AVS International Symposium , Albuquerque, NM, October 17-22, 2010

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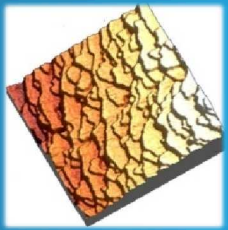
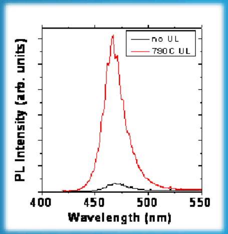
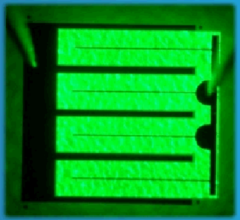
Studies of InGaN Growth Morphology and Its Relationship to Multiple Quantum Well Luminescence







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Sandia National Laboratories

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

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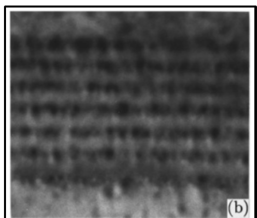
Is there a role of structure in InGaN QW emission intensity?

Strong emerging belief that some sort of localization phenomena enhances InGaN MQW and LED efficiency.

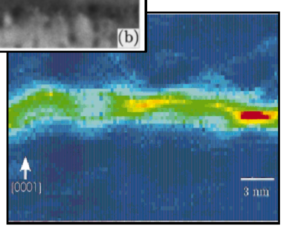
Several proposed explanations for localization

Narukawa, APL 70, 981 (1997)

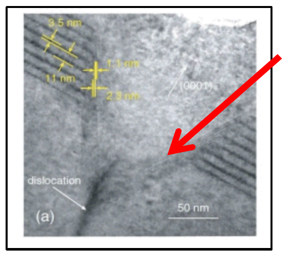


Q-dots form Likely in TEM

Indium segreg-ation?

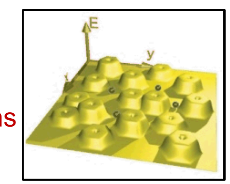


Gerthsen, Phys. Stat. A Sol. 177, 145 (2000).



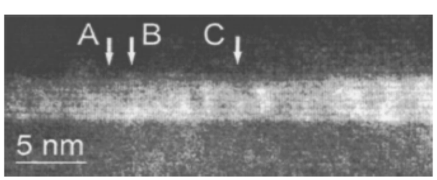
Thinner QWs around v-defects

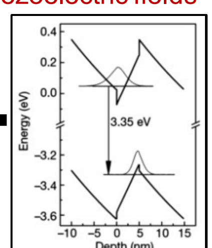
Energetic screening around dislocations



Hangleiter, PRL 95, 127402 (2005).

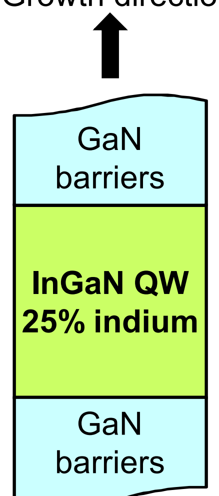
QW thickness fluctuations coupled to strong piezoelectric fields





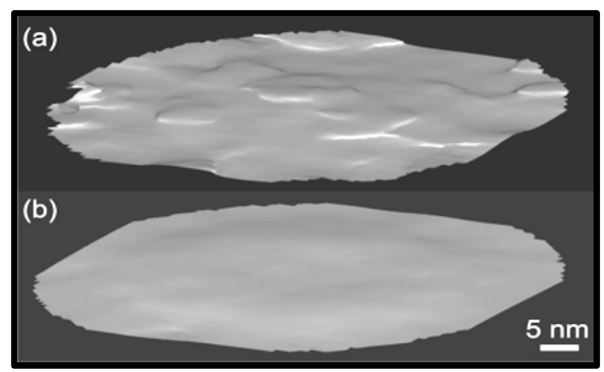
Graham, JAP 97, 103508 (2005)

- Many observations of InGaN quantum well structure (dots, v-defects, clustering, steps).
- Do these structured QWs have improved light emission? Is there a best structure?



Engineered QW designs – "gappy" QWs

3D Atom probe images of a bright commercial green LED showing a rougher top QW interface



Upper QW interface

Lower QW interface

Colin Humphreys' group - EMC 2008, Vol. 2: Materials Science, pp. 41–42 (2008)

Outline

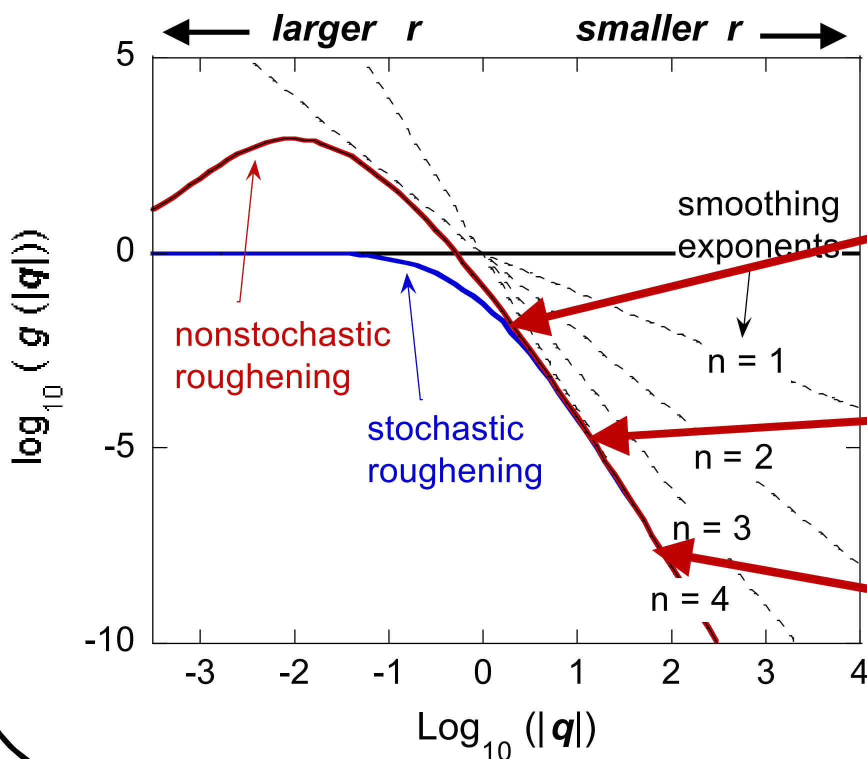
Goal – Study GaN and InGaN surface morphology changes and determine how (and if) it relates to the luminescence intensity observed MQWs and LEDs.

- Describe how power spectral density (PSD) can be used to quantify smoothing mechanisms and length scales.
- Influence of smoothing mechanisms on resulting GaN and InGaN morphology – especially step structure.
- Determine if correlation exists between short length scale roughness and MQW luminescence intensity.
- Future work and conclusions

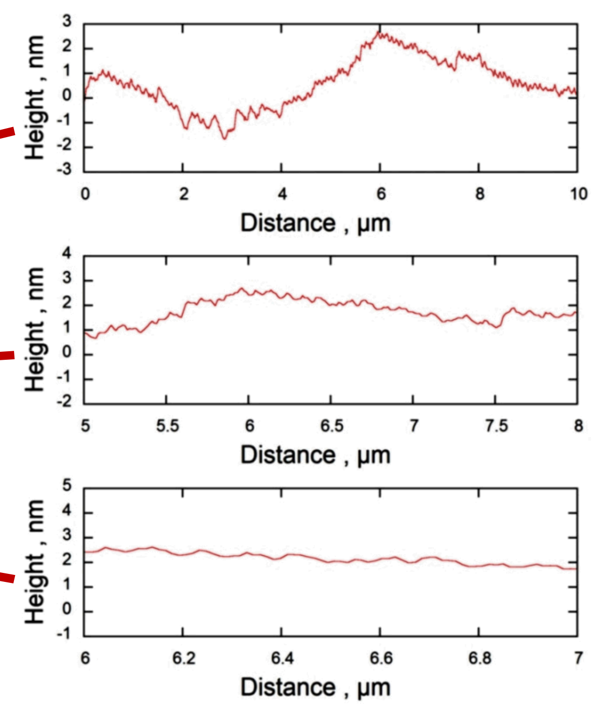
Power spectral density (PSD) is a length scale roughness

From AFM image, the PSD is the height-height correlation function, $h(x,y)$
The PSD called g is calculated as a function of q = *1/r (reciprocal of distance)*.

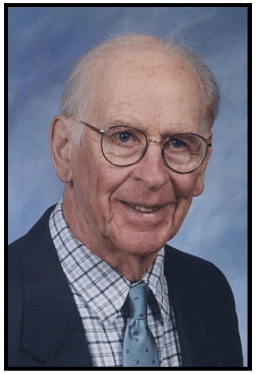
Discussed by Tong and Williams in Ann. Rev. Phys. Chem. 45, 401 (1994).



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



Smoothing mechanisms calculated by Herring in 1950



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**

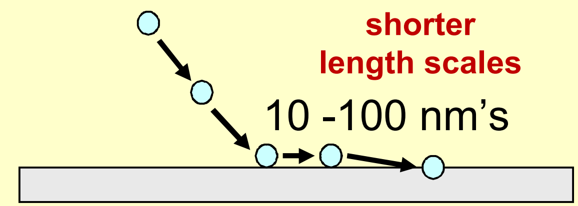
Geometric details of mechanisms could influence the values of n by as much as 0.5.

Mechanism influences length scale over which the smoothing occurs.

***n* = 4**

surface diffusion

(InGaN and GaN T < 900 °C)

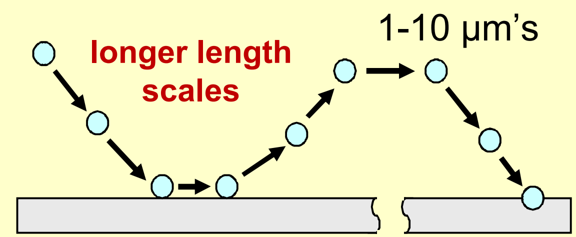


See Koleske et al., JAP 84, 1998 (1998).

***n* = 2**

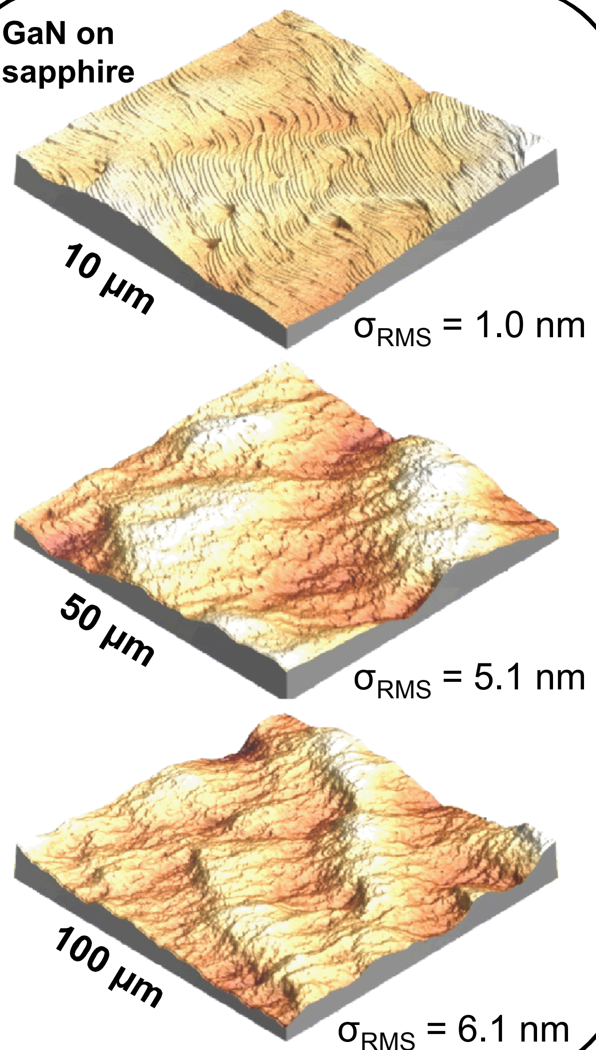
evaporation and recondensation

(GaN for T > 900 °C)

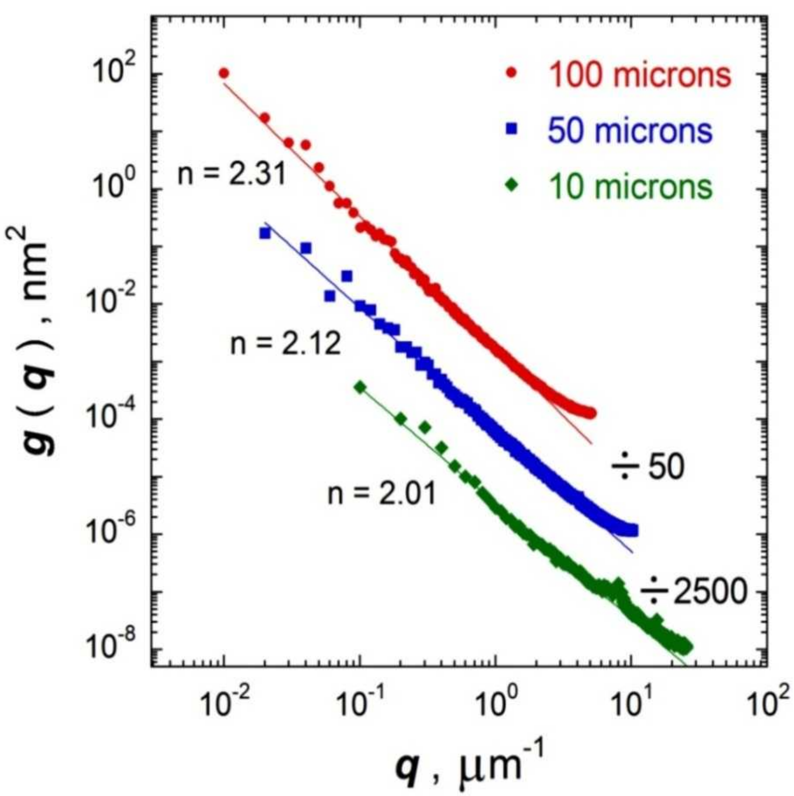


See Mitchell et al., JCG 222, 144 (2001).

PSD analysis of GaN films on sapphire



σ_{RMS} typically depends on scan size

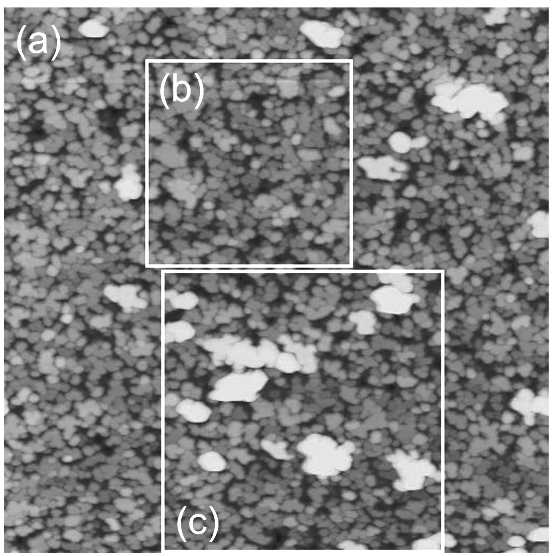


Smoothing mechanism is evaporation and recondensation
This mechanism also observed on m-plane GaN

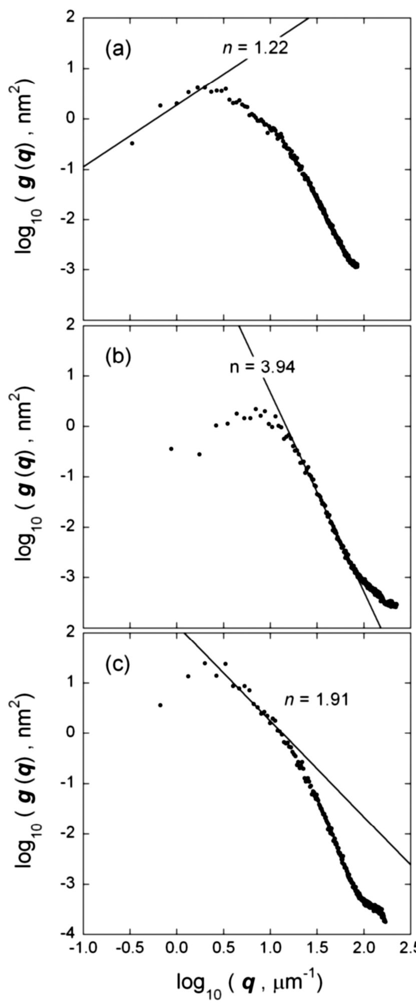
PSD analysis of GaN nucleation layer evolution

AFM scan of NL at 1000 °C

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

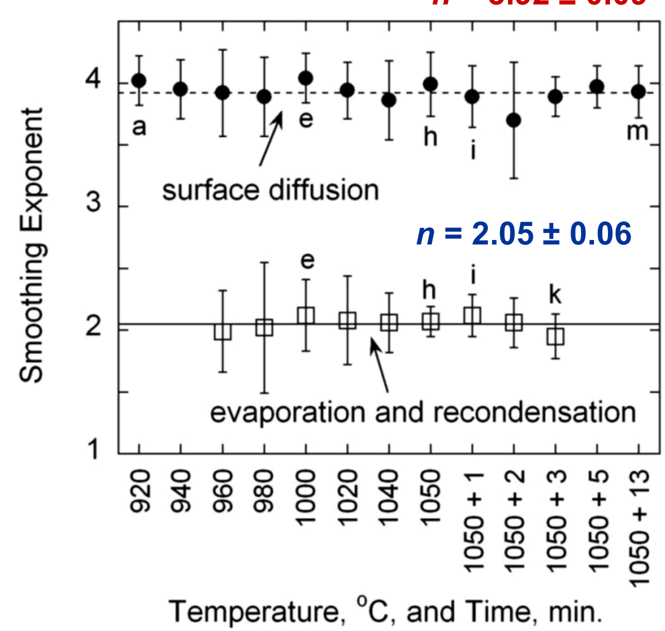


GaN nuclei form out of deposited GaN NL via evaporation and reconden-sation mechanism, *n* = 2.



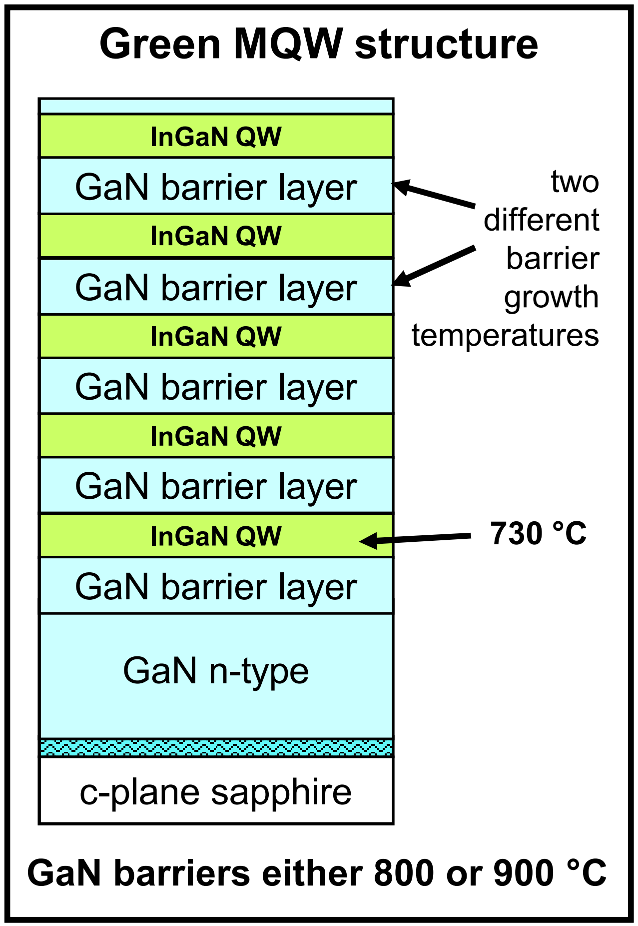
Study of 30 nm thick GaN NLs grown at 540 °C on sapphire.

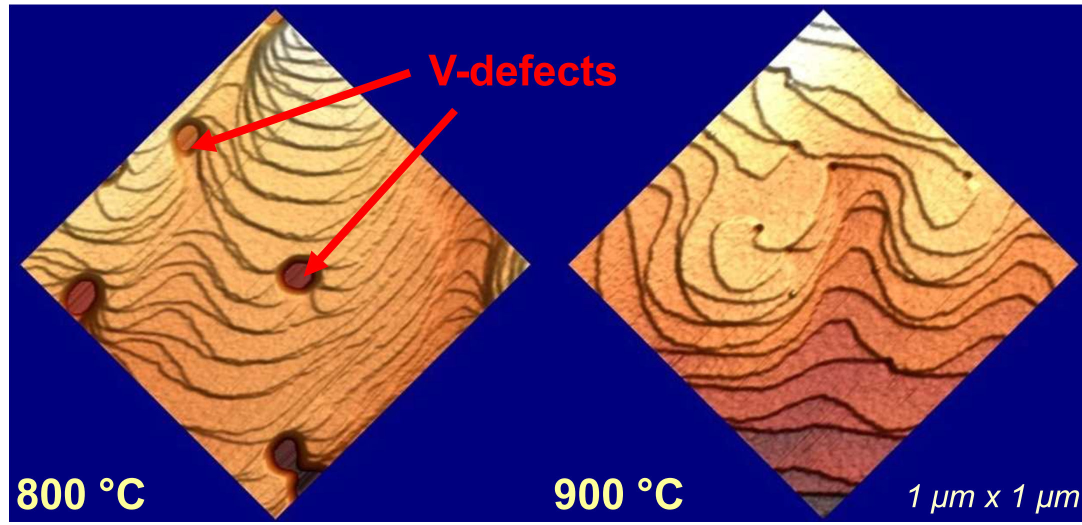
The NLs were stopped along different points in the annealing schedule and NL morphology measured using AFM.



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

InGaN morphology can be changed by varying GaN barrier growth temperature

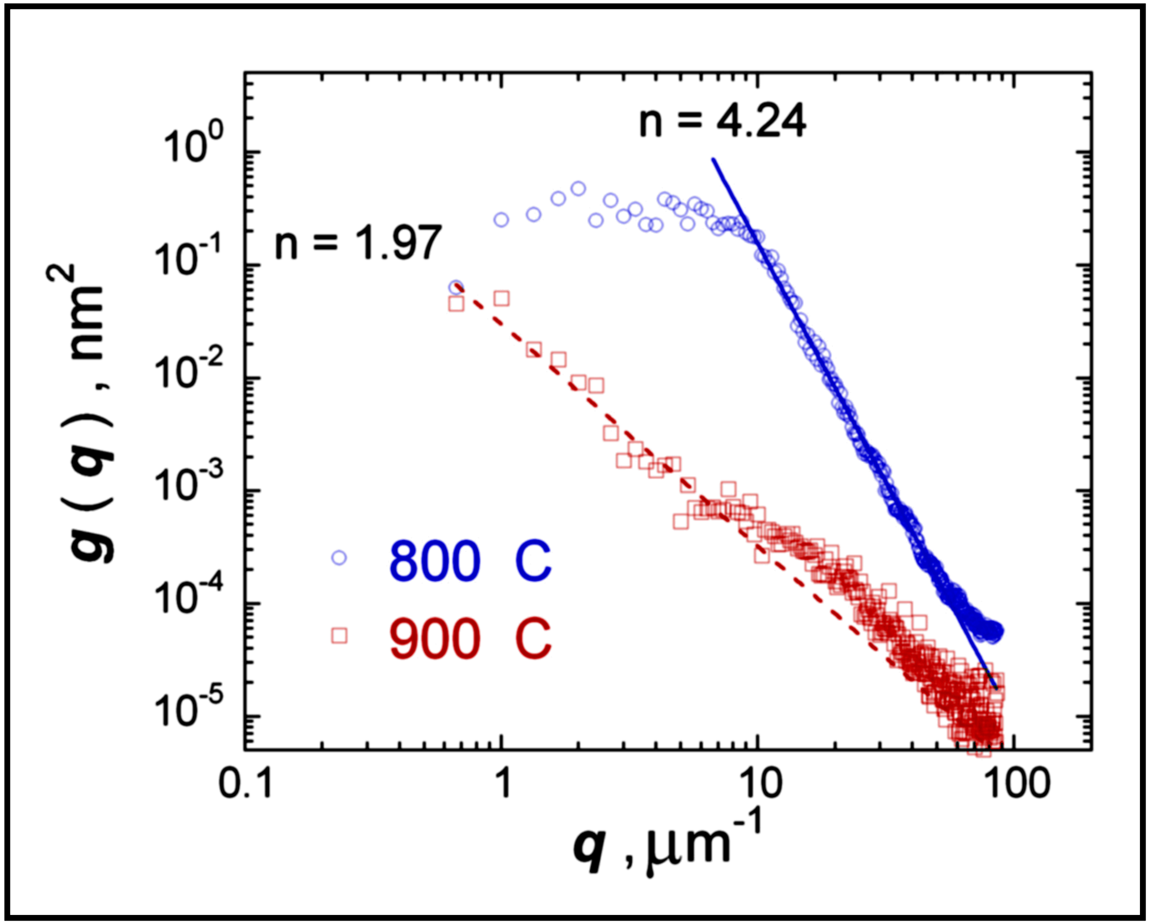




For the multiple quantum wells the InGaN is grown at 730 ºC and the GaN barrier layers were grown at either 800 ºC or 900 ºC.

Morphology differences include:
800 ºC – increased V-defects & double layer steps.
900 ºC – fewer V-defects & double layer steps.

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



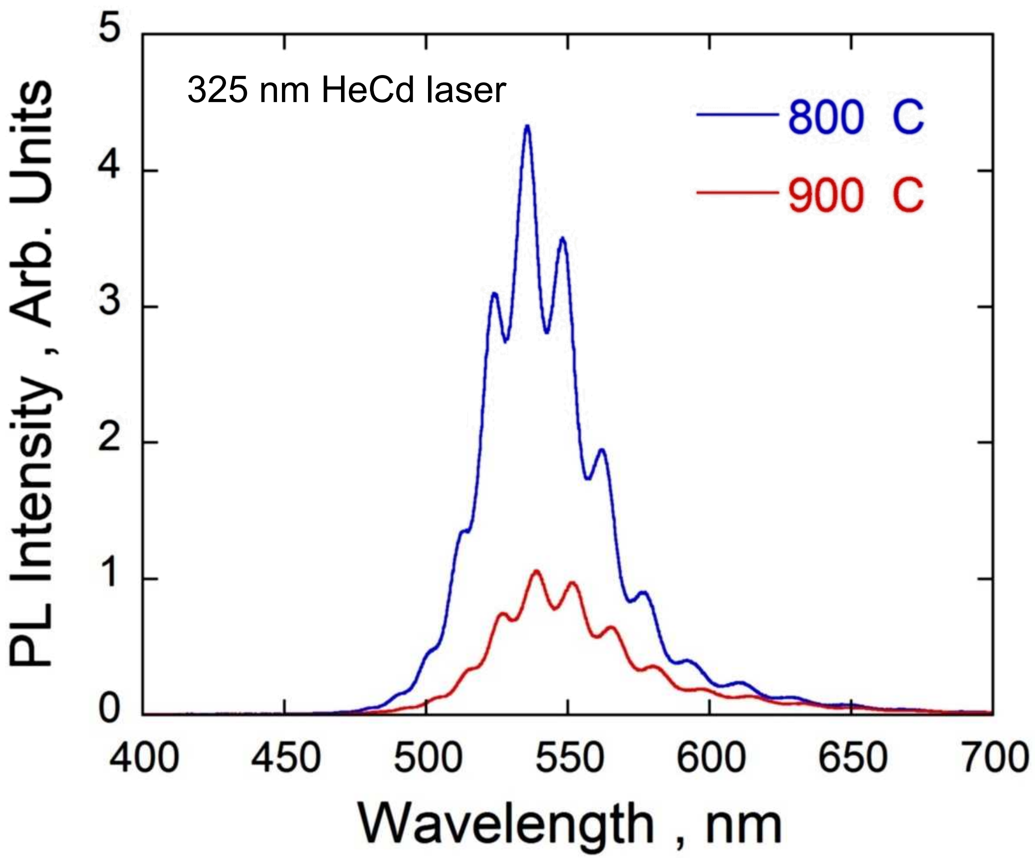
n = 2 evaporation and recondensation

n = 4 surface diffusion

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

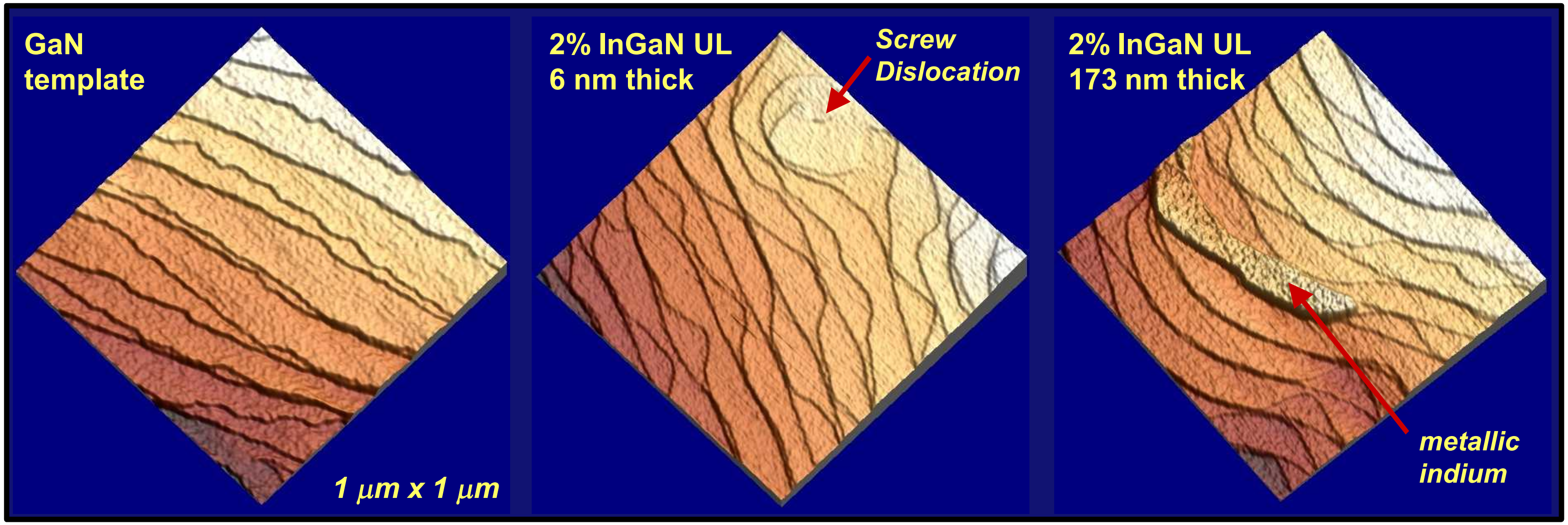


Same intensity and wave-length trends are observed for resonant optical pumping at 407 nm.

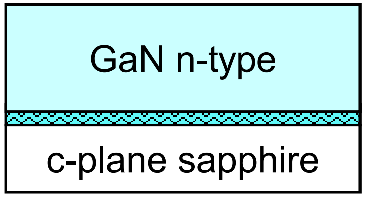
Suggests that the rougher morphology produces QW with increased PL intensity.

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).

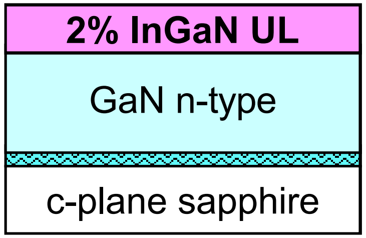
Adding indium to GaN growth changes the step structure

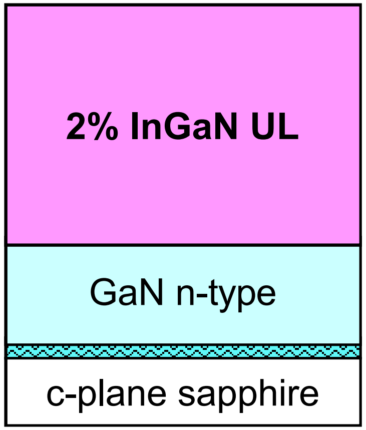


Same GaN template used for each growths.

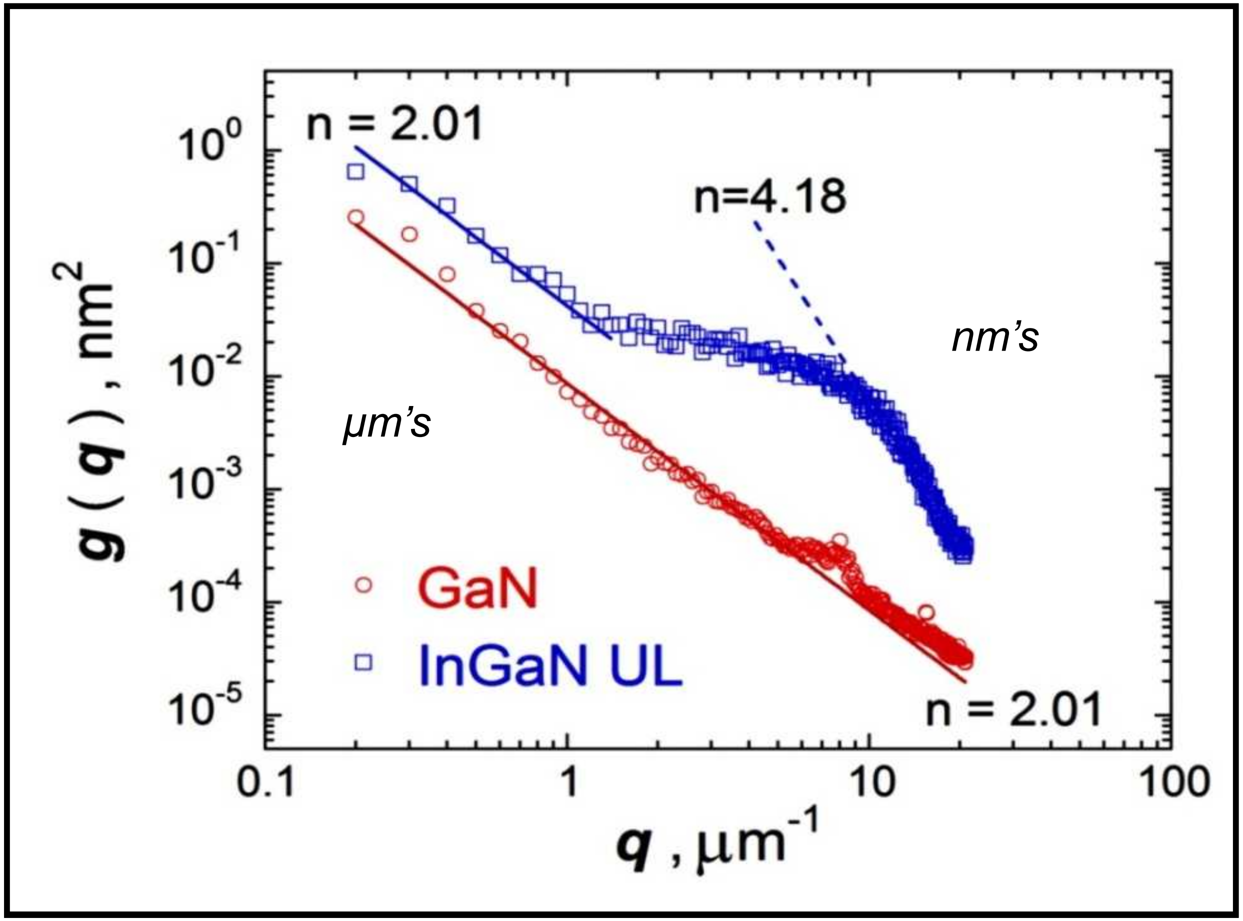


InGaN growth at 880 ºC using a high flow rate of indium





PSD analysis of 2% indium concentration InGaN (ULs)



n = 2 evaporation and recondensation

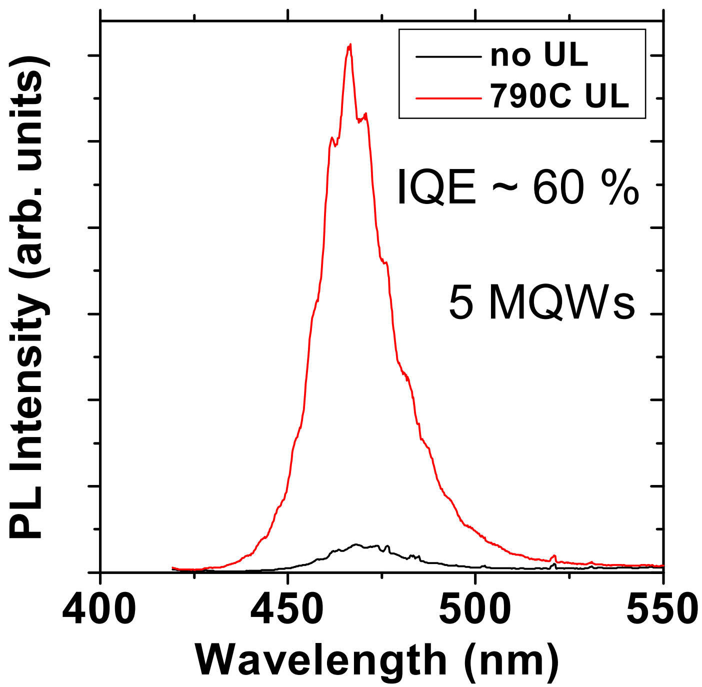
n = 4 surface diffusion

2% InGaN UL roughening is caused by surface diffusion (short length scale).

InGaN underlayers increase IQE of MQWs

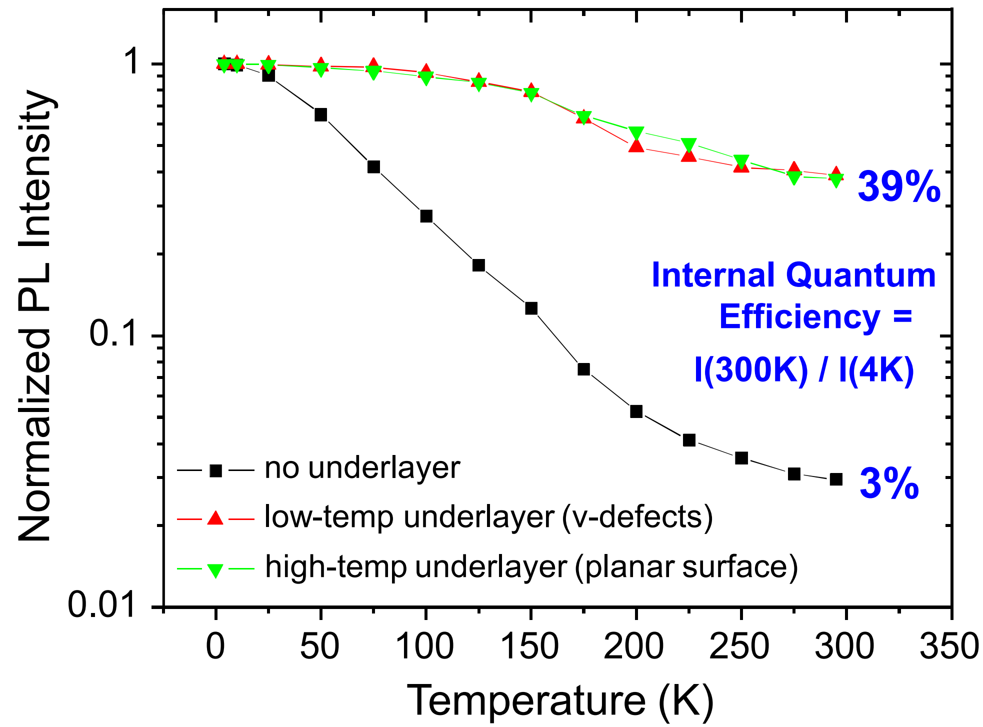
Especially helps emission of single QWs

15X increase in integrated PL emission with InGaN UL



Temperature dependent PL studies by Mary Crawford

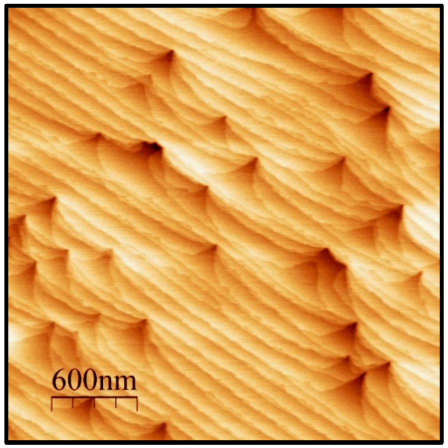
$$IQE = \eta_{rad} / (\eta_{rad} + \eta_{nonrad})$$



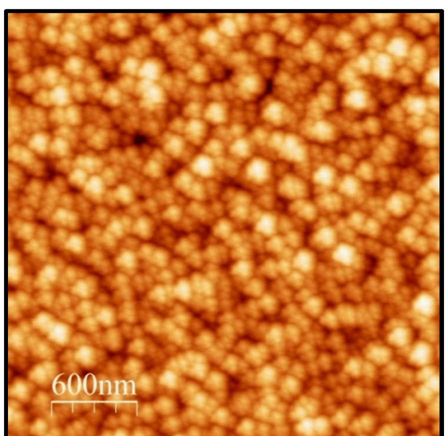
Underlayers enhance efficiency compared to same MQW with no underlayer.

Future work

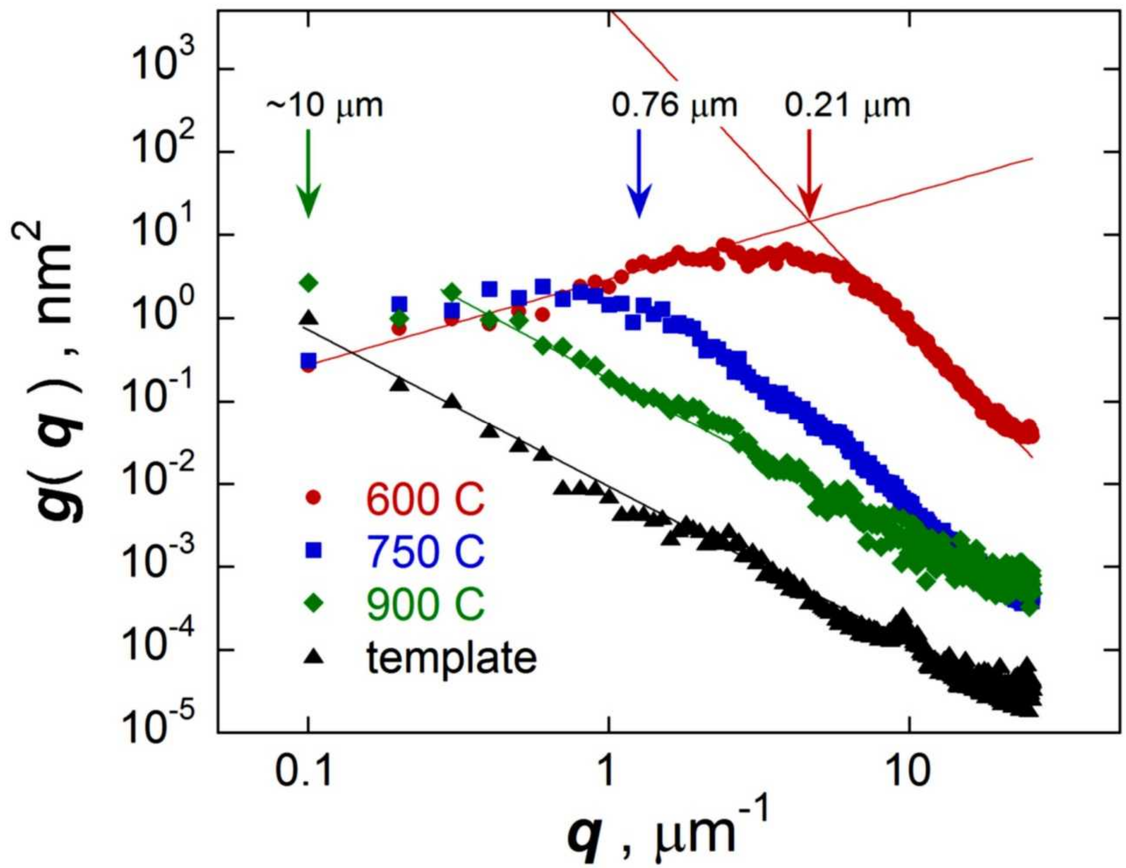
GaN template films



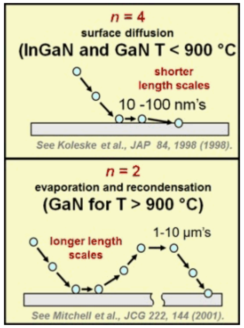
100 nm GaN at 600 ºC



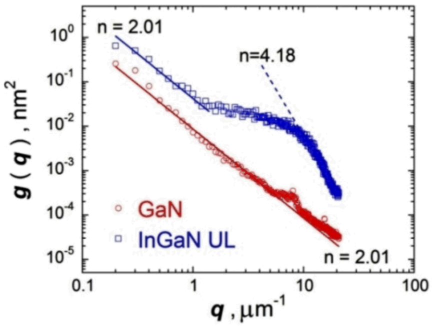
Correlate changes to smoothing mechanisms and length scales with MOCVD growth conditions



Conclusions



InGaN and GaN growth controlled by surface diffusion and evaporation/recondensation mechanisms.



InGaN morphology can be controlled with temperature
- **Lower T – rougher at short lengths – surface diffusion**
- **Higher T – smoother at short lengths – evap./recondens.**

Possible correlation between increased short length scale roughness and increased PL emission. The exact physical reason for this correlation is currently not understood – localization?