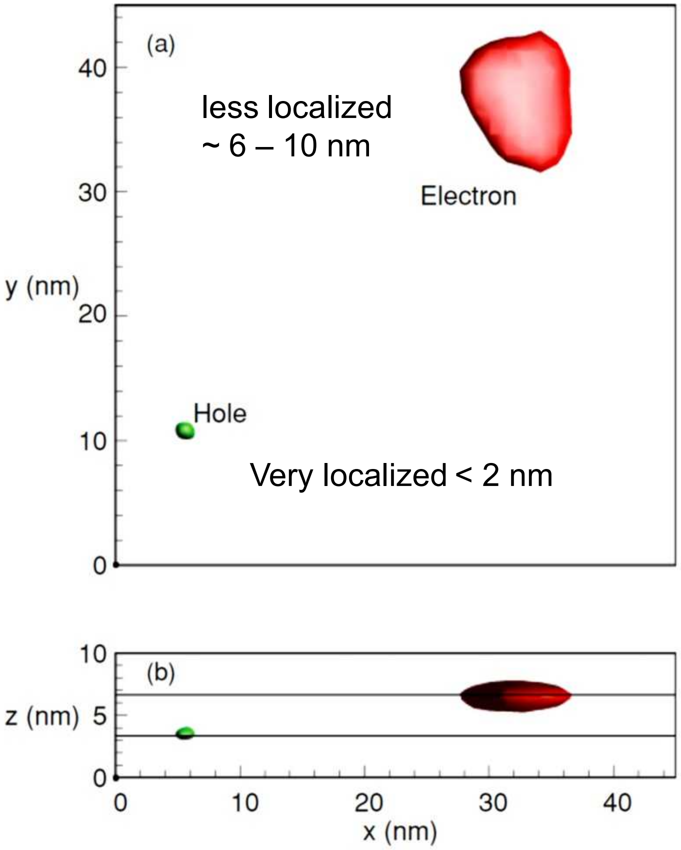
Watson-Parris, et al., Phys. Rev B ***83, 115321 (2011)***



An isoconcentration surface based on APT data illustrating the roughness of the lower and upper interface of an InGaN QW.



Indium fraction in a 3 nm thick QW with an average indium concentration of 25%.



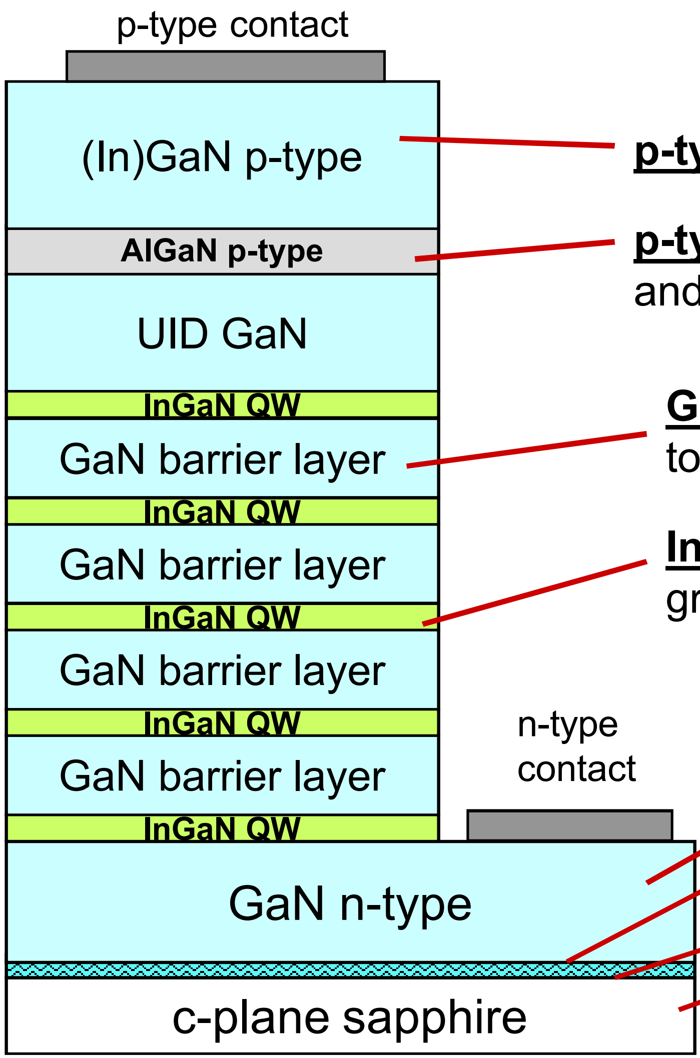
The calculated ground state probability density of an electron (red) and a hole (green).

Random fluctuations in alloy concentrations sufficient to localize carriers.

Holes strongly localized in regions of higher indium content.

Electrons are more strongly localized by mono-layer well width fluctuations.

Typical LED structure and growth procedure



During growth changes in temperature, gas flows, molar flow rates, and pressure

p-type GaN grown at same temperature as electron block.

p-type AlGaN electron block grown at ~ 970 °C for blue and 930 °C for green – add H_2, 200 torr.

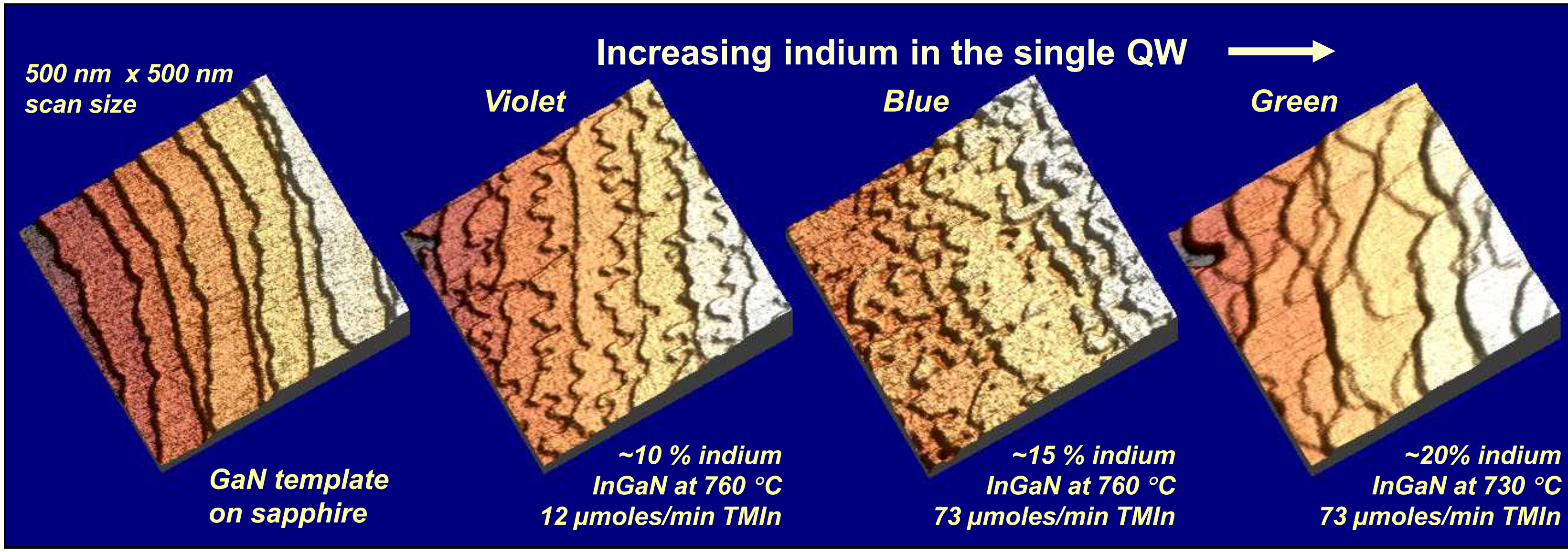
GaN barrier raise temperature to 850 °C then back down to QW growth temperature.

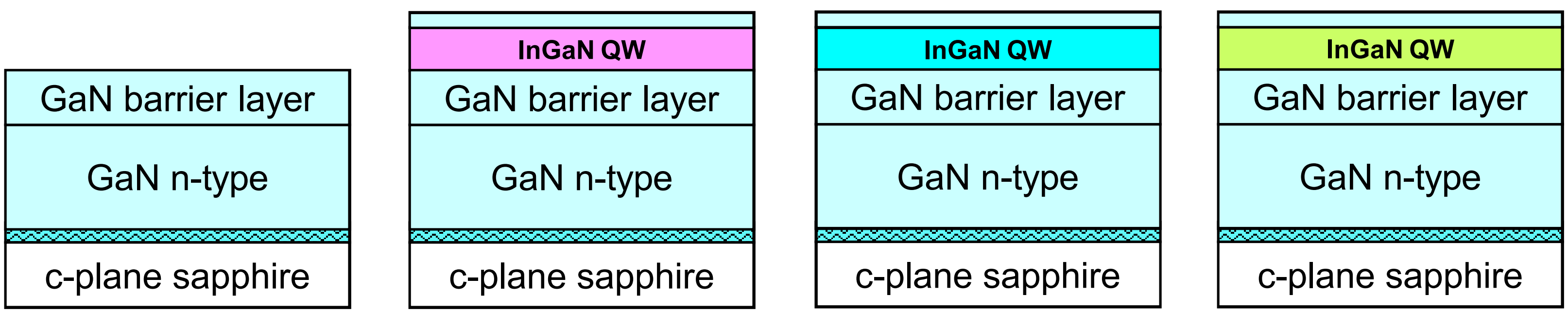
InGaN QW growth at 760 °C for blue and 730 °C for green LEDs – use only N_2 and NH_3, 300 torr.

GaN bulk on top of annealed NL.
Heat NL to 1050 °C in NH_3, H_2, and N_2.

GaN nucleation layer at 530 °C, 500 torr.
Anneal sapphire in H_2 to 1050 °C.

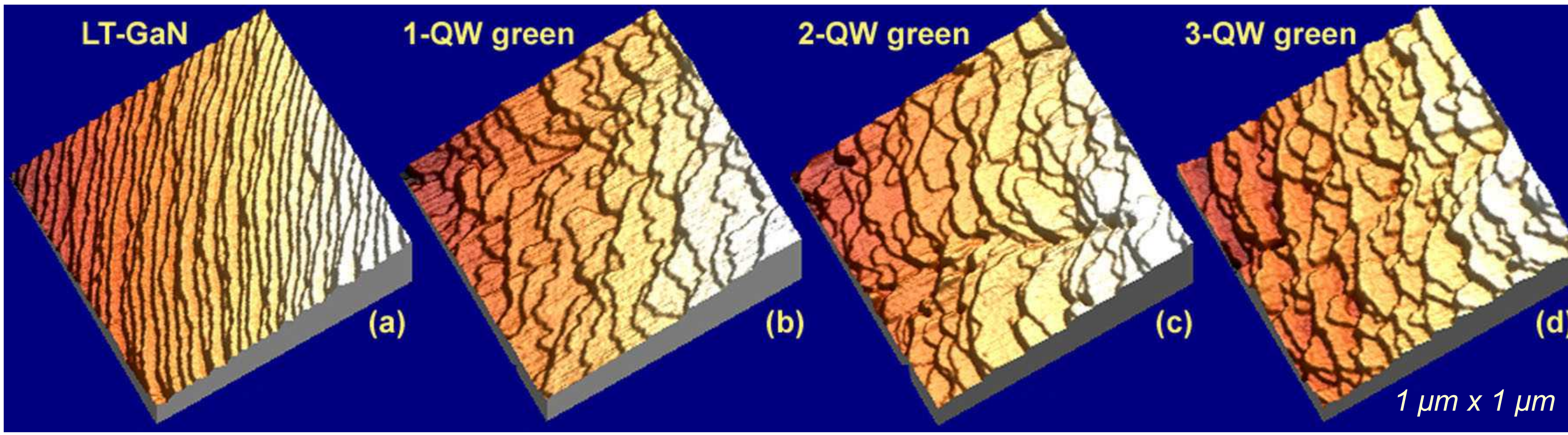
Increased indium in single QWs increases multi-layer steps



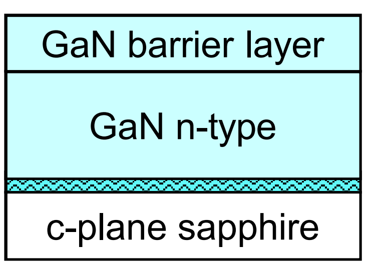


The multiple-layer step density increases as the indium incorporation increases

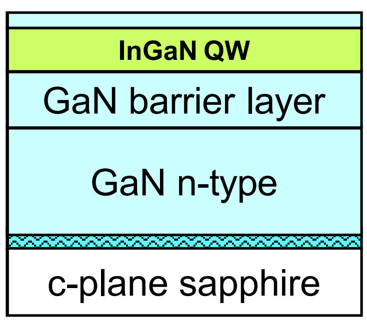
Observation of increased multi-layer steps in green MQWs

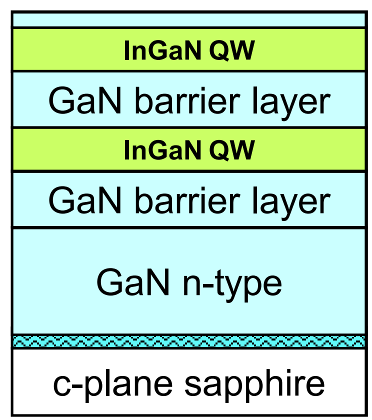


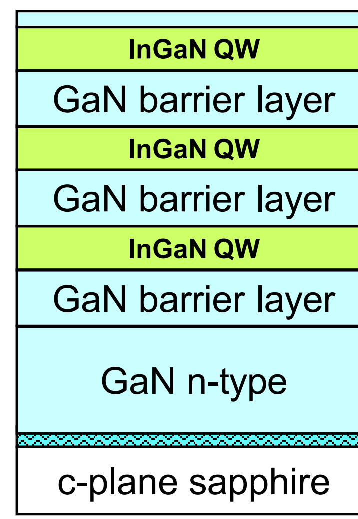
10 nm thick LT GaN barrier layer has the same step structure as the underlying HT GaN.



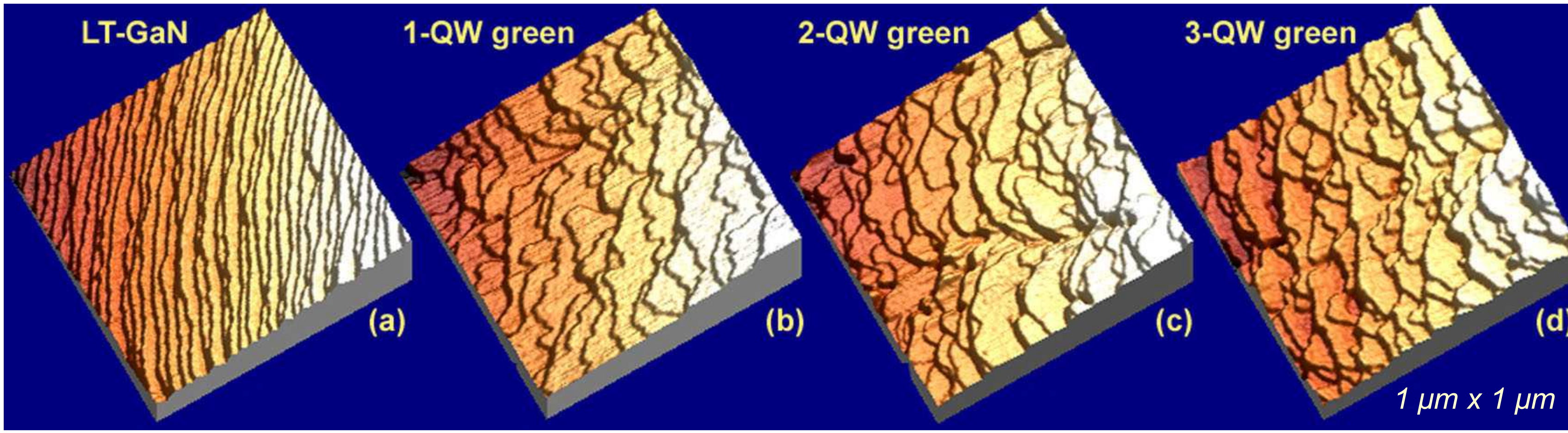
Addition of single 3 nm InGaN QW capped with 1.5 GaN barrier layer

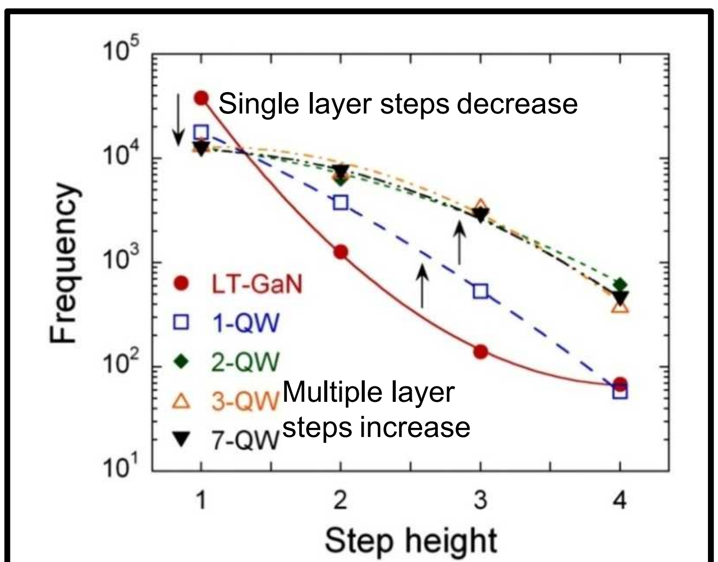






Observation of increased multi-layer steps in green MQWs





As the number of QWs increases the number of multiple layer steps increases, but reaches a steady configuration after the 2nd QW.

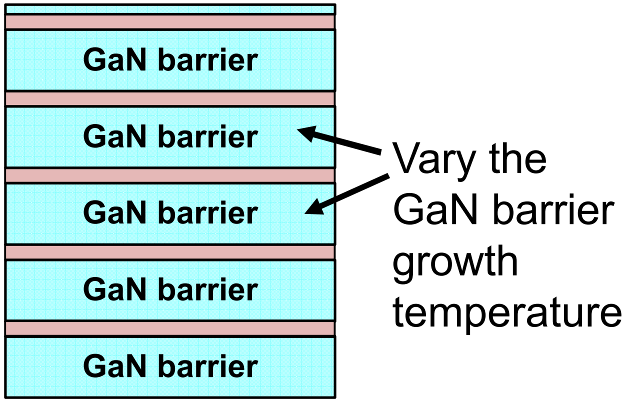
Suggests that while the InGaN QWs roughen the surface, the GaN barrier layer smooth the surface.

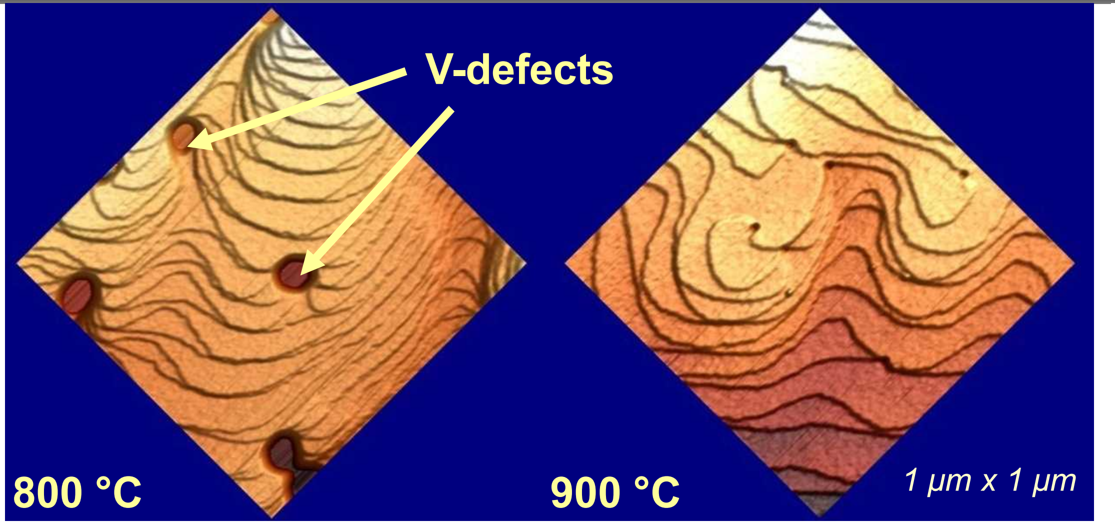
What are the smoothing mechanisms?

GaN barrier growth temperature can be used to control step morphology

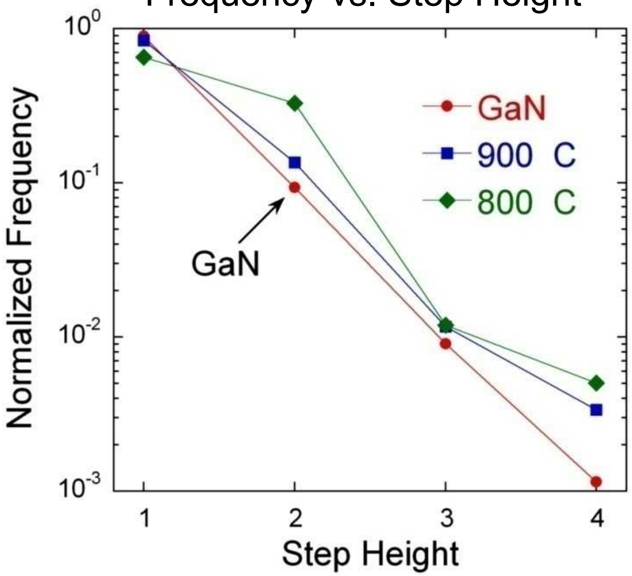
Vary the GaN barrier temperature, keep green QW growth conditions the same.

MQW sample structure





Frequency vs. Step Height



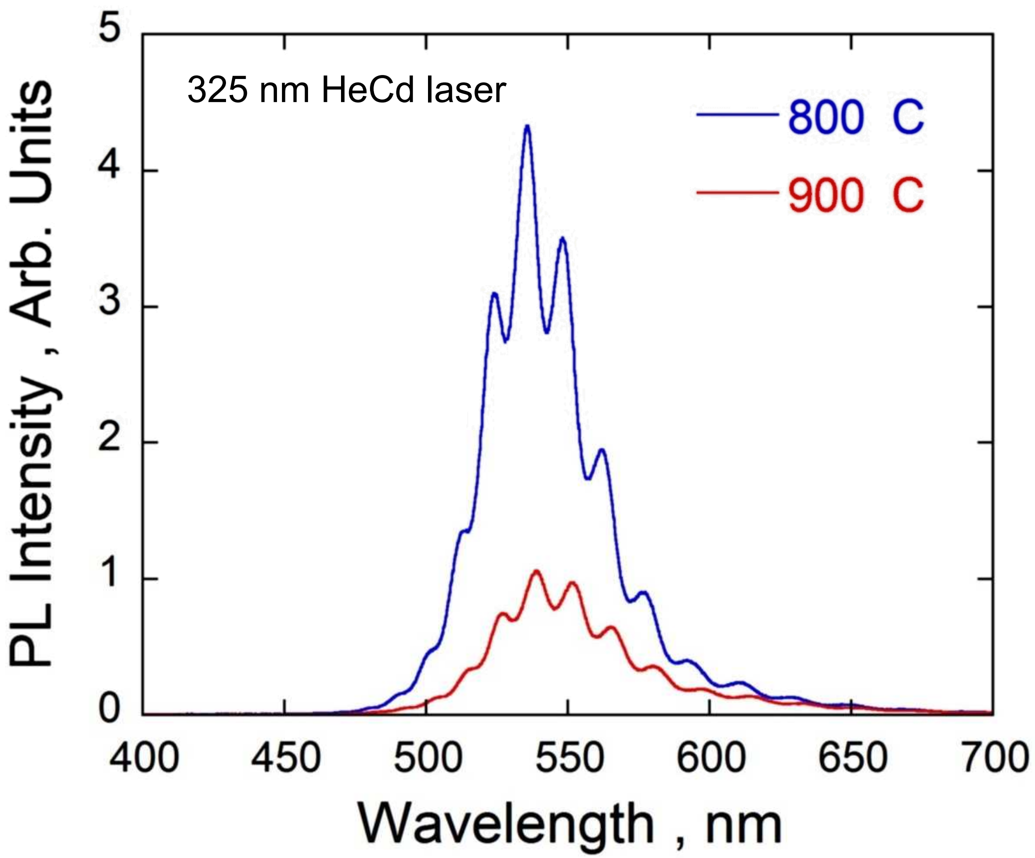
Increased number of double layer steps at 800 °C compared to 900 °C.

The 900 ºC step height frequency distribution is closer to the starting GaN template than 800 ºC.

Implies - higher temperature GaN growth can be used to control the step height frequency and increase the surface smoothness.

PL analysis of the green MQWs with different GaN barrier growth temperature

Higher PL intensity for GaN barriers at 800 ºC



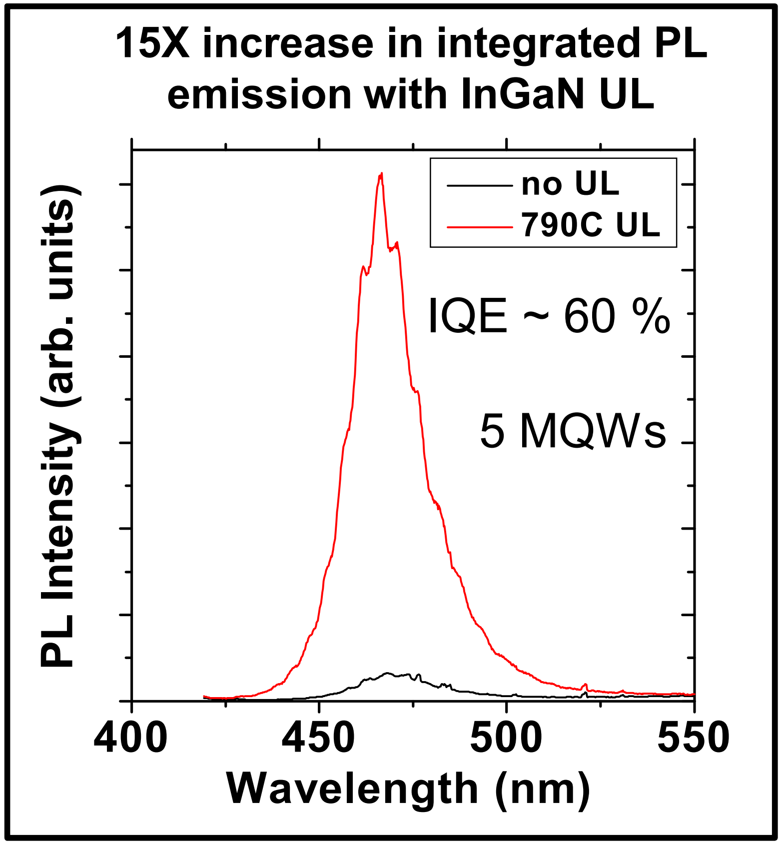
Same intensity and wave-length trends are observed for resonant optical pumping at 407 nm.

Suggests that the rougher step morphology produces QW with increased PL intensity.

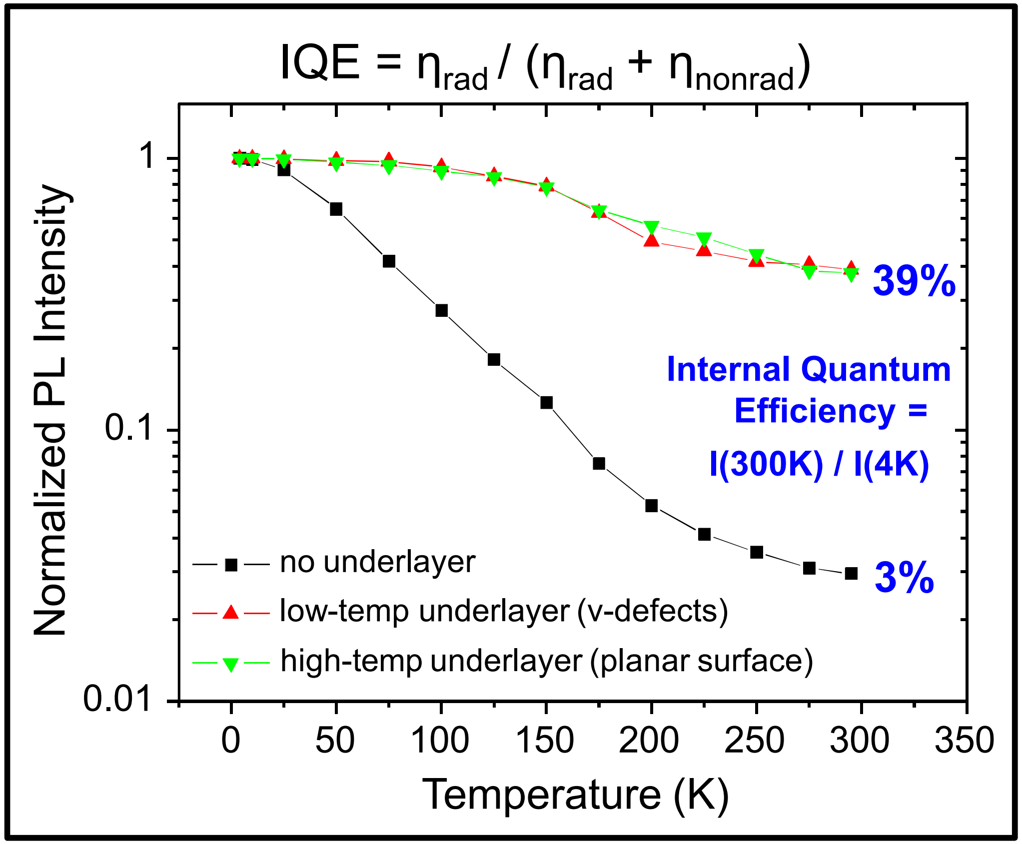
The morphology could produce QW thickness fluctuations coupled to the strong piezo-electric fields to produce electron/hole localization. Graham et al., JAP 97, 103508 (2005).

InGaN underlayers increase IQE of MQWs

Especially help emission of single QWs



Temperature dependent PL studies by Mary Crawford



Underlayers enhance efficiency compared to same MQW with no underlayer.

Optimal MQW growth conditions

- InGaN underlayers
  – 2-3% indium, 850- 880 °C, ~ 200 nm thick
- InGaN QWs growth
  – High temperature – high indium flow
  – indium incorporation limited by indium desorption
- Vary GaN barrier growth temperature
  – Least influence on 440 nm, most influence on 530 nm

Have achieved IQE of 60 % for 440 nm MQWs

Topics for Discussion

- Current SSL programs at Sandia
- Heteroepitaxy studies – GaN on sapphire
- MOCVD reactor chemistry
- InGaN growth related to improving LED brightness
- Semipolar GaN growth – brighter green?

Semi-polar GaN Materials Technology for High IQE Green LEDs

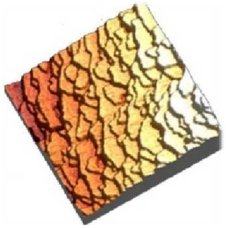
<u>Overall Goal</u>: Fabricate a 540 nm LED with an IQE of 50%.

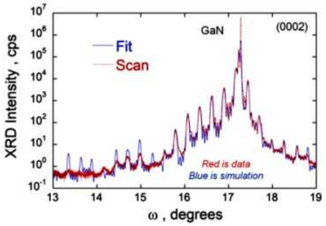
The proposed work relates to subtask A.1.2 of MYPP(Emitter materials research) which encourages the development of highly-efficient green and red emitters to greatly improve the efficiency of color-mixing LED packages.

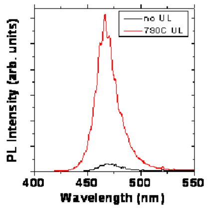
Metric(s)	2009 Status(s)	2020 Target(s)
Internal Quantum Efficiency (IQE) @ 35 A/cm2	80% (Blue) 40% (Green) ← Focus 75% (Red) ← Focus	90% (Blue, Green, Red)
External Quantum Efficiency (EQE) @ 35 A/cm2	64% (Blue) 30% (Green) 38% (Red)	81% (Blue, Green, Red)

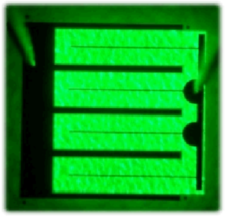
<u>Process</u>: Explore m-plane and semipolar GaN orientations to determine which orientations produce the highest indium incorporation (longest wavelength) and highest IQE.

substrates from



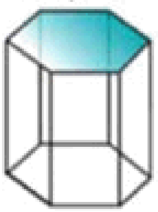


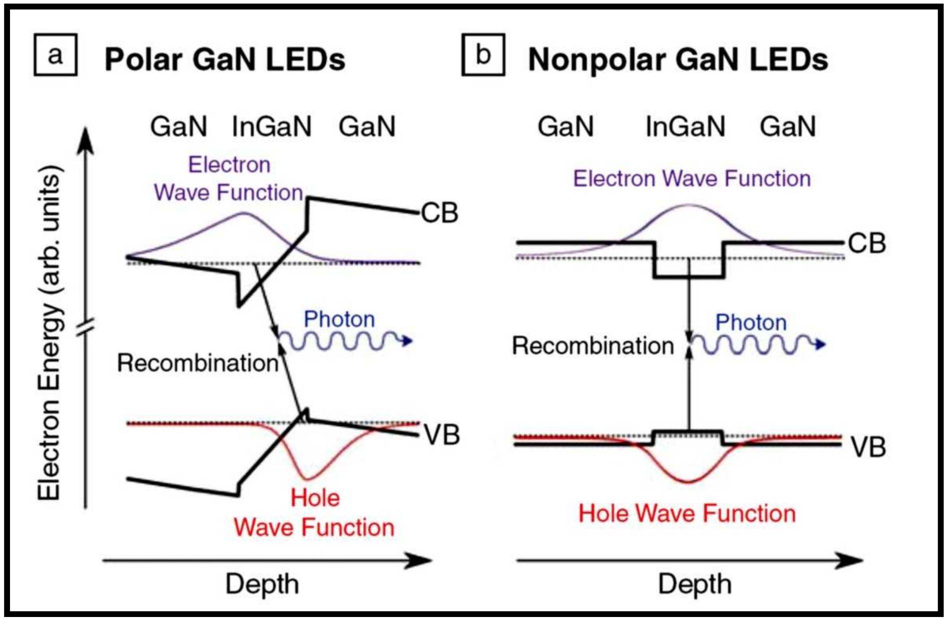


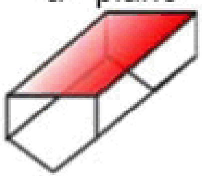


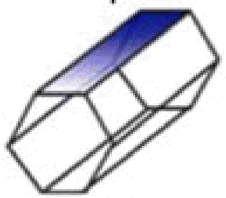
Why nonpolar or semipolar GaN?

From Speck and Chichibu, MRS BULLETIN 34, 304, (2009)









For Polar

- Electron and hole wavefunction spatial separation reduces likelihood of radiative recombination. Nonpolar – no spatial separation – better wavefunction overlap.

- The carrier confinement and the electron and hole wavefunction separation can be balanced if QW is ~25 Å – high carrier density. Nonpolar – can make the QWs thicker - lower carrier density.

- EL blue shift due to energy tail states caused by thickness fluctuations in the QWs grown at low temperature – efficiency droop? Nonpolar – might still have these thickness fluctuations.

No QCSE on nonpolar so need to incorporate more indium achieve similar wavelengths

Possibly higher indium incorporation on semipolar GaN

On c-plane GaN, indium is limited to ~ 22%.

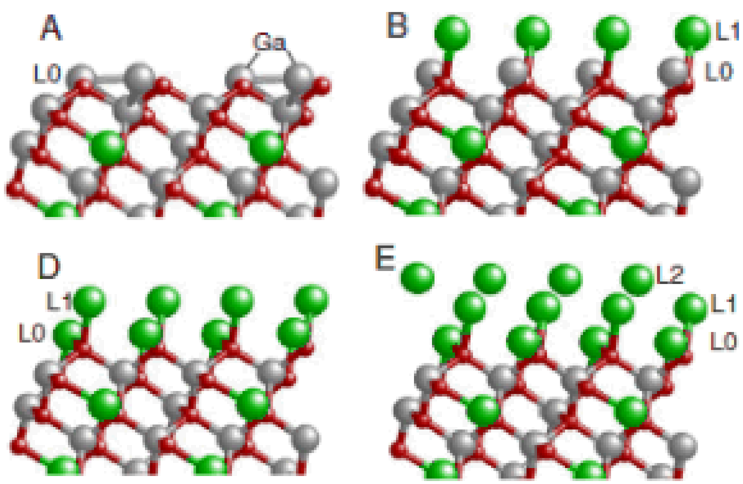


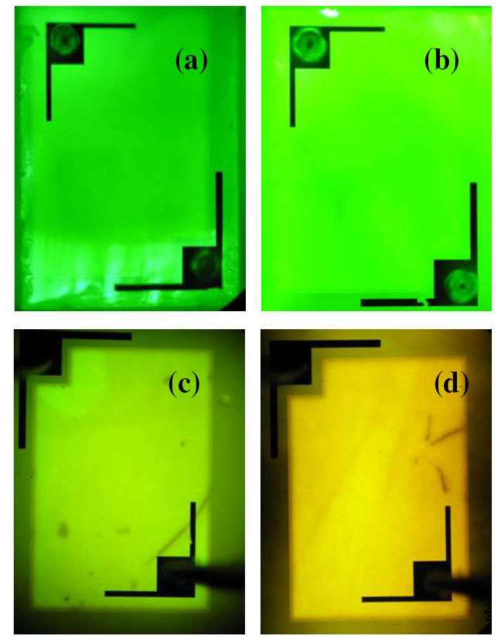
FIG. 3. (Color online) InGaN(11$\bar{2}$2) surfaces. A, B, D, and E contain successively more In atoms in layers L0, L1, and L2. Indium atoms are large green spheres, Ga atoms are gray, and N atoms are small red spheres.

J. E. Northrup, Appl. Phys. Lett. 95, 133107 (2009).

Recent DFT calculations predict greater indium incorporation on GaN (11-22) compared to GaN (10-11) due to reduced strain between the surface incorporated indium atoms.

Implies that higher indium concentrations > 22% can be achieved leading to yellow and longer wavelength LEDs.

Fellows et al., JJAP 47, 7854 (2008).



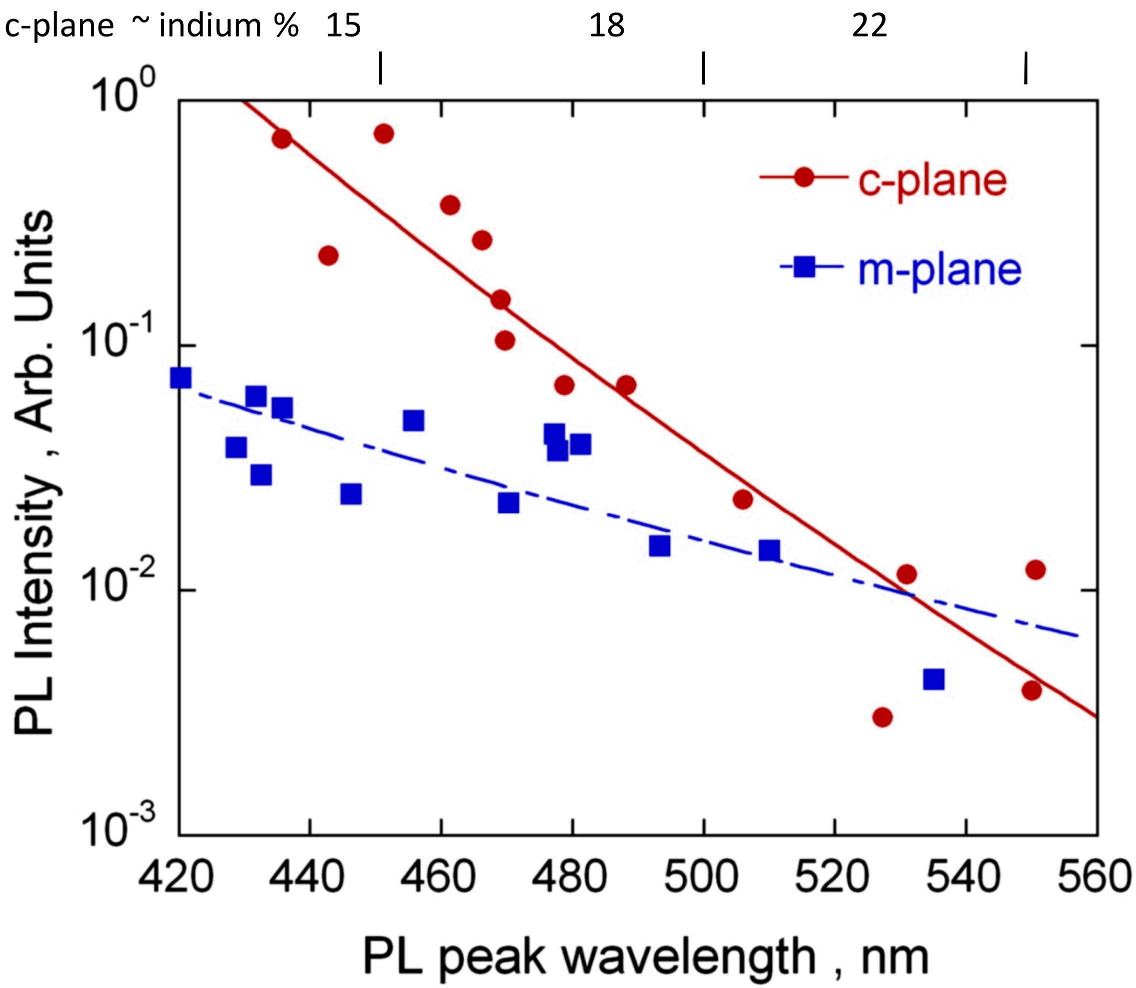
(11$\bar{2}$2)

λ = 568 nm
EQE = 8.0%

LEDs shown at 1 mA forward bias

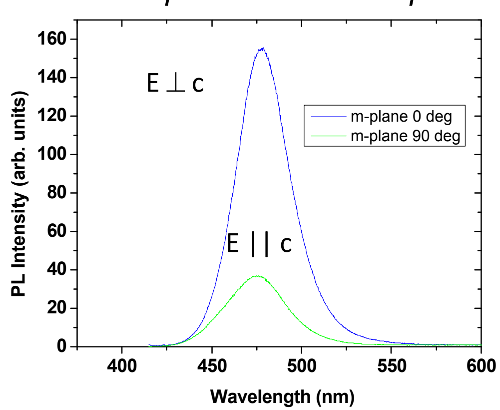
Since there is minimal QCSE, there has to be ~ 40% indium concentration in the QW to reach these wavelengths.

Comparison of MQWs on c- and m-plane GaN



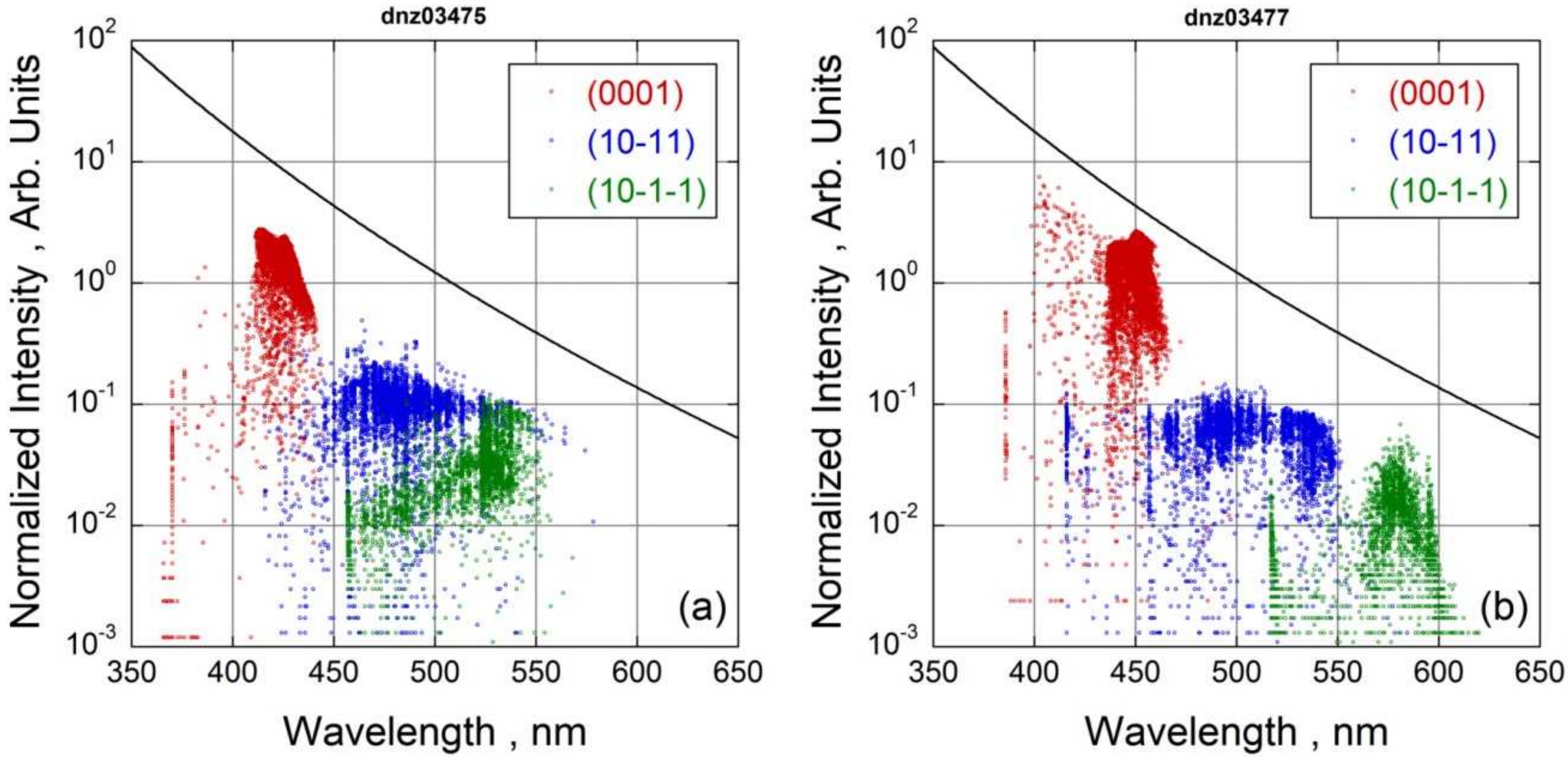
- The PL intensity of MQWs on c-plane decreases more as the wavelength increases compared to m-plane.
- Polarization dependence of the m-plane MQWs not accounted for in these plots.
- Indicates that for λ > 530 nm MQW on m-plane might be brighter than on c-plane.

Polarization-dependent PL of m-plane MQWs



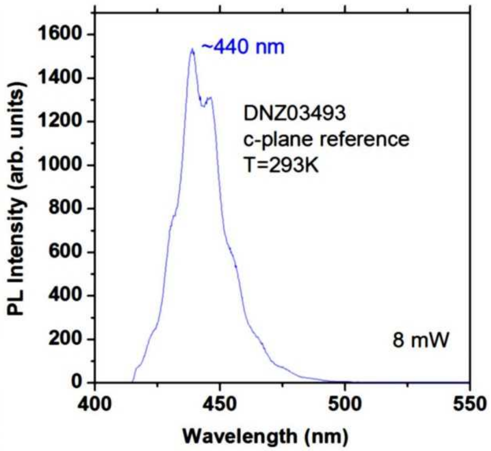
Longer wavelength emission on semipolar substrates

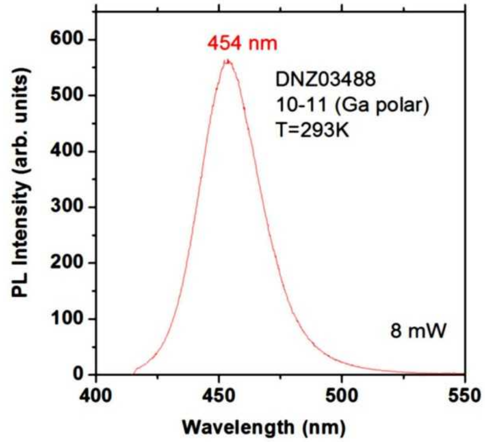
Co-load c-plane and Ga-polar (10-11) and N-polar (10-1-1) substrates – grow same MQW sample on all three substrates.



Observe that PL wavelengths are longest on (10-1-1), followed by (10-11) and c-plane

Recent IQE of MQWs on c-plane and (10-11)





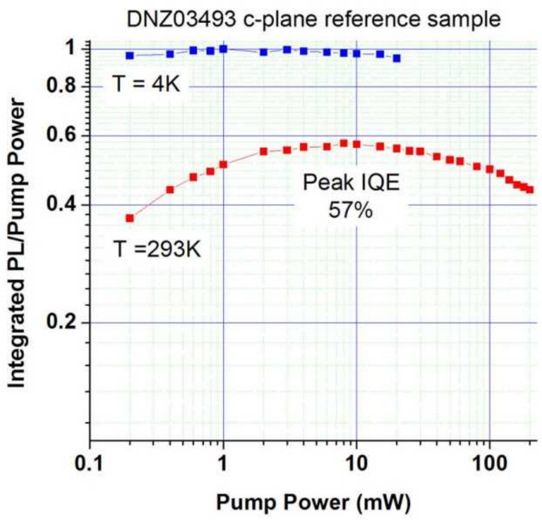
Define IQE as PL (300K)/PL(4K)

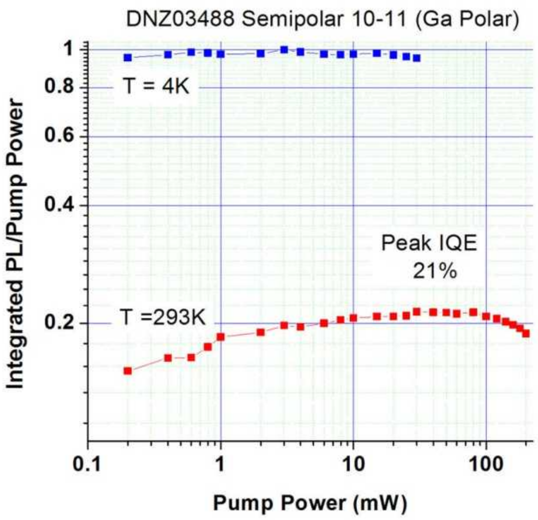
Perform PL at various pump powers to identify:

- Max PL intensity/pump power at 4K (100% IQE)
- **Peak IQE** at room temperature

Result: Peak IQE ~ 21% at room temperature. Also achieved ~ 11% for MQWs on m-plane GaN

Outstanding issue: IQE shows little variation with pump power—need to understand





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