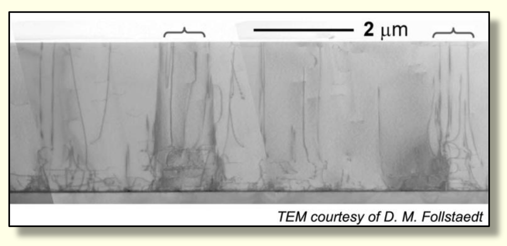
Basic Energy Sciences

InGaN Morphology Evolution and Relationship to Light Emission

D. D. Koleske, S. R. Lee, M. H. Crawford. K. C. Cross, and M. E. Coltrin

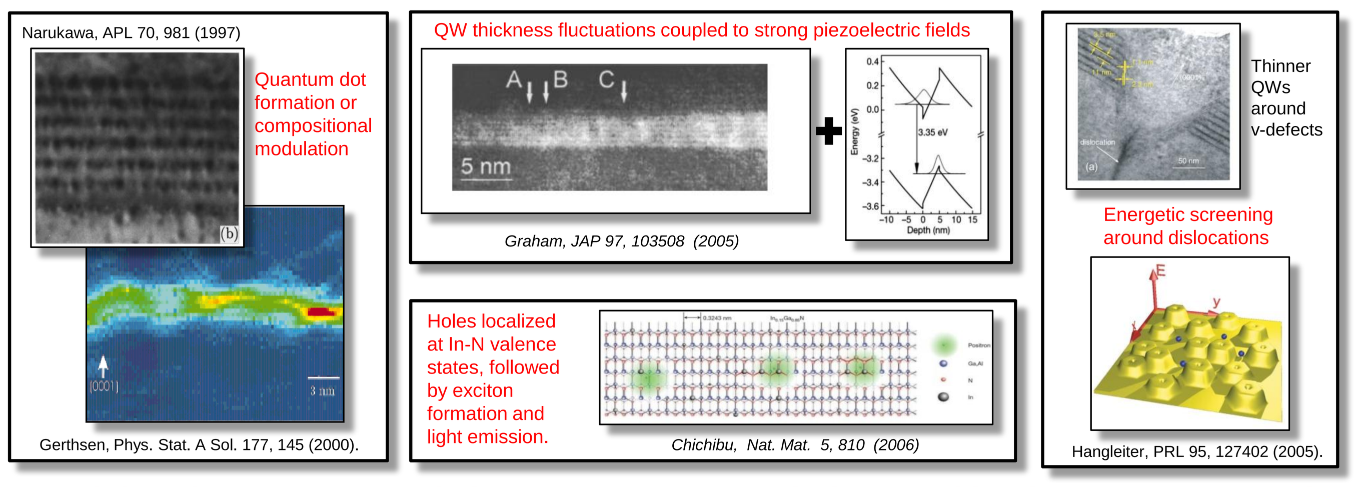
With high dislocation density, how can InGaN LEDs be so bright?



- High brightness LEDs can be 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.

Dislocations ↔ nonradiative recombination sites

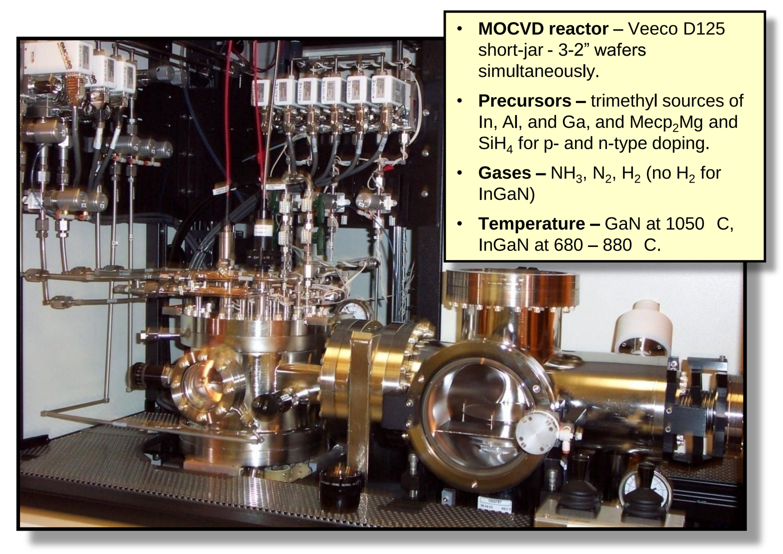
High efficiency suggests some sort of carrier localization; the exact phenomena is unknown?



Several theories suggest a role between InGaN morphology and luminescence properties.

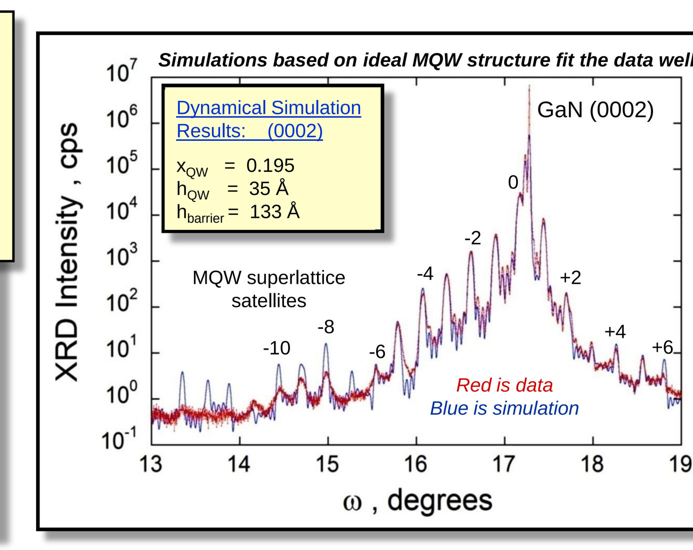
Custom MOCVD growth to investigate InGaN morphology

Hypothesis: InGaN film structure influences the quantum efficiency of InGaN QW films.



- **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 GaN and InGaN are, lower temperature, higher NH_3, no H_2, slower growth rate (less total MO).

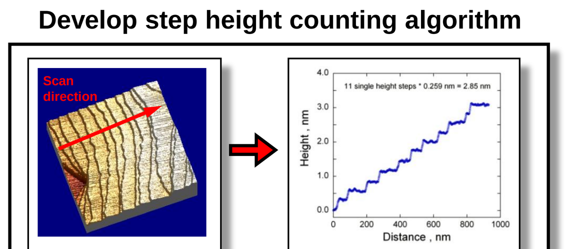


Both the dynamic diffraction fit and lack of change in $K_\parallel$ in the k-space map indicate that the InGaN QW are coherently strained.

Custom growth followed by structural verification (XRD and AFM) and optical characterization (PL and variable temperature PL to measure internal quantum efficiency) allows correlation between InGaN structure and quantum efficiency.

Determining Step Height Distributions on InGaN Underlayers with AFM

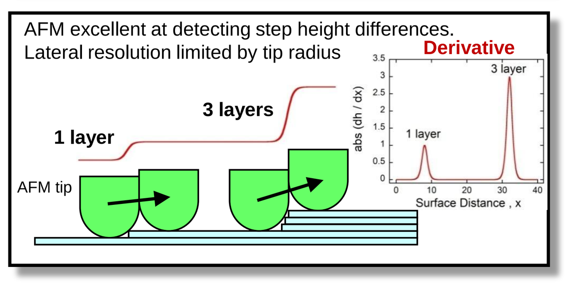
Develop step height counting algorithm



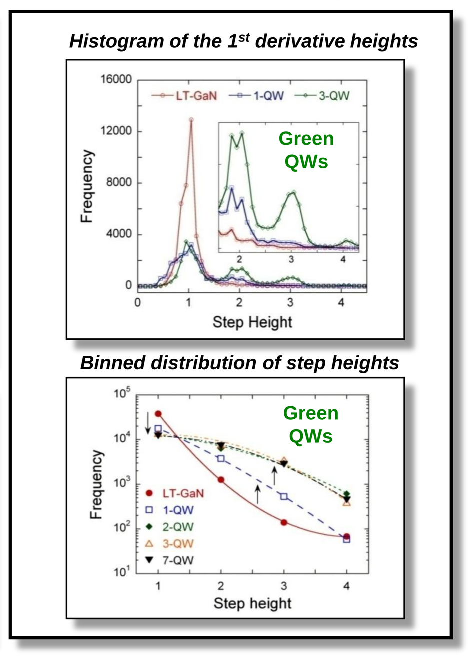
Use AFM image to quantify the step heights.

1). Calculate the first and second derivative.
2). Magnitude of 1st derivative = number of step layers.
3). Second derivative = 0, gives step location.

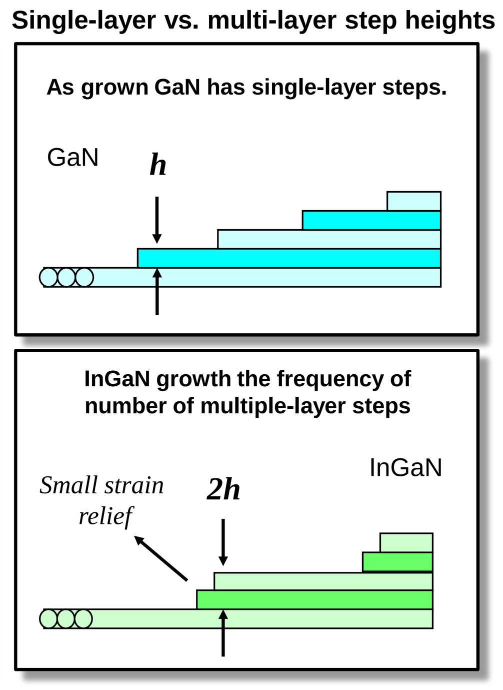
AFM excellent at detecting step height differences. Lateral resolution limited by tip radius



Bin single-layer to multi-layer step heights



Single-layer vs. multi-layer step heights

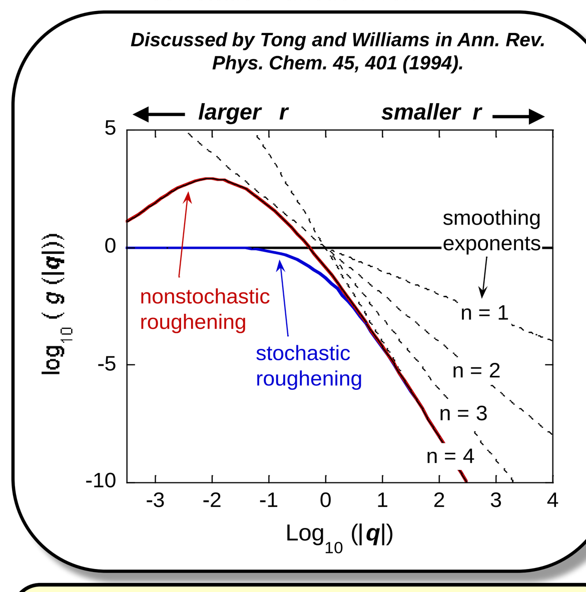


The step layer counting method depends heavily on the quality of the AFM images. It works best when the scan is aligned with the steps increasing in height parallel to the scan direction as shown above.

Use Power Spectral Density to Determine Smoothing Mechanism

Power spectral density (PSD) is the height-height correlation function from AFM

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



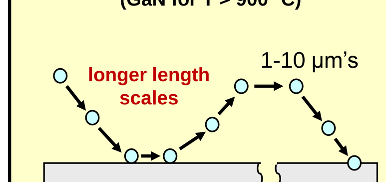
Smoothing mechanisms in C. Herring, JAP 21, 301 (1950).

- n = 1 - plastic flow driven by surface tension
- n = 2 - evaporation and recondensation
- n = 3 - volume diffusion
- n = 4 - surface diffusion

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

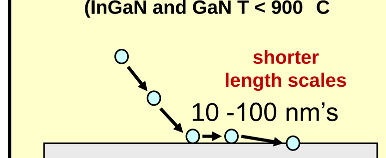
$$g(|\mathbf{q}|,t) \propto \frac{\Omega}{c_n|\mathbf{q}|^n}$$

n = 2
evaporation and recondensation (GaN for T > 900 C)

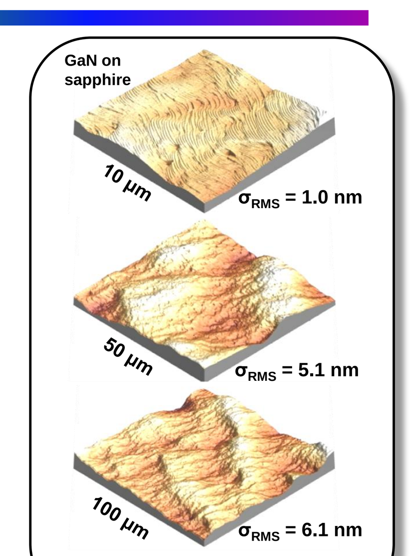


See Mitchell et al., JCG 222, 144 (2001).

n = 4
surface diffusion (InGaN and GaN T < 900 C)

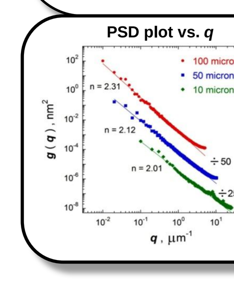


See Koleske et al., JAP 84, 1998 (1998).



Roughness increases with scan size

PSD plot vs. q



PSD analysis suggests an n=2 evaporation/ recondensation mechanism.

Example 1: MQWs with Different GaN Barrier Growth Temperatures

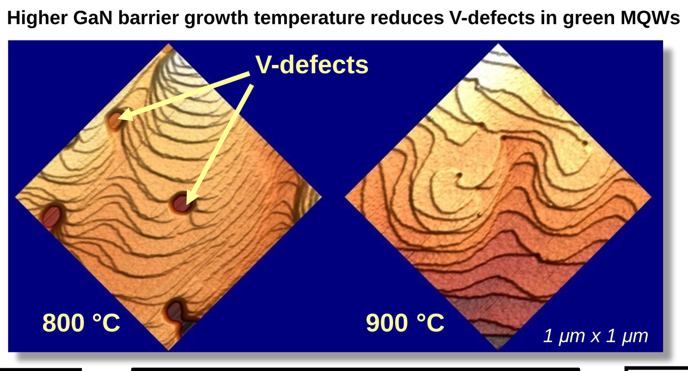
Green MQW structure

InGaN QW
GaN barrier layer
InGaN QW
GaN barrier layer
InGaN QW
GaN barrier layer
InGaN QW
GaN barrier layer
InGaN QW
GaN barrier layer
GaN n-type
c-plane sapphire

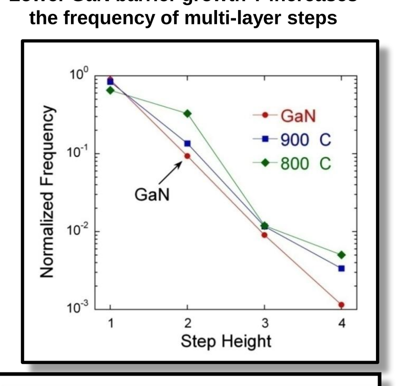
730 C

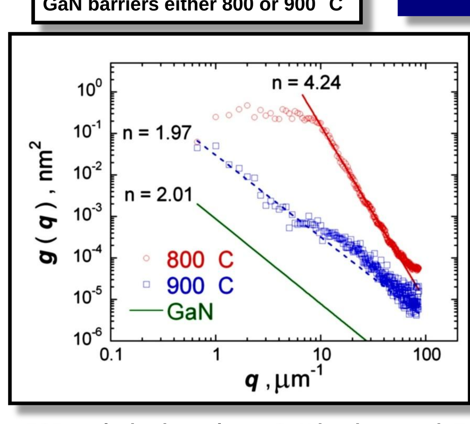
GaN barriers either 800 or 900 C

Higher GaN barrier growth temperature reduces V-defects in green MQWs

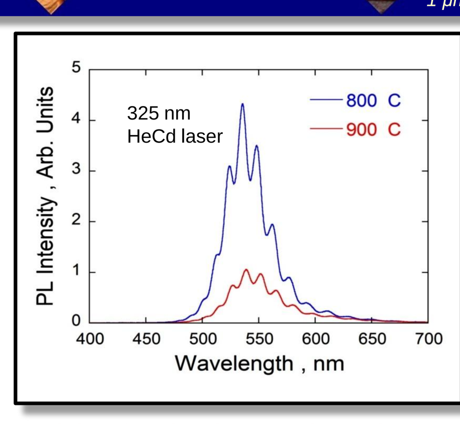


Lower GaN barrier growth T increases the frequency of multi-layer steps

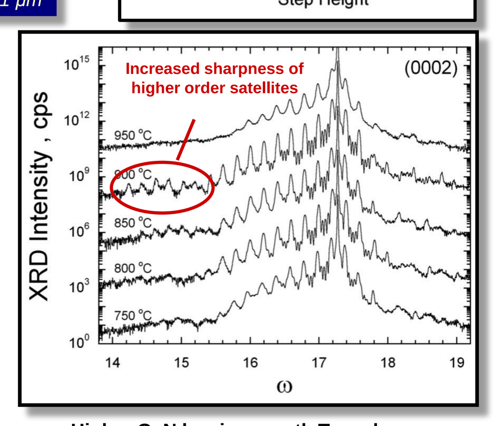




PSD analysis shows lower GaN barrier growth T is smoothed by surface diffusion (n=4).



Higher GaN barrier growth T reduces the PL emission intensity.



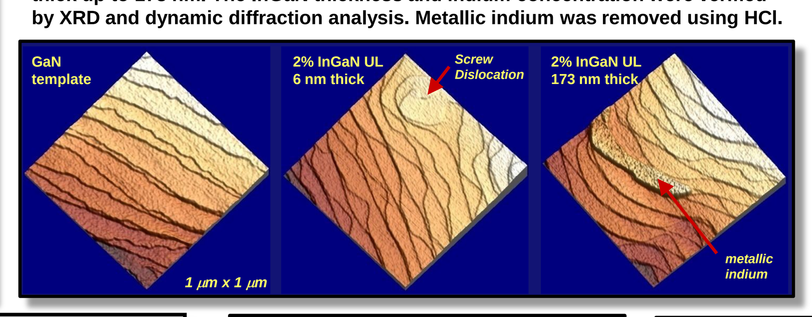
Higher GaN barrier growth T produces smoother InGaN/GaN interfaces (n=2)

Example 2: Increasing Thickness of InGaN Underlayers

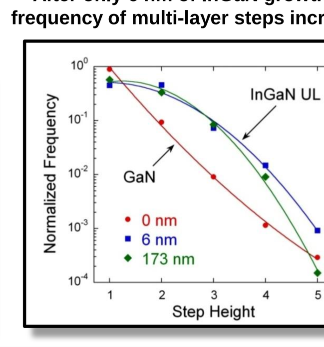
InGaN (2%) UL structure

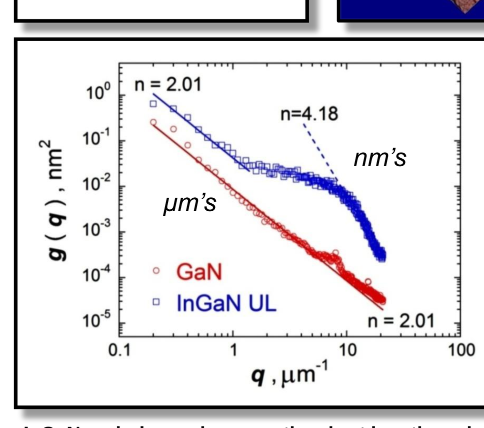
2% InGaN UL	880 C
GaN n-type	1050 C
c-plane sapphire	

A series of InGaN underlayers were grown on GaN templates ranging from 6 nm thick up to 173 nm. The InGaN thickness and indium concentration were verified by XRD and dynamic diffraction analysis. Metallic indium was removed using HCl.

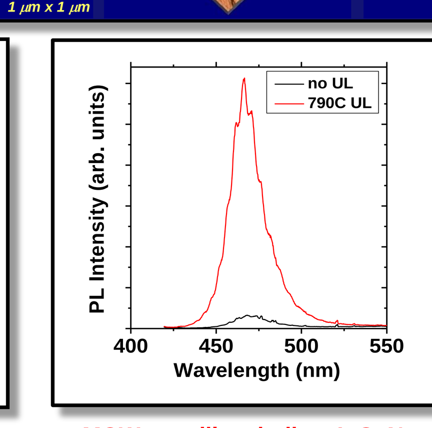


After only 6 nm of InGaN growth the frequency of multi-layer steps increases.

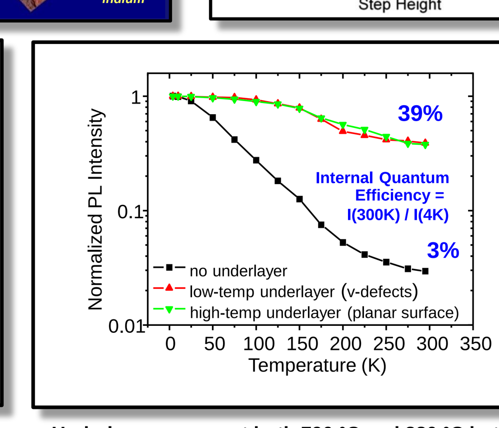




InGaN underlayers increase the short length scale roughness via a surface diffusion mechanism (n=4).



MQWs on dilute indium InGaN underlayers produce increased PL emission.



Underlayers grown at both 790 °C and 880 °C both increase the internal quantum efficiency of MQW compared to MQWs grown directly on GaN.

Future work: Further correlation between InGaN morphology and PL emission

1). Continue experiments to correlate InGaN morphology to luminescence properties with the overall goal of uncovering the exact mechanism.

2). Develop model to explain change in step morphology as indium is added to GaN.

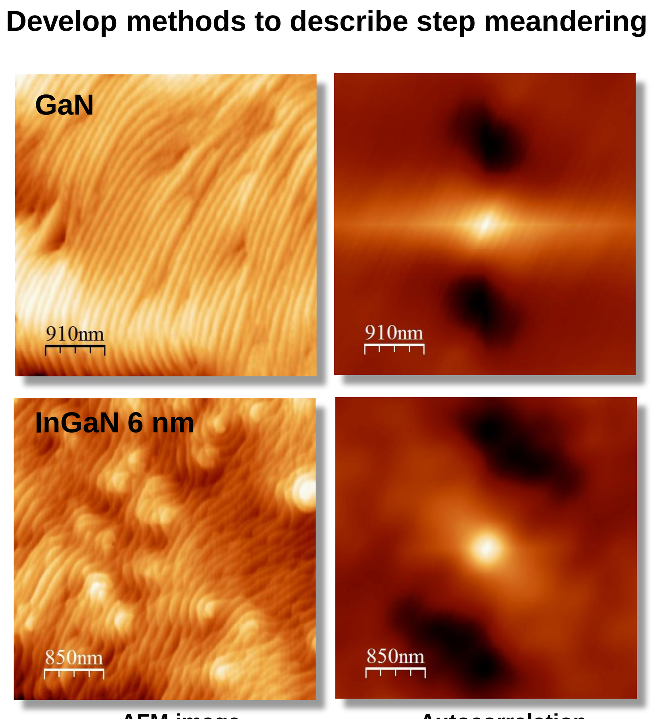
3). Develop method to quantify increased step meandering on InGaN surfaces using auto-correlation methods (see images to the right).

4). Determine degree of indium surface accumulation (surfactant effect) and determine the role of surface indium in step morphology evolution.

5). Investigate difference between trimethyl- and triethyl-gallium for the growth and luminescence properties of InGaN underlayers.

Methodology developed in this work will be used to study InGaN growth on nonpolar and semipolar GaN substrates (see nonpolar and semipolar future work poster).

Develop methods to describe step meandering



Well defined periodicity with minimal mounding.

Less defined periodicity and larger sized mounding.

AFM image / Autocorrelation

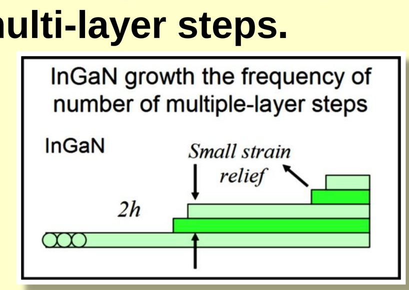
Calculated autocorrelation (right) of AFM scans (left) to determine if direction and degree of step meandering can be quantified.

Conclusions for InGaN morphology and PL studies

In addition to examples 1 and 2 above, the frequency of multi-layer steps increases

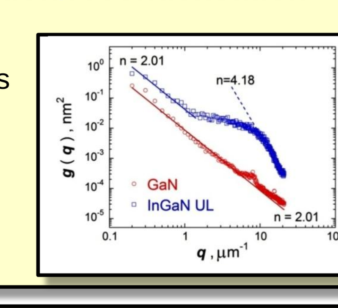
- As the indium increases (Violet → Green).
- As the number of QWs increases (up to 2).
- Even in thin underlayers with only 2% indium.
- As the GaN barrier temperature is lowered.

The change in the InGaN step structure is likely caused by forming *strain relief* provided by forming the multi-layer steps.

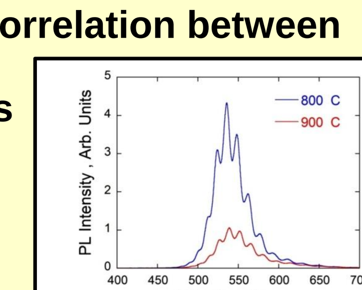


Temperature controls morphology
Lower T - surface diffusion
Higher T - evaporation/recondensation

Smoothing mechanisms determined from the power spectral density (PSD) analysis of the AFM images.



Demonstrated correlation between the presence of multi-layer steps increased PL intensity.



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