Impact of Point and Extended Defects on InGaN LED Efficiency

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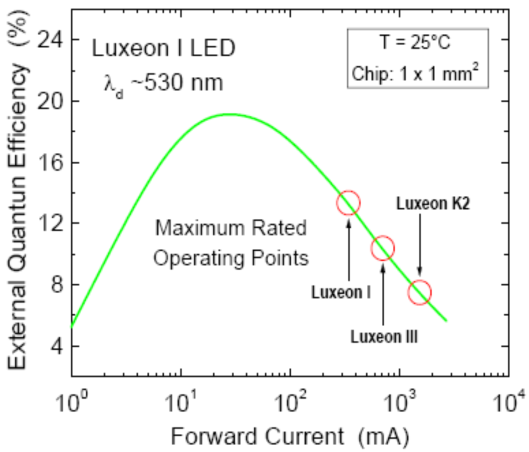
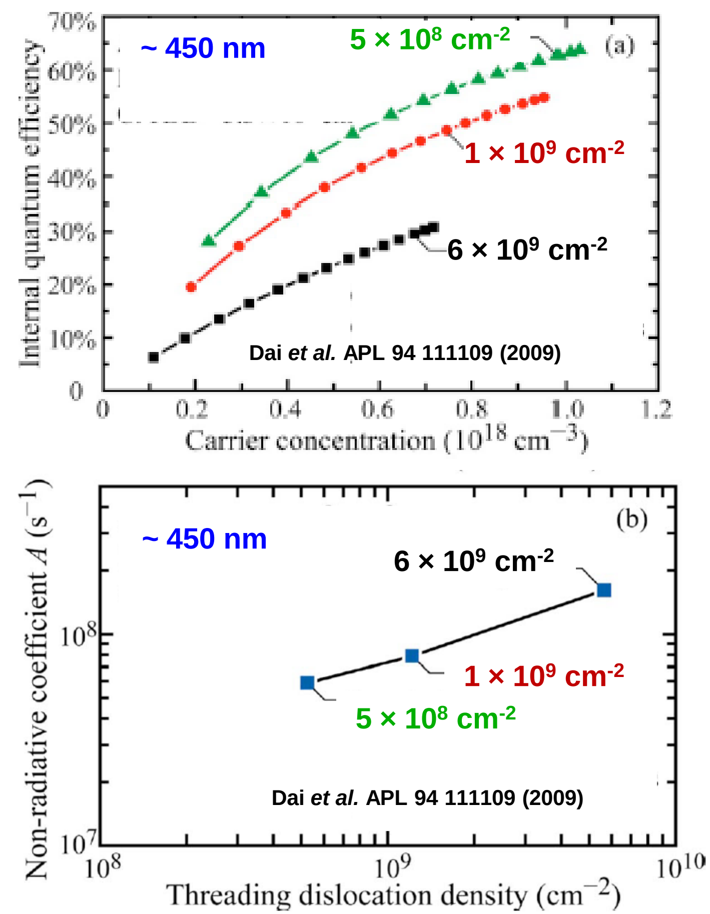
How do defects limit LED efficiency?

"Efficiency Droop" of InGaN LEDs



Philips Lumileds

Threading dislocations reduce peak efficiency



Goal: Quantify relationship between LED TDD and deep level incorporation

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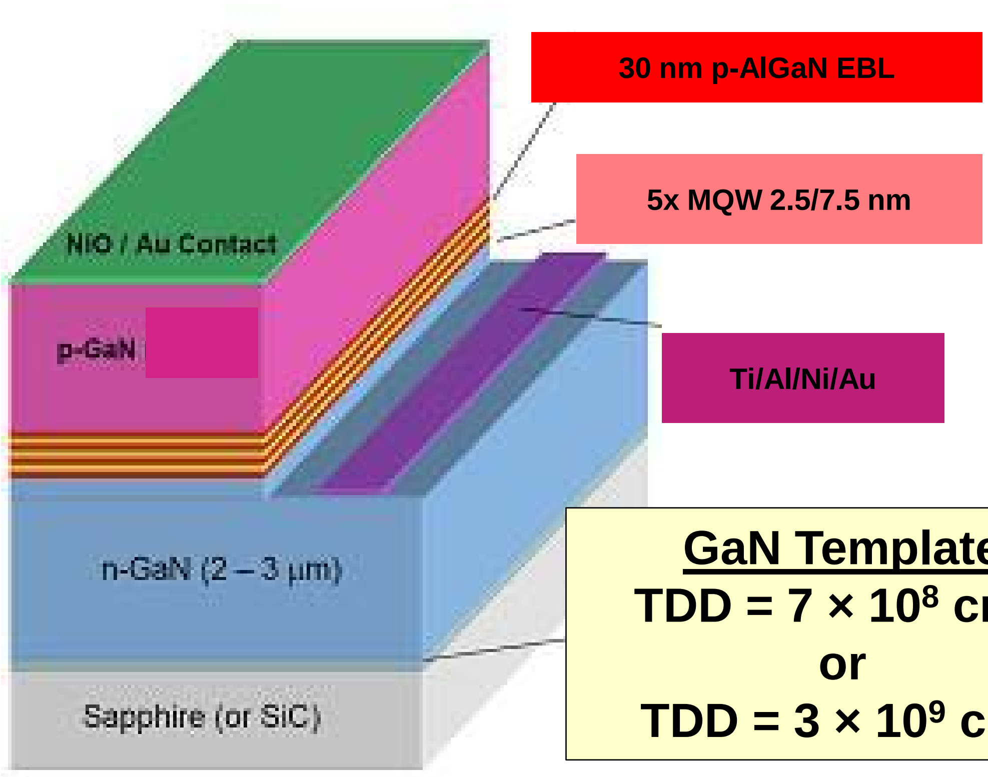
Threading dislocations reduce LED non-radiative lifetime

$In_{0.13}Ga_{0.87}GaN/GaN$ LEDs

- MOCVD on c-plane GaN
- Simultaneous LED growth on co-loaded templates
- TDD controlled by template nucleation and coalescence parameters



GaN Template

TDD = 7×10^8 cm^{-2}

or

TDD = 3×10^9 cm^{-2}

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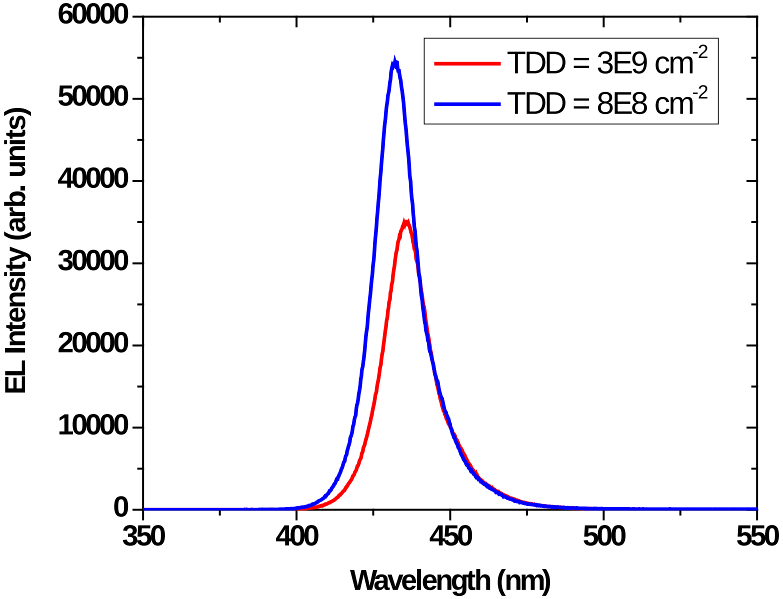
Threading dislocations reduce LED non-radiative lifetime

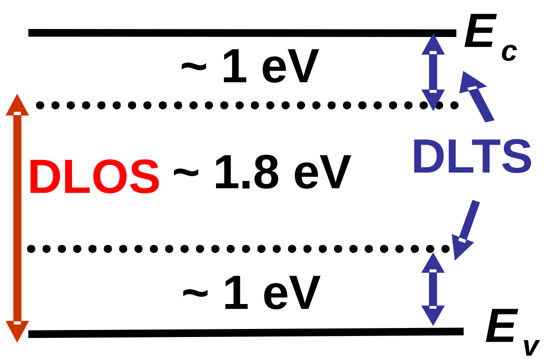
LED efficiency vs. TDD



- Improved EQE for reduced TDD
- Suspect defect reduction as root cause

Standing challenges to studying defect levels in LEDs

- **Sensitivity to non-radiative defects**
- **Quantify deep level defect density (N_t)**
- **Quantify deep level energy (E_o)**
- **Sensitivity to mid-gap deep levels**
- ***Nanoscopic depth sensitivity within MQW region***



- **How to satisfy all of these requirements?**

  ➡ **Deep Level Optical Spectroscopy (DLOS)**

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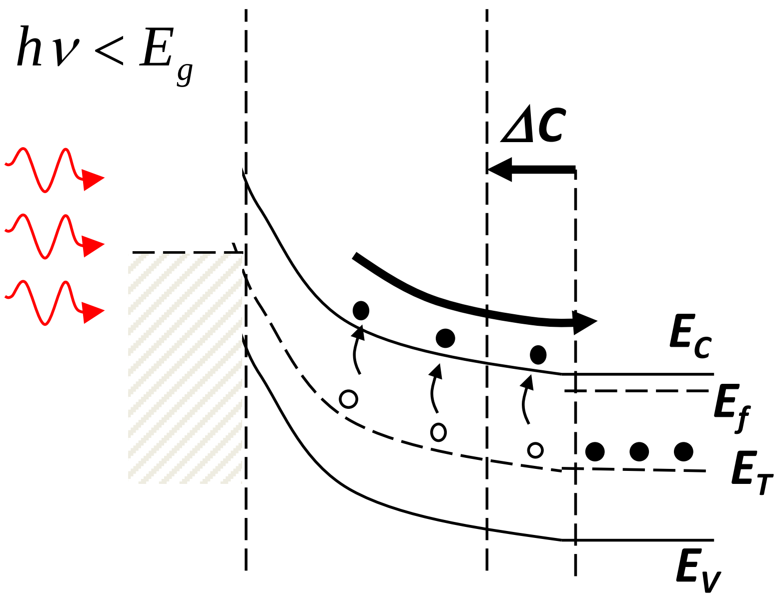
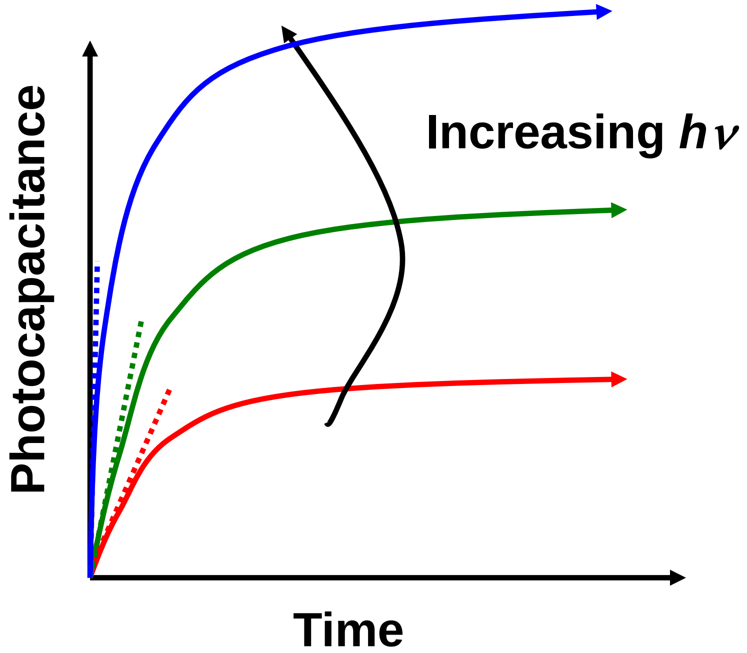
Deep Level Optical Spectroscopy

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

- ➢ **Photocapacitance technique**
- ➢ ***<u>Backside, sub-band gap optical stimulation</u>* to photoionize defect levels**
- ➢ ***<u>Quantify non-radiative</u>* defect level energy and density**





- ***<u>DLOS only sensitive to depleted regions</u>***

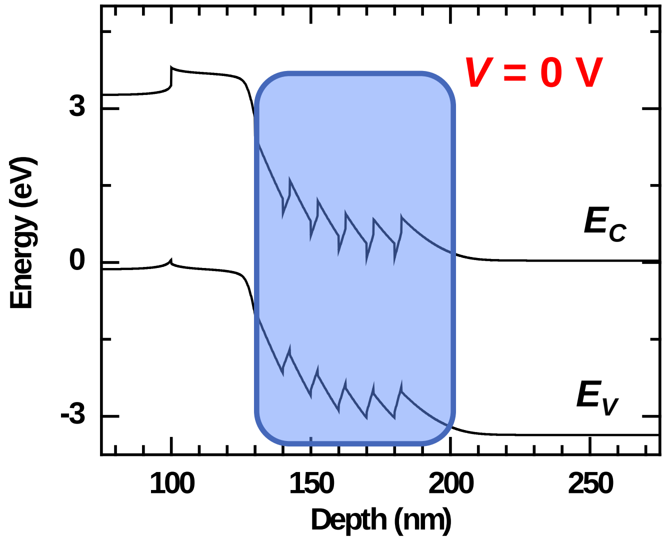
1. **Chantre *et al.* PRB 23, 5335 (1981).**

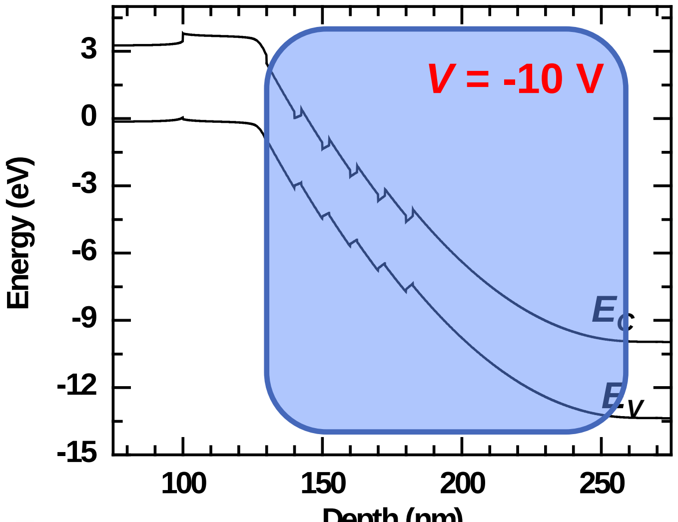
- **Optical cross-section $\sigma^o = e^o/\Phi = \alpha/N_t$**
- **$\sigma^o(h\nu) \propto dC(t)/dt|_{t=0}$**
- **Measure optical ionization energy E^O**

DLOS provides depth resolution in LEDs

LED MQW 1D-SP calculations*

*G. Snider UND



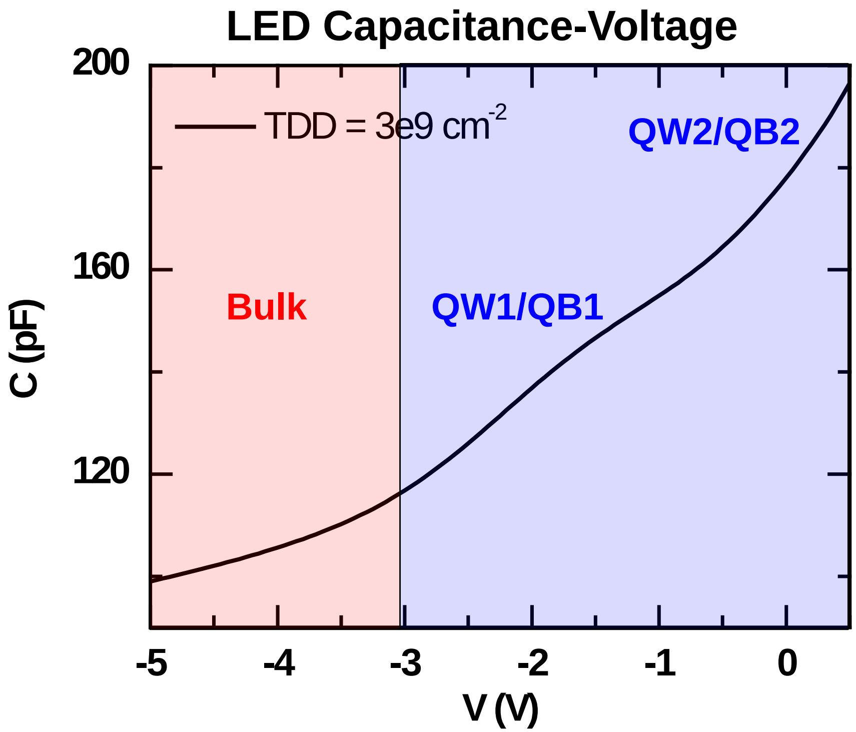


***V* ~ 0 V: DLOS selective to the MQW region**
- **Detect both InGaN QW and GaN QB defects**
- **How to distinguish?**

***V* ~ -10 V: DLOS "sees" MQW and n-GaN region**
- **Reduced sensitivity to QW defects**
- **Enhanced sensitivity to GaN defects (QB, bulk)**

QW defects identified by DLOS spectra that quench at large V_r

CV analysis relates V_r and depth sensitivity



- V_r = -3 V delineates MQW region from *n*-type bulk
- DLOS at V > - 3V sensitive to MQW region
- DLOS at V < - 3V emphasizes n-type bulk GaN

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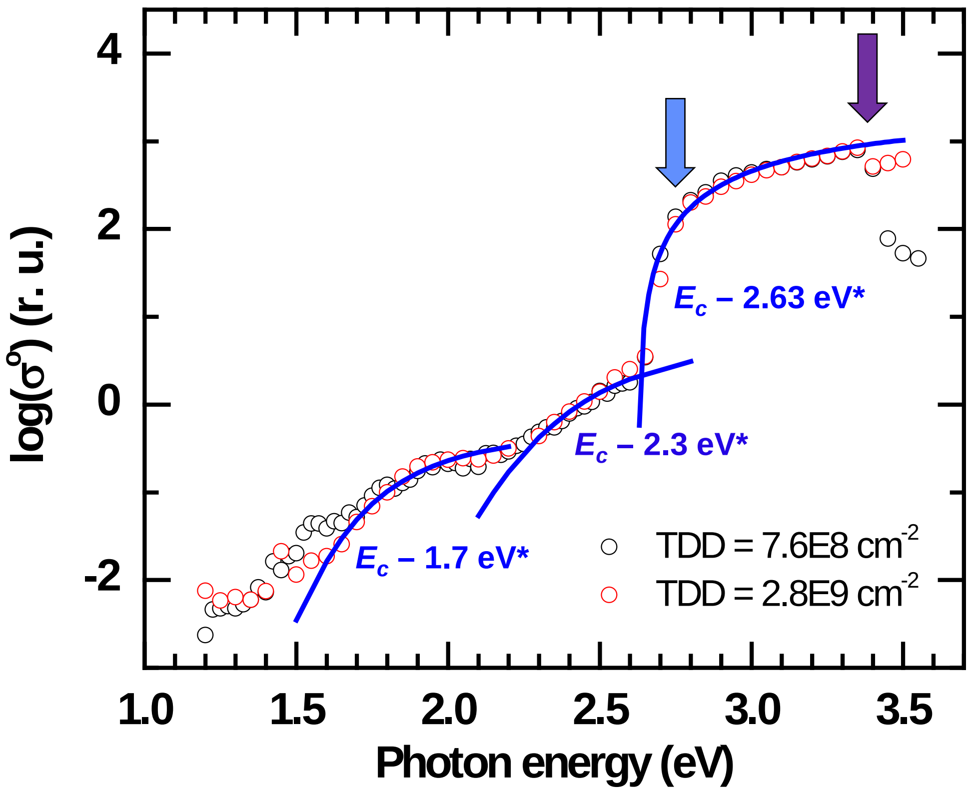
-3 V DLOS reveals MQW deep levels

-3 V DLOS of MQW region

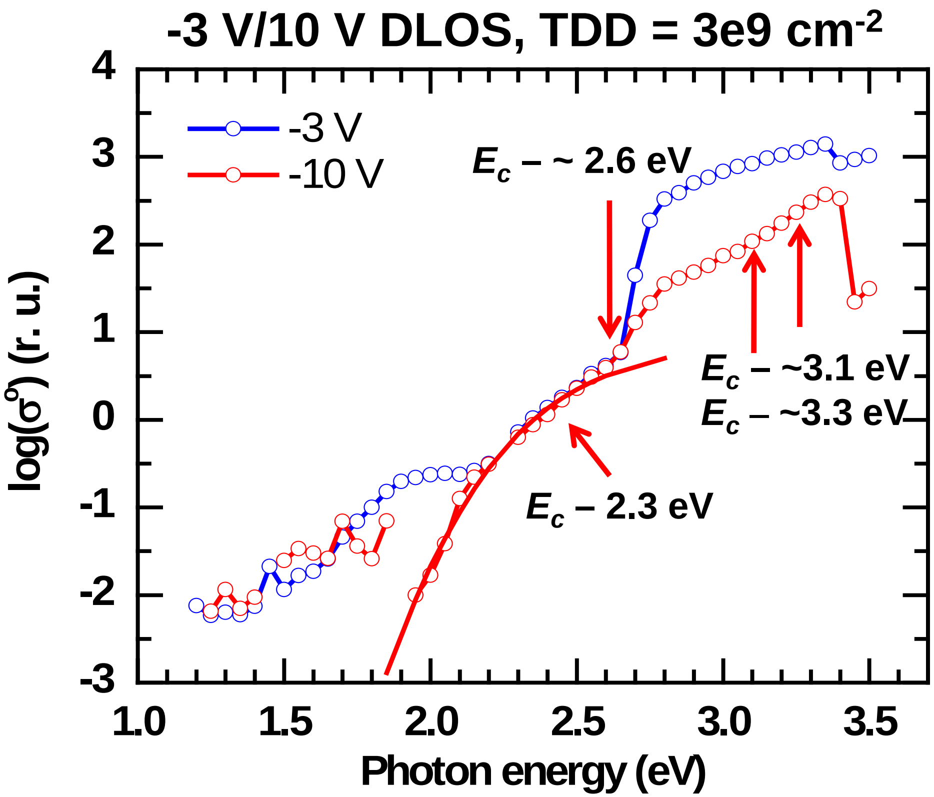


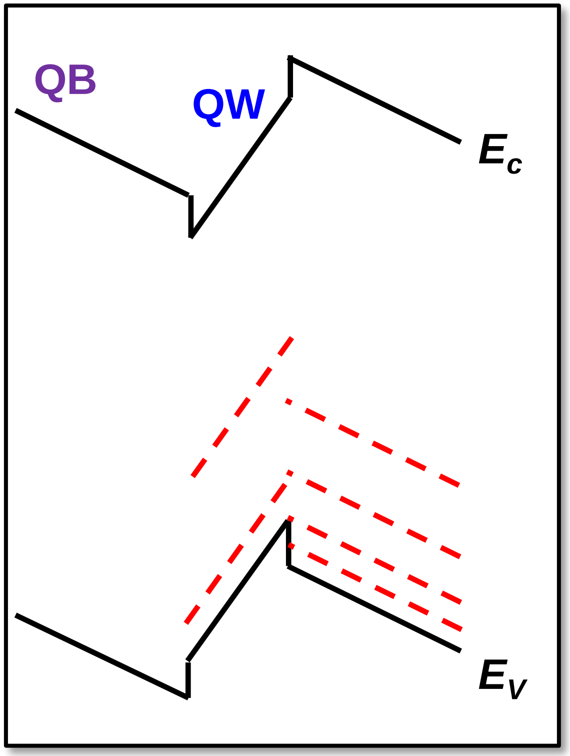
Observe three deep levels in MQW region:

- Saturation near the $In_{0.13}Ga_{0.87}N$, GaN band edges
- Similar deep levels for both samples – no new defect states with increased TDD
- Location of defects (QB vs. QW) not yet clear

*Fit to model of R. Paessler, JAP 96 715 2004

- 10 V DLOS identifies QB/bulk deep levels

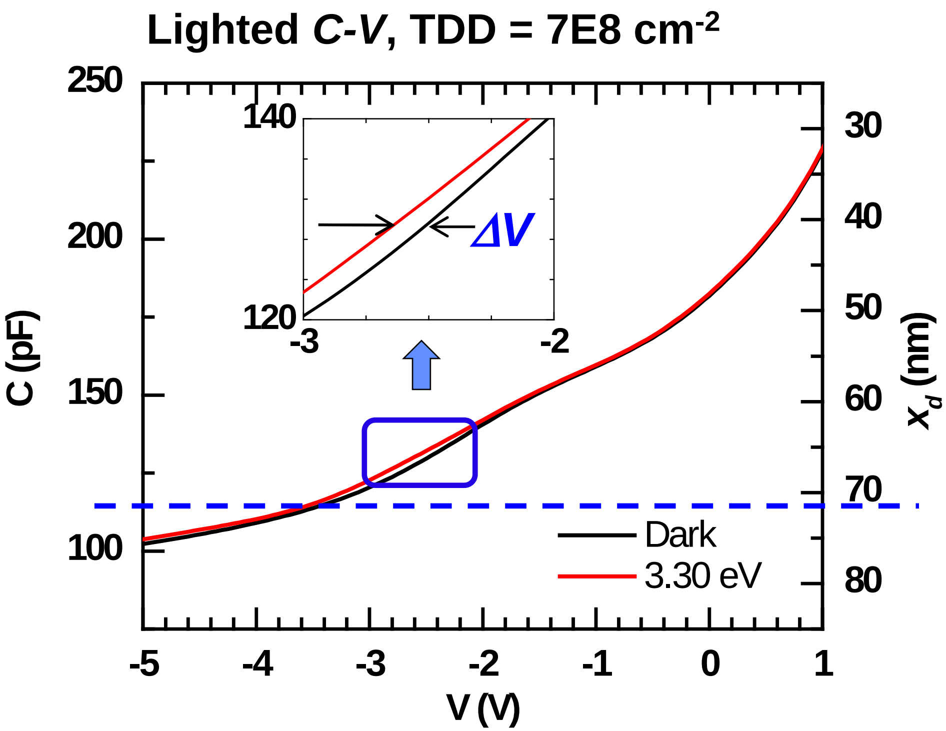


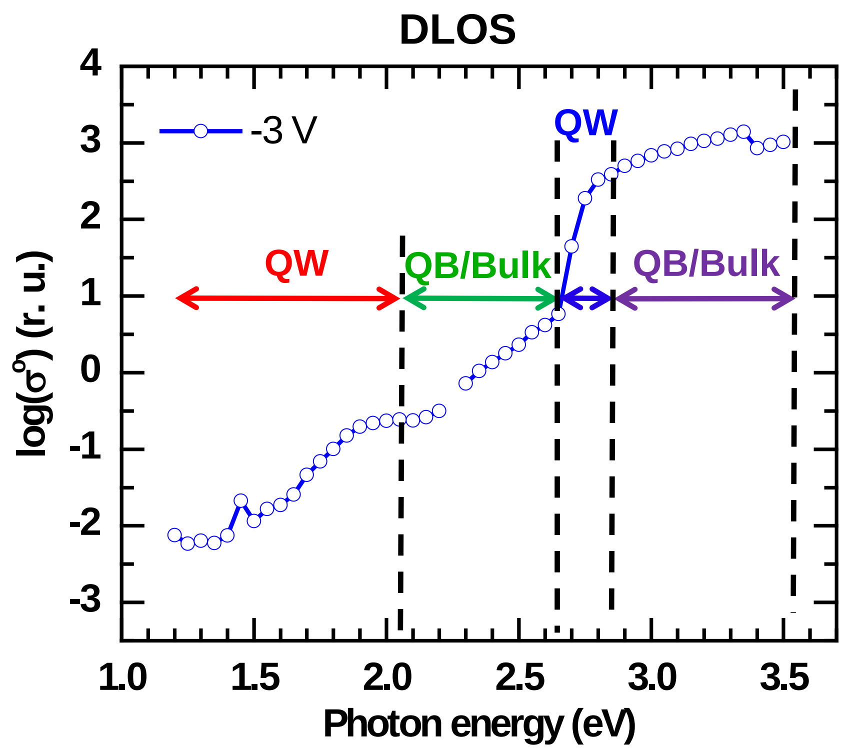


- E_c – 1.7, 2.63 eV levels quenched – attribute to QW
- E_c – 2.3, ~2.6 eV levels fully revealed – attribute to QB/Bulk
  - E_c – 2.6 eV spectra similar to reports for V_{Ga},[1] carbon[2,3]
- Emergent levels at E_c - 3.1, 3.3 eV – attribute to QB/Bulk
  - E_c – 3.3 eV level similar to report for carbon[2]

1. Reschikov *et al.,* MRS Symp. Proc. 693, I6.19 (2002). 2. Armstrong *et al.,* JAP 98, 053704 (2005). 3. Lyons *et al.,* APL 97, 152108 (2010).

Lighted-*CV* quantifies defect density





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

- **Poisson Equation relates *ΔV* and N_t**
- **Focus on *ΔV* for MQW region (x_d < ~70 nm)**
- **Lighted *C-V* apportions N_t among deep levels**

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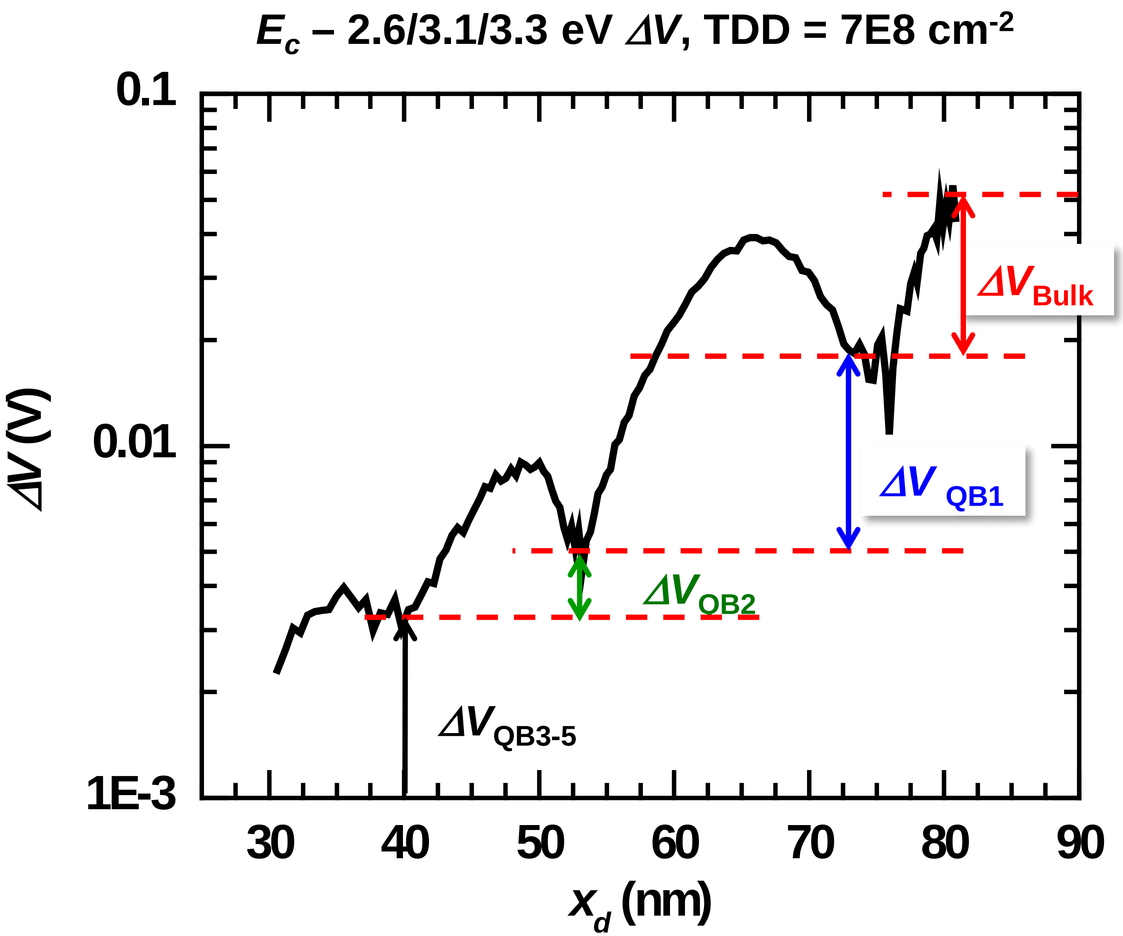
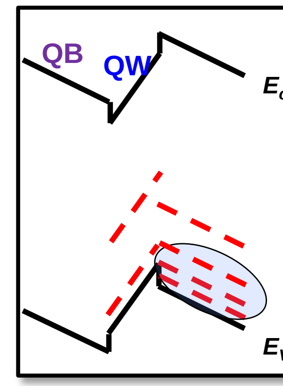
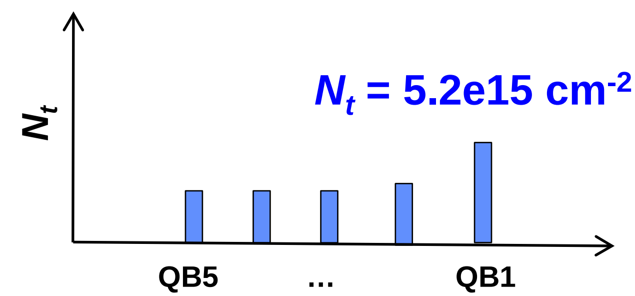
LCV can measure N_t for individual QWs/QBs

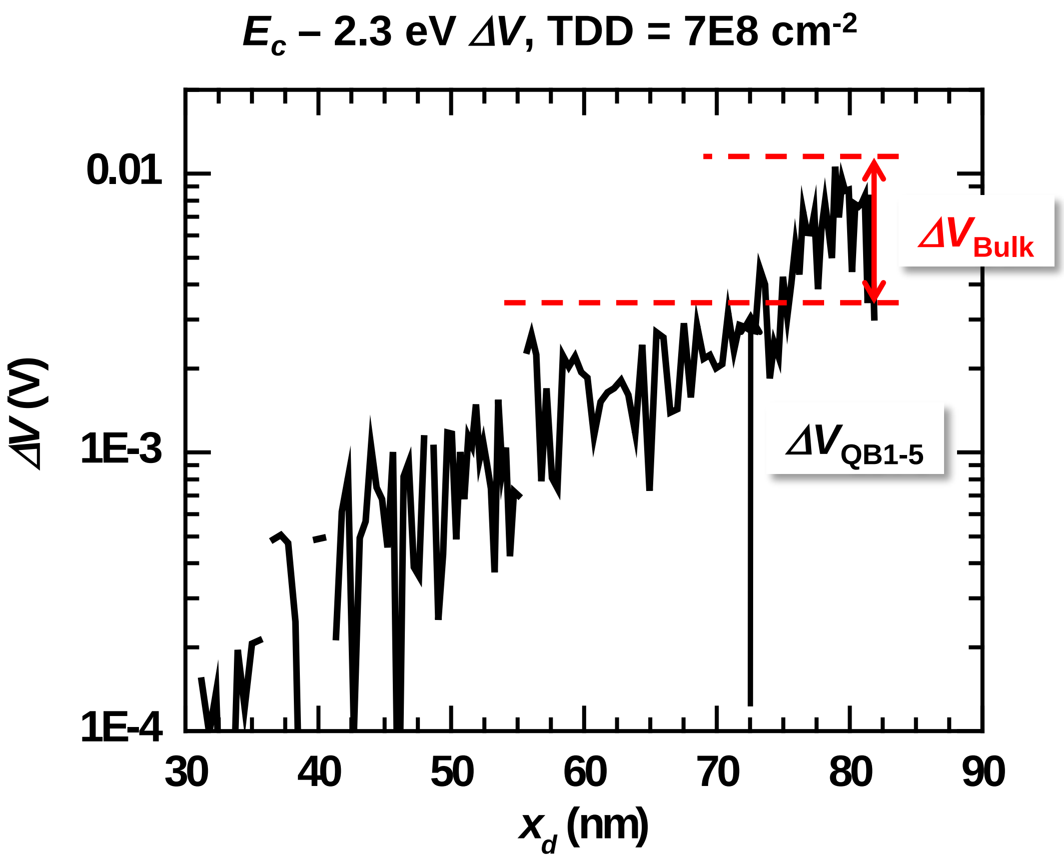


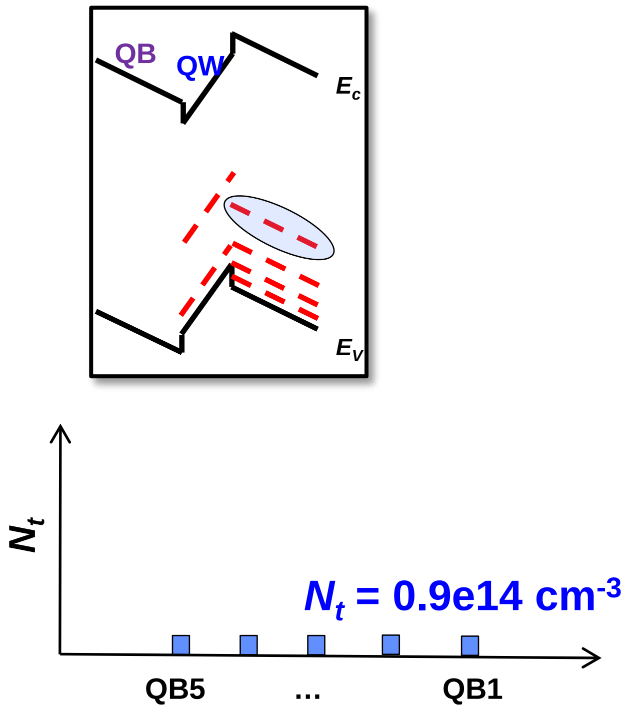




- N_t decreases toward the *p*-side

Lighted-*CV* quantifies defect density





• E_c – 2.3 eV QB appears equally distributed among QBs

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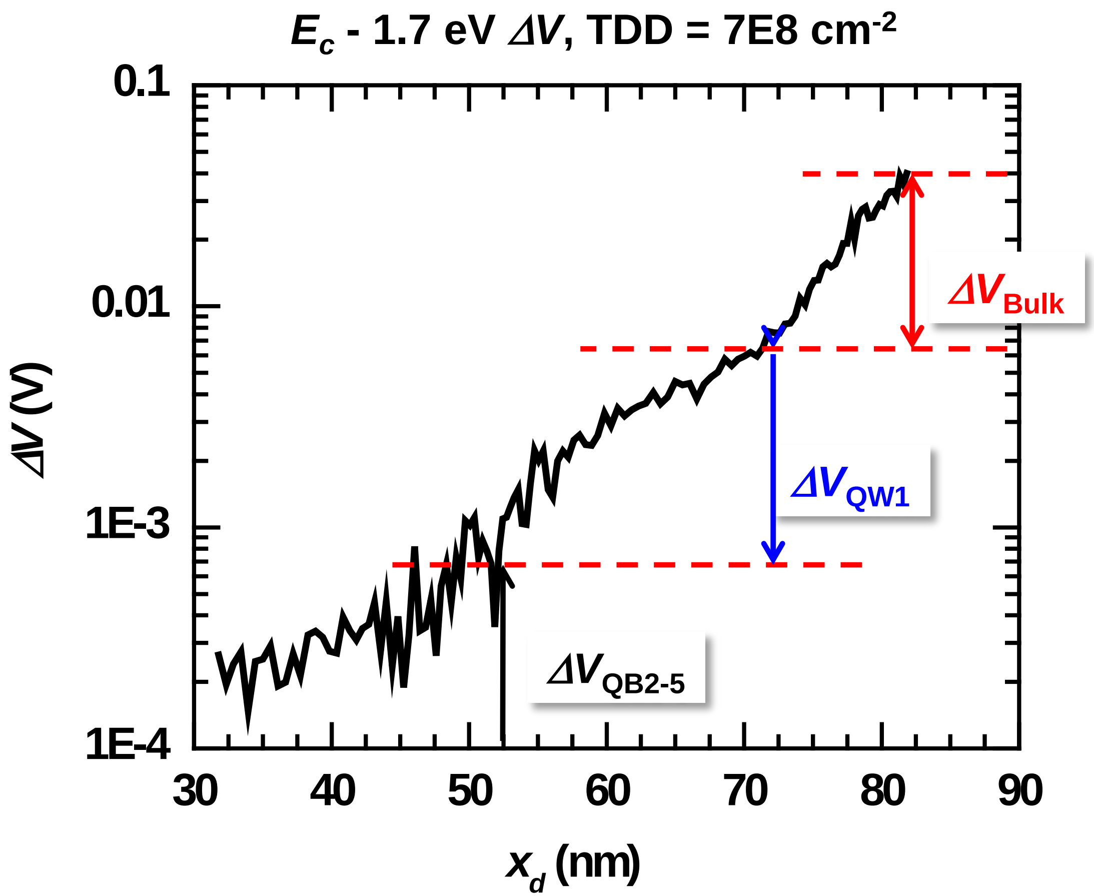
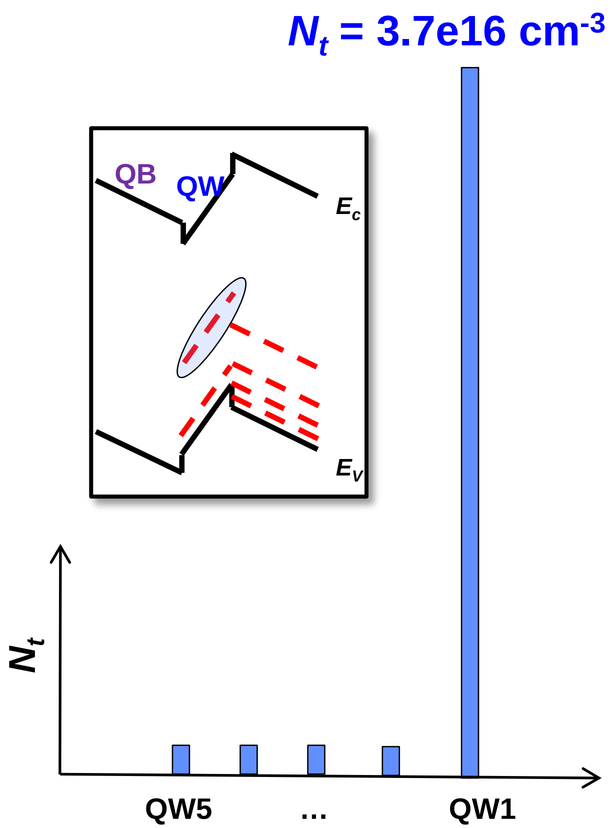
Lighted-*CV* quantifies defect density





- E_c – 1.7 eV QW deep level concentrated in *n*-side QW

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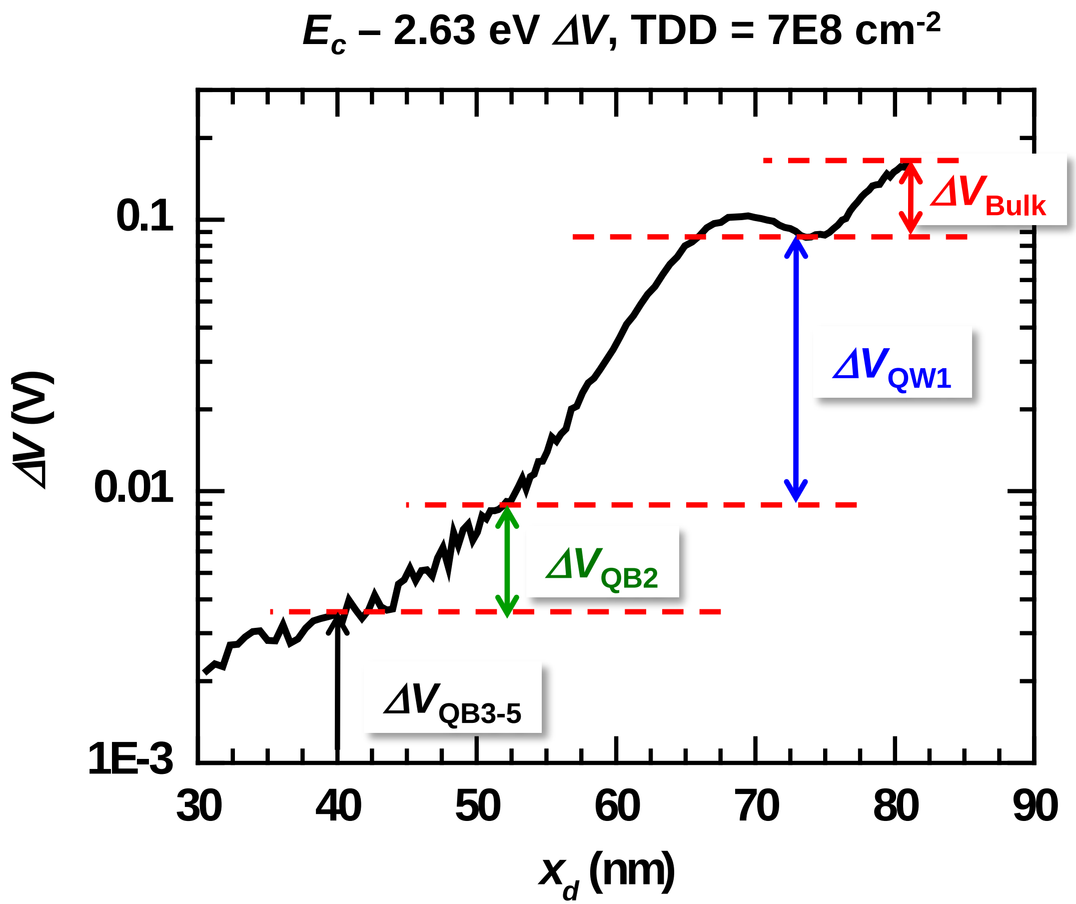
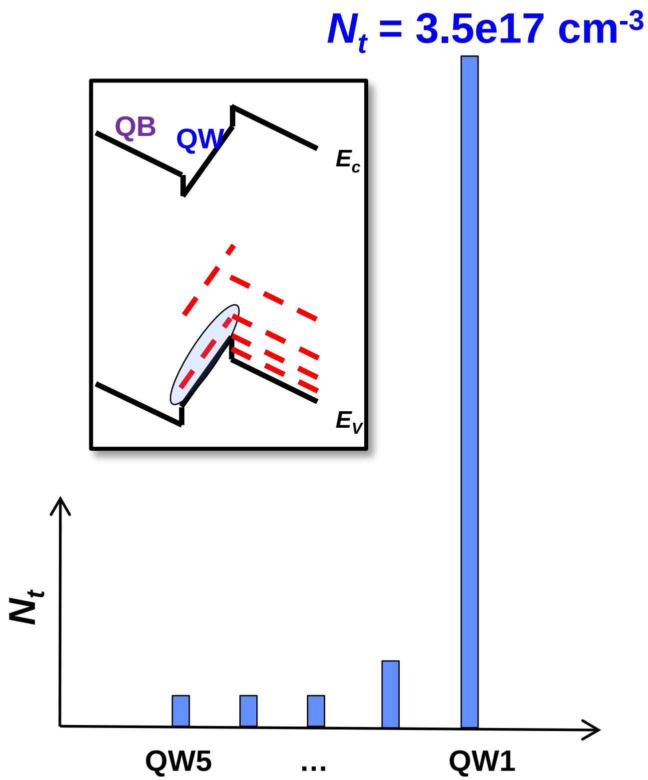
Lighted-*CV* quantifies defect density





- E_c – 2.63 eV QW deep level concentrated near *n*-side
- May result from longer QB T_g exposure for *n*-side QW

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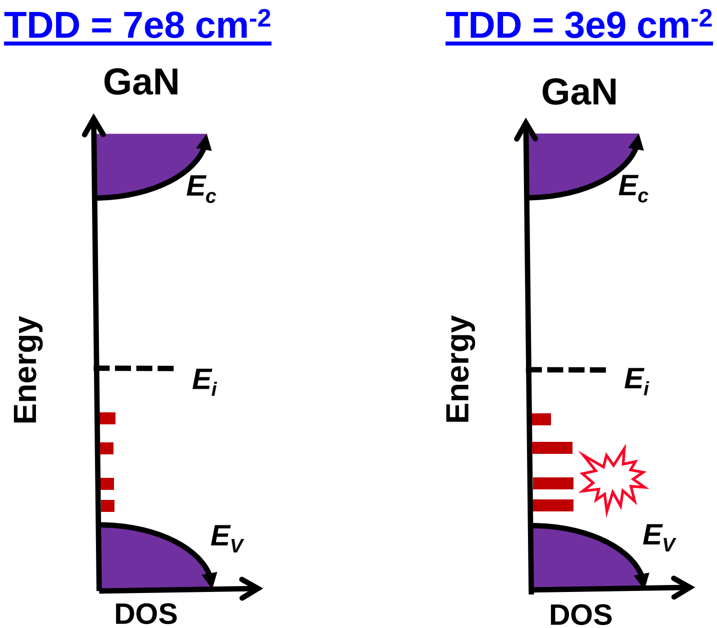
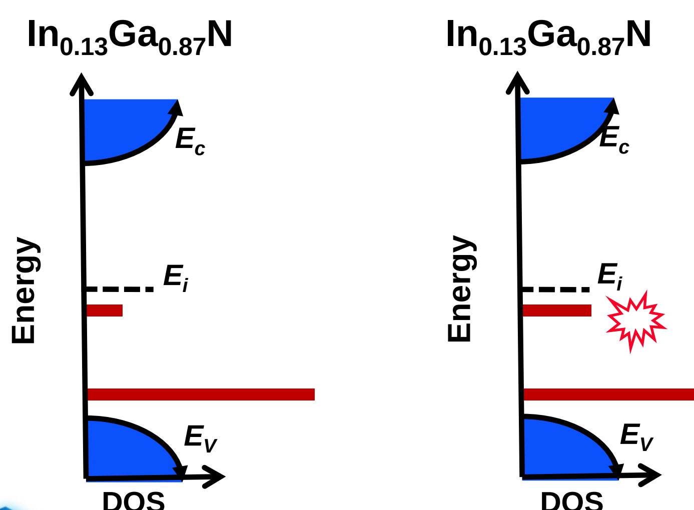
Enhanced TDD increases density of most observed deep levels!





N_t vs. TDD

Defect Level (eV)	Location	TDD=7.6e8 cm^{-2} N_t (cm^{-3})	TDD=2.8e9 cm^{-2} N_t (cm^{-3})	ΔN_t
E_c – 1.7	QW1	2.0e16	3.7e16	1.9x
E_c – 2.3	BAR1	0.9e15	1.0e15	--
E_c – 2.65	QW1	1.2e17	3.5e17	2.9x
E_c – 2.6/3.1/3.3	BAR 1	2.2e16	5.2e16	2.4x

- Enhanced N_t with TDD agrees with reduced LED τ_{nr}[1]
- QWs more defective than QBs
- Large N_t increase for levels near-E_v and mid-gap
  - Consistent with simple SRH and negative-*U* models of non-radiative recombination
- Suspect TDD facilitates point defect incorporation as well, e.g. carbon and E_c – 2.6, E_c – 3.3 eV GaN levels[2]

1. Dai *et al.* APL 94 111109 (2009)
2. Armstrong *et al.*, JAP 98, 053704 (2005).

Summary and Conclusions

- Studied impact of TDD on InGaN/GaN LED efficiency
  - LED efficiency reduces with increased TDD

- Used DLOS and LCV to correlate TDD and LED deep level density
  - First quantitative, depth-resolved method to study deep levels in III-Nitride emitters

- Excess deep level incorporation with increasing TDD
  - Agrees with reduced τ_{nr} with greater TDD[1]
  - Increase in mid-gap and near-E_v levels consistent with simple SRH and negative-U models for non-radiative recombination
  - Preponderance of QW deep levels near *n*-side likely due to mismatched T_g in MQW region
  - General correlation of deep level incorporation and TDD suggests TDs facilitate point defect incorporation

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1. Dai *et al.* APL 94 111109 (2009)

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