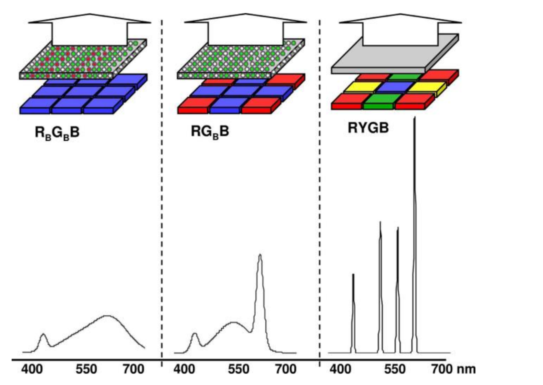
SAND2011-1664P

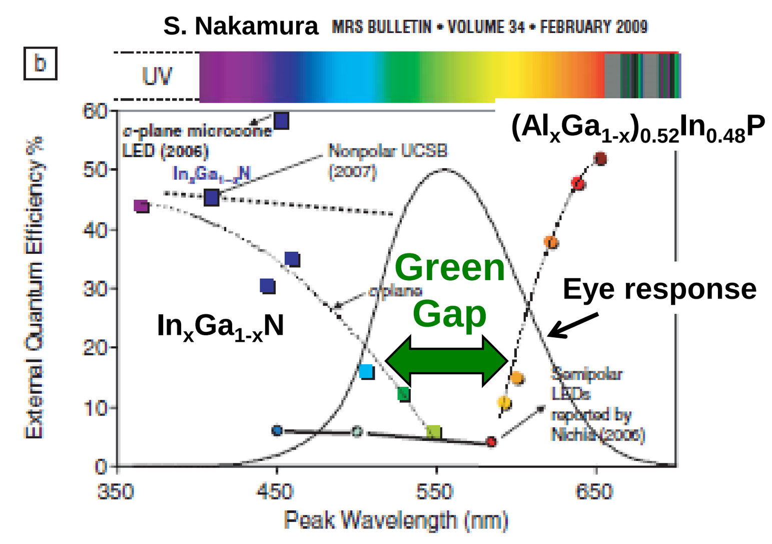
# Goal: Increase EQE of InGaN 540 nm LEDs through defect reduction

**Objective: Increase efficiency of deep green-emitting InGaN/GaN LEDs through InGaN defect reduction**




M. Crawford, IEEE J. Sel. Top. Quant. Elec. 15 1028 (2009).

Multichip LEDs promise better efficiency than phosphor-converted LEDs, but…




Goal: Mitigate InGaN defects in InGaN/GaN MQWs
Challenge: Develop *quantitative* defect spectroscopy for $In_{0.2}Ga_{0.8}N$ epilayers

## Major Project Milestones:

- ***Develop*** quantitative defect spectroscopy for nanoscale $In_xGa_{1-x}N$ films
- ***Reduce*** defect incorporation and improve IQE for 540 nm InGaN QWs
- ***Improve*** EQE for 540 nm InGaN LEDs via reduced defect incorporation

## Problems to be addressed:

- Understand $In_xGa_{1-x}N$ ($x > 0.15$) deep level defect activity
- Correlate defect incorporation and $In_xGa_{1-x}N$ growth parameters
- Determine impact of defects on LED External Quantum Efficiency (EQE)

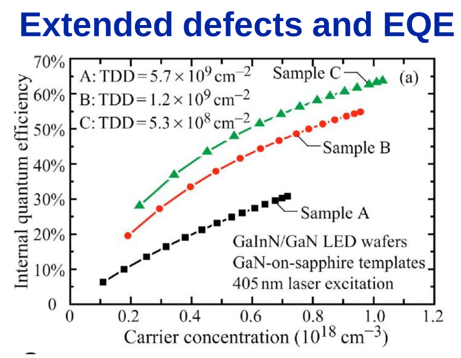
## Expected Benefits to SSL:

- Enhanced EQE of (540 nm) LEDs
- Increase both luminous efficiency and CRI for RBG color-mixing
- Accelerate white SSL penetration into lighting market

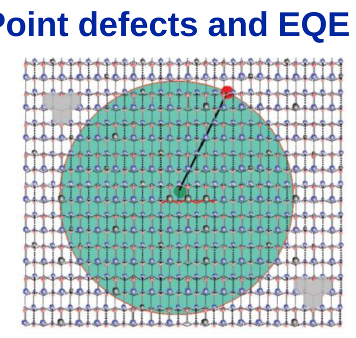
# Impact of InGaN Defects on Efficiency

## Impact of defects on radiative efficiency

**Extended defects and EQE**

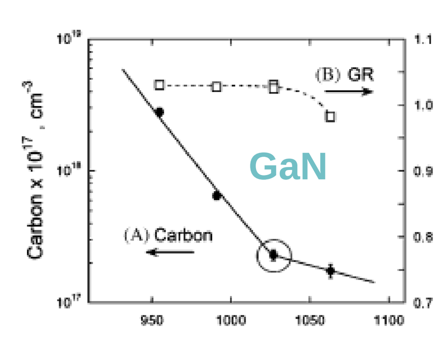



**Point defects and EQE**

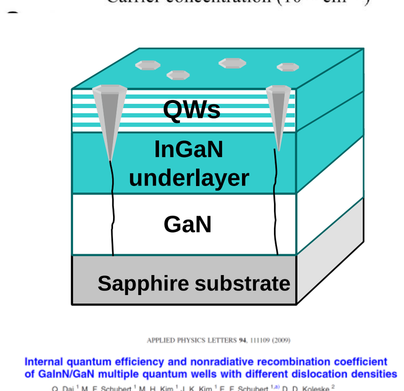


Chichibu *et al.* Philos. Mag. 87 2019 (2007)

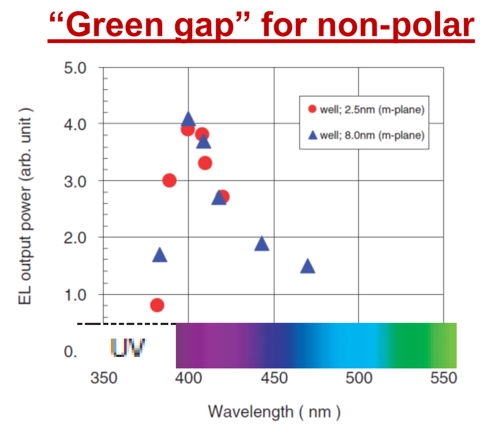
**Growth conditions and strain**



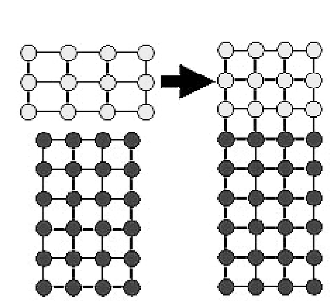

Koleske *et al.*, JCG 242 55 (2002)




"Green gap" for non-polar

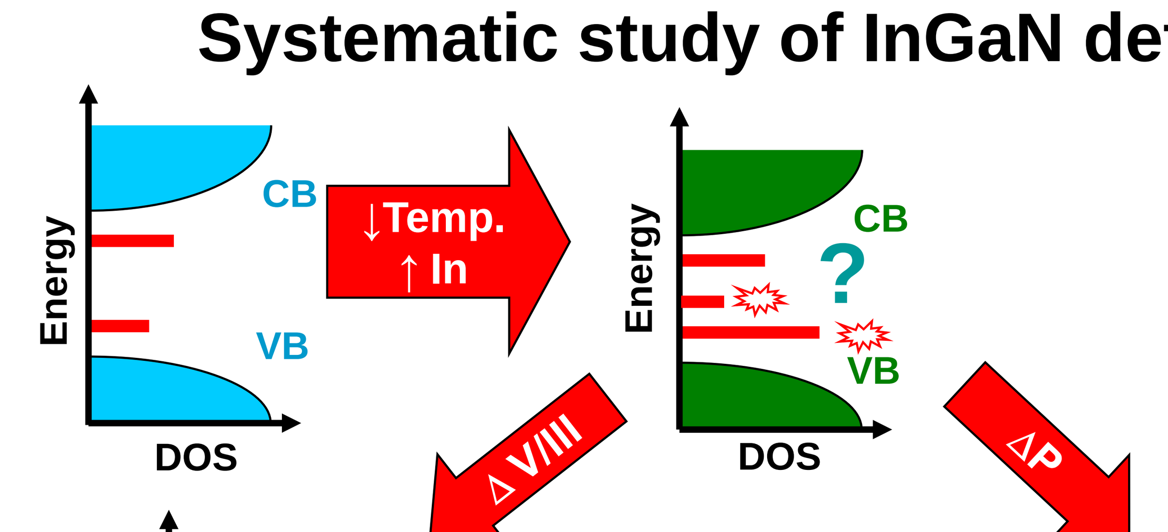


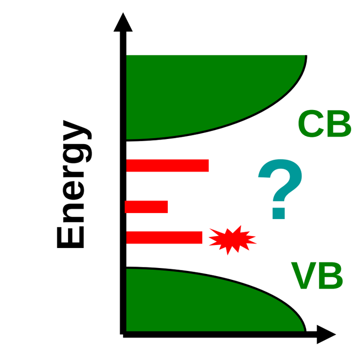

Yamada *et al.* Appl. Phys. Exp. 1 041101 (2008)




- How to connect InGaN growth conditions, defects and EQE?
- ***Solution:*** Adapt Deep Level Optical Spectroscopy for InGaN LEDs

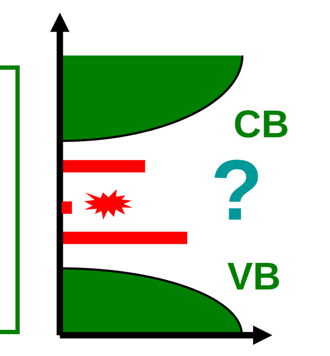
## Systematic study of InGaN defects




**Parameters to be varied include:**

- Growth temperature
- Growth pressure
- $NH_3$ flow rate
- InGaN growth rate




- Need method to ***quantify*** deep level defect energy and density
- Correlate defect studies with EQE
- Vary growth parameters to mitigate critical defects and improve EQE

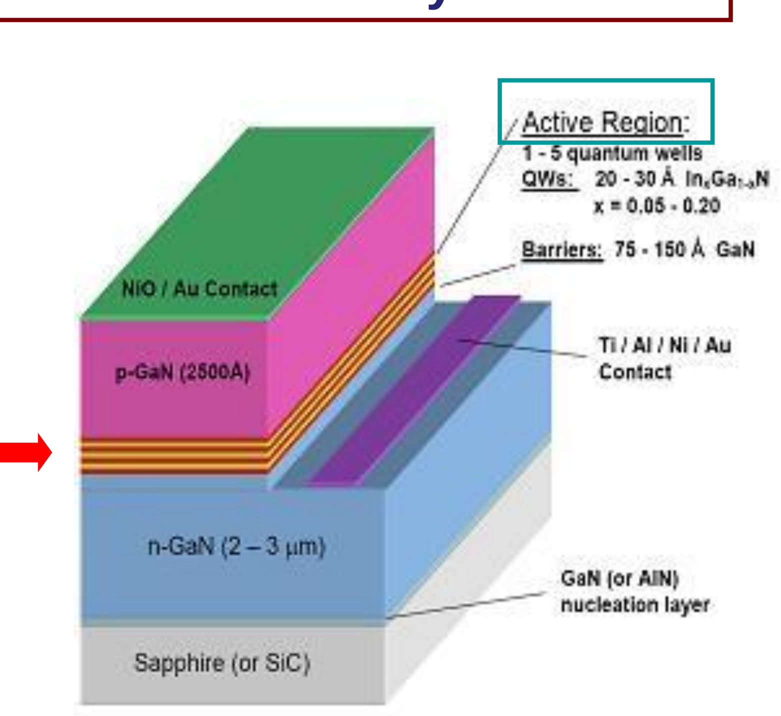
# Challenge and Solution

## Problem: How to study InGaN LED defects?

LEDs are complicated nanoscale, multi-heterolayer, bipolar devices with strongly varying (In,Al,Ga)N alloy compositions

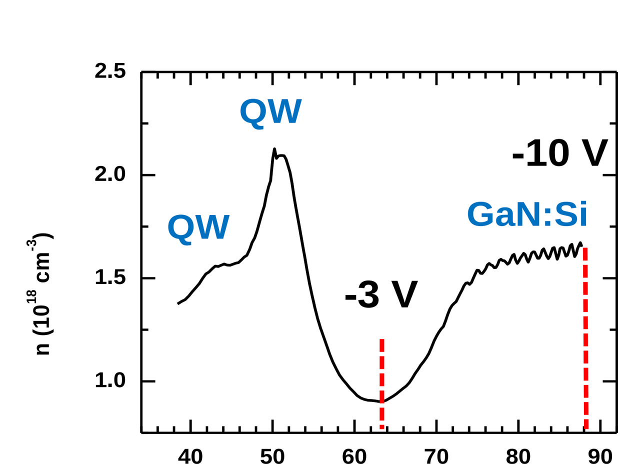
**Defects located near the optically active MQW region are most critical to LED radiative efficiency**

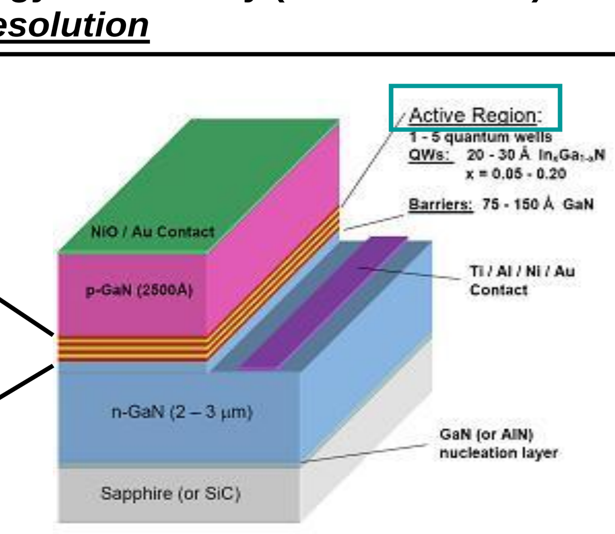
How to isolate and study defects in the ***nanoscopic*** MQW region embedded in a microscopic LED?




## Solution: Depth-resolved Deep Level Optical Spectroscopy

**Deep Level Optical Spectroscopy (DLOS)[1]**
- Photocapacitance technique
  - ***Sub-band gap optical stimulation*** to photoionize defect levels (reverse of PL)
  - ***Quantify non-radiative*** defect level energy and density (difficult for PL)
  - Depletion region technique for ***depth resolution***



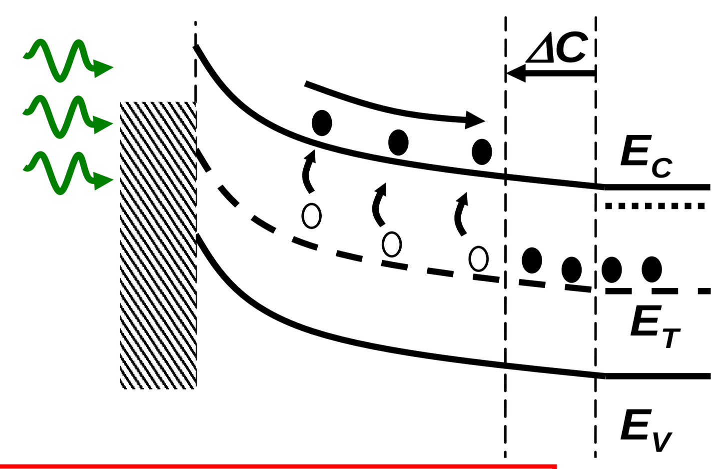
- DLOS depth resolution from pin LED junction
- Junction contains the MQW region and the n-GaN region
- Use electrical bias to emphasize defects in either the MQW or n-GaN regions


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

# Concept of Depth-resolved DLOS

## Fundamentals of DLOS

**Sub-band gap, monochromatic light to scan defect states**



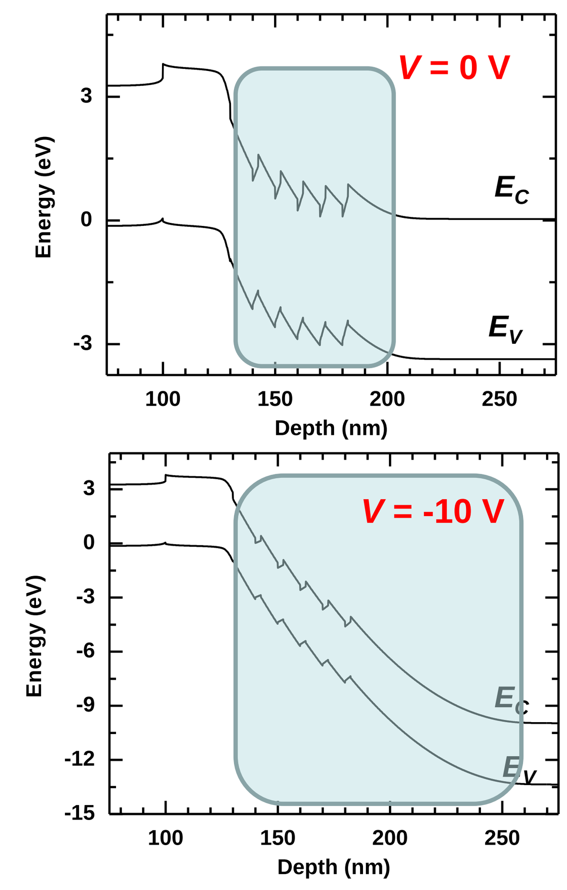

**Steady-state photocapacitance**
- **Depletion region technique**
- $\Delta C$ indicative of $N_t$
- (+) onset → Majority carrier emission
- (-) onset → Minority carrier emission

**Deep Level Optical Spectroscopy[1]**
- Measures deep level optical cross-section $\sigma^o$:
  - $dC(t)/dt|_{t=0} \propto \sigma^o(h\nu)\Phi(h\nu)$
- Fitting $\sigma^o(h\nu)$ to model[2] extracts deep level defect properties
  - Optical ionization energy $E^O$
  - Franck-Condon shift $d_{FC}$ (a measure of defect-phonon coupling)

**DLOS and SSPC Measurement Conditions**
- Xe lamp and monochromator for $h\nu$ = 1.20 – 3.60 eV, 20 meV resolution
- 297 K, various fill and reverse biases for depth sensitivity
- Lock-in amplifier at 5 kHz


1. Chantre *et al.* PRB 23, 5335 (1981). 2. Paessler JAP 96, 715 (2004).


## Depth-resolved LED DLOS



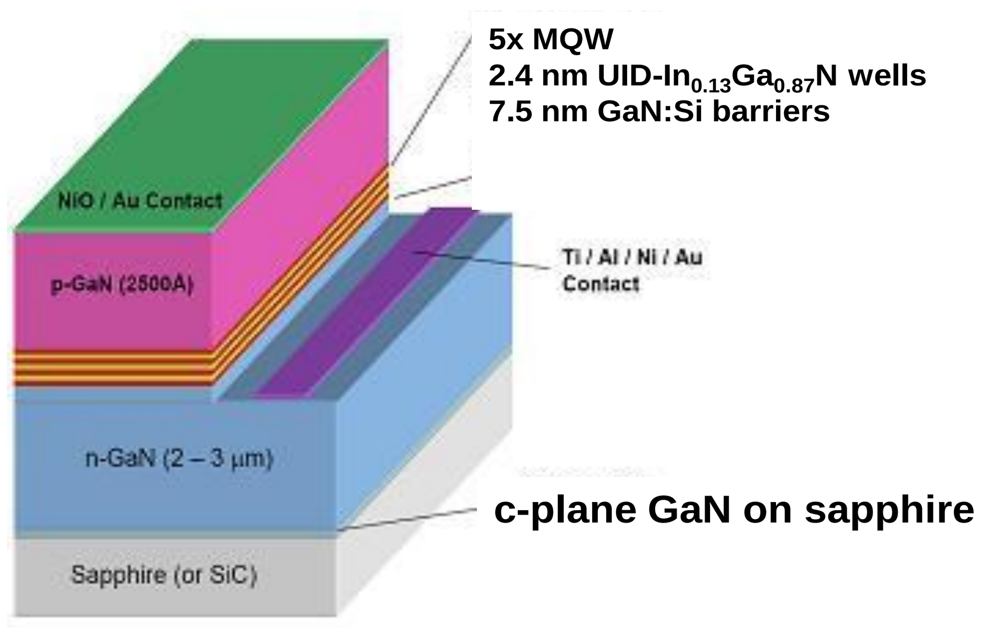

**V = 0 V: DLOS "sees" mostly the MQW region**
- Detect InGaN well and GaN barrier defects

**V = -10 V: DLOS "sees" MQW and n-GaN region**
- Weak sensitivity to InGaN well defects
- Strong sensitivity to GaN defects

**DLOS at small and large reverse bias discerns GaN *vs.* InGaN defects in LEDs**

# Test case – Impact of Dislocations on InGaN/GaN LED EQE

## InGaN/GaN LED structure



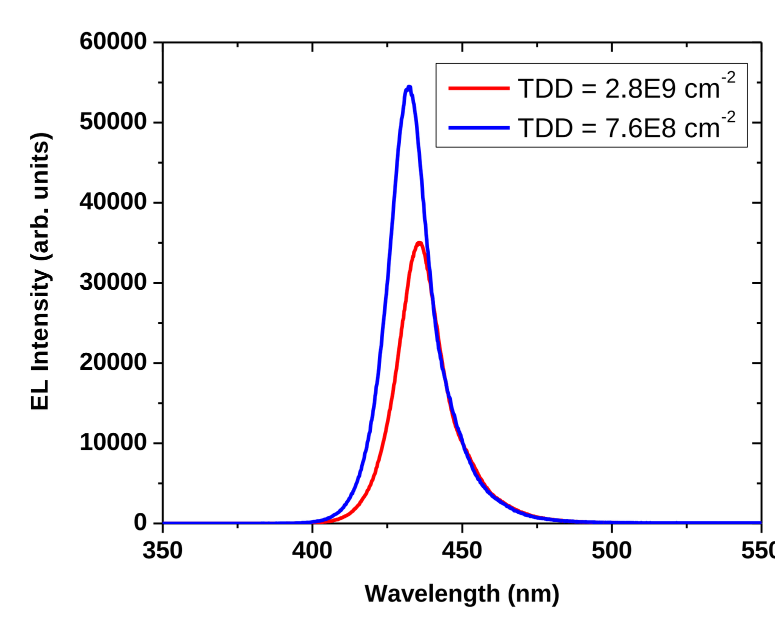

- **MOCVD grown**
- **Threading dislocation density (TDD) ~ 7.6 x $10^8$ $cm^{-2}$ or 2.8 x $10^9$ $cm^{-2}$**
- **TDD controlled by GaN nucleation and coalescence parameters[1]**
- **TDD measured via x-ray diffraction rocking curve analysis[2]**


1 M. F. Schubert, S. Chhajed, J. K. Kim, E. F. Schubert, D. D. Koleske, M. H. Crawford, S. R. Lee, A. J. Fischer, G. Thaler, and M. A. Banas, Appl. Phys. Lett. **91**, 231114 (2007).

2 S. R. Lee, A. M. West, A. A. Allerman, K. E. Waldrip, D. M. Follstaedt, P. P. Provencio, D. D. Koleske, and C. R. Abernathy, Appl. Phys. Lett. **86**, 241904 (2005).


## LED characterization

**TDD vs. EL for on-chip test devices**

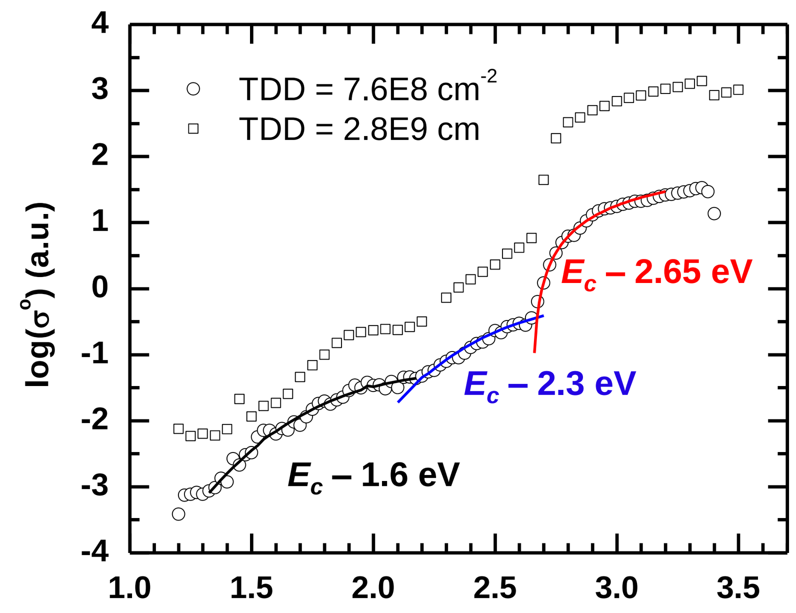



- 50% improved integrated electroluminescent (EL) intensity for lower TDD
- Relative EL intensity of on-chip test devices indicative of relative LED EQE
- Consistent with earlier reports, but details TDD role on EL unknown…

# MQW vs. n-region defects

## Survey of LED MQW region defects

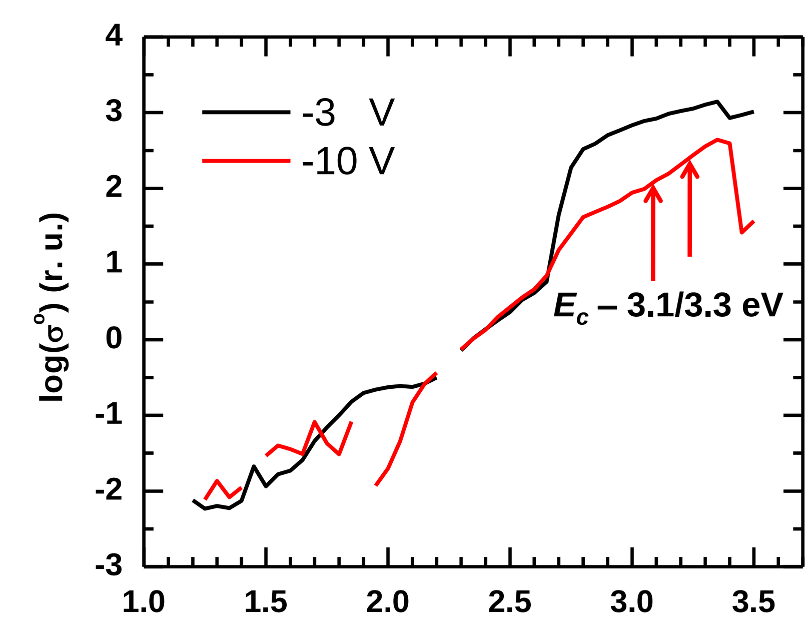
**-3 V DLOS**




**Observe three defect states in MQW region:**
- Similar defect states for both samples – no new defects with increased TDD
- $E_c$ – 2.65 eV likely InGaN-related due to proximity to InGaN band edge
- Location of remaining defect levels unclear

## Survey of *n*-region defects

**-3 V (MQW) *vs.* -10 V (MQW + *n*-region) DLOS**

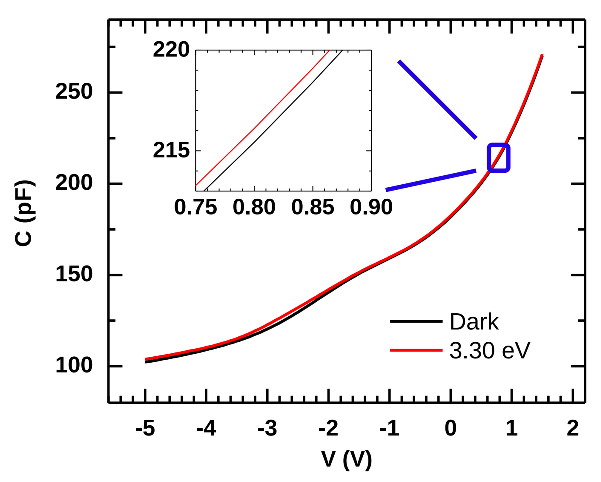



- New GaN-related defect levels at $E_c$ – 3.1/3.3 eV
- $E_c$ – 2.3 eV level still evident – likely GaN-related
- No $E_c$ – 1.6 eV level – likely InGaN-related

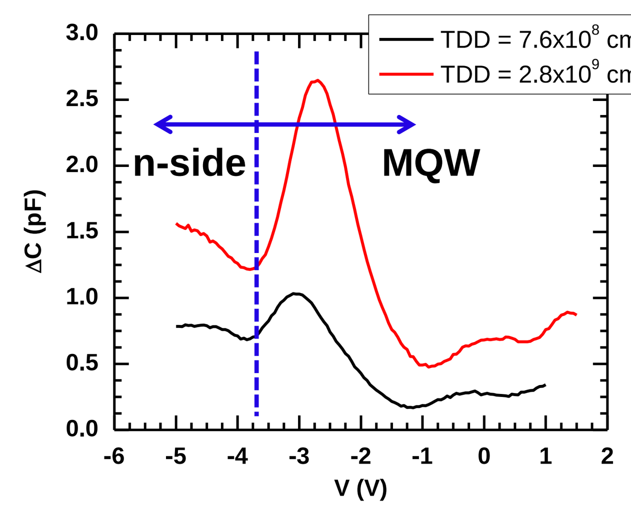
# Impact of TDD on Defect Density

## Measuring LED defect density

**Lighted C-V for TDD = 7.6E8 $cm^{-2}$**



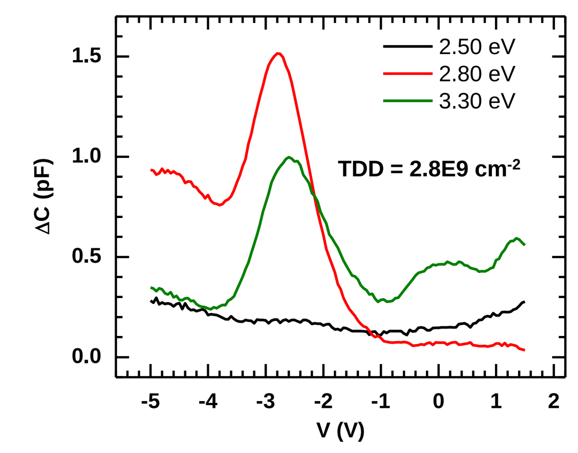

**LCV comparison *vs.* TDD**

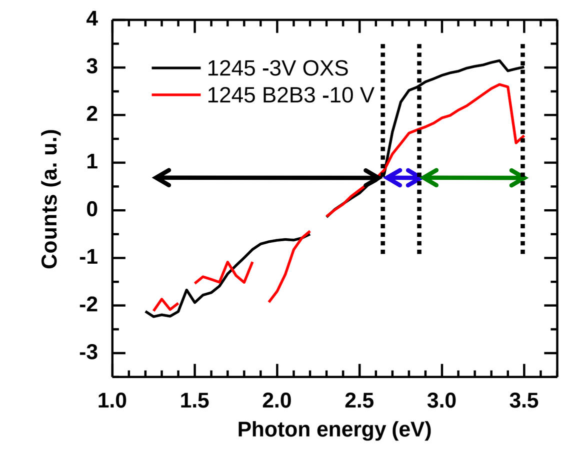



Lighted Capacitance-Voltage (LCV) measurements quantify defect density ($N_t$)
- Area under *C-V* curve proportional to space-charge density in LED junction
- Increase in capacitance with light ($\Delta$C) results from defect photoionizatoion
- Calculate average $N_t$ from area under *LCV* curve

## LED defect density *vs.* TDD

***LCV* for individual defect states**




**Average $N_t$ for MQW-region defect states**

| Defect Level (eV) | TDD = 7.6e8 $cm^{-2}$ $N_t$ ($cm^{-3}$) | TDD = 2.8e9 $cm^{-2}$ $N_t$ ($cm^{-3}$) | $\Delta N_t$ |
|---|---|---|---|
| $E_c$ – 1.6/2.3 | 8.8e14 | 3.2e15 | 3.6x |
| $E_c$ – 2.65 | 1.8e16 | 3.2e16 | 1.8x |
| $E_c$ – 3.1/3.3 | 3.7e15 | 1.4e16 | 4x |

- Strong decrease in $N_t$ with reduced $N_t$ for both InGaN- and GaN-related defects
- Universal decrease in $N_t$ suggests TDD impacts both point and extended defect density incorporation in LEDs

# Summary and Outlook

## Summary and Future Work

- ***First quantitative defect spectroscopy for InGaN LEDs***
- Reducing TDD reduces point and extended defect incorporation in InGaN/GaN LEDs
- 50% enhancement of LED radiative efficiency with defect reduction

- Extend DLOS study to blue- and green-emitting LEDs
- Identify defects that correlate with reduced EQE with increase wavelength
- Systematic reduction in targeted defects to improve InGaN/GaN LED EQE at 540 nm


## Acknowledgement of Support

NETL

Sandia National Laboratories

**This work was funded by EERE/NETL, United States Department of Energy under project number M6802094, Brian Dotson and Sean Evans, Program Managers.**

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