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Distribution of deep level defects in InGaN/GaN LEDs and their dependence on In alloying

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Outline

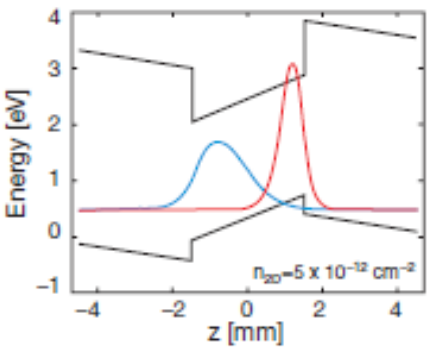
I. Green gap for InGaN/GaN and role of deep level defects
II. Quantitative characterization of QW deep levels in InGaN/GaN LEDs
III. QW deep level defect evolution with indium alloying (*c*-plane)
IV. Origin of QW deep level defects
V. Conclusions

Green-gap limits InGaN/GaN LEDs and LDs

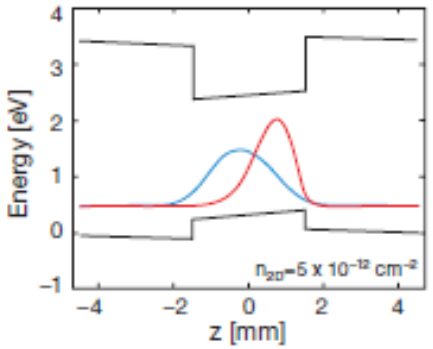
- "Green gap" persists in semi- and non-polar InGaN/GaN LEDs, LDs
  - Efficiency drops with increasing λ
  - Not completely explained by Quantum-confined Stark Effect (QCSE)
- Suggests a contribution from defects

Green gap more than QCSE

***c*-plane**

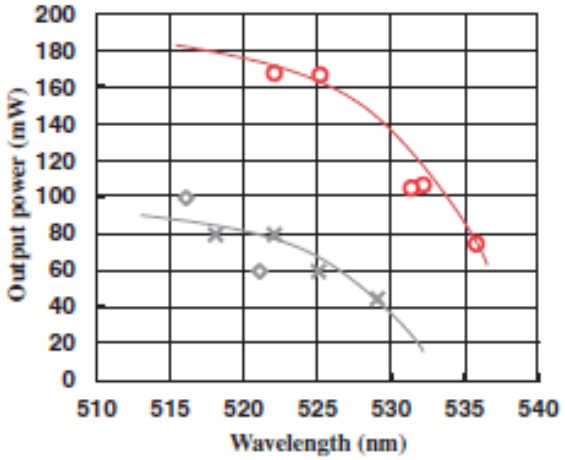


Semi-polar



Ulrich T. Schwarz and Wolfgang G. Scheibenzuber Optics & Photonics News

Semi-polar LD power vs. λ



Takagi *et al.* Applied Physics Express 5 (2012) 082102

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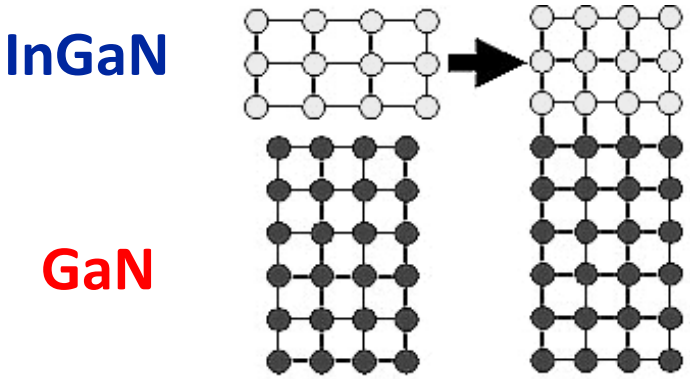
Defects and InGaN/GaN MQWs

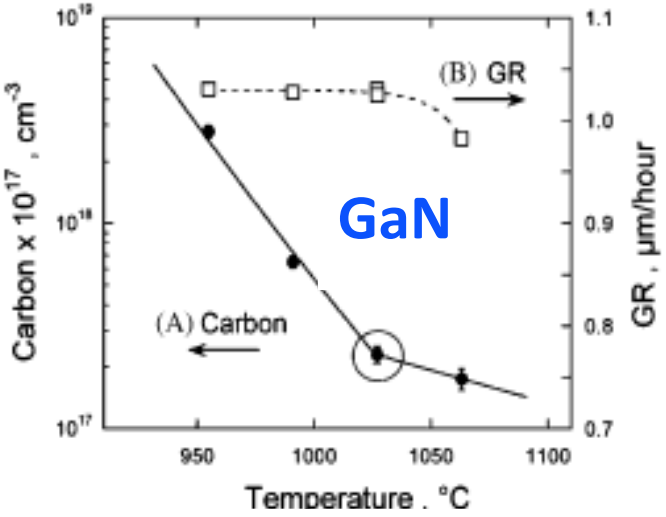
InGaN/GaN MQWs have potential for high defect density:

- **Highly mis-matched epitaxy**
- **Heterostructures force trade-offs between growth conditions**

Mis-matched epitaxy and strain



Non-ideal growth conditions



Koleske *et al.*, JCG 242 55 (2002)

Defect formation more likely with increasing indium, λ

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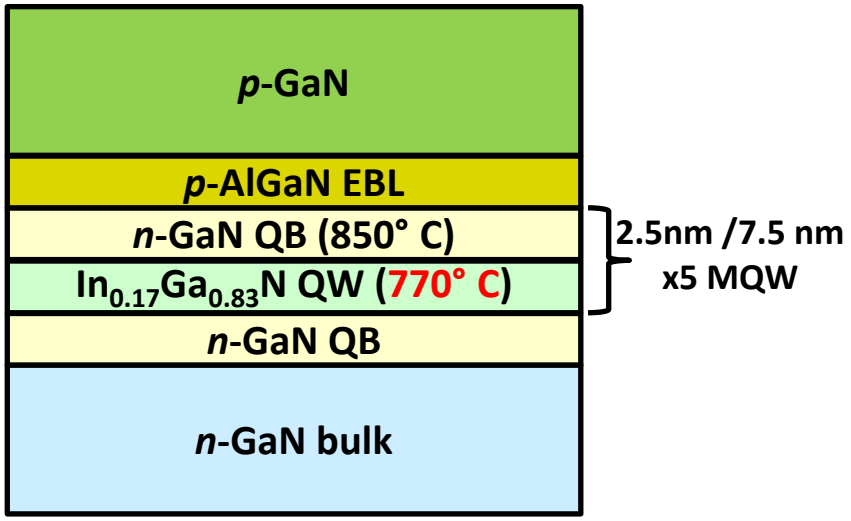
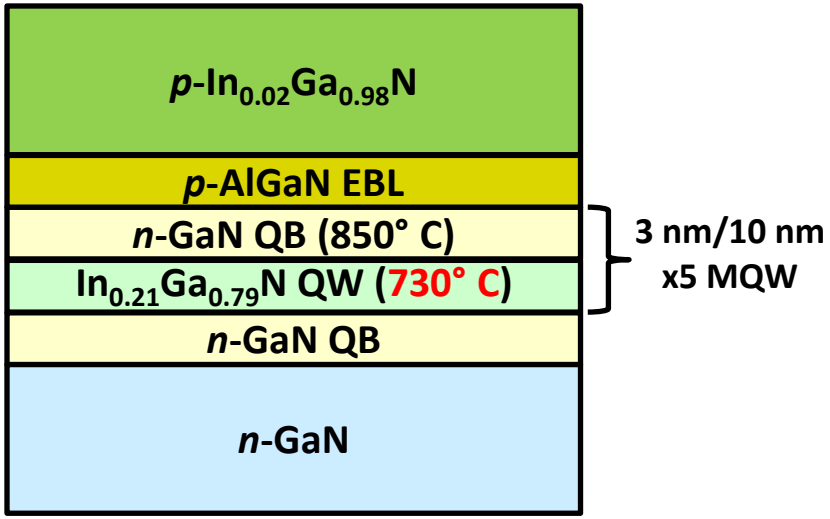
Sample description

450 nm InGaN/GaN LED



530 nm InGaN/GaN LED



- MOCVD-grown LEDs on *c*-plane
- Reduced QW T_g for green LED

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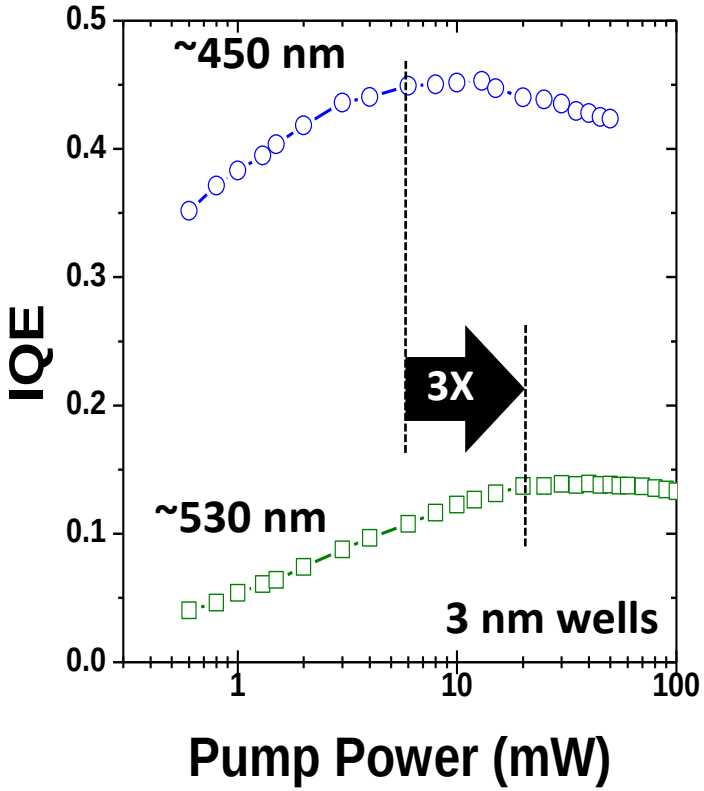
Green LED IQE indicates excess defects

LED IQE vs. optical pump power



$$IQE = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

$$n_p = \sqrt{\frac{A}{C}}$$

- Peak IQE shifts to larger power with increasing indium
- Suggests additional non-radiative recombination

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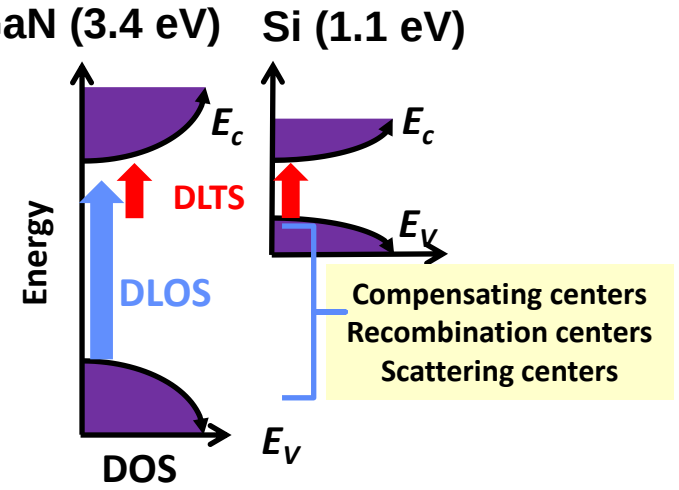
Quantitative LED defect spectroscopy is difficult

Challenge: Wide (In)GaN band gap (2.3 – 3.4 eV)

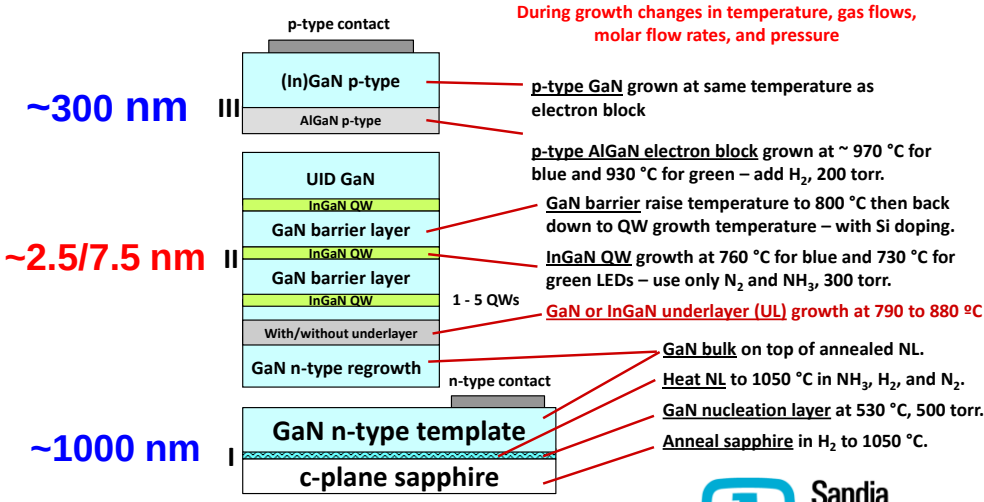
- Thermal emission rates decrease exponentially with trap energy



Challenge: Needle in a "haystack"

- Need nanoscale depth resolution to differentiate QW and QB defects

LED design - NOT TO SCALE!



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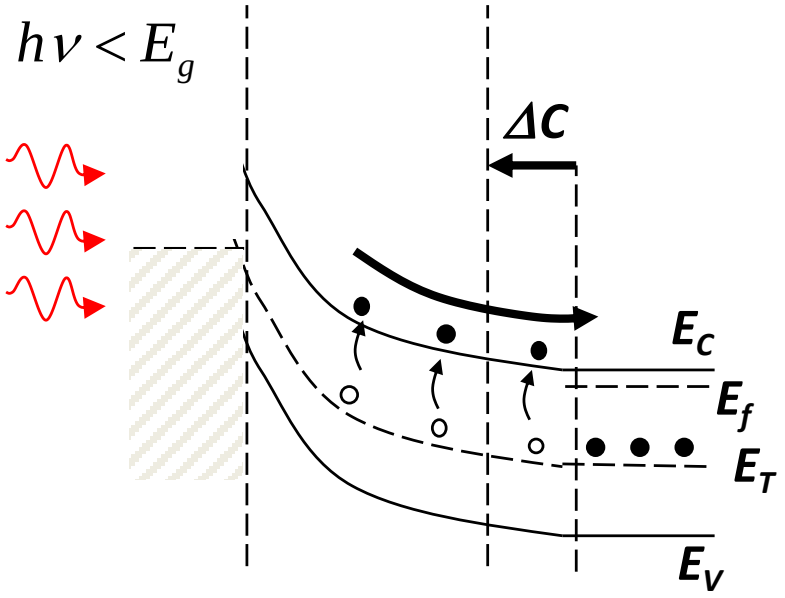
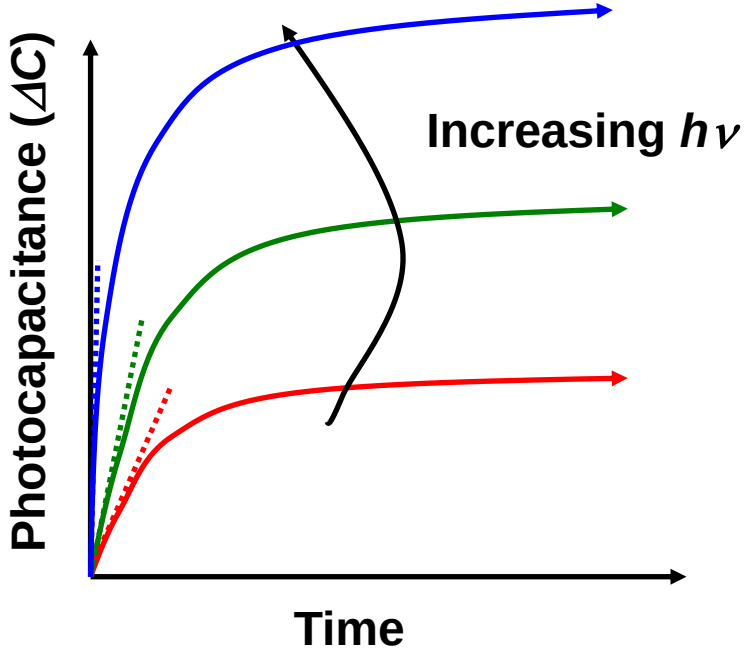
Deep Level Optical Spectroscopy

"Thin film" Deep Level Optical Spectroscopy (DLOS)[1]

- Photocapacitance technique
- ***Sub-band gap optical stimulation*** to photoionize defect levels
- ***Quantify non-radiative*** defect level energy (E^o)





- **DLOS only sensitive to depleted regions**

1. Chantre *et al.* PRB 23, 5335 (1981).

- Optical cross-section $\sigma^o = e^o/\Phi = \alpha/N_t$
- $\sigma^o(h\nu) \propto dC(t)/dt|_{t=0}$
- Fit $\sigma^o(h\nu)$ to model for E^o
- Address defect density later…

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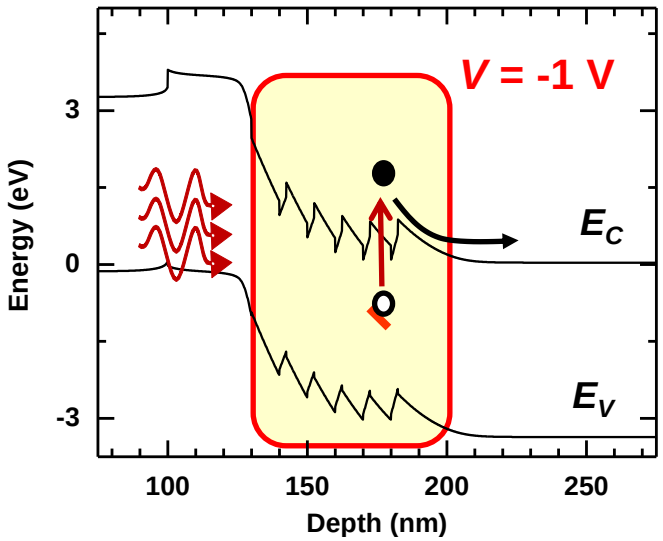
DLOS provides depth resolution in LEDs

LED MQW 1D-SP calculations*



*G. Snider UND

***V* = -1 V: DLOS selective to the MQW region**

- **Detect both InGaN QW and GaN QB defects**

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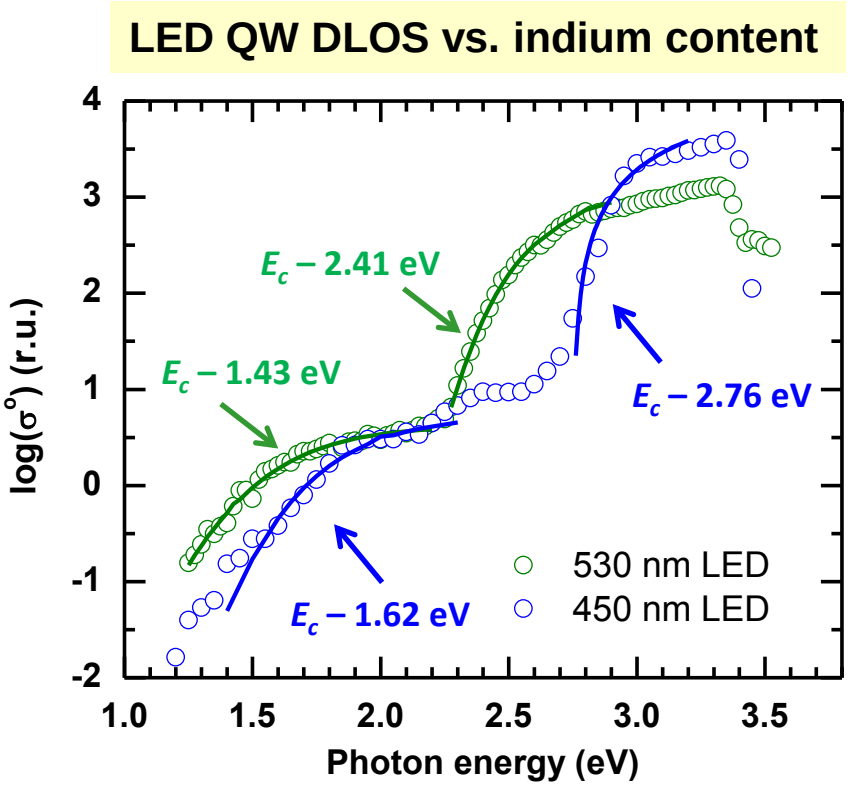
LED QW deep level evolve with Indium content



- InGaN band edges demonstrate QW sensitivity
- Near-E_v and near mid-band gap deep levels
- Identify QW defect levels from red-shift with increasing indium

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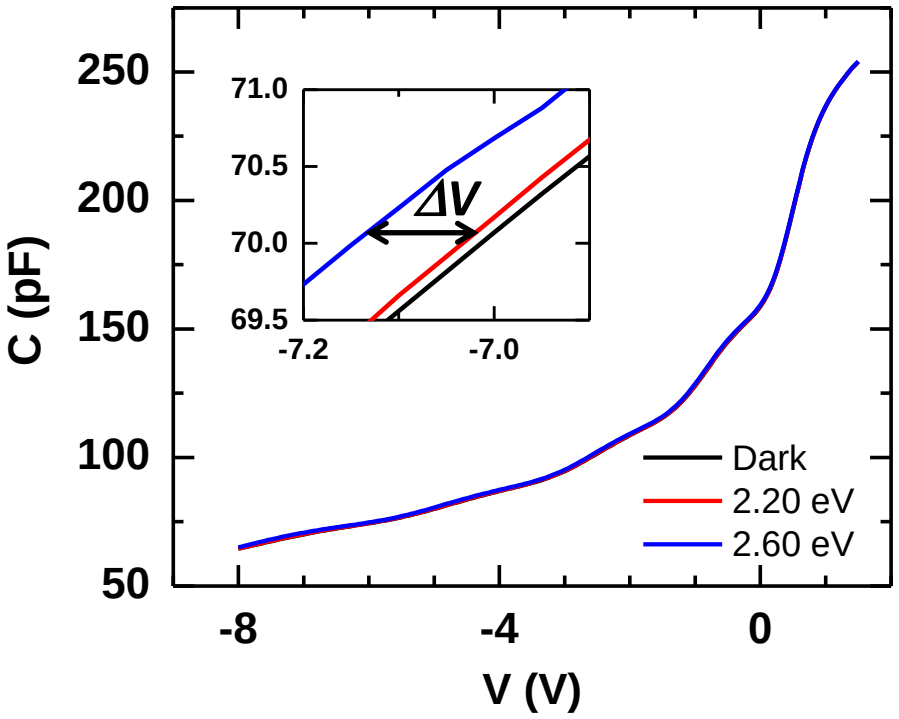
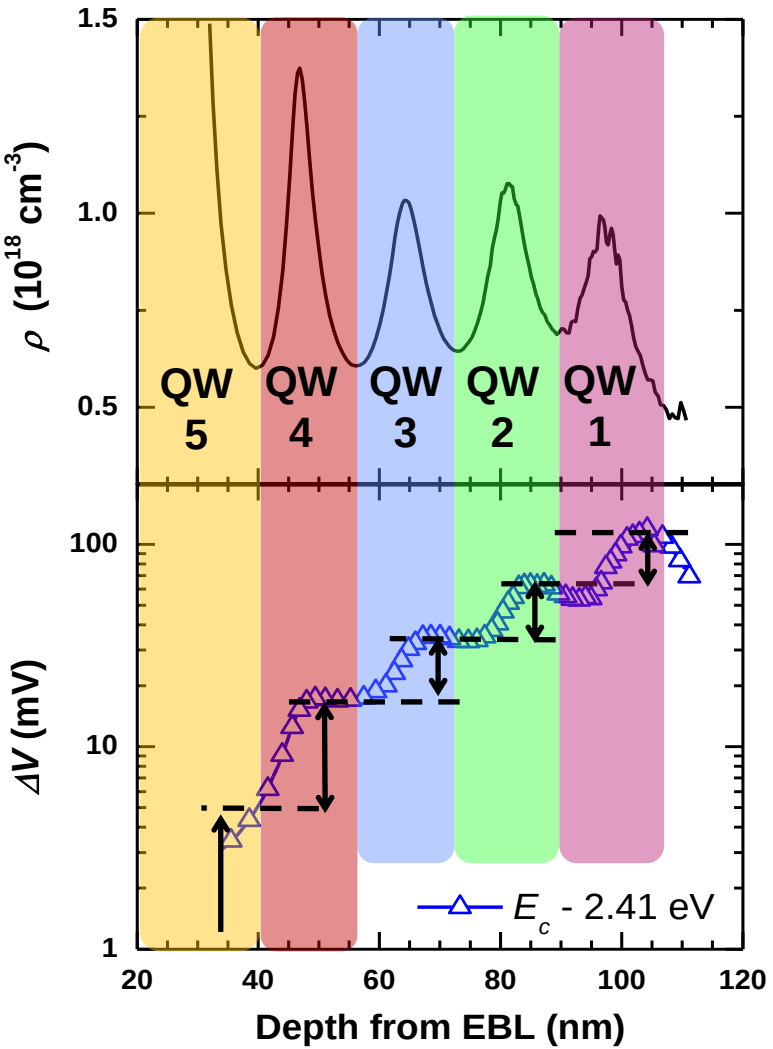
Lighted-*CV* quantifies QW defect density

Lighted C-V of 530 nm LED



$$\Delta V = \frac{q}{\varepsilon}\int_{x1}^{x2} x N_t dx$$

Depth profile of MQW defects



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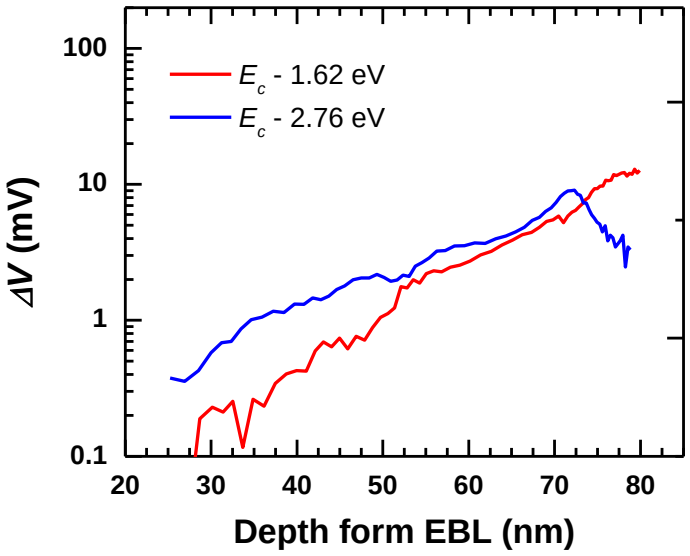
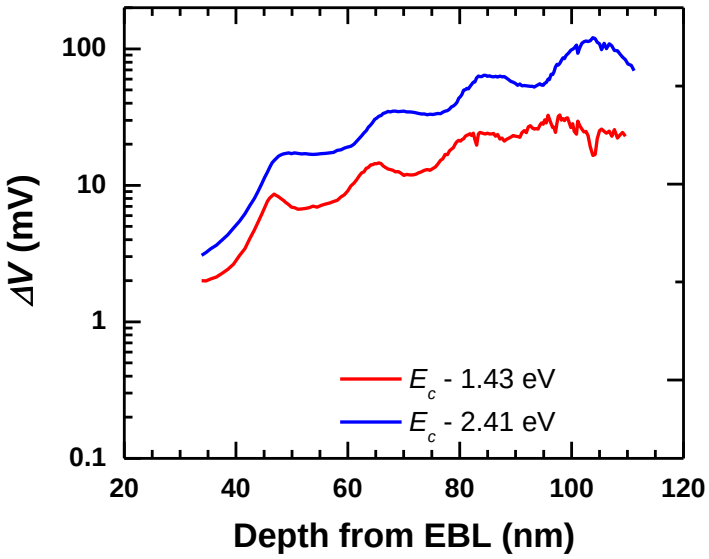
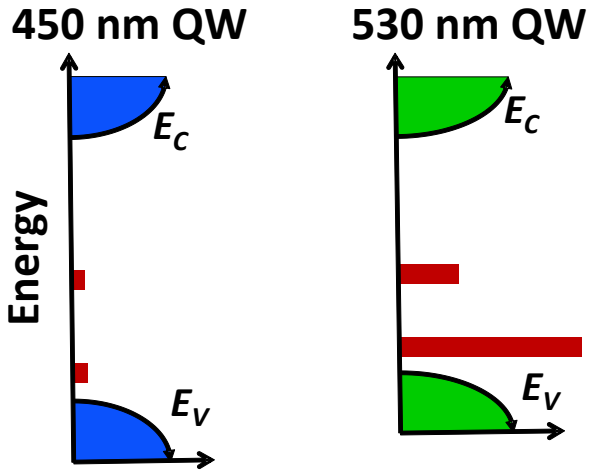
QW deep level defect density

LCV of 450 LED



LCV of 530 LED





Deep level density of states

Defect Level (eV)	N_t (cm^{-3})	ΔN_t
E_c – 1.62	4.1e15	4.4x
E_c – 1.43	1.8e16	
E_c – 2.76	4.4e15	13x
E_c – 2.43	5.5e16	

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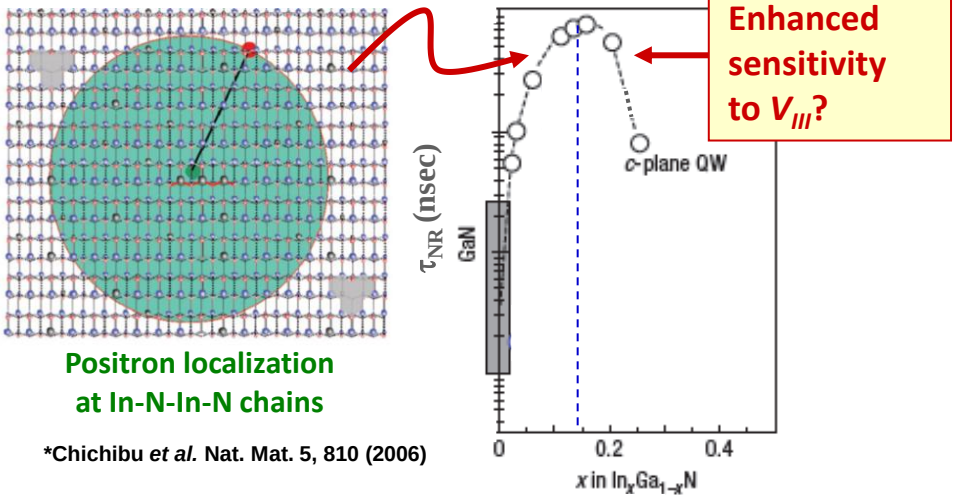
Possible origin of QW defects – V_{III} and/or carbon

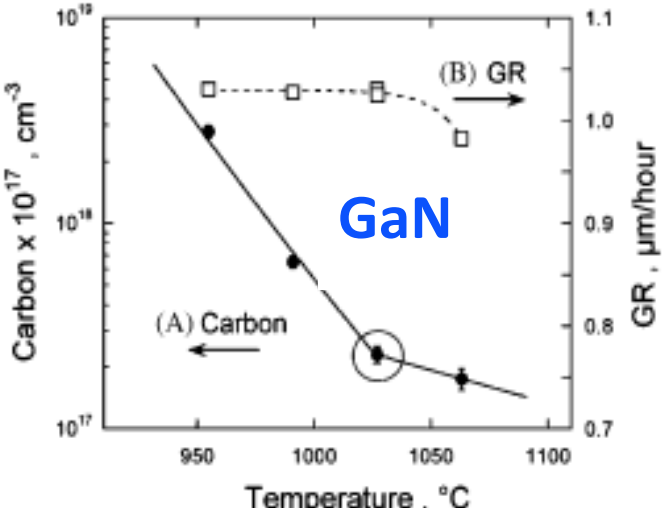
V_{III} density increases with indium



Positron localization at In-N-In-N chains

*Chichibu *et al.* Nat. Mat. 5, 810 (2006)

[C] increases with lower T_g



Koleske *et al.*, JCG 242 55 (2002)

- V_{III} and carbon are well know non-raidaitive recombination centers in GaN
- PAS and PL studies* show that [V_{III}] increases and τ_{NR} decreases with indium
- Reasonable that carbon also incorporation increases with reduced QW T_g

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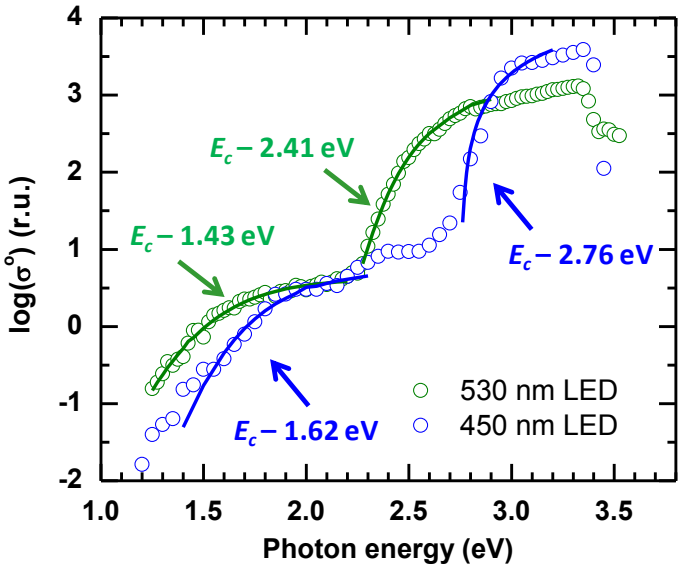
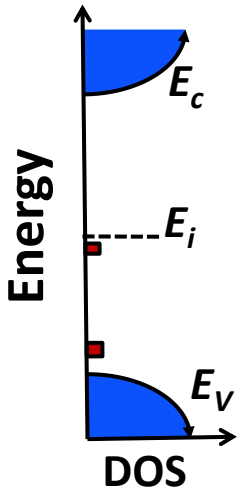
Conclusions

LED QW DLOS vs. indium content

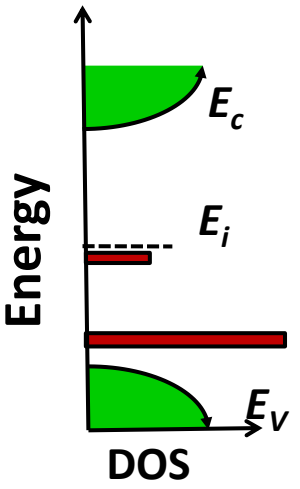


Defect density

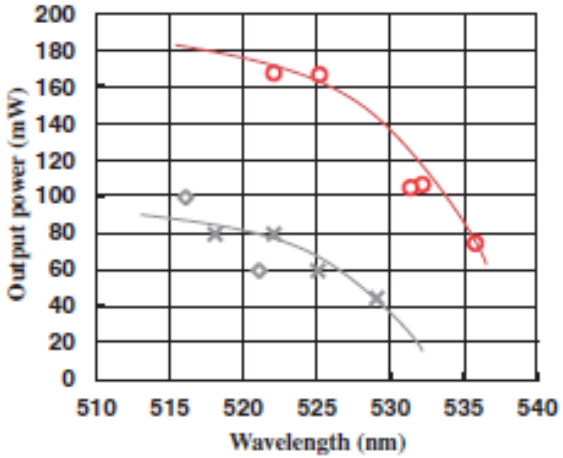
$In_{0.14}G_{0.86}N$ QW



$In_{0.22}Ga_{0.78}N$ QW

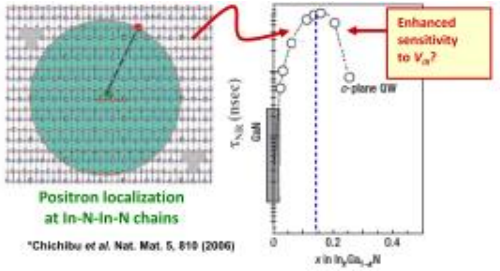


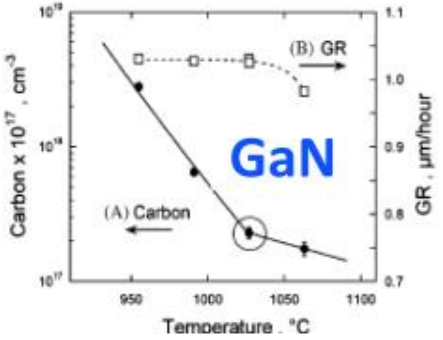
Semi-polar LD power vs. λ



Takagi *et al.* Applied Physics Express 5 (2012) 082102

Defect density





Koleske *et al.*, JCG 242 55 (2002)