SAND2014-2564P

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Somehow GaN works!

From the University of Chicago to Solid State Lighting

Philips 10 W - DOE L-prize winner

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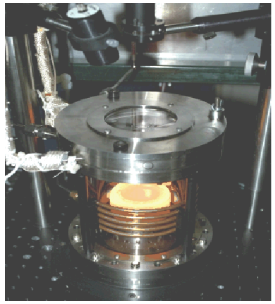
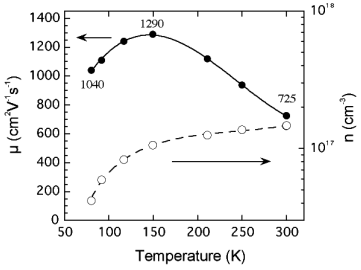
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

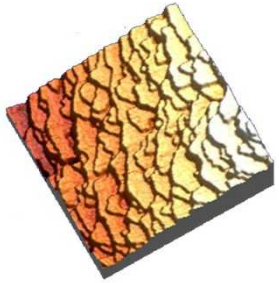
Sandia National Laboratories

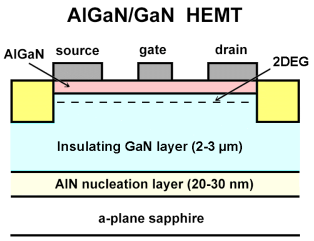
Outline

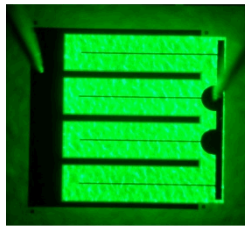
- Yep - GaN started at the University of Chicago.
- At NRL - Yes it's a job - but where's the research?
  - GaN decomposition kinetics.
- At Sandia – Adventures in Solid State Lighting
  - Are InGaN/GaN interfaces fortuitous for light emission?
  - How to control InGaN/GaN interface roughness.
  - Using H_2 to structure InGaN/GaN interfaces - 2D to 3D.











First Synthesis of GaN

Published in J. Phys. Chem. 36, 2651-2654 (1932). Yep that's JPC not JCP

NITROGEN COMPOUNDS OF GALLIUM
III. Gallic Nitride*

BY WARREN C. JOHNSON, JAMES B. PARSONS AND M. C. CREW

Introduction

A nitride of each member of Family B, Group III, of the periodic system

with the excepti

nitride has been

tained the nitrid

passed a mixture

nitrides of aluminium and indium. The following report shows that gallic nitride resembles aluminium nitride and boron nitride in its apparent stability towards heat, solutions of acids and of bases.

Experimental

Metallic gallium was obtained from germanite ore according to a procedure previously described.[7] It was purified by fractional crystallization on a platinum wire from the supercooled liquid metal.[8] Liquid ammonia was thoroughly dried with sodium before being used in any of the experiments.

* Contribution from the George Herbert Jones Laboratory of the University of Chicago.

[1] Stock and Blix: Ber., 34, 3039 (1901).

First Synthesis of GaN

Published in J. Phys. Chem. 36, 2651-2654 (1932). Yep that's JPC not JCP

Reaction was found to proceed slowly at a temperature as low as 700°, but it was necessary to heat the metal to 900-1000° for several hours in order to obtain an amount of the nitride sufficient for analysis and study.

The reaction may be expressed as follows:

$$2Ga + 2NH_3 = 2GaN + 3H_2. \quad (1)$$

Need high temperatures for growth.
Ammonia dissociation is catalytic.

Heating GaN in flowing H_2 to 800 ºC produces a weight loss.

Decomposition!

More on this later.

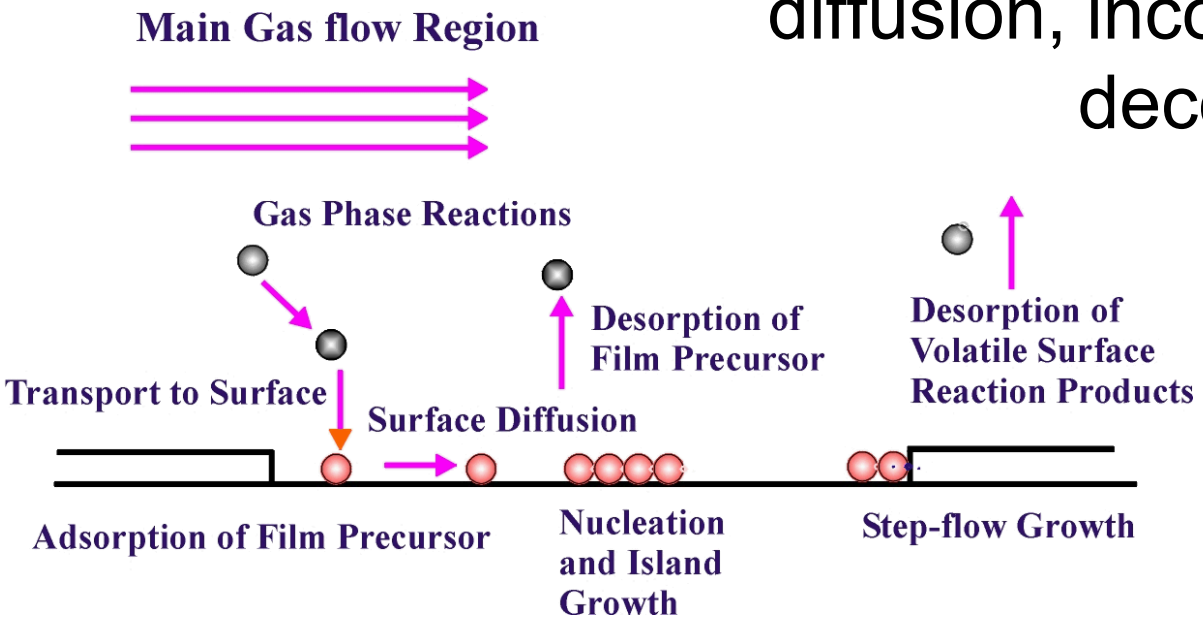
A small sample of the nitride, 0.1592 g, was heated in a stream of hydrogen at 800° for 24 hours. An examination of the material at the end of this period showed no change in its appearance but a loss in weight of 0.0385 g was noted. On the other hand, a considerable quantity of a grey substance resembling the nitride collected on the walls of the quartz tube outside the heated area. If the nitride were to be completely reduced to metallic gallium without any distillation, the loss in weight would be only 0.0266 g to correspond to the nitrogen. Accordingly, the material remaining in the boat was analyzed for nitrogen by the method indicated above. The results given in Table I (sample 3) show the material to be identical with gallic nitride. This conclusion is substantiated by the fact that the gases discharged from the reaction tube failed to produce any effect on a dilute HCl solution. Evidently, the nitride is slightly volatile at 800°, under a pressure of 1 atmos. of hydrogen, without suffering decomposition or reduction.

MOCVD Growth of GaN

Chemistry: $Ga(CH_3)_3 + NH_3 \rightarrow GaN + 3\ CH_4$

$Al(CH_3)_3$ for AlGaN and $In(CH_3)_3$ for InGaN

Dynamics: transport, adsorption, desorption, diffusion, incorporation, decomposition …



Interesting since the details can be quite complex

GaN Decomposition Studies

- Covered in the first GaN synthesis (by JPC in JPC)
- Initiates at 600 to 1000 °C.
- Depends on annealing conditions.
- Wide range of measured activation energies (E_A).
  - E_As from 0.4 eV to almost 4.0 eV.

Growth = Incorporation – Decomposition

For growth, Incorporation > Decomposition

GaN Decomposition Kinetics

From 4 measurements ...

1. 

weight (initial)

2. 

weight after heating

3. 

weight after removal of metallic Ga (HNO_3)

4. 

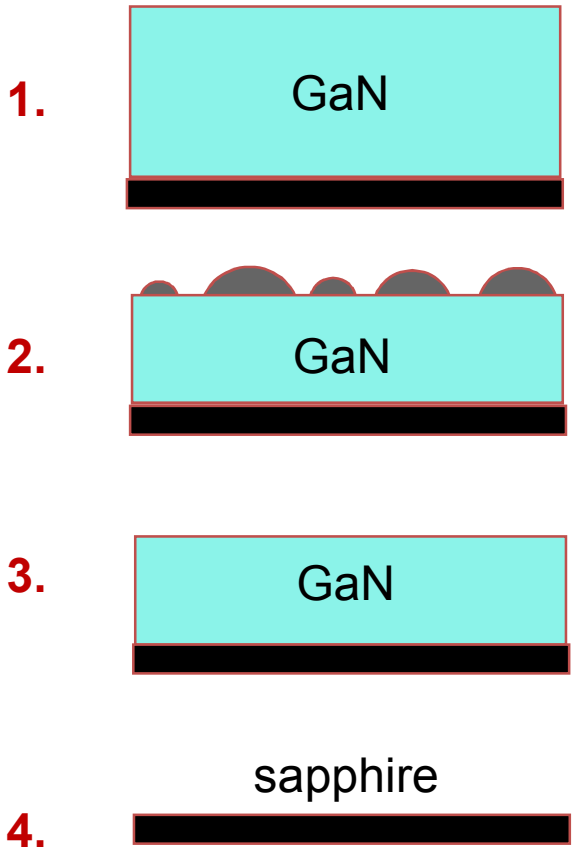
weight of bare sapphire

Mettler Analytical Balance
Weight to within 0.1 mg

GaN Decomposition Measurements

D.D. Koleske , et al., Journal of Crystal Growth 223, 466 (2001).

The following rates can be determined…



A). GaN decomposition (3 – 1).

B). Surface Ga metal (2 – 3).

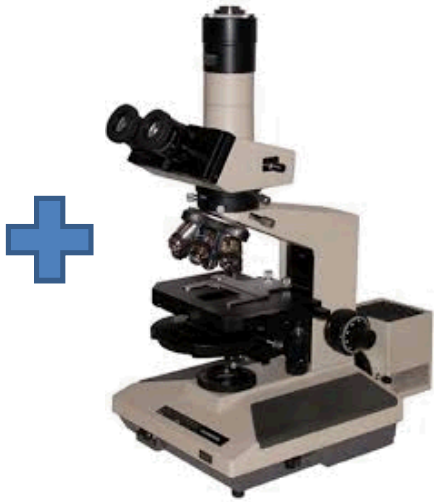
C). Ga desorption rate (A – B)

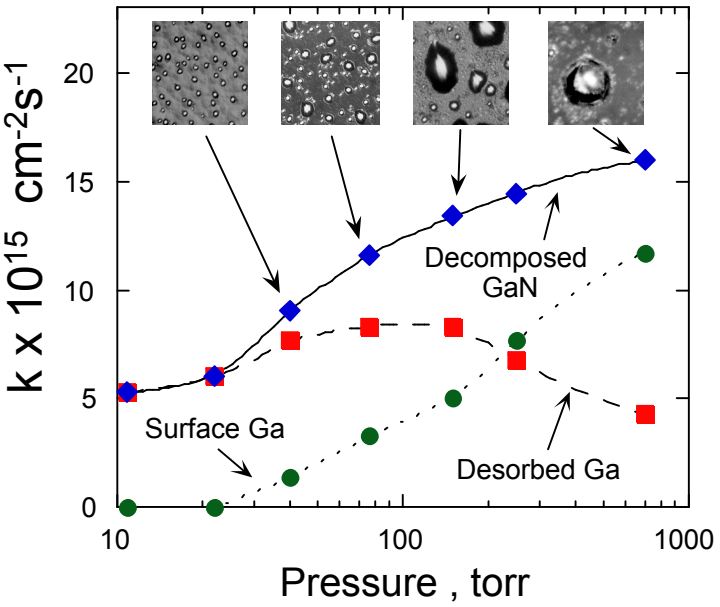
D). Bare sapphire to convert to rate per unit area (4).

GaN Decomposition Measurements in H_2

- GaN decomposition rate increases as the H_2 pressure increases.
  - In H_2 and NH_3 flows, ~ 10 - 100 times slower.
  - N desorption rate can exceed the Ga desorption rate – see Ga droplets.
- This work resulted in 5 papers and several invited talks.

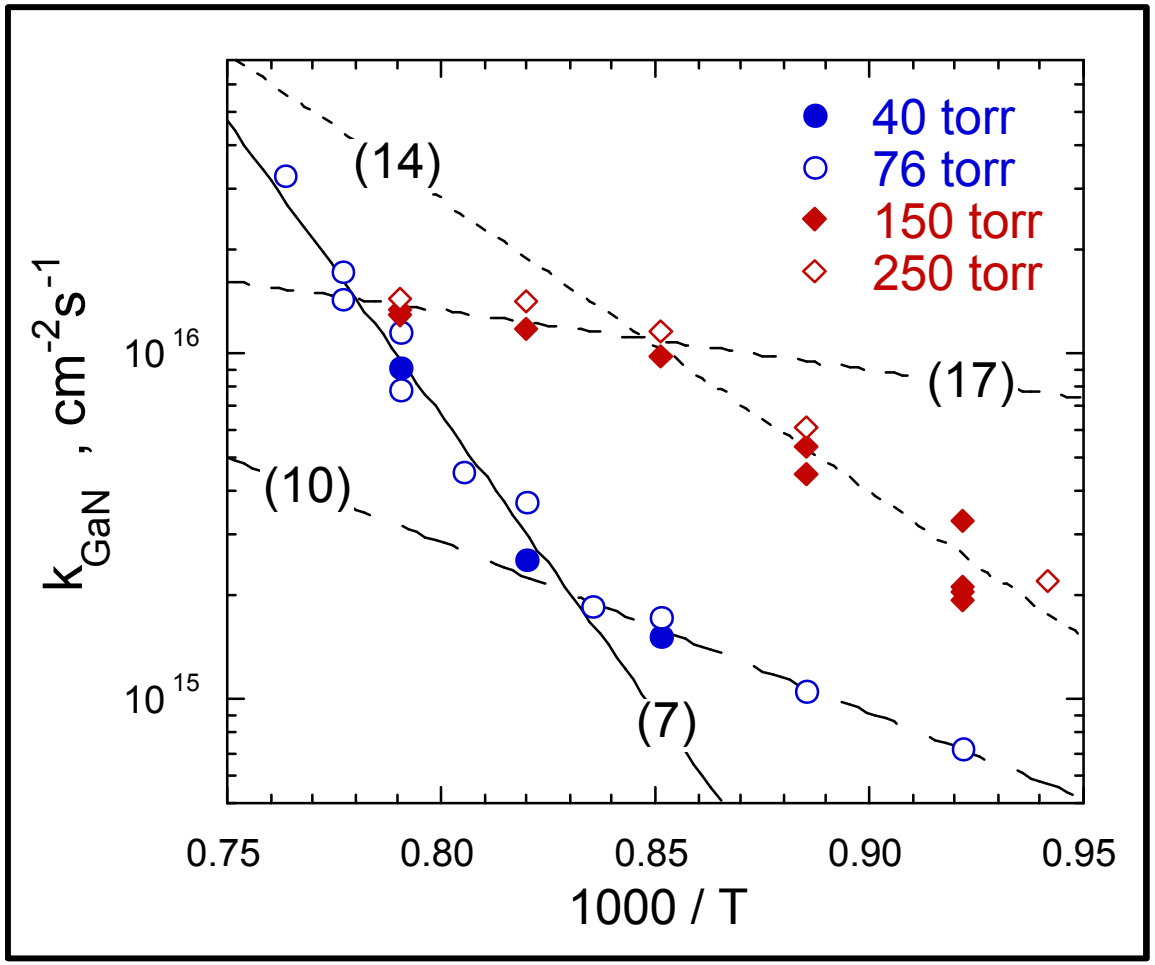
D. D. Koleske et al., APL 73, 2018 (1998).





Balance + Microscope = Applied Science

Arrhenius Plot of GaN decomposition rates in H_2



- Four different slopes suggests four different rate limiting mechanisms.
- Behavior different at low pressure (≤ 76 torr) vs. high pressure (≥ 150 torr).

Summary: Kinetic Parameters for GaN decomposition

Table 1
Measured kinetic parameters for GaN decomposition (groupings A–D) and Ga desorption (grouping E) gathered from the literature and the present work. For each grouping label (i.e. A–E) the conditions for pressure and temperature are listed. The first column lists the measurement technique used for measuring the kinetic parameters. The second column lists the pre-exponential factor, A_0, in units of $cm^{-2}s^{-1}$, while the third column lists the base 10 logarithm of A_0. The fourth column lists the activation energy, E_A, for each measurement in eV. The last column lists the reference from the literature and the year the work was conducted in square brackets

Event and experimental conditions	A_0 ($cm^{-2}s^{-1}$)	$Log_{10}(A_0)$ ($cm^{-2}s^{-1}$)	E_A (eV)	Ref. [Year]
GaN Decomposition				
(A) GaN decomposition, $P \leqslant 76$ Torr, $T > 925$°C,	N_2 formation and desorption limited			
(1) Thermogravimetric	—	—	2.7	30 [1956]
(2) Thermogravimetric	4×10^{29}	29.60	3.1	31 [1965]
(3) Mass spectroscopy in vacuum	5×10^{28}	28.70	3.1	32 [1974]
(4) Mass spectroscopy in vacuum	1.2×10^{31}	31.08	3.93	33 [1996]
(5) Ga flux in vacuum	5.0×10^{29}	29.70	3.45	34 [1998]
(6) Reflectivity data in vacuum	5.1×10^{31}	31.7 ± 1.2	3.7 ± 0.3	35 [1999]
(7) Microbalance at 760 Torr	1.4×10^{29}	29.1	3.2	36 [2000]
(8) Weight loss in H_2 at 40 and 76 Torr	2.8×10^{29}	29.4 ± 1.8	3.4 ± 0.2	This work
(9) Weight loss in N_2 at 76 and 150 Torr	1.2×10^{29}	29.1 ± 1.6	3.62 ± 0.14	This work
(B) GaN decomposition, $P \leqslant 76$ Torr, $T < 925$°C,	$N_2H_{2<x<4}$ formation and desorption limited			
(10) Surface photoadsorption N loss in H_2	—	—	0.91	37 [1998]
(11) Weight loss in H_2 at 40 and 76 Torr	8.7×10^{19}	19.94 ± 0.40	0.98 ± 0.07	This work
(C) GaN decomposition, $P \geqslant 150$ Torr, $T < 900$°C,	NH_3 formation and desorption limited			
(12) Redhead analysis of NH_3 TPD peak	—	—	1.6–2.0	19 [1999]
(13) Gravimetric in H_2 at 760 Torr	—	—	1.8	26 [1974]
(14) Reflectometry at 760 Torr	1×10^{25}	25	1.87	28 [1999]
(15) Weight loss in H_2 at 150 and 250 Torr,	7.9×10^{24}	24.9 ± 1.3	1.7 ± 0.2	This work
(D) GaN decomposition $P \geqslant 150$ Torr, $T > 900$°C,	Ga diffusion limited			
(16) Ga diffusion E_A—theory calculation	—	—	0.4	38 [1999]
(17) Reflectometry at 760 Torr	3×10^{17}	17.5	0.38	28 [1999]
(18) Microbalance at 760 Torr	1×10^{15}	15	0.44	36 [2000]
(19) Weight loss in H_2 at 150 and 250 Torr	3.5×10^{17}	17.54 ± 0.53	0.34 ± 0.1	This work
Ga Desorption				
(E) Ga desorption, in vacuum and at all pressures in N_2, and H_2				
(20) Desorption from liquid Ga	—	—	2.8	39 [1969]
(21) RHEED study of hexagonal GaN	—	—	2.76	40 [1996]
(22) RHEED study, cubic GaN	1.0×10^{28}	28.0 ± 0.26	2.69 ± 0.05	6 [1996]
(23) Weight loss in H_2 at 40–250 Torr	6.5×10^{26}	26.81 ± 0.34	2.74 ± 0.08	24 [1999]
(24) Weight loss in N_2 at 76 and 150 Torr	5.4×10^{25}	25.73 ± 1.5	2.69 ± 0.4	24 [1999]

D.D. Koleske et al., JCG 223, 466 (2001).

Grouping of E_A's and Possible Rate Limiting Steps

Table 1
Measured kinetic parameters for GaN decomposition (groupings A–D) and Ga desorption (grouping E) gathered from the literature and the present work. For each grouping label (i.e. A–E) the conditions for pressure and temperature are listed. The first column lists the measurement technique used for measuring the kinetic parameters. The second column lists the pre-exponential factor, A_0, in units of $cm^{-2}s^{-1}$, while the third column lists the base 10 logarithm of A_0. The fourth column lists the activation energy, E_A, for each measurement in eV. The last column lists the reference from the literature and the year the work was conducted in square brackets

Event and experimental conditions	A_0 ($cm^{-2}s^{-1}$)	$Log_{10}(A_0)$ ($cm^{-2}s^{-1}$)	E_A (eV)	Ref. [Year]
(A) GaN decomposition, $P \leqslant 76$ Torr, $T > 925$°C, N_2 formation and desorption limited				
(1) Thermogravimetric	—	—	2.7	30 [1956]
(2) Thermogravimetric	4×10^{29}	29.60	3.1	31 [1965]
(3) Mass s			3.1	32 [1974]
(4) Mass s			3.93	
(5) Ga flu			3.45	
(6) Reflect			3.7 ± 0.3	
(7) Microl			3.2	
(8) Weigh			3.4 ± 0.2	This work
(9) Weight loss in N_2 at 76 and 150 Torr	1.2×10^{29}	29.1 ± 1.6	3.62 ± 0.14	This work
(B) GaN decomposition, $P < 76$ Torr, $T < 925$°C, N_2H_x formation and desorption limited				
(10)			0.91	
(11)			0.98 ± 0.07	
(C) GaN decomposition, $P \geqslant 150$ Torr, $T < 900$°C, NH_3 formation and desorption limited				
(12) Redhead analysis of NH_3 TPD peak			1.6–2.0	
(13)			1.8	
(14)			1.87	
(15)			1.7 ± 0.2	
(D) GaN decomposition $P \geqslant 150$ Torr, $T > 900$°C, Ga diffusion limited				
(16) Ga			0.4	
(17) Refl			0.38	
(18) Mic			0.44	
(19) Weight loss in H_2 at 150 and 250 Torr	3.9×10	17.54 ± 0.33	0.34 ± 0.1	
(E) Ga desorption, in vacuum and at all pressures in N_2, and H_2				
(20) Desorption from liquid Ga	—	—	2.8	39 [1969]
(21) RHEED study of h			2.76	
(22) RHEED study, cub		0.26	2.69 ± 0.05	
(23) Weight loss in H_2 a		± 0.34	2.74 ± 0.08	
(24) Weight loss in N_2 at 76 and 150 Torr	5.4×10^{25}	25.73 ± 1.5	2.69 ± 0.4	24 [1999]

GaN Decomposition

Ga Desorption

N_2 formation and desorption
Low P, high T

E_A = 3.4 eV

N_2H_x desorption - Low P, low T

E_A = 1 eV

NH_3 desorption, High P, low T

E_A = 1.7 eV

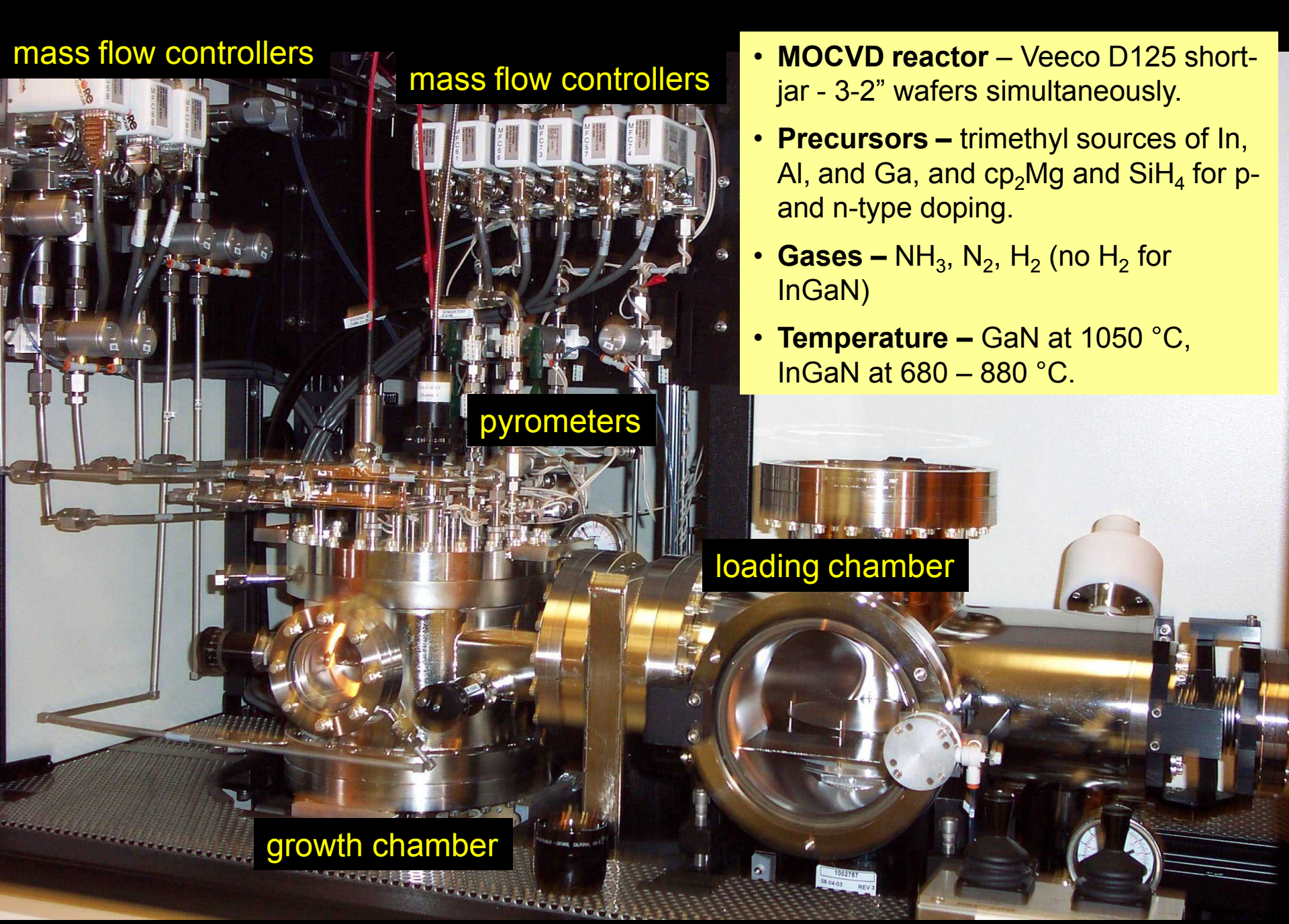
Ga(l) diffusion, High P, high T

E_A = 0.4 eV

Ga desorption

E_A = 2.7 eV

D.D. Koleske et al., JCG 223, 466 (2001).

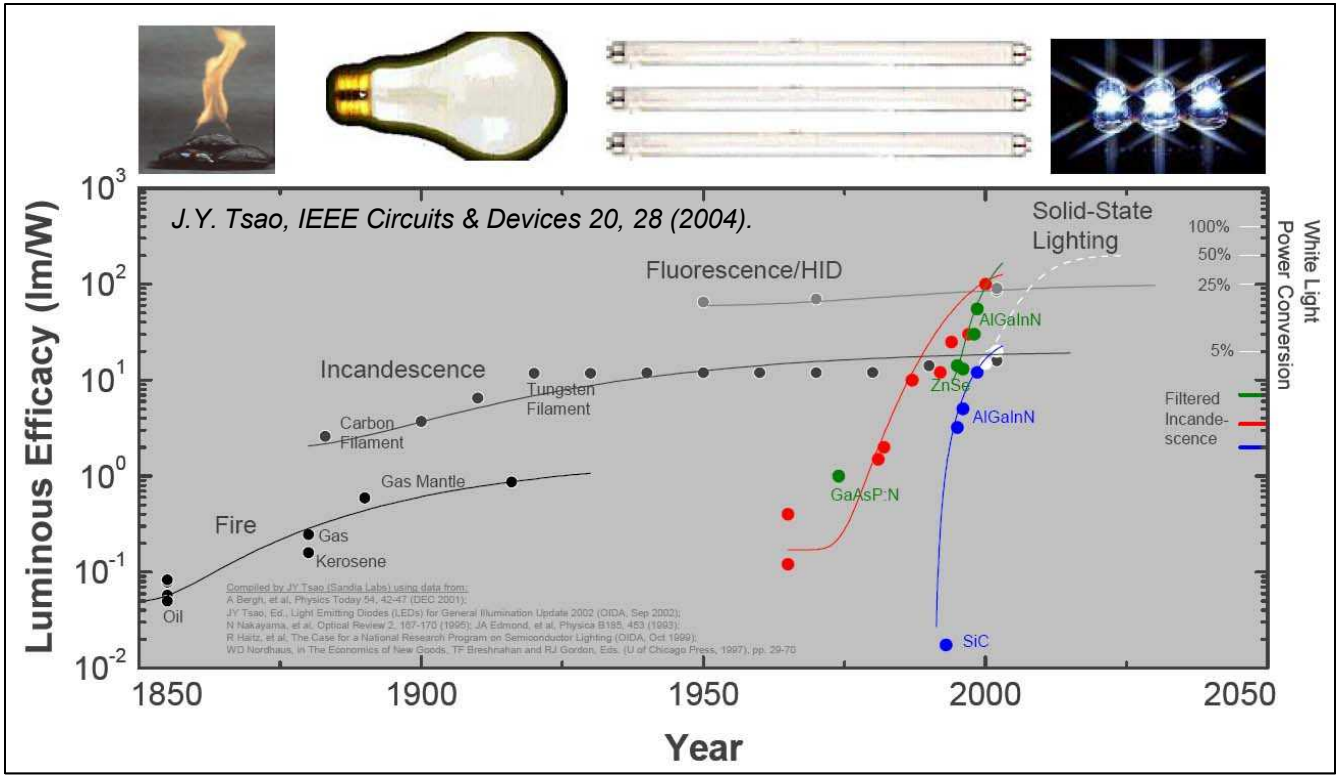


- **MOCVD reactor** – Veeco D125 short-jar - 3-2” wafers simultaneously.
- **Precursors –** trimethyl sources of In, Al, and Ga, and cp_2Mg and SiH_4 for p- and n-type doping.
- **Gases –** NH_3, N_2, H_2 (no H_2 for InGaN)
- **Temperature –** GaN at 1050 °C, InGaN at 680 – 880 °C.

14

Why Solid State Lighting?

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



Power Conversion Efficiency

Incandescent ~ 5%

Fluorescent ~ 20%

SSL Goal ~ 50%

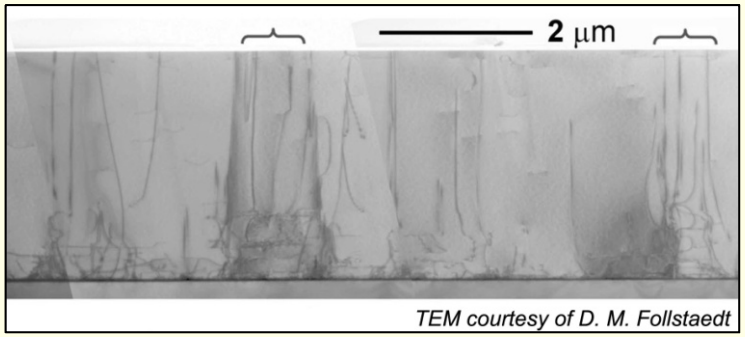
LED package ~ mid 1990's

Cree® XLamp CXA3590
10,000-18,000 lumens
maximum current 150 A

DOE has a stated goal of producing SSL with 50% wall-plug efficiency by 2025 (> 200 lm/W)

On Feb. 2013, Cree XLamp - CCT= 4400K, 0.35 A, 276 lm/W

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

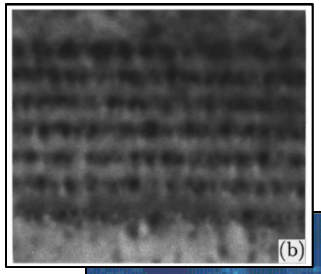


TEM courtesy of D. M. Follstaedt

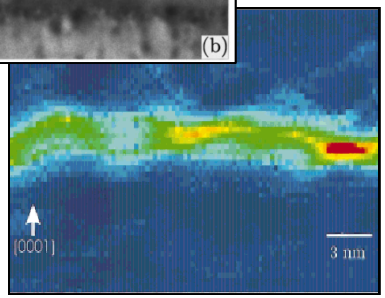
- High brightness LEDs are typically grown on high dislocation density GaN (10^9 cm^{-2}).
- Dislocations believed to be non-radiative recombination centers
- Carrier diffusion are lengths minimal

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

Narukawa, APL 70, 981 (1997)

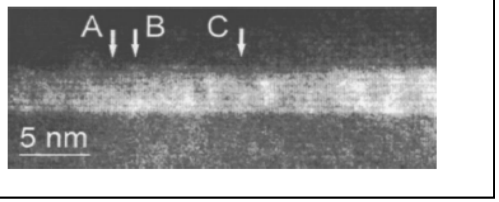


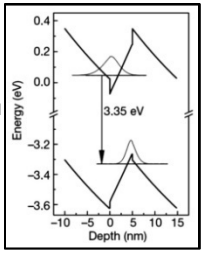
Quantum dot formation or compositional modulation



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

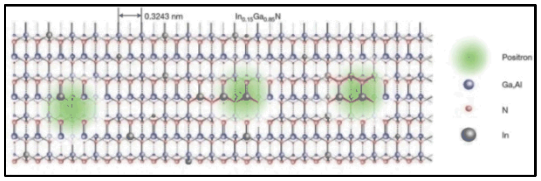
QW thickness fluctuations coupled to strong piezoelectric fields



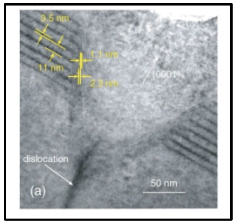


Graham, JAP 97, 103508 (2005)

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

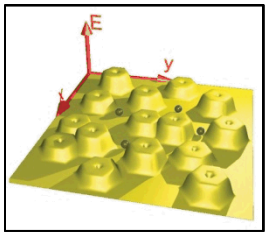


Chichibu, Nat. Mat. 5, 810 (2006)



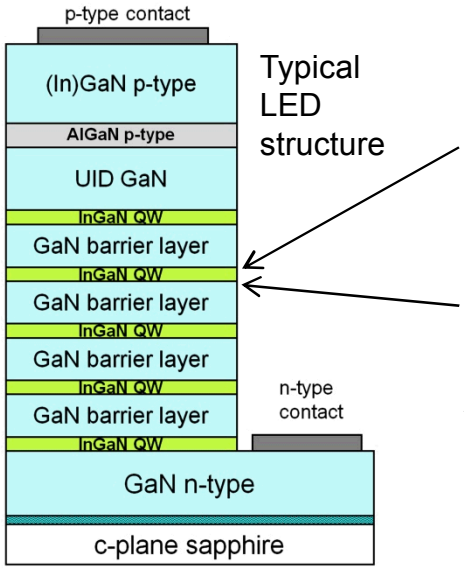
Thinner QWs around v-defects

Energetic screening around dislocations

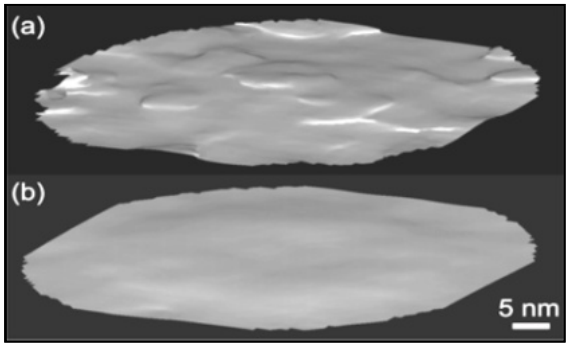


Hangleiter, PRL 95, 127402 (2005).

Evidence for carrier localization at InGaN/GaN interfaces



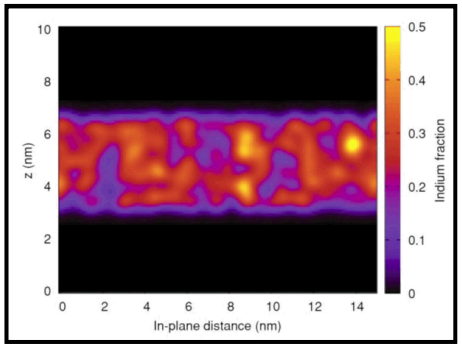
Typical LED structure



An isoconcentration surface based on APT data illustrating the roughness of the lower and upper interface of an InGaN QW.
Oliver et al. J. Phys. D: Appl. Phys. 43, 354003 (2010).

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

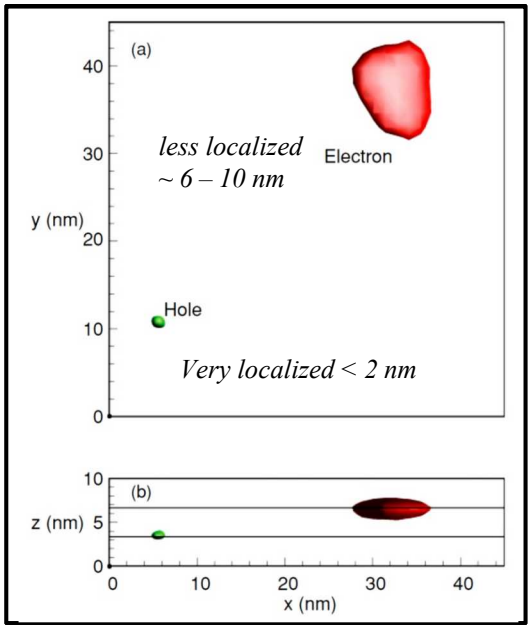
Random indium distribution in a QW with an average indium of 25%.



Assuming random alloy and indium distribution:

Holes strongly localized at bottom interface in regions of higher indium content.

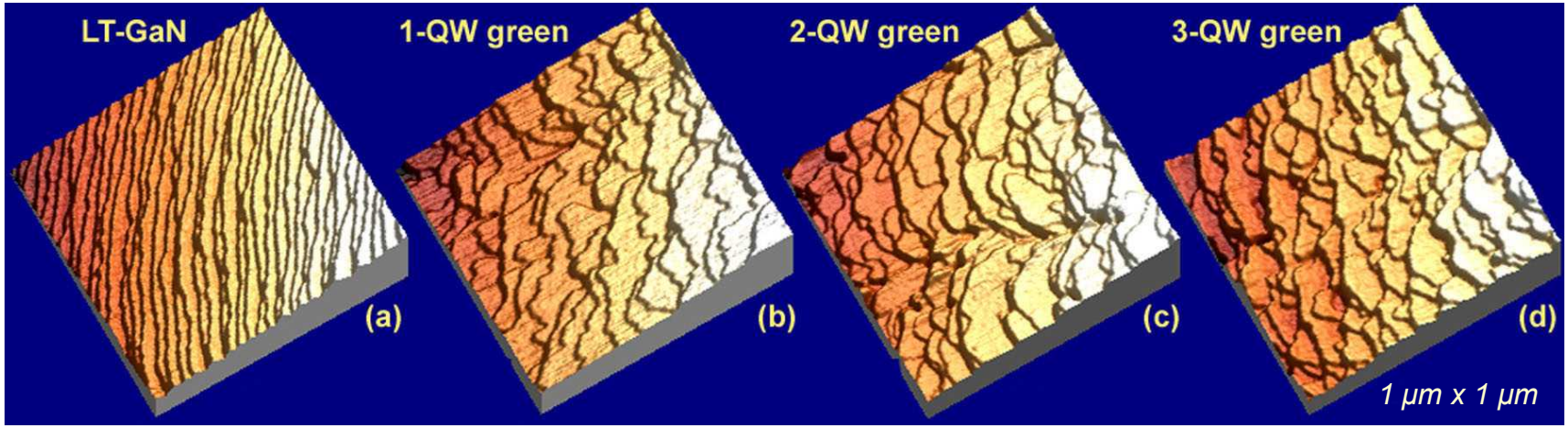
Electrons less localized at the top interface and the degree of localization might be enhanced by mono-layer well width fluctuations.



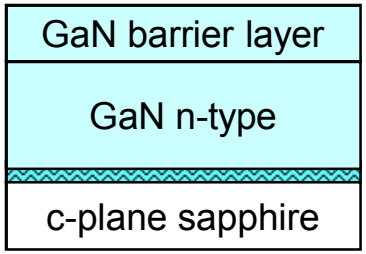
The calculated ground state probability density of an electron (red) and a hole (green).

Is InGaN/GaN interface roughening is fortuitous?

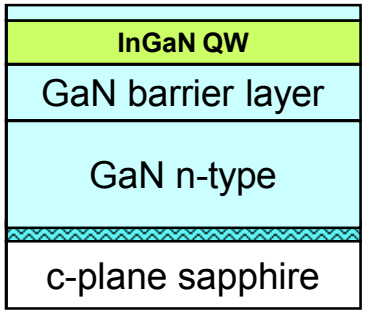
Observation of increased multi-layer steps in green MQWs

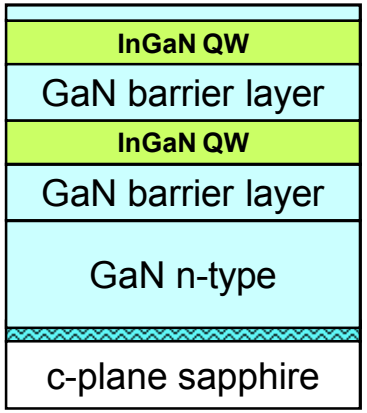


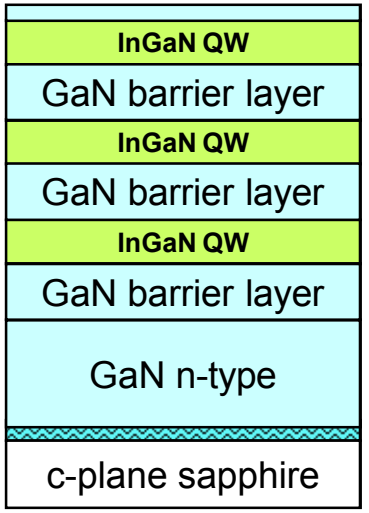
10 nm thick LT GaN barrier layer has the same step structure as the underlying HT GaN.



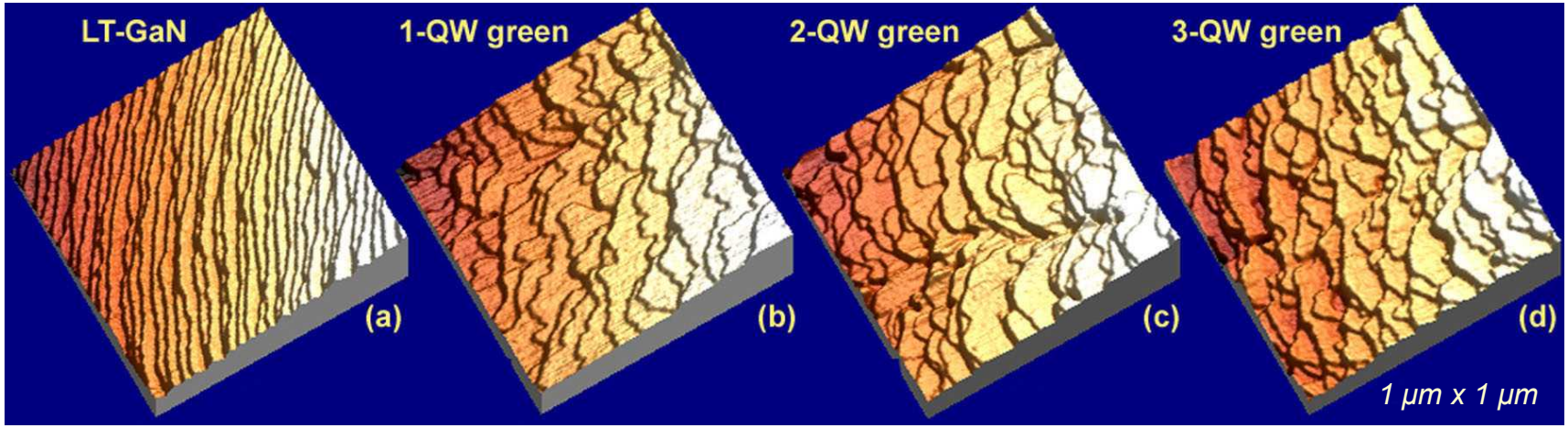
Addition of single 3 nm InGaN QW capped with 1.5 GaN barrier layer

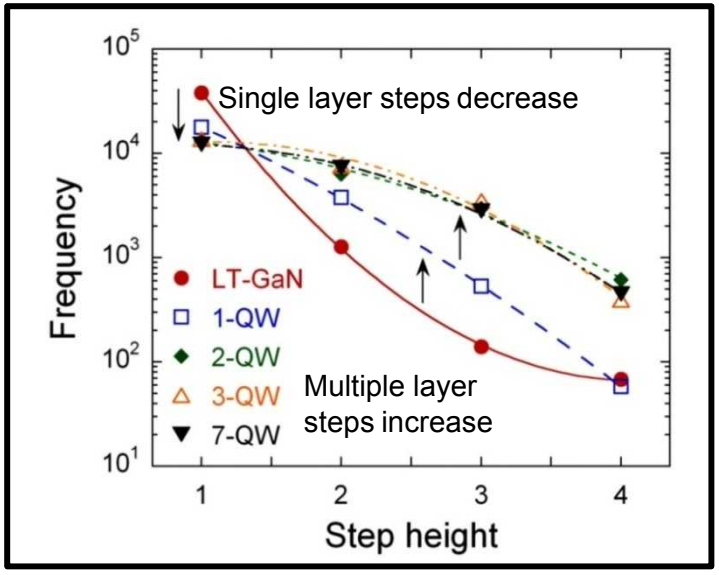






Observation of increased multi-layer steps in green MQWs





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

Multiple layer steps preferred to reduce layer strain, however strain reduction per layer is only a 1 - 2 % at most.

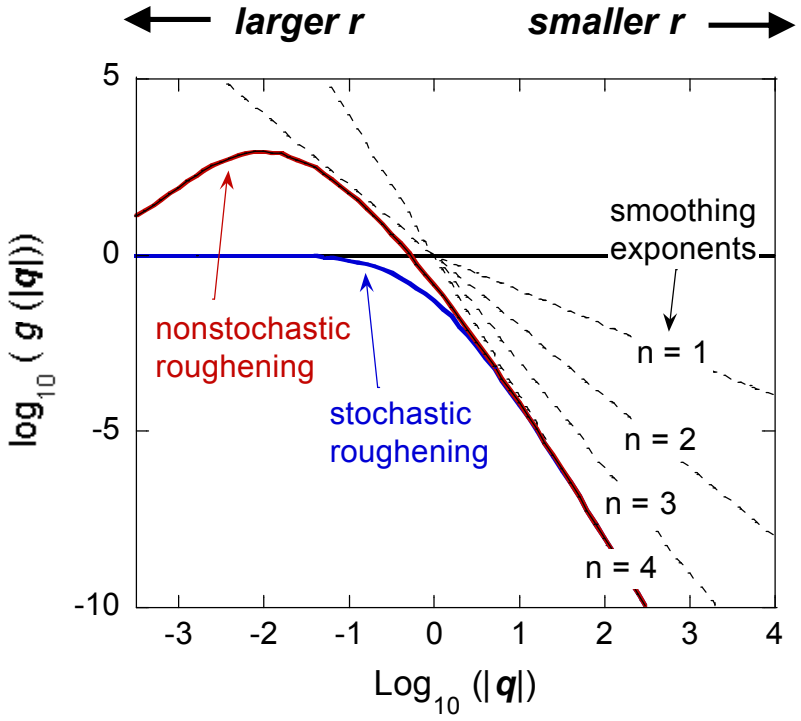
Details in D.D. Koleske et al. APL 97, 071901 (2010).

Power Spectral Density and Smoothing Mechanisms

Stan Williams talk at U of C in ~1990 – see Tong and Williams in Ann. Rev. Phys. Chem. 45, 401 (1994).

Use AFM image and calculate the height-height correlation function = PSD
PSD or *g* can be calculated from h(*x*,*y*) as a function of *q, where q = 1/r*.

PSD essentially is a length scale roughness!



Smoothing mechanisms

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

n = 1 - plastic flow driven by surface tension

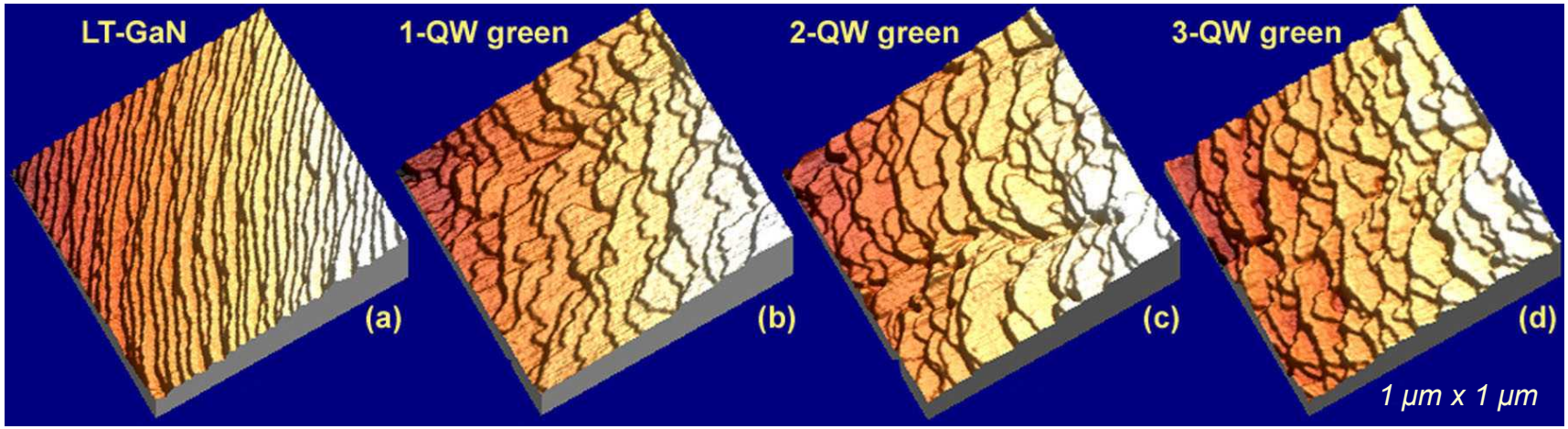
n = 2 - evaporation and recondensation (gas phase)

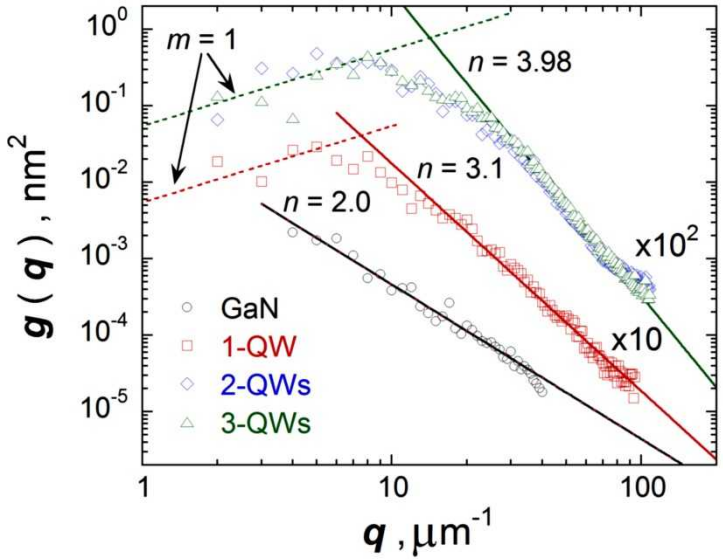
n = 3 - volume diffusion

n = 4 - surface diffusion

Exponents derived by C. Herring, J. Appl. Phys. 21, 301 (1950).

Observation of increased multi-layer steps in green MQWs



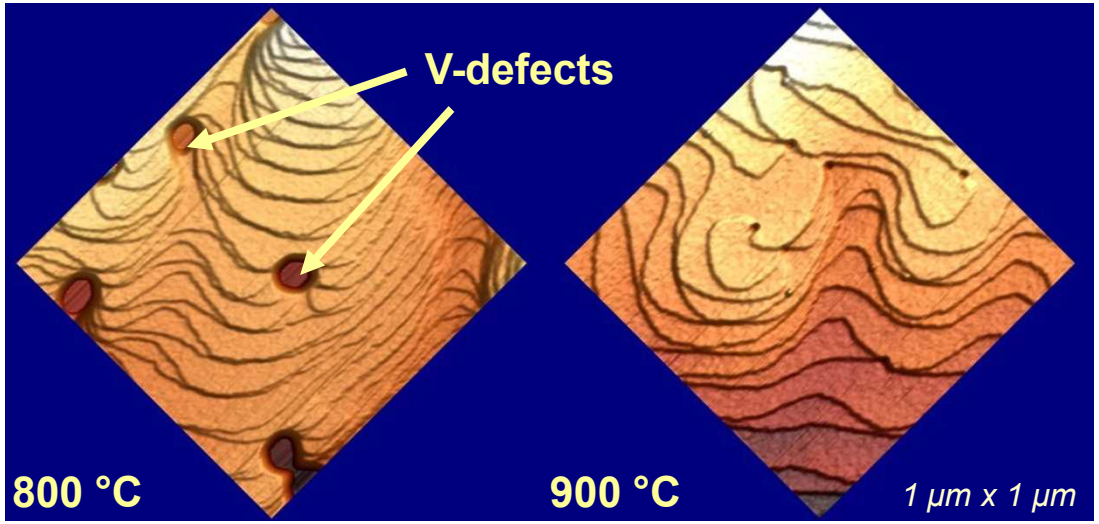


PSD analysis shows a change from gas phase diffusion (n = 2) to surface diffusion (n = 4) mechanism as the number of QWs increases.

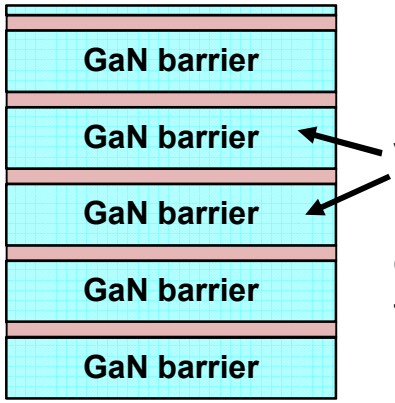
Develop a peak in the PSD at 100 nm.

QW intensity 3 QWs > 2 QWs >> 1 QWs

Growth temperature used to control step morphology



MQW sample structure

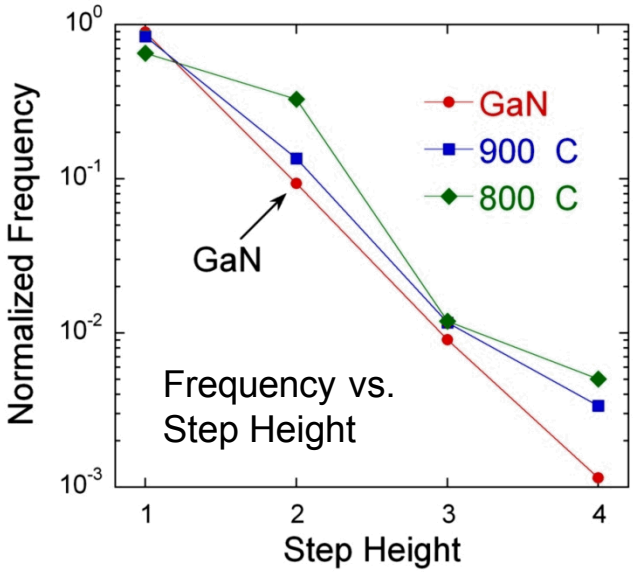


Vary the GaN barrier growth temperature

Keep green QW growth conditions (730 ºC) the same.
800 ºC – surface diffusion dominant
900 ºC – gas-phase diffusion dominant

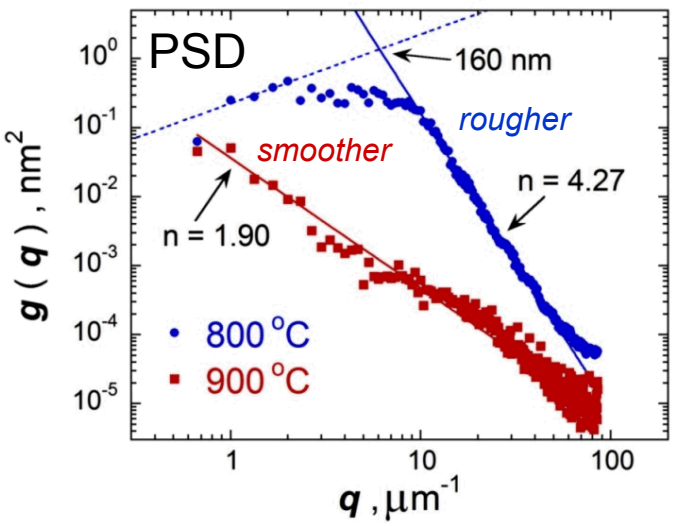
In general the number of multiple step heights is higher for 800 °C GaN barriers compared to 900 °C GaN barriers.

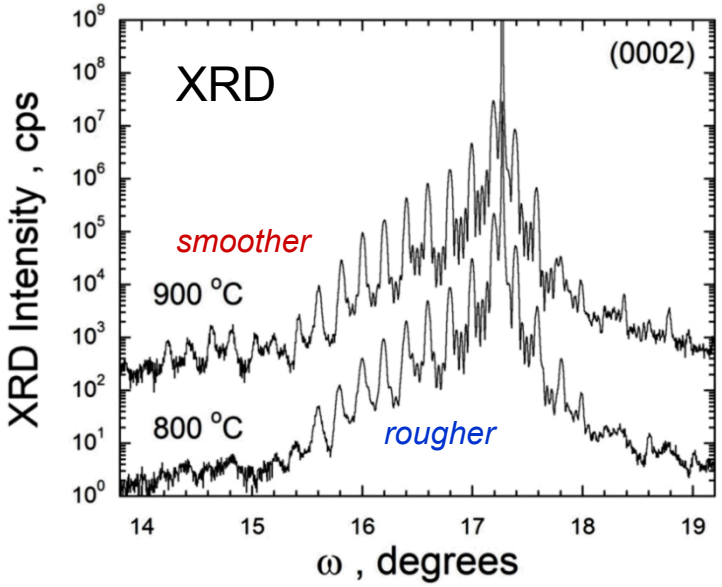
Fewer multiple step heights – smooth interfaces



Growth temperature used to control step morphology

D. D. Koleske et al., JCG 391, 85 (2014).



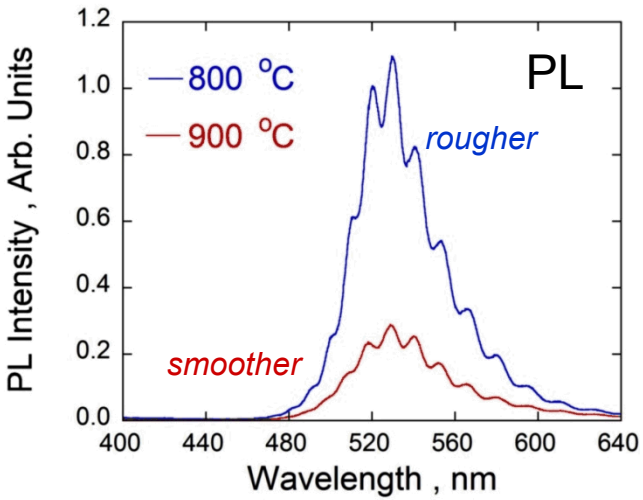


900 °C GaN barriers → n = 2 – sharper interfaces.

800 °C GaN barriers → n = 4 – rougher interfaces.

The PL intensity higher for 800 ºC barriers than for the 900 ºC barriers.

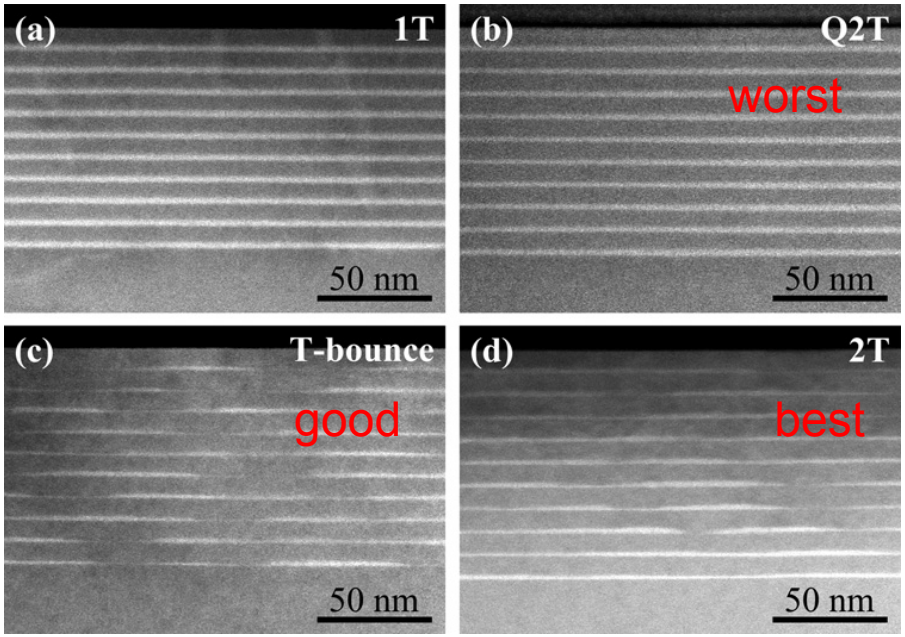
Suggests that some degree of interface roughness increases carrier localization?



Generating discontinuous QWs for improved emission

Use temperature ramp after QW growth to create discontinuous QWs

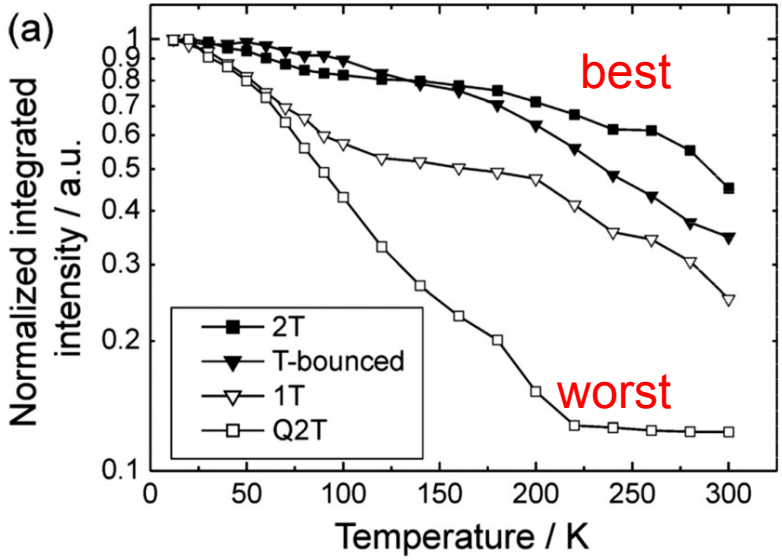
Cambridge work - R.A. Oliver, et al., APL 103, 141114 (2013).



TEM images of MQWs grown by four different methods: (a) 1T, (b) Q2T, (c) T-bounced, and (d) 2T.

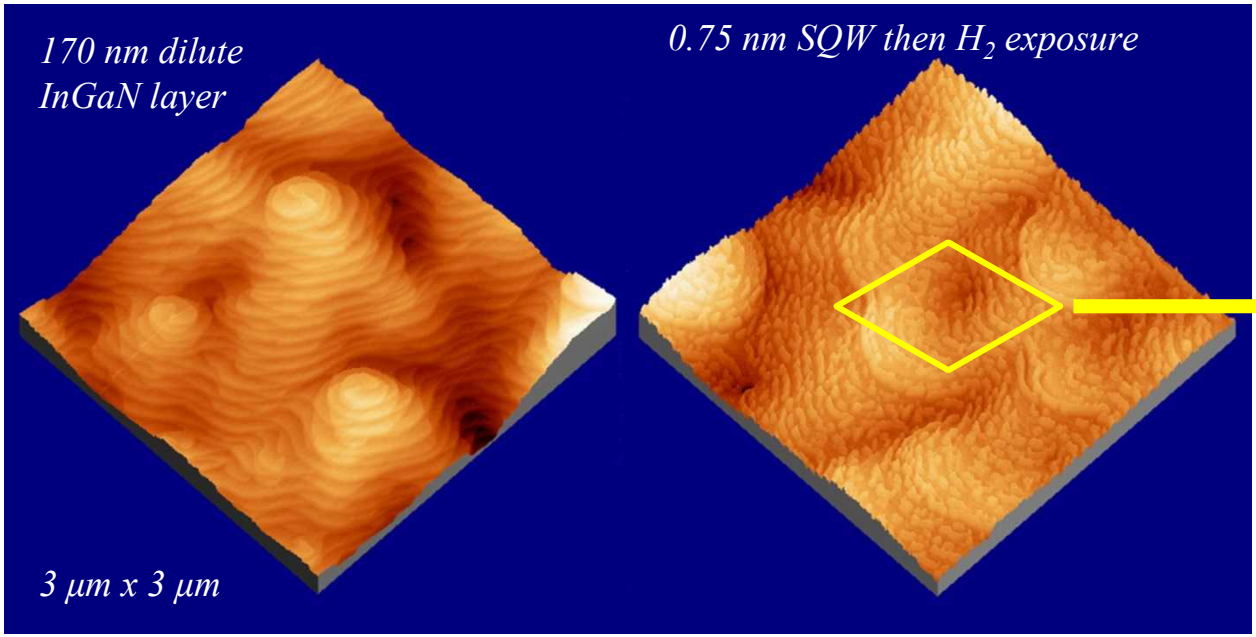
Discontinuous QWs ((c) and (d)) are better!

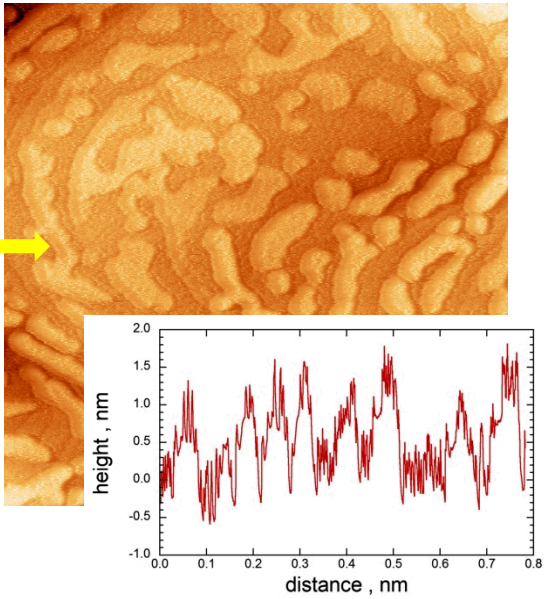
For MQWs grown by 4 different methods: Low power internal quantum efficiency (IQE) determined by temperature dependent PL at 6 W cm^{-2}.



Can also use H_2 after QW growth to create discontinuous QWs.

Hydrogen: The magic InGaN eraser

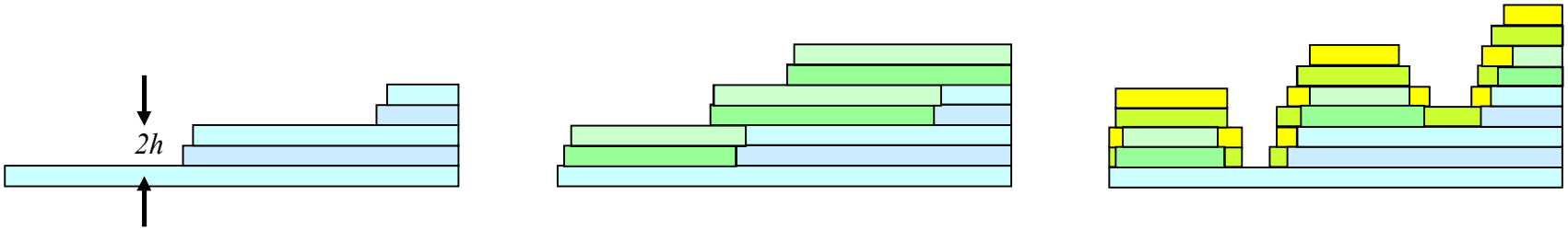




Dilute InGaN layer
(170 nm thick)

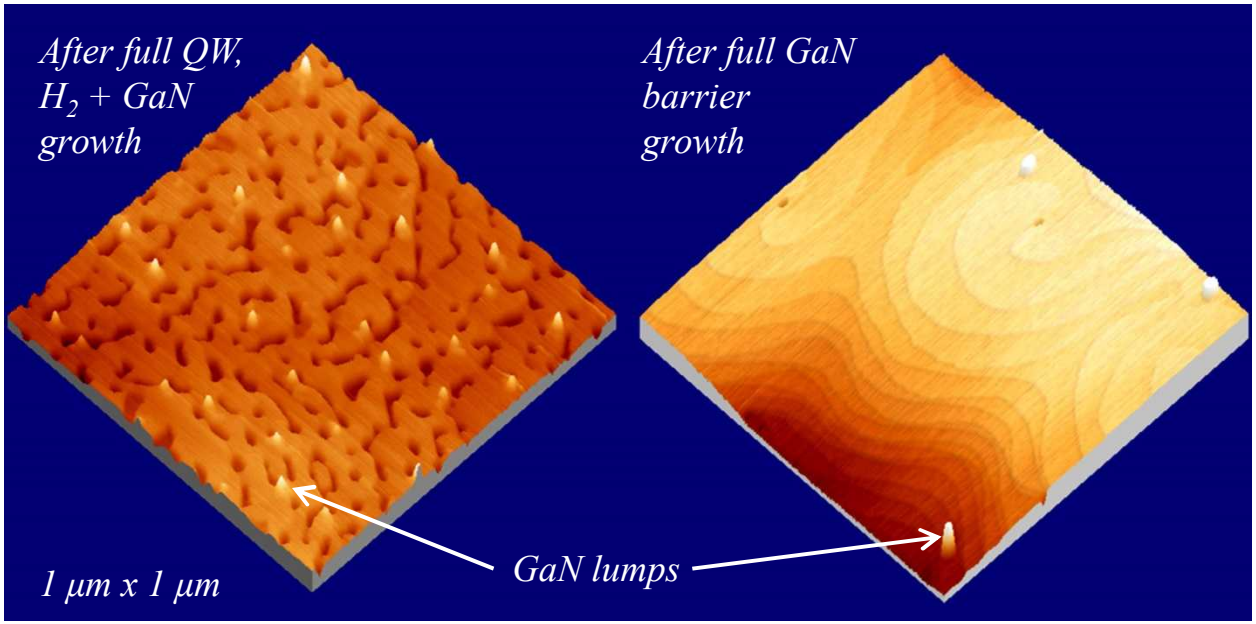
Grow $In_{0.14}Ga_{0.84}N$ QW
(about ¼ thickness of typical QW)

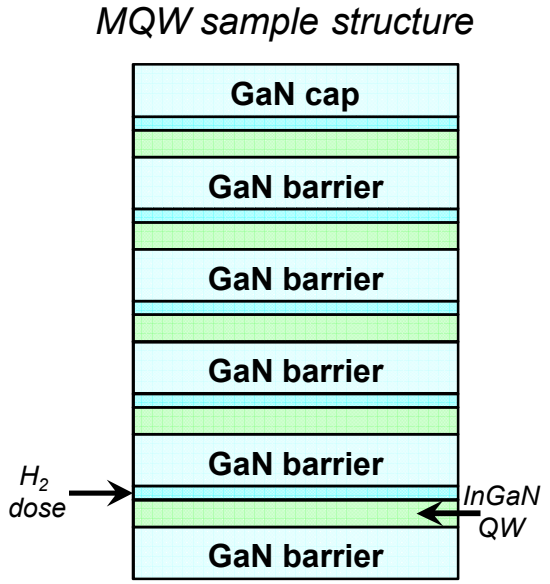
Add 2 SLM H_2 for ¼ min.
(discontinuous QW etching)



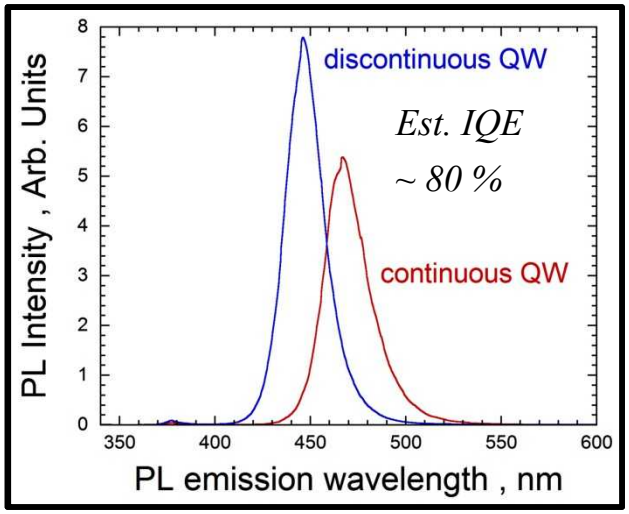
InGaN islands preferentially line outer step edge – lower strain region

Hydrogen: Discontinuous MQWs





- Adding H_2 to GaN capping layer after InGaN QW growth results in holes in QW.
- Ga atoms left over from the InGaN etching result in GaN lumps.
- GaN capping layer smoothens the surface
- PL emission intensity improved in these QWs



SSLS EFRC People & Resources: 2011 Snapshot

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
Jeff Kempisty
Tony Coley
Karen Cross
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

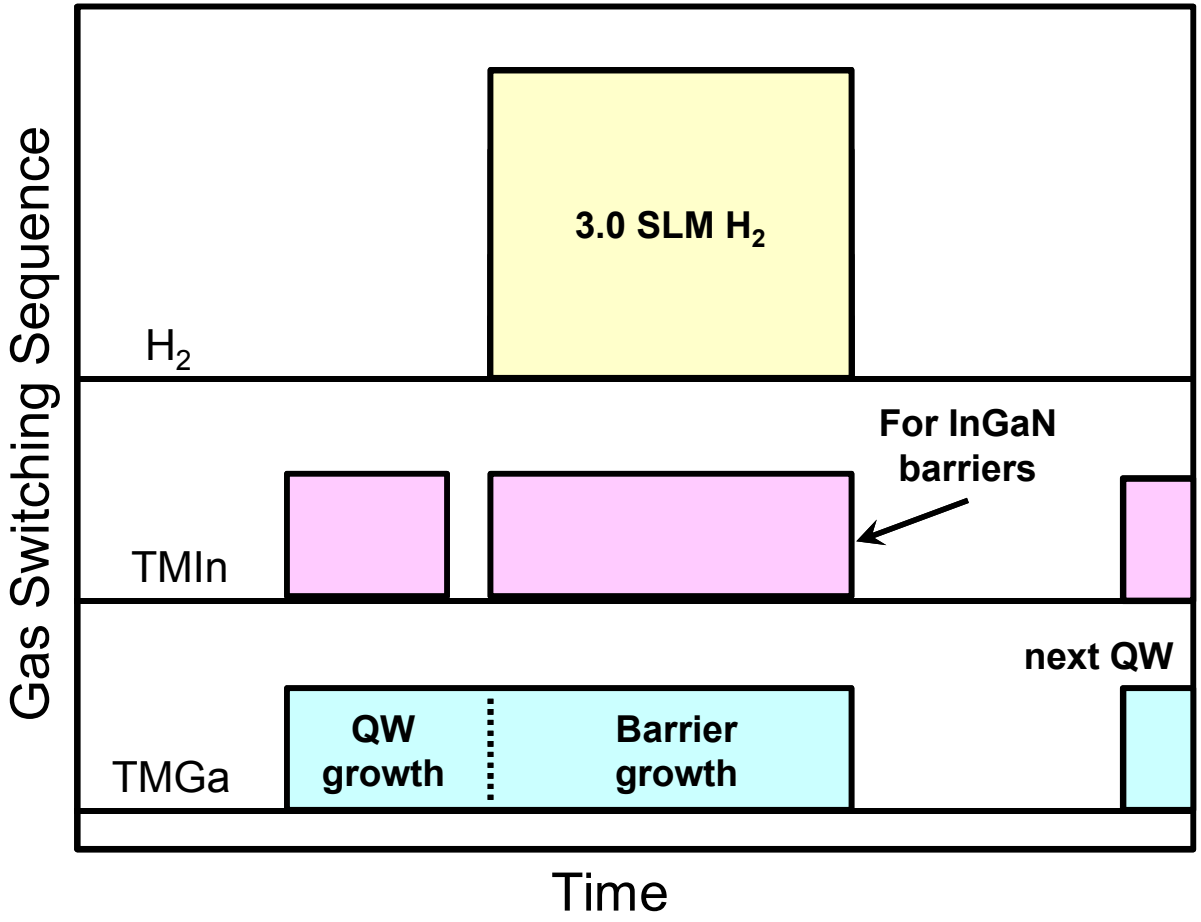
UC Merced
Professor David Kelley

Philips Lumileds
Mike Craven

Extra Slides

InGaN barriers growth conditions

D.D. Koleske et al., JCG 390, 38 (2014).



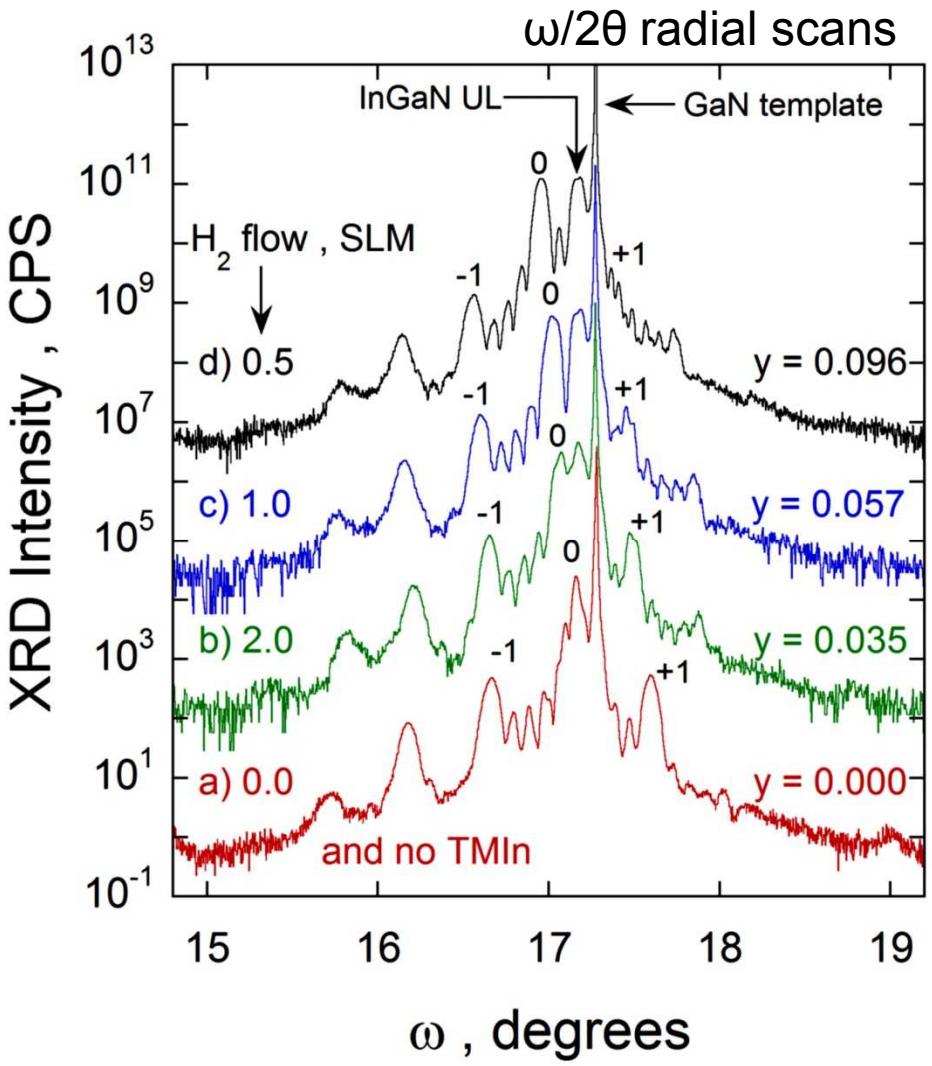
Use the same indium flow for the QW and InGaN barrier growth.

Grow both the QW and barriers at the same temperature 730 – 770 ºC.

Increase the amount of H_2 flowing during the InGaN barrier growth.

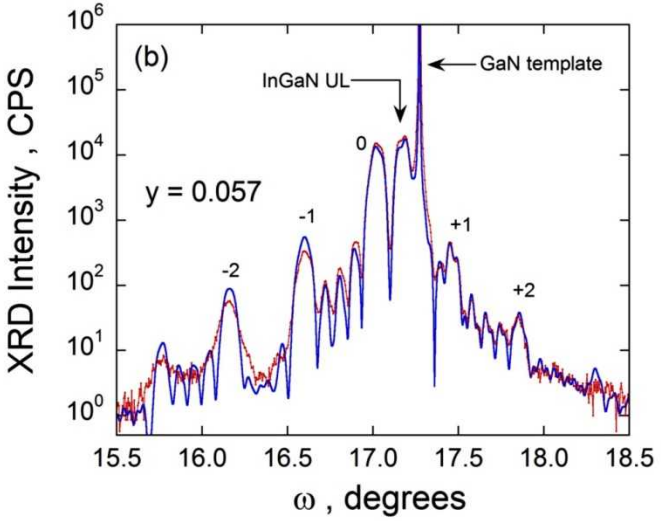
Flow 9 indium atoms for each gallium atom, growth rate dominated by gallium flow rate – indium desorption rate high, gallium desorption rate low.

XRD of 5 period MQWs with InGaN barriers



Using dynamic diffraction analysis software, the indium composition and thicknesses of the QW and barrier can be fit.

Here, growth at 750 ºC

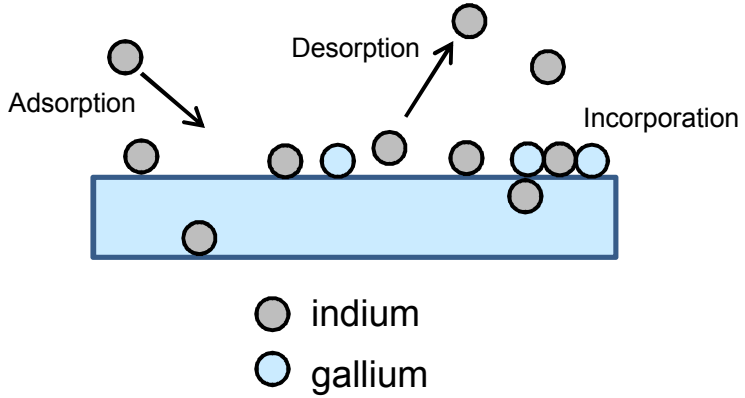


Mechanism for indium removal from surface

Adsorption (fast) Incorporation (slow)

$$In(g) \rightleftharpoons In(surf) \rightarrow In(s).$$

Desorption (fast)



Indium incorporates because it gets buried so In(s) depends on In(surf).

Two channels for indium desorption

$$In(surf) \rightarrow In(g). \quad (1)$$

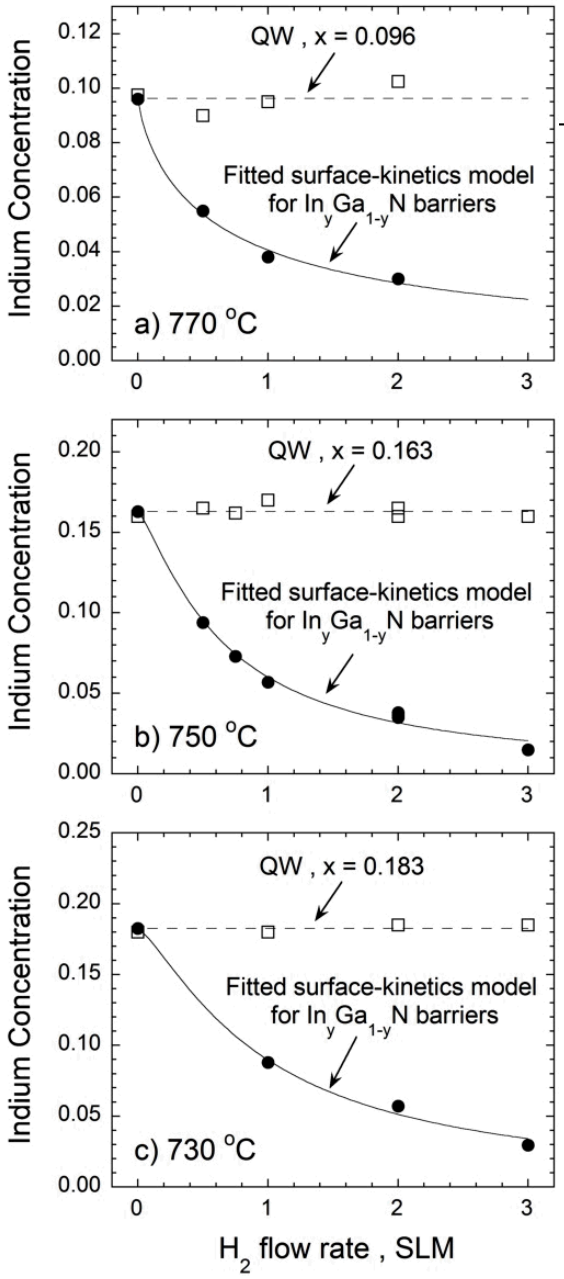
$$In(surf) + n\ H_2(g) \rightarrow In(surf) + 2nH\ (surf) \rightarrow InH_{2n}(surf) \rightarrow InH_{2n}(g\ ). \quad (2)$$

The indium surface coverage at any time is

$$d[In(surf)]/dt = k_{ads}\ [In(g)] - k_{des(1)}[In(surf)] - k_{incorp}[In(surf)] - k_{des(2)}[In(surf)]\ [H_2]^n$$

Soon after the indium is turned on and for most of the growth, $d[In(surf)]/dt = 0$ and after some arrangement, we get,

$$[In(surf)] / [In(g)] = 1 / (\{k_{des(1)} / k_{ads} + k_{incorp} / k_{ads}\} + k_{des(2)} / k_{ads}\ [H_2]^n).$$



Fit to InGaN QW and barrier data

For the QWs no H_2 and [In(g)] is constant so,

$$[In(surf)] / [In(g)] = 1 / \{k_{des(1)} / k_{ads} + k_{incorp} / k_{ads}\} = x$$

Fit is equal the indium concentration in the QWs as shown by the dashed lines at the three growth temperatures.

For the InGaN barriers as the H_2 increases,

$$[In(surf)] / [In(g)] = 1 / (1/x + k_{des(2)} / k_{ads} [H_2]^n)).$$

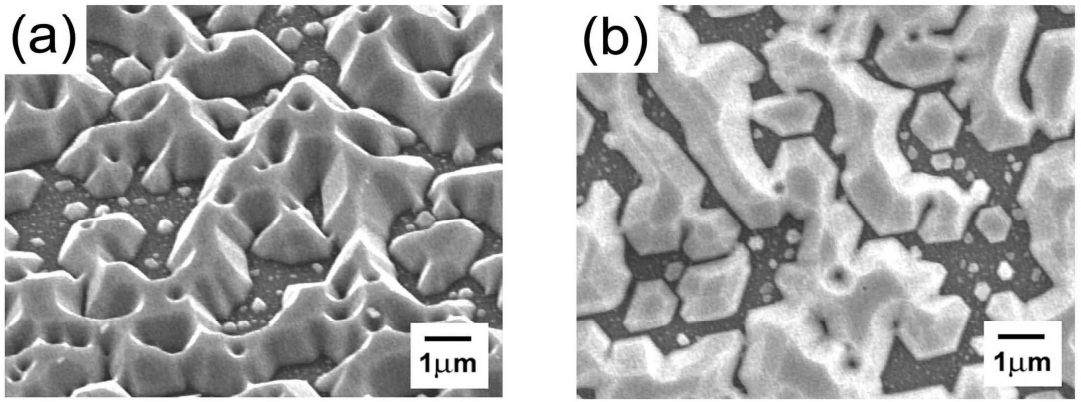
Fits are shown by the solid lines, if k_{incorp} is small, then

Temperature , ºC	$k_{des(2)} / k_{des(1)}$	2n
770	1.36	1.6
750	1.69	2.5
730	1.04	2.6

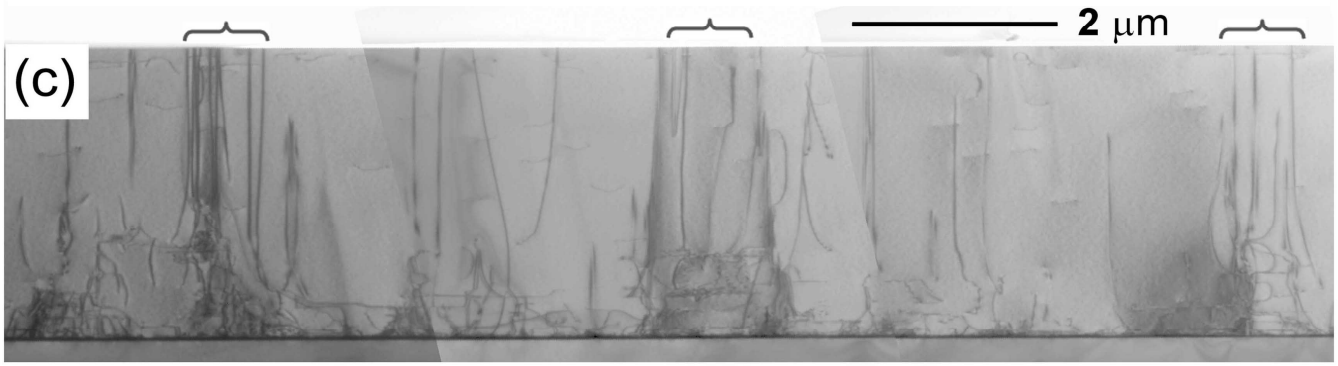
Suggests indium removal by InH, InH_2, InH_3 depending on InGaN growth temperature.

Initial GaN growth is 3D then 2D

SEM Images of 3D GaN grain growth



After the film has coalesced – 10^9 cm^{-2} dislocations are observed.

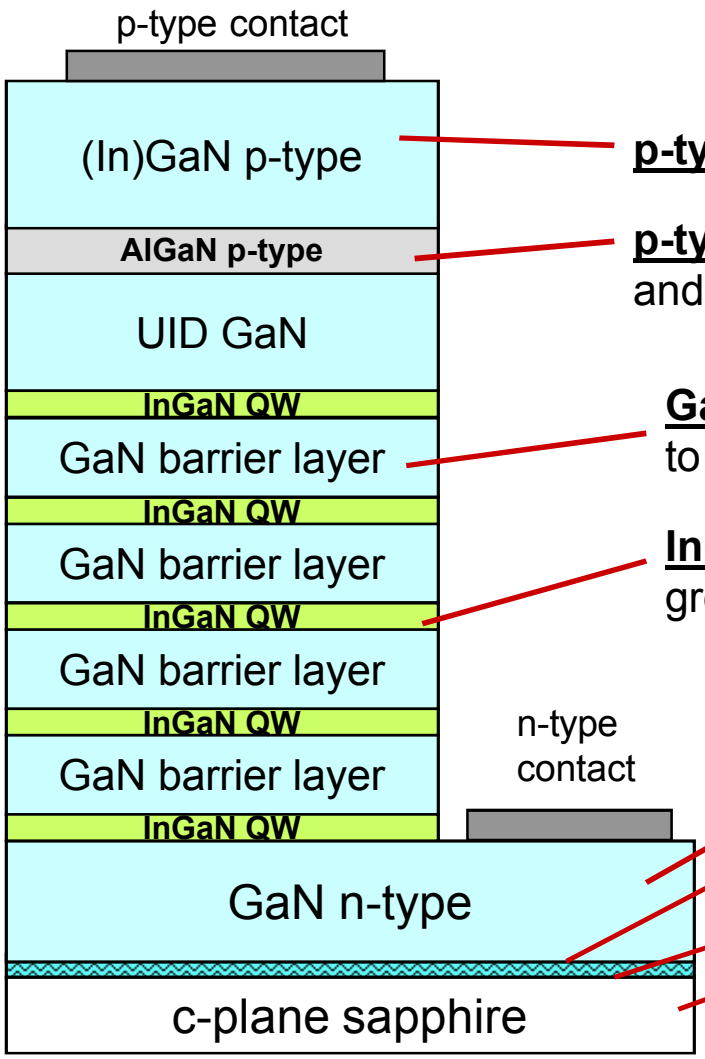


TEM cross section

TEM courtesy of D. M. Follstaedt

Dislocations primarily generated during grain coalescence

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 800 °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.

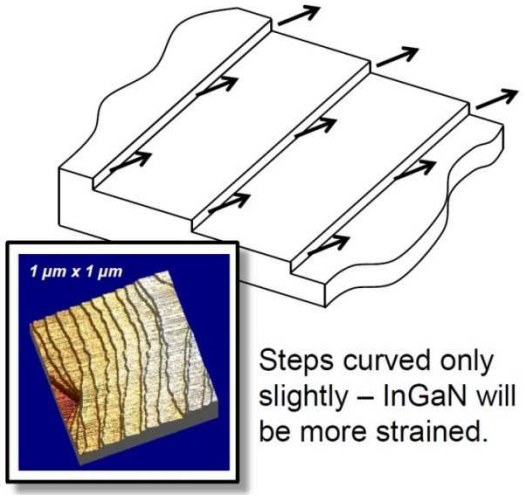
GaN bulk on top of annealed NL.
Heat NL to 1050 °C in NH_3, H_2, and N_2.

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

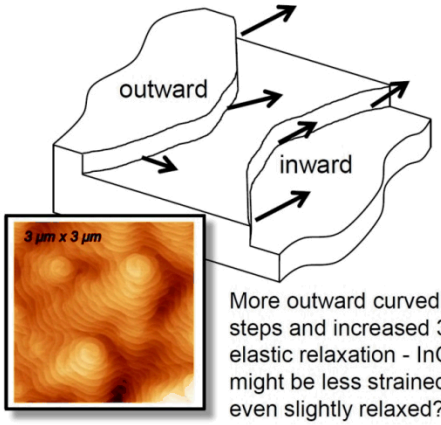
Established growth conditions, however issues with MOCVD reactors

MQWs on thick InGaN provide some strain relief

Have achieved IQE of 90 % in blue QWs in APL 101, 241104 (2012).



Steps curved only slightly – InGaN will be more strained.

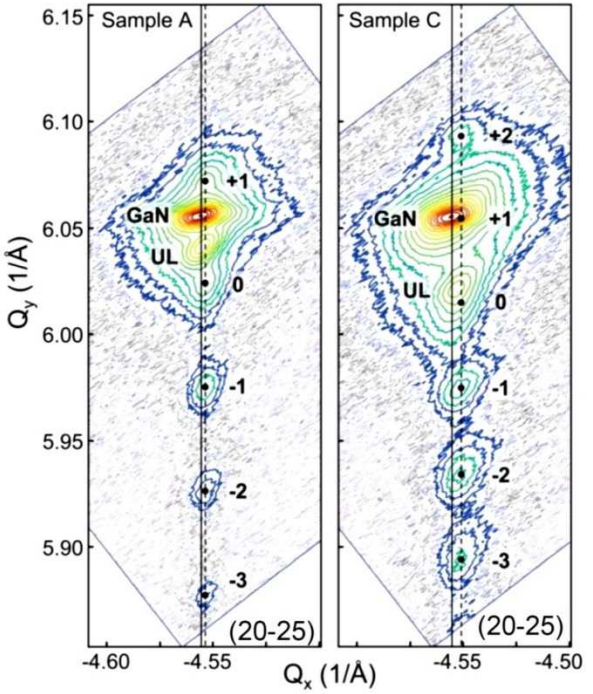


More outward curved steps and increased 3D elastic relaxation - InGaN might be less strained or even slightly relaxed?

outward curving steps > inward curving steps

S.R. Lee et al. JCG 355 (2012) 63.

Strain relaxation is observed in k-space maps for MQWs on ULs.



Sample A - InGaN UL and a 5-period $In_{0.17}Ga_{0.83}N$/GaN MQW – 2.8% per QW.

Sample C - InGaN UL and a 10-period $In_{0.20}Ga_{0.80}N$/GaN MQW – 4.2% per QW.

Lee et al. J. Crystal Growth 355, 63 (2012)

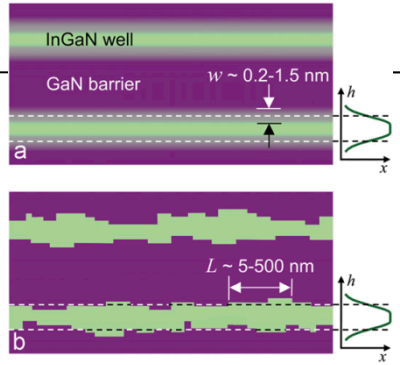


Fig. 2. Schematic diagrams of interfacial grading in InGaN/GaN MQWs showing (a) true compositional grading at a compositionally diffuse interface and (b) apparent compositional grading arising from lateral averaging along a roughened or stepped but compositionally abrupt interface.The laterally averaged composition, x, plotted versus depth, h, appears similar for both true and apparent grading.

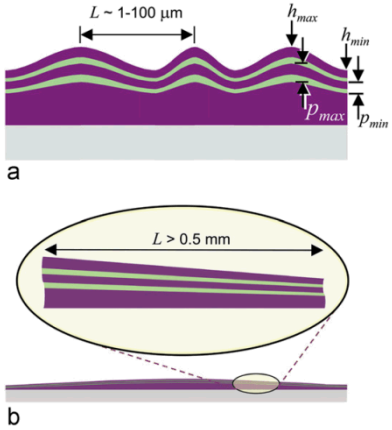


Fig. 3. Schematic diagrams of lateral thickness variations in InGaN/GaN MQWs showing (a) a microscopic lateral variation in film thickness and (b) a macroscopic lateral variation in film thickness. With in superlattices, a lateral variation in film thickness, h, manifests as a lateral variation in superlattice period, p.

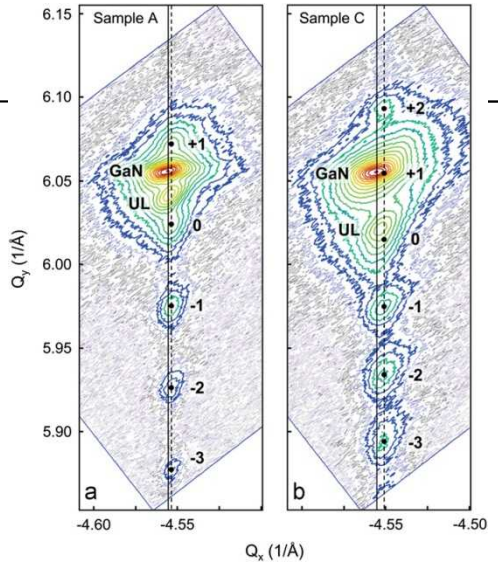


Fig. 4. (20–25) reciprocal space maps of sample A, a 5-period In0.17Ga0.83N/GaN MQW and InGaN underlayer, and sample C, a 10-period In0.20Ga0.80N/GaN MQW and InGaN underlayer. Reciprocal lattice units are chosen such that $|Q| = 2\pi/d$, where Q is the reciprocal lattice vector and d is the interplanar spacing.

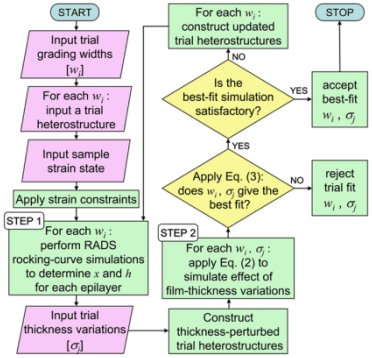


Fig. 1. Flowchart describing the modeling approach used to simulate the effect of interface \grading and lateral film-thickness variation on x-ray diffraction by InGaN/GaN MQWs.

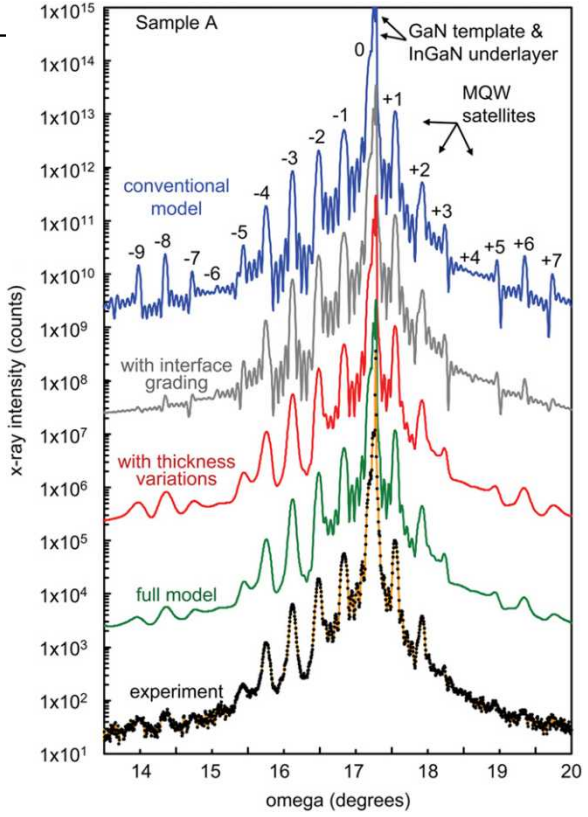


Fig. 5. Fitted simulations and measured (0002) ω/2θ scans for Sample A, a 5-period In0.17Ga0.83N/GaN MQW and InGaN underlayer. The fitted full model gives an interface width w = 0.8 nm and a lateral thickness variation σ = 0.024. The scans are vertically offset for visual clarity.