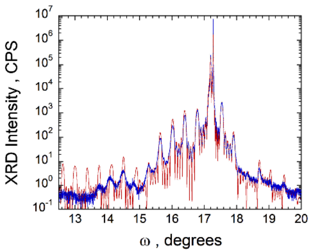
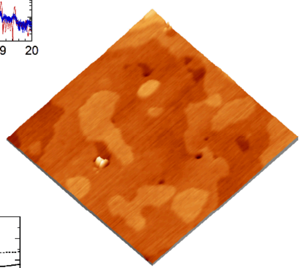
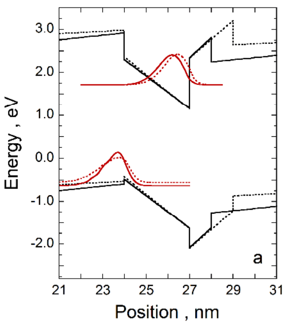
SAND2015-6760C

Increased Indium Incorporation and Efficiency in InGaN Quantum Wells Emitting at 530-590 nm with AlGaN Interlayers







Daniel D. Koleske*, Arthur J. Fischer, B. N. Bryant and Jonathan J. Wierer, Jr‡.

Sandia National Laboratories, Albuquerque, NM, 87185, USA

**ddkoles@sandia.gov*

‡ *currently at Lehigh University, Dept. Electrical and Computer Engineering.*

Sandia National Laboratories

Exceptional service in the national interest

The 17th U.S. Biennial Workshop on Organometallic Vapor Phase Epitaxy (OMVPE-17)
August 2nd-7th, 2015, Big Sky, Montana, USA

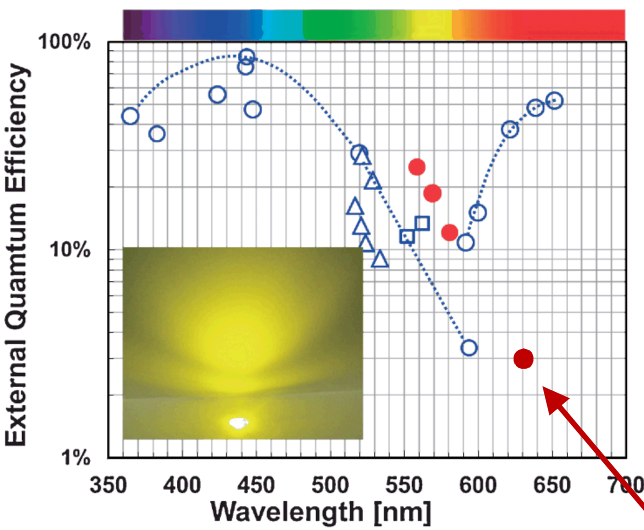
U.S. DEPARTMENT OF ENERGY

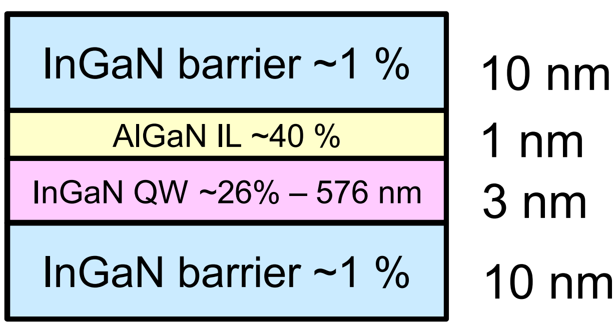
NNSA National Nuclear Security Administration

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.

Bright yellow and red LEDs from Toshiba

Higher EQE at green-gap wavelengths
Saito – Appl. Phys. Exp. 6 (2013) 111004

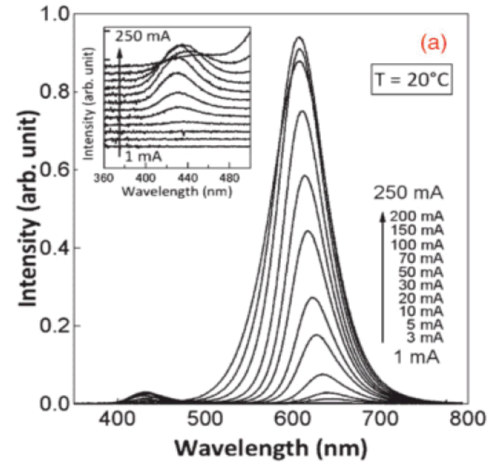


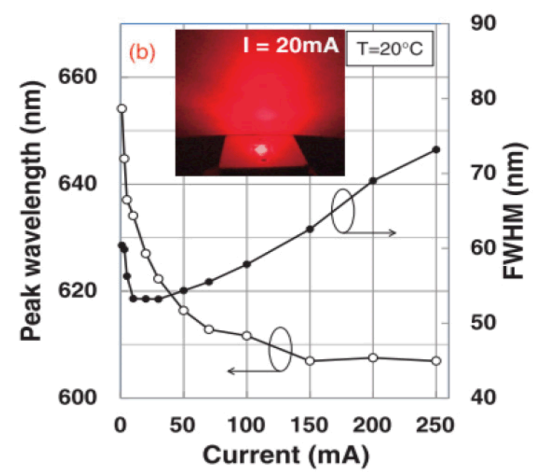


Is capping the QW with AlGaN IL the key?

Hwang – Appl. Phys. Exp. 7 (2014) 071003.

35% InGaN QWs?





Achieved 1.1 mW @ 20 mA and EQE of 2.9 %, 629 nm @ 20 mA and 608 nm @ 200 mA

How does the AlGaN interlayer (IL) work?

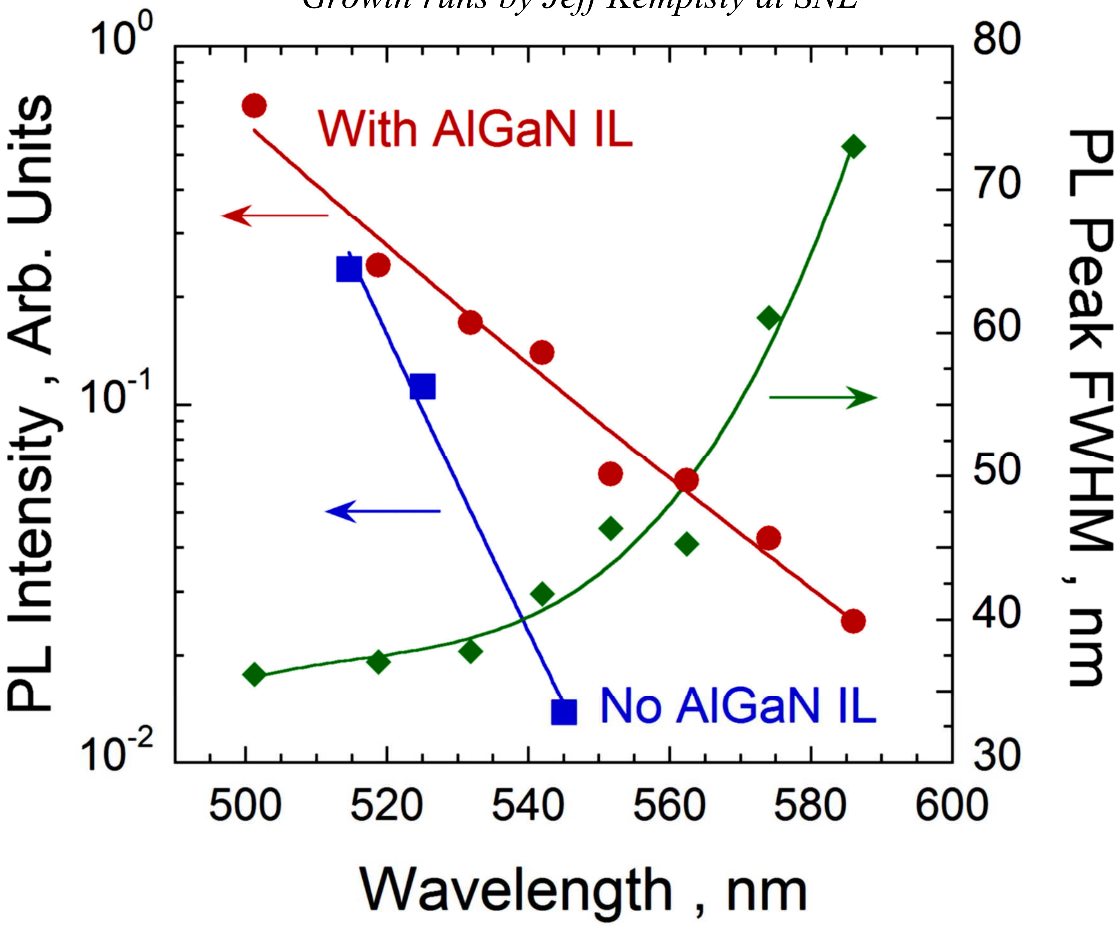
More details in D.D. Koleske et al., Journal of Crystal Growth 415 (2015) 57-64

- What are the exact growth conditions?
  - AlGaN IL growth?, special conditions?
  - Use GaN barriers instead of 1 % InGaN barriers. Optimal temperature?
  - Growth sequence? When to ramp? When to start GaN barrier growth?
  - Can the structures be verified using XRD?
- Influence of AlGaN IL on the QW emission properties.
  - Can more indium be put in the InGaN QW?
    - Is it possible to go above the ~20% coherency strain limit for InGaN on GaN.
    - Does the InGaN QW strain relax?
    - Can the AlGaN IL prevent InGaN QW decomposition?
- AlGaN IL also influences the polarization fields
  - PL wavelength?, and PL intensity?

Yes it works – to some degree

- OMVPE Equipment
  - Veeco D125 - short jar
  - Active region @ 300 torr
  - 700 RPM
- InGaN growth
  - TMIn ~100 µmoles/min, temperature controls indium
  - 15 SLM NH_3, 10 SLM N_2
- QW growth
  - T = 690 to 730 ºC
  - QWs on InGaN underlayers*
  - Gray QWs below 730 ºC without AlGaN ILs
- AlGaN interlayer (IL)
  - Same temperature as QWs
- GaN barriers
  - Grown at 800 to 900 ºC

Growth runs by Jeff Kempisty at SNL

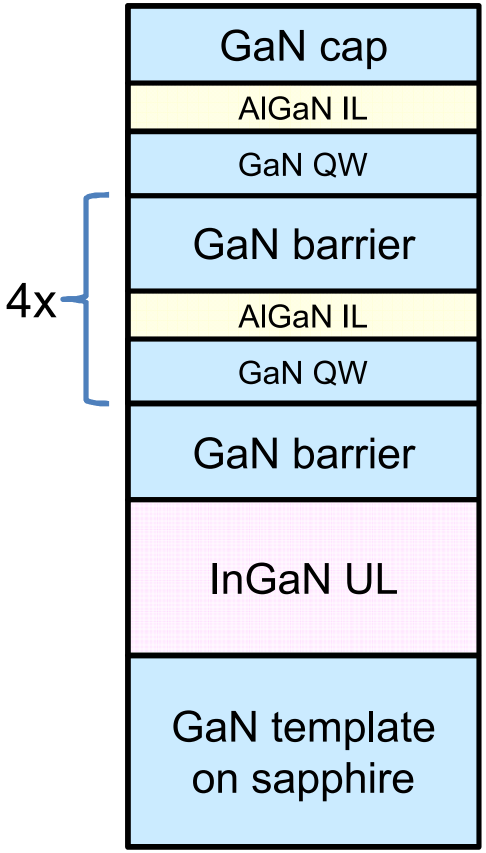


**For UL reference see Armstrong, JAP 117, 134501 (2015).*

10x improvement in PL intensity with IL, helps only for wavelengths > 520 nm

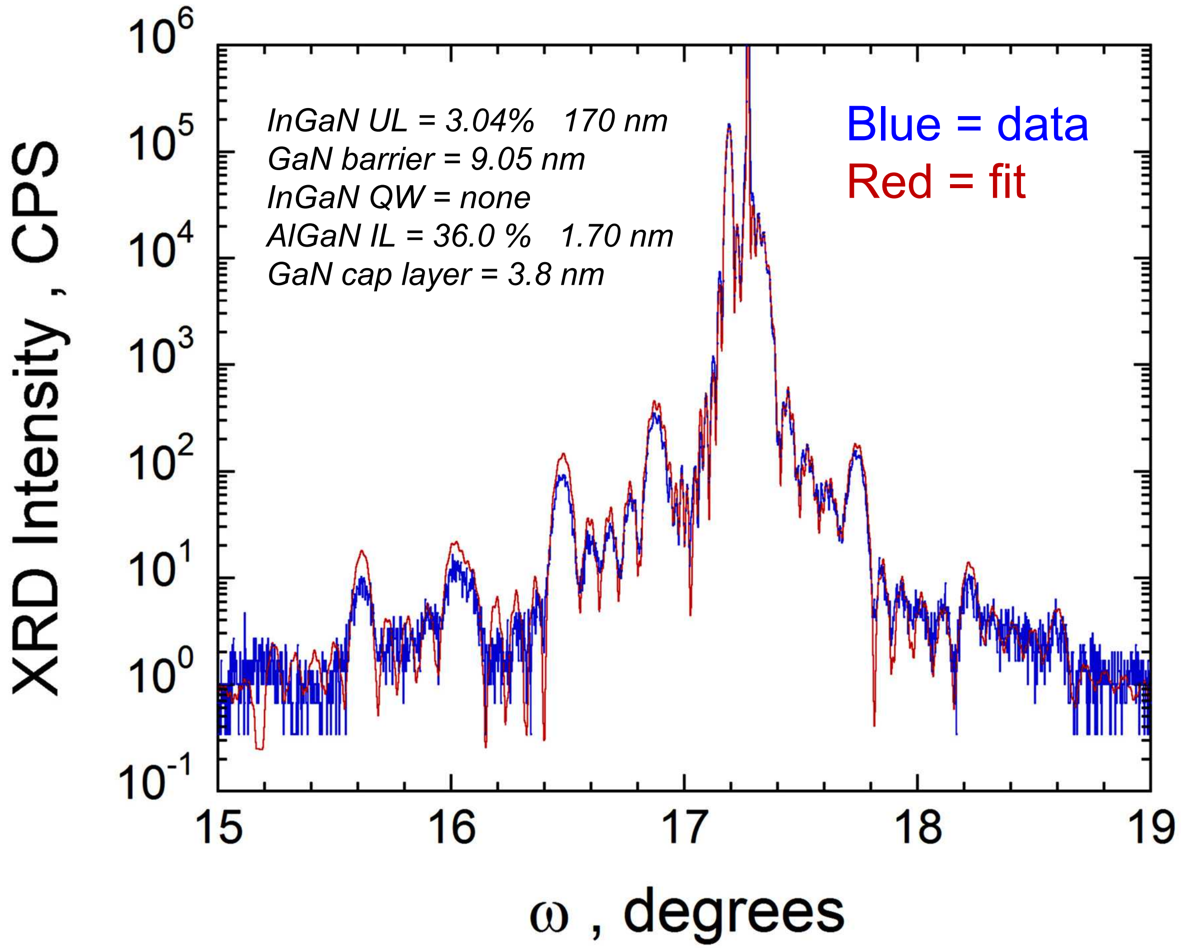
Calibration of the AlGaN layer using XRD

Grow InGaN QW structure without indium



Target gas phase Al/(Al+Ga) = 0.40

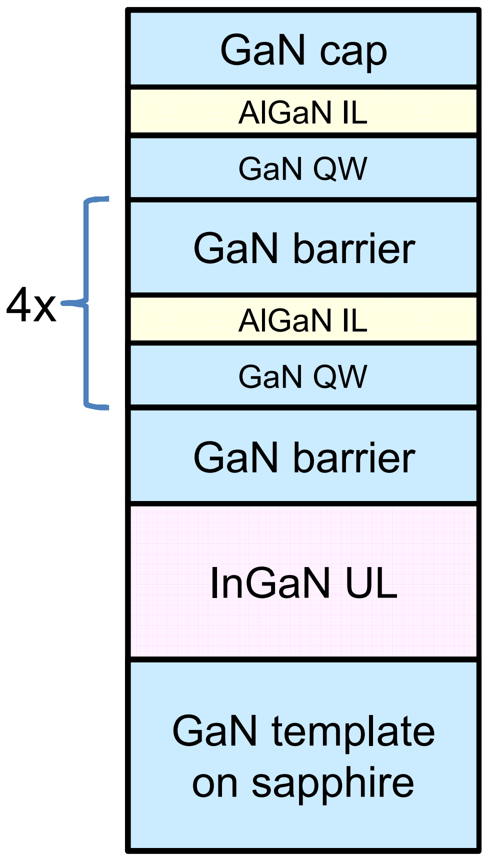
Get solid phase Al/(Al+Ga) = 0.36, 1.7 nm



XRD fit uses Panalytical's Expert 4.0

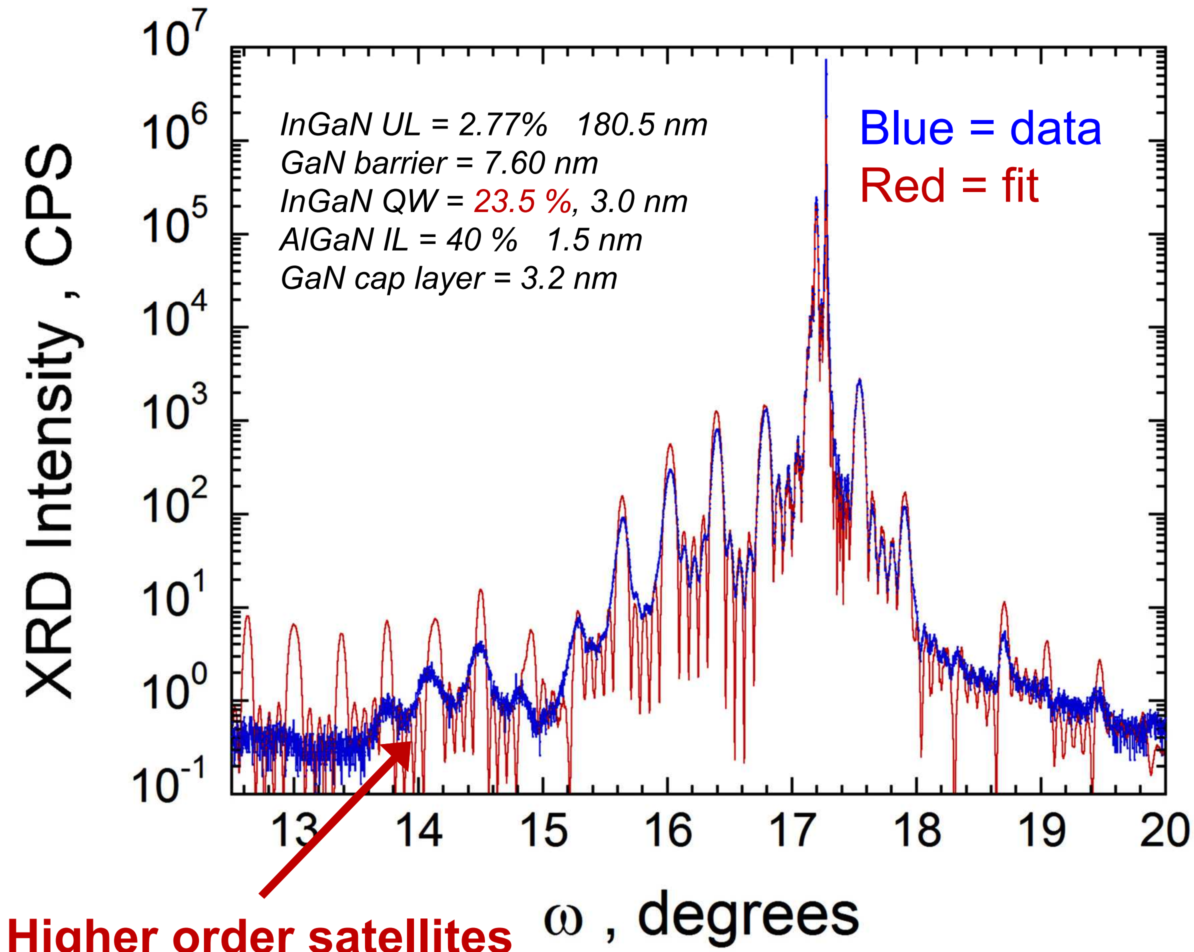
XRD fit of the full structure

Put indium back into the QW structure



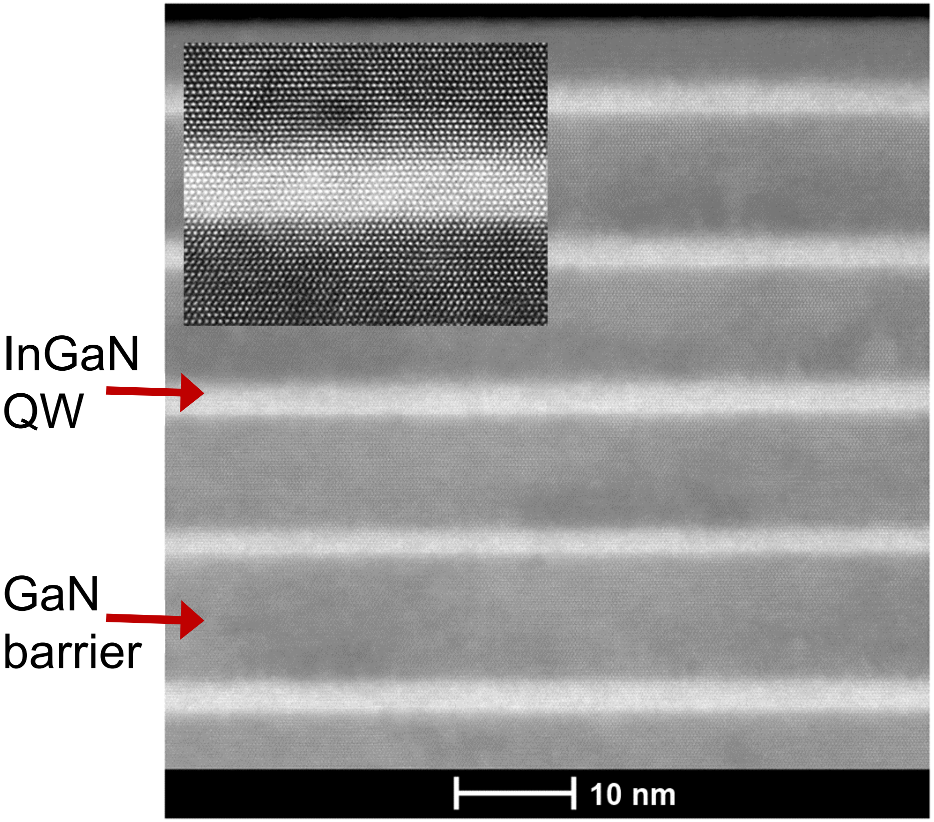
Adjust aluminum flows to get 40 % AlGaN

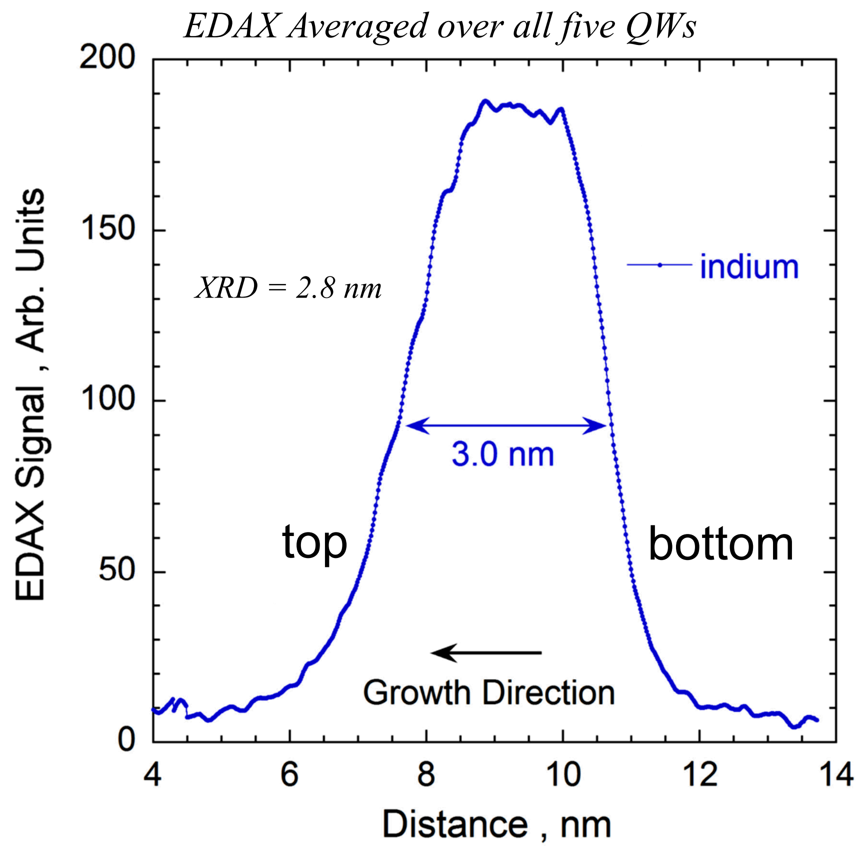
Verified with XRD that QW has 23.5 % indium



STEM and EDAX for MQW without IL

QW at 730 ºC, grow GaN barrier at 730 ºC for 1 nm, continue GaN barrier growth while heating to 800 ºC.



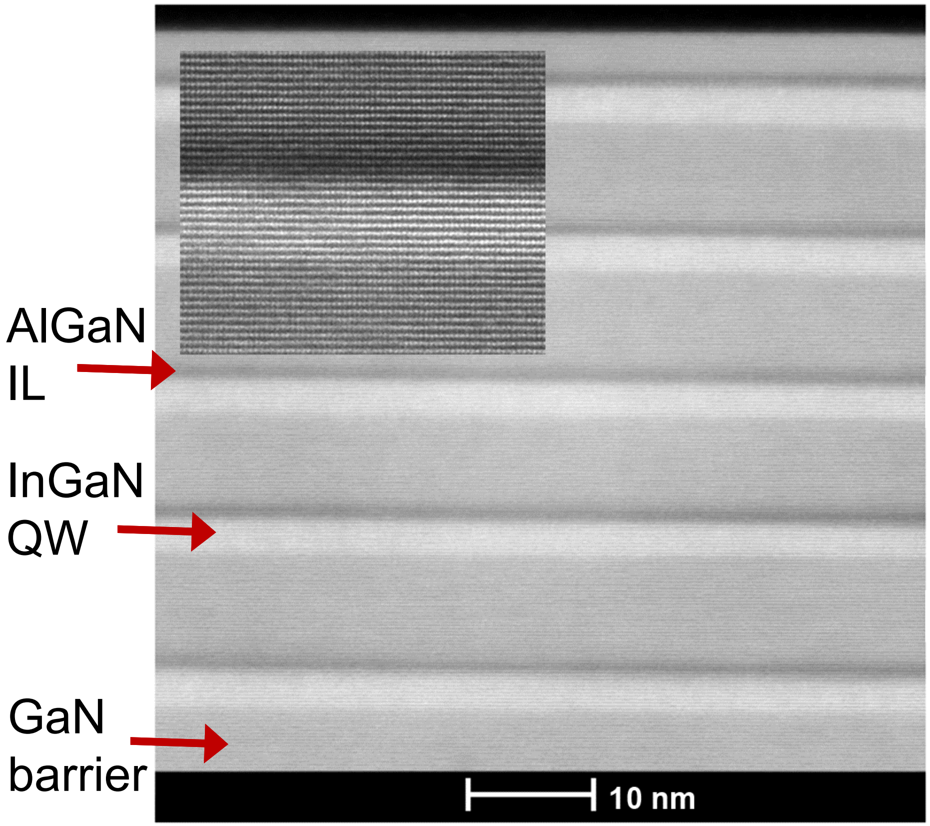


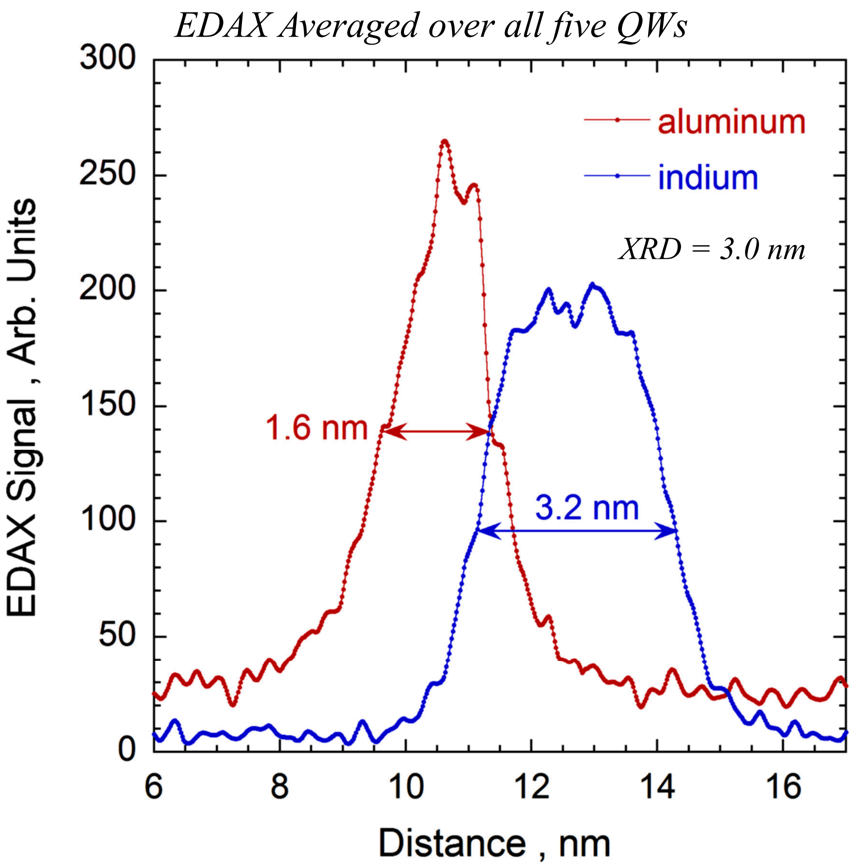
Top interface 0.5 nm thicker than bottom interface.

Reason that top interface is thicker, 1) surface indium depletion into GaN barrier or 2) indium diffusion through GaN cap during heating. 3). Can't rule out steps.

STEM and EDAX for MQW with IL

Cap QW with IL at 700 ºC, heat to 850 ºC with no MOs flowing, then grow GaN barrier.

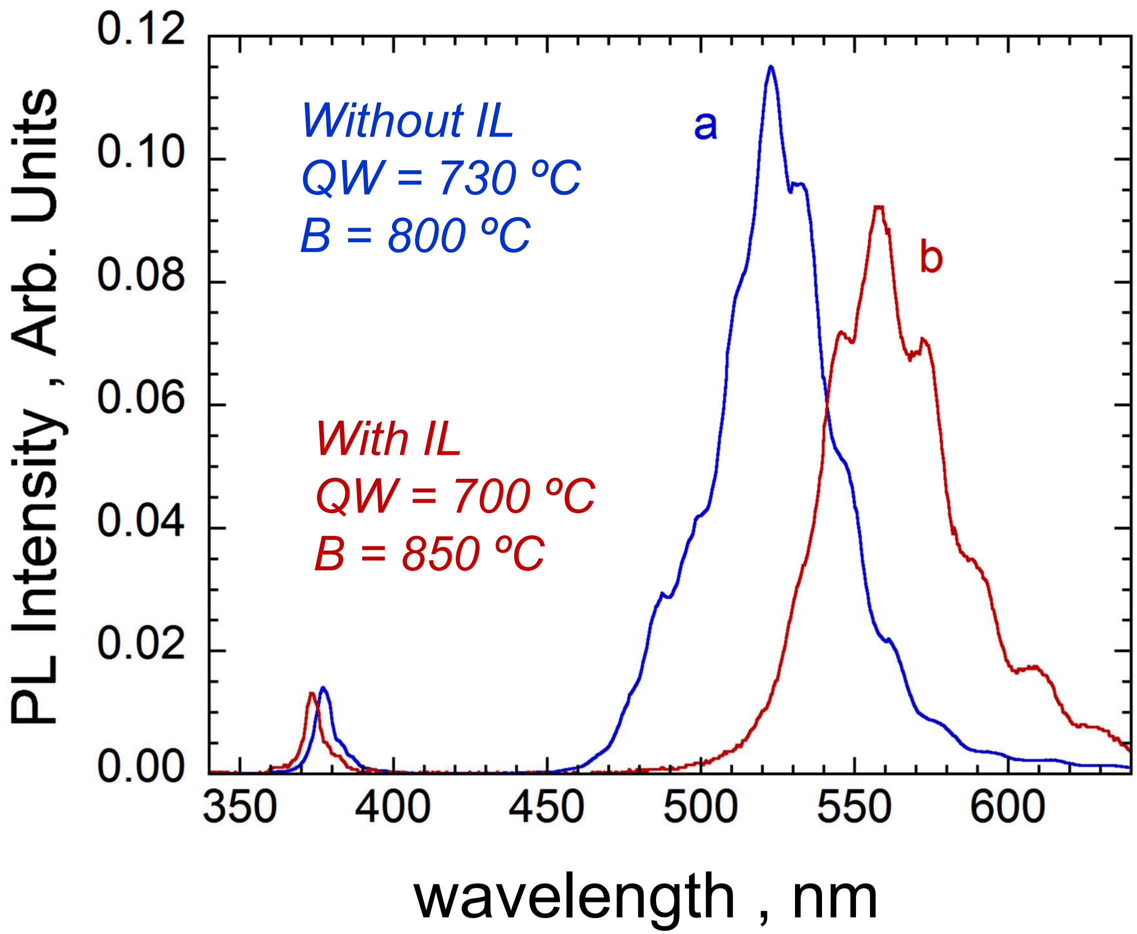




Top and bottom InGaN interfaces are both ~ 1 nm thick.

Similar InGaN interface width gives the higher order satellite peaks in the XRD. (see S.R. Lee, JCG 355 (2012) 63-72 for more details).

Shift in PL wavelength using the AlGaN IL

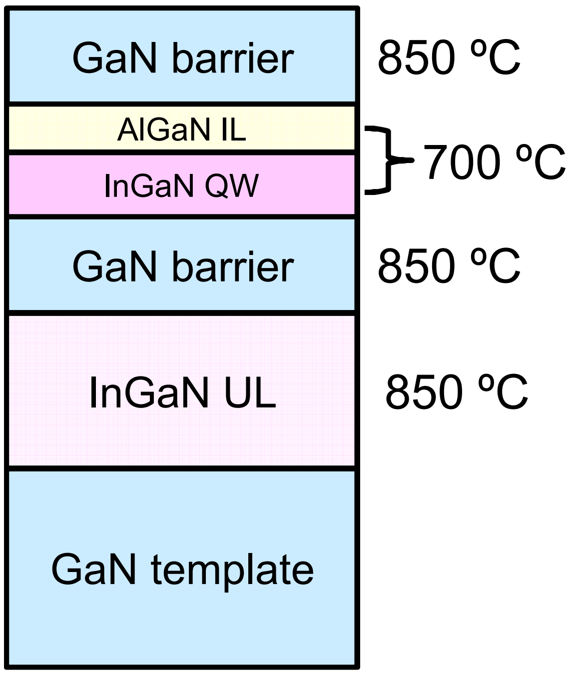


Similar PL intensity with higher indium concentration using the IL.

How do the growth steps influence the XRD structure and PL intensity?

Single QW with IL cap - study

SQW structure

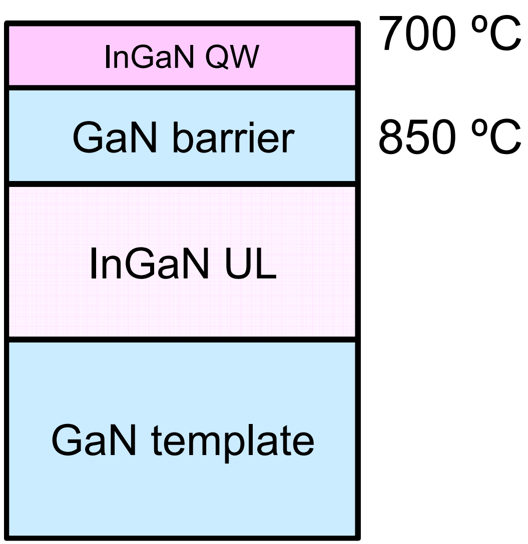


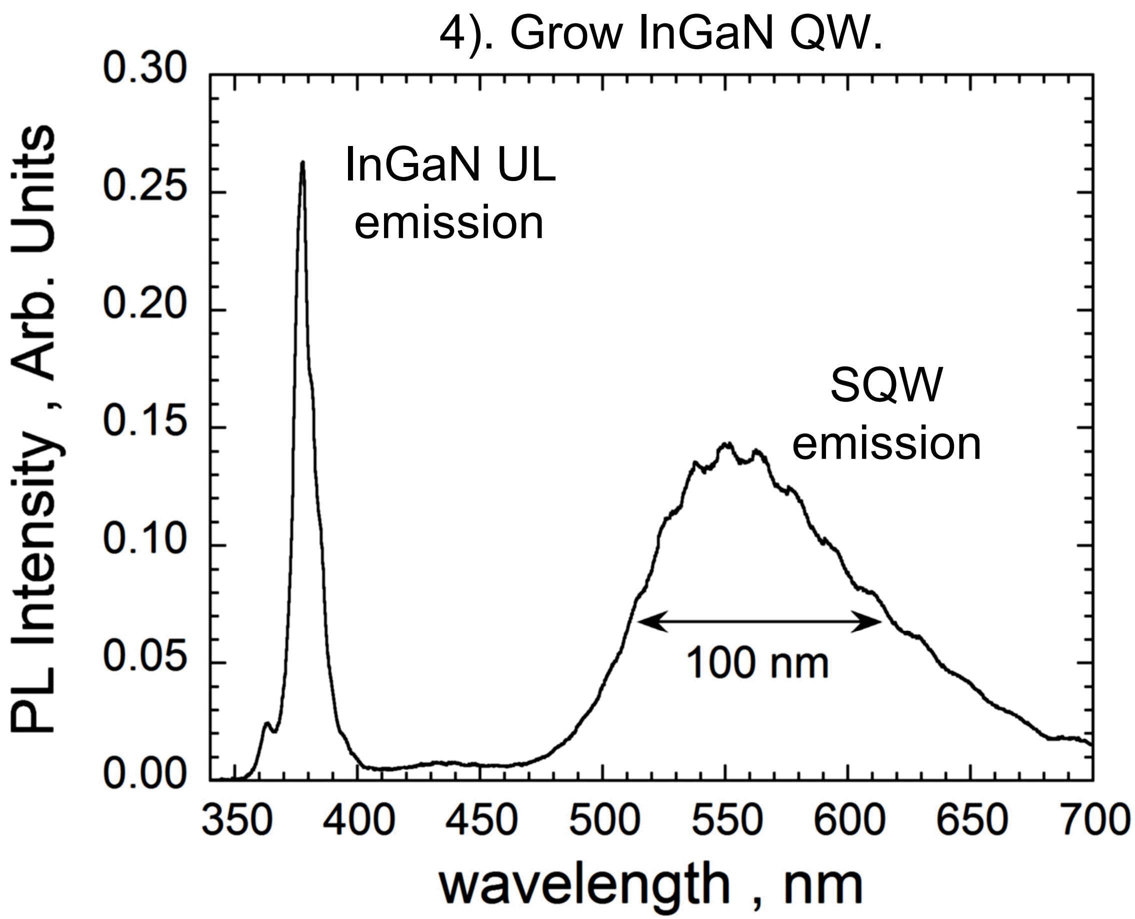
Growth steps

1). InGaN UL growth at 850 ºC
2). GaN barrier layer at 850 ºC
3). Lower to 700 ºC – stabilize
4). Grow InGaN QW (3.0 nm, 0.5 min.)
5). Grow AlGaN IL (1.5 nm, 0.3 min.)
6). MOs off, ramp to 850 ºC (1.5 min.)
7). TMGa on for GaN barrier (5-6 min.)

In separate growths, stop sequence after steps 4), 5), 6), and 7).

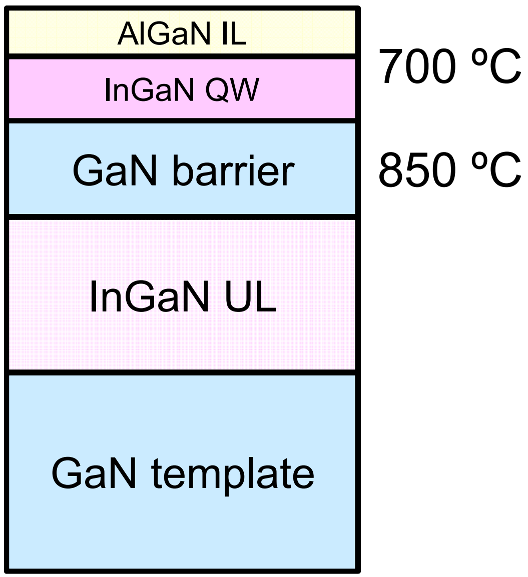
Single QW annealing study

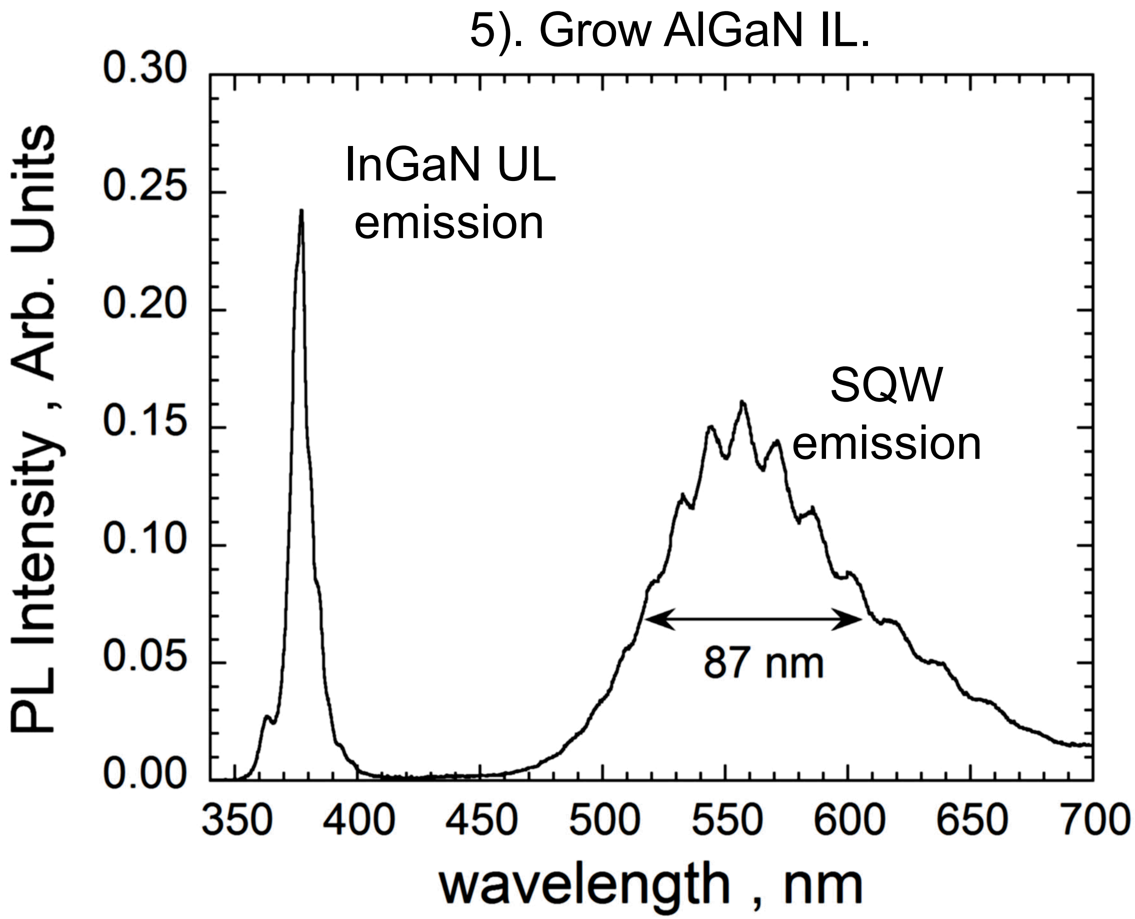




PL emission intensity broad – looks like yellow band

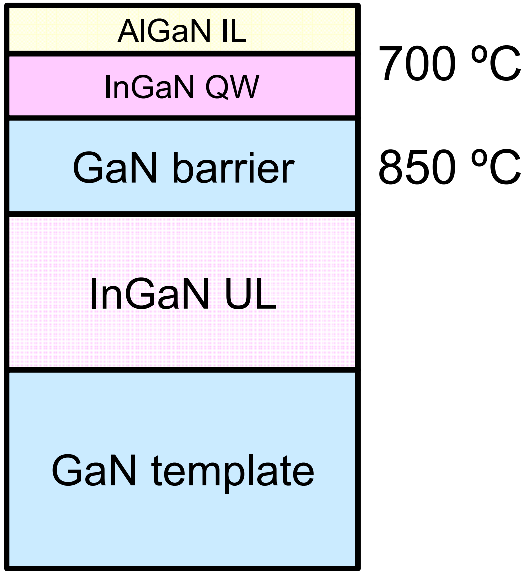
Single QW annealing study

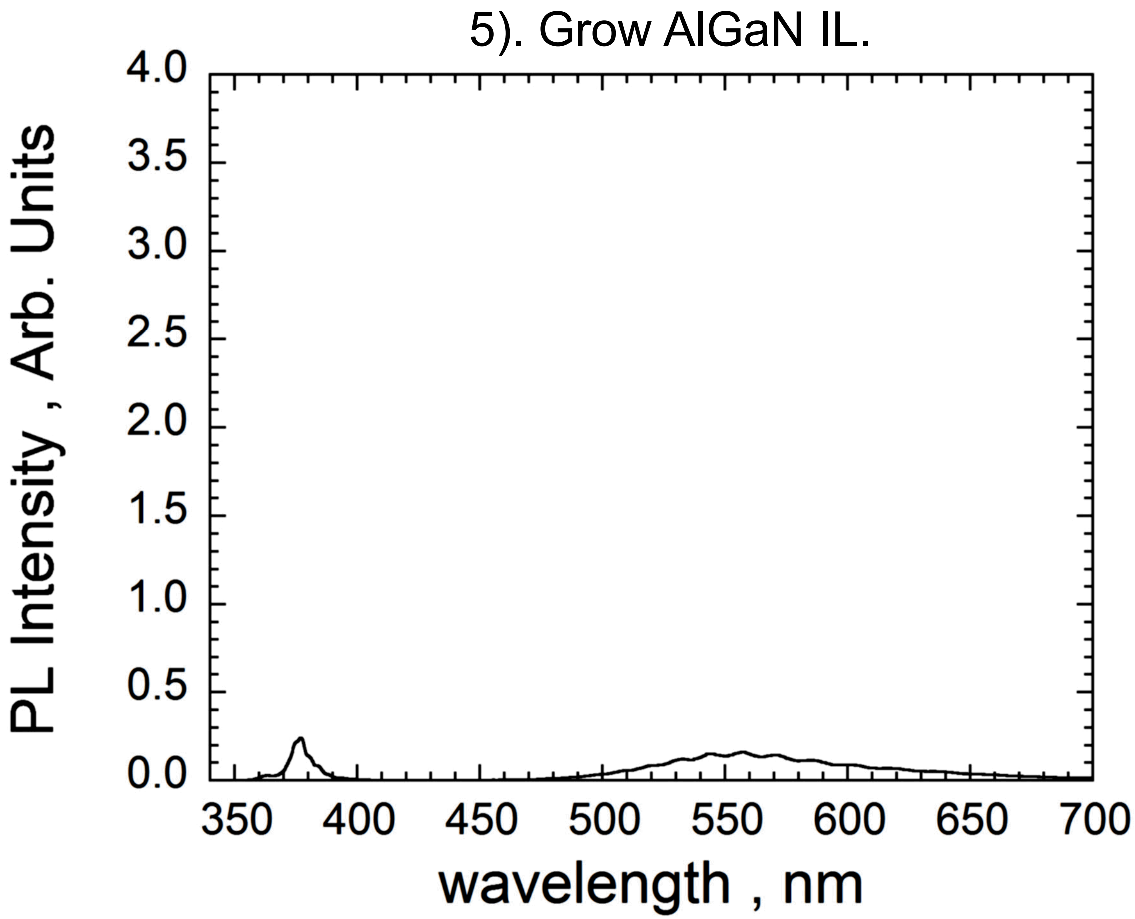




After AlGaN IL cap layer PL emission looks similar

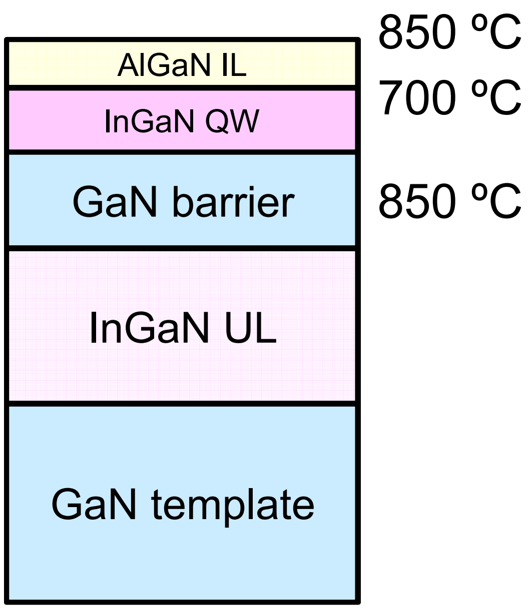
Single QW annealing study

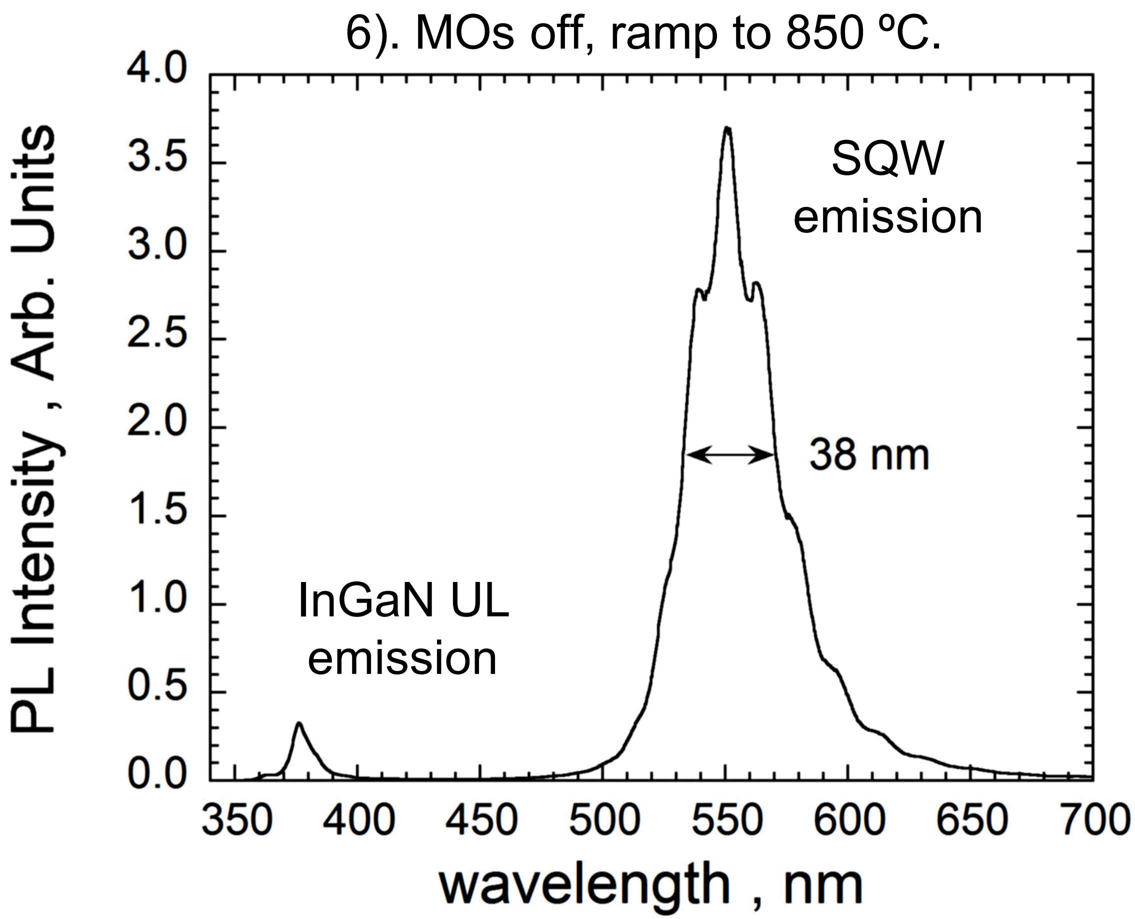




Change PL intensity scale to match next slide

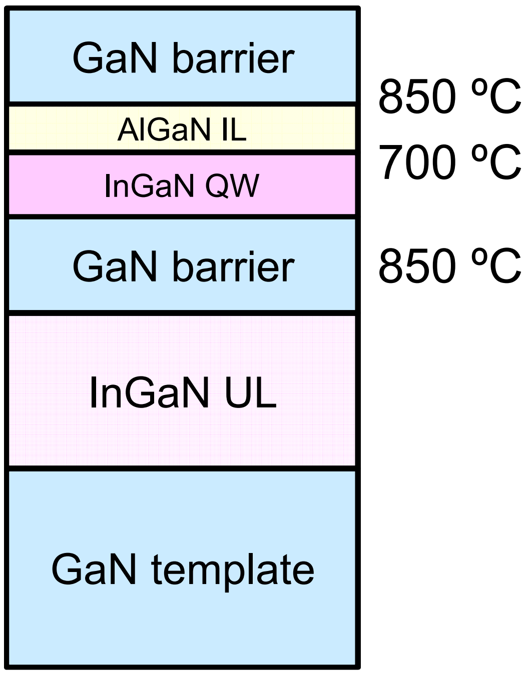
Single QW annealing study

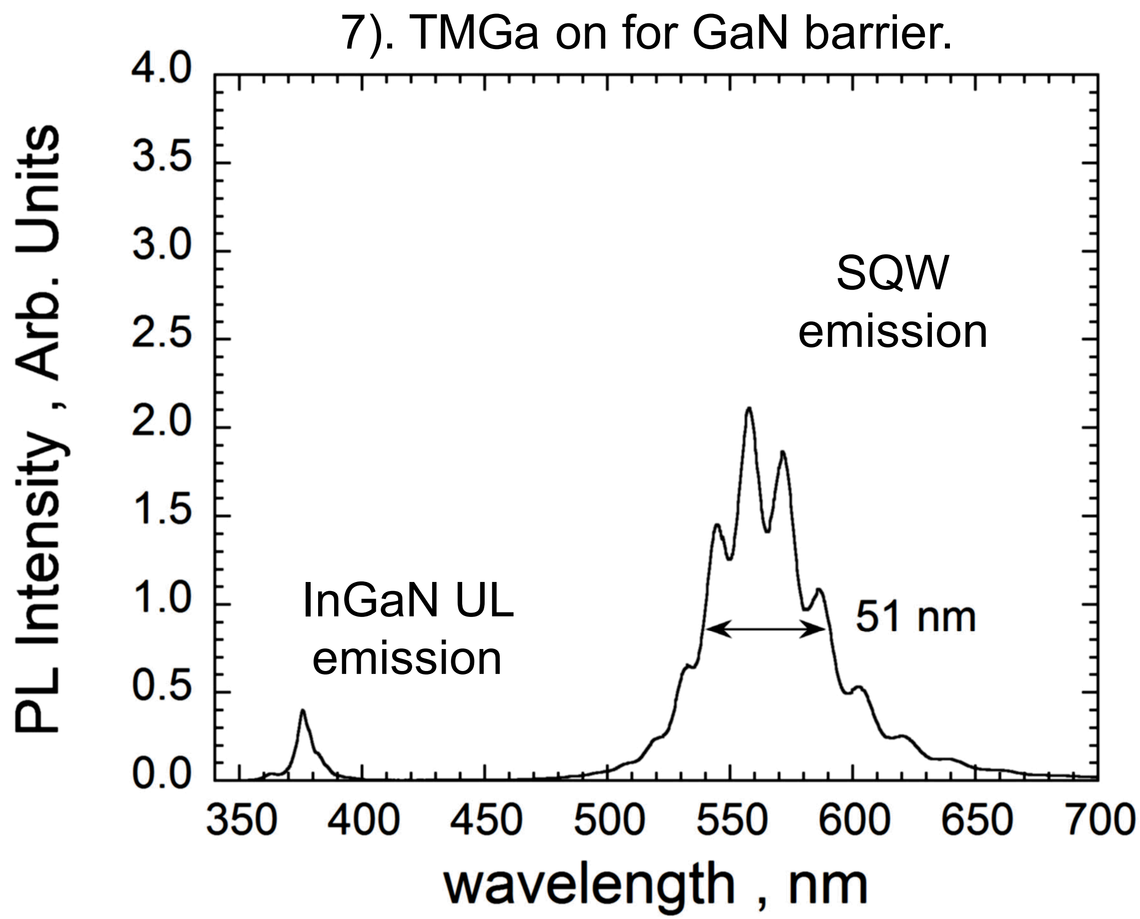




Annealing the AlGaN IL capped QW improves intensity ~25x

Single QW annealing study

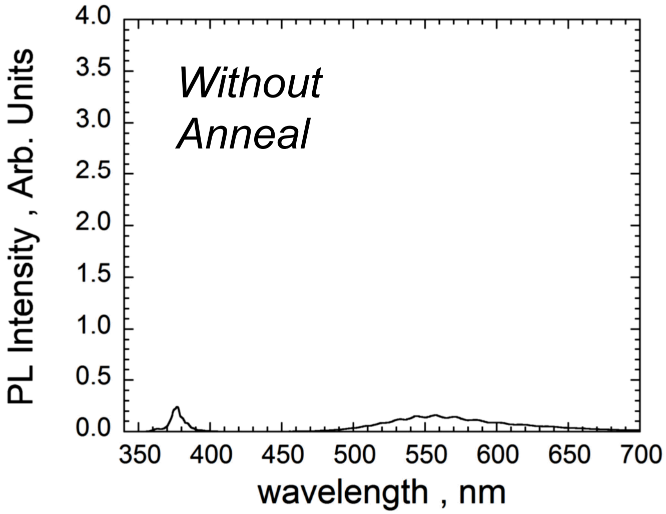




After the GaN barrier, decrease in intensity and slight redshift

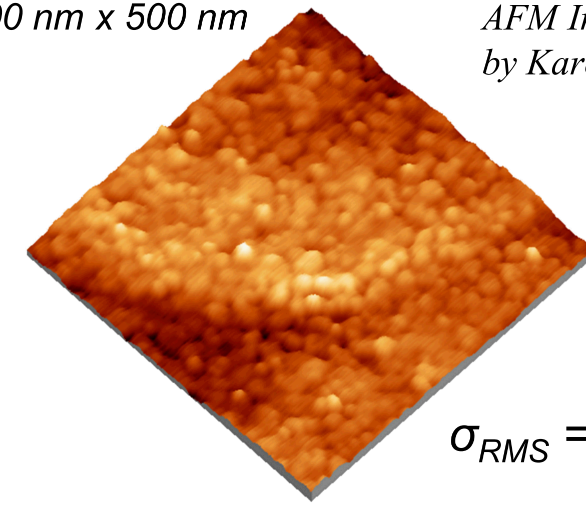
Change in AlGaN IL surface after annealing

5). Grow AlGaN IL.



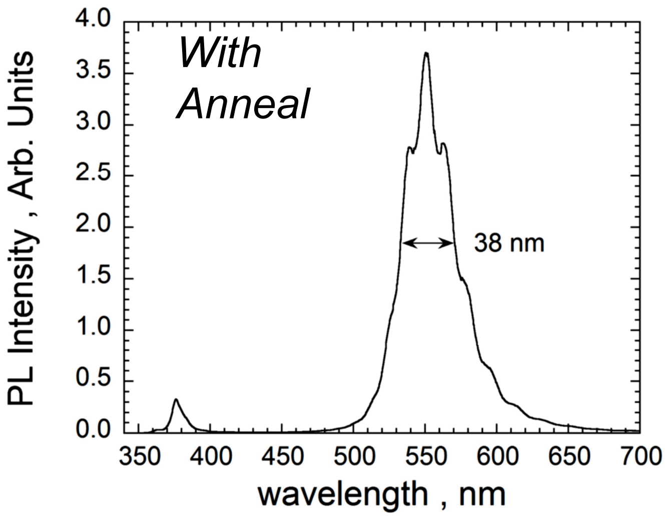
500 nm x 500 nm

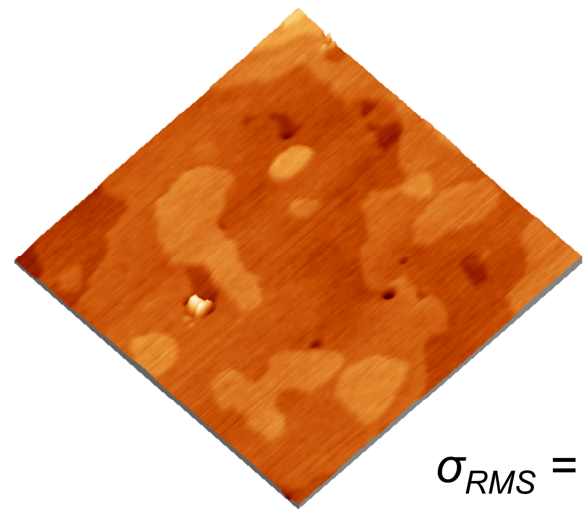
AFM Images measured by Karen Cross at SNL



σ_{RMS} = *0.48 nm*

6). MOs off, ramp to 850 ºC.

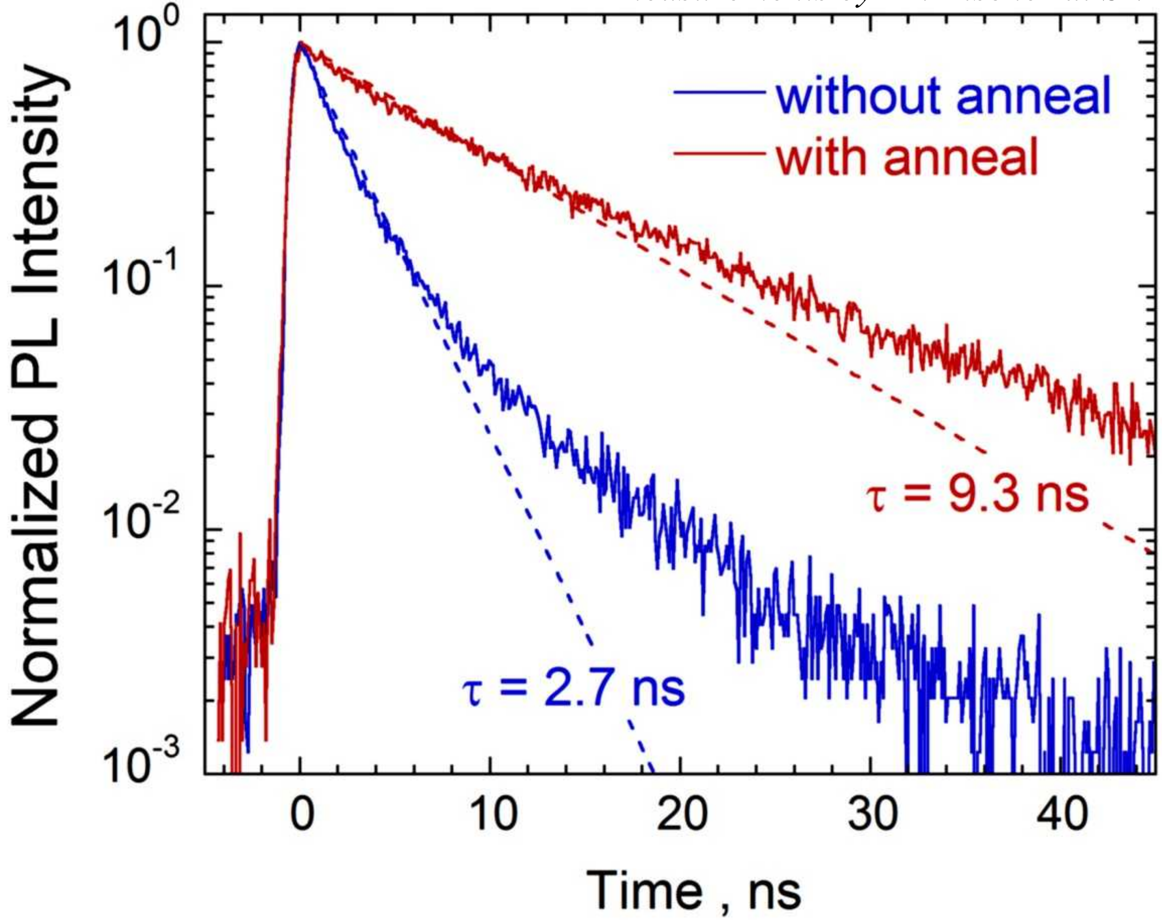




σ_{RMS} = *0.18 nm*

Time Resolved PL with/without annealing

TRPL measurements by Art Fischer at SNL



Annealed AlGaN/InGaN layer has longer lifetime than without anneal.

Suggests decrease in non-radiative recombination centers.

Summary of AlGaN interlayer (IL) work

- What are the exact growth conditions?
  - AlGaN IL growth? – Use InGaN QW temperature and flows. In off, Al on!
  - Use GaN barriers. Optimal temperature is between 850 to 875 ºC.
  - Growth sequence? Cap QW with IL, no MO's, ramp, then GaN barrier.
  - Can the structures be verified using XRD? Yes – leave out indium in QWs.
- Influence of AlGaN IL on InGaN QWs.
  - Can more indium be put in the InGaN QW? – Yes, can get λ to 590 nm.
    - Is it possible to go above the ~20% coherency strain limit for InGaN on GaN? Yes
    - Does the InGaN QW strain relax? No.
    - Does AlGaN IL prevent InGaN QW decomposition? Yes, better than GaN layers.
- AlGaN IL also influences the polarization fields
    - PL wavelength? – red shift, and PL intensity? – increases after annealing.
      - If AlGaN is too thick PL intensity decreases (modeled in paper).

More in D.D. Koleske et al., Journal of Crystal Growth 415 (2015) 57-64

Thanks to

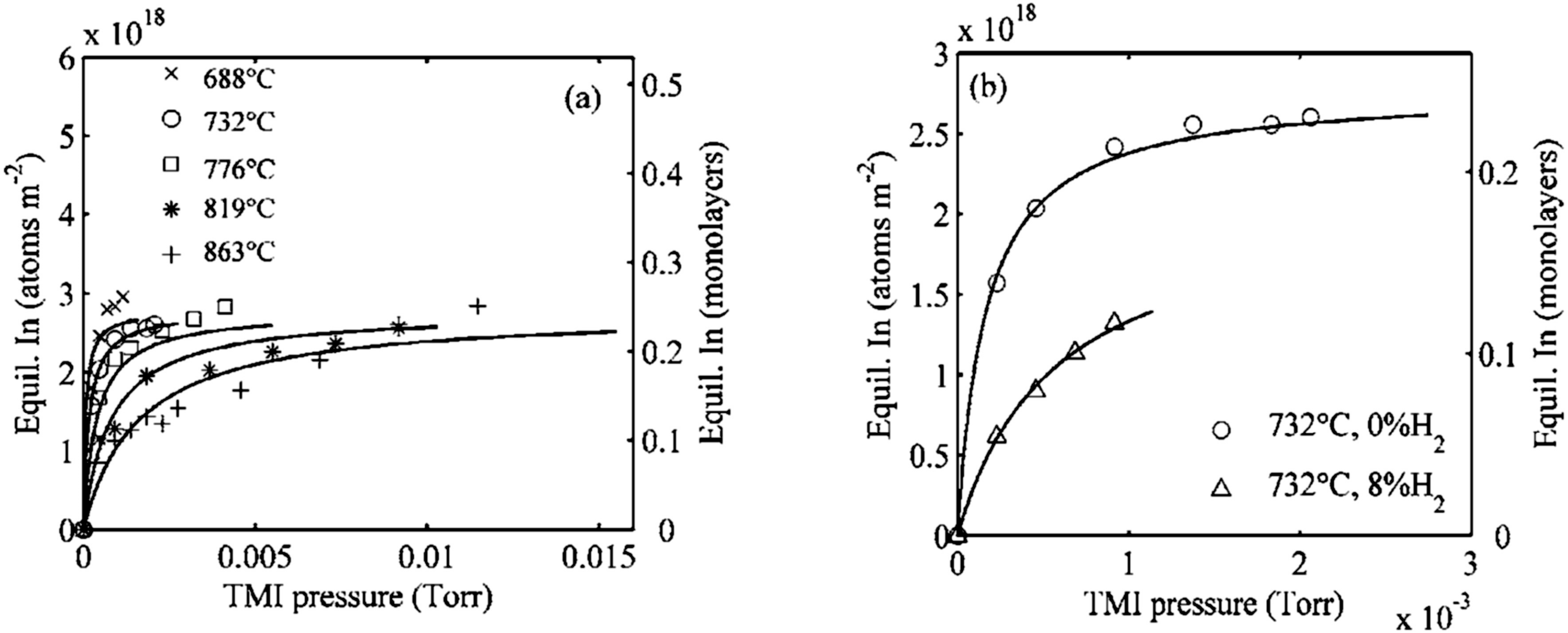
- Jeff Kempisty – MOCVD growth (sorry OMVPE growth)
- Jeff Figiel – OMVPE (just doesn't sound right) growth assistance.
- Karen Cross – AFM images extraordinaire
- Paul Katula – XTEM images and EDAX profiles.
- Mike Coltrin and Jeff Tsao – Feedback on JCG manuscript.

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

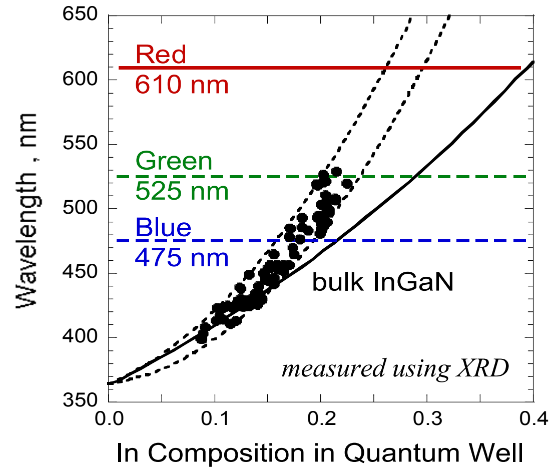
Extra Slides

Indium coverage up to 0.25 ML

Jiang - APL 89, 161915 (2006).
Indium adsorption on GaN under metal-organic chemical vapor deposition conditions

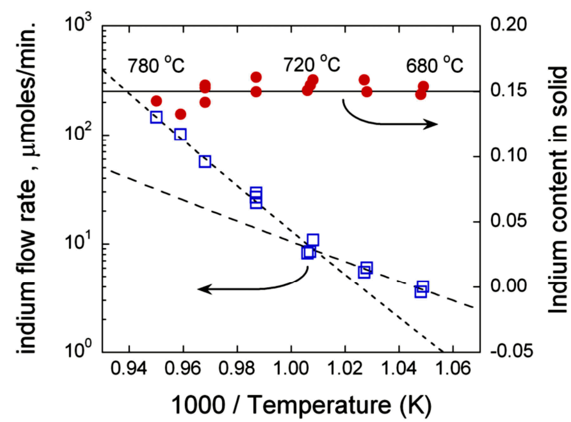


Motivation and Issues



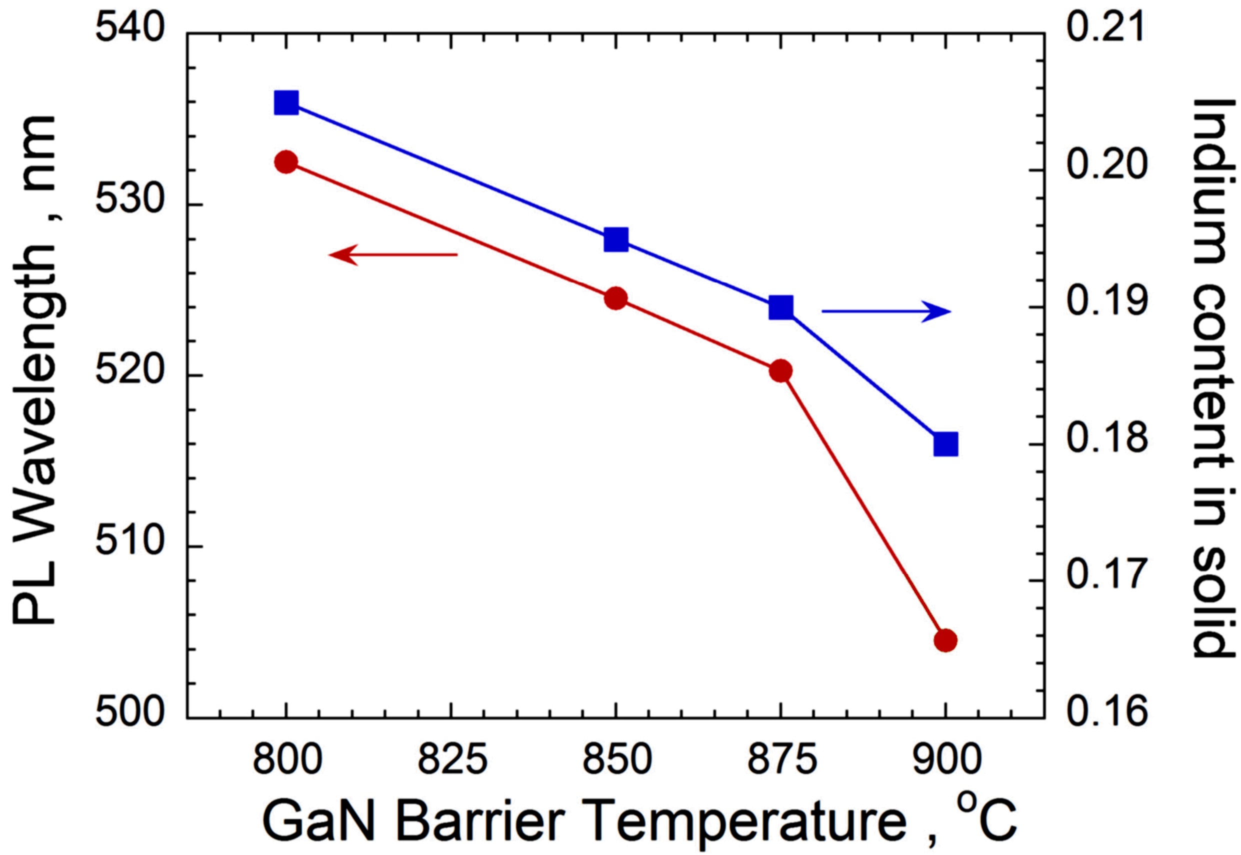
- Green to Red λ LEDs have low intensity
  - Need ~ 20 % indium for green, ~26-30 % red.
  - Lower temperatures required to incorporate more indium. More defects (point & impurity).
  - Increased strain on QW.
    Beneficial for red-shifting the wavelength - QCSE.
    Detrimental for e/h overlap.

- InGaN growth issues
  - Indium reservoir on the surface.
    Takes time build up and deplete.
    Hard to produce abrupt interfaces.
  - Like to grow InGaN QWs as hot as possible, however need exponentially more indium to reach same indium %.



Influence of GaN barrier temperature

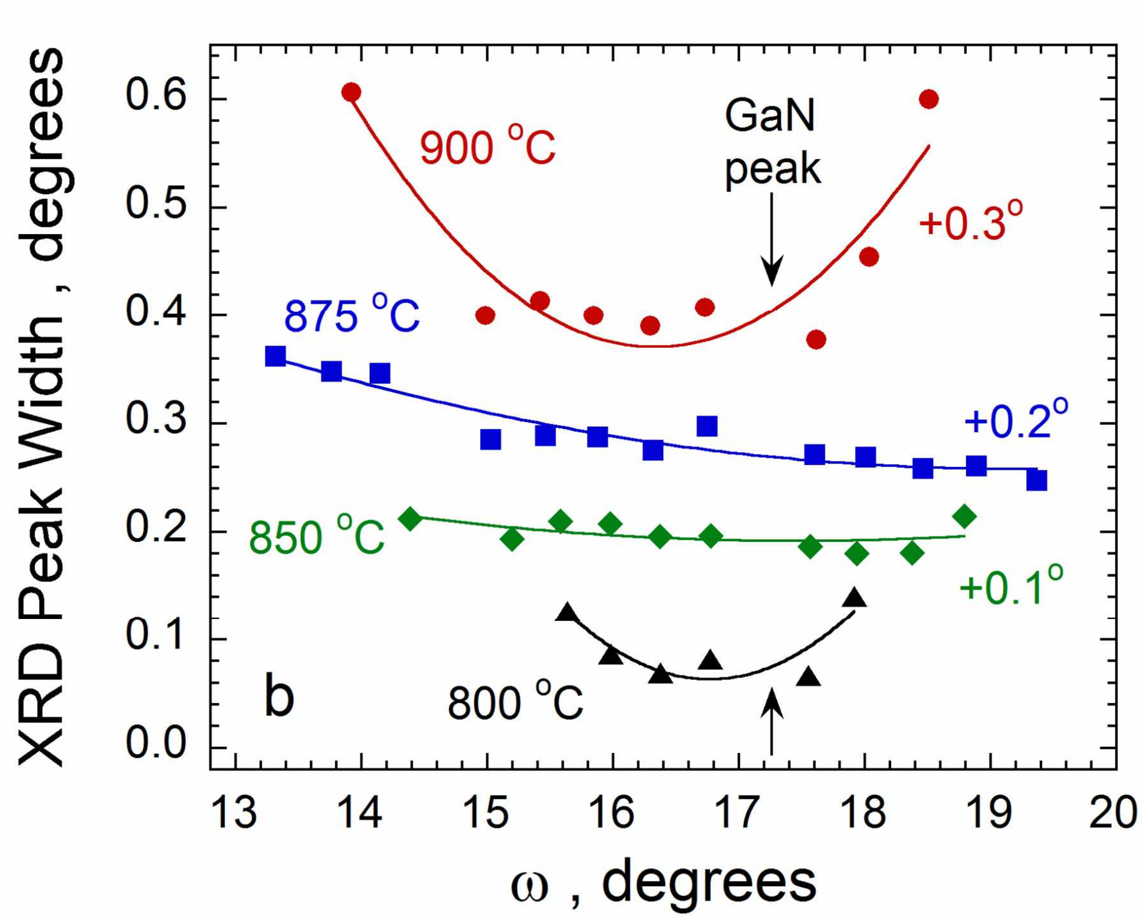
QW at 710 ºC, AlGaN at 710 ºC, temperature ramp, GaN barrier growth



During the anneal some indium from QW escapes through the AlGaN cap layer. More indium would escape if GaN barriers were used.

Influence of GaN barrier temperature

XRD satellite peakwidth as a function of angle

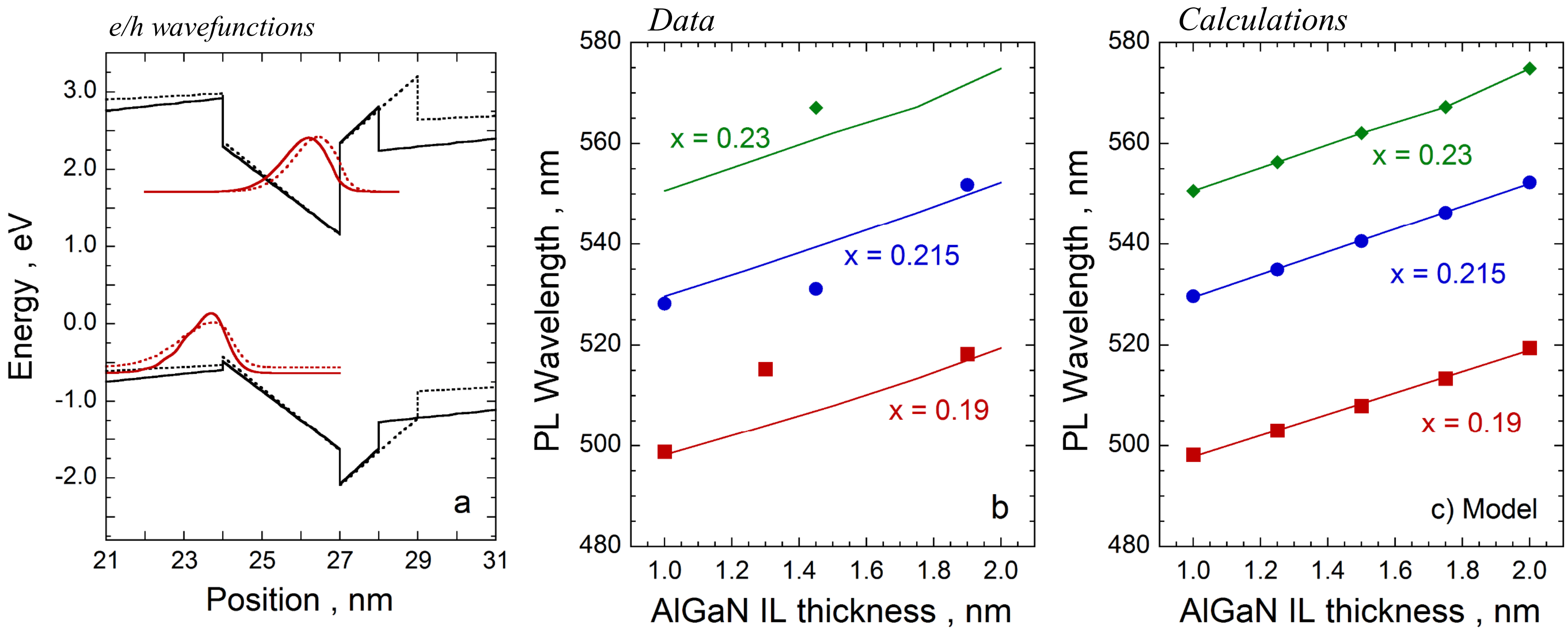


Consistent with the TEM, GaN barriers at 850 ºC

Smoothest interfaces for GaN barriers grown at 850 and 875 ºC

Wavelength shift vs. AlGaN IL thickness

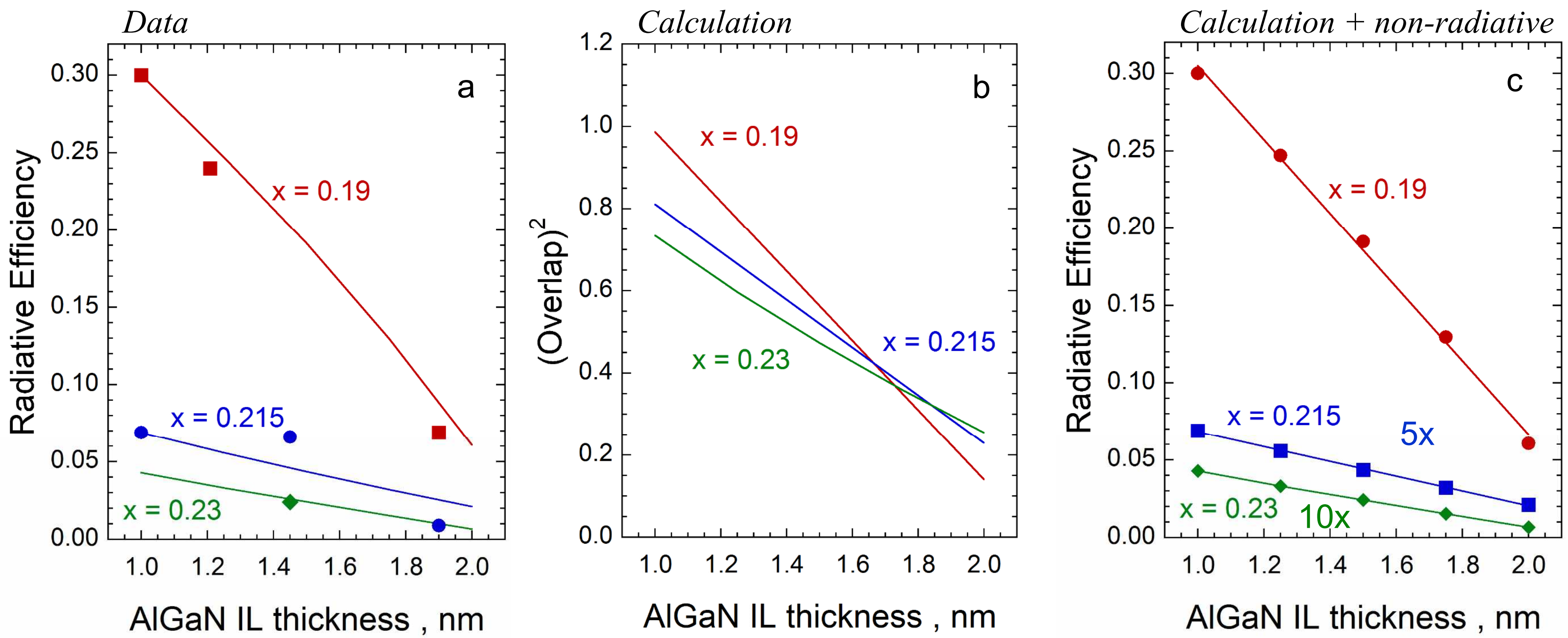
NEXTNANO3 (www.nextnano.de) calculations by Jon Wierer.



- Used 40 % AlGaN IL, 3 nm QW with $In_xGa_{1-x}N$, and 10 nm GaN barriers
- Increasing AlGaN IL thickness – brings e/h wavefunctions closer, but decreases overlap.
- QWs grown at 700 (x = 0.23), 710 (x = 0.215), and 730 ºC (x = 0.19), barrier at 800 ºC.

PL wavelengths increases as the AlGaN IL thickness increases

PL Intensity vs. AlGaN IL thickness



- Experimental radiative efficiency decreases as the AlGaN IL thickness increases.
- Wavefunction overlap squared decreases as the AlGaN IL thickness increases.
- Adding non-radiative component (SRH) as indium (x) increases gives better date match.

Annealing QW gets rid of some of the non-radiative centers, but not all.