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SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Group III Nitride Growth for Solid State Lighting

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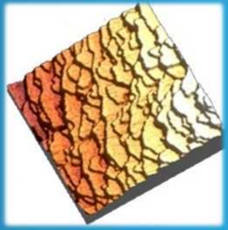
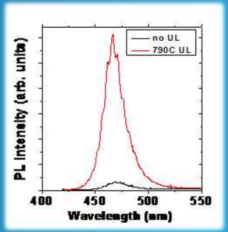
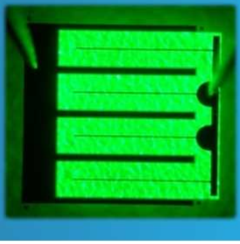
Sandia National Laboratories







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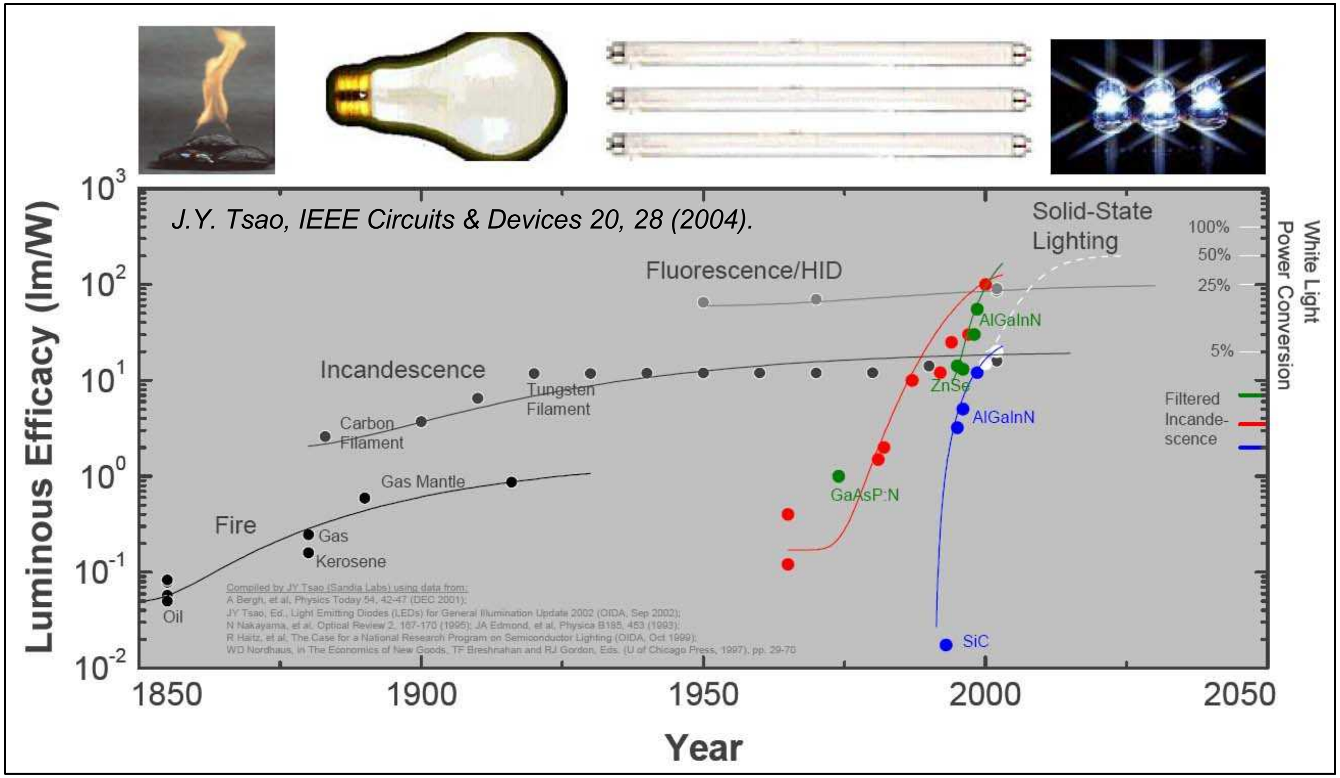
Covered in this Talk

- Current status of Solid State Lighting (SSL).
  - Remaining issues that need to be addressed.
- Growth of group III nitrides with a focus on InGaN.
  - Examples of GaN on sapphire and InGaN QWs on GaN.
  - Factors that limit indium incorporation of InGaN on GaN.
- How InGaN morphology impacts MQW brightness.
- Linking MQW IQE to non-radiative defect concentration.
- Summary and Conclusions.

Why Solid State Lighting?

Luminous efficacy from conventional light sources has stagnated for the last 50 years



Power Conversion Efficiency

Incandescent ~4%

Fluorescent ~ 18%

SSL Goal ~ 50%

LED package mid 1990's

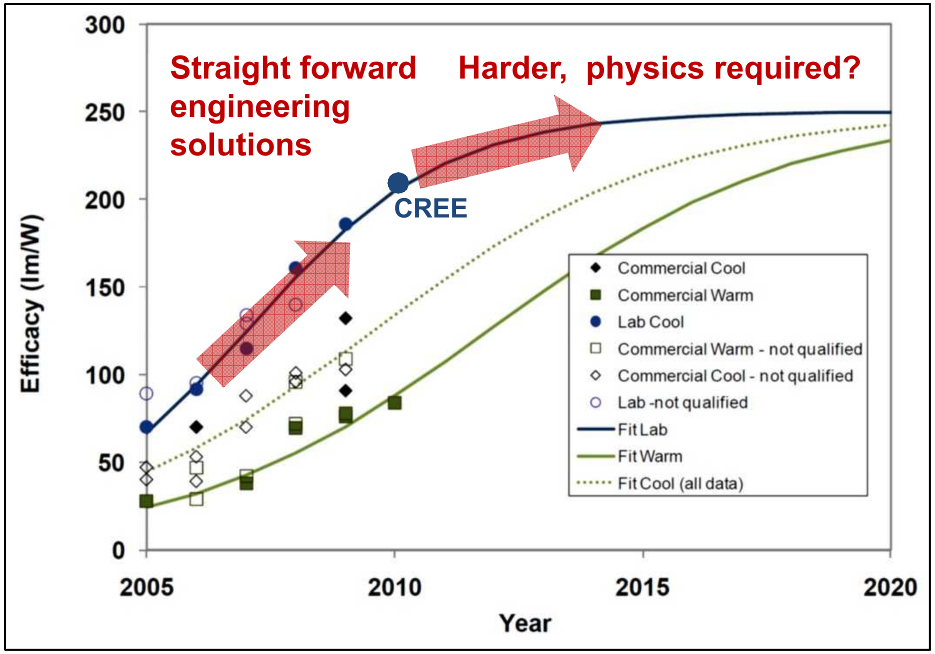
Lumileds 5 W package, 2009

DOE has a stated goal of producing SSL with 50% wall-plug efficiency by 2025 (~ 230 lm/W)

In Feb. 2010, Cree reported a 208 lm/W cool white LED.

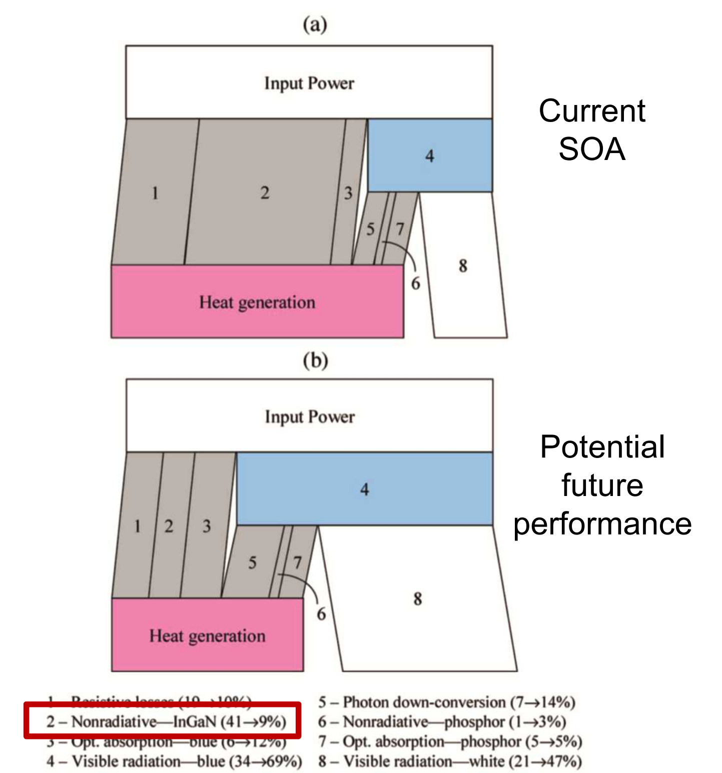
Despite huge success, LED progress is getting more difficult

From the DOE SSL 2010 Multi-Year Plan Technology R&D



Beyond 2010, improving LEDs may be limited by physical understanding.

From Krames, et al., J. Display Tech. 3, 160 (2007)

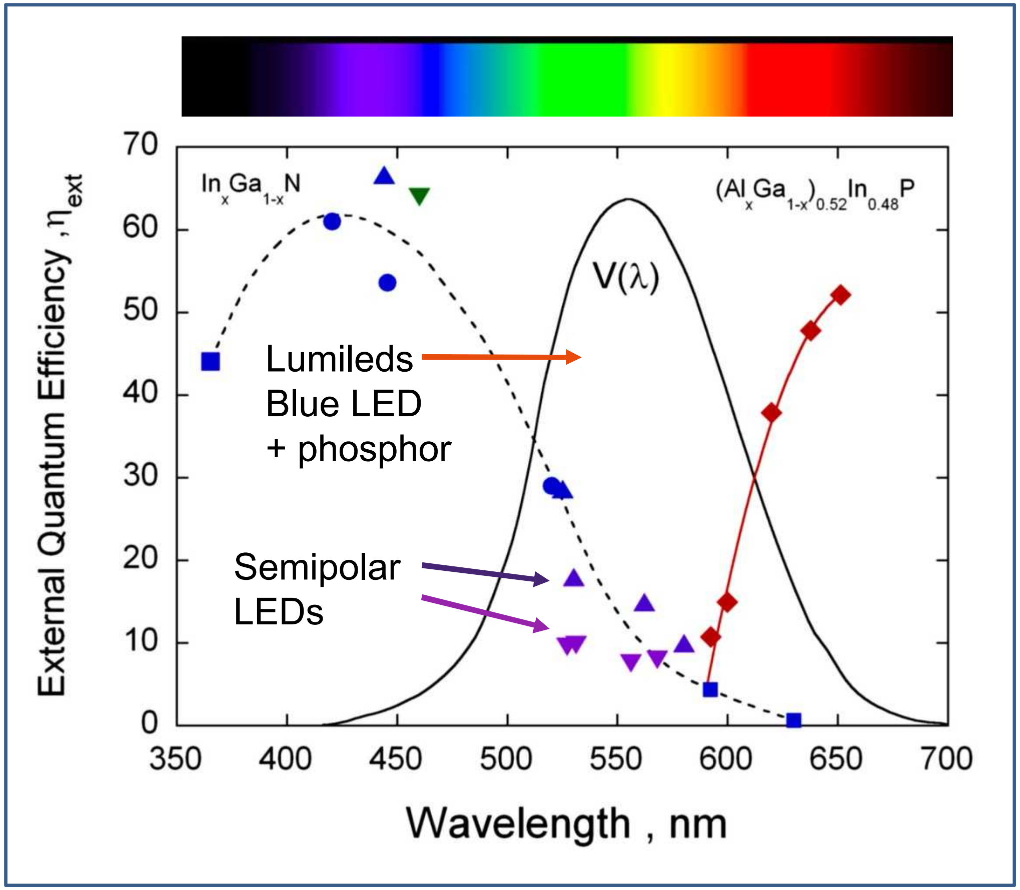


2 - Nonradiative – InGaN (41 → 9%)

What are the nonradiative defects and how do we remove them?

DOE Goal: Improve IQE of All Visible Emitters to 90%

Current EQE of SOA LEDs, V(λ) = CIE standard eye response



InGaN for blue & green LEDs
AlGaInP for red LEDs

Green LEDs on semipolar GaN are showing promise.

white LEDs are obtained using blue + yellow phosphor (have ~30% Stokes loss).

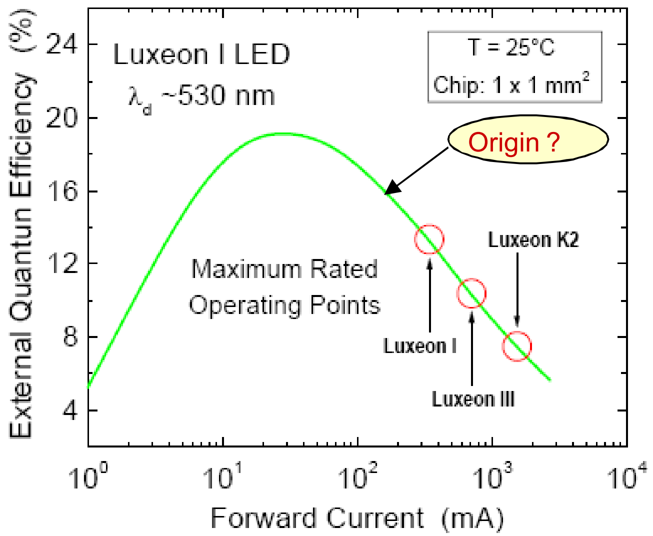
Most efficient white LEDs will be obtained using red + green + blue approach or a four color solution.

Monochromatic LEDs can be made using a blue LED pumping a longer wavelength phosphor.

Need brighter green and yellow LEDs!

Four major issues of InGaN-based SSL

"Efficiency Droop"

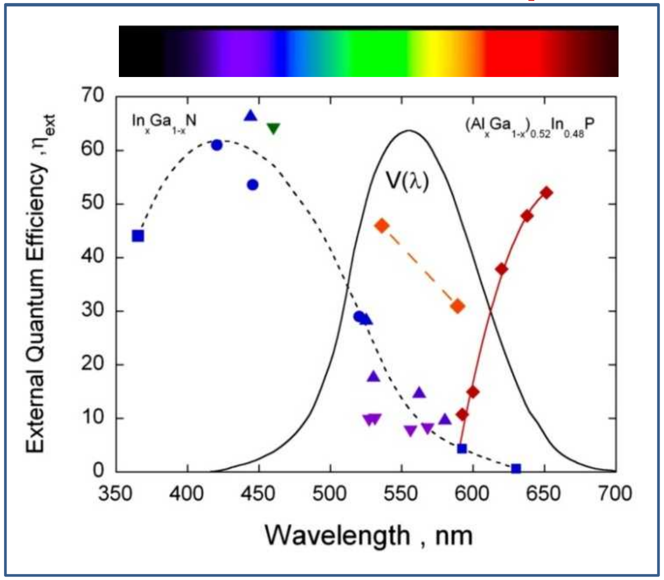


Auger?

Phonon-assisted Auger?

Carrier leakage?

"Green-Yellow Gap"



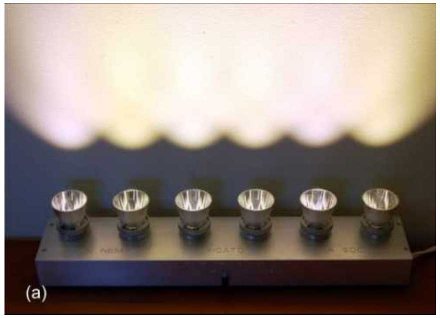
Needed for RGB or RYGB LED combination

Not necessary for blue + phosphor

"Color Control"

Growth temperature influences indium concentration

Need better temperature control and uniformity.



Depending on the blue LED λ and the phosphor can get different color temperature.

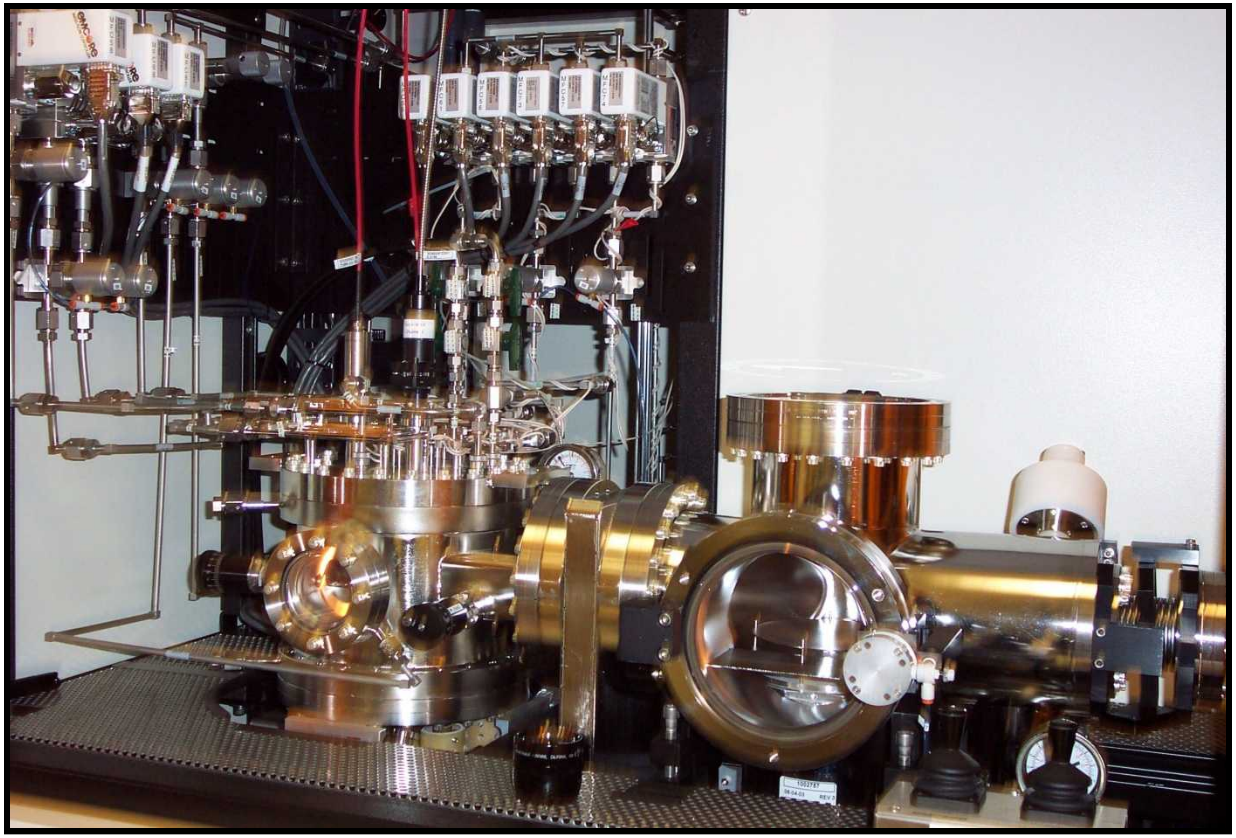
Can be solved by matching LED and phosphor.

"COST"

Has to be reduced by ~20x

7 Watt LED Light Bulb –
60 Watt Replacement
Reg Price: ~~$49.00~~ Spring
Sale: $39.89

Group III-N films grown using MOCVD

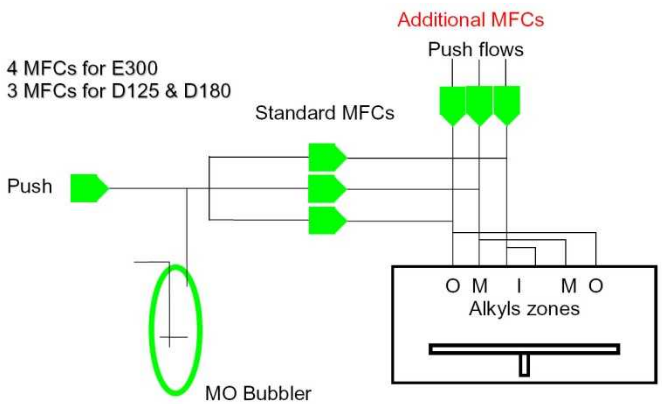


- **MOCVD reactor** – Veeco D125 short-jar - 3-2" wafers simultaneously.
- **Precursors –** trimethyl sources of In, Al, and Ga, and $Mecp_2Mg$ and SiH_4 for p- and n-type doping.
- **Gases –** NH_3, N_2, H_2 (no H_2 for InGaN)
- **Temperature –** GaN at 1050 °C, InGaN at 680 – 880 °C.
- **Pressure** – 75 to 500 torr.

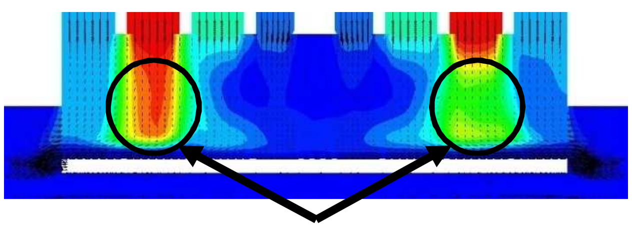
Growth differences between InGaN and GaN are:
lower temperature, higher NH_3, no H_2, slower growth rate (less total MO).

Injector design for Veeco D125 “mini GaNzilla” short jar

Use additional push flows for velocity matching
(L. Kadinski, J. Cryst. Growth 261 (2004) 175)

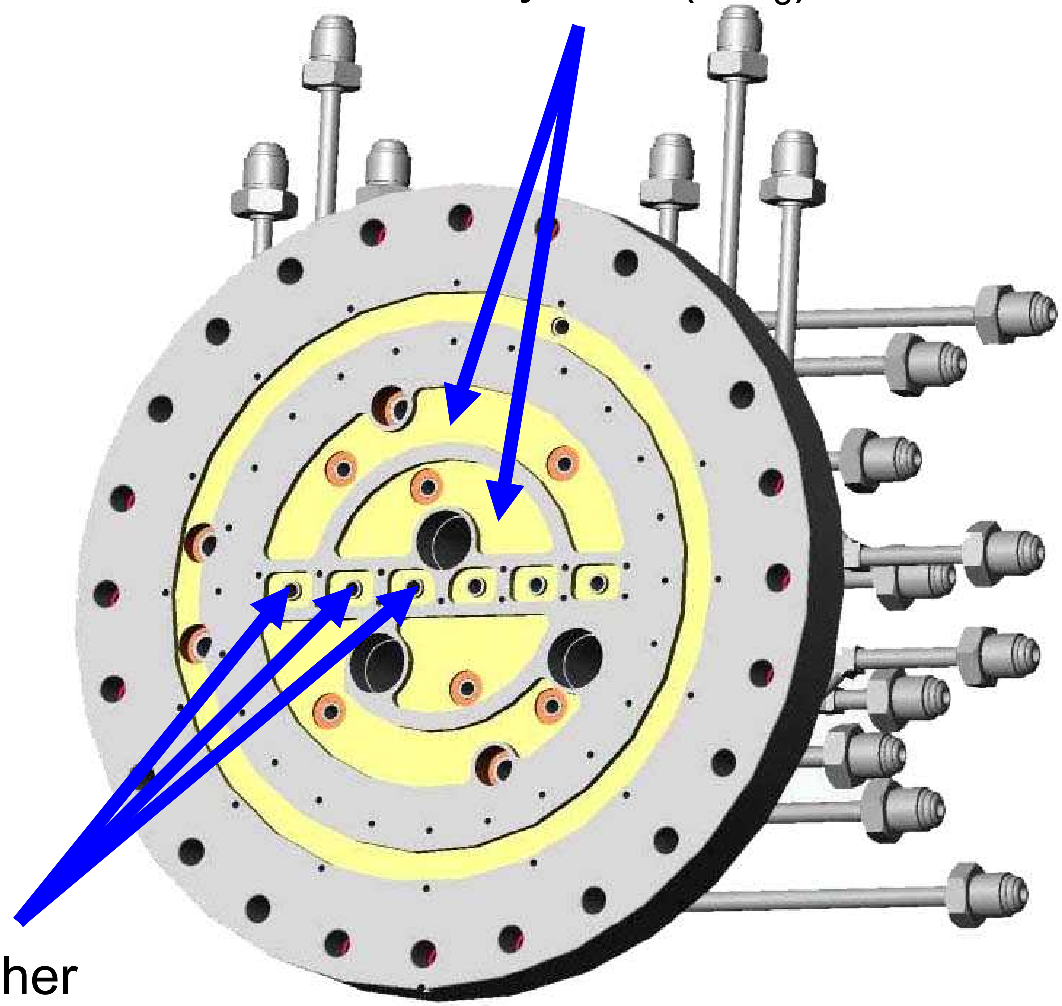


Simulated Flow in GaNzilla Reactor with Addition of Alkyl Push Flow.



No recirculation observed in flow simulation.

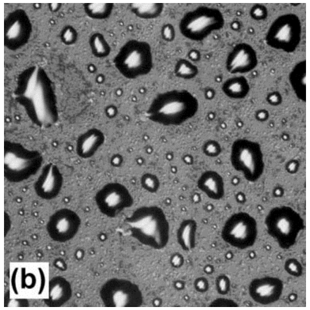
Two hydride (NH_3) zones



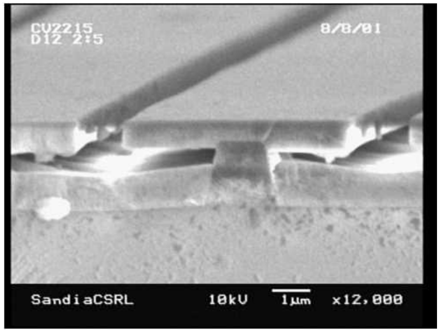
Three alkyl (MO) zones
Inner, middle, and outer tied together

What makes GaN growth so difficult?

- No substrate → grow on sapphire or SiC → dislocations.
  - Use GaN nucleation layers – enough of a dislocation reduction.
- Low growth temperature (1050 °C) compared to melting temperature (2520 °C).
  - Growth farther from Equilibrium than other III/V's
- GaN decomposes starting near 800 °C. →



  - More stable in N_2 than H_2, grow using V/III ratios > 1000.
- Low surface diffusion lengths.
  - One plus: Gas phase diffusion mechanism increases lateral diffusion length (ELO). →



Nitride-based SSL revolution started slowly

- 1932- 1986, GaN grown on sapphire. Material contains high (> 10^{10} cm^{-2}) dislocation density, rough morphology & high impurity levels.
- 1986, Amano[1] *et al.* used thin AlN "buffer layers" or nucleation layers (NLs) to improve GaN growth on sapphire – lower dislocation density!
- 1991, Nakamura[2] and Wickenden[3] *et al.* develop **GaN NLs** for GaN growth on sapphire – better material quality < 10^9 cm^{-2} dislocations.
- 1991, Nakamura reports 80 mcd blue LEDs x10 brighter than SiC-based LEDs.
- 1992, Nakamura also reports on **thermal annealing to activate p-GaN**.
- 1993, Nakamura reports a 125 µW LED at 20 mA current.
- 2002, LumiLeds sells 20 lm/W LEDs
- 2010, Cree reports a 208 lumens/watt white LED.

Two key developments for InGaN-based LEDs – NLs and p-GaN annealing.

1) Amano *et al.* Appl. Phys. Lett. **48**, 353 (1986); 2) S. Nakamura, Jpn. J. Appl. Phys., Part 2 **30**, L1705 (1991); 3) D.K. Wickenden, *et al.*, Mater. Res. Soc. Symp. Proc. **221**, 167 (1991).

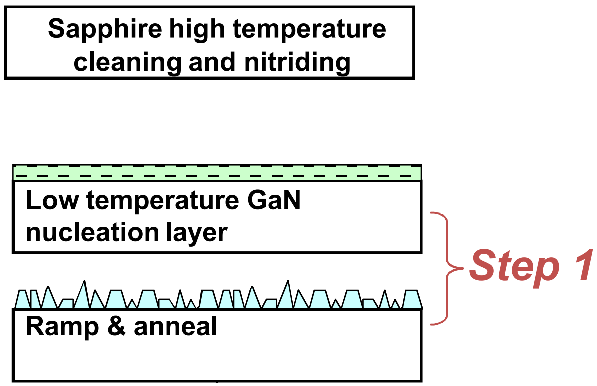
Typical "two step" heteroepitaxy of GaN on sapphire

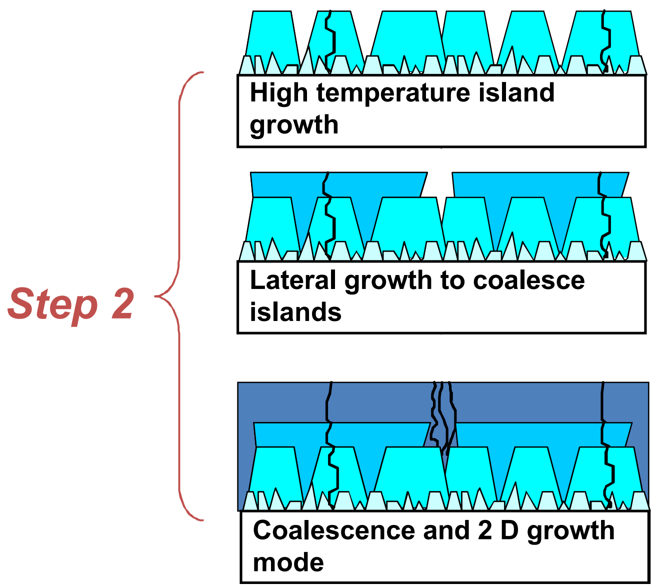
K. Hiramatsu, et al., JCG 115, 628 (1991).

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.



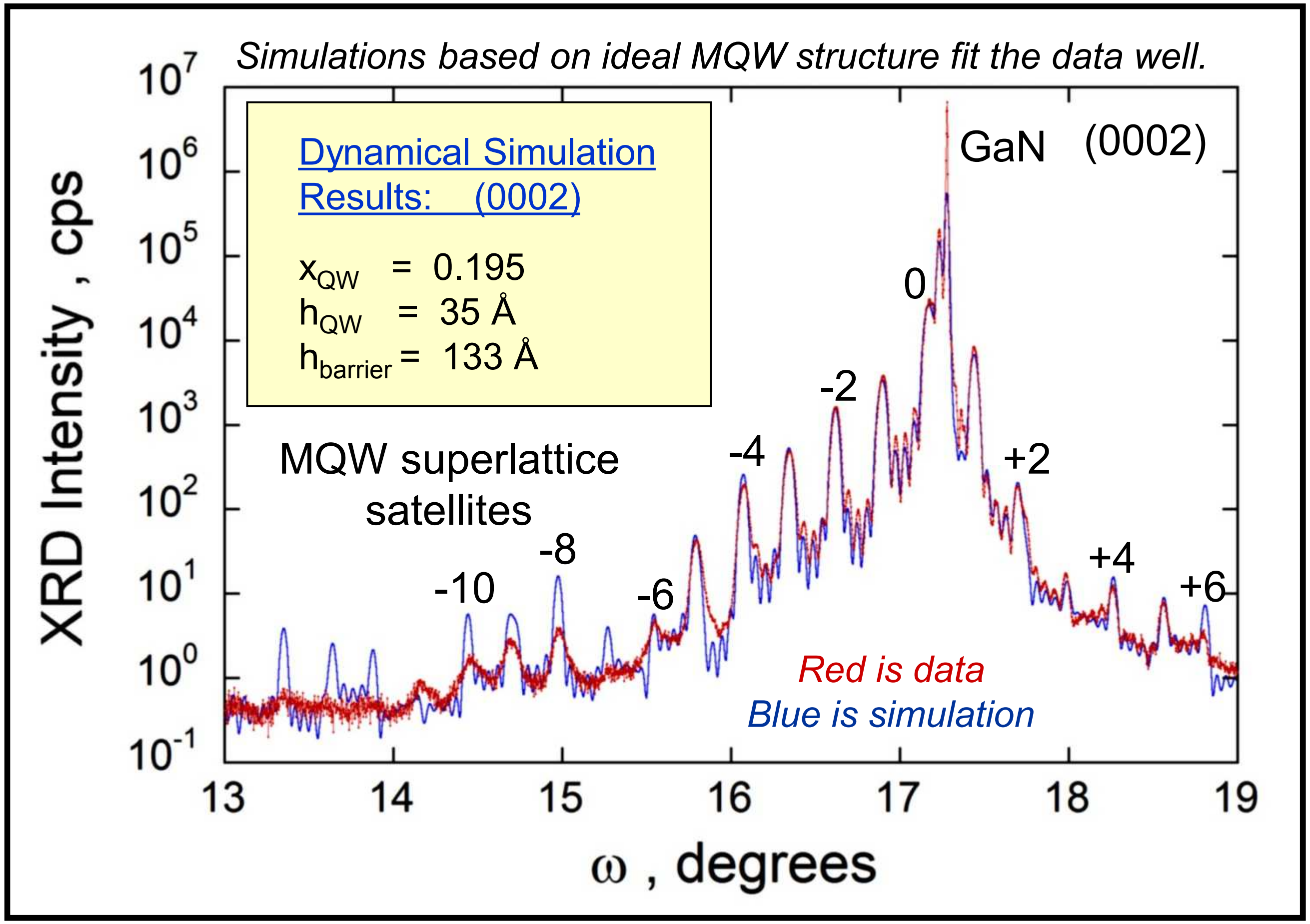


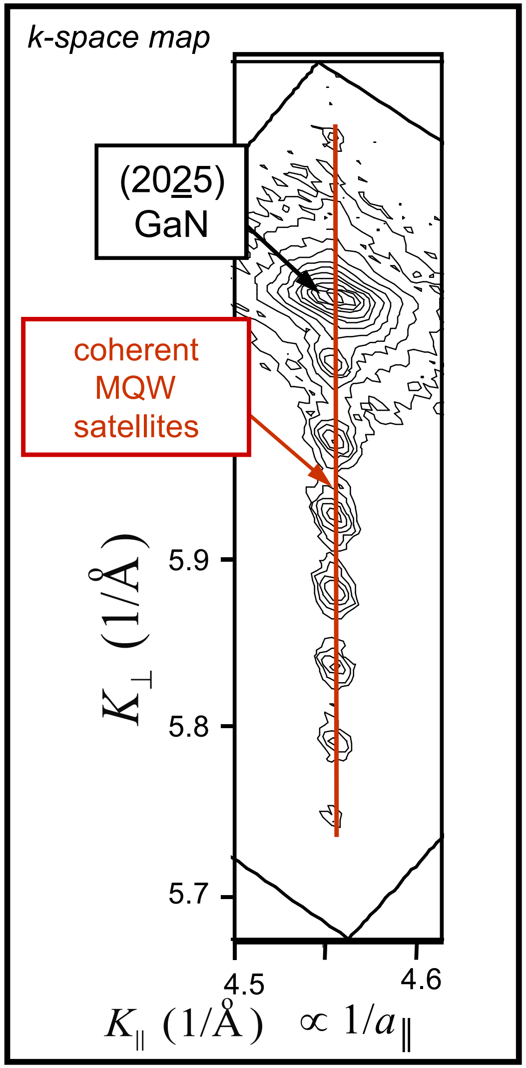
4) At high temperature, Ga source is turned on. Isolated GaN grains grow on the GaN nuclei. Some dislocations propagate up from the GaN grains.

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.

X-ray diffraction is used extensively to determine InGaN MQW and thin film structural information

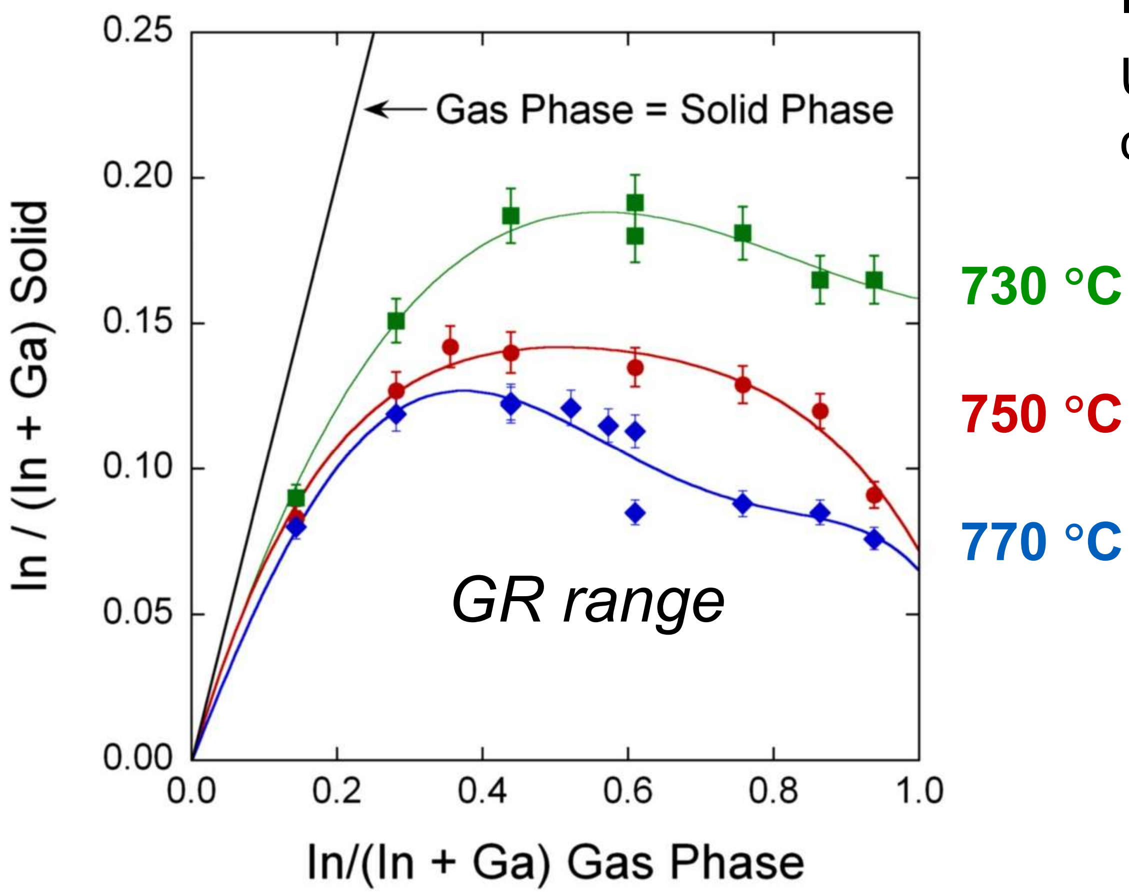




Both the dynamic diffraction fit and lack of change in $K_{\|}$ in the k-space map indicate that the InGaN QW are coherently strained.

Gas phase ≠ solid phase indium incorporation

XRD used to determine MQW indium concentration



InGaN growth in N_2 and NH3

Use 15 SLM NH_3 for InGaN compared to 7 SLM for GaN

Reasons that InGaN growth is non-ideal

1). Indium desorption (T)

2). Gas-phase indium/Ga clustering.

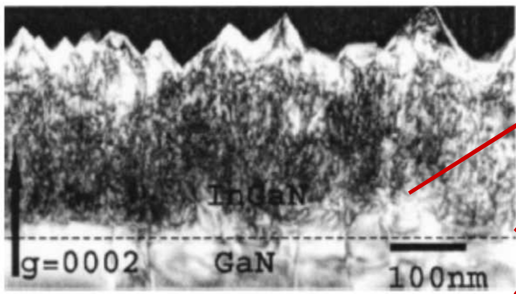
3). Indium incorporation depends on growth rate.

4). Strain limit

Indium incorporation depends heavily on temperature.

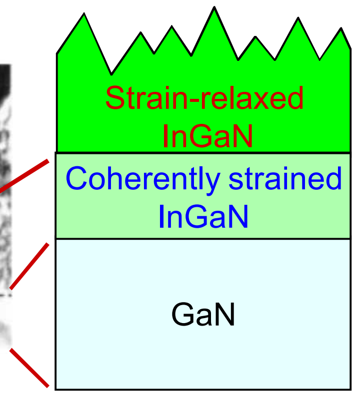
Coherency strain limits the indium composition to 20-25%

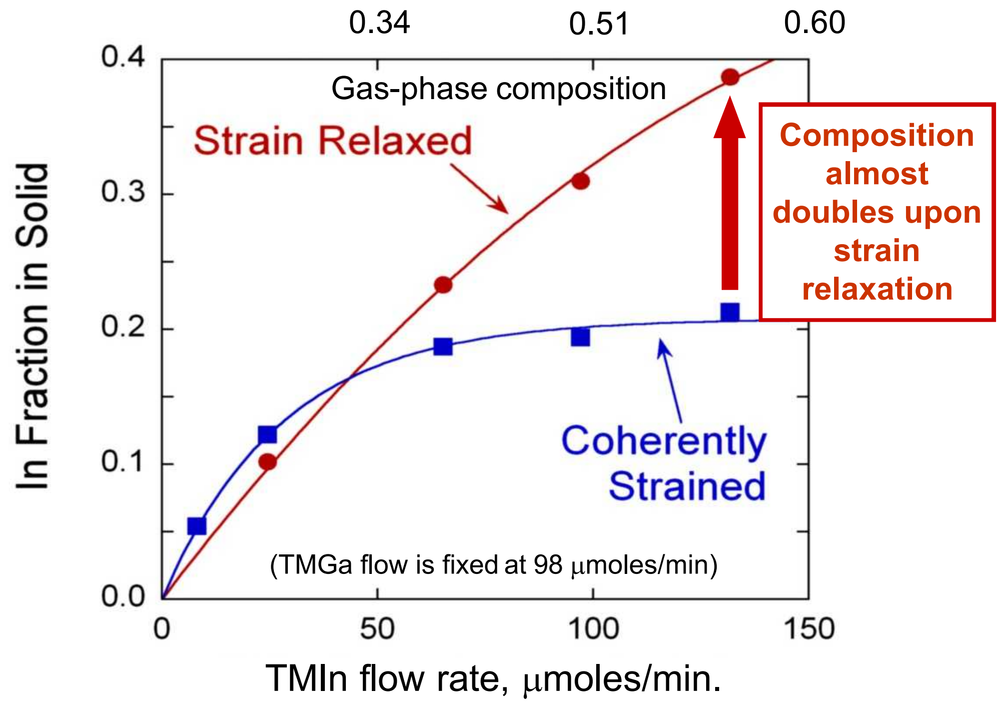
When InGaN strain relaxes on GaN, many defects are formed.



M. Rao, et al., APL 85, 1961 (2004).

~100-nm-thick InGaN on GaN at 760 C:





Strain state measurements by Steve Lee

Related observations:

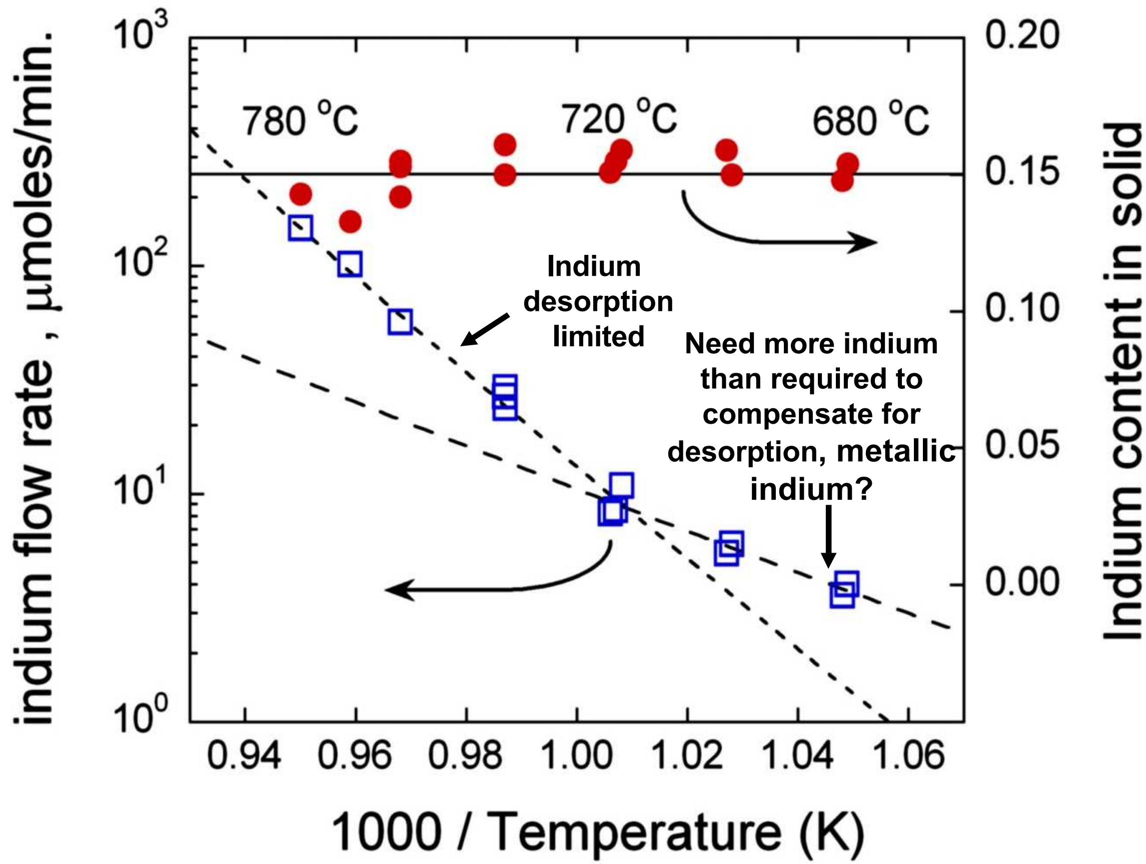
Z. Liliental-Weber, et al., J. Electron. Mat. **30** (2001) 439.
S. Pereira, et al., APL **80** (2002) 3913.
Shimizu, et al., JJAP **36** (1997) 3381.

While strain relaxed InGaN films can be grown on GaN with indium concentrations higher than 20%, their emission efficiency is low due to the high defect density.

Growths to achieve similar QW structure and indium content at different growth temperatures

Goal: achieve the same structure at different QW growth temperatures

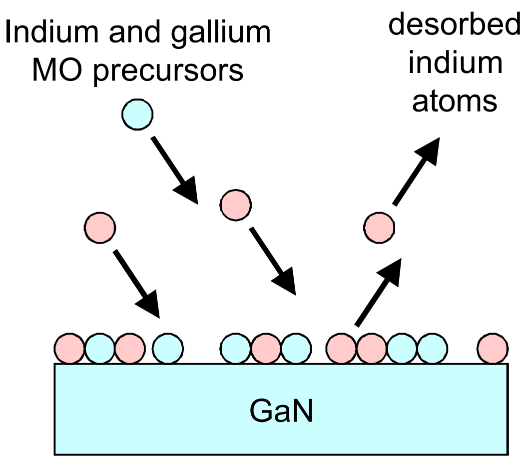
Each of the MQW structures has:
Indium content = 15.1 ± 0.7 %
QW thickness = 26.3 ± 3.4 Å
Barrier thickness = 94.6 ± 6.2 Å
PL wavelength = 457 ± 6 nm



Need less indium as the QW growth temperature is decreased

Summary of factors that limit indium incorporation

Indium desorption



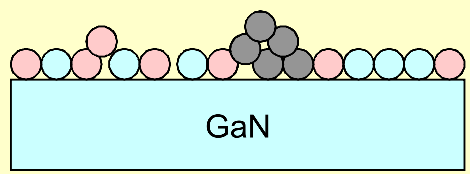
$k_{In} \sim \exp(-E_{A,des}/kT)$

Increases as the QW growth temperature increases. Can be compensated by higher indium fluxes.

Indium metal formation

Indium metal precipitates form on surface.

Lower NH_3 catalytic dissociation decreases at lower temperature.

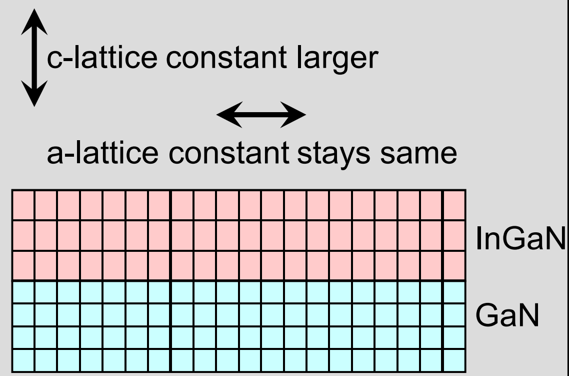


Lattice constant for metallic indium same as $In_{0.2}Ga_{0.8}N$.

Occurs at low growth temperature and high indium surface coverage.

Coherency strain

InGaN is coherently strained on GaN



To strain relax the a-lattice constant defects need to form.

Occurs when InGaN film thickness is below critical thickness for strain relaxation.

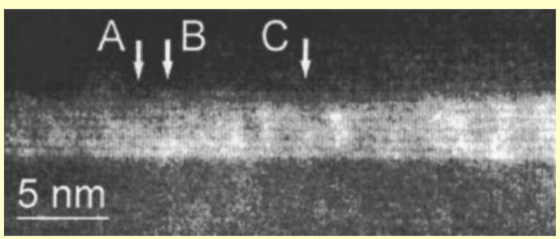
Possible importance of InGaN/GaN step morphology in controlling localization

If indium is homogeneously distributed in the InGaN QW, how is localization created?

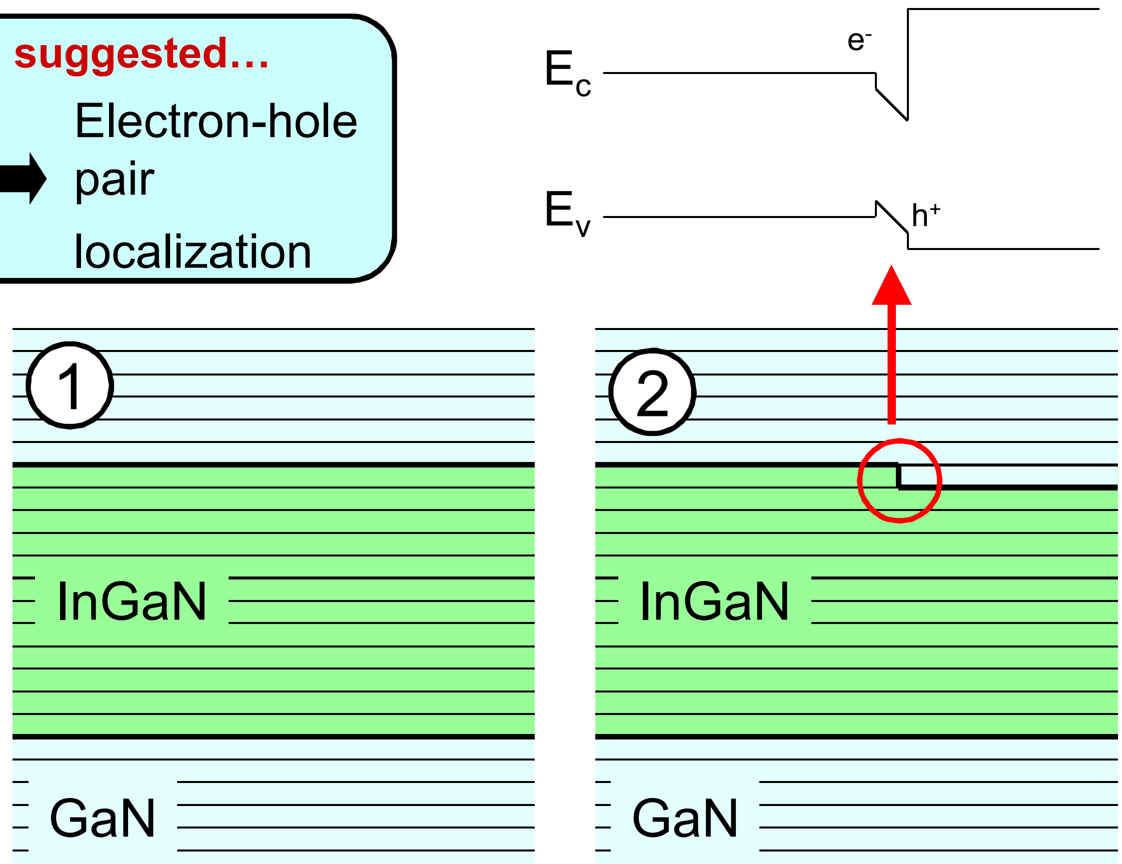
One possibility that has been suggested…

Fluctuations in the QW thickness + Strong piezoelectric fields → Electron-hole pair localization

D. M. Graham, et al., - JAP ***97****, 103508 (2005).*



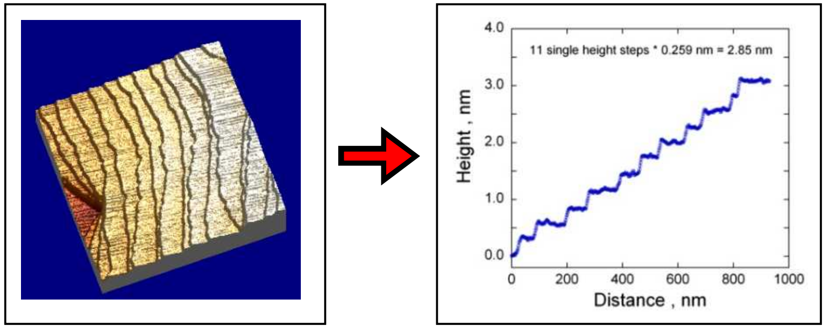
Monolayer thickness fluctuations on top InGaN/GaN interface



No thickness fluctuation results in no localization.

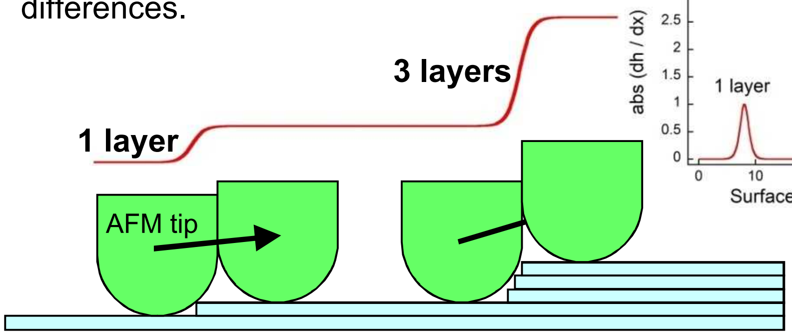
Some thickness fluctuation yields some localization.

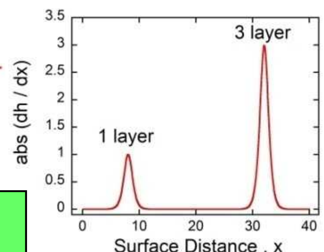
Counting step height distributions



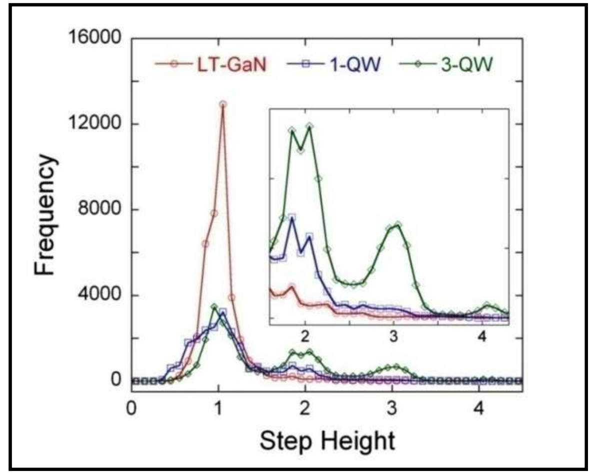
Can use AFM image to quantify the step heights, single layer steps, double layer steps, triple layer steps, etc...
1). Calculate the first and second derivative.
2). Magnitude of 1st derivative gives number of layer steps.
3). Second derivative = 0 gives step location.

AFM excellent at detecting height differences.

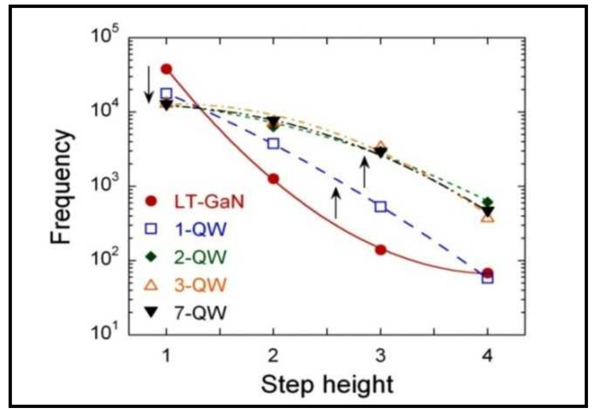




Histogram of the 1st derivative heights



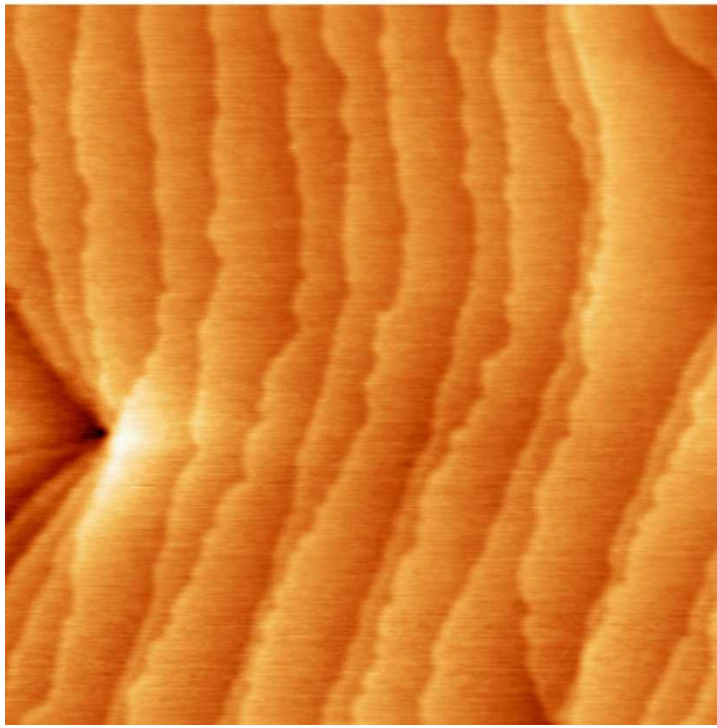
Binned distribution of step heights

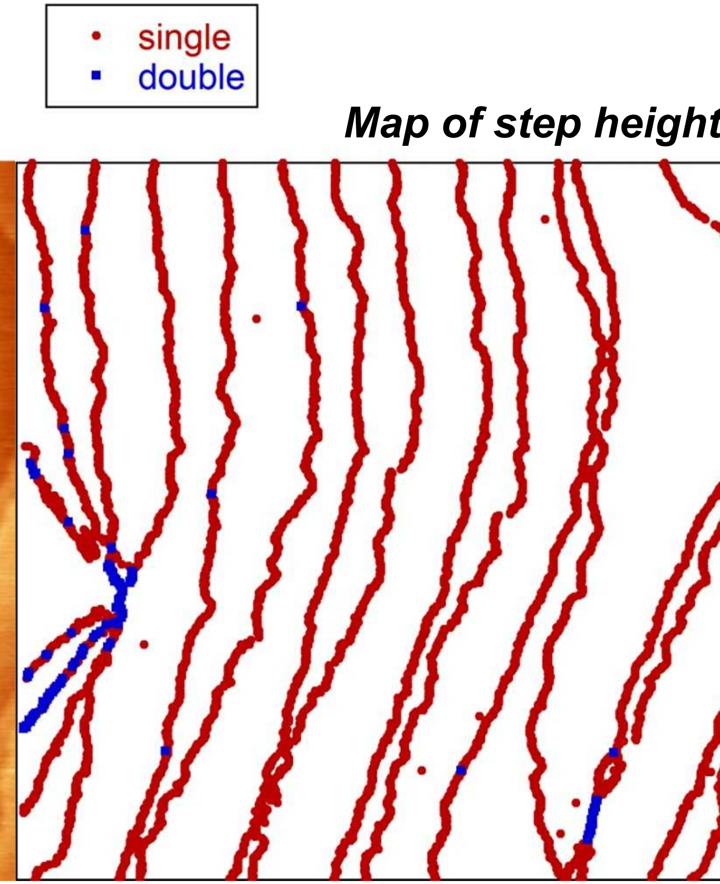


Quantifying step heights: GaN template

AFM images show predominantly single layer step heights. Some hints of double layer steps near dislocations.

Map of step heights

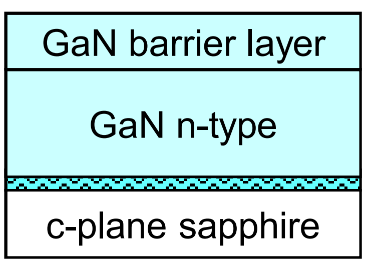




AFM images before and after low temperature (~800 ºC) GaN barrier growth are similar is step structure.

Film Structure

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



Quantifying step heights: InGaN underlayers on GaN

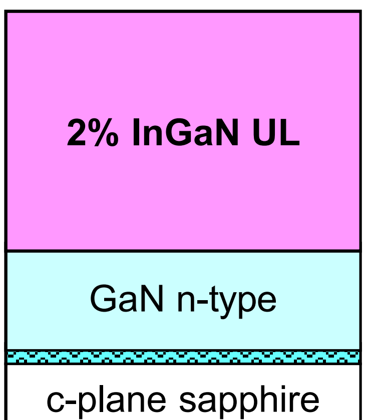
Increased frequency of double and triple layer step heights. Decreased step edge roughness.

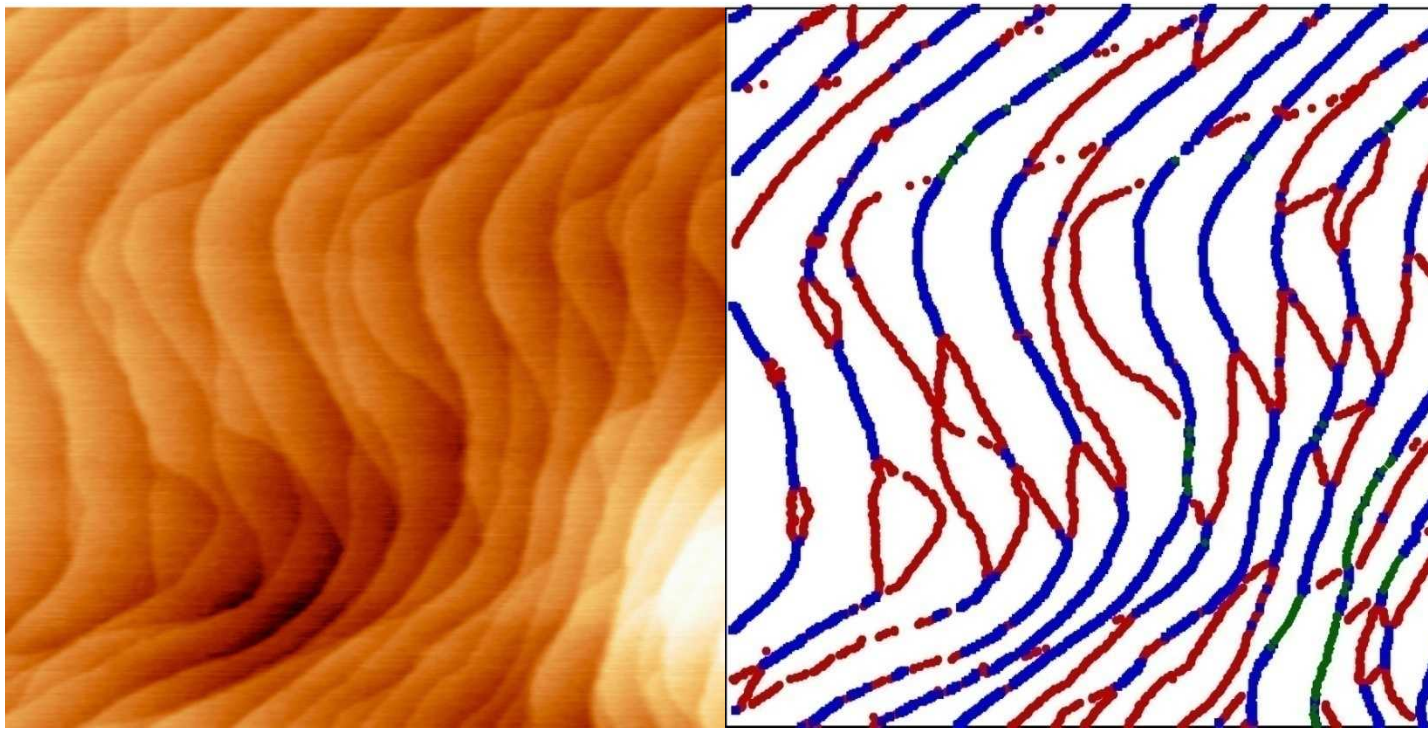
- single
- double
- triple+

InGaN MQWs on underlayers show increased PL emission!

Film Structure

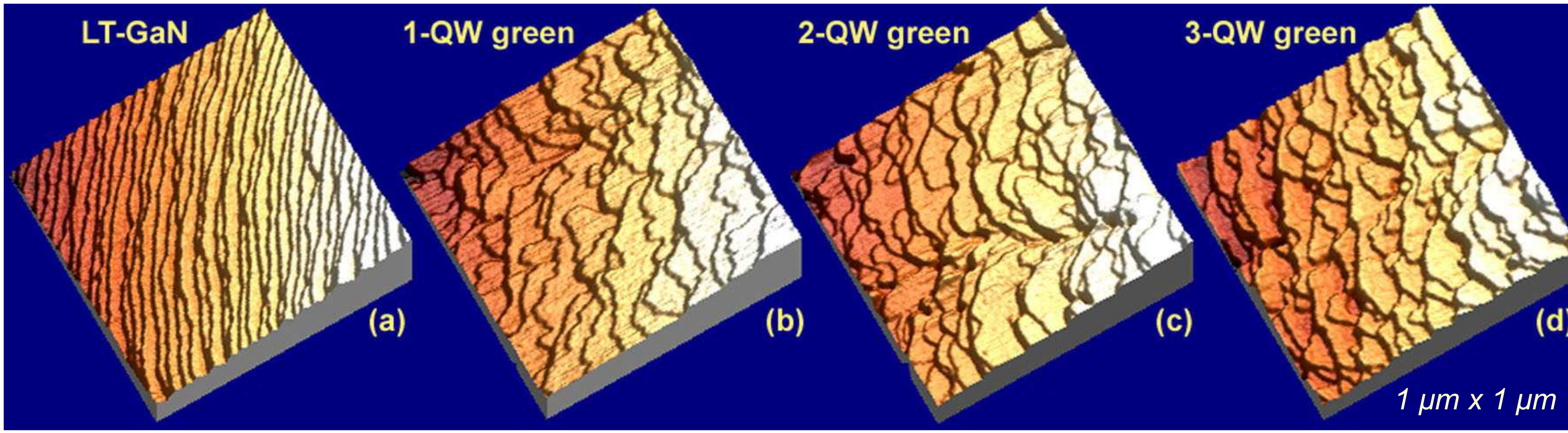
10 nm thick LT GaN barrier layer has the same step structure as the underlying HT GaN.



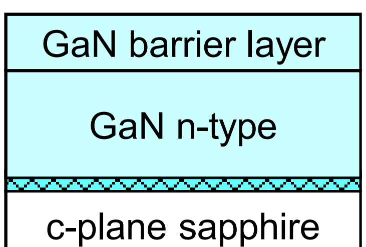


Change in InGaN step structure is due to the addition of indium to the growth rather than temperature – film strain restructuring.

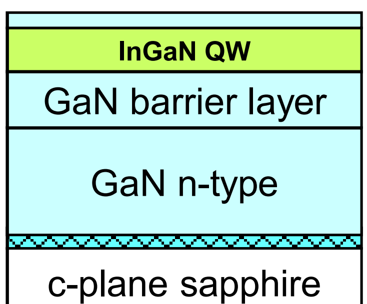
Step morphology change for green QWs

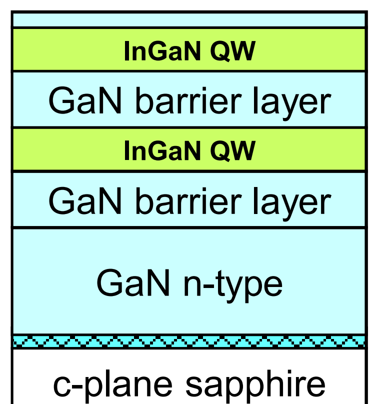


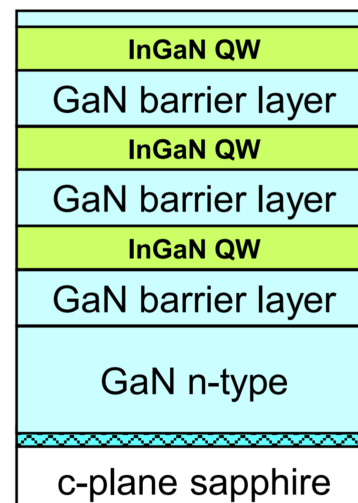
10 nm thick LT GaN barrier layer has the same step structure as the underlying HT GaN.



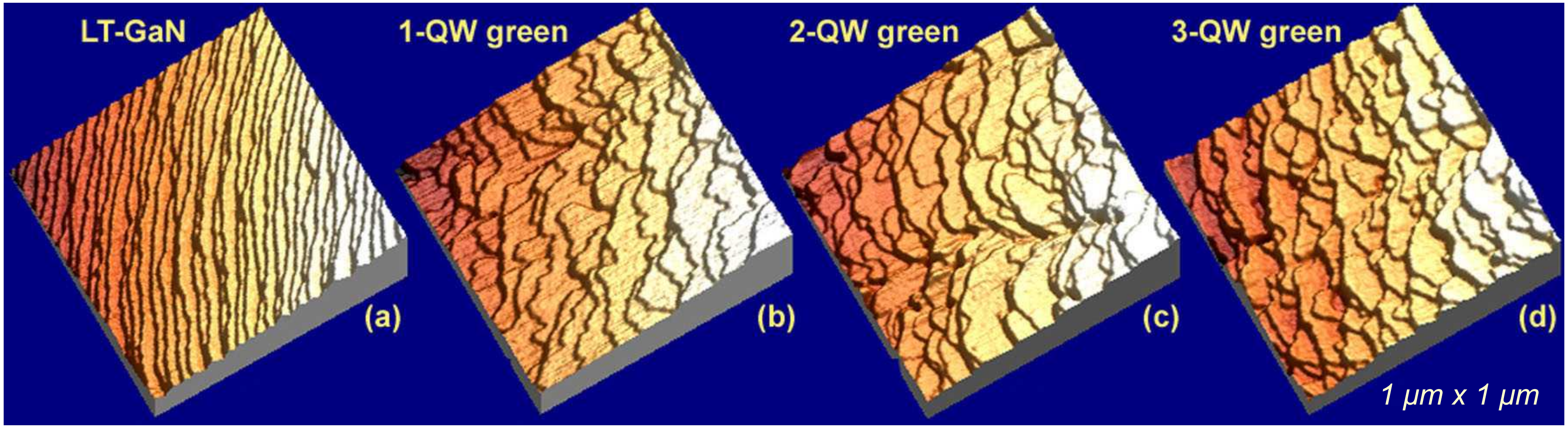
Addition of single 3 nm InGaN QW capped with 1.5 GaN barrier layer

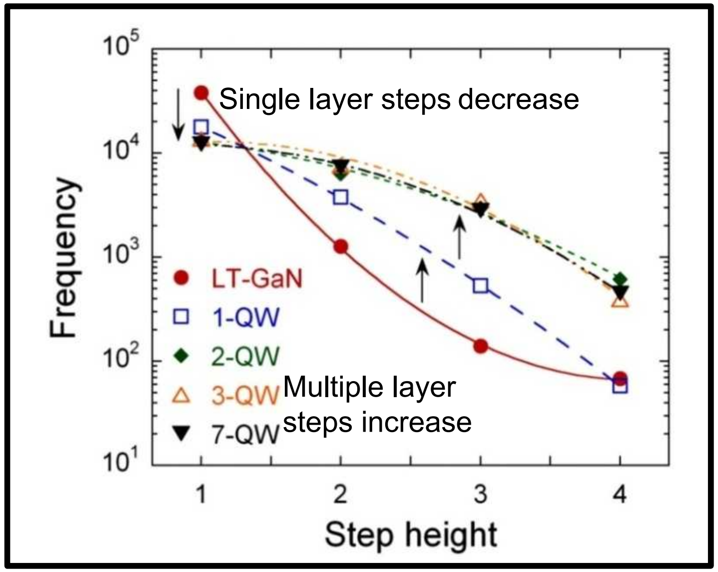






Observation of increased multi-layer steps in green MQWs





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

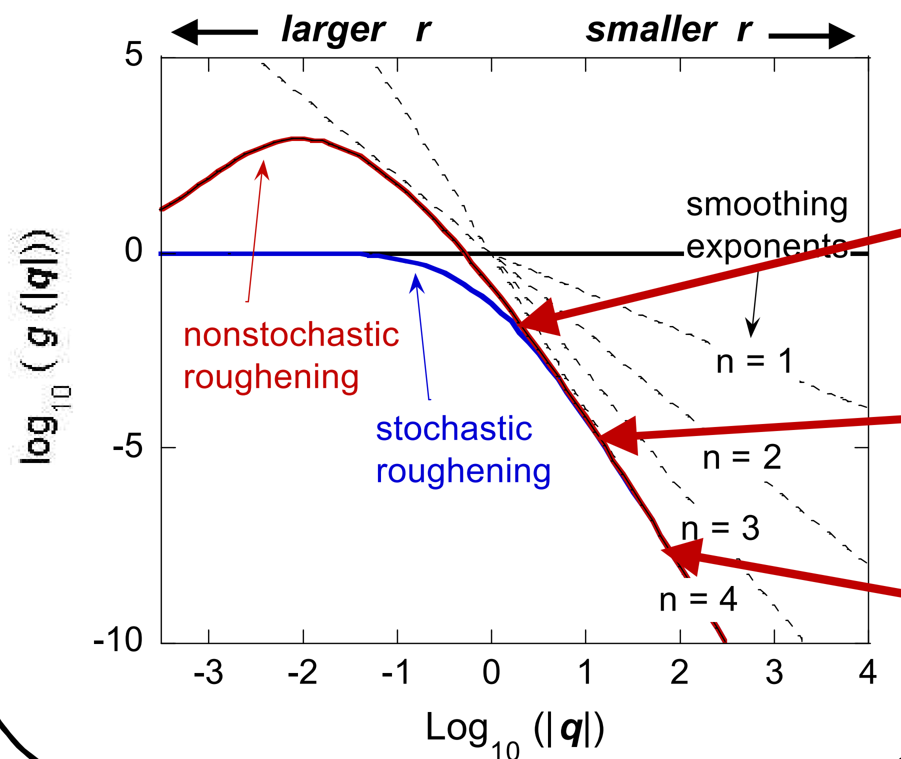
Suggests that while the InGaN QWs roughen the surface, the GaN barrier layer smooth the surface.

What are the smoothing mechanisms?

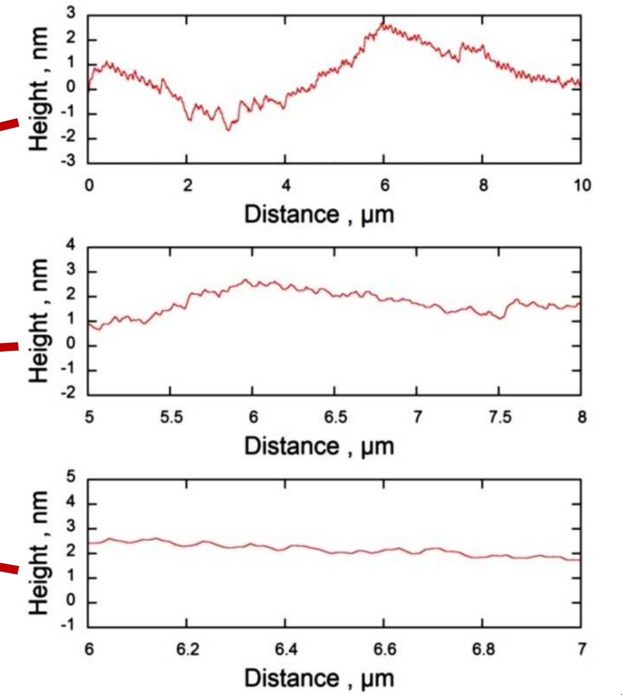
Smoothing mechanisms can be obtained from PSD analysis of AFM images

Power spectral density (PSD) is the height-height correlation function from AFM PSD or *g* can be calculated from h(*x*,*y*) as a function of *q, where q = 1/r*.

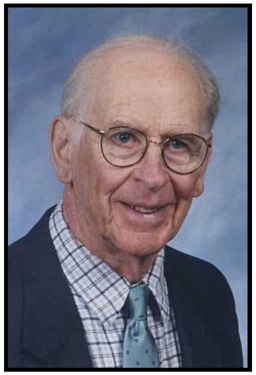
Discussed by Tong and Williams in Ann. Rev. Phys. Chem. 45, 401 (1994).



$$\sigma_{RMS} = (\Sigma\, g\,(\,q\,))^{1/2}$$



Various smoothing mechanisms calculated by Herring



Conyers Herring
1914 - 2009

J. Appl. Phys. 21, 301 (1950).

The PSD can be smoothed by various mechanisms that decrease *g*(*q*) at large *q*,

$$g(|\mathbf{q}|,t) \propto \frac{\Omega}{c_n|\mathbf{q}|^{n}}$$

Smoothing mechanisms

n = 1 - plastic flow driven by surface tension

***n* = 2 - evaporation and recondensation**

n = 3 - volume diffusion

***n* = 4 - surface diffusion**

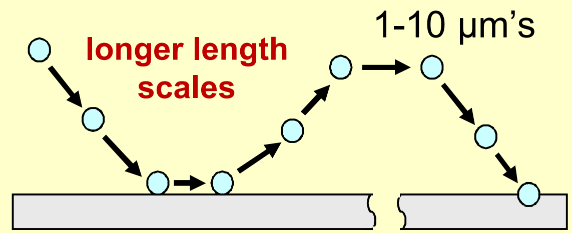
Geometric details of mechanisms could influence the values of *n* by as much as 0.5.

Mechanism influences length scale over which the smoothing occurs.

***n* = 2**

evaporation and recondensation

(GaN for T > 900 °C)

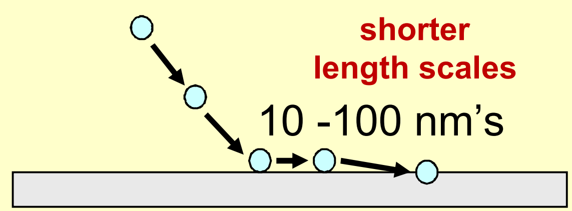


See Mitchell et al., JCG 222, 144 (2001).

***n* = 4**

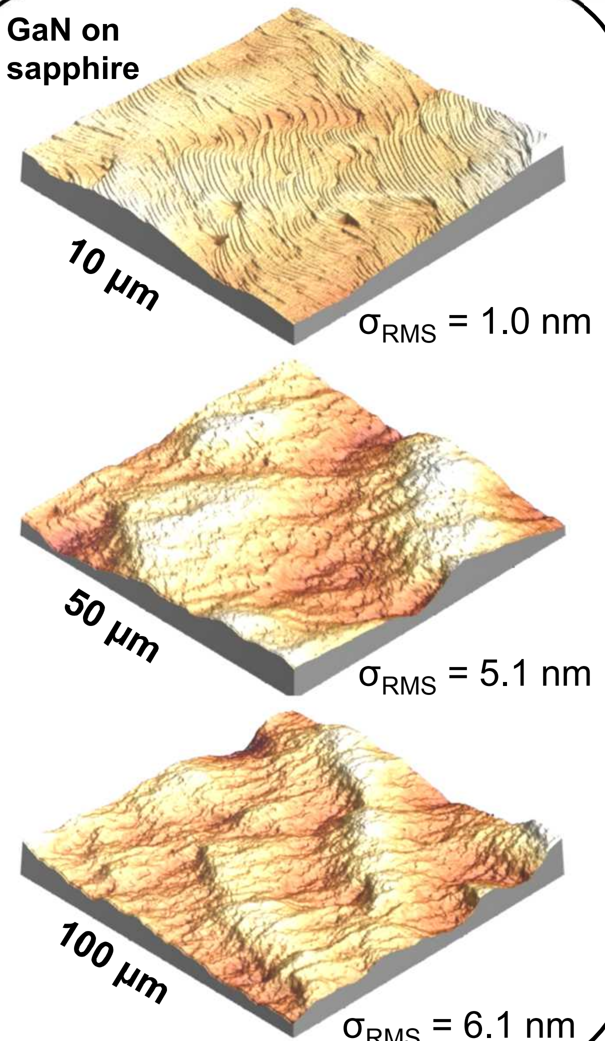
surface diffusion

(InGaN and GaN T < 900 °C

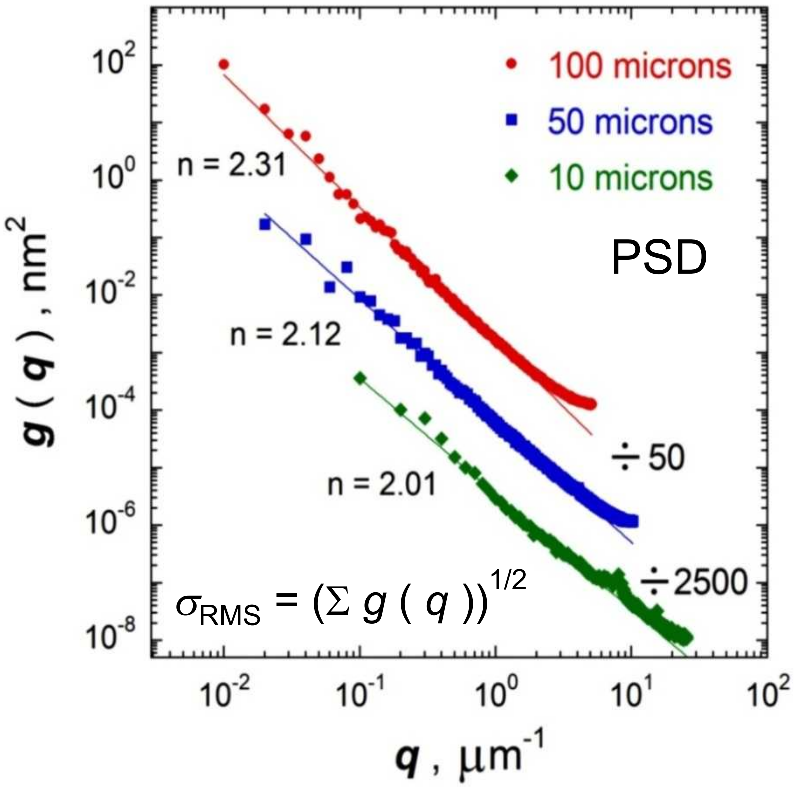


See Koleske et al., JAP 84, 1998 (1998).

PSD analysis of GaN films on sapphire



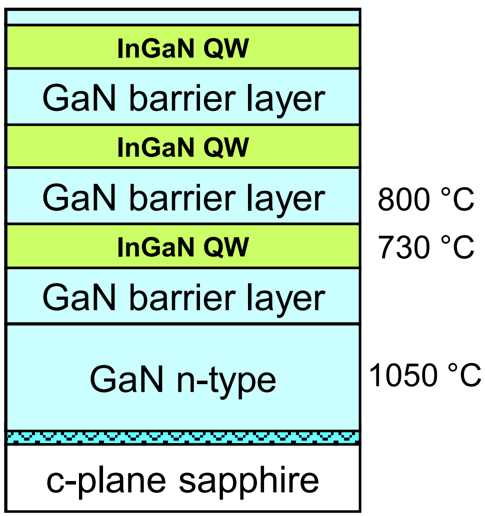
σ_{RMS} typically depends on scan size

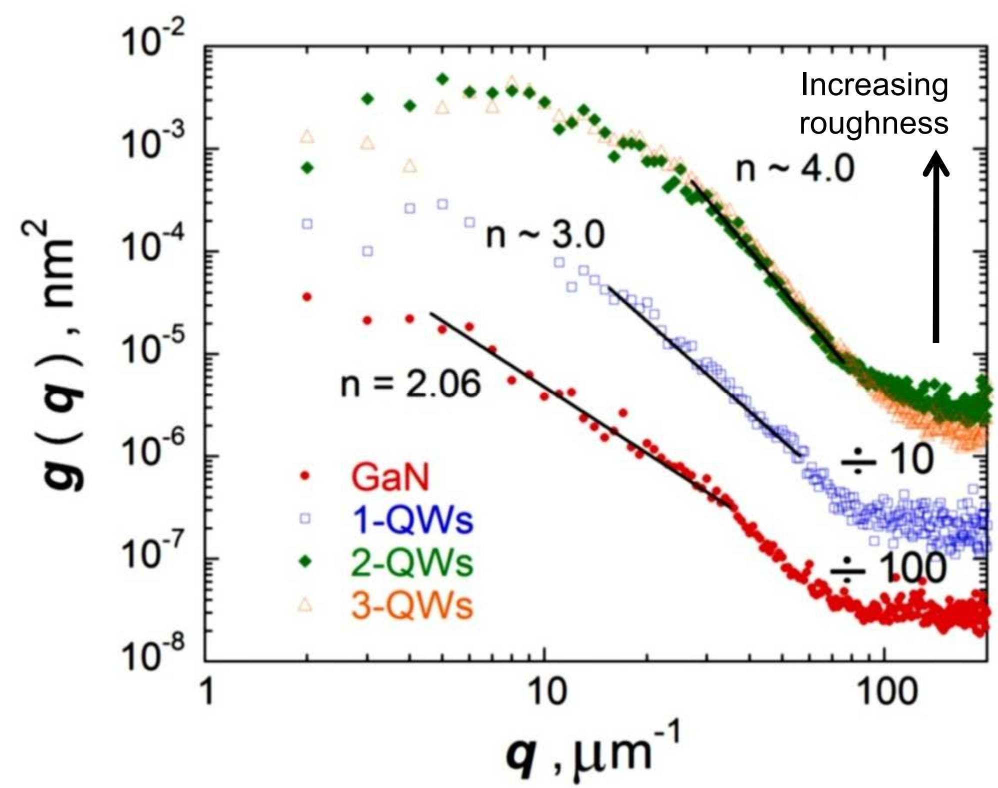


***n* ~ 2 - implies the smoothing mechanism is evaporation and recondensation of Ga atoms**

PSD analysis of green MQWs as number of QWs increases

Green MQW structure





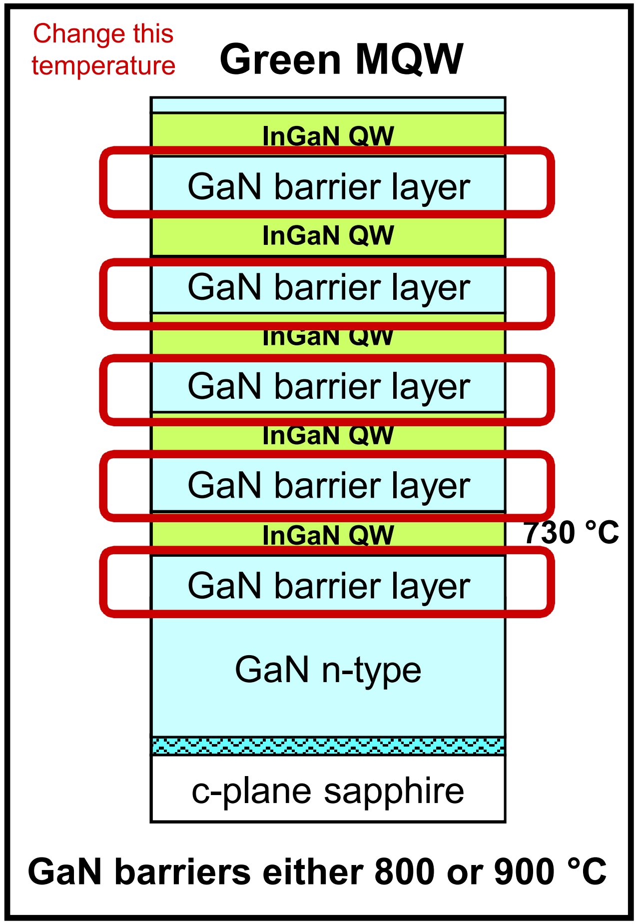
n = 2 = evaporation / recondensation

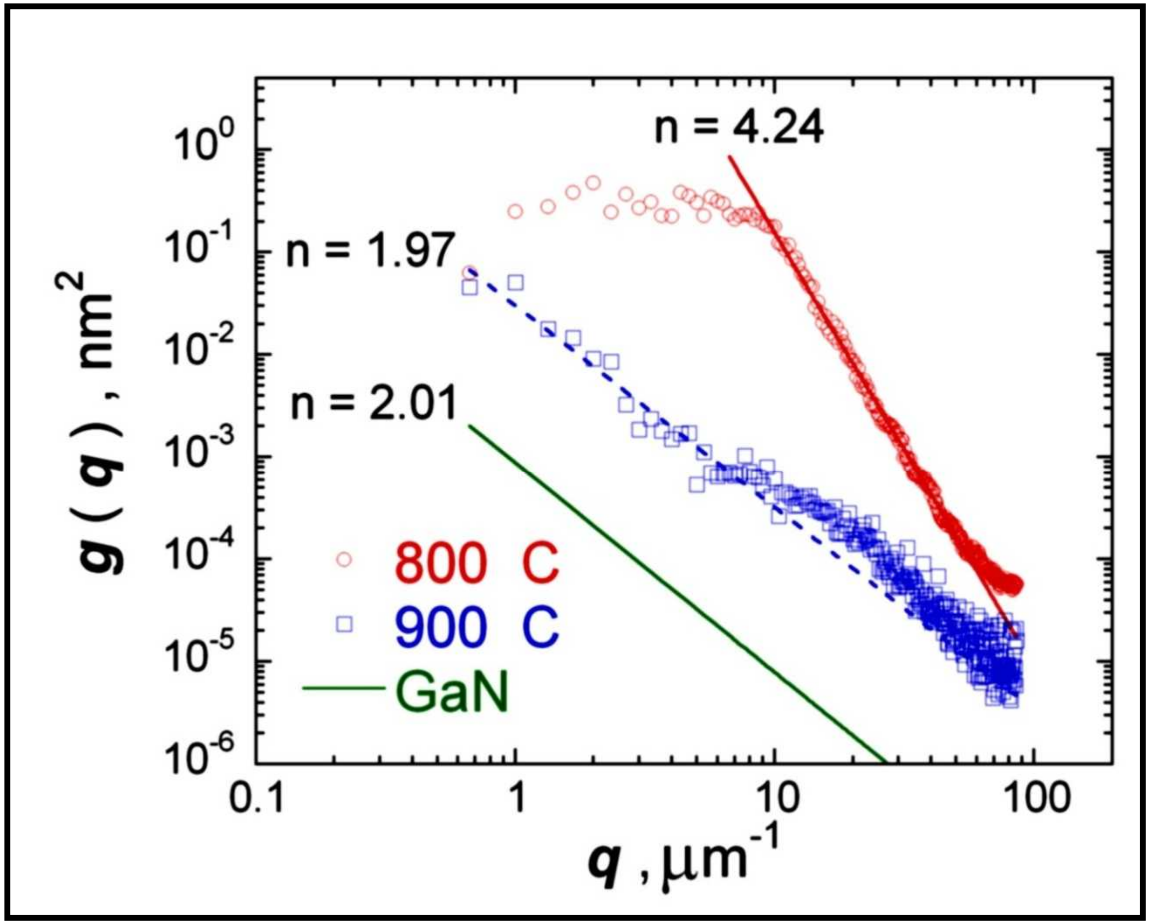
n = 4 = surface diffusion

n = 3 = average 2 & 4?

Smoothing exponent increases from 2 to 4 as the number of QWs increases.

PSD analysis of the green MQWs with 800 and 900 °C GaN barrier growth temperature

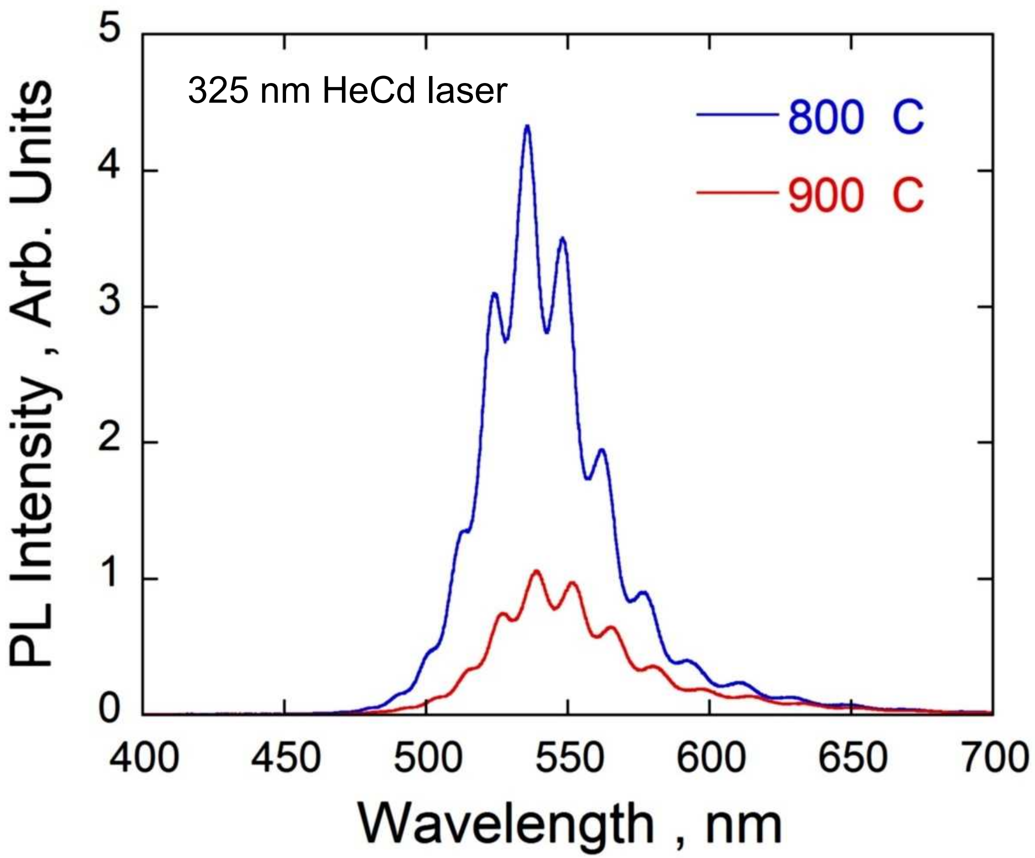




GaN barriers at 900 °C smoother than GaN barriers at 800 °C
Suggests a way to control the InGaN/GaN interface roughness.

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.

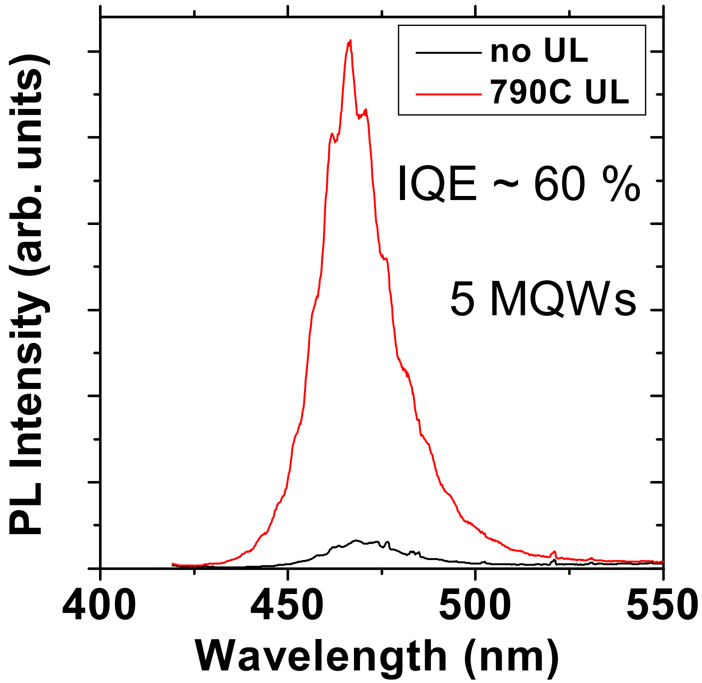
Suggests that the rougher step morphology produces QW with increased PL intensity.

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

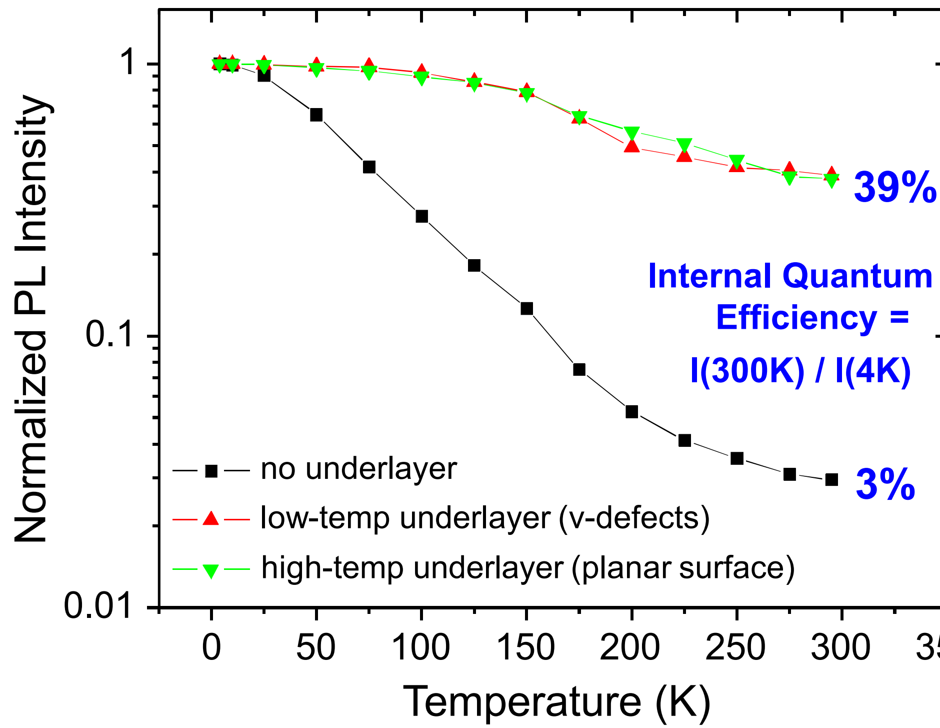
Especially help emission of single QWs

15X increase in integrated PL emission with InGaN UL



Temperature dependent PL studies by Mary Crawford

$$IQE = \eta_{rad} / (\eta_{rad} + \eta_{nonrad})$$

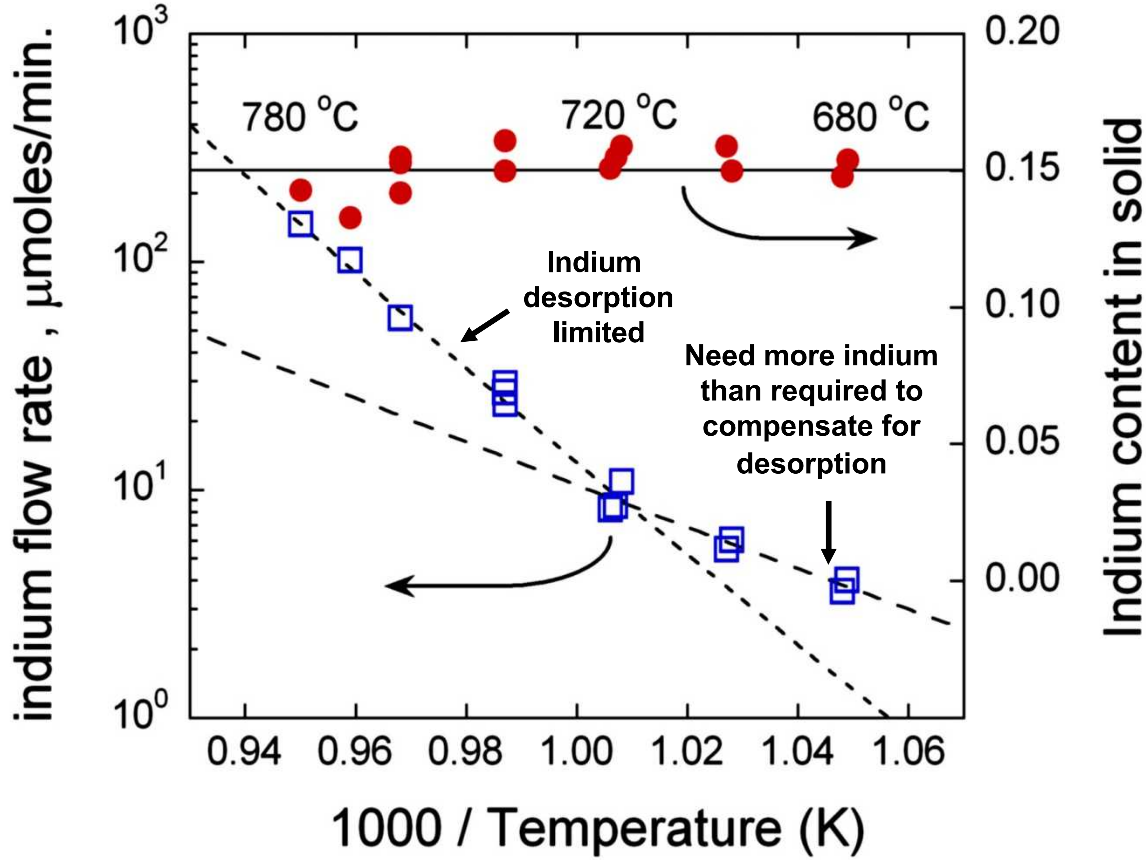


InGaN underlayers have multiple layer step heights similar to MQWs.

Growths to achieve similar QW structure and indium content at different growth temperatures

Goal: achieve the same structure at different QW growth temperatures

Each of the MQW structures has:
Indium content = 15.1 ± 0.7 %
QW thickness = 26.3 ± 3.4 Å
Barrier thickness = 94.6 ± 6.2 Å
PL wavelength = 457 ± 6 nm



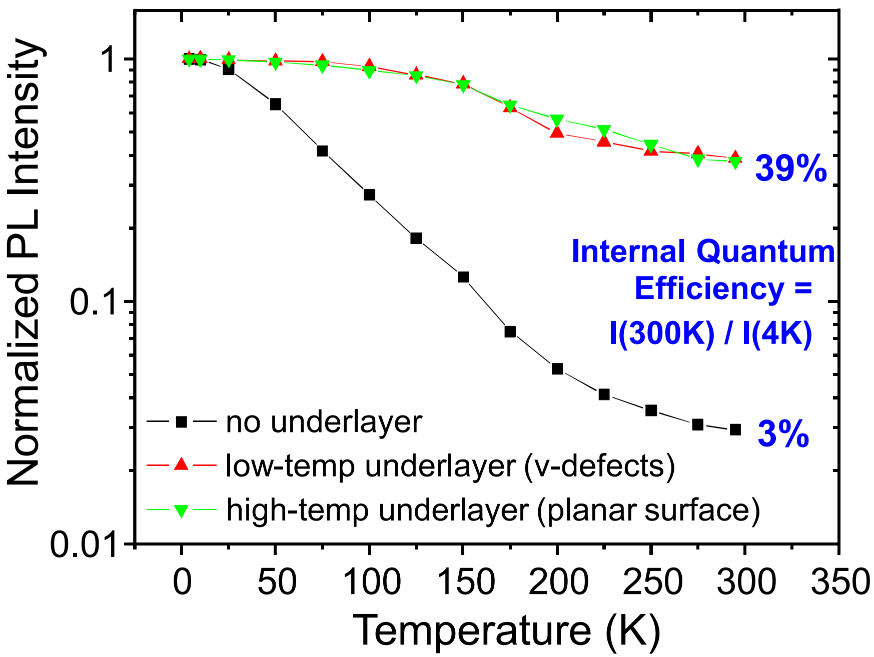
Need less indium as the QW growth temperature is decreased

Measuring internal quantum efficiency (IQE) using variable temperature PL

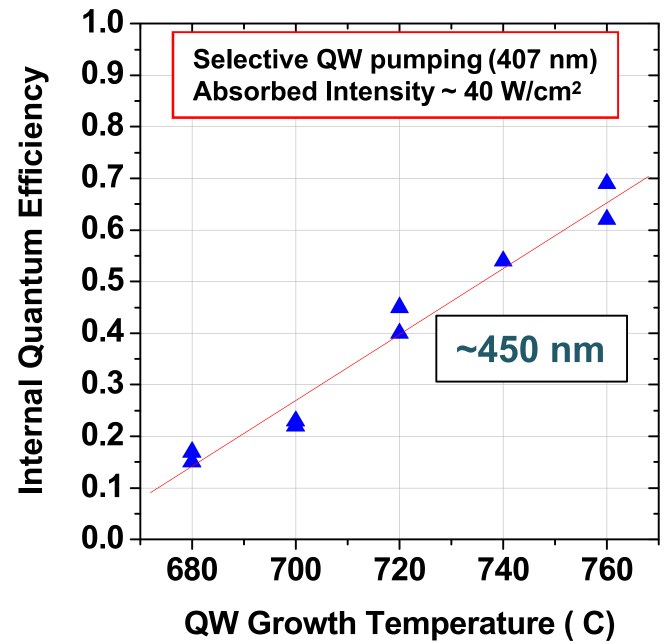
Temperature dependent PL studies by Mary Crawford

Measure PL intensity at room and liquid He temperatures

$$IQE = \eta_{rad} / (\eta_{rad} + \eta_{nonrad})$$



IQE for blue QWs grown at different temperatures

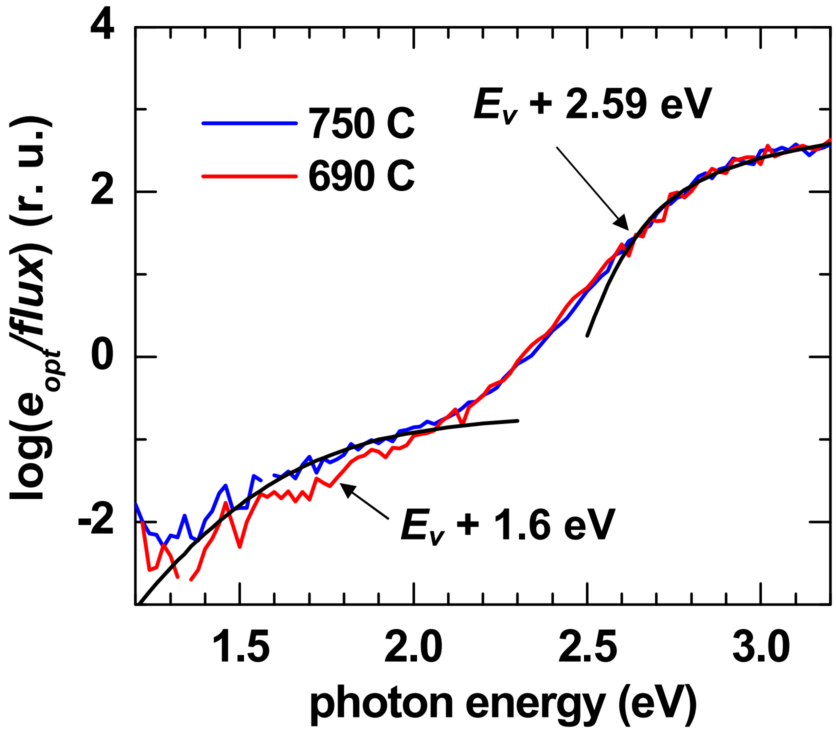


- **Decreasing IQE with decreasing T_{QW}**
- **Fix MQW structure, [V-defect], TDD, UL**
- ***<u>Point defects are likely cause</u>***

InGaN growth temperature influences defect concentration

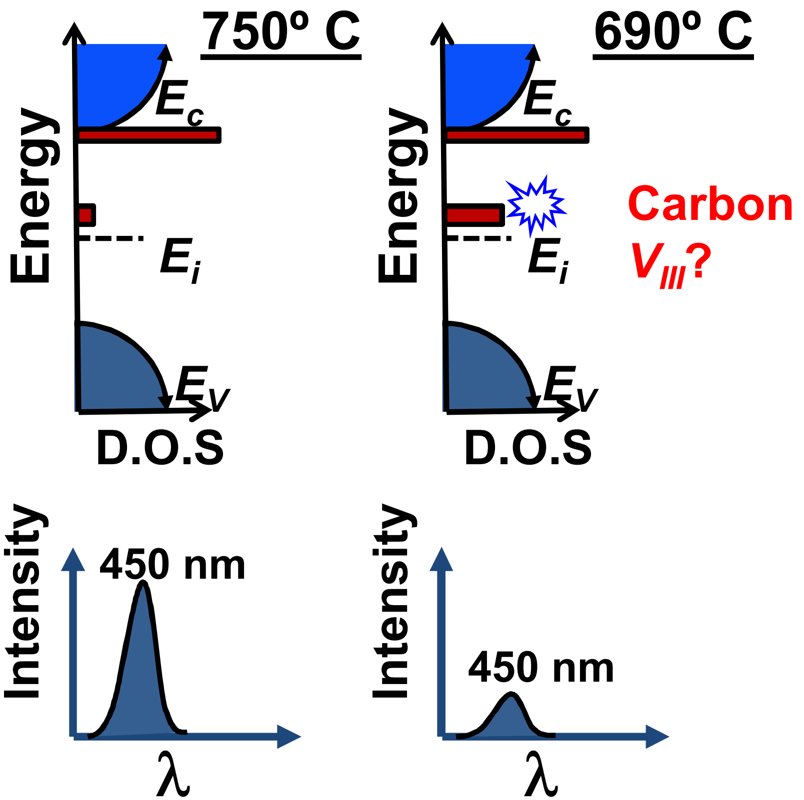
DLOS studies by Andy Armstrong

"Deep Level Optical spectroscopy" of InGaN at two different temperatures. Photo-capacitance is used to determine concentration.



Densities of Deep Levels

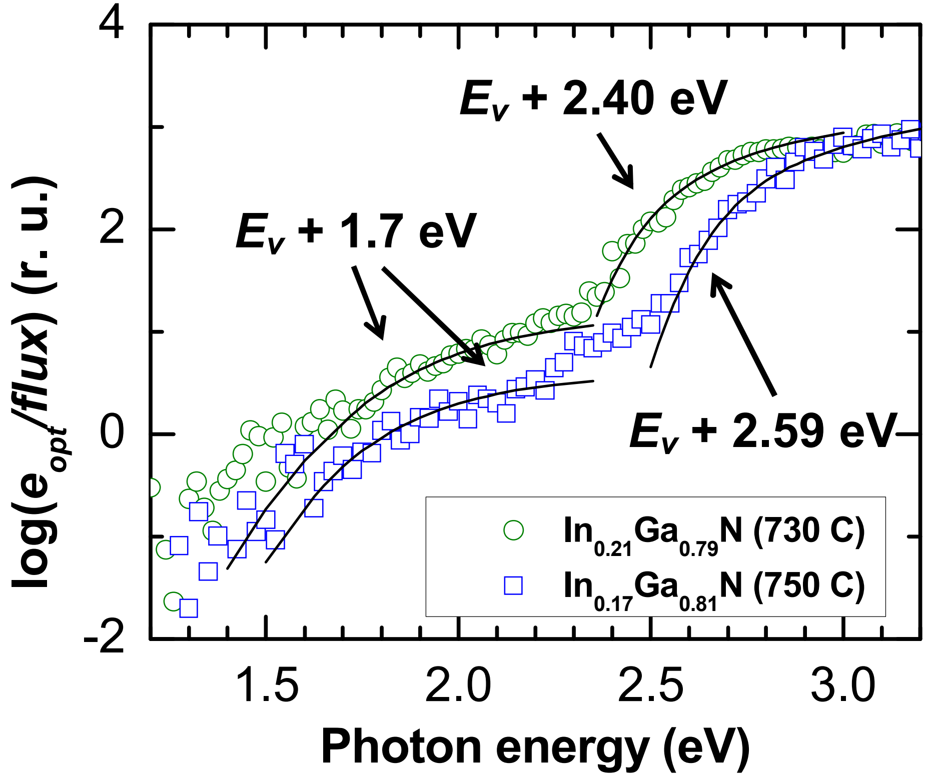
	T_g = 690°C	T_g = 750°C
E_v + 1.6 eV	20e10 cm^{-2}	7e10 cm^{-2}
E_v+ 2.59 eV	**2e12 cm^{-2}**	**2e12 cm^{-2}**



Similar defect levels, different concentrations

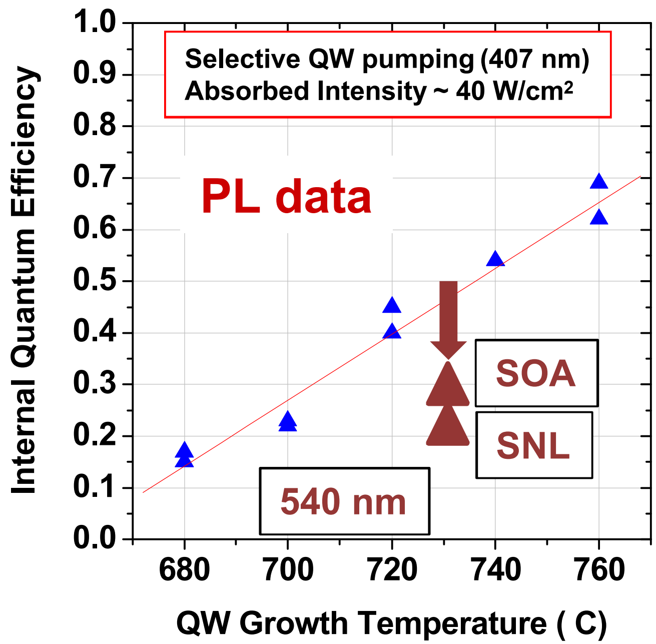
Higher indium concentrations needed for green MQWs further increases the defect concentration

DLOS of blue and green InGaN layers



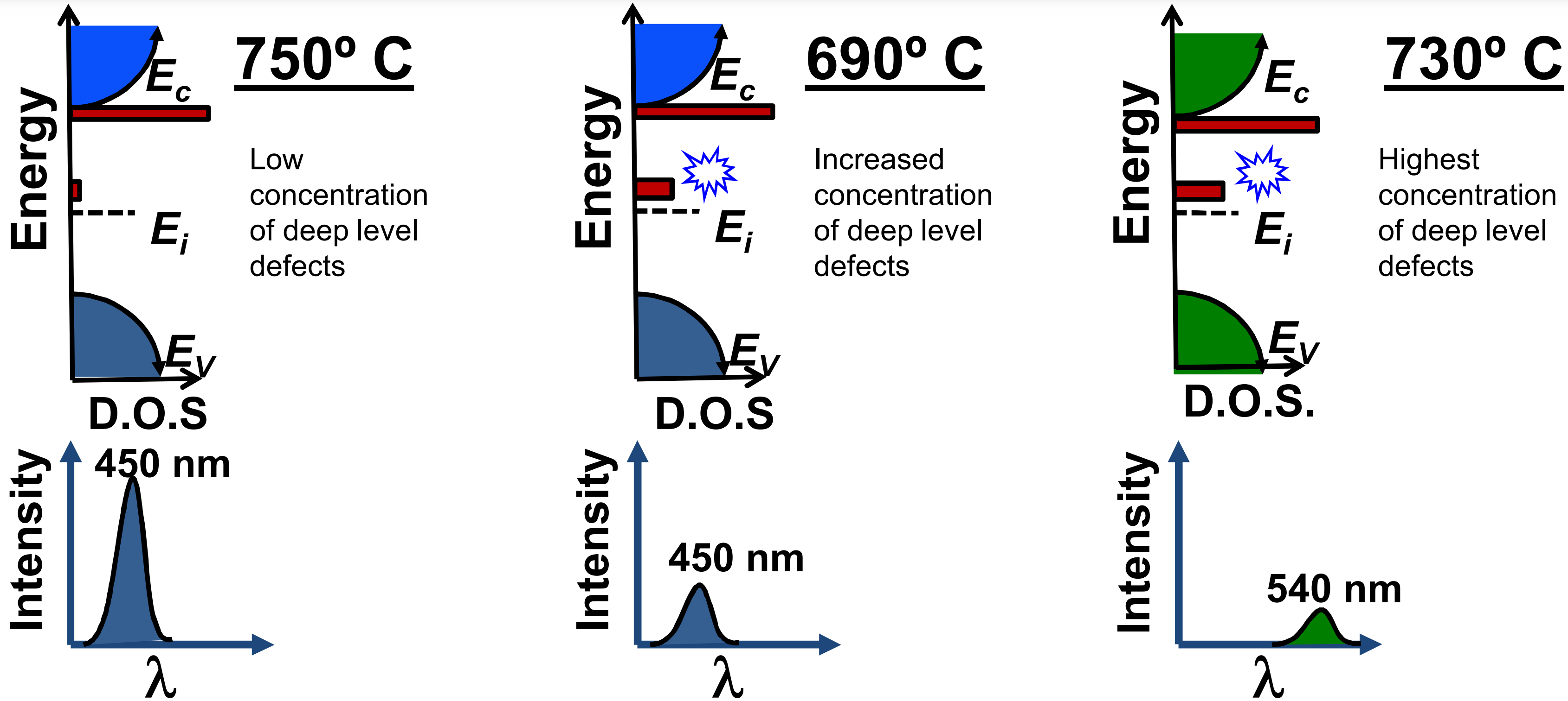
Densities of Deep Levels

	Blue InGaN	Green InGaN
E_v + 1.7 eV	7e10 cm^{-2}	28e10 cm^{-2}
E_v + 2.40 eV	**--**	**5e11 cm^{-2}**
E_v+ 2.59 eV	**5e11 cm^{-2}**	**--**



***4x* increase in [E_v+ 1.7 eV] can contribute to "green gap"**

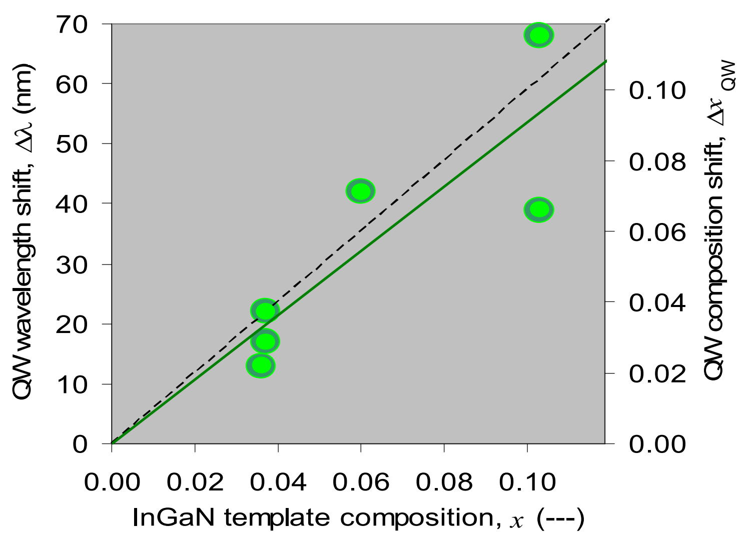
Summary of DLOS and photoconductance studies



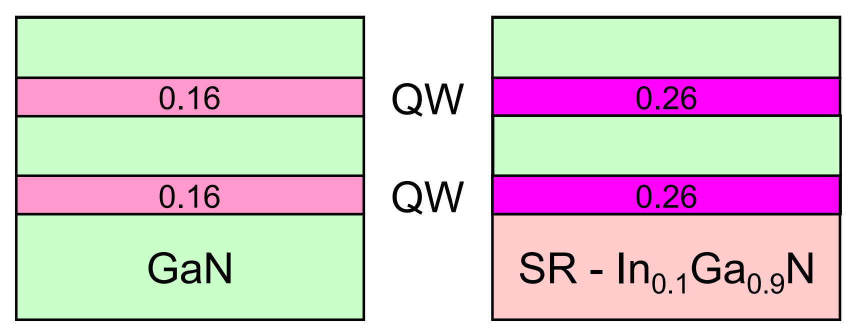
- ***First demonstration of quantitative*** **defect spectroscopy for coherently-strained $In_{0.2}Ga_{0.8}N$ epilayers**
- **Correlated T_g, defects and IQE**
- **Suggest 1.7 eV InGaN defect contributes to the "green gap"**

Strain Relaxed InGaN buffer layers for Green Light Emission

growth run #	GaN template, l_{QW} (nm)	InGaN template, l_{QW} (nm)	Dl_{QW} (nm)	InGaN template, x (---)	InGaN QWs, Dx_{QW} (---)
dnz01166	431	444	13	0.036	0.022
dnz01254	---	479	42	0.060	0.071
dnz01299	442	466	22	0.037	0.037
dnz01376	463	531	68	0.103	0.115
dnz01439	429	446	17	0.037	0.029
dnz01439	429	468	39	0.103	0.066



- **QW emission shifts to longer wavelength on strain-relaxed InGaN templates**
- **Nominal QW compositions on standard GaN templates were x_{QW}~0.16**
- **Compositions of similarly grown QWs on relaxed $In_{0.10}Ga_{0.90}N$ approach x_{QW}~0.26**
- **Able to get increased indium into the QW above the GaN coherency strain limit!**

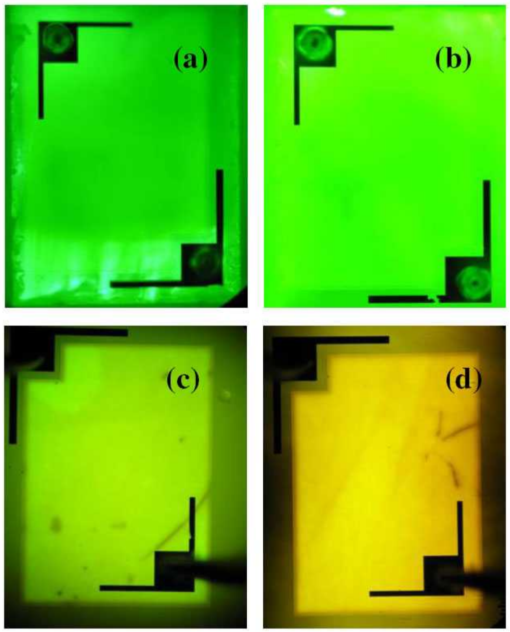


Same growth run

Strain relaxed InGaN developed with Steve Lee

Higher indium incorporation on semipolar GaN

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.

On c-plane GaN, indium is limited to ~20-25%.

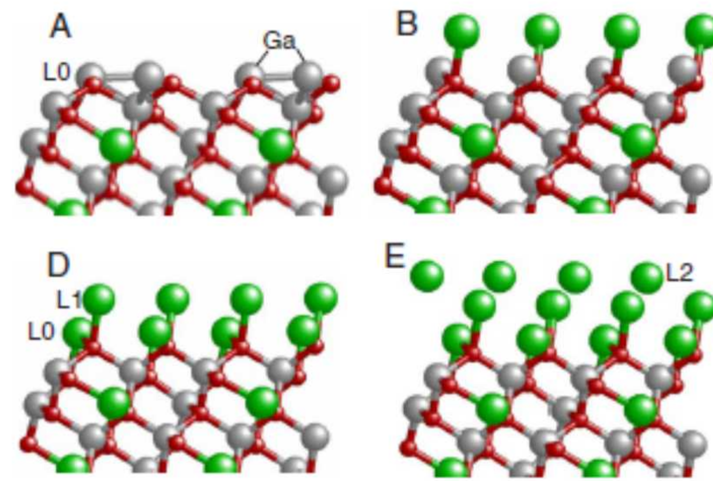


FIG. 3. (Color online) InGaN$(11\bar{2}2)$ surfaces. A, B, D, and E contain successively more In atoms in layers L0, L1, and L2. Indium atoms are large green spheres, Ga atoms are gray, and N atoms are small red spheres.

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 can be achieved above the coherency strain limit.

Conclusions

- SSL is expected to replace incandescent and fluorescent light sources in the next 10-20 years.
- Understanding of the science of SSL lags behind the Edisonian advances – this will likely continue.
- Suspected correlation between InGaN QW morphology and luminescence efficiency – quantification underway.
- Consequences of strain in the InGaN films include; surface structure rearrangements, vacancy formation, and reduced indium incorporation.
- Deep level defects (~1.7 eV) may be non-radiative recombination centers decreasing IQE of blue and green MQWs. May be responsible for the “green-yellow gap.”

Thanks to:

Sandia Colleagues:

Steve R. Lee – XRD analysis, strain relaxed InGaN
Mary H. Crawford – PL, LED studies
Andy Armstrong – DLOS and photocapacitance work
Mike Coltrin – GaN NL evolution studies
Karen Cross – AFM images.
Jerry Thaler – MOCVD growth now at Lasertec.
J. J. Figiel – MOCVD tech.
J. M. Kempisty – MOCVD tech.
R. M. Biefeld – Manager

Supplementary slides

Summary of InGaN step morphology

- Frequency of multiple-layer steps increase…
  - As the amount of indium increases (**V** → **B** → **G**).
  - As the number of QWs increases (up to 2).
  - In thin InGaN underlayers with only 2% indium.
  - As the GaN barrier temperature is lowered.

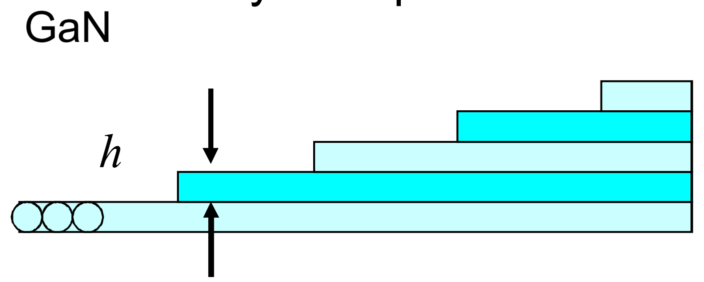
- Two influences on InGaN step structure.
  - Strain relief by forming a multiple-layer step edge. Not sufficient for bulk InGaN strain relief (XRD).

InGaN compressive strain will increase as the indium concentration increases and/or the film thickness increases. Strain relief by point defect generation is also possible.

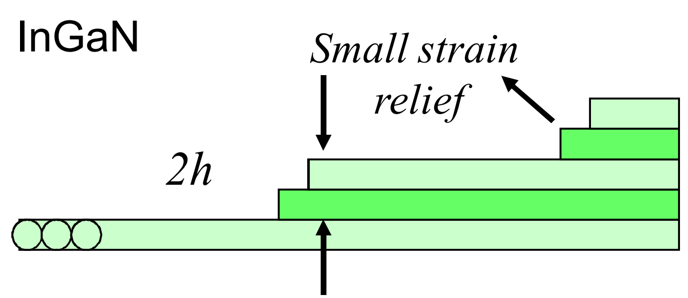
Explore possible changes in growth mechanism in comparing GaN to InGaN growth.

Measure the different smoothing mechanisms responsible for changes in growth morphology.

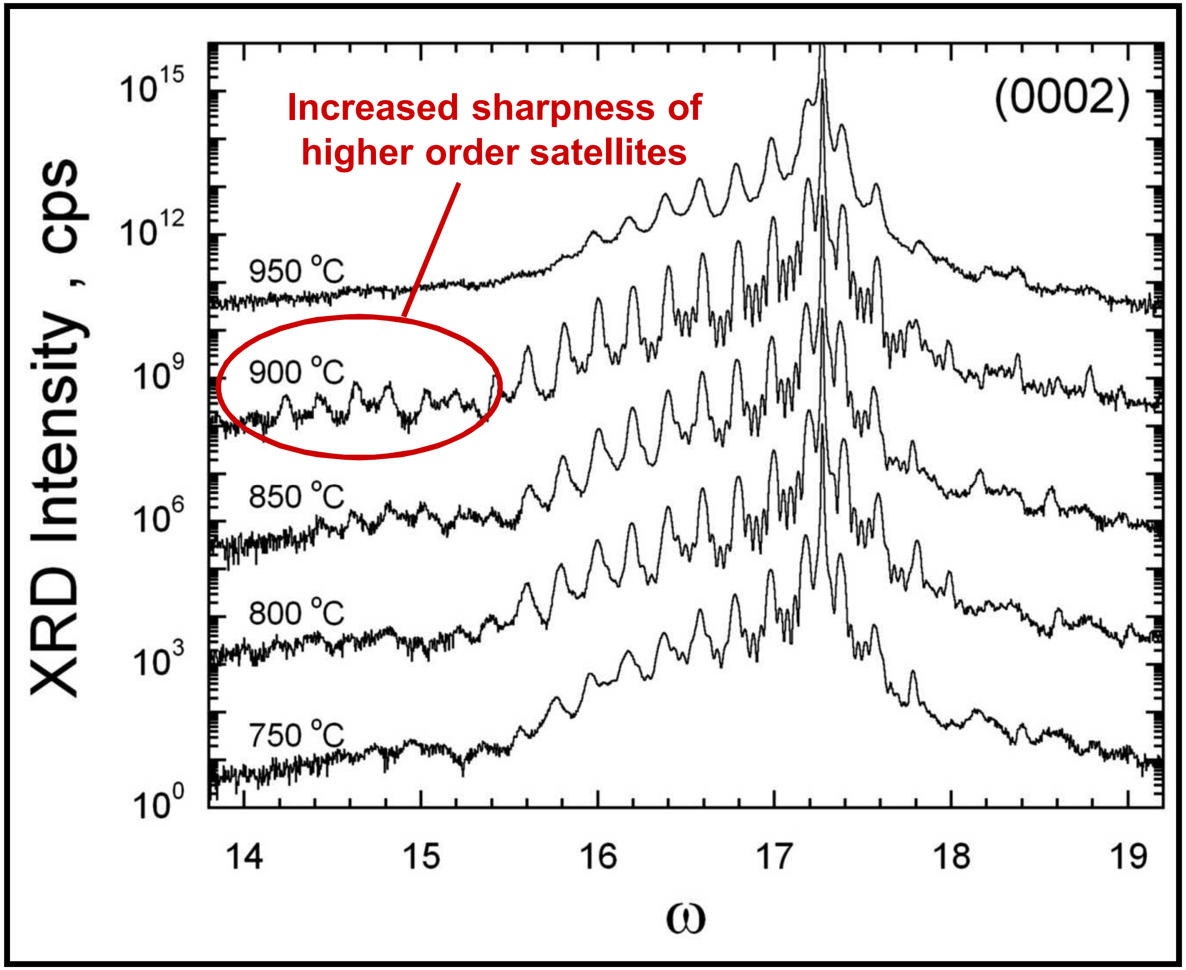
As-grown, GaN has single-layer steps.



InGaN growth increases the frequency multiple-layer steps



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



Using dynamic diffraction fits

Indium content = 0.21 ± 0.01

QW thickness = 3.5 ± 0.1 nm

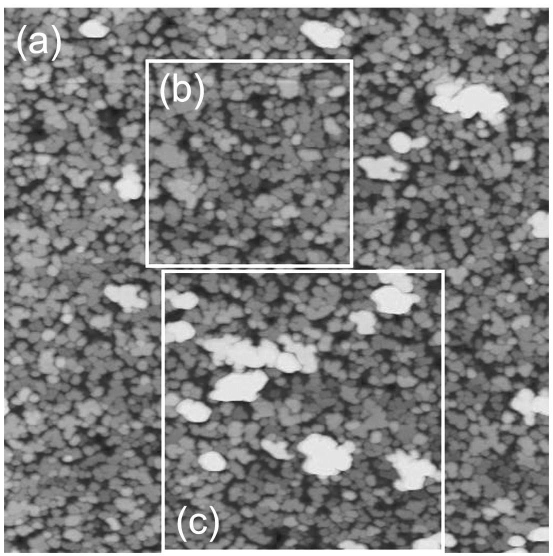
GaN barrier = 19.6 ± 0.5 nm

The sharpness of the higher order satellites indicates better interface alignment for GaN barrier layers grown at 900 ºC compared to those grown at 800 ºC.

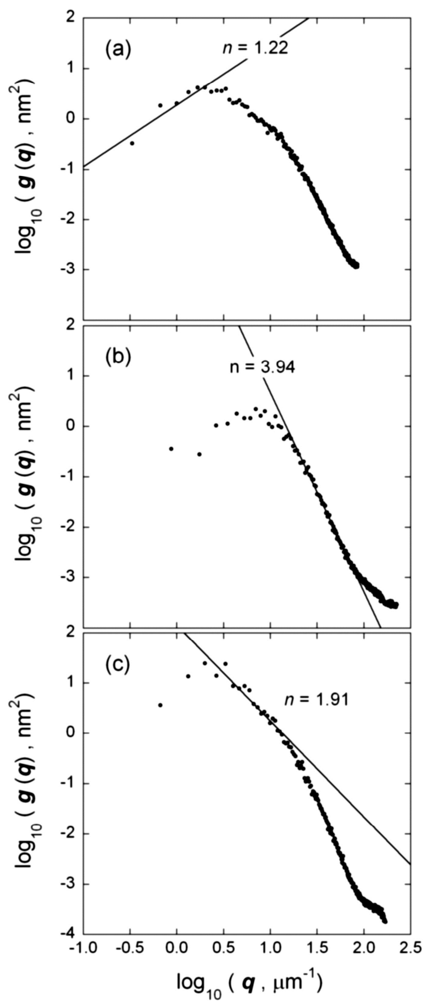
PSD analysis of GaN nucleation layer evolution

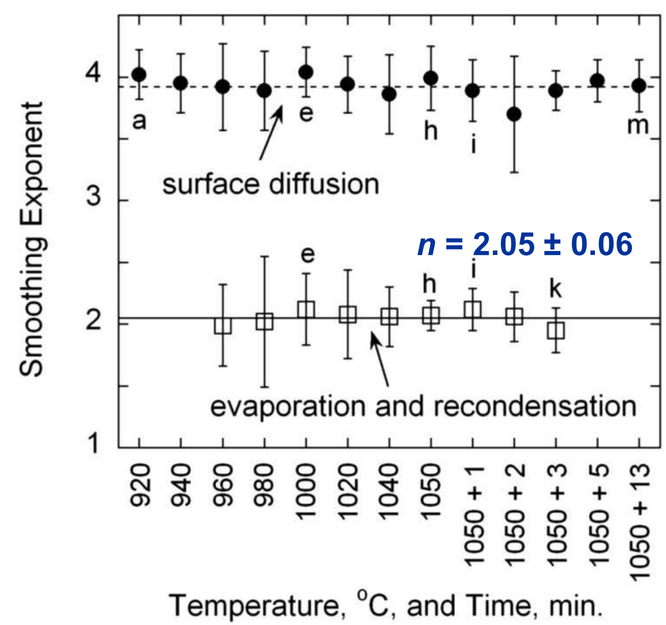
AFM scan of NL at 1000 °C

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



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



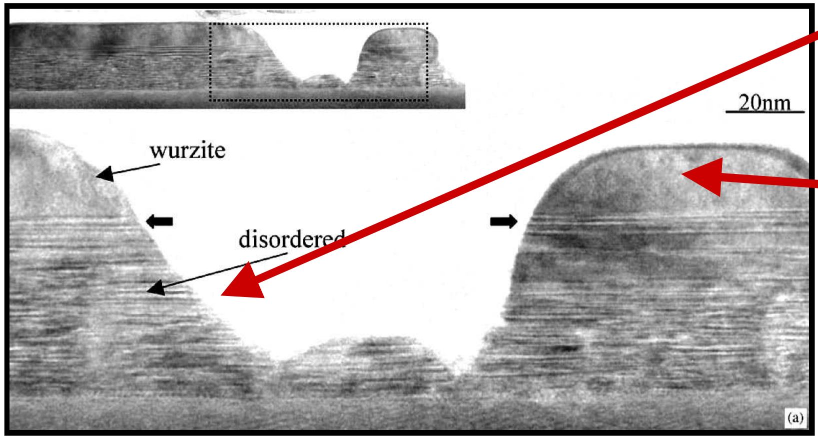


Consistent with gas phase transport model of Mitchell, *et al.*, J. Crystal Growth 222, 144 (2001).

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

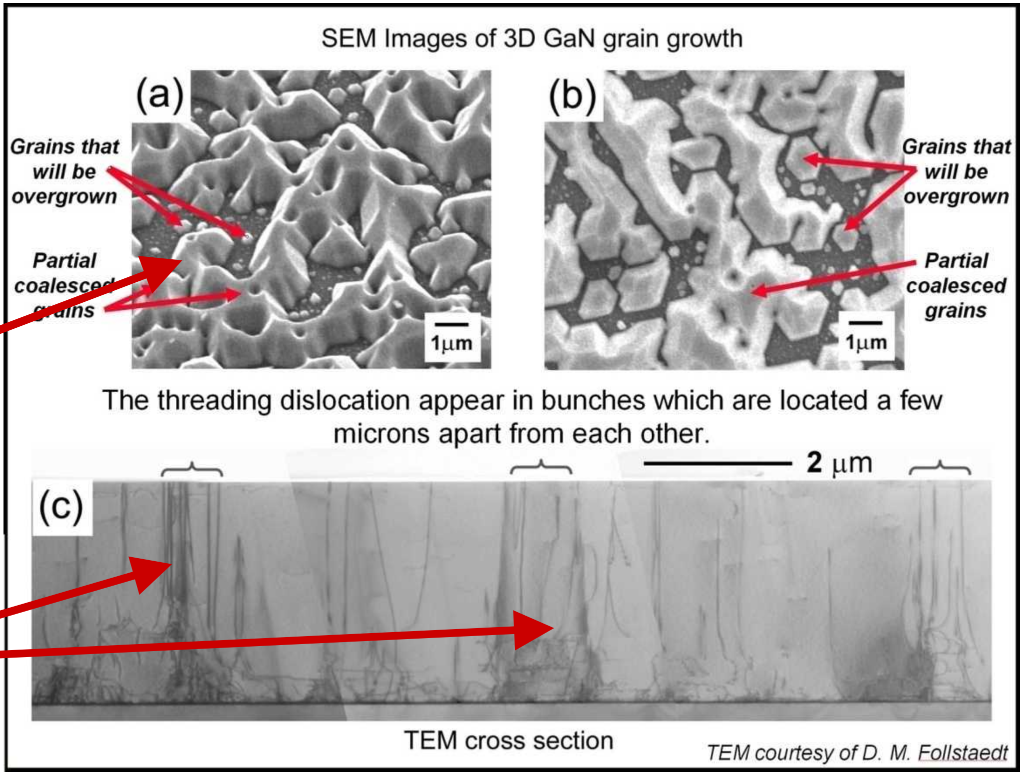
GaN morphology evolution on sapphire

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

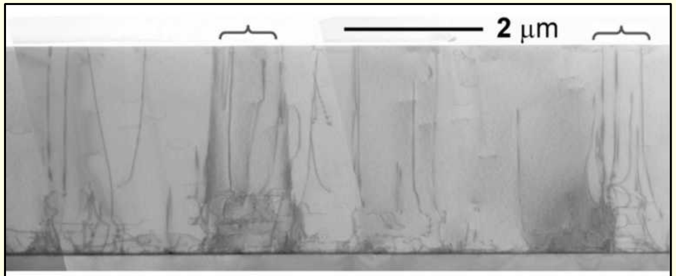


- As grown GaN nucleation layers contain disordered GaN with many stacking faults.
- Once annealed, wurtzite GaN forms on top of disordered GaN NL, forming nano-sized GaN nuclei.

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



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



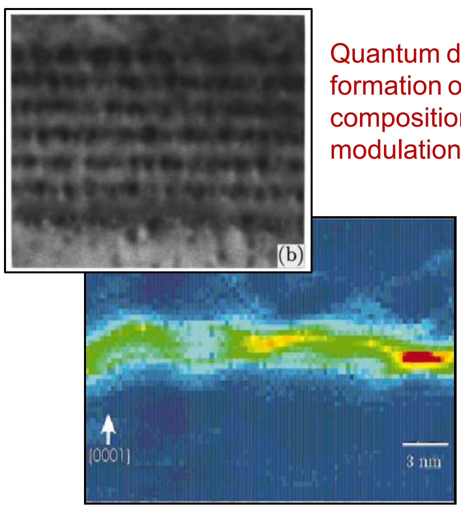
TEM courtesy of D. M. Follstaedt

- 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!

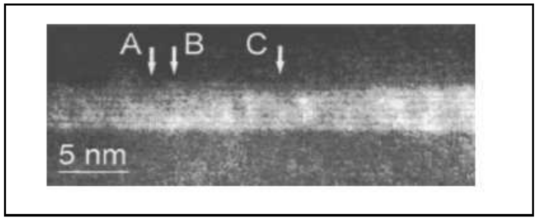
Narukawa, APL 70, 981 (1997)

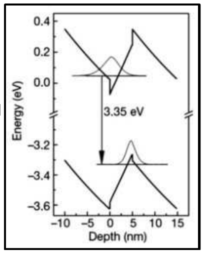


Quantum dot formation or compositional modulation

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

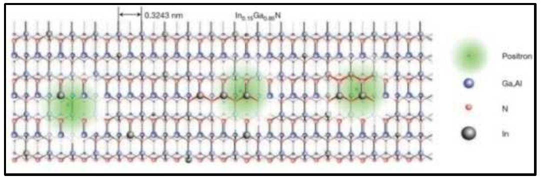
QW thickness fluctuations coupled to strong piezoelectric fields



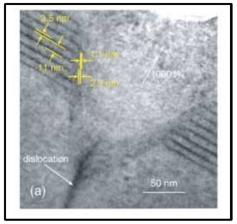


Graham, JAP 97, 103508 (2005)

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

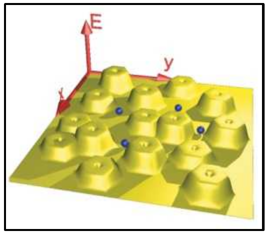


Chichibu, Nat. Mat. 5, 810 (2006)



Thinner QWs around v-defects

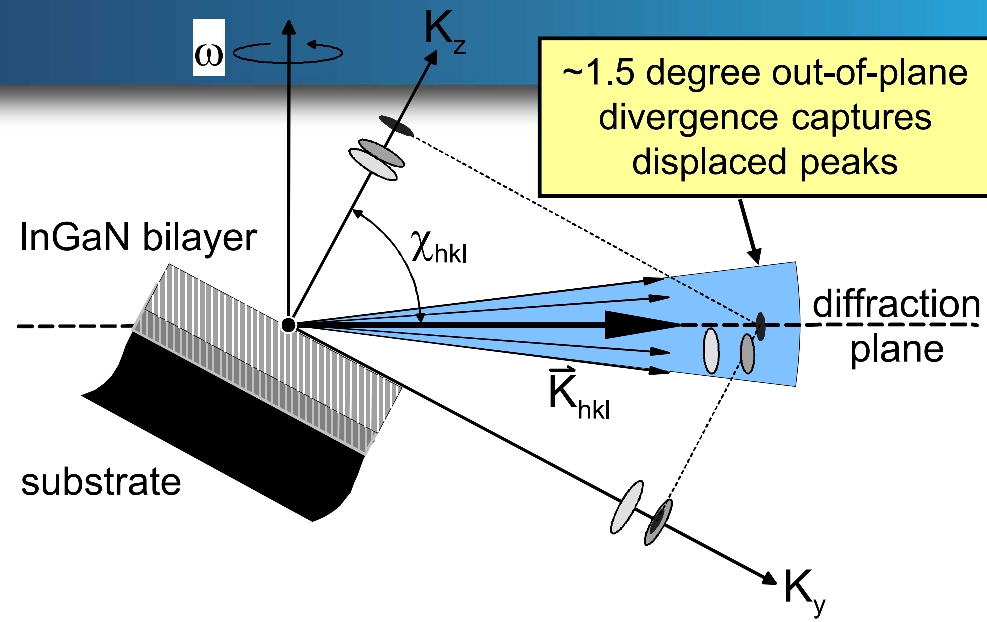
Energetic screening around dislocations



Hangleiter, PRL 95, 127402 (2005).

Sandia National Laboratories

The composition and strain of thick InGaN epilayers were measured by x-ray diffraction.



Scanning procedures:

- Measured 2θ using radial "2θ/ω" scans
- Used skew sample geometry

Reflections:

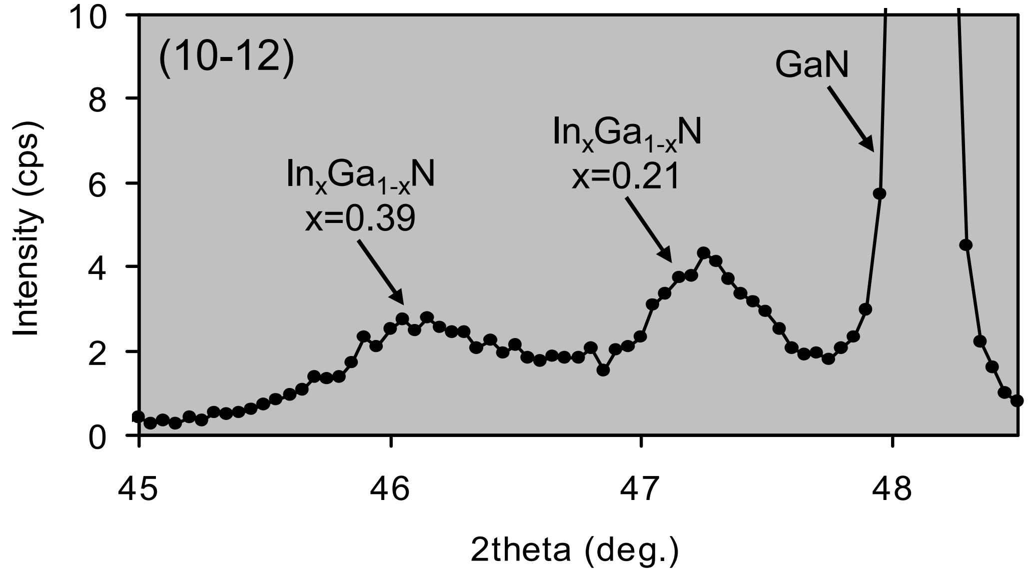
- (0004)
- (10-12) or (20-25)

Key Equations:

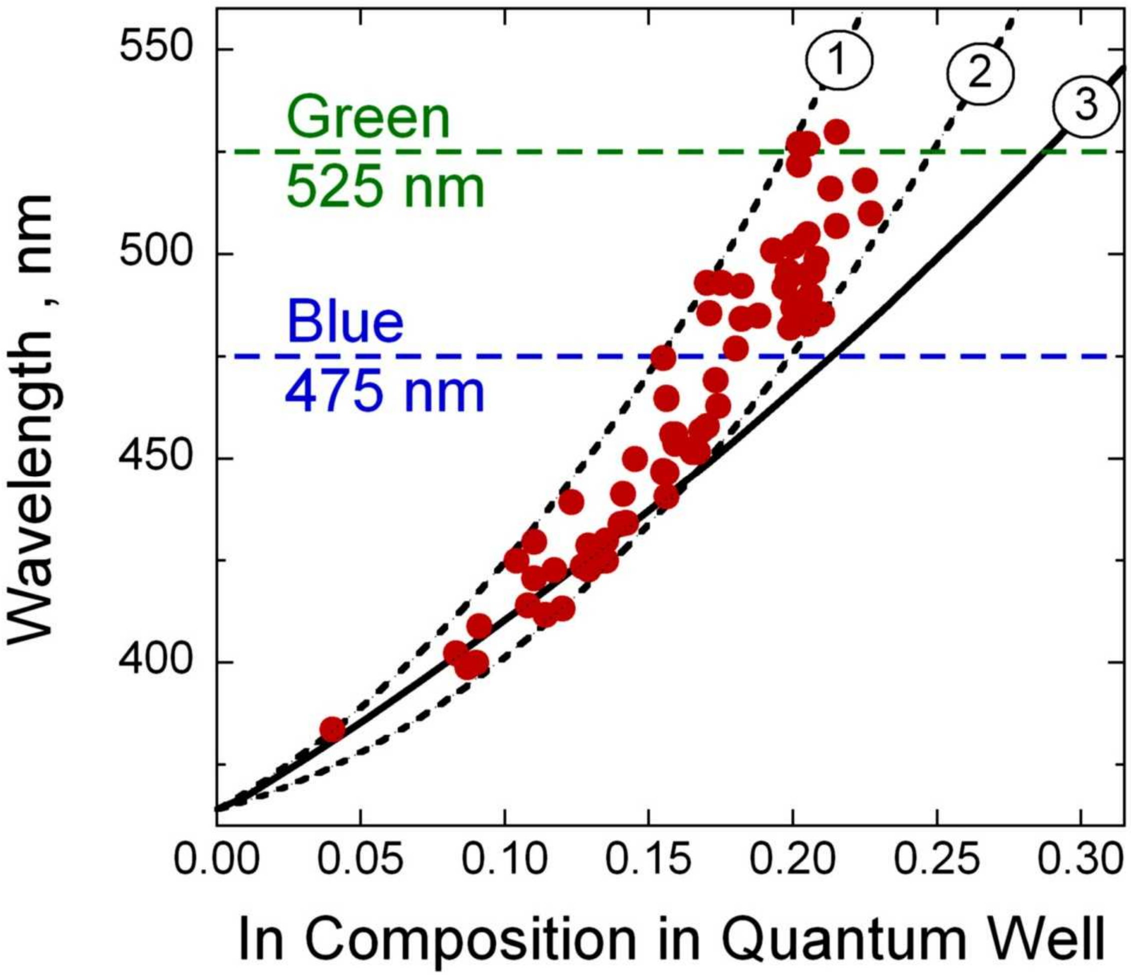
- Bragg's Law gives d-spacings
- Lattice geometry gives a and c
- Vegard's Law gives $a_0(x)$, $c_0(x)$
- Strain couples a to a_0 and c to c_0:
  $\varepsilon_{xx}=(a-a_0)/a_0$, $\varepsilon_{zz}=(c-c_0)/c_0$
- Biaxial stress: $\varepsilon_{zz}=-2(c_{13}/c_{33})\varepsilon_{xx}$

Instrumentation:

- Cu K-α_1 radiation
- Parabolic mirror
- 4-bounce (220) Ge monochromator
- 4-circle goniometer
- 3-bounce (220) Ge beam analyzer



MQWs development work suggests that green emission is possible at x = 0.20



Similar trends are observed for LEDs

In contrast the "folklore" is "bulk values" – <u>Line 3</u>

- 20% In for blue.
- 30% In for green.

However, in some early works the InGaN compositions were incorrect.

<u>Line 1</u> – minimum indium needed for each wavelength

<u>Line 2</u> – maximum indium needed for each wavelength

A single InGaN composition can yield multiple wavelengths because of MQW design considerations.

Eg. Wider wells yield larger piezoelectric induced red shifts