SAND2007-6574P

Mechanisms for Enhanced Quantum Efficiency of InGaN Quantum Wells Grown on InGaN Underlayers

M. H. Crawford, D. D. Koleske, N. A. Missert, S. R. Lee, M. A. Banas, D. M. Follstaedt, K. H. A. Bogart, G. Thaler, K. C. Cross
Sandia National Laboratories, Albuquerque, NM

Y. Xia, C. Wetzel, E. F. Schubert
Rensselaer Polytechnic Institute, Troy, NY

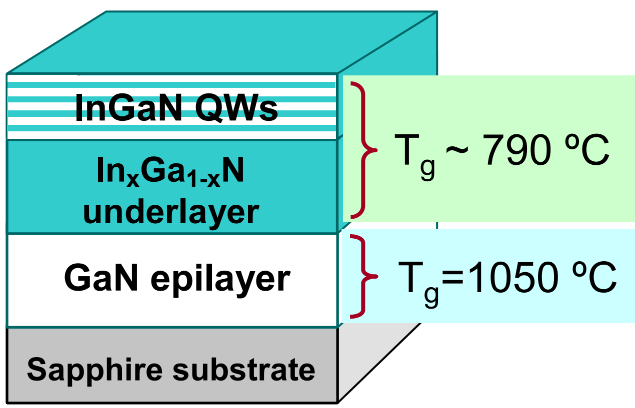
Acknowledgements: DOE Office of Basic Energy Sciences
Laboratory Directed Research and Development (NINE)

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000

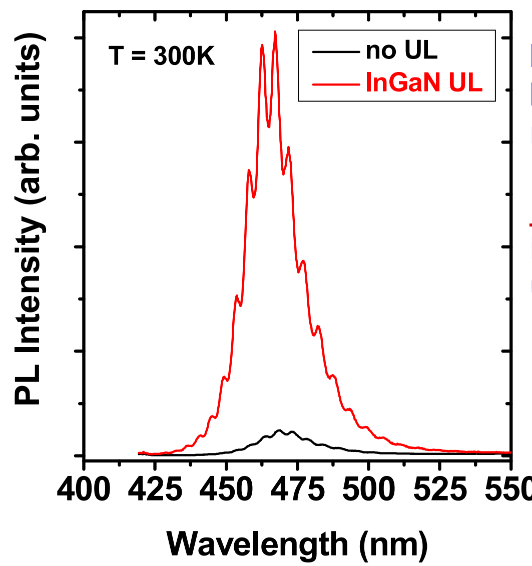
Motivation for Study of InGaN Underlayers

- Understanding the mechanisms that impact luminescence efficiency in InGaN QWs and LEDs is critically important for achieving high-energy-efficiency solid-state lighting
- A dramatic increase in InGaN QW luminescence has been observed when InGaN "underlayers" (ULs) are inserted beneath InGaN QWs

Underlayer Sample Structure



Room Temperature Photoluminescence (PL)



InGaN MQW on 200-nm-thick $In_{0.02}Ga_{0.98}N$ underlayer vs. no underlayer

15X increase in room temp integrated PL achieved with underlayer

Goal: Clarify mechanisms behind underlayer-induced luminescence enhancement

Sandia National Laboratories

Previous Work and Focus of this Work

Various models have been proposed that may explain the impact of underlayers:

- Separation of QWs from defective growth interface

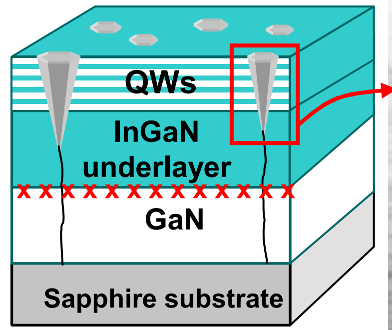
  [Akasaka et al., APL (2004)]

- Reduction of non-radiative defect populations in QWs

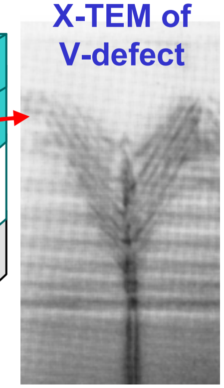
  [Akasaka et al., APL (2005); Son et al., J Cryst Growth (2006)]

- Formation of "V-defects" with energy barriers that prevent non-radiative recombination at dislocations

  [Takahashi et al., JJAP (2000); Hangleiter et al., PRL (2005)]

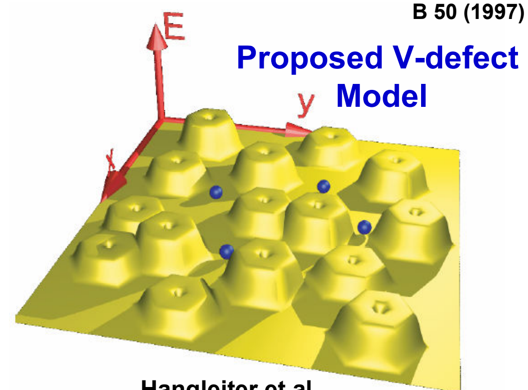


X-TEM of V-defect



Scholz et al. Mat Sci & Eng B 50 (1997) 238

Proposed V-defect Model



Hangleiter et al. PRL 95 (2005) 127402

Focus of this Work:

- Evaluation of the role of V-defects through control of UL growth temperature
- Evaluation of the role of UL indium composition, $In_xGa_{1-x}N$ x =0-0.09

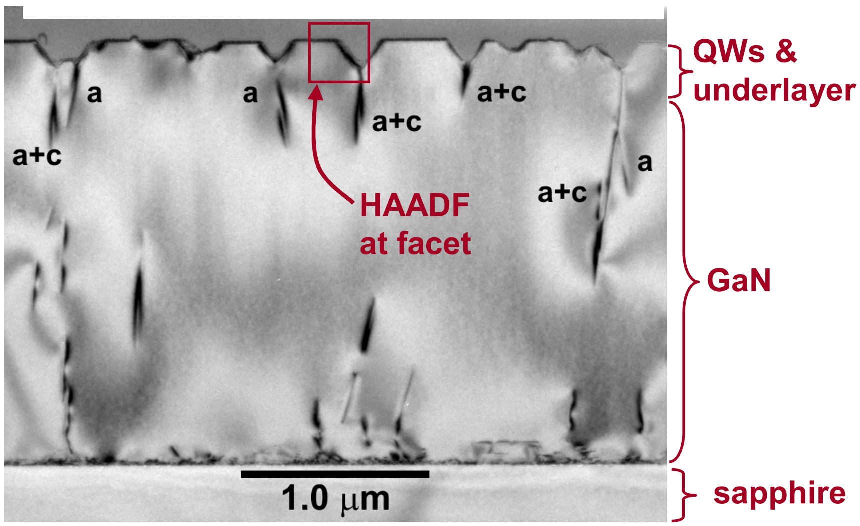
Sandia National Laboratories

Microstructure of threading dislocations and V-defects in InGaN QW-on-underlayer samples

Open Microstructural Questions:

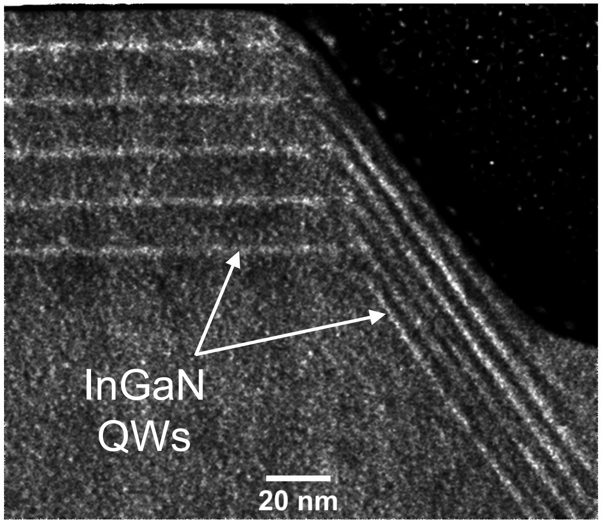
- Does every thread terminate at a V-defect?
- Does this vary with dislocation type?
- Are there really QWs on the pit sidewalls?

Bright-field X-TEM image with **g**=(11-20)



- **g•b** analysis of 32 threads shows 50% are edge (**b**=**a**) and 50% are mixed (**b**=**a**+**c**)
- Detailed inspection confirms all of both types reaching the surface terminate at V-defects

HAADF-STEM image of V-defect facet



- Composition-sensitive STEM images demonstrate QWs exist on the sidewall facets of the V-defects

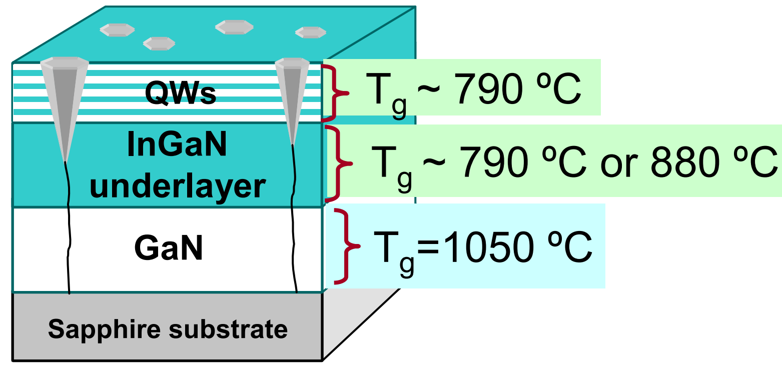
Microstructural results appear consist with screening by V-defects

Sandia National Laboratories

If we eliminate V-defects in the underlayer, does the InGaN QW photoluminescence decrease?

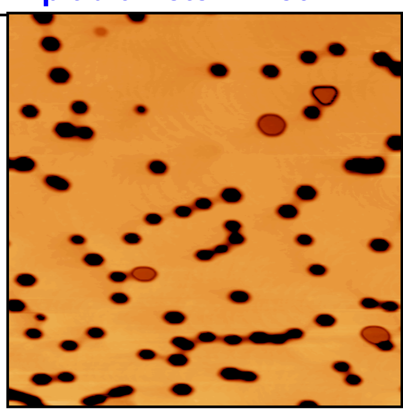
Sample design for "identical" InGaN QWs *with* and *without* V-defects:

- Two similar 200-nm-thick $In_{0.02}Ga_{0.98}N$ underlayers
- Grown at different temperatures to control V-defects
- 5-period $In_{0.15}Ga_{0.85}N/GaN$ MQWs on top

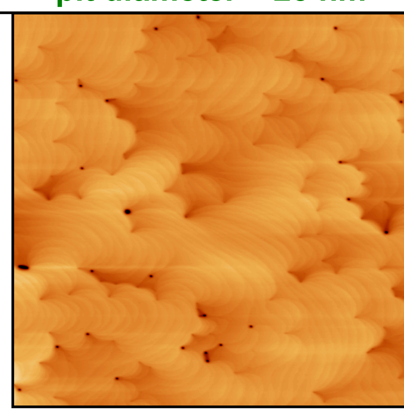


3x3 μm² AFM Images

Standard 790 ºC Underlayer
rms roughness = 7.7 nm
pit diameter ~ 150 nm

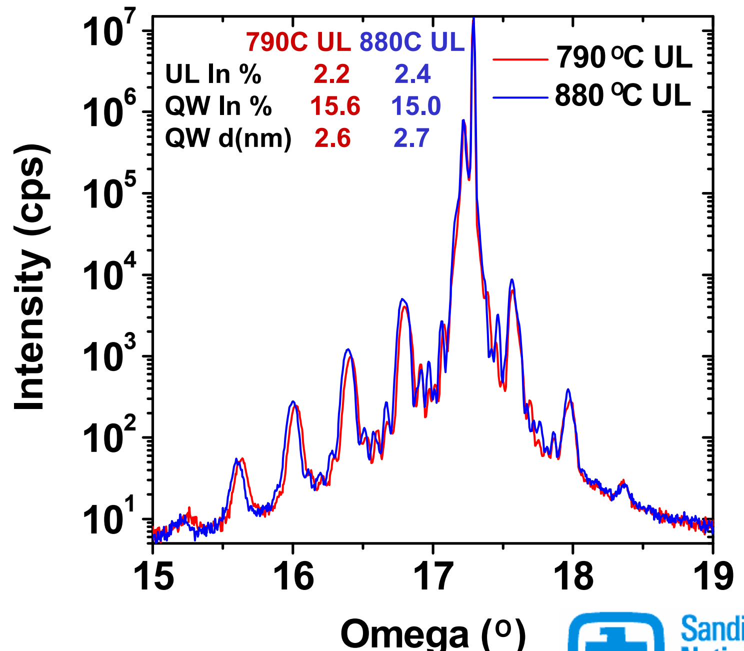


Planarized 880 ºC Underlayer
rms roughness = 0.6 nm
pit diameter < 25 nm



Last QW capped with thin (~10 nm) GaN barrier

X-Ray Diffraction Data

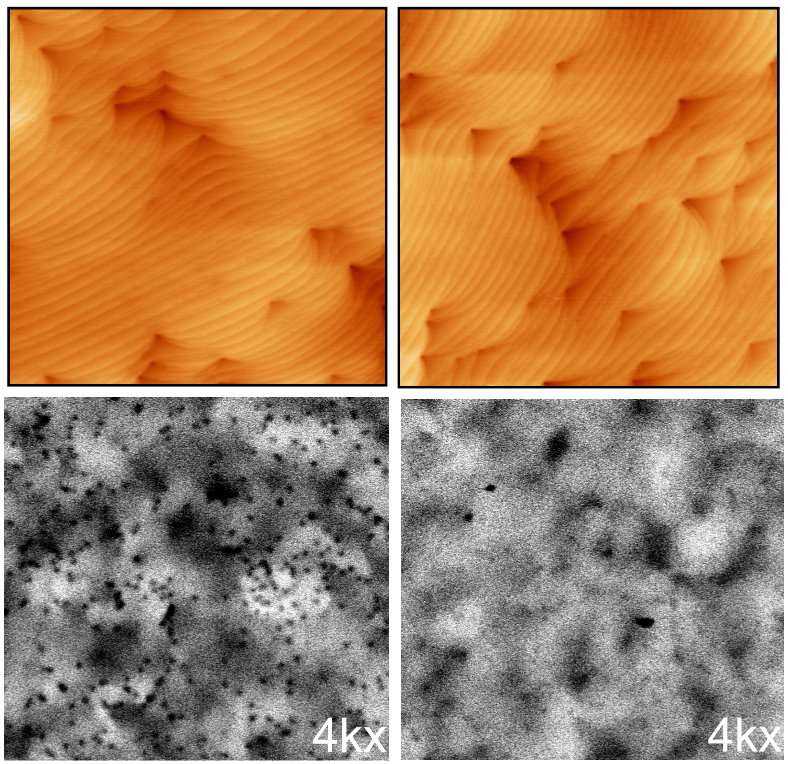


Sandia National Laboratories

Temperature Dependent Photoluminescence Study of capped InGaN MQW-on-UL structures

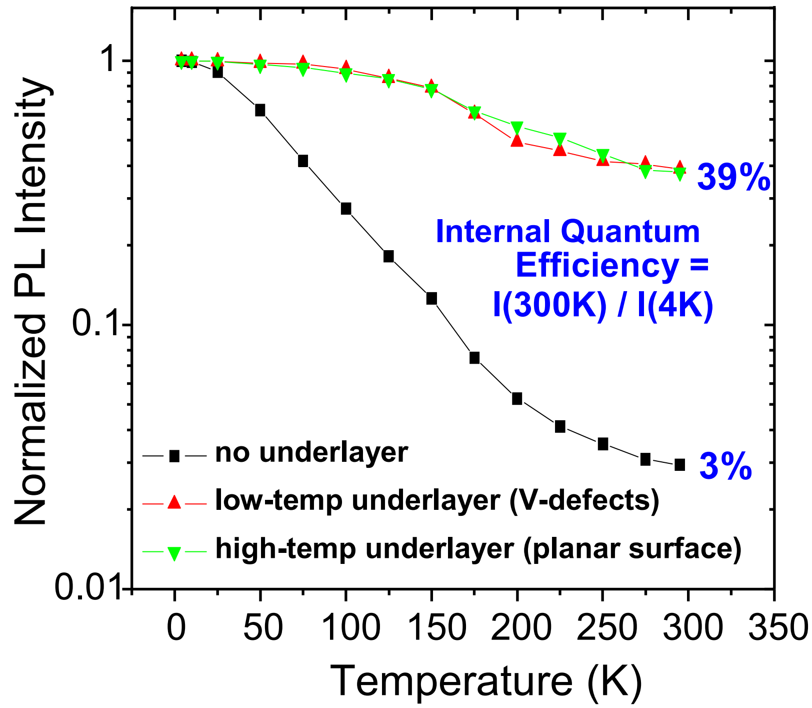
AFM and CL data for GaN capped MQW structure (similar to LEDs)

InGaN MQWs with ~100 nm GaN cap (Tg ~950ºC)



Temperature-Dependent Photoluminescence (PL)

415 nm excitation→ selective QW pumping



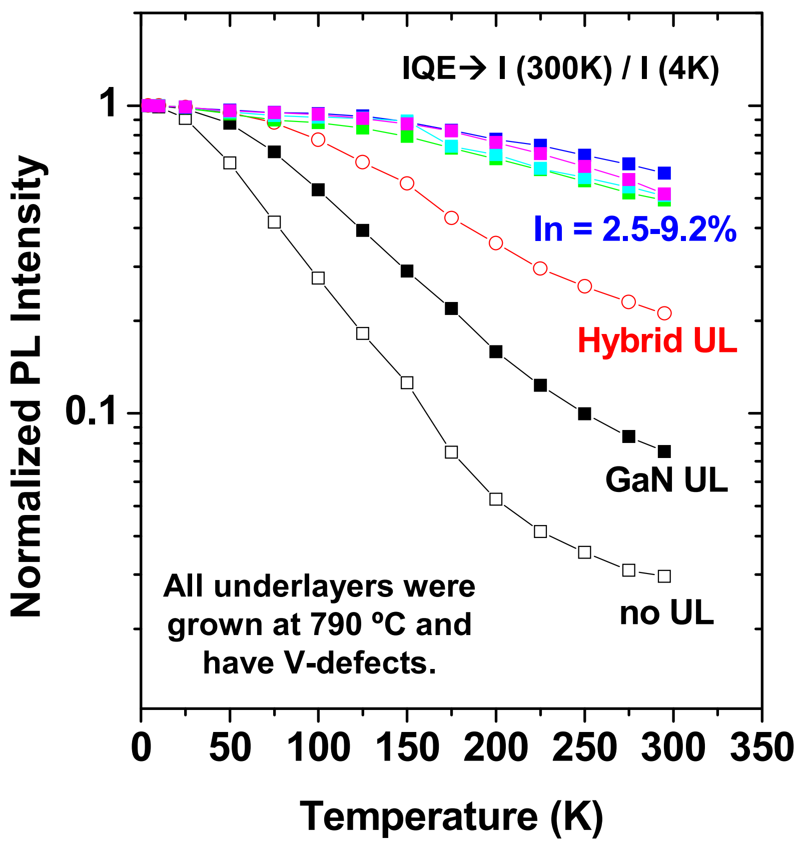
Underlayers enhance efficiency *even without V-defects!*

Sandia National Laboratories

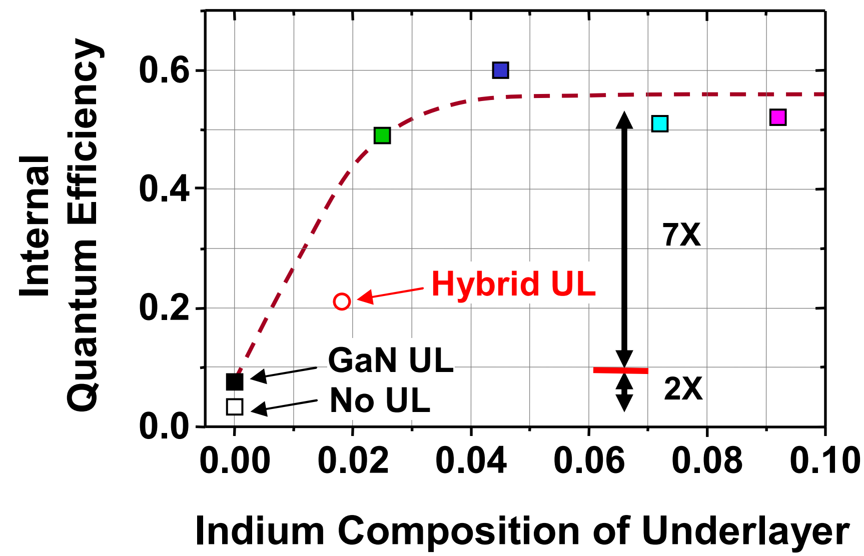
How does indium composition in the $In_xGa_{1-x}N$ underlayer influence InGaN QW efficiency?

Sample Designs:
- Varied underlayer composition from x=0 to 0.09; 200-nm-thick; InGaN QWs on top
- “Hybrid” sample: 20-nm-thick InGaN (x=0.018) on top of 180-nm-thick, 790 ºC GaN

Temperature-Dependent Photoluminescence



QW Quantum Efficiency versus Composition



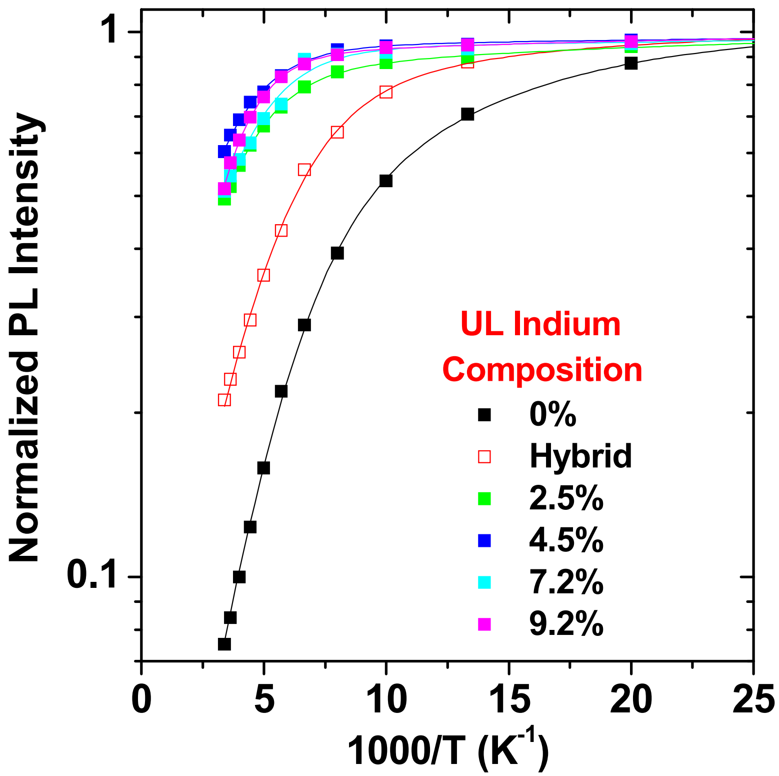
- **We find high IQE for all underlayers once Indium composition rises above ~2%**
- **Also, striking IQE improvement (~3X) for the hybrid underlayer with just 20 nm of InGaN (x=0.018)**

PL studies reveal the *critical role of indium in the underlayer for increased IQE*

Sandia National Laboratories

Arrhenius Analysis of the Temperature-Dependent Photoluminescence (PL)

Temperature Dependent PL Data



Fitted to a Two-Channel Arrhenius Model

$$I(T) = \frac{I_o}{1 + A^*\exp(-E_a/kT) + B^*\exp(-E_b/kT)}$$

Fitted model parameters as a function of UL indium composition:

In Comp(%)	A	E_a (meV)	B	E_b (meV)
0	73.5	50.3	2.6	12.5
Hybrid *	22.1	47.4	0.62	10.3
2.5	6.0	52.0	0.3	6.8
4.5	4.8	54.2	0.07	3.44
7.2	7.47	53.1	0.09	2.95
9.2	14.4	71.2	0.09	4.64

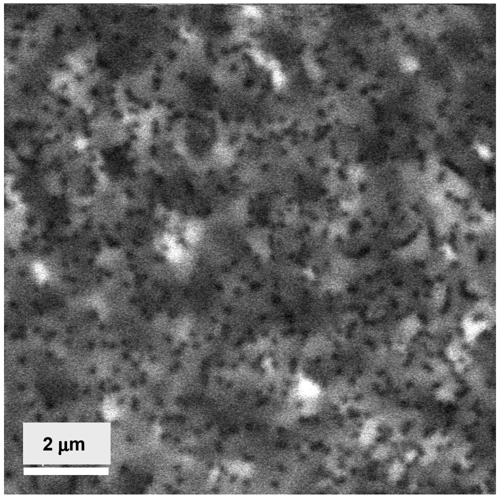
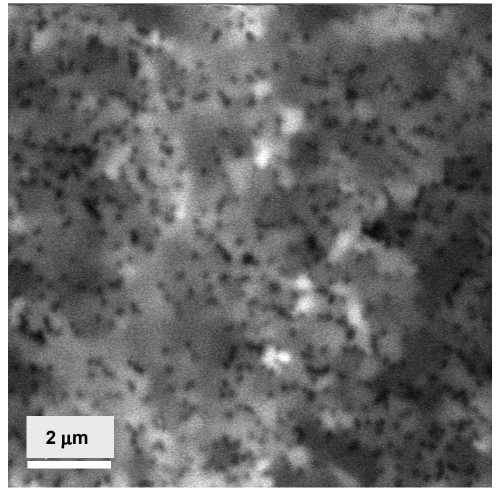
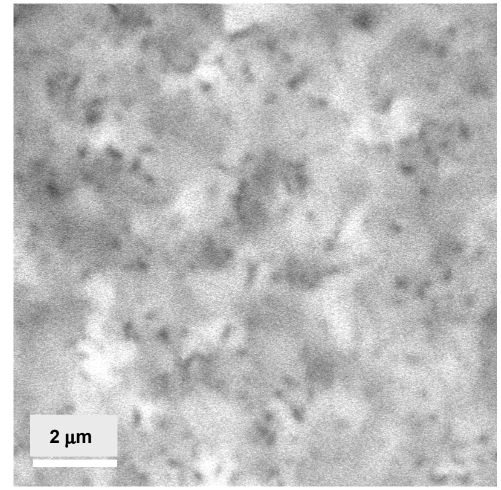
* Top 20 nm 1.8% In

possible mechanisms: exciton dissociation (E_a); carrier delocalization (E_b)

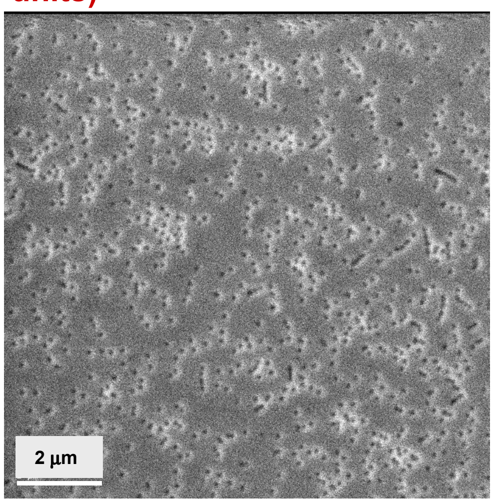
- **Adding indium does not modify the dominant PL-quenching mechanism (similar Ea)**
- **Instead, amplitude trends suggest free carriers encounter *fewer non-radiative recombination centers* for all underlayer samples containing indium**

Sandia National Laboratories

Cathodoluminescence (CL) Study of InGaN Quantum Wells on Underlayers with Different Indium Compositions

	200-nm GaN UL	Hybrid (20-nm InGaN on top)	200-nm InGaN UL, x=2.5%
CL			
CL intensity scale: (arb. units)	90-270	180-540	180-540

SEM



- The nm-scale "dark spots" in scanning CL images correspond one-to-one to V-defects in SEM images, consistent with reduced QW emission on the V-defect sidewalls
- On the micron-scale the CL emission varies in intensity and exhibits a mottled structure for all samples

Relatively uniform *increase* of CL across the sample with the addition of indium to ULs is qualitatively consistent with reduced point defects or impurities.

Sandia National Laboratories

Conclusions

Several hypotheses for PL enhancement by underlayers were evaluated:

- Defective interface due to change in growth temperature:
  Low-temperature GaN underlayers move this interface away from the QW region but produce only a limited increase in quantum efficiency.
- V-defect mediated screening of threading dislocations:
  We see similar quantum-efficiency gains with & without V-defects.
- Reduction of non-radiative recombination centers inside the QWs:
  Consistent with temperature-dependent PL data & spatially resolved CL data.

Future Work:

- Clarification of reduction of non-radiative recombination centers:
  What are the dominant centers (point defects/impurities)?
  How do indium ULs influence their populations?
- Validation of luminescence enhancement with electrical injection (LEDs):
  Carrier transport and capture distinctions between resonant PL vs. EL
  → ref: Akasaka et al, APL 2006: 5X EL enhancement from 420 nm InGaN QW LEDs for InGaN vs. GaN underlayers

Sandia National Laboratories