Mitigating Structural Defects in Droop-Minimizing InGaN/GaN Quantum Well Heterostructures

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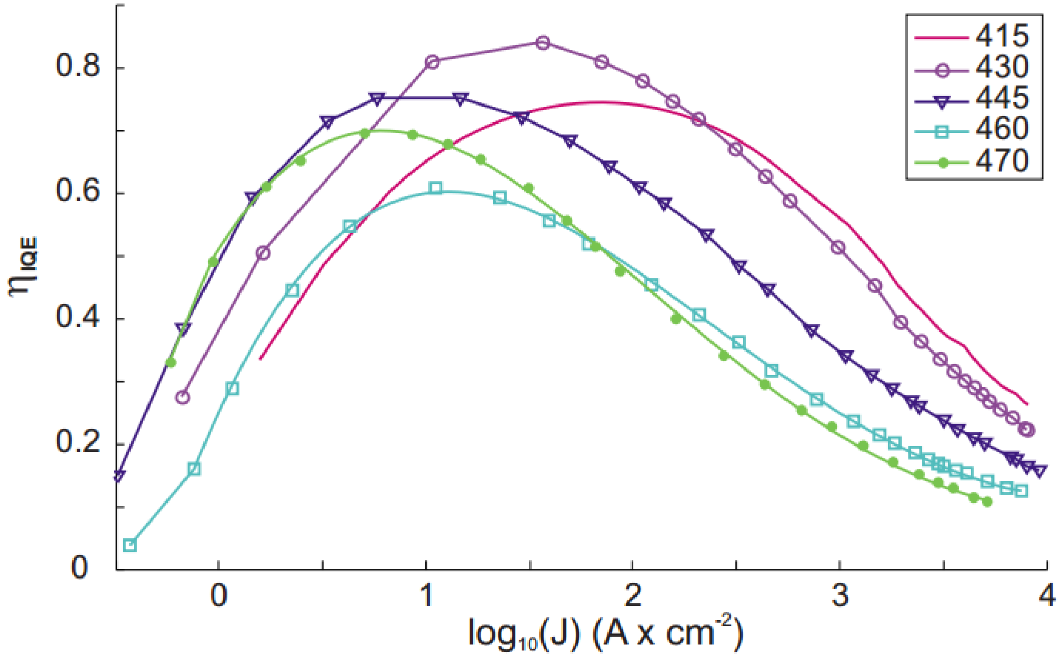
Efficiency Droop in III-Nitride LEDs

Wavelength-dependent droop measurements in InGaN QWs



III-Nitride LEDs continue to suffer from efficiency losses at high current:

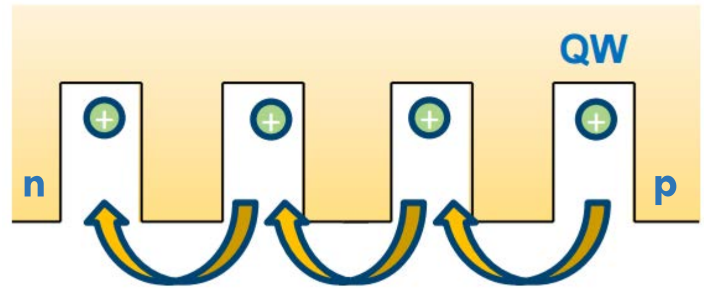
- Mechanism likely arises from Auger recombination
- Significant gains in flux per dollar/watt remain to be realized
- Droop is more significant at longer wavelengths

A. David and M. J. Grundmann, *Applied Physics Letters*, 97, **2010**

Strategies to Address Efficiency Droop

1) Improve carrier spreading across quantum wells

Standard active region design: carriers localized to p-side wells



Improved hole transport design: carriers distributed more evenly

2) Reduce QW thickness to enhance radiative recombination rate

$$R = An + {\color{red}B}n^2 + Cn^3$$

Increase in ${\color{red}B}$ reduces steady-state carrier concentration

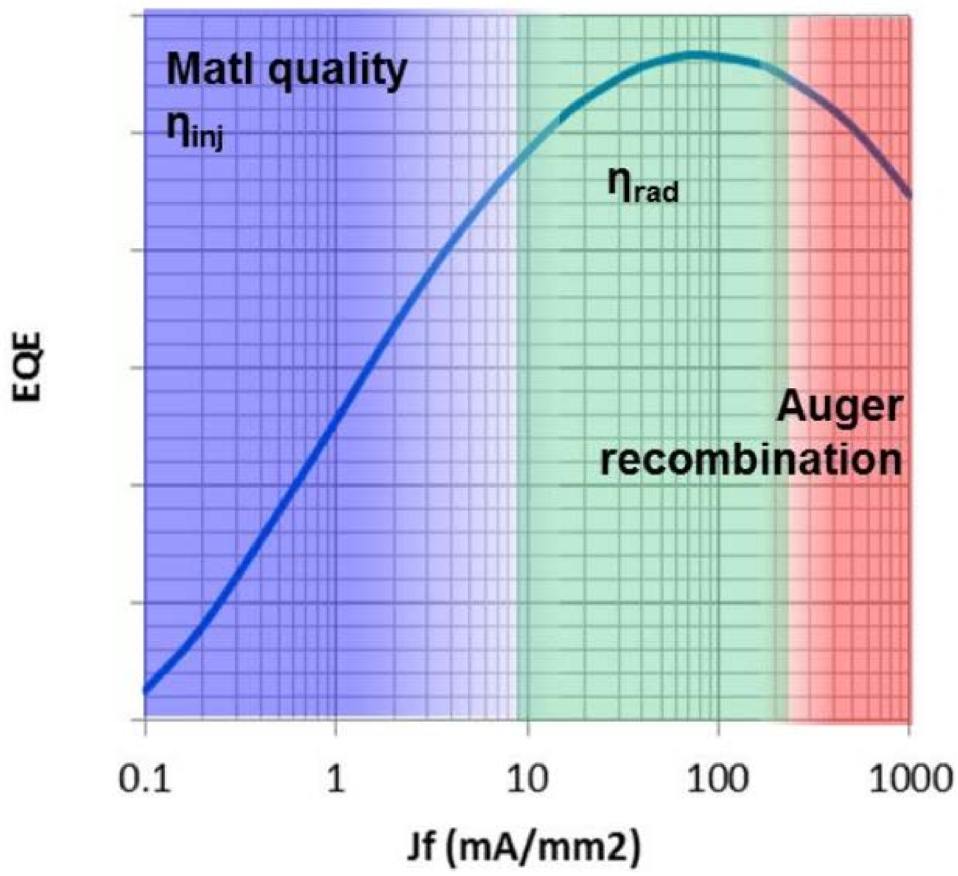
3) Increase QW thickness to reduce Auger matrix element

$$M = \iint d^3\vec{r}_1 d^3\vec{r}_2 \phi_1^*(\vec{r}_1)\phi_2^*(\vec{r}_2) \boxed{\frac{\exp[-\lambda r_{12}]}{r_{12}}} \phi_{1'}(\vec{r}_1)\phi_{2'}(\vec{r}_2)$$

Thicker QWs → More screening → Screening length (λ^{-1}) shorter → Smaller M

Image courtesy of I. Wildeson

Understanding Impacts of Material Quality



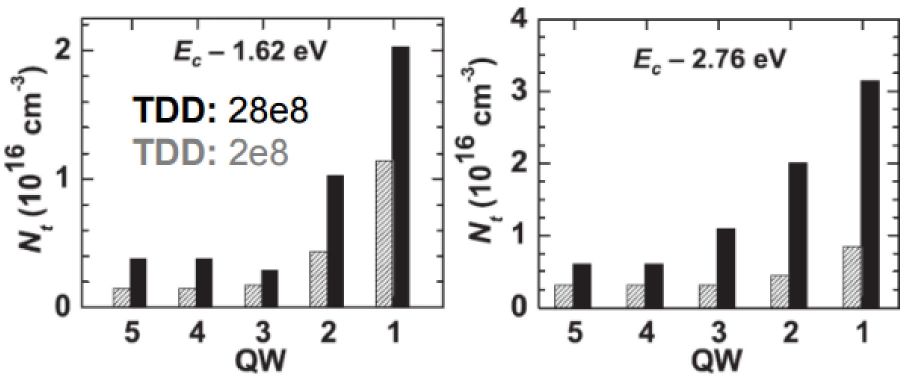
Different droop mitigation strategies impact different regions of the efficiency curve BUT interlinked physical processes in the QWs make it difficult to **improve droop** without hurting **material quality**

Image courtesy of I. Wildeson

Understanding Impacts of Material Quality

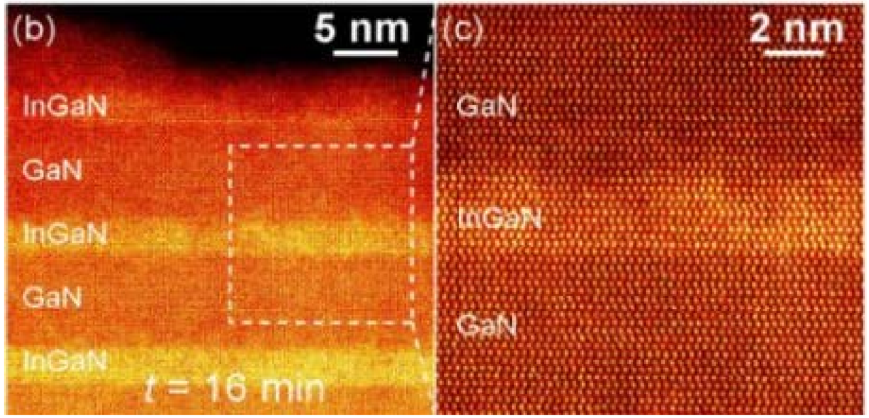
Need for intelligent design process informed by fundamental material characterization:

DLOS: electronic nature of defects



- Energy and density of defects present in heterostructure
- Bias/depth-dependent DLOS provides limited spatial resolution

STEM: atomistic nature of defects



- Atomically resolved imaging and compositional analysis
- Artifact-free under low-dose imaging conditions

DLOS data courtesy of A. Armstrong
K. Baloch, et al., *Applied Physics Letters*, 102, **2013**

S/TEM Imaging Parameters

A. Aberration-corrected FEI Titan S/TEM

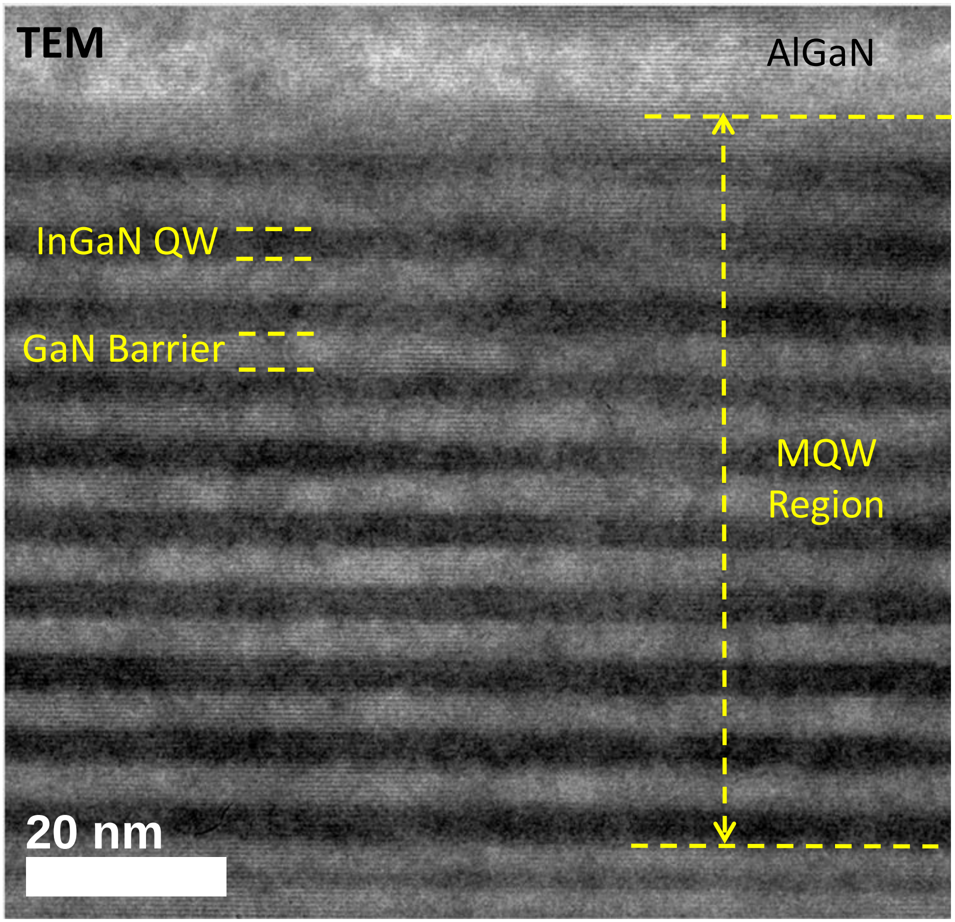
- Sample preparation: FIB milling (2 kV)
- Accelerating Voltage: 80 kV
- Imaging modes: bright-field TEM and HAADF STEM
- Enables acquisition of artifact-free TEM micrographs below knock-on threshold for beam damage

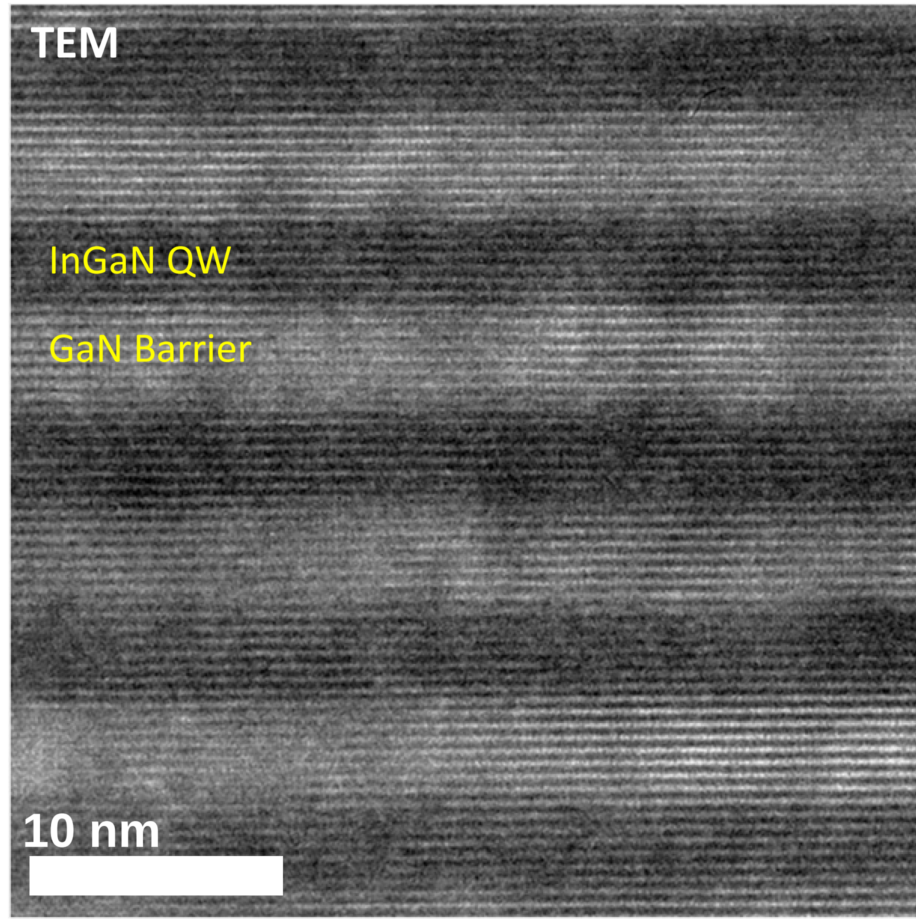
B. JEOL 2010F Field Emission Gun S/TEM

- Sample preparation: FIB milling (2 kV)
- Accelerating Voltage: 200 kV
- Imaging modes: bright-field TEM and HAADF STEM

Growth A: SRH Penalty

Structural changes result in a measured performance penalty in low current regimes





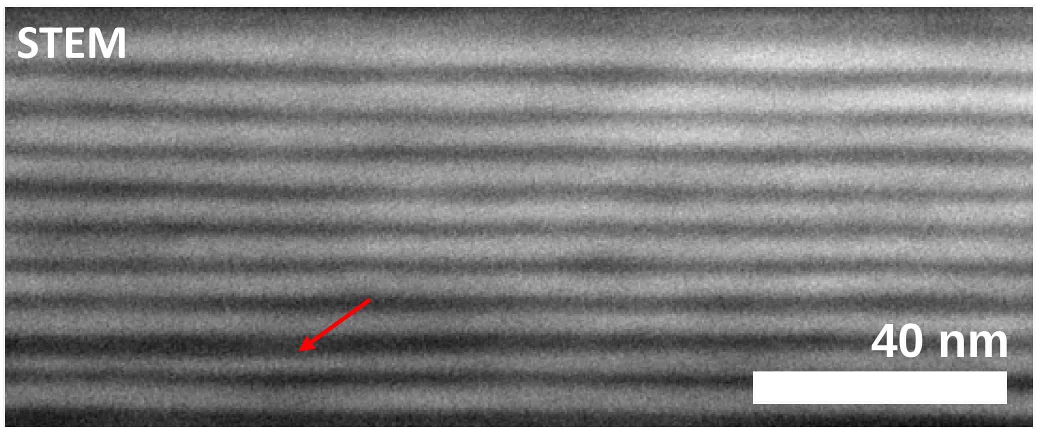
No obvious structural defects were observed in TEM imaging

Growth B: Severe SRH Penalty

Growth process modified to exaggerate detrimental structural changes

GaN (dark)

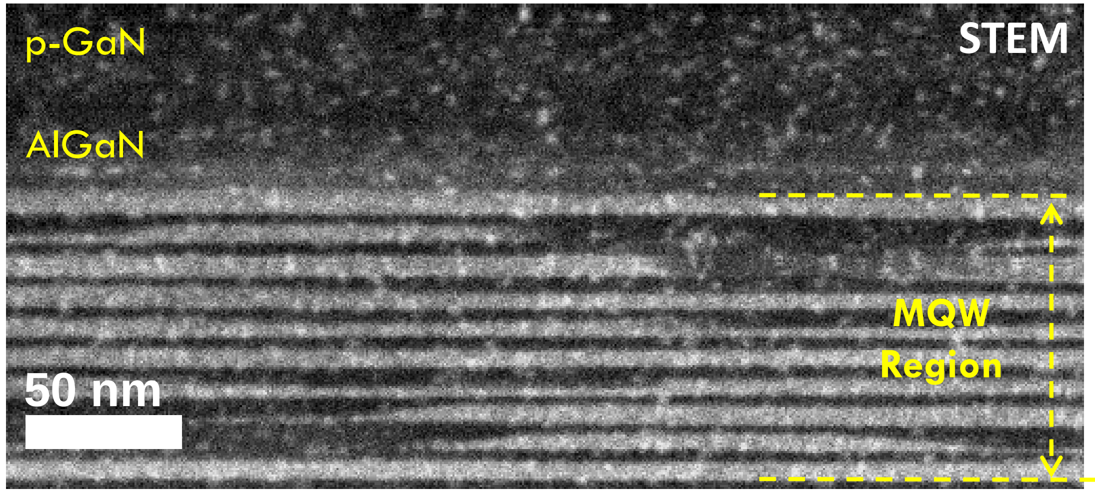
InGaN (bright)

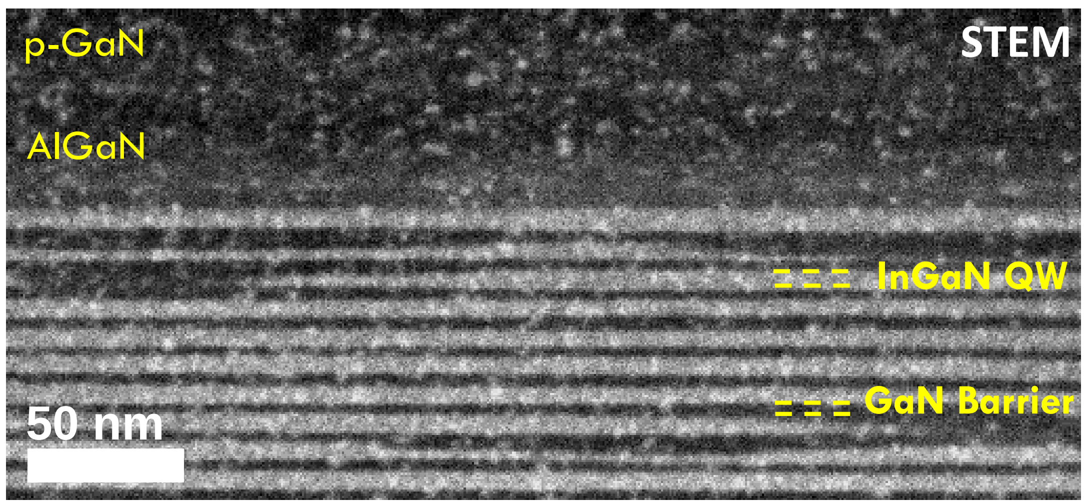


InGaN/GaN Quantum Well Region

Observed gross well width fluctuations (WWFs) in HAADF STEM

Growth B: Severe SRH Penalty

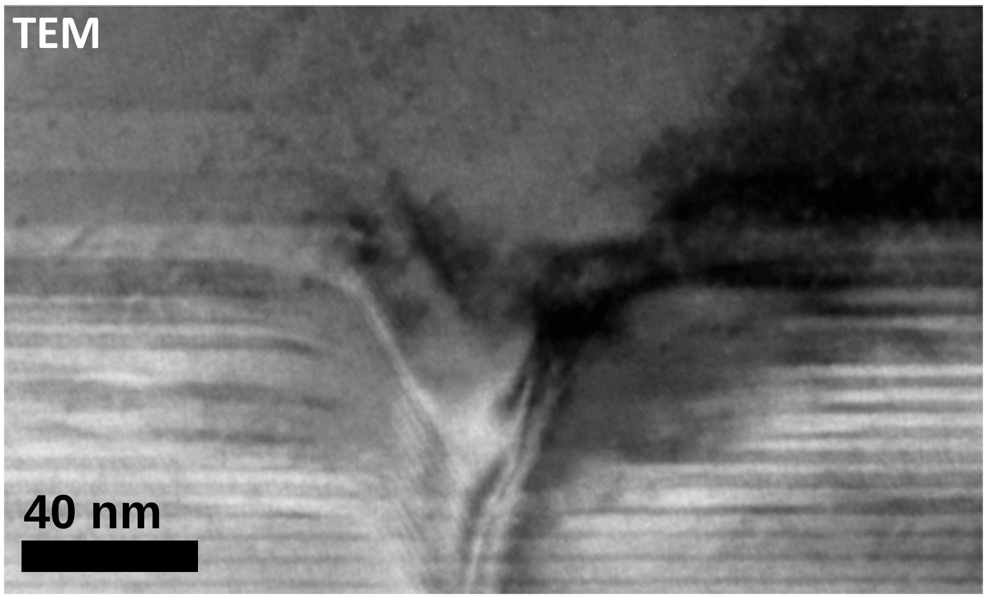


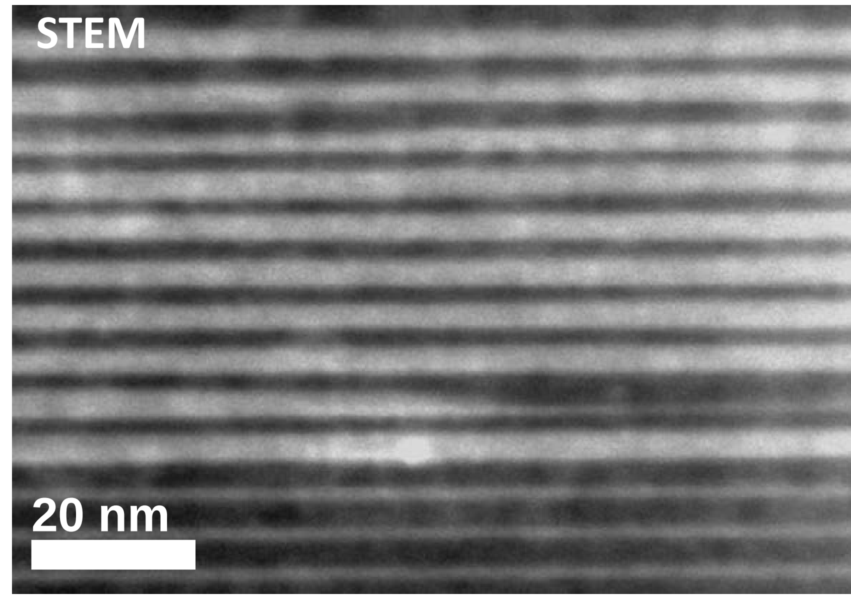


HAADF STEM imaging performed at 80 kV rules out the possibility that the observed WWFs are artifacts of beam damage

Growth B: Severe SRH Penalty

Presence of gross WWFs were observed concurrently with V-pit defects opening in the QW active region





Suggests growth process is sensitive to local variations in strain: local alloy composition may vary as a result of strain-based In incorporation

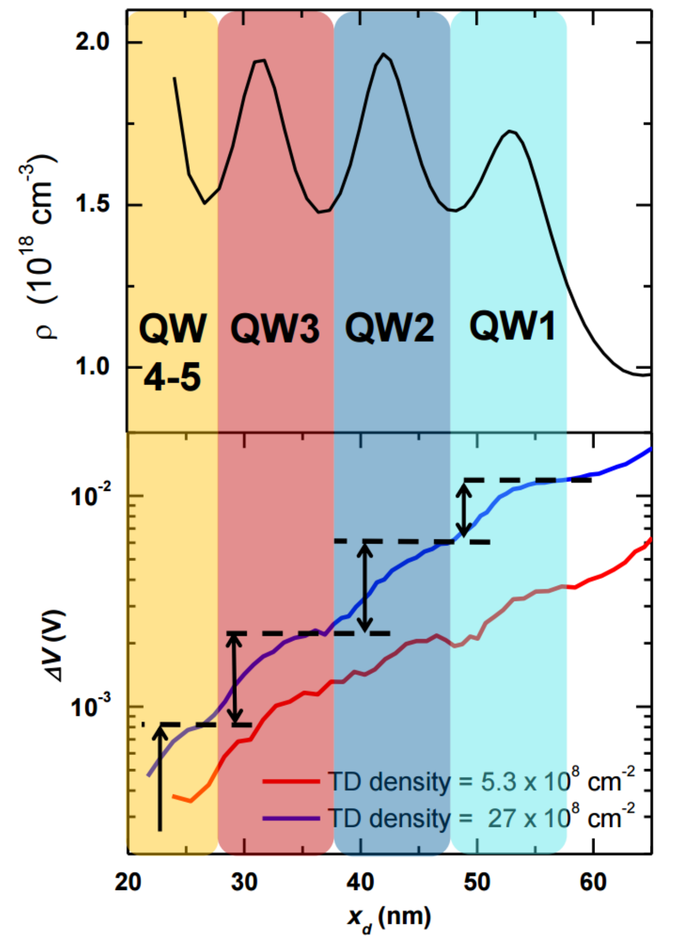
Defect Levels via Deep-level Optical Spectroscopy

<u>Deep-level optical spectroscopy (DLOS)</u>

- Can directly probe energy levels of defects present in heterostructure
- Defect density can be calculated from lighted C-V transients
- Bias/depth-dependent DLOS provides limited spatial resolution

DLOS shows high densities of a midgap defect state within the active region which correlates with measured IQE

Example of Depth Profile of MQW Defects

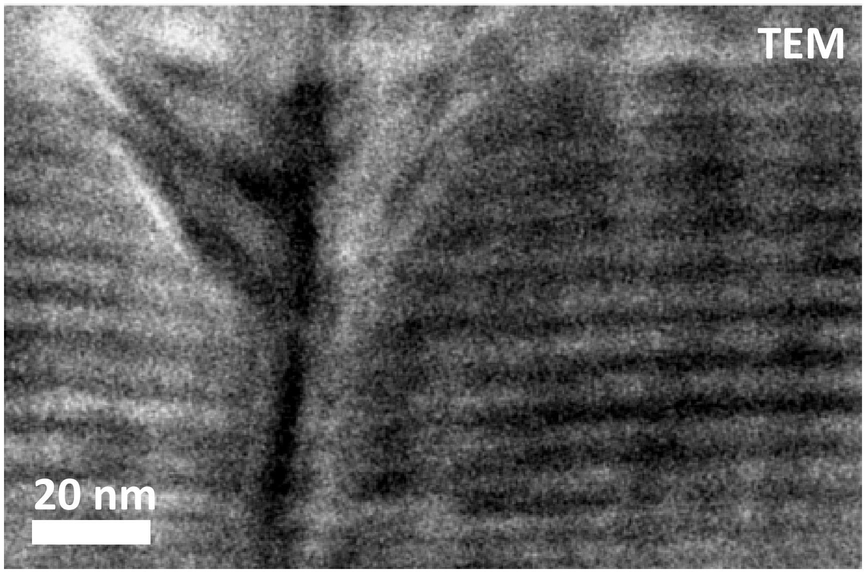


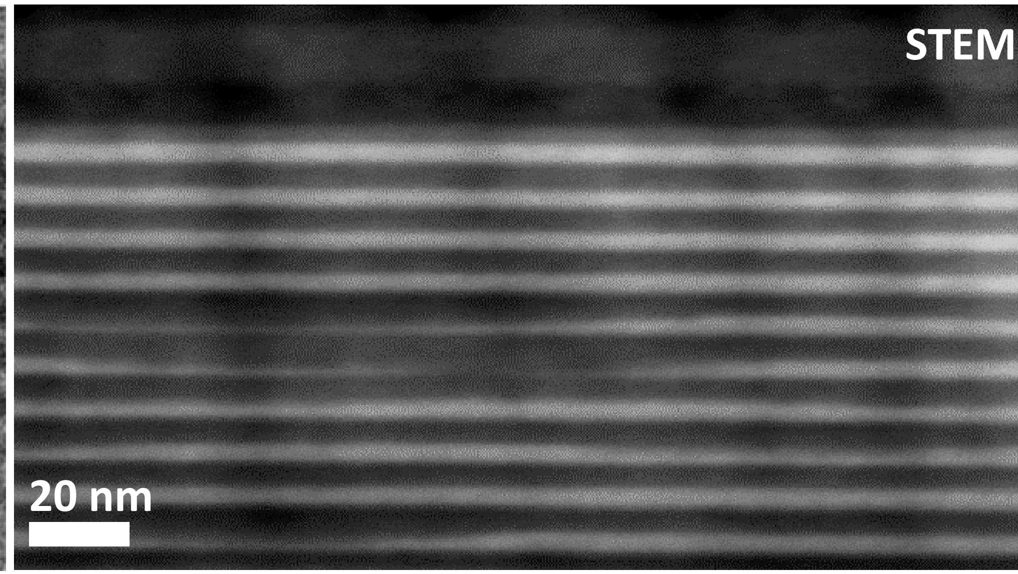
Do the observed well-width fluctuations correlate with performance?

Courtesy of A. Armstrong

Growth C: Low SRH Penalty

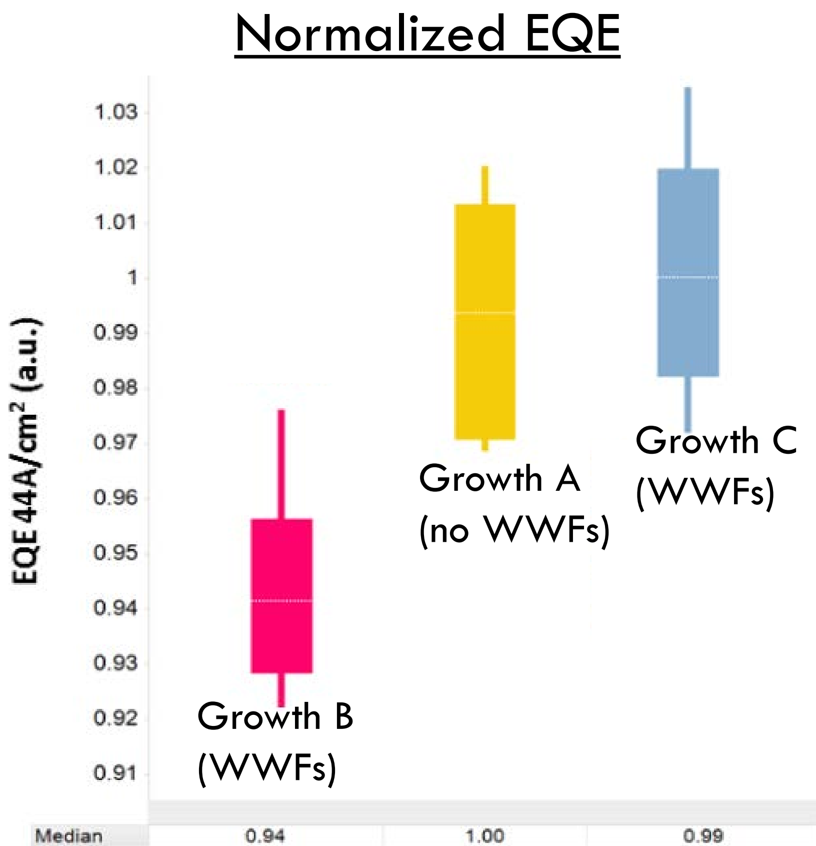
Structure and measured performance similar to Growth A (no WWFs) but grown with process similar to Growth B (gross WWFs)





S/TEM images again demonstrate correlation between V-pits opening up in QW region and nearby WWFs

Performance Comparison Between Growths



EQE performance does not seem to be entirely dominated by WWFs

Conclusions and Future Work

Conclusions

- Observed QW width fluctuations arising from growth changes in droop-minimizing epitaxial InGaN/GaN heterostructures
  - Presence of WWFs correlated with V-pits opening in QW region
  - May be a result of strain-dependent In incorporation into QW layer
- QW width fluctuations do not dominate EQE performance
  - WWFs are not necessarily indicative of severely compromised material quality
- DLOS suggests dominant defects are localized to QW region

Future/Ongoing Work

- Current sample set: no WWFs but still exhibit performance penalty
  - C_s-S/TEM and EELS measurements at Brookhaven National Lab
  - Atom probe tomography: local composition and interface quality
  - Cathodoluminescence in STEM: directly correlate microstructural features with optical emission

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