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Spatial and compositional dependence of deep level defects in InGaN LEDs

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Outline

- Importance of point defects in InGaN/GaN LEDs
- Application of deep level optical spectroscopy (DLOS) to InGaN/GaN LEDs
- Indium compositional dependence of QW deep level defects
- Nanoscale depth-dependence of QW deep levels in MQW region
- Controlling deep levels in active regions designed for droop reduction
- Summary

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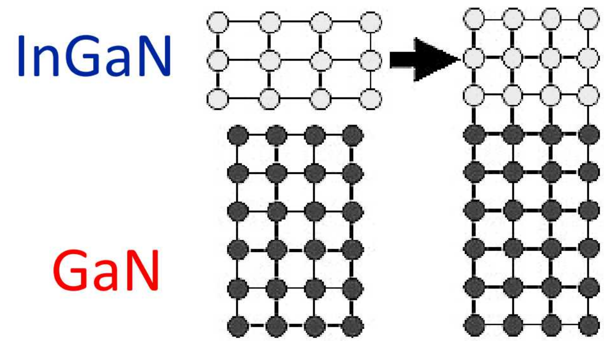
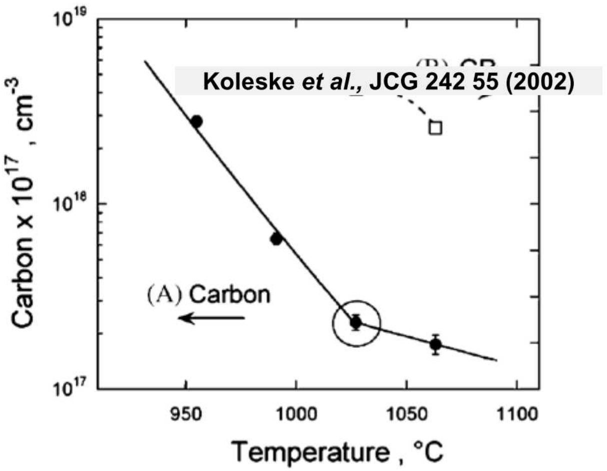
Defects must be carefully managed in InGaN/GaN LEDs

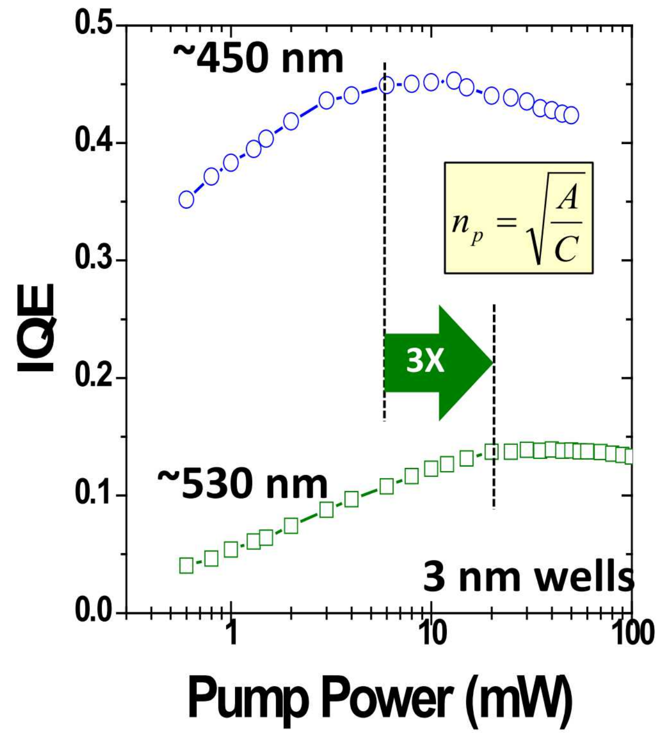
Mis-matched epitaxy and strain



Carbon incorporation



LED IQE vs. optical pump power



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

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

- Defects depress peak IQE
- Defect incorporation increases with increasing indium content
- Defects likely to contribute to "green gap"

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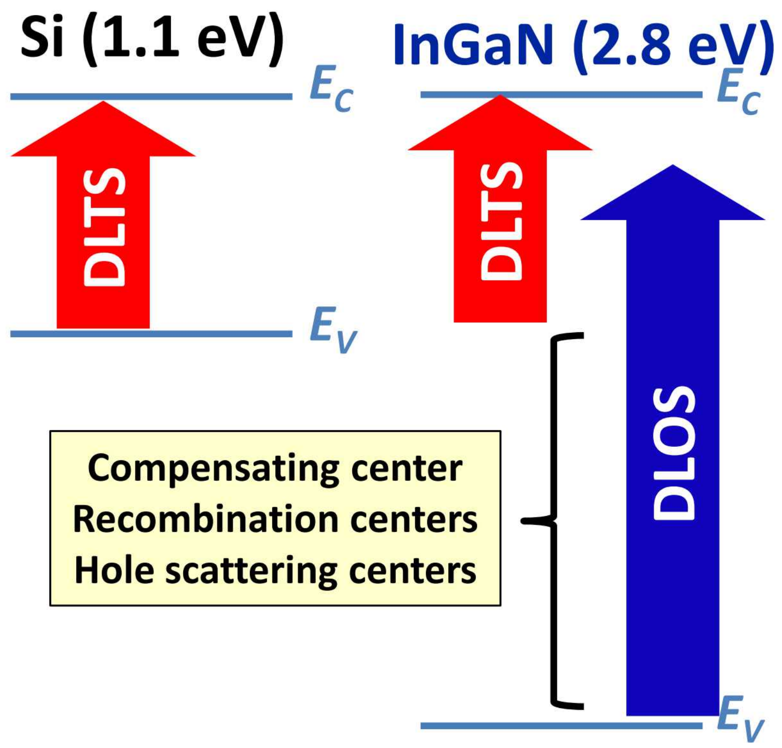
Deep level spectroscopy of InGaN LEDs is difficult

- Thermal emission techniques limited to ~ 1 eV of band edge
- Luminescence insensitive to non-radiative centers and not quantitative



Solution: Deep Level Optical Spectroscopy (DLOS)

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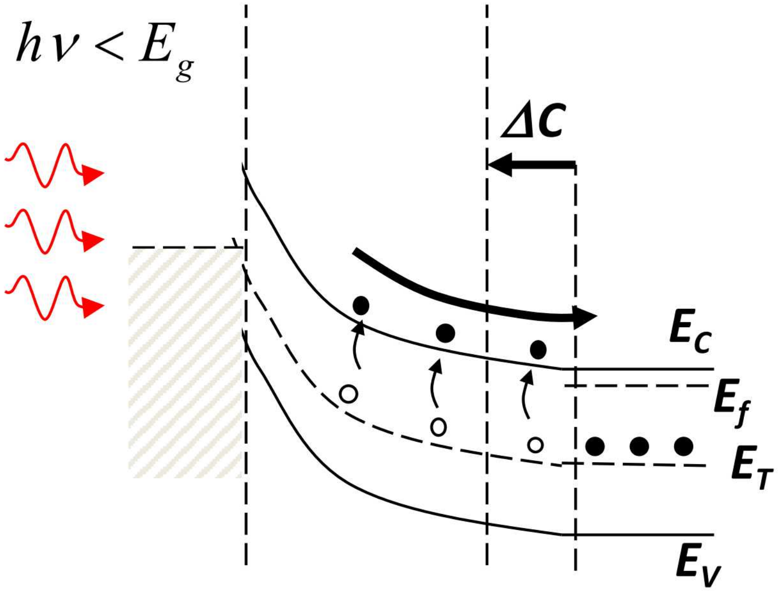
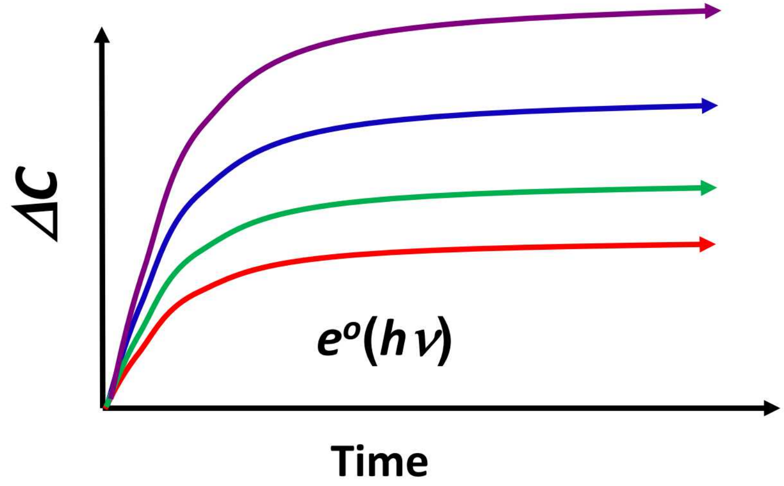
Deep Level Optical Spectroscopy

<u>Deep Level Optical Spectroscopy (DLOS)[1]</u>

- Photocapacitance technique
- Sub-band gap light photoionizes defect levels
- DLOS only senses deep level defects in the depletion region





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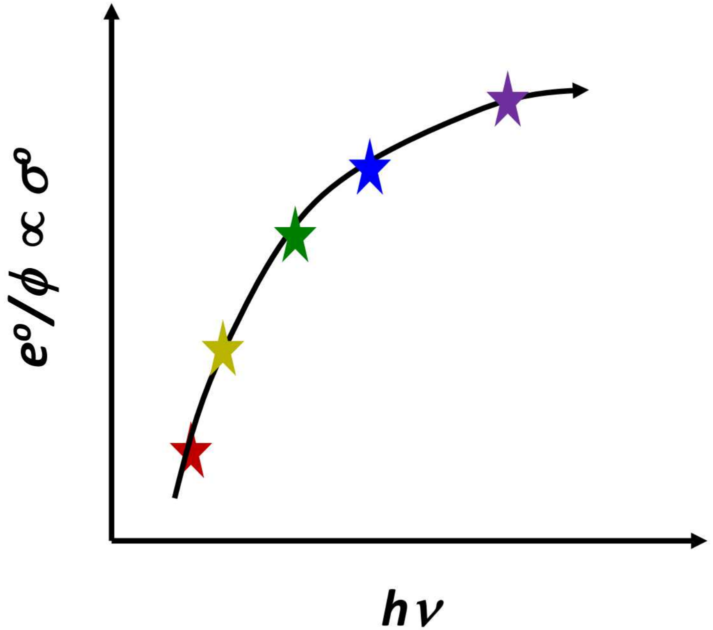
1. Chantre *et al.* PRB 23, 5335 (1981).

Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- Fundamental physics from optical cross-section: $\sigma^o(h\nu) = e^o(h\nu)/\phi(h\nu) = \alpha/N_t$
- Determine deep level energy E_o from spectral line shape of $\sigma^o(h\nu)$
- Discuss defect density later…

Optical analog of Arrhenius plot



$$\sigma^o(h\nu) \propto \frac{1}{E_0}\left\{\left(\frac{E_0}{h\nu}\right)\cdot\left(1-\frac{E_0}{h\nu}\right)\right\}^{3/2}$$

$$\sigma^o(h\nu,T) \propto \frac{E_o^2}{h\nu\sqrt{4k_B T\pi d_{FC}}}\int_1^\infty dx\sqrt{\frac{x-1}{E_o}}\frac{1}{[(x-1)/E_o+m]^2} \times \exp\left[-\frac{E_o^2(h\nu/E_o-x)^2}{4k_B T d_{FC}}\right], \quad (4)$$

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

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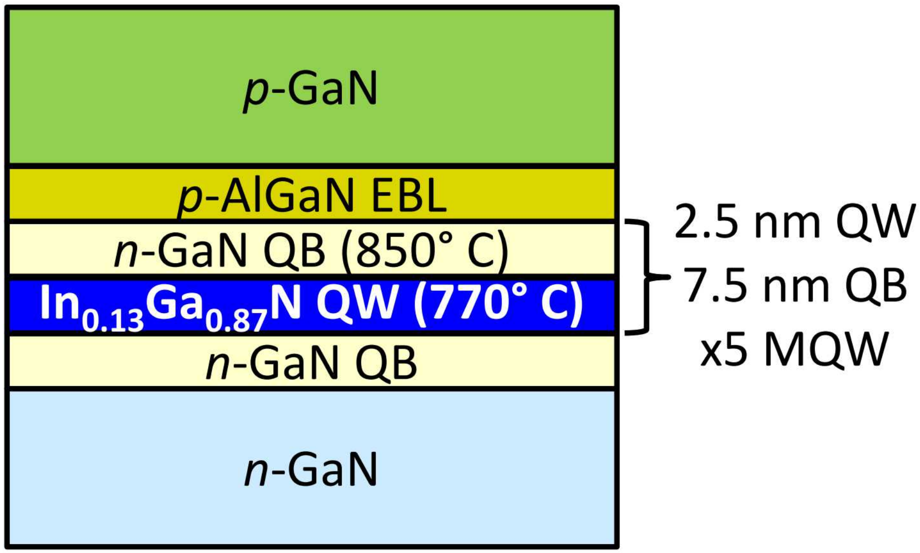
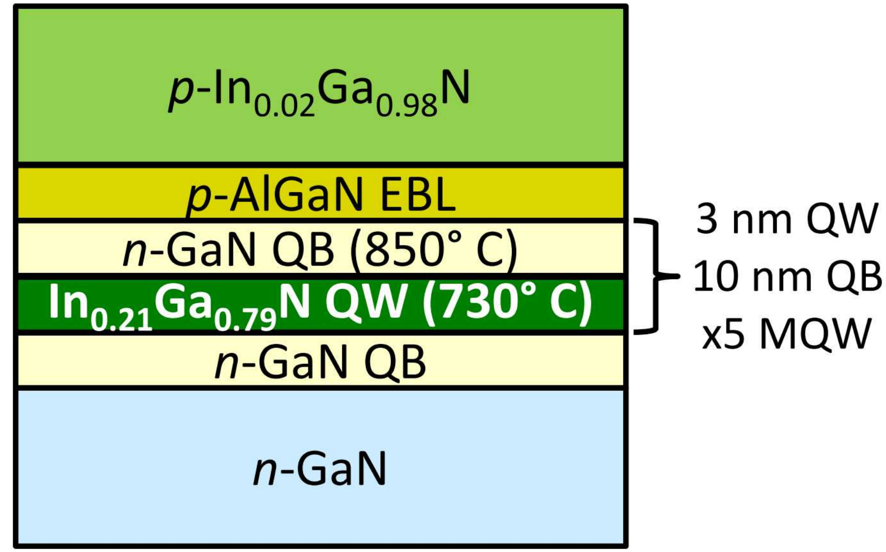
Compare MQW deep levels in blue vs. green LEDs

440 nm InGaN/GaN LED



530 nm InGaN/GaN LED



- Sandia-grown MOCVD c-plane LEDs on sapphire
- What is the impact of increased In and reduced T_g on QW deep levels?

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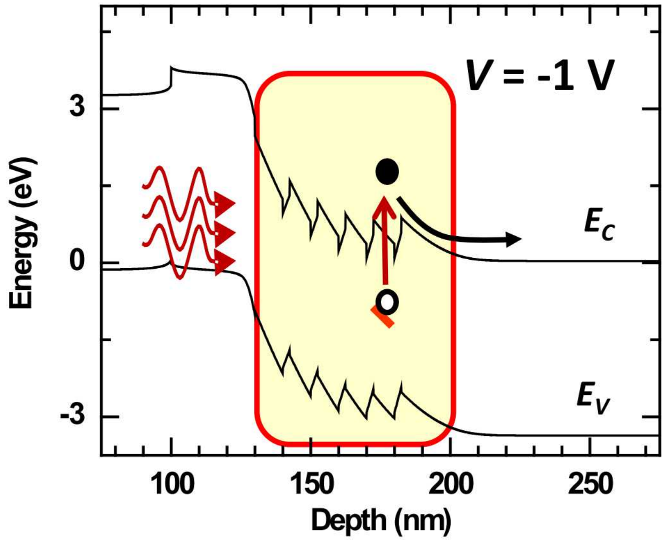
DLOS provides depth resolution in LEDs

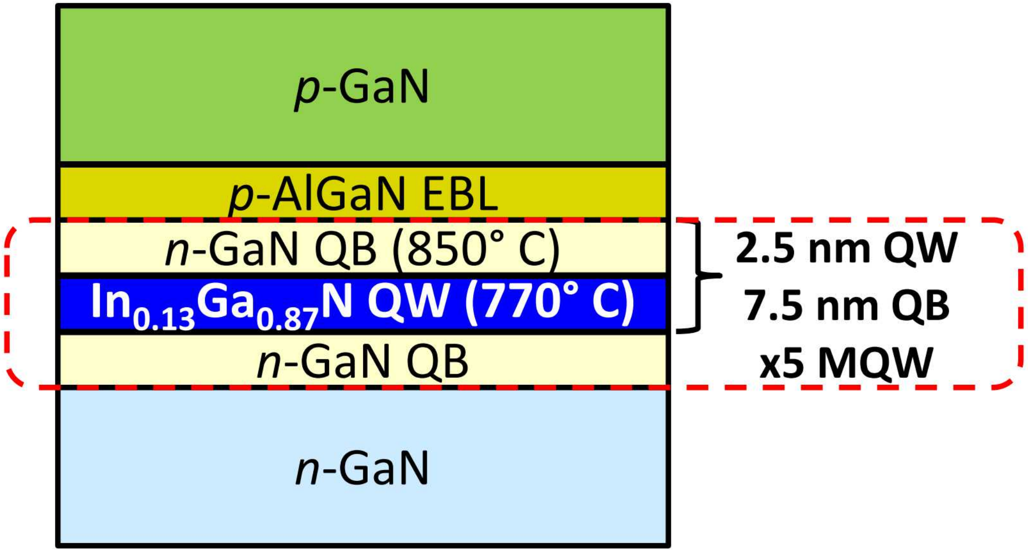
LED MQW 1D-SP calculations*



*G. Snider UND

- Control DLOS depth resolution with applied bias
- DLOS selective to the MQW region for *V* = -1 V

440 nm InGaN/GaN LED



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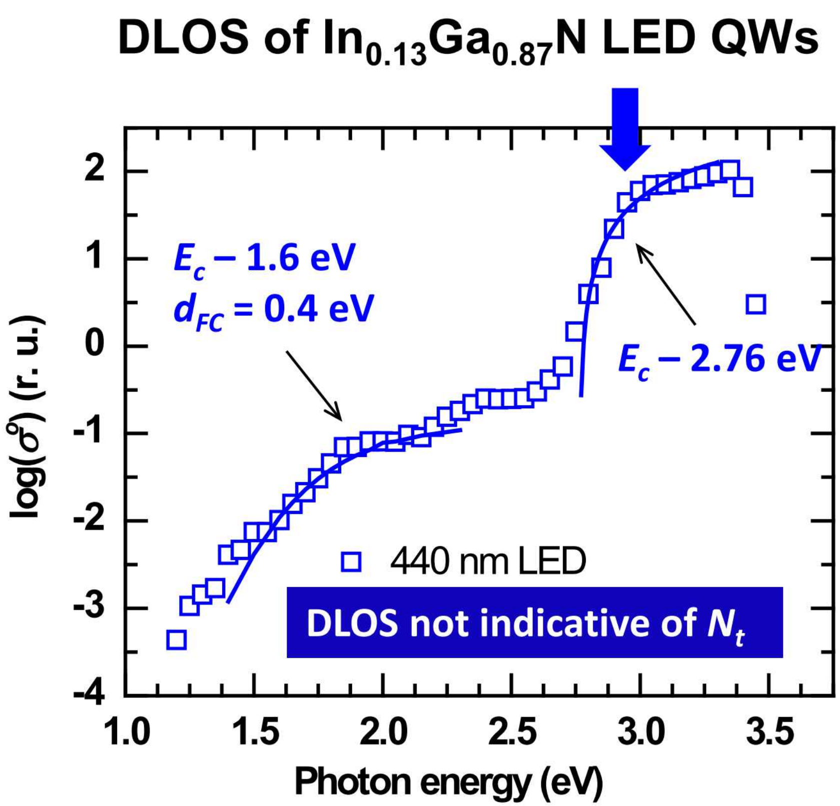
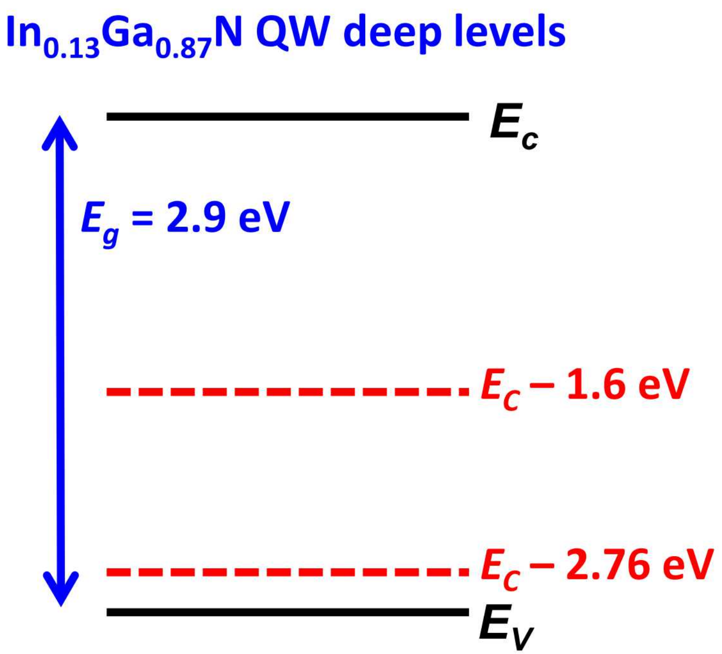
Identify QW-related defects in LEDs





- 2.9 eV InGaN band edge confirms sensitivity to QWs
- QW-related deep levels at E_c – 1.6 eV and E_c – 2.76 eV
- How to know these are QW- and not QB-related deep levels?

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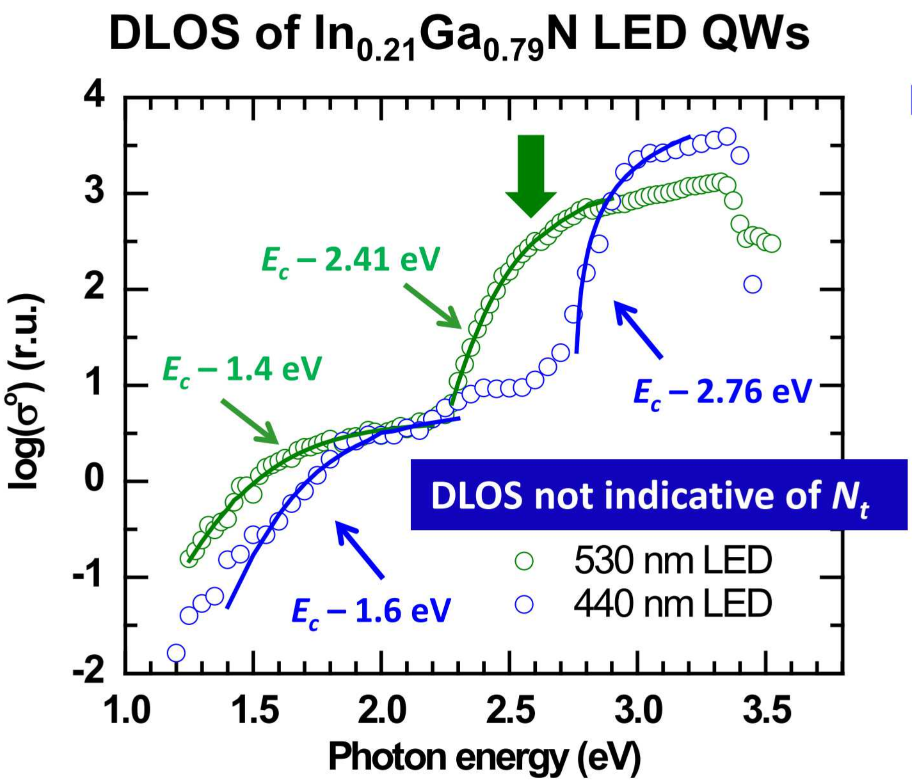
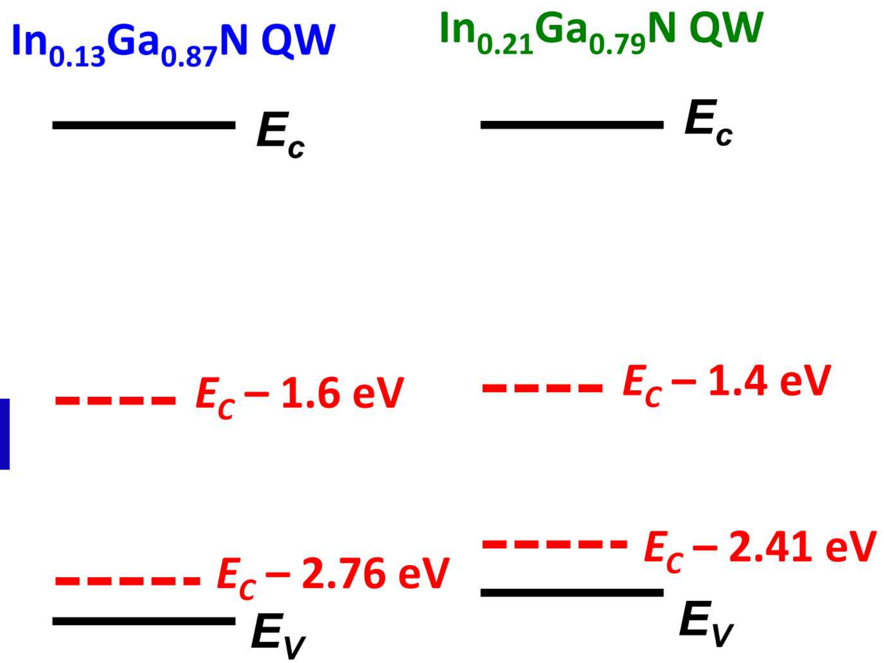
LED QW deep levels evolve with Indium content





- Red shift in QW band edge with increased indium
- Corresponding red shift of deep level spectra with indium alloying
- Confirms QW-related defects

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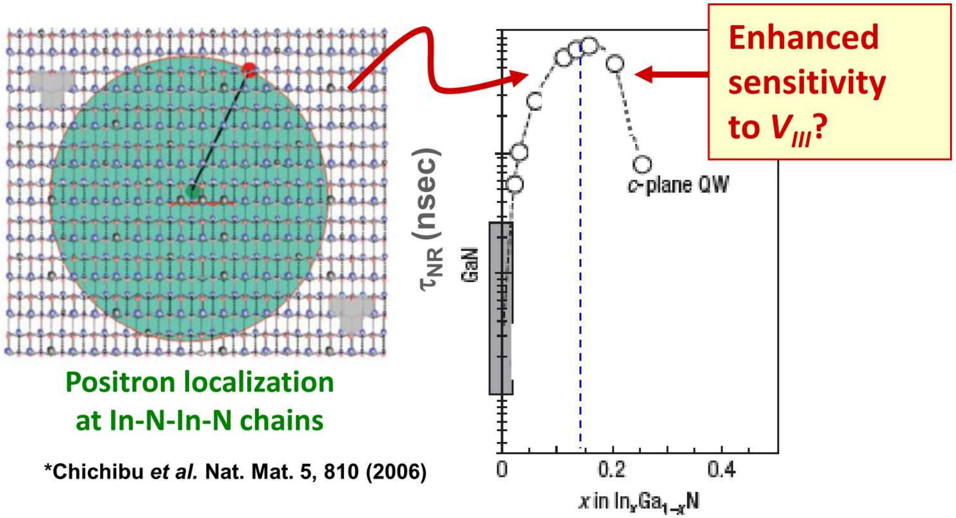
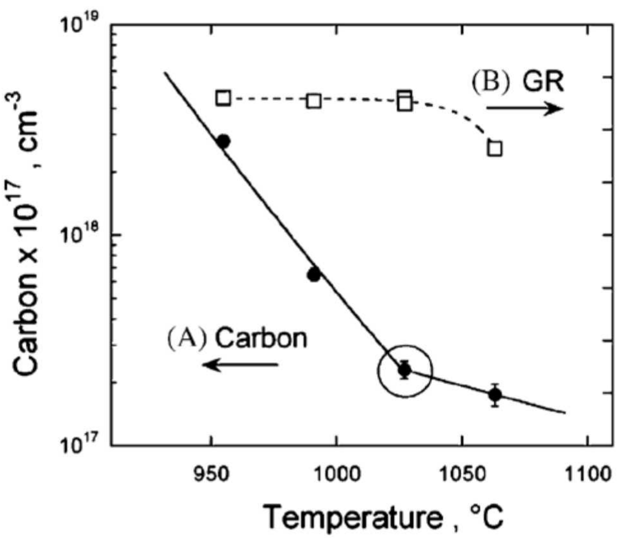
V_{III} density increases with indium



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-radiative recombination centers in GaN
- PAS/PL studies* show that [V_{III}] increases indium and likely contributes to green gap
- Reasonable that carbon incorporation also increases with reduced QW T_g

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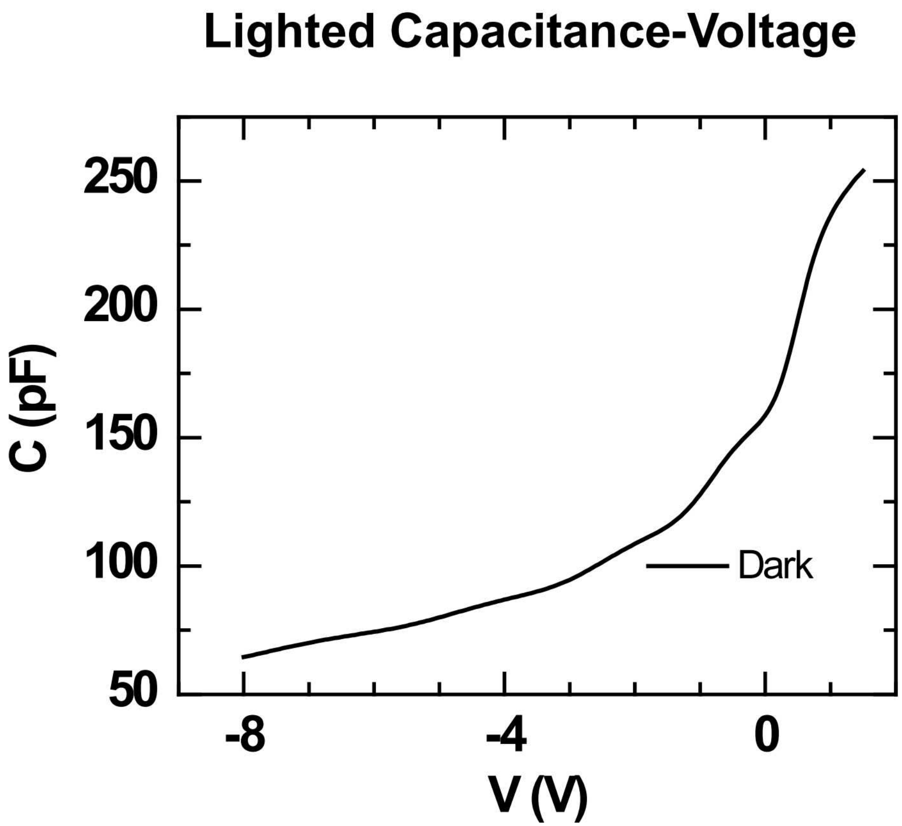
Lighted-*CV* quantifies QW defect density



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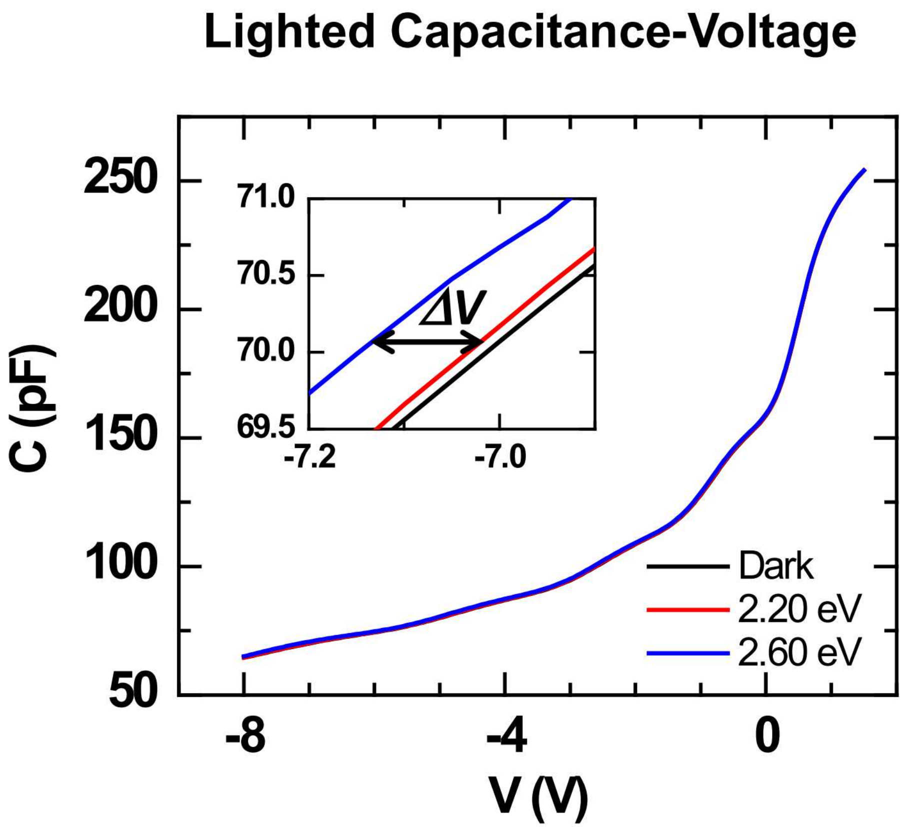

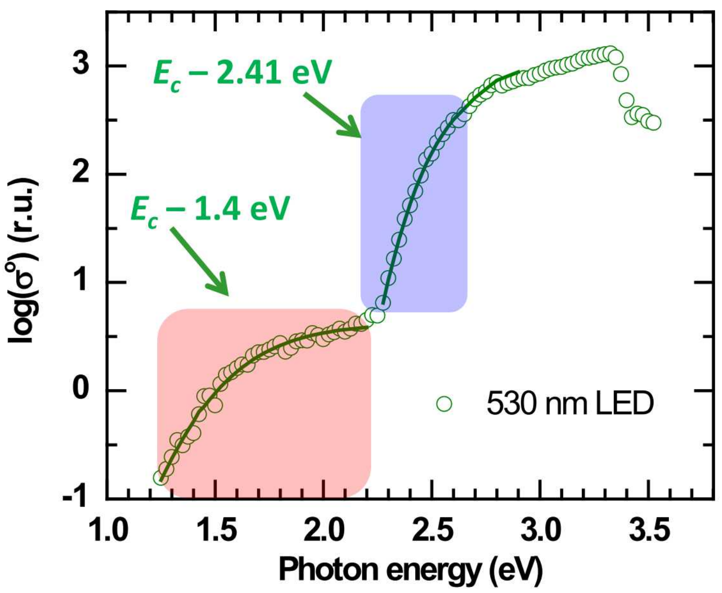

$$\Delta V = \frac{q}{\varepsilon}\int_{x1}^{x2} x N_t \, dx$$

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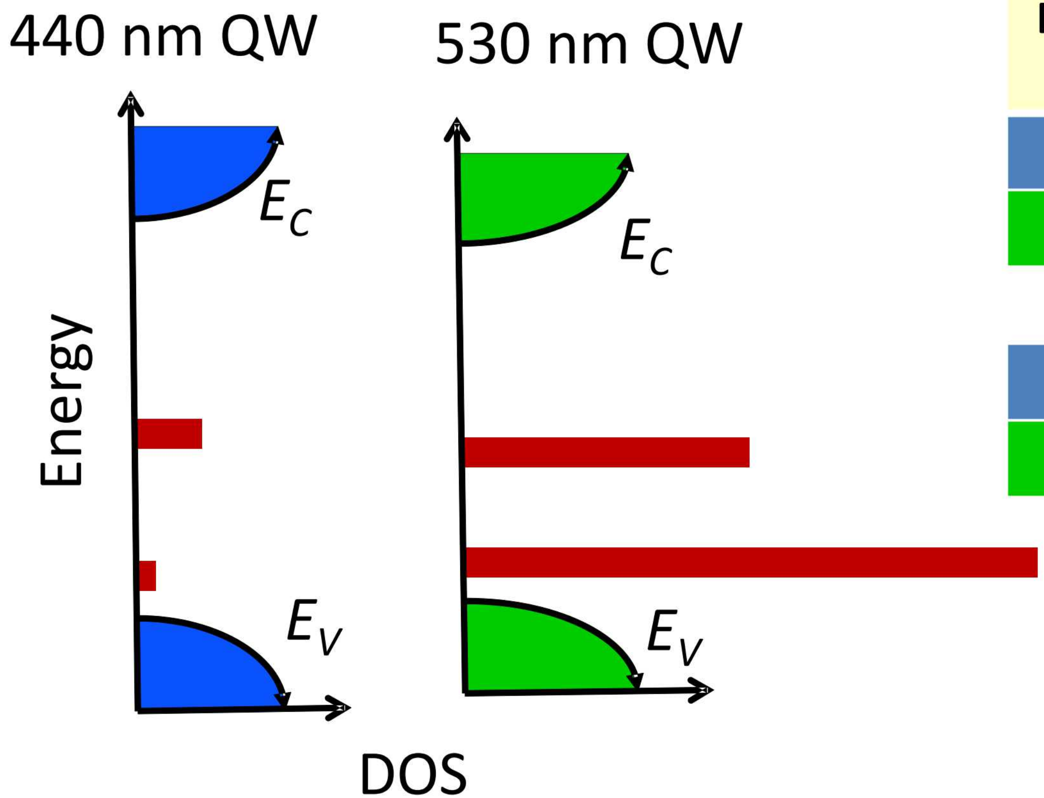
QW deep level defect density vs. Indium content



Defect Level (eV)	N_t (cm^{-3})	ΔN_t
$E_c - 1.6$	4.6e15	4.3x
$E_c - 1.4$	2.0e16	
$E_c - 2.76$	1.3e15	30x
$E_c - 2.43$	4.0e16	

- Substantial increase in mid-band gap and near-E_v deep levels
- Expect QW defects contribute to green gap problem by:
  - Increasing non-radiative recombination
  - Reducing hole injection efficiency

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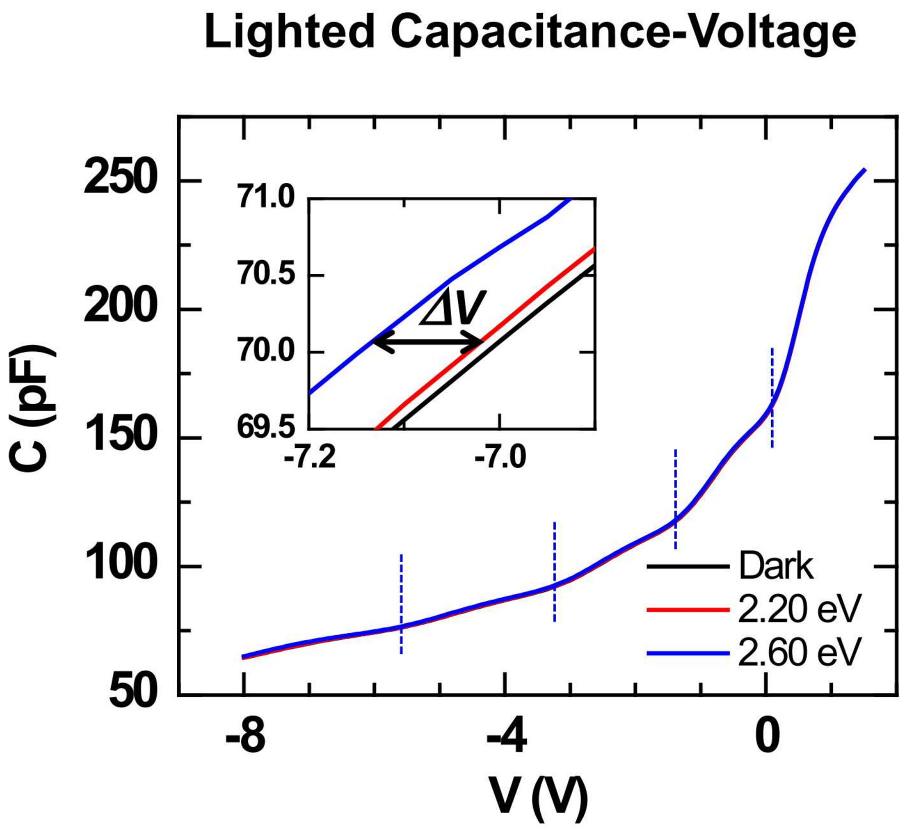

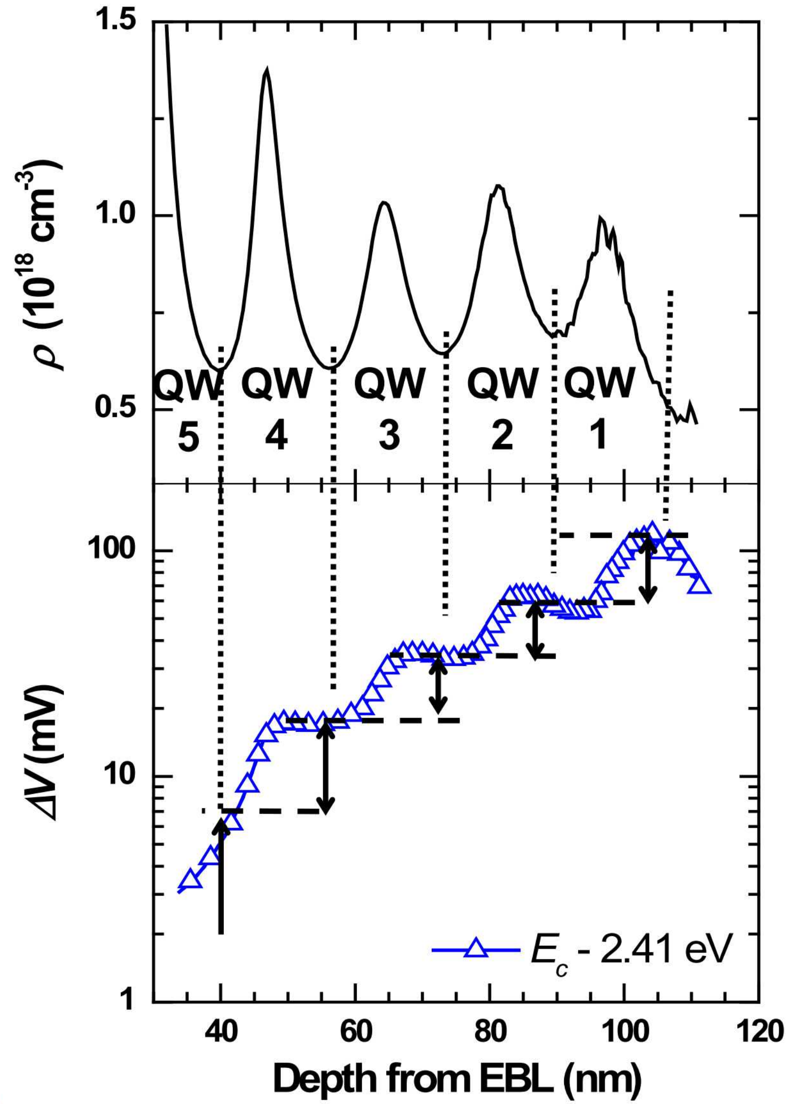

$$\Delta V = \frac{q}{\varepsilon}\int_{x1}^{x2} x N_t \, dx$$

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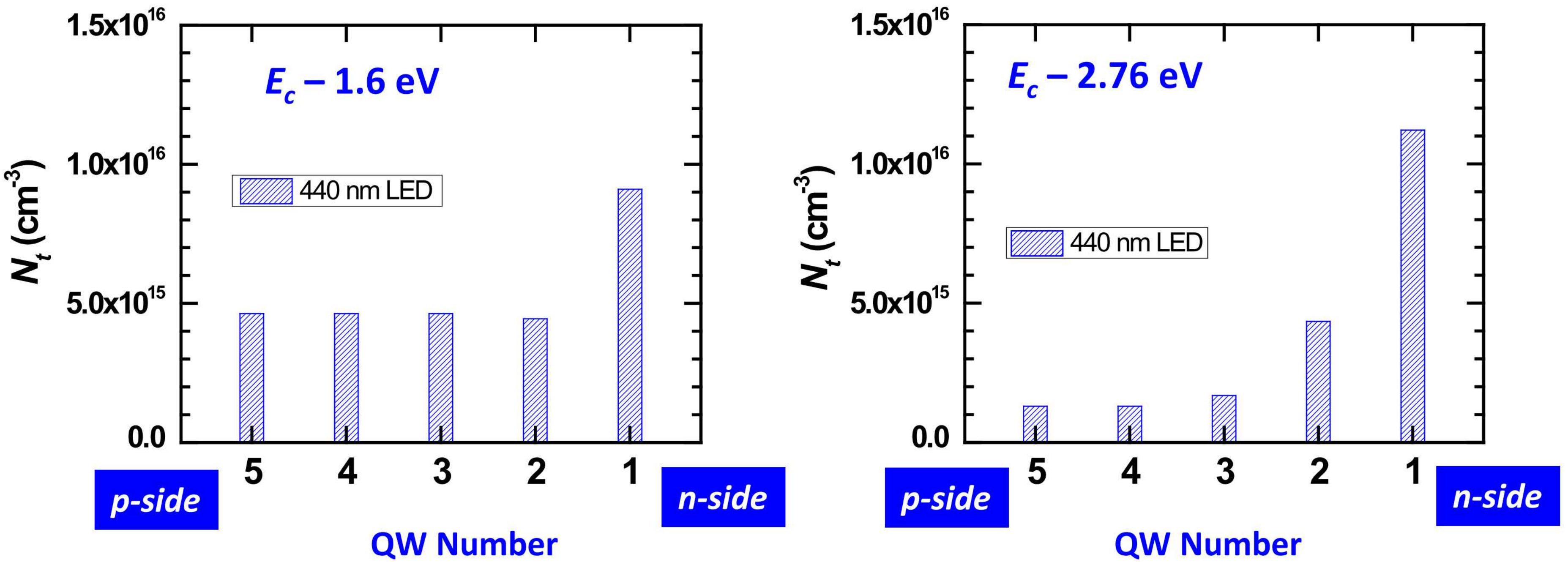
LCV reveals strong depth dependence of QW deep levels

Depth profile of QW defects in 440 nm LED



- Non-destructive, TEM-like spatial resolution of point defect distribution in LEDs
- First QWs grown are more defective than subsequently grown QWs
- InGaN/GaN may act as gettering[1] or conditioning layer that sequesters defects

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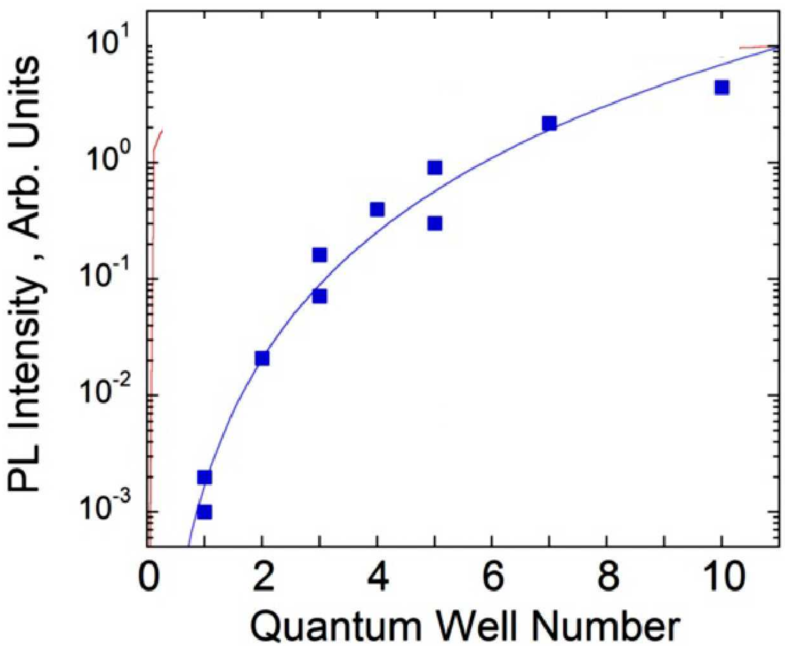
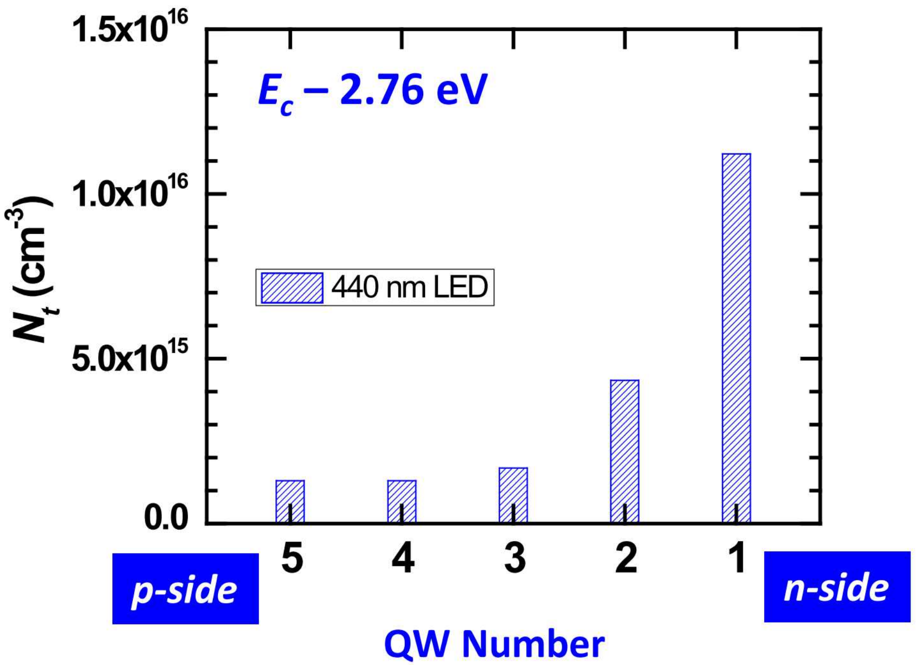
1. Petroff et al. APL 44 217 (1984)

LCV reveals strong depth dependence of QW deep levels





➢ Explains rapid, super-linear in MQW PL intensity vs. # of QWs

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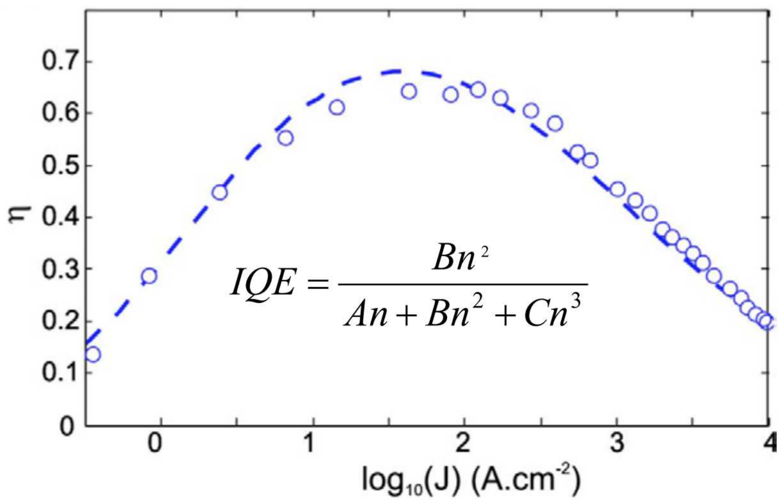
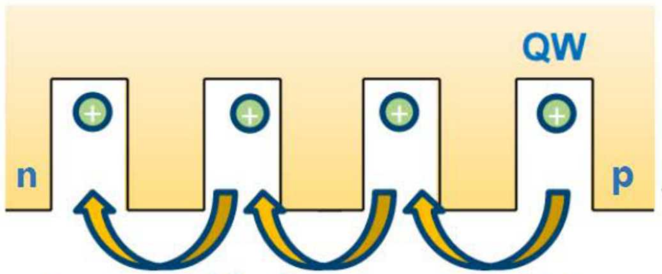
Deep levels can become important to reducing droop

InGaN LED efficiency droop



David and Grundmann, APL 96 106504 (2010)

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



Improved hole transport design: carriers distributed more evenly

- Efficiency droop attributed to Auger recombination[1,2] at large carrier density
- Reduce droop by improving carrier transport
- DLOS of Lumileds LEDs to understand impact of defects on active region design

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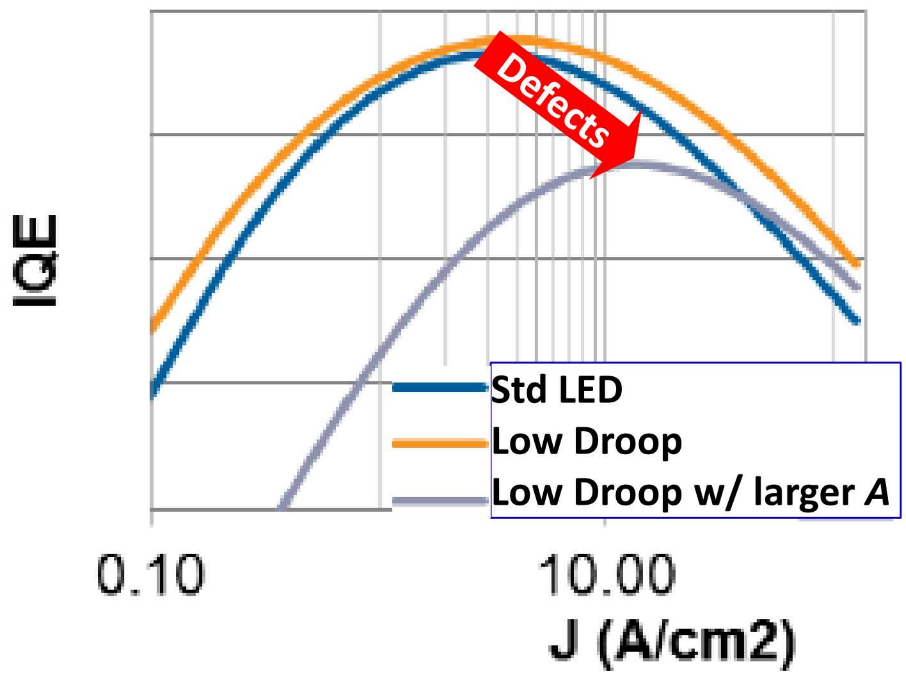
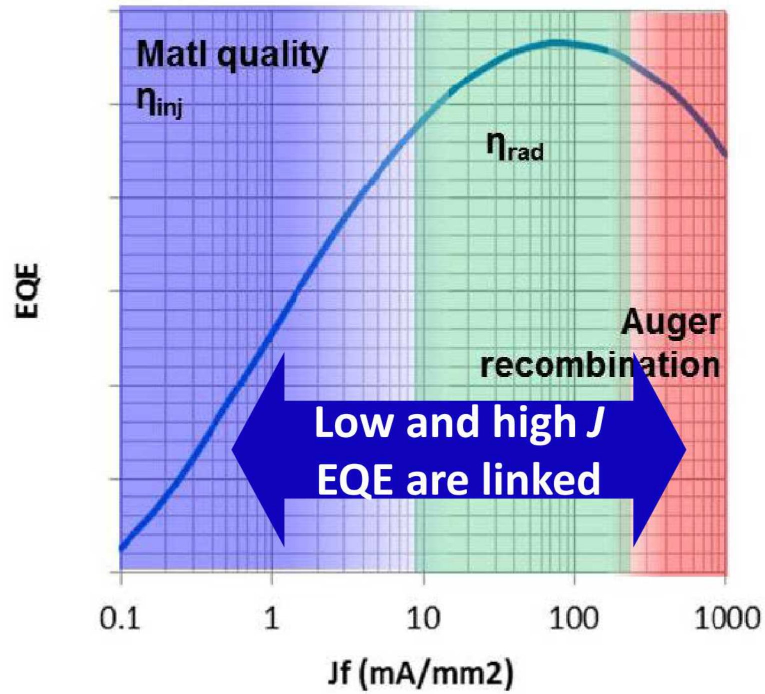
1. Shen et al. APL 91 141101 (2007). 2. Iveland et al. PRL 110 177406 (2013).

Deep levels can become important to reducing droop

Representative LED IQE



Typical LED EQE *vs. J*



- Initial active region designs improve droop but at the cost of peak efficiency
- Maximum reduction in droop requires reducing *n* while *maintaining low N_t*

DLOS provides quantitative feedback for rational design and growth optimization

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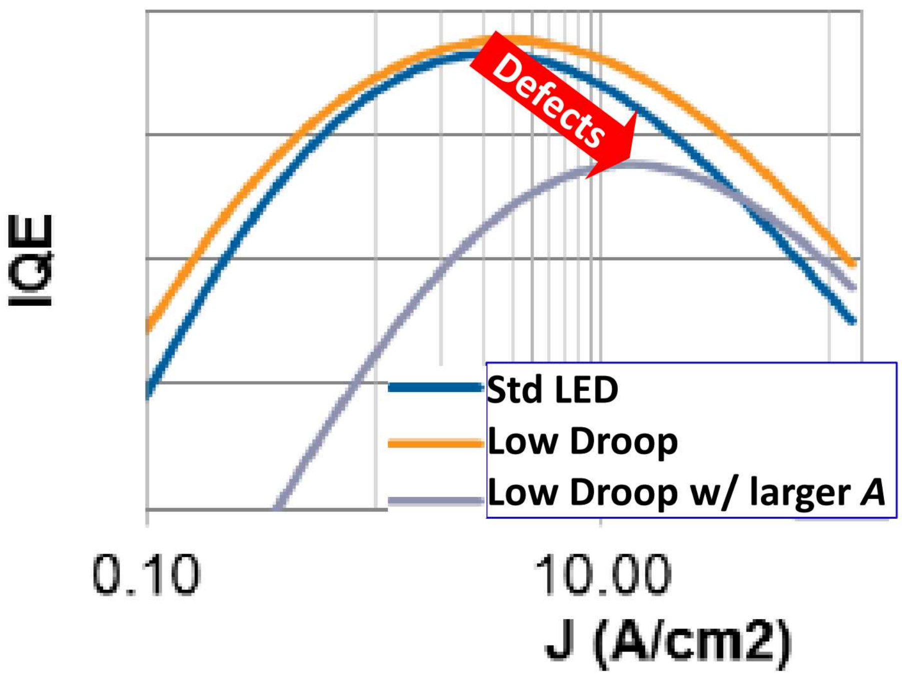
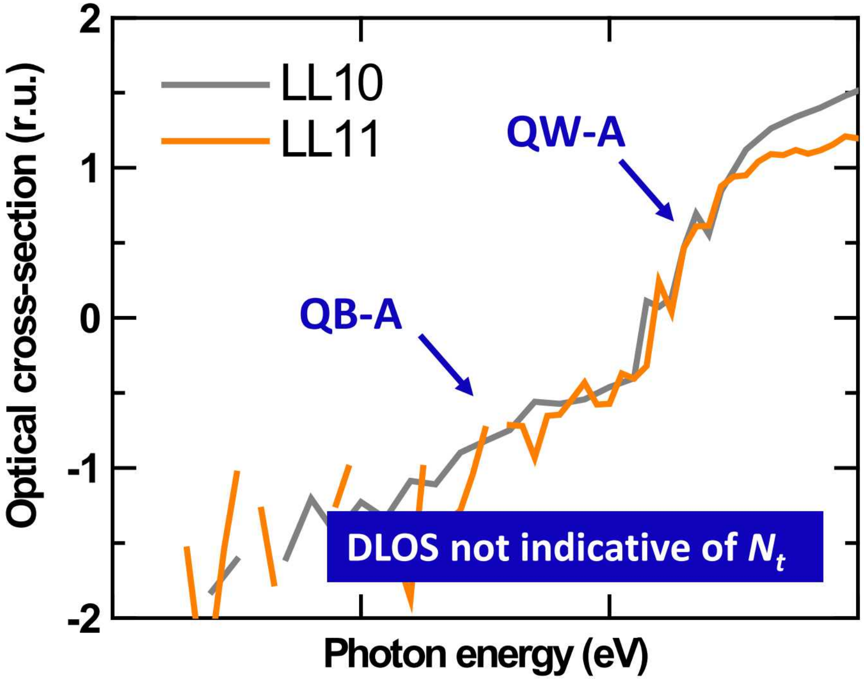
DLOS of low droop LEDs

Representative LED IQE



DLOS of Lumileds 450 nm LEDs



- Examined low droop LEDs LL10 vs. LL11 with improved design and growth
- Same types of deep level defects in both low droop LEDs
- Differences EQE likely due to differences in N_t

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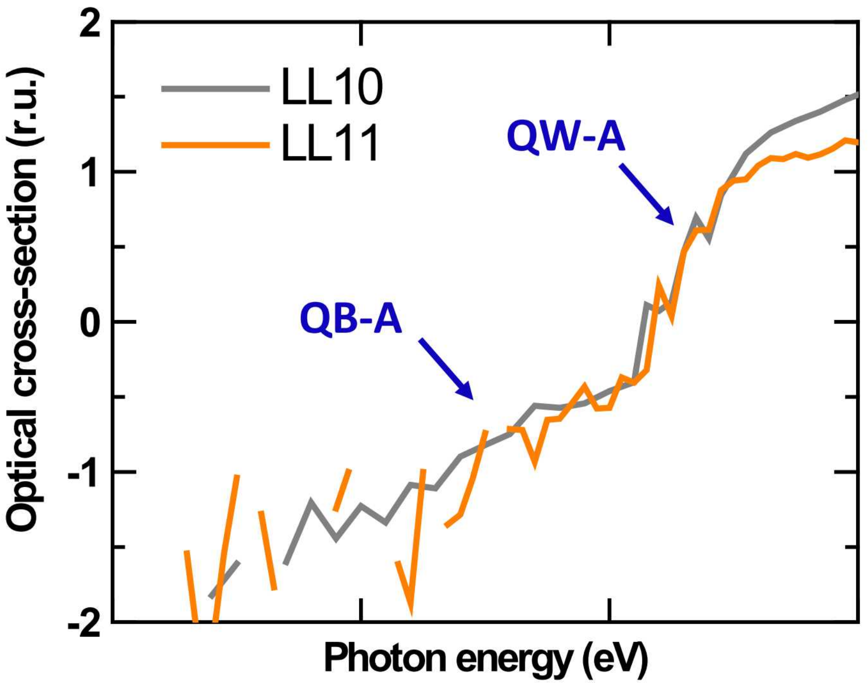
Deep level reduction correlated with improved EQE

LED N_t from LCV

	QB-A (cm^{-3})	QW-A (cm^{-3})
LL10	9.3e15	1.0e16
LL11	3.6e15	4.9e15
Δ	-62%	-51%

DLOS of Lumileds 450 nm LEDs



➢ >2x reduction of N_t for QB-A and QW-A in LL11

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Deep level reduction correlated with improved EQE

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	QB-A (cm^{-3})	QW-A (cm^{-3})
LL10	9.3e15	1.0e16
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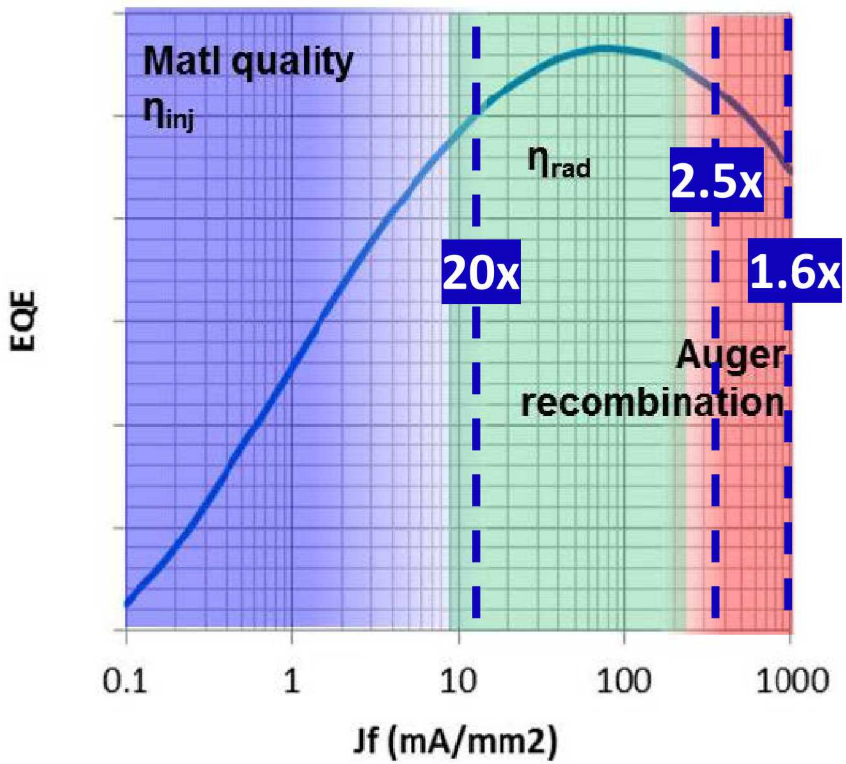
Δ	-62%	-51%

Relative EQE gain *vs.* *J* @ 85 °C



- >2x reduction of N_t for QB-A and QW-A in LL11
- Correlated with significant EQE gains throughout LED operational range

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Summary

- DLOS quantifies deep level defect energy in LED QWs
- LCV provides nanoscale depth-dependence of QW deep level density
- Increase in QW N_t with increasing indium that likely contributes to green gap
- Depth-dependence of QW deep levels suggests InGaN/GaN defect gettering
- Controlling deep levels can be important to maximizing droop reduction

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