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Deep level defect spectroscopy in reduced dimension semiconductor materials and devices

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Outline

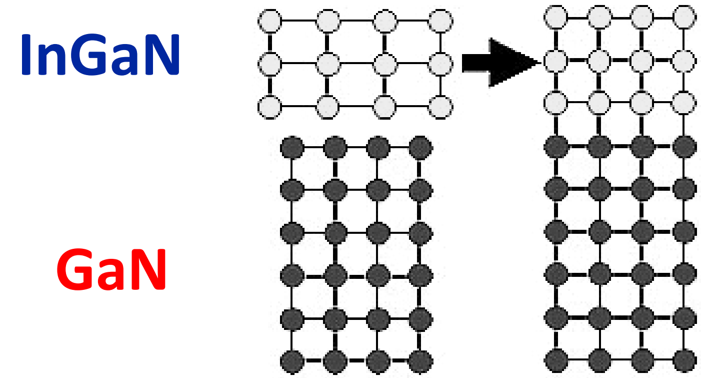
I. Why are defects so important in III-Nitrides?
II. Deep Level Optical Spectroscopy (DLOS)
III. DLOS at reduced dimensions:
   A. 2D - DLOS study of InGaN/GaN Light Emitting Diodes
   B. 1D - DLOS study of AlGaN/GaN nanowire heterostructures
IV. Summary

Defects and III-Nitrides

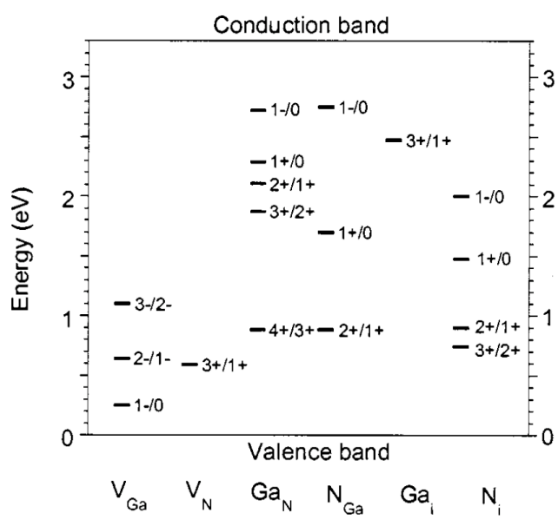
<u>Defects incorporate with larger density in III-Nitrides</u>

- **Highly mis-matched epitaxy**
- **Heterostructures force trade-offs between alloy growth conditions**
- **Facile compensating defect formation in wide band gap materials: $N_t \sim e^{Eg/kT}$**

Mis-matched epitaxy and strain

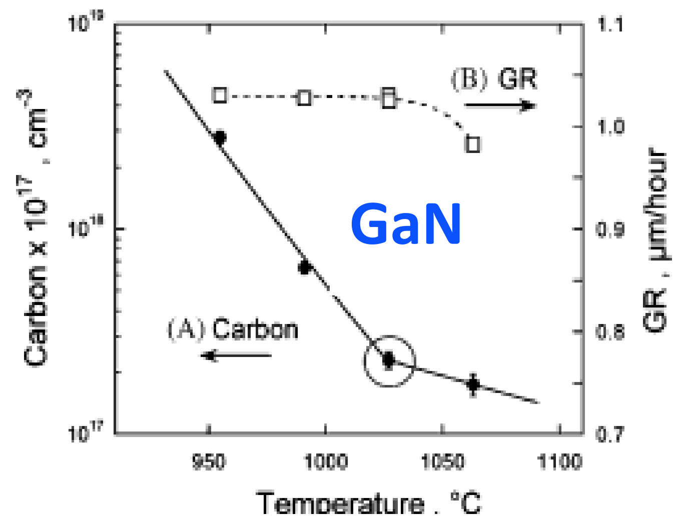


Reduced defect formation energy



Limpijumnong and Van de Walle, PRB 2004.

Non-ideal growth conditions



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

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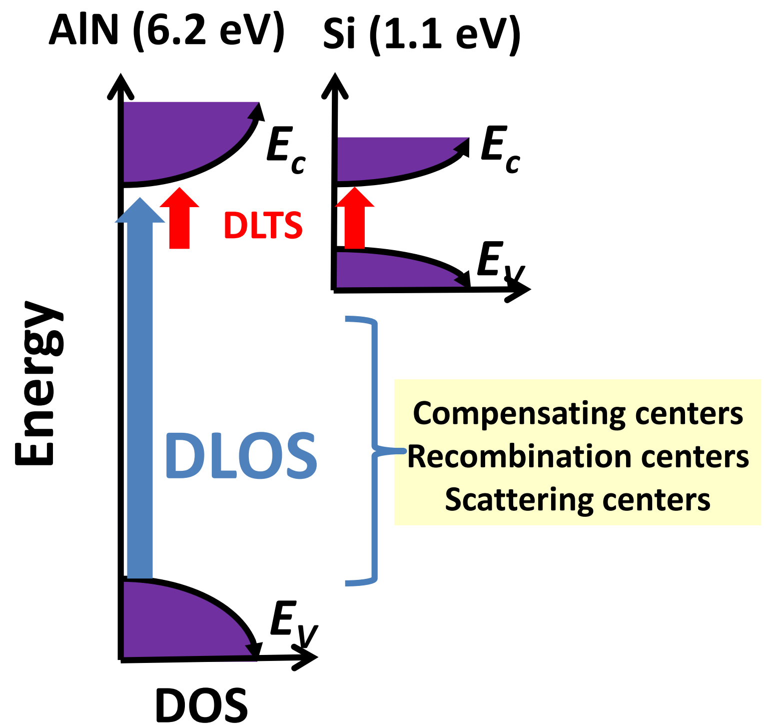
Challenges to studying defects in III-Nitrides

Wide bandgaps limit the use of thermal emission detection methods

- Thermal emission rates decrease exponentially with trap energy

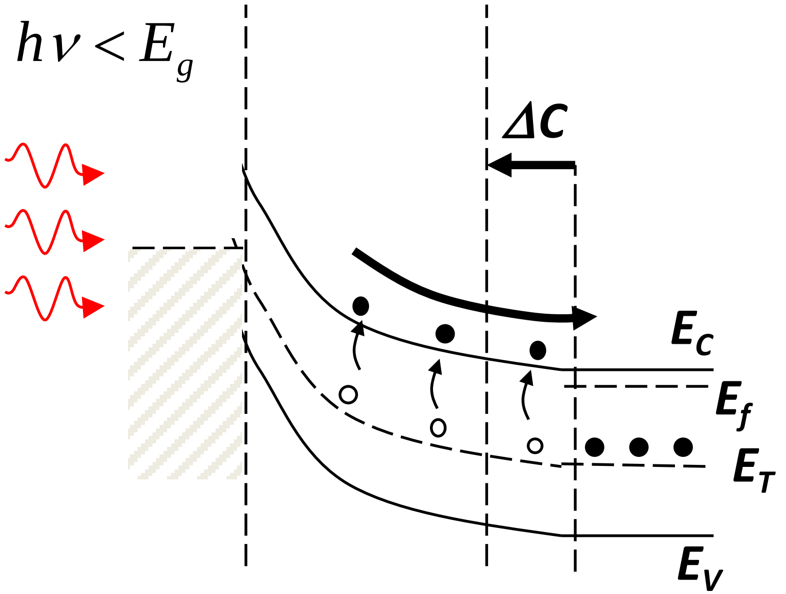


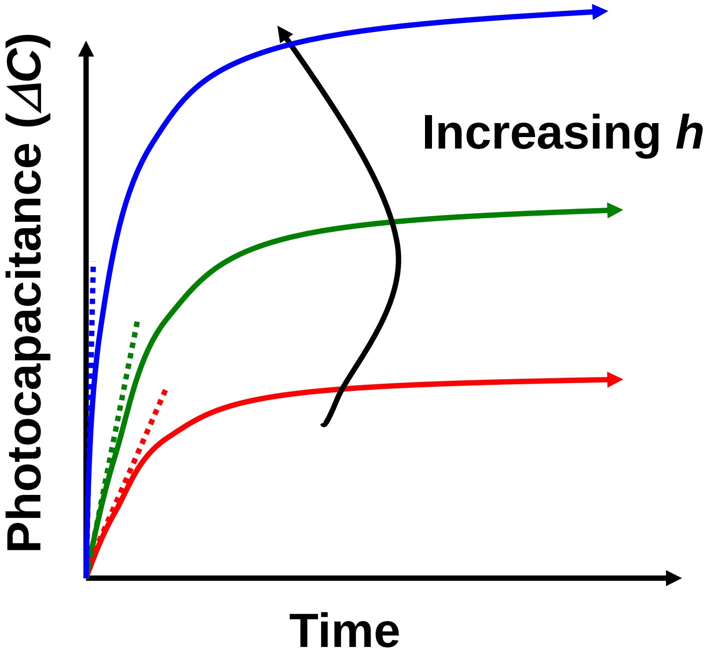
Solution: Deep Level Optical Spectroscopy (DLOS)

Deep Level Optical Spectroscopy

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

- **Photocapacitance technique**
- ***<u>Sub-band gap optical stimulation</u>* to photoionize defect levels**
- ***<u>Quantify non-radiative</u>* defect level energy**





- **DLOS only sensitive to depleted regions**

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

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

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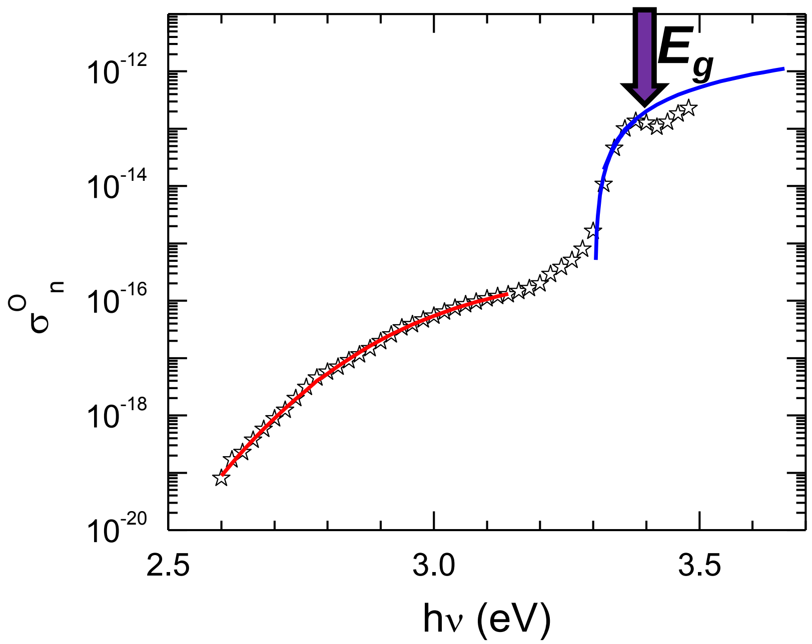
Interpretation of DLOS spectra

DLOS of GaN:Si:C

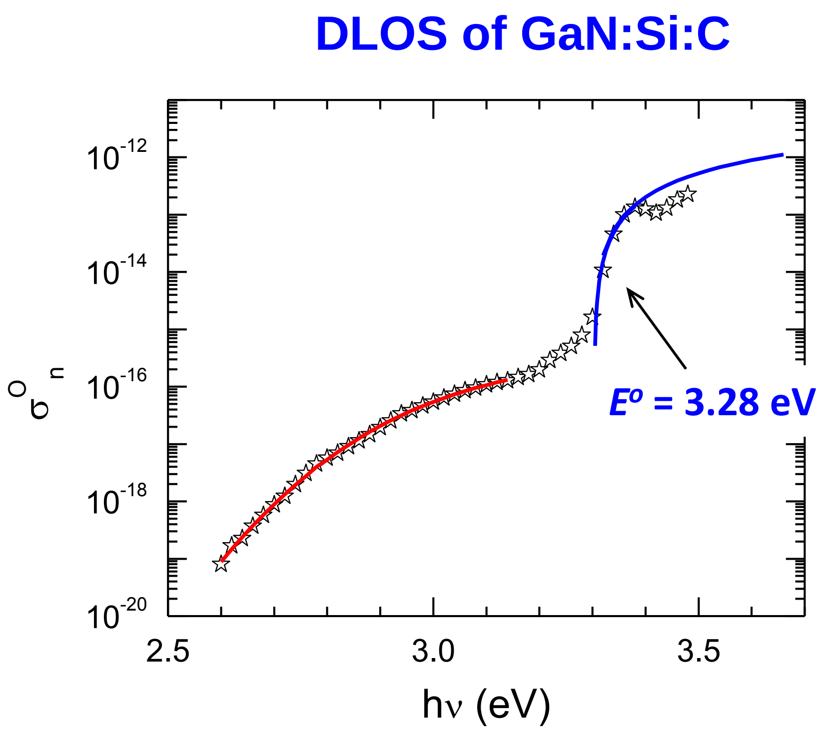


Armstrong et al, APL 84, 374 (2004)

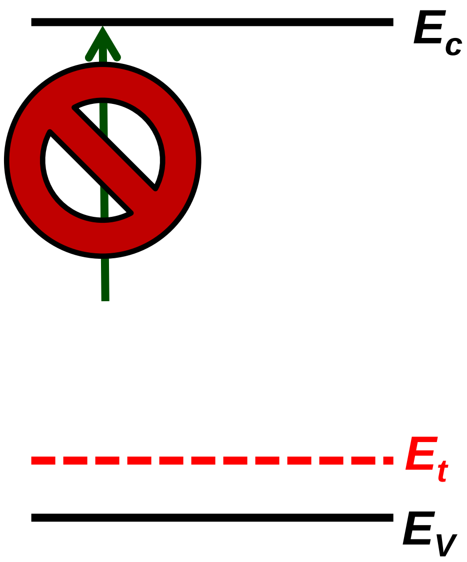
Chantre, et al., PR B 23, 5335 (1981)

Lucovsky, Solid State Commun. 3, 299 (1965)

Interpretation of DLOS spectra



Armstrong et al, APL 84, 374 (2004)



Chantre, et al., PR B 23, 5335 (1981)
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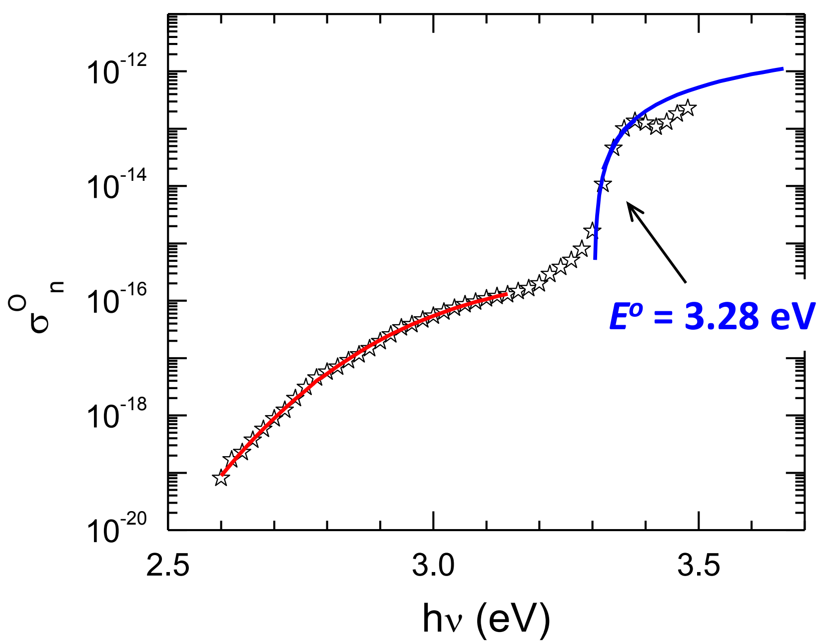

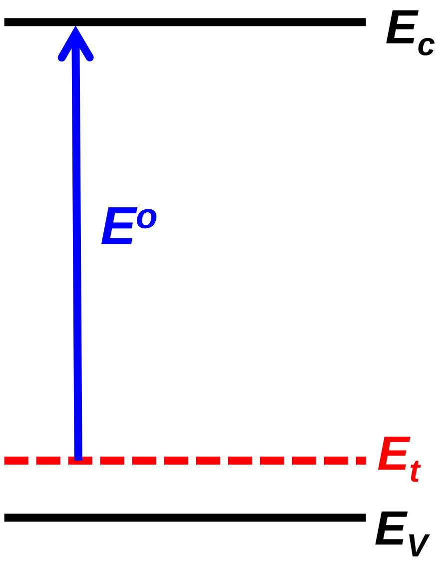

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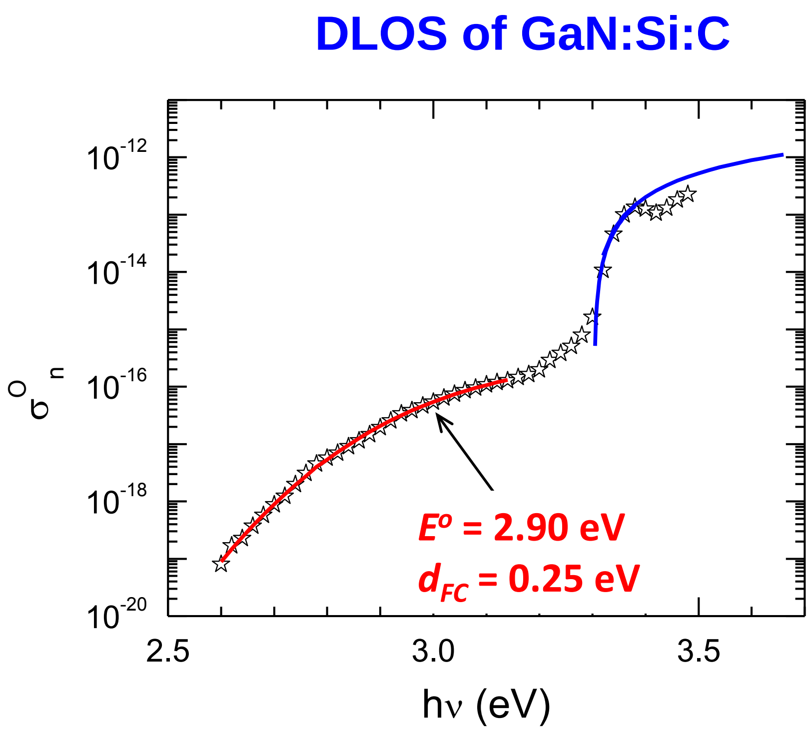
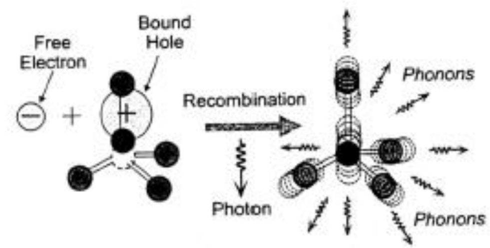
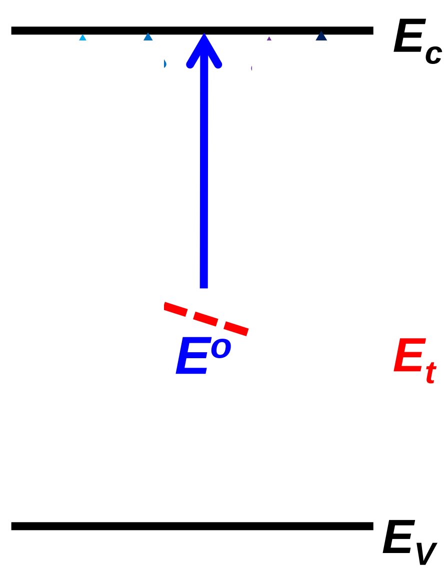


Armstrong et al, APL 84, 374 (2004)



M. A. Reshchikov JAP 97 061301 2005



Quantify E^o for sharp and broad defect absorption spectra

Chantre, et al., PR B 23, 5335 (1981)

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Interpretation of DLOS spectra

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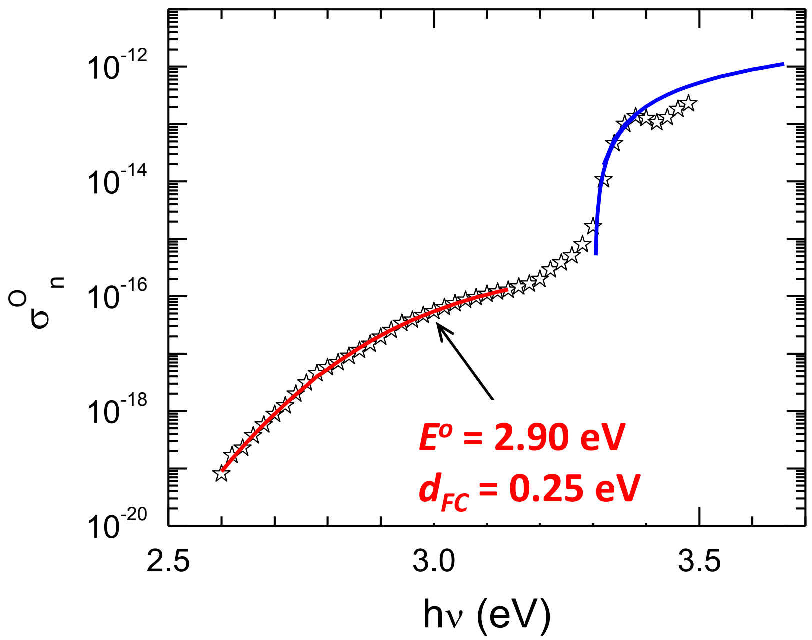

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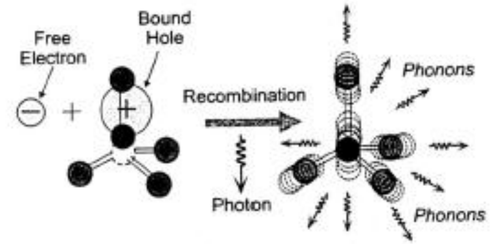
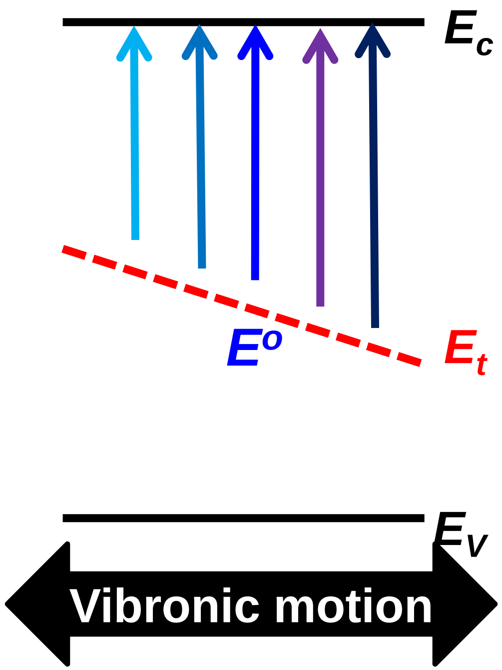


M. A. Reshchikov JAP 97 061301 2005



Quantify E^o for sharp and broad defect absorption spectra

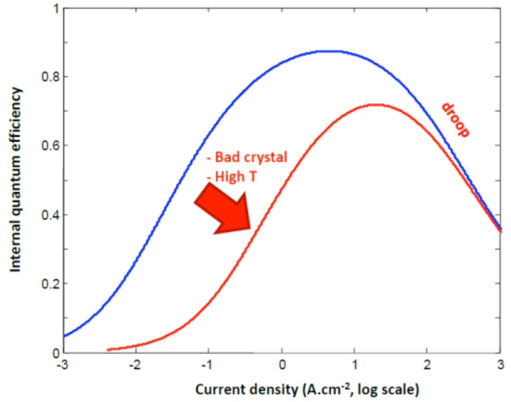
Chantre, et al., PR B 23, 5335 (1981)

Lucovsky, Solid State Commun. 3, 299 (1965)

DLOS application to 2D heterostructures

- Efficiency of InGaN/GaN multi-quantum well (MQW) light emitting diodes (LEDs) drives Solid-state Lighting
  - Solid-State Lighting can reduce 2025 energy consumption by >$100B/yr and carbon emission by >100 MT/yr
- Despite commercial success, defects still limit the efficiency of LEDs
  - Efficiency droop and "green-yellow" gap
- Use DLOS to understand and control defects in LEDs

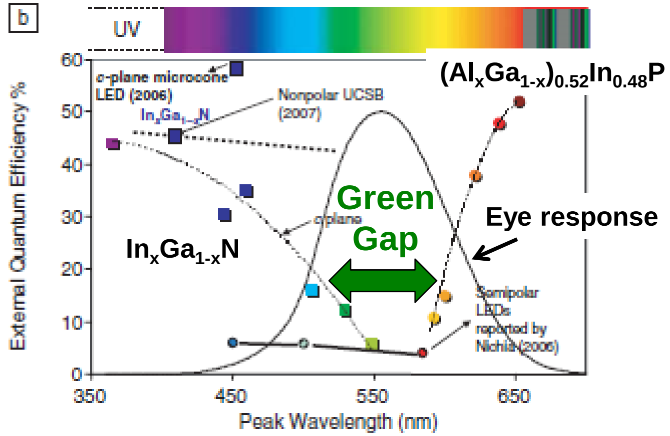
InGaN/GaN LED IQE vs. J



A. David, 2012 DOE SSL R&D Workshop

EQE for non-polar and polar InGaN

S. Nakamura MRS BULLETIN • VOLUME 34 • FEBRUARY 2009



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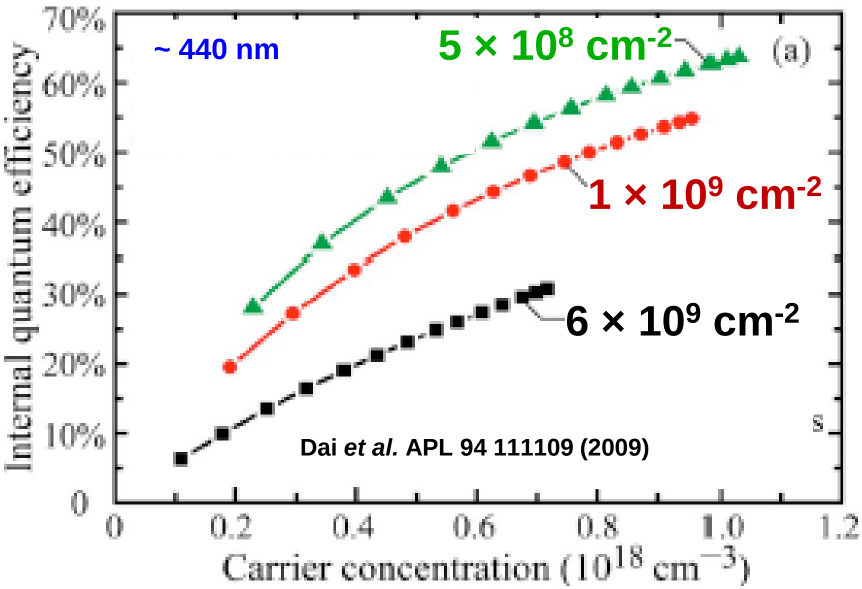
Defects limit peak LED efficiency

Threading dislocations (TDs) reduce LED peak efficiency

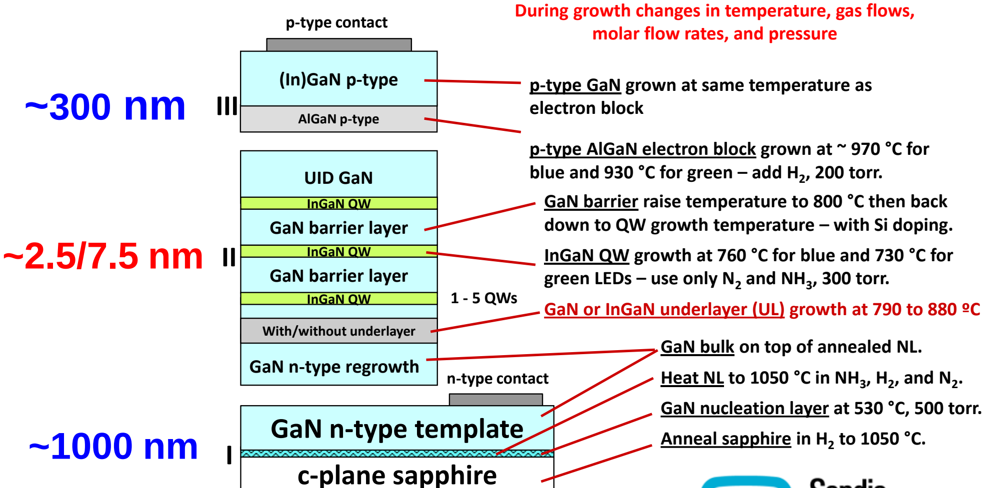


- What are the defect energy levels (E^o)?
- At what density (N_t)?
- Where do they form in the LED ?

Challenge: Needle in a "haystack"

- Need nanoscale depth resolution to differentiate QW and QB defects

LED design - NOT TO SCALE!



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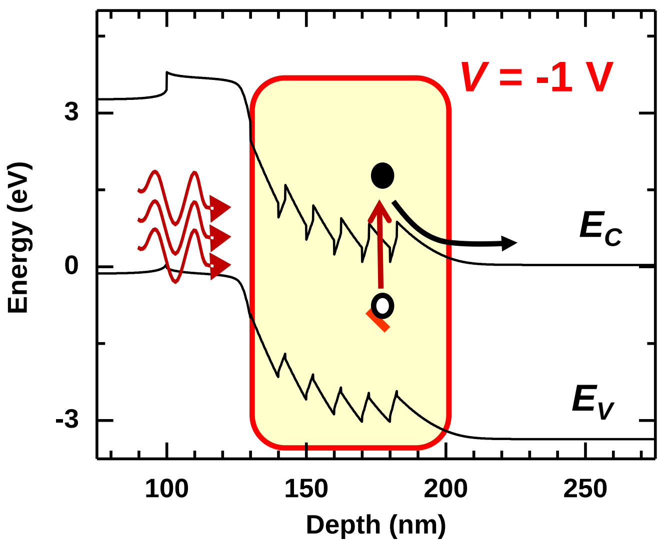
DLOS provides depth resolution in LEDs

LED MQW 1D-SP calculations*

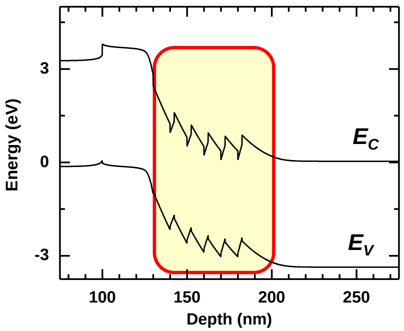
*G. Snider UND

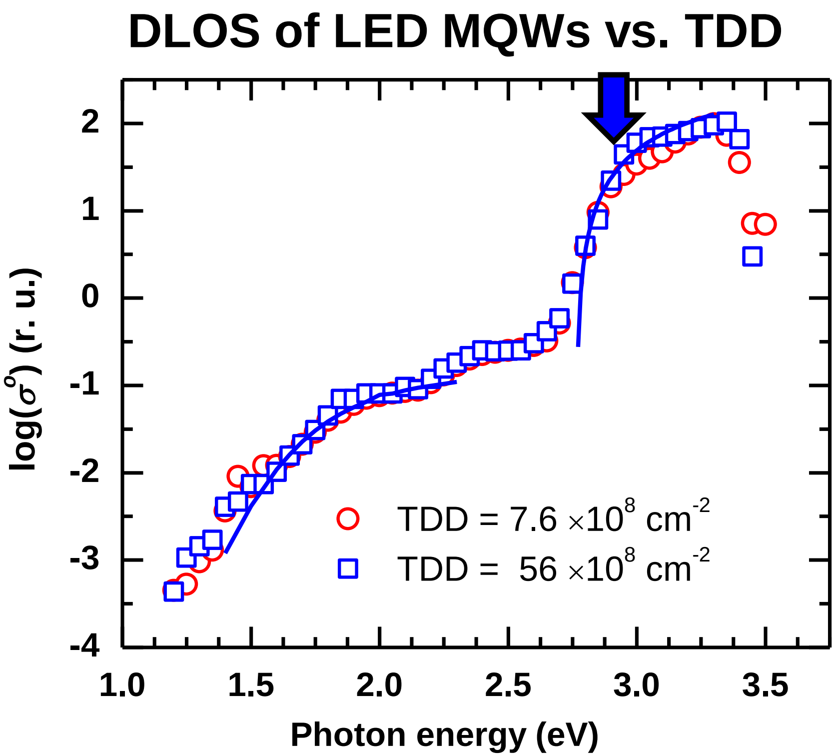


V = -1 V: DLOS selective to the MQW region

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

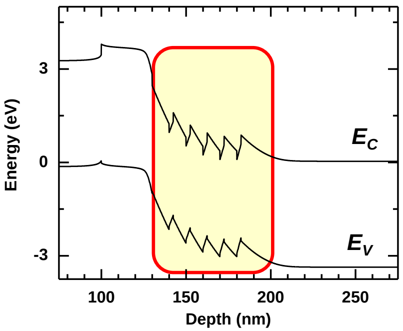
Identify QW-related defects in LEDs



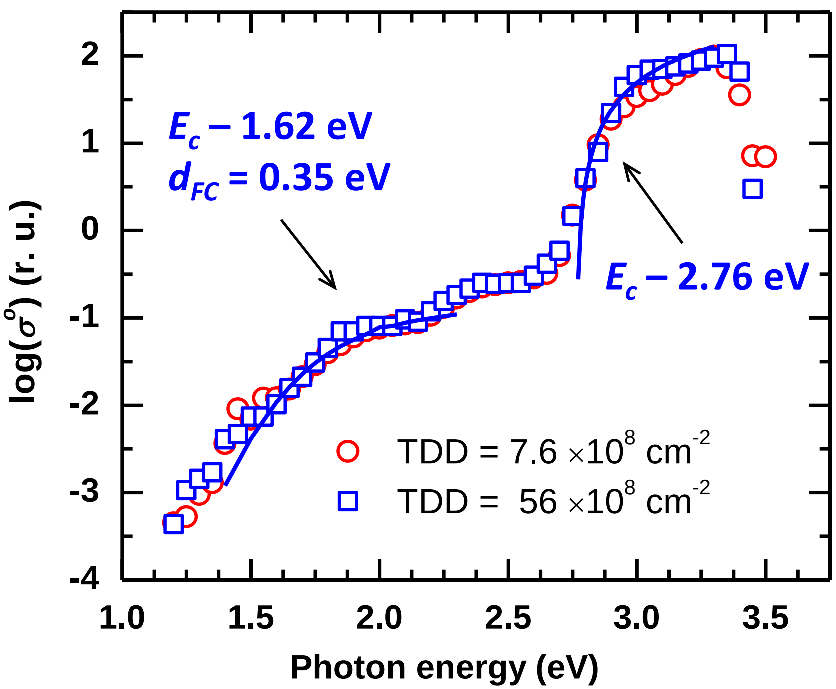


➢ **~2.9 eV $In_{0.13}Ga_{0.87}N$ QW band edge**

Identify QW-related defects in LEDs



DLOS of LED MQWs vs. TDD



- ~2.9 eV $In_{0.13}Ga_{0.87}N$ QW band edge
- No new defect states with increased TDD

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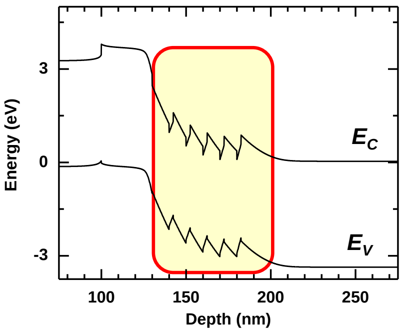
Identify QW-related defects in LEDs



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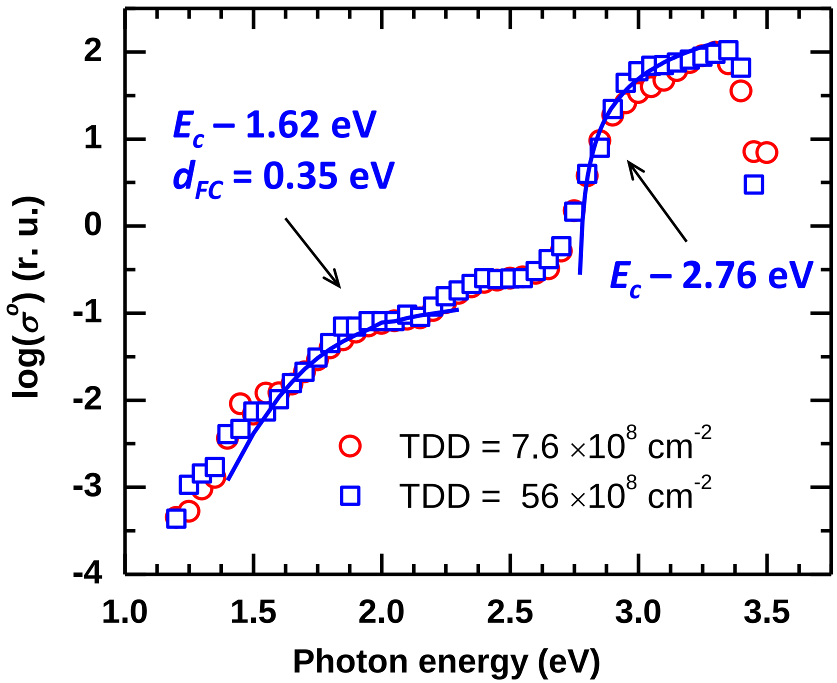
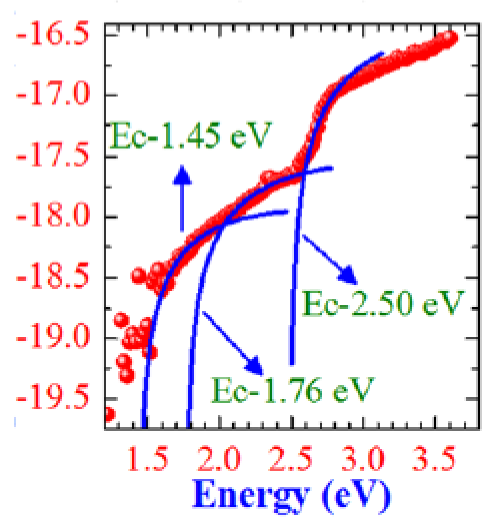


DLOS of thin film UID-$In_{0.2}Ga_{0.8}N$



Emre Gür,[1,2,a)] Zeng Zhang,[2] Sriram Krishnamoorthy,[2] S. Rajan,[2] and S. A. Ringel[2]

APPLIED PHYSICS LETTERS 99, 092109 (2011)

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

Identify defects in 2.5 nm optically active QWs!

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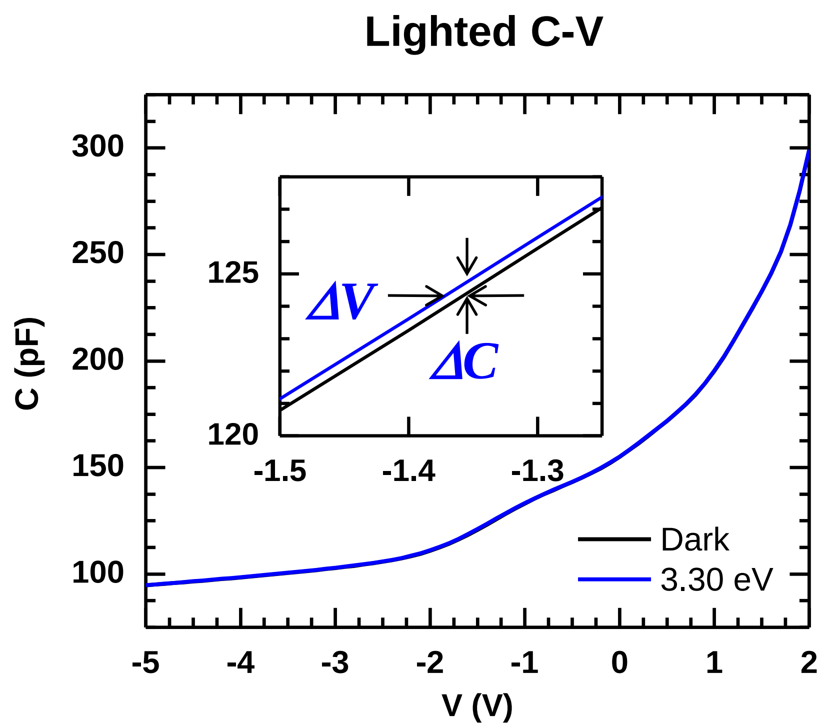
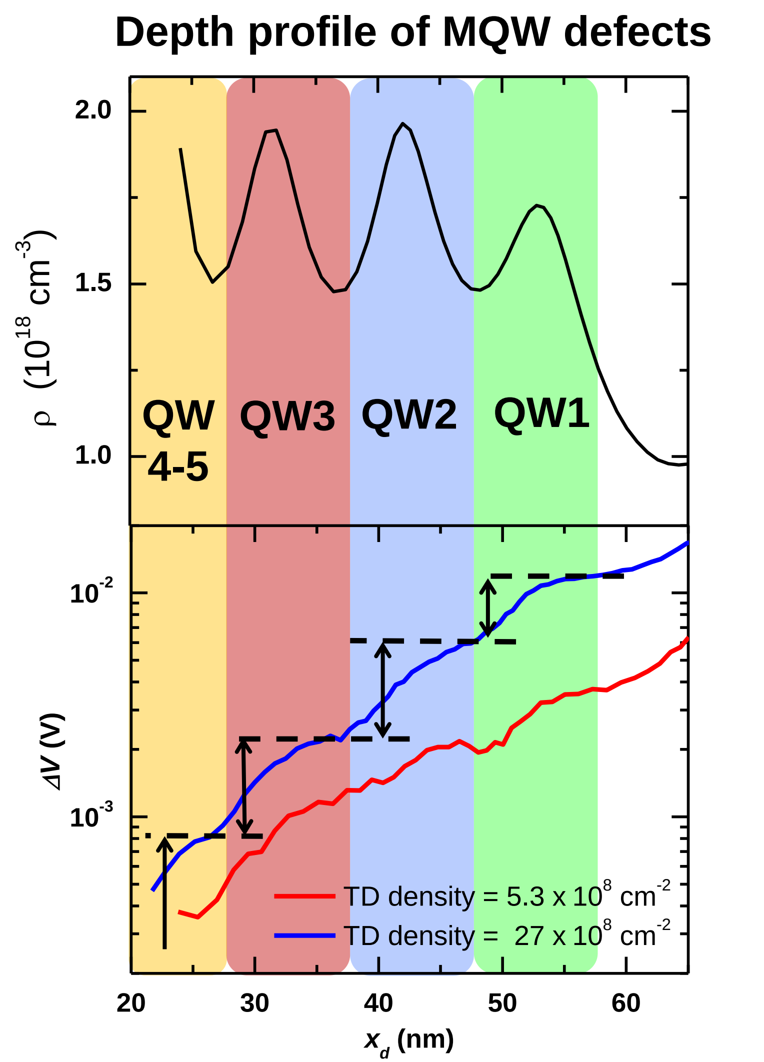
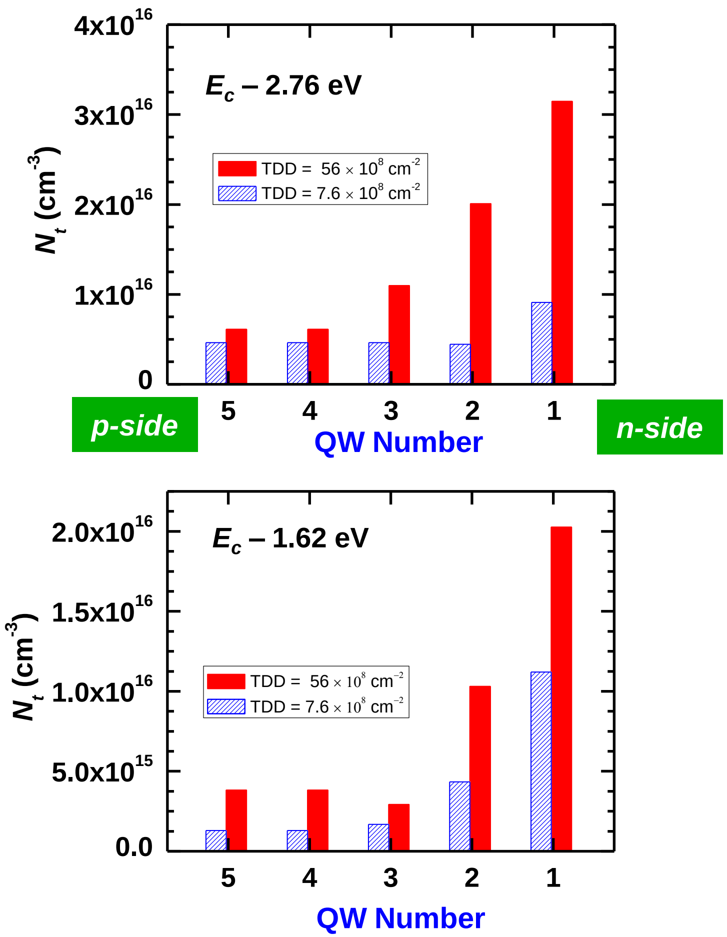
Lighted-*CV* quantifies defect density



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



Enhanced TDD increases density of all observed deep levels!

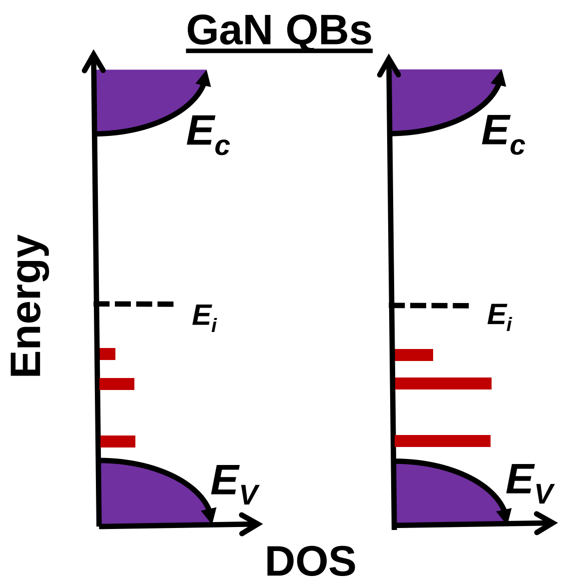


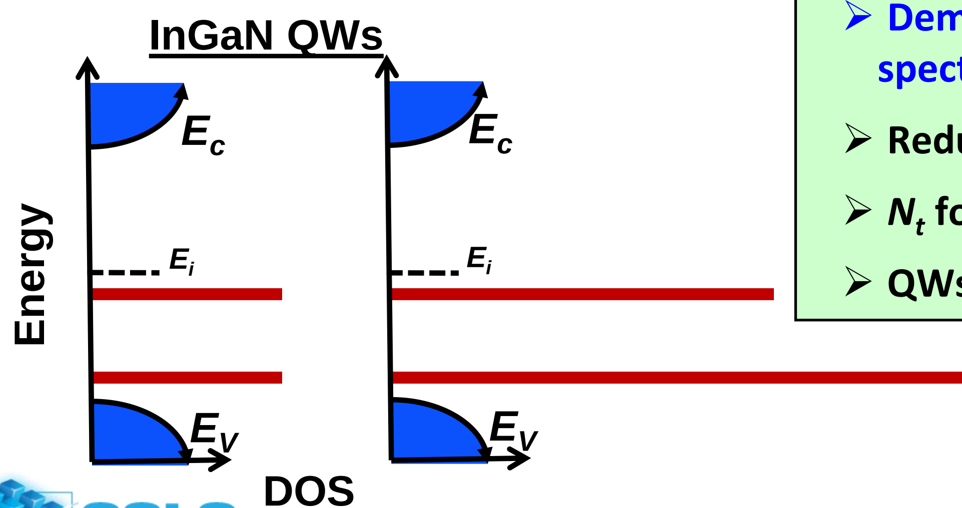
- **Decrease in N_t with lower TDD**
- **Depth-dependence of N_t *not* expected for TD-related defects**
- **Suggests interaction among point (C, V_{Ga}) and extended defects during growth[1,2]**

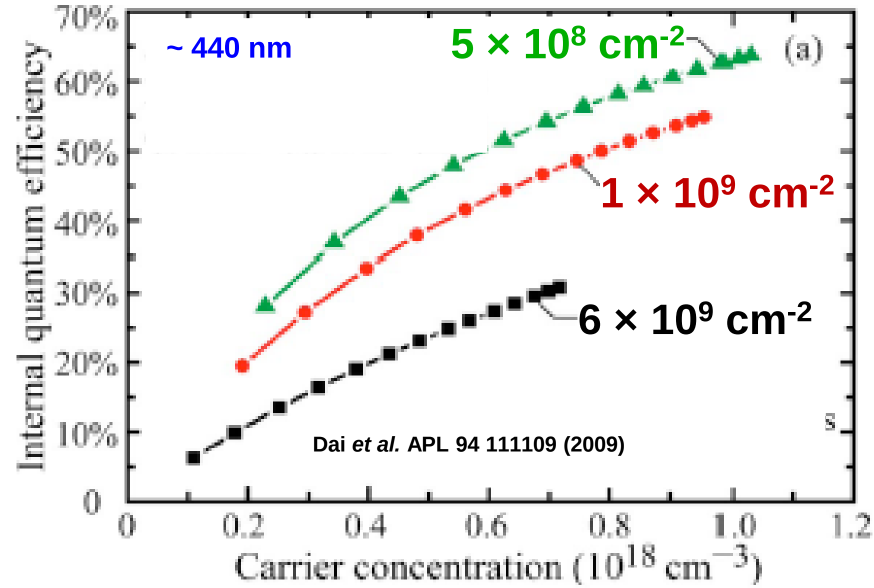
1. Hashimoto et al., J. Crystal Growth 298, 871(2007).
2. J. Elsner, et al., Phys. Rev. B 58, 12571 (1998).

Enhanced TDD increases density of most observed deep levels

TDD: 7.6×10^8 cm^-2   56 × 10^8 cm^-2







- **Demonstrated quantitative and nanoscale defect spectroscopy in MQW active region of LEDs**
- **Reduced N_t with TDD correlates with better LED IQE**
- **N_t for near-E_v and mid-gap levels trend with IQE**
- **QWs are more defective than QBs**

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

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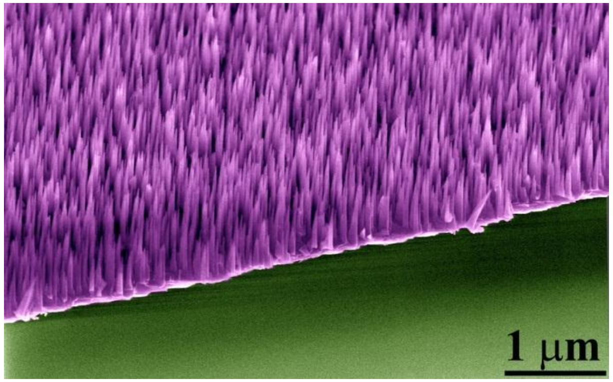
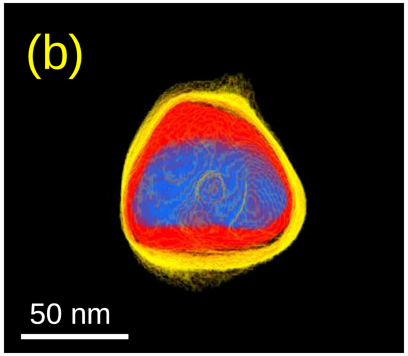
DLOS can be applied to (quasi-)1D systems

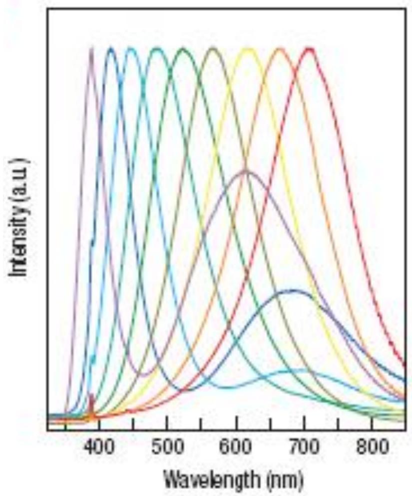
III-N nanowires (NWs) have attractive electrical and optical properties



False color SEM of GaN NWs



STEM of AlGaN/GaN NW



PL of InGaN NWs
Kuyendall *et. al* Nature Materials 6 951 2007

- **Sensor applications**
- **Solid-State Lighting**
- **No TDs, but point defects are still a concern**

Too small for photocapacitance (DLOS) measurements

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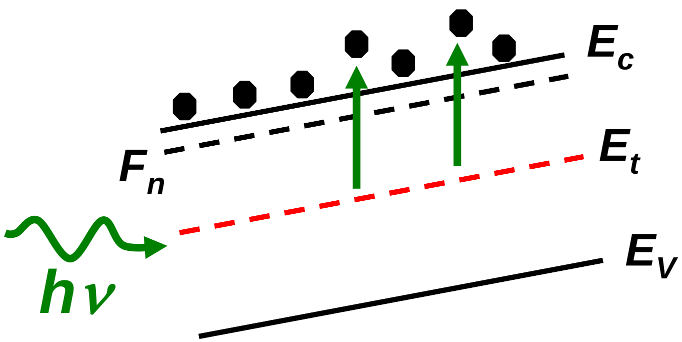
Defect spectroscopy of GaN NWs

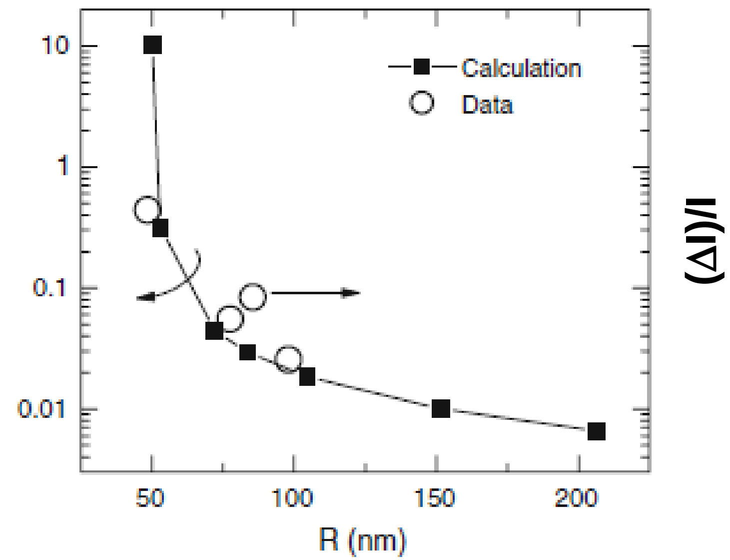
- **Sub-bandgap photoconductivity – what is the physical mechanism?**

Free carrier generation



$$\Delta I / I_0 \approx \frac{N_t}{n_0}\left(\frac{e^o}{e^o + C_n n_0 + 1/\tau}\right)$$

GaN NW Sub-gap Photoconductivity



Armstrong *et al.* JEM 38 484 (2009).

- ➢ **Weak photoconducitivty for diffuse light**
- ➢ **Does not explain *R* dependence**

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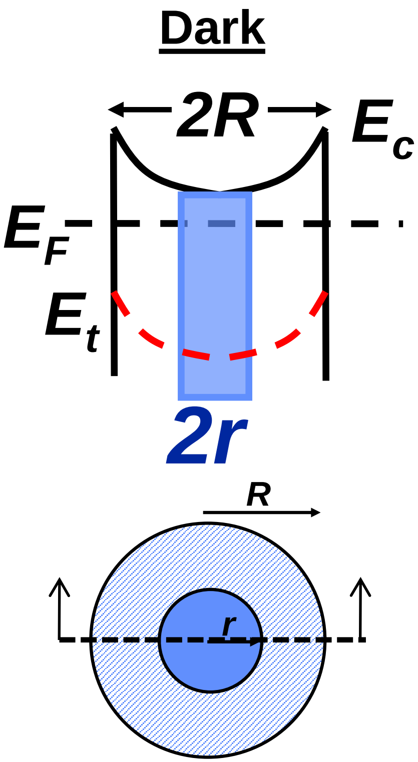
Photoconductivity-mode DLOS for GaN NWs

"Nano" DLOS - Modulate NW surface depletion region[1]



1. Calarco *et al.* Nano Lett. 5 981 (2005).

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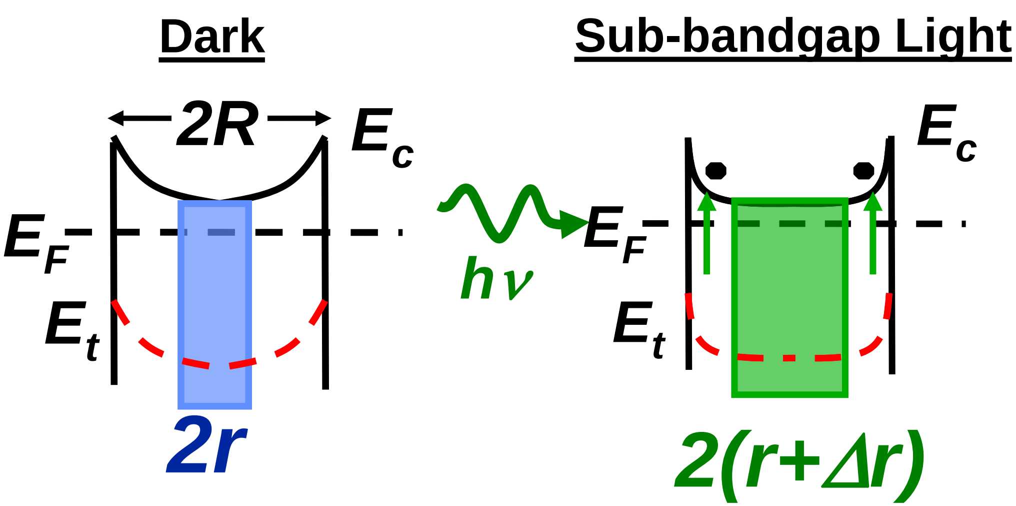

- No *e*-*h* pair creation
- Carrier mobility unaffected
- **Photoconductivity from increase in conductive cross-sectional area A_σ**

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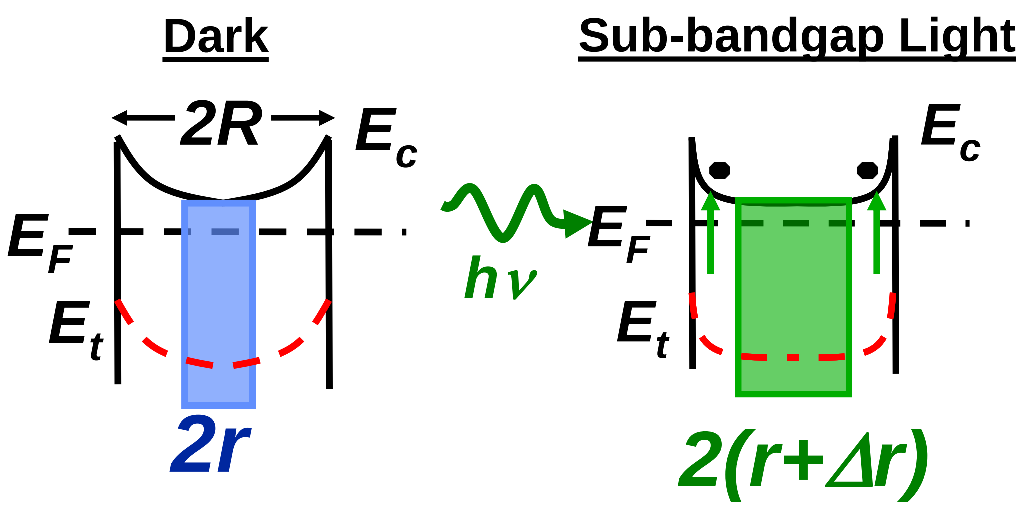
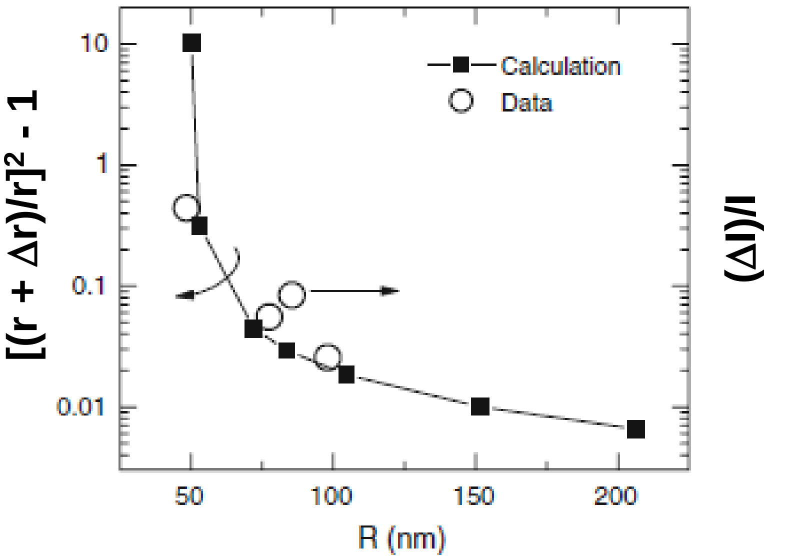


NW Steady-State Photoconductivity



Armstrong *et al.* JEM 38 484 (2009).

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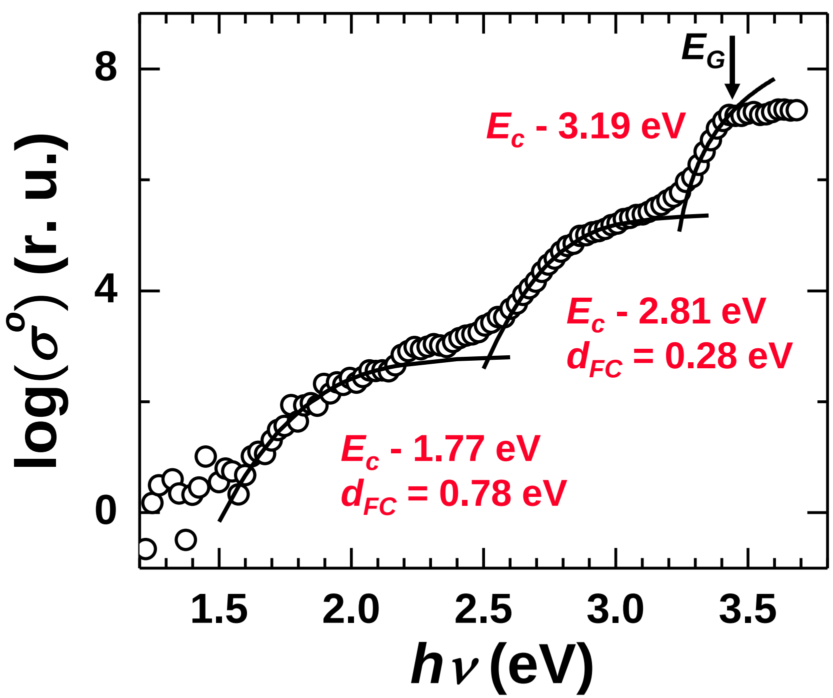
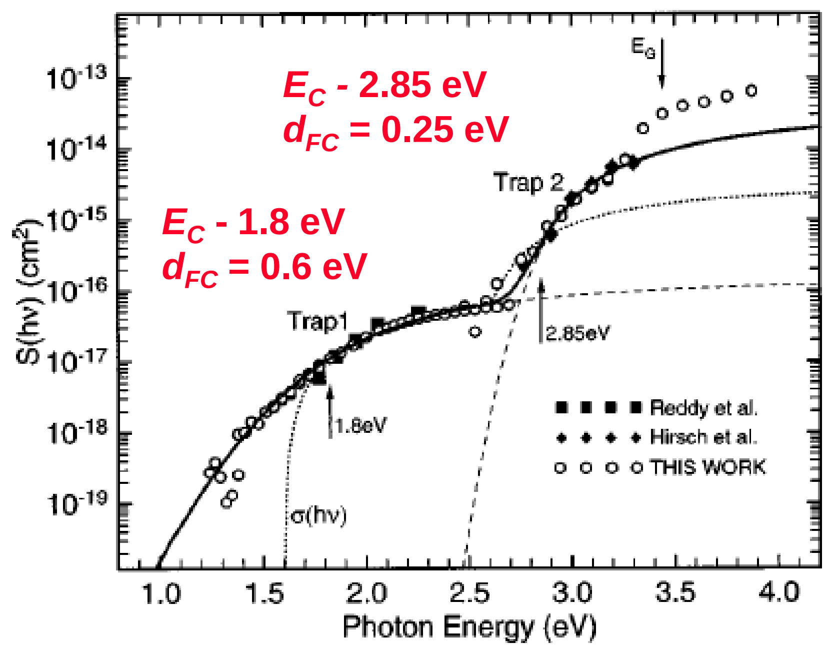
1. Calarco *et al.* Nano Lett. 5 981 (2005).

DLOS of GaN NWs

DLOS of MOCVD GaN NW



DLOS of MOCVD bulk GaN:C

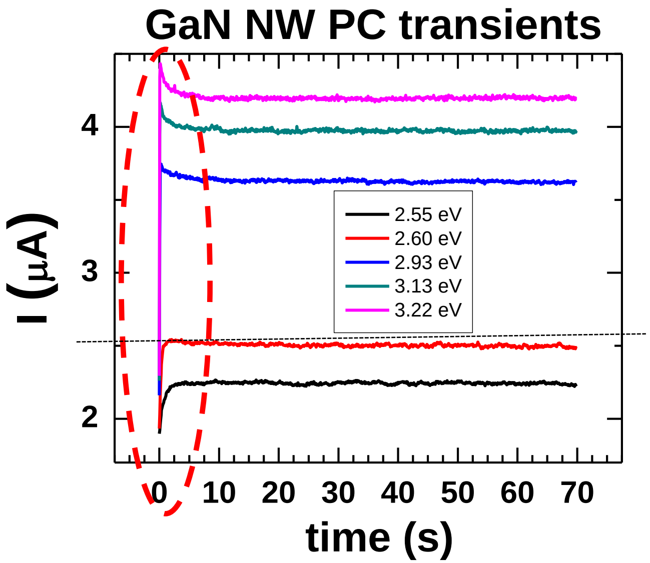


1. Klein *et al.* APL 75 4016 (1999).

- NW deep level defect spectra similar to bulk GaN:C
  - Not likely to be surface states
  - Possibly carbon-related defects
- What about surface states?

Photoconductiviy transients suggest surface states

Negative photoconductivity component for $h\nu > 2.6$ eV



1 Van de Walle *et al.*, JAP 101 081704 (2008).

GaN vs. AlGaN/GaN core-shell NWs

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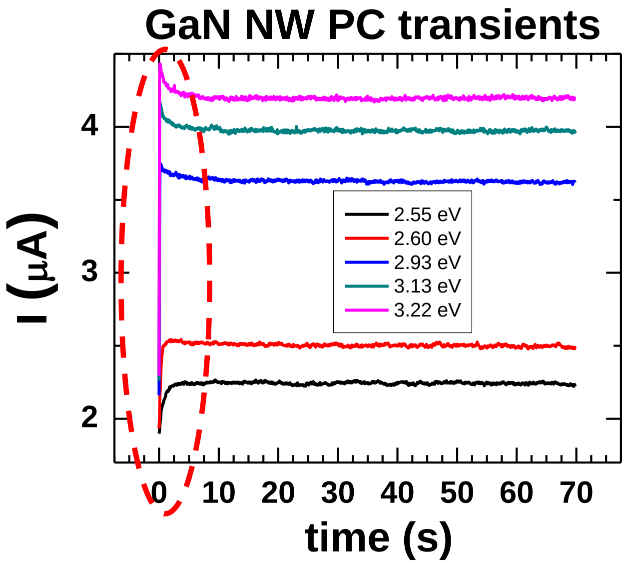

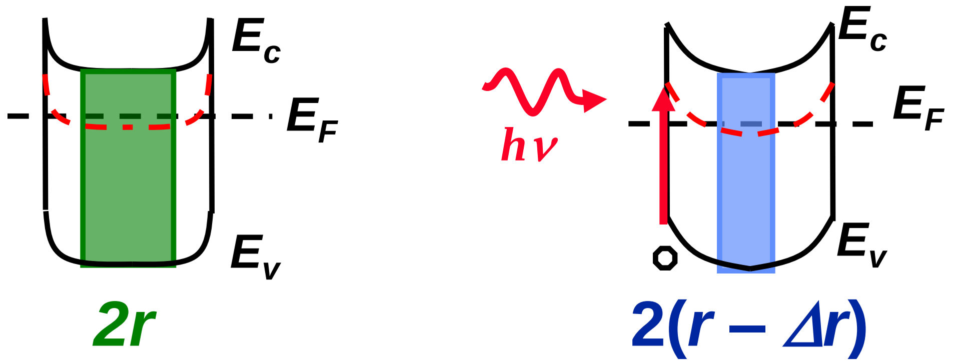

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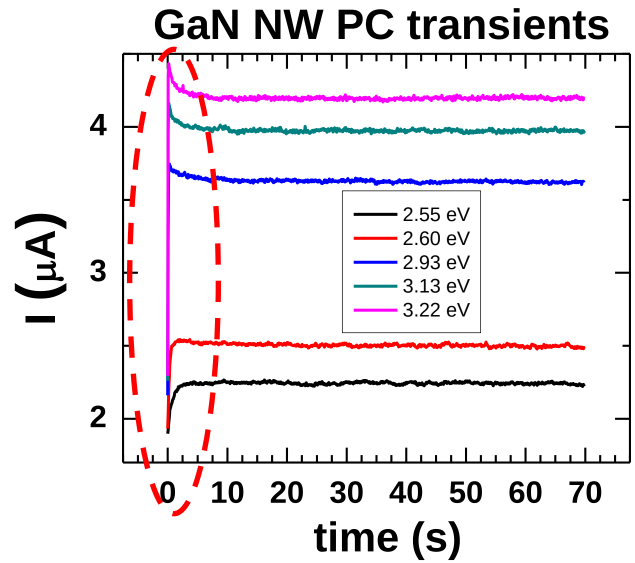
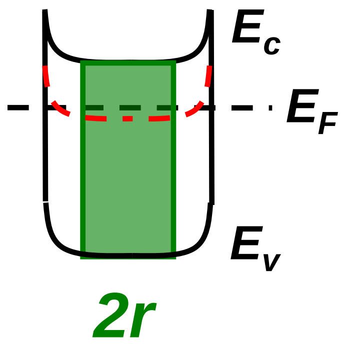
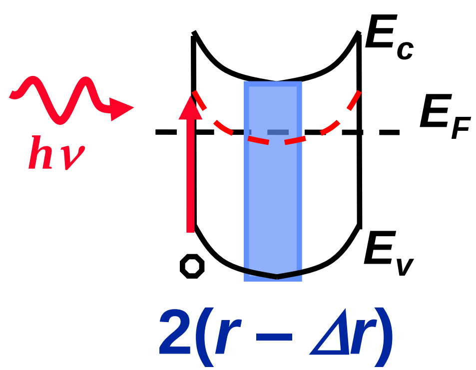
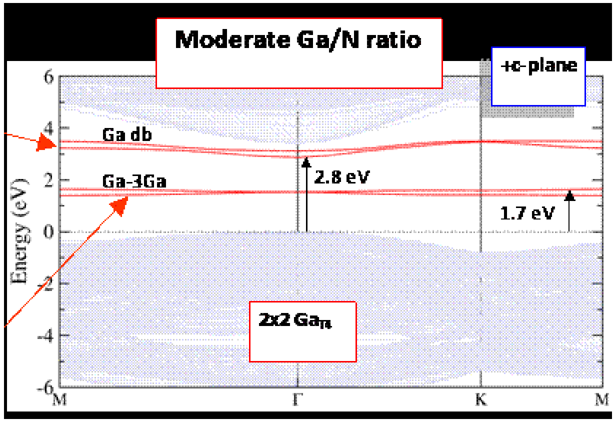
Negative photoconductivity component for $h\nu$ > 2.6 eV





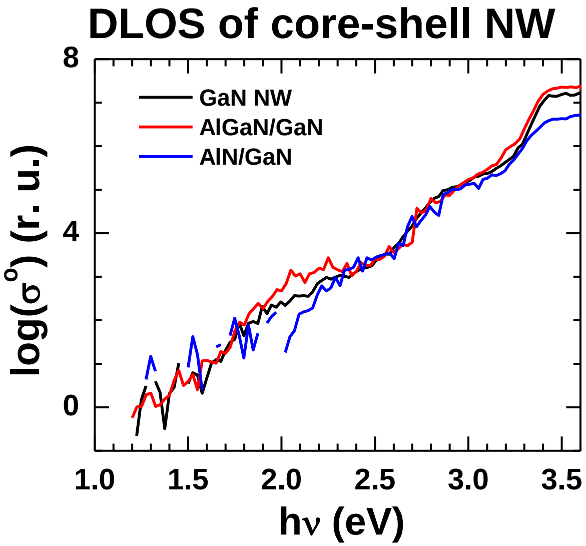


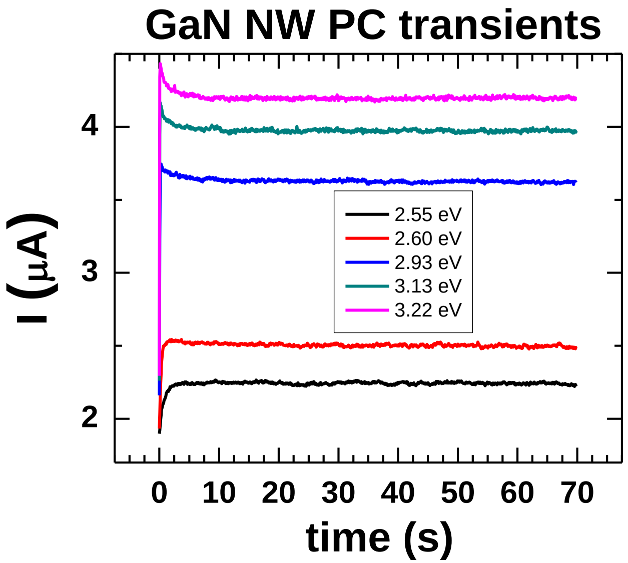


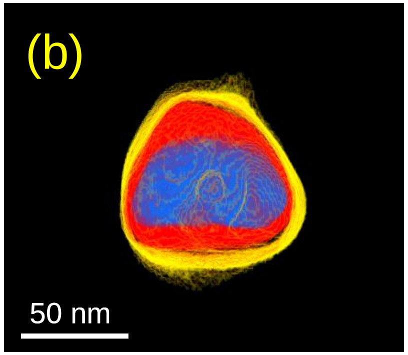
- Minority carrier deep level near E_v + 2.6 eV/E_C - 0.8 eV
  - E_c - 0.6 eV surface state predicted for *n*-type, *c*-plane GaN surface[1]

1 Van de Walle *et al.*, JAP 101 081704 (2008).

GaN vs. AlGaN/GaN core-shell NWs





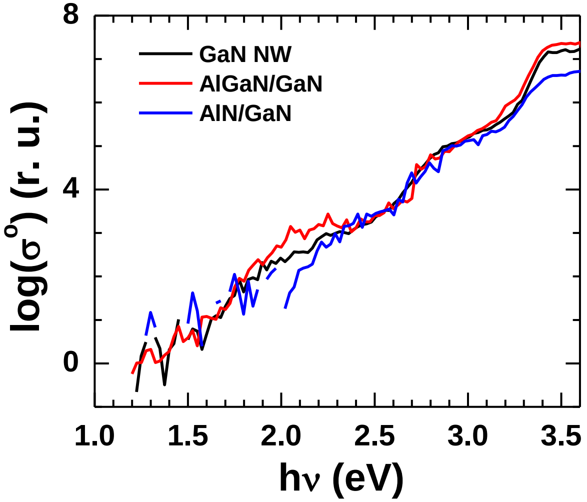


HAADF-STEM of AlGaN/GaN NW

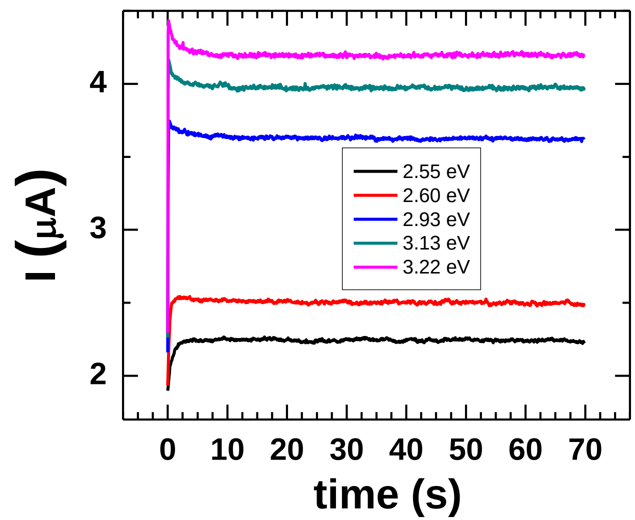
- **Similar DLOS spectra for GaN, Al(Ga)N/GaN core-shell NWs**
  - **Same "bulk" defects**

GaN vs. AlGaN/GaN core-shell NWs

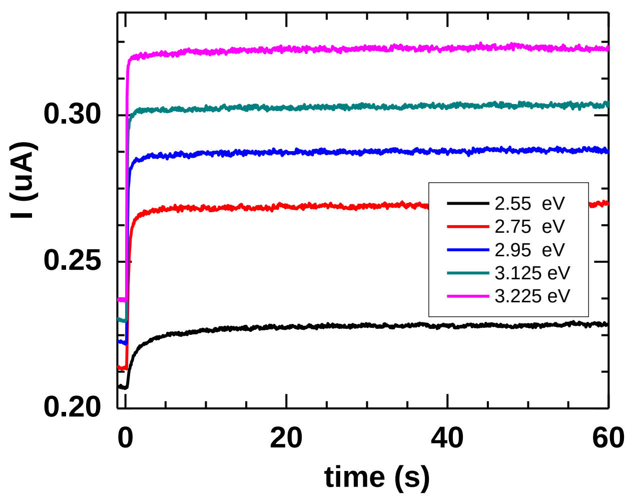
DLOS of core-shell NW



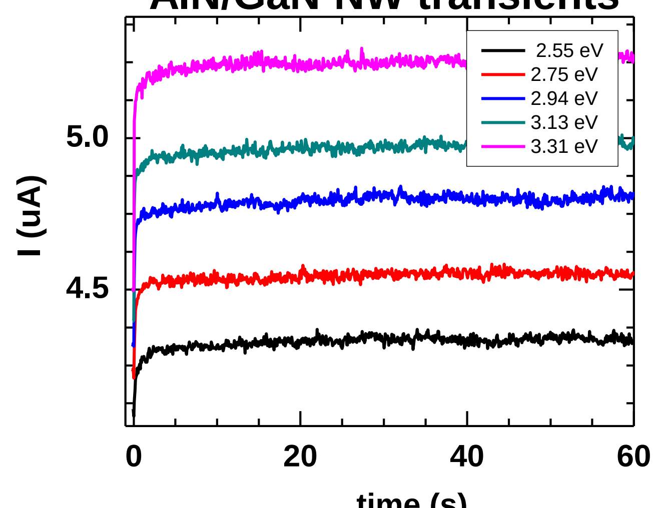
GaN NW PC transients



AlGaN/GaN NW transients



AlN/GaN NW transients



- E_C - 0.8 eV level missing in core-shell Al(Ga)N/GaN NWs
  - Further evidence for GaN surface-related defect

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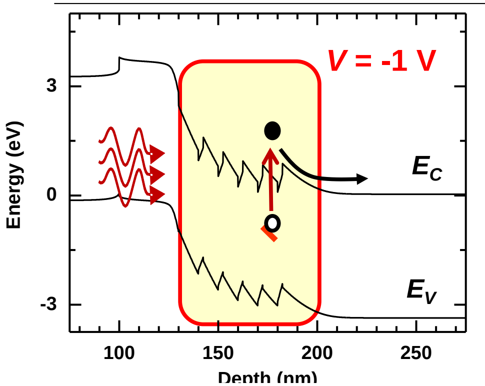
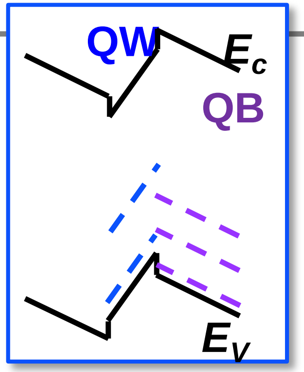
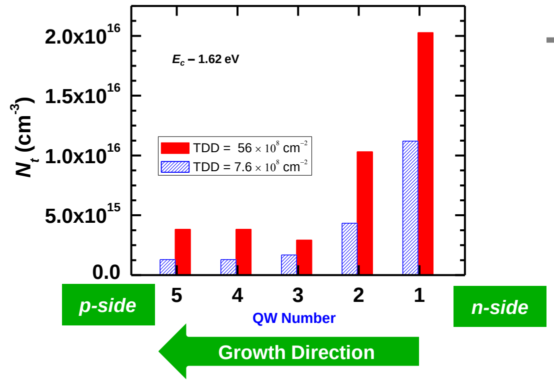
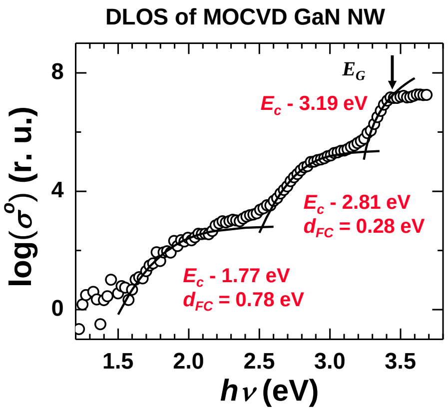
Summary

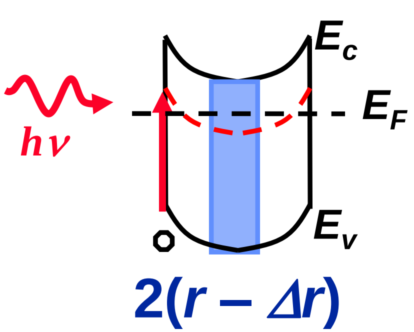


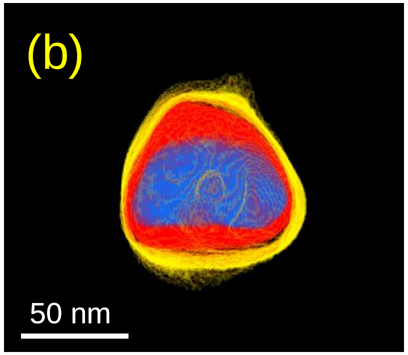




- Quantitative and nanoscale depth profiling of defect levels in LED
- Correlated deep level density to optical efficiency
- Strong interaction among point and extended LED defects







- Quantify deep level energy and density in GaN NWs
- Bulk-like defects prevalent
- Observed surface states in GaN NWs
- Control surface states with epitaxial passivation layers

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