

Quantitative and nanoscale MQW defect characterization in InGaN/GaN LEDs

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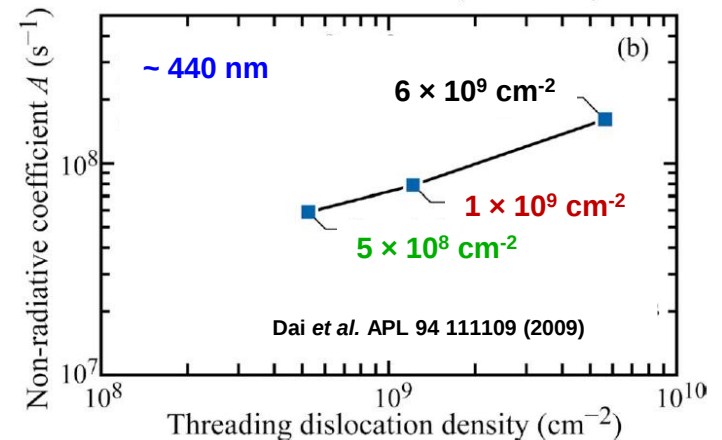
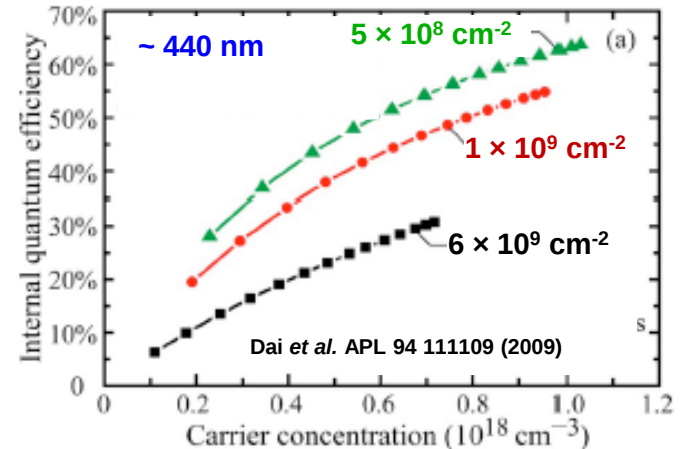


How do defects limit LED efficiency?

Threading dislocations reduce peak efficiency

$$IQE = \frac{BN^2}{\textcircled{AN} + BN^2 + CN^3 + \dots}$$

➤ TDs reduce peak LED IQE

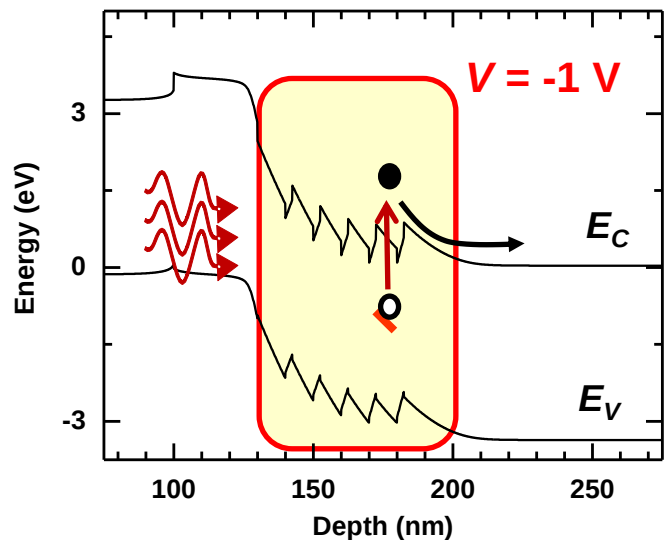


Goal: Understand relationship among TDD, deep level incorporation and EQE

DLOS provides depth resolution in LEDs

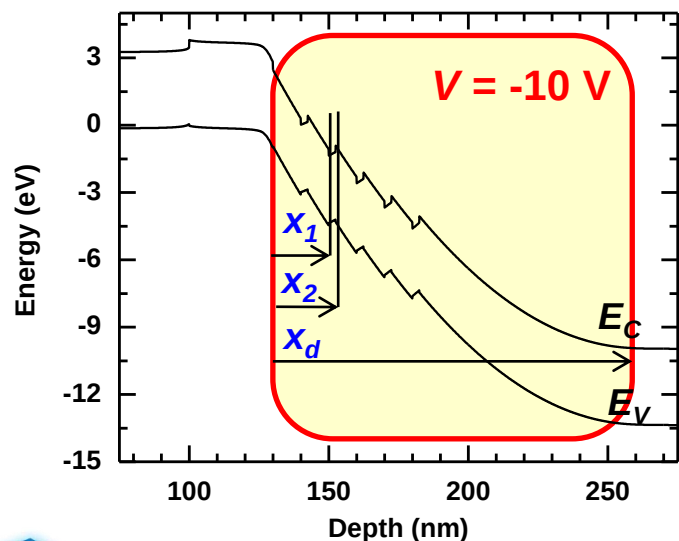
LED MQW 1D-SP calculations*

*G. Snider UND



$V = -1 \text{ V}$: DLOS selective to the MQW region

- Detect both InGaN QW and GaN QB defects
- How to distinguish?



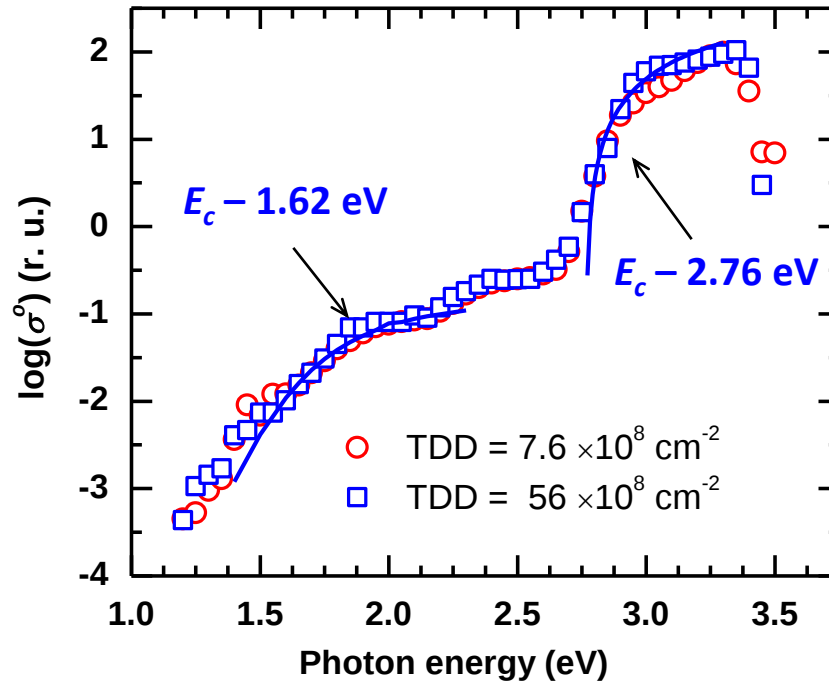
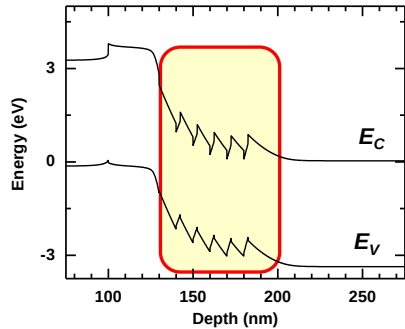
$V = -10 \text{ V}$: DLOS “sees” MQW and n -GaN Bulk

- Reduced sensitivity to QW defects

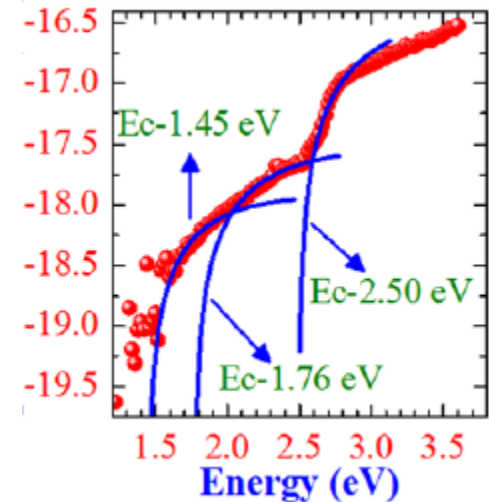
$$\Delta C = \left(\frac{N_t A \epsilon}{2 N_d x_d} \right) \left(\frac{x_2^2 - x_1^2}{x_d^2} \right)$$

DLOS of LED MQW region

- 1.7 V LED DLOS



DLOS of bulk UID-In_{0.2}Ga_{0.8}N



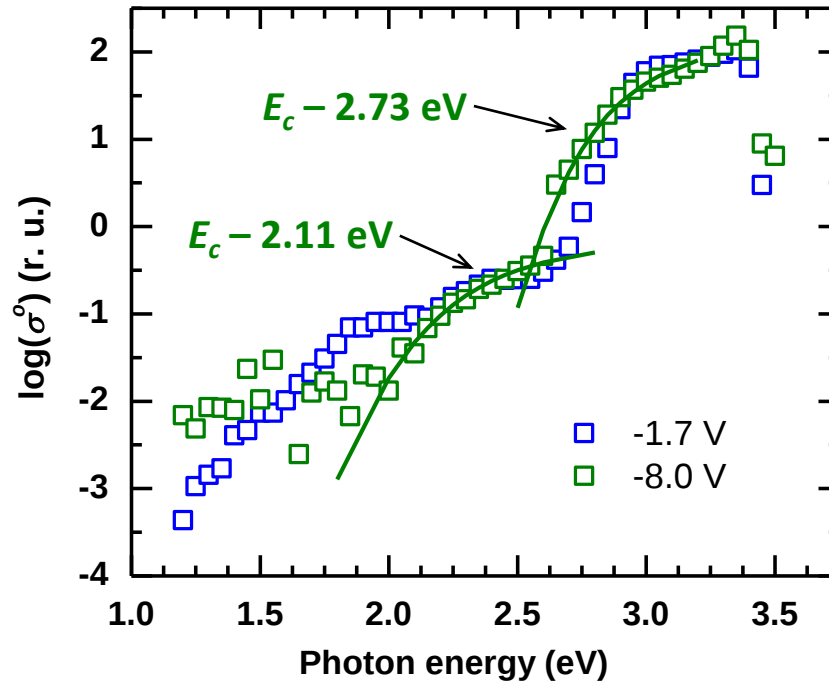
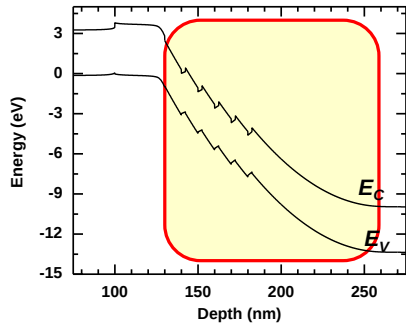
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Detailed characterization of deep level defects in InGaN Schottky diodes by optical and thermal deep level spectroscopies

- ~2.9 eV In_{0.13}Ga_{0.87}N band edge
- No new defect states with increased TDD
- Similar to bulk InGaN deep levels – likely QW defects

DLOS of LED MQW region

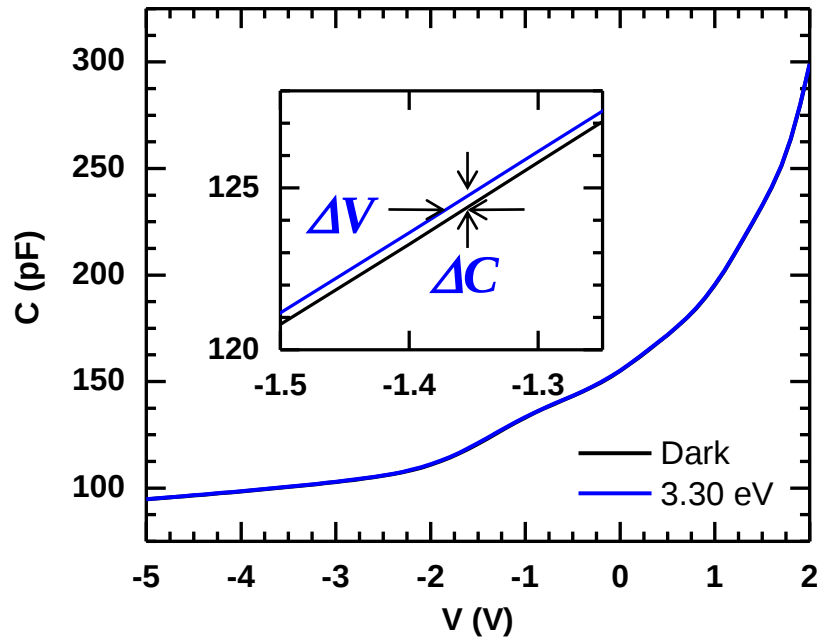
- 8 V LED DLOS



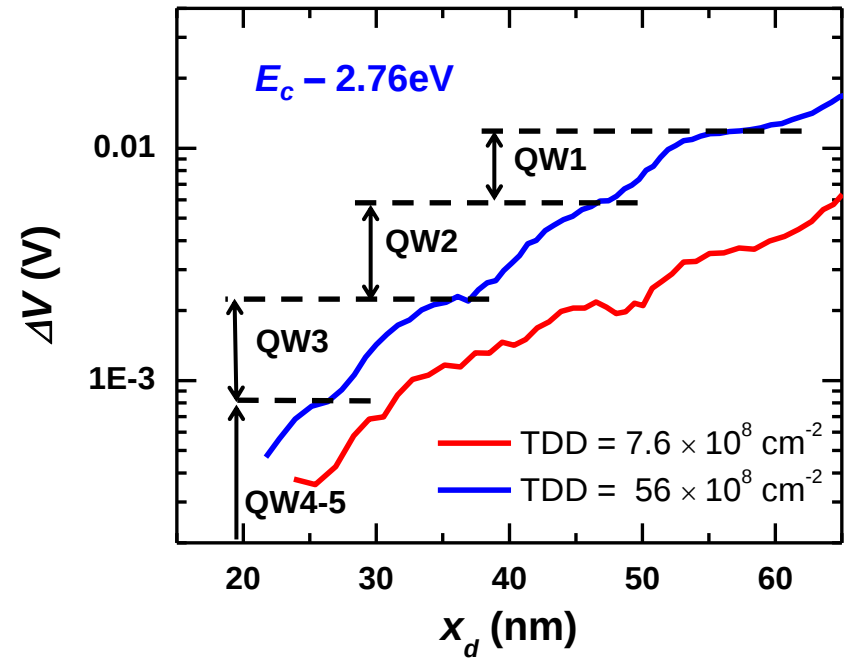
- $E_c - 1.62, 2.76$ eV levels do not appear – attribute to InGaN QWs
- $E_c - 2.11, 2.73$ eV levels fully revealed – attribute to GaN
 - Broad 2.6 – 3.0 eV GaN spectra similar to reports for V_{Ga} ¹ carbon in GaN^{2,3}

Lighted-CV quantifies defect density

Lighted C-V

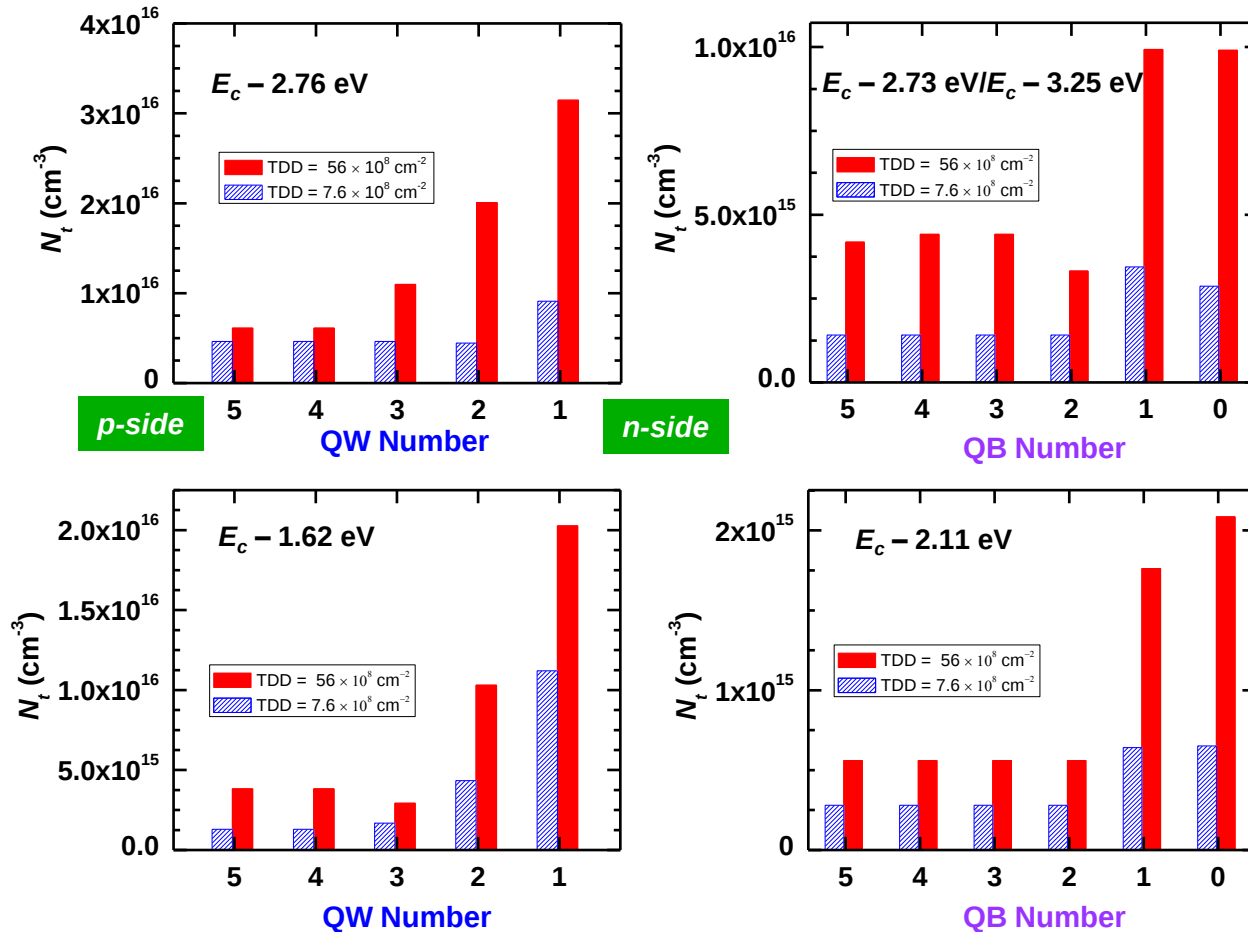


Depth profile of MQW defects



$$\Delta V = \frac{q}{\epsilon} \int_{x_1}^{x_2} x N_t dx$$

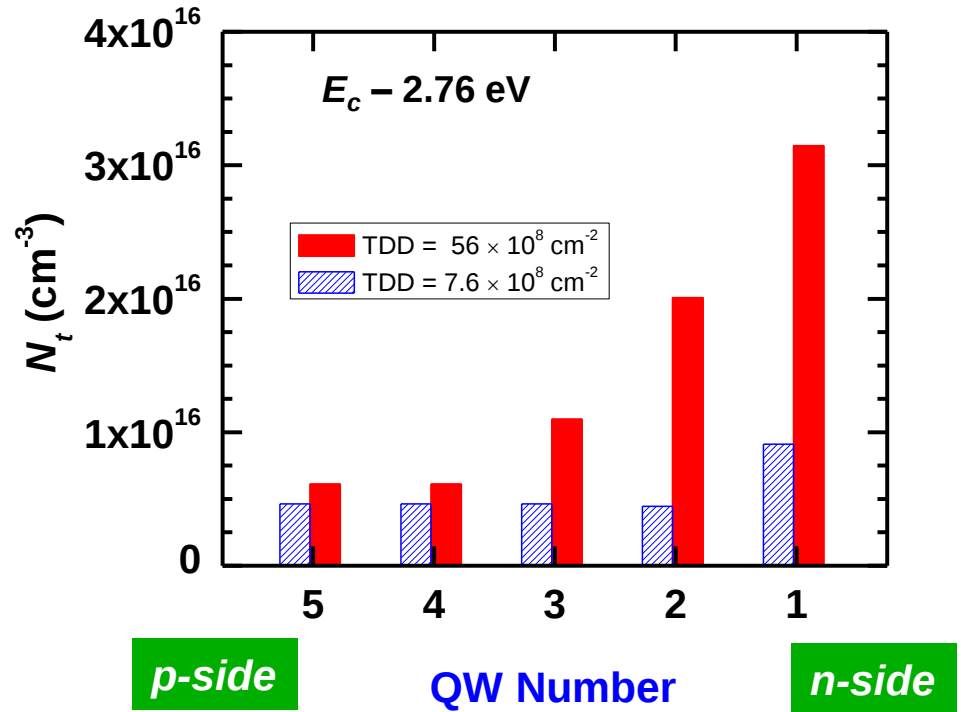
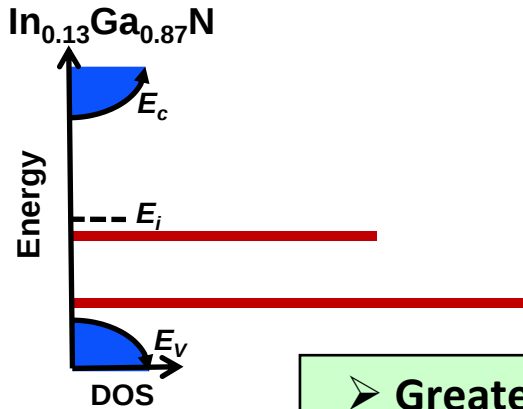
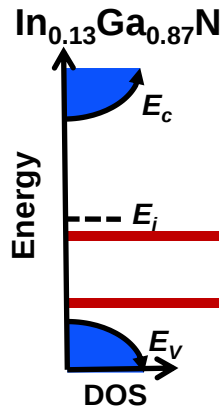
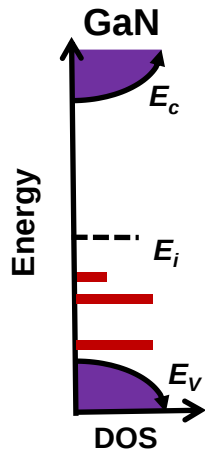
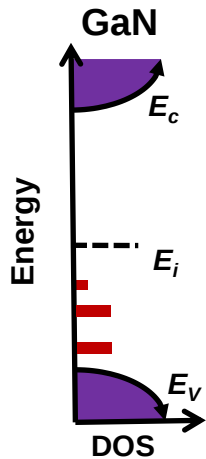
Enhanced TDD increases density of all observed deep levels!



- Universal decrease in N_t with lower TDD explains reduced A
- Depth-dependence of N_t not expected for TD-related defects
- Suggests interaction among point and extended defects during growth

Enhanced TDD increases density of most observed deep levels!

TDD = $7.6 \times 10^8 \text{ cm}^{-2}$ TDD = $56 \times 10^8 \text{ cm}^{-2}$



- Greater N_t with TDD corroborates increased A^1
- N_t increases for near- E_v and mid-gap levels
- Strong interaction among point and extended defects