SAND2014-20160C

Understanding and Controlling Deep Level Defects for Next-Generation Power Electronics

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Outline

- Why III-N's for solid-state lighting and power electronics?
- Importance of defects in III-N materials
- Deep Level Optical Spectroscopy (DLOS)
- Impact of defects on doping efficacy of Al-rich AlGaN
- Summary

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- **Why III-N's for solid-state lighting and power electronics?**
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- **Impact of defects on doping efficacy of Al-rich AlGaN**
- **Summary**

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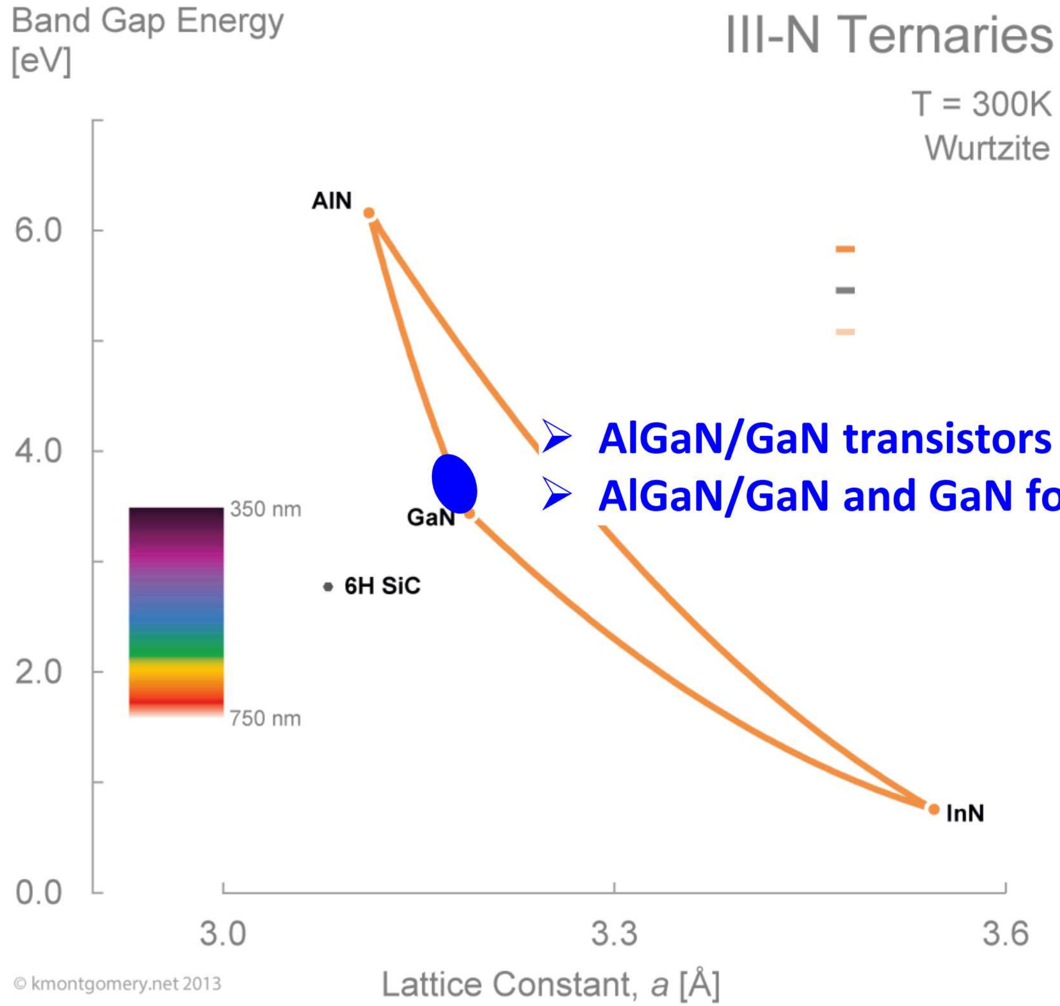
Why III-N's?



- AlGaN/GaN transistors for RF electronics
- AlGaN/GaN and GaN for next-gen power electronics

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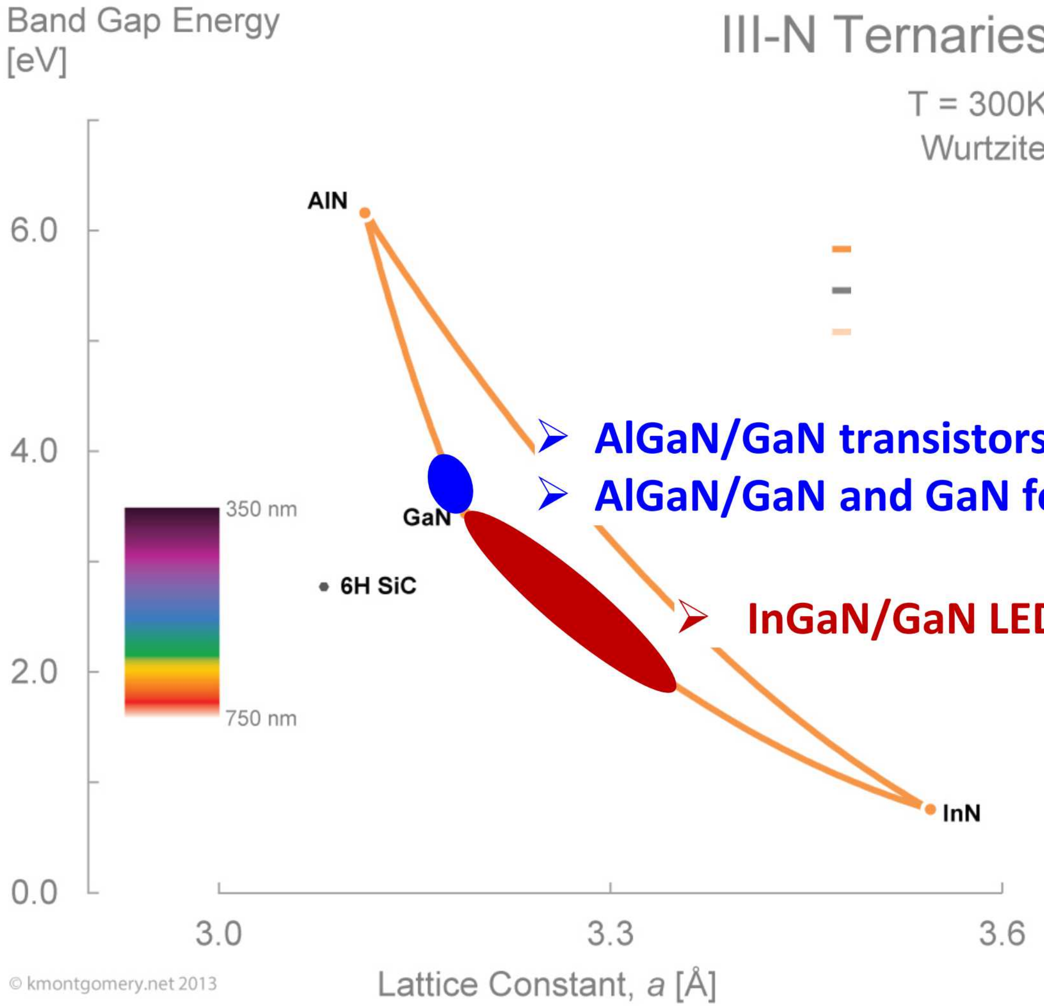

- AlGaN/GaN transistors for RF electronics
- AlGaN/GaN and GaN for next-gen power electronics
- InGaN/GaN LEDs for solid-state lighting

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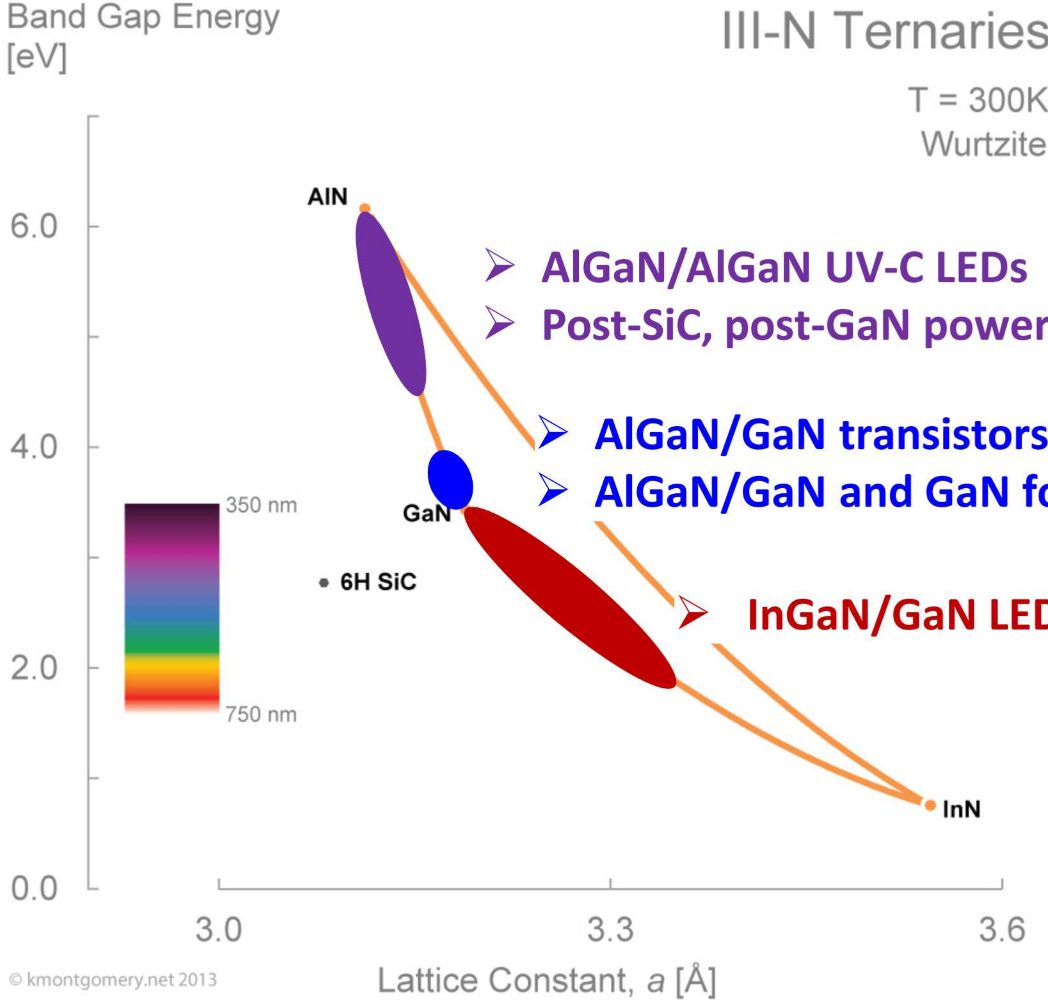

- AlGaN/AlGaN UV-C LEDs
- Post-SiC, post-GaN power electronics
- AlGaN/GaN transistors for RF electronics
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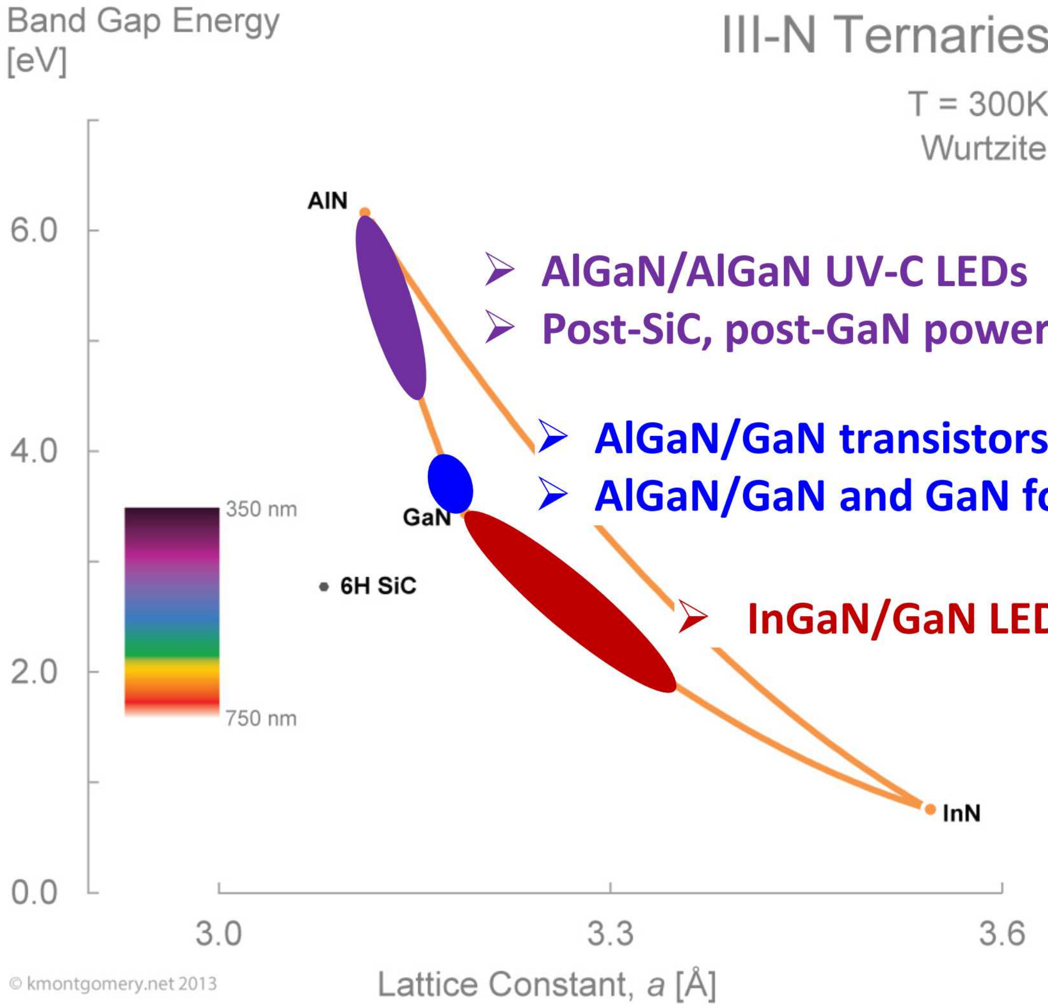
Why III-N's?



- ➢ AlGaN/AlGaN UV-C LEDs
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- ➢ AlGaN/GaN transistors for RF electronics
- ➢ AlGaN/GaN and GaN for next-gen power electronics
- ➢ InGaN/GaN LEDs for solid-state lighting

➢ Persistent III-N challenges: doping and defects

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Importance of defects for III-Nitride materials

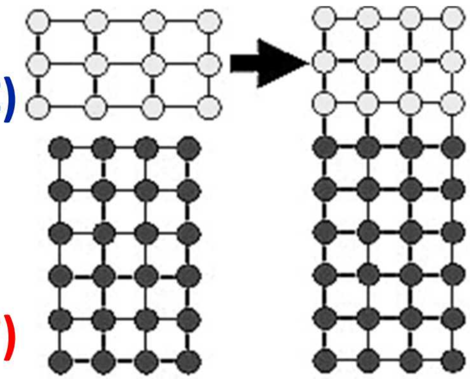
Defects incorporate with large density in III-N's

- Highly mis-matched epitaxy
- Non-ideal heterostructure growth conditions
- Facile defect formation: $N_t \sim \exp(E_g/kT)$

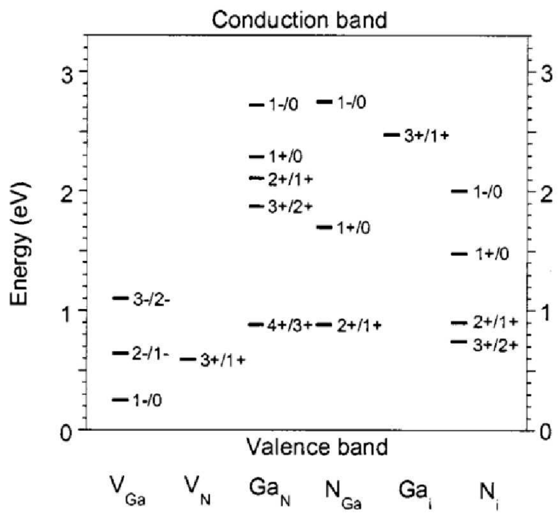
Mis-matched epitaxy and strain

InGaN
(T_g ~750 °C)

GaN
(T_g ~ 1000 C°)

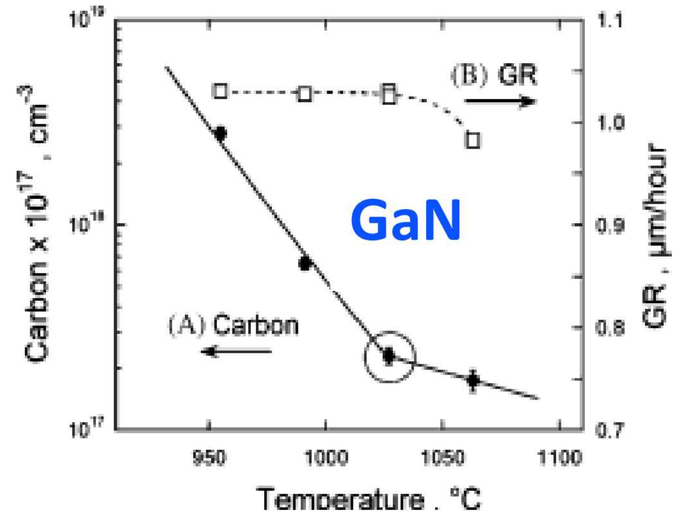


Reduced defect formation energy



Limpijumnong and Van de Walle, PRB 2004.

Non-ideal growth conditions



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

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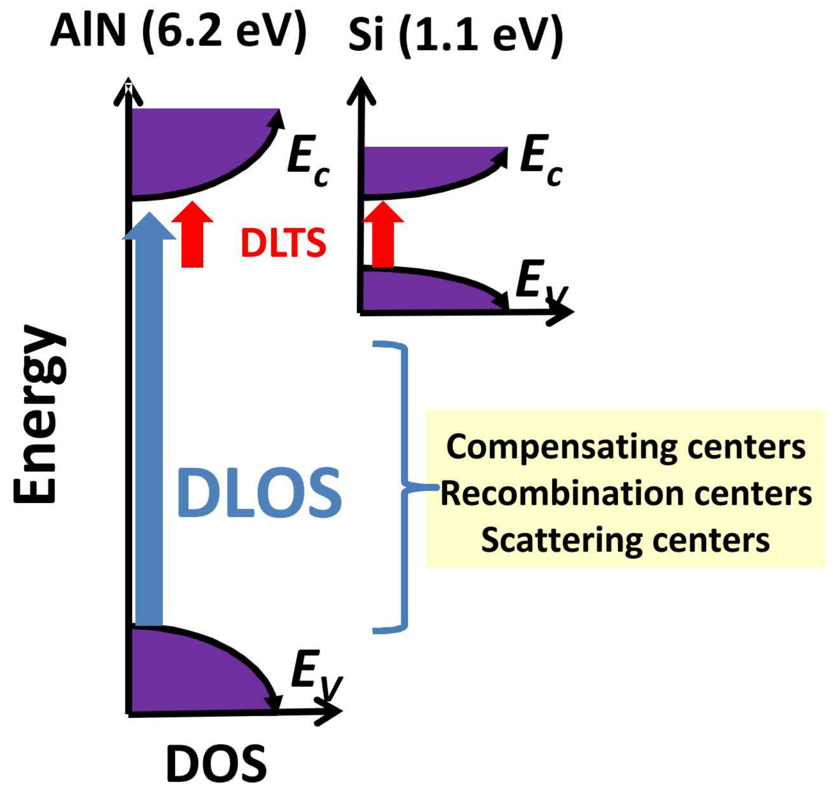
Challenges to studying defects in III-Nitrides

<u>Quantitative defect spectroscopy is difficult for wide bandgap semiconductors</u>

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



Solution: Deep Level Optical Spectroscopy (DLOS)

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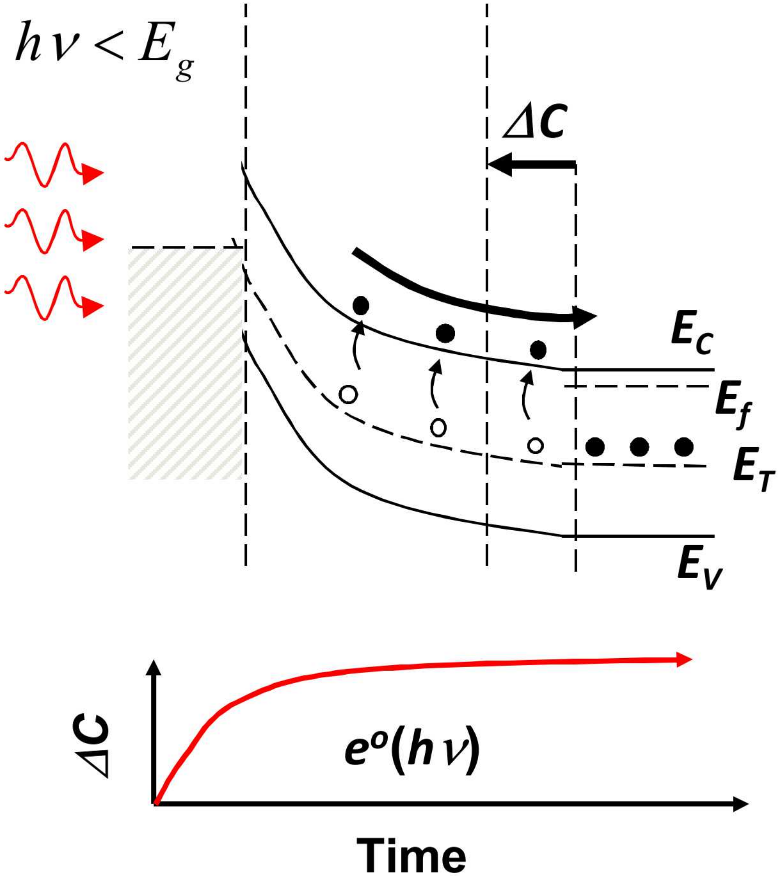
Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- ***Electrical measurement*** **of** ***optical absorption*** **by deep level defects**
- **Photocapacitance technique**
- **Sub-band gap optical stimulation to photoionize defect levels**



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

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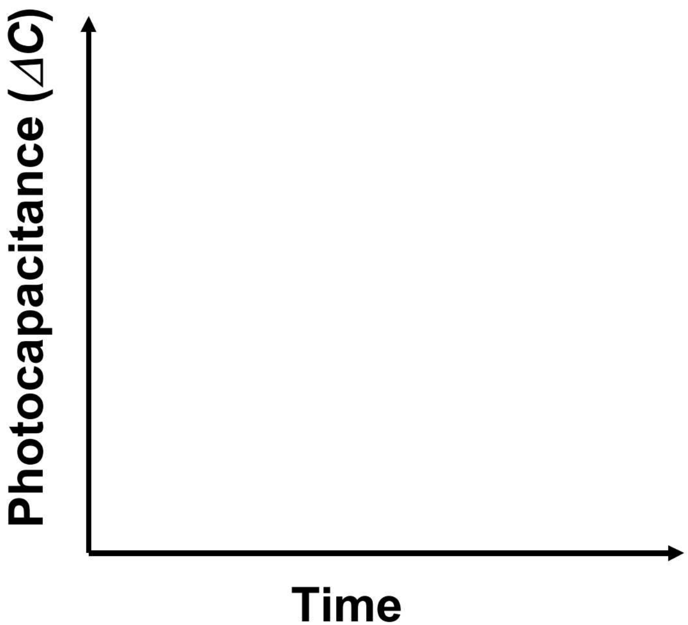
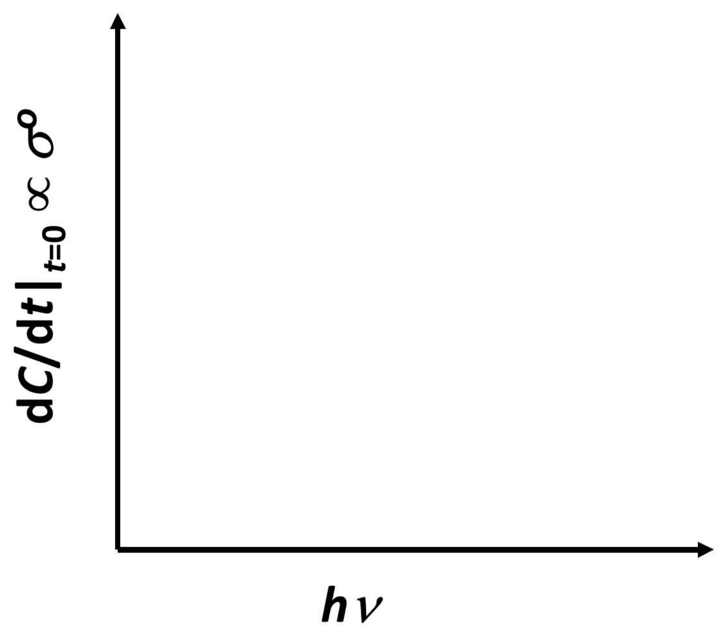
Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- **Deep level defect optical cross-section:** $\sigma^o = e^o/\phi = \alpha/N_t$
- $\sigma^o(h\nu) \propto \mathrm{d}C(t)/\mathrm{d}t|_{t=0}$





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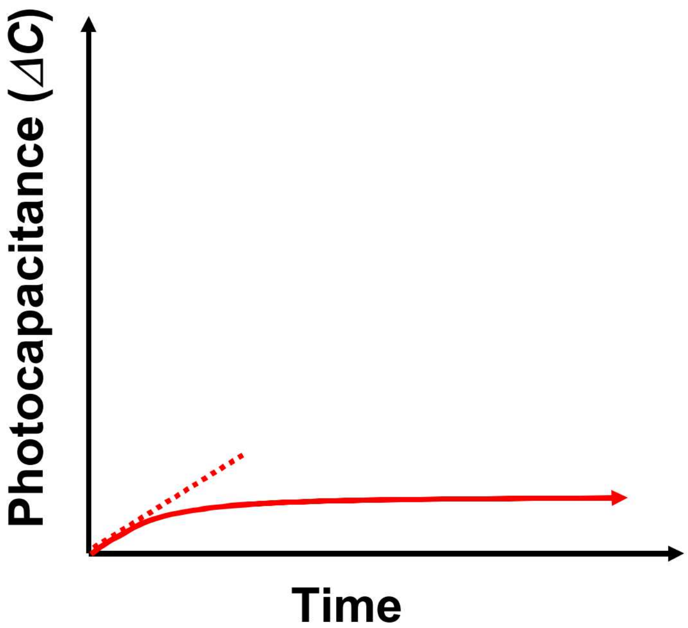

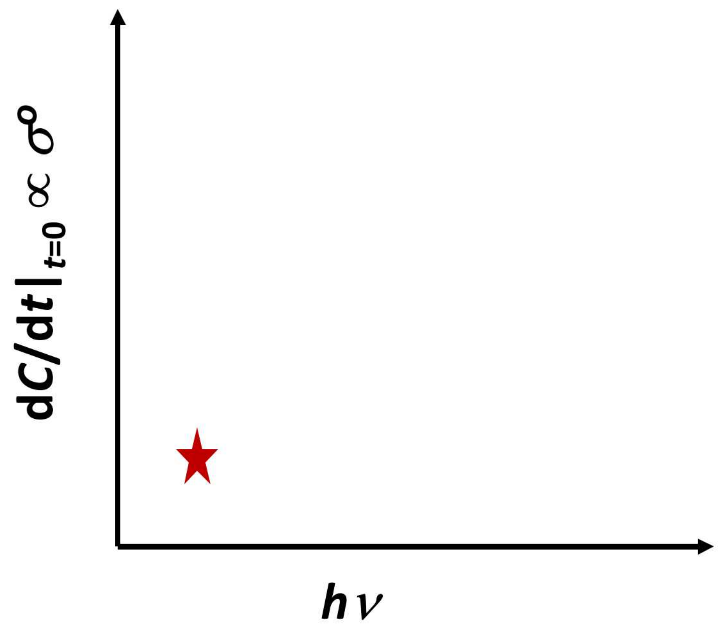

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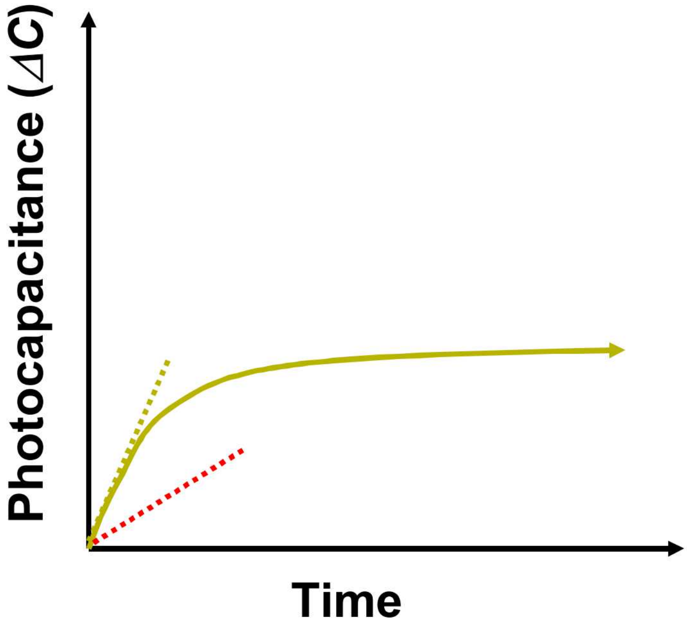

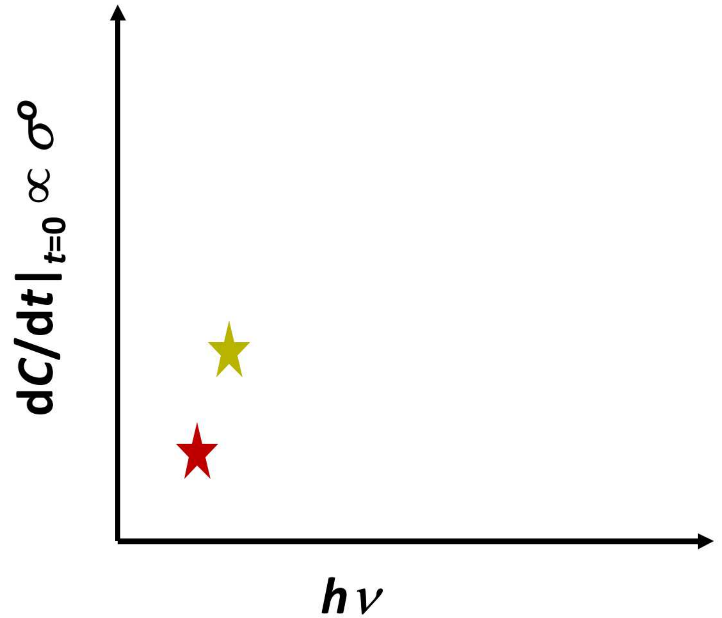

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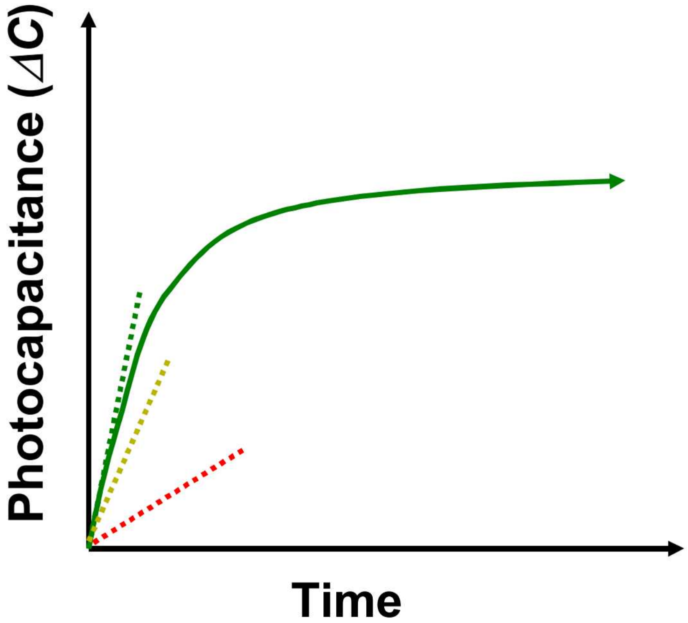

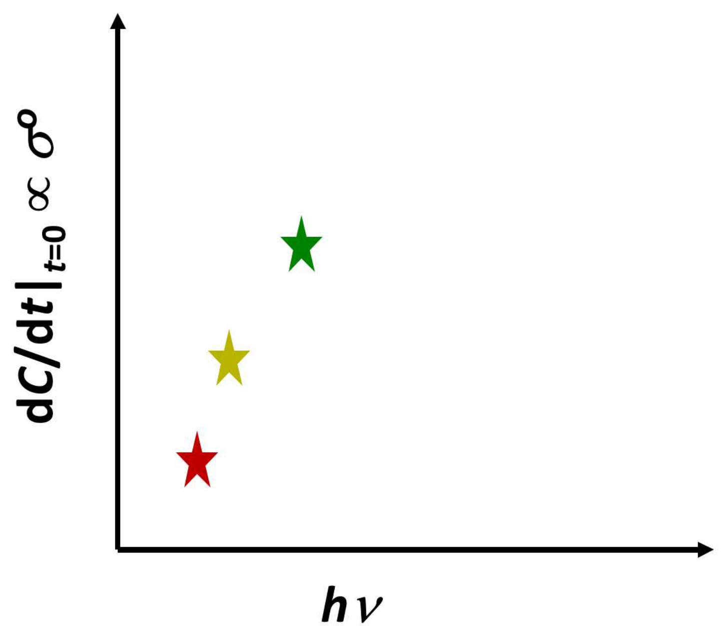

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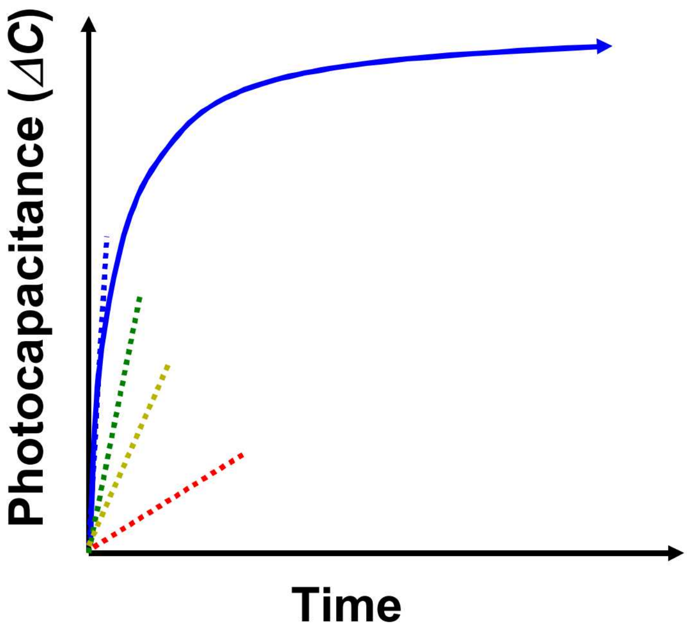

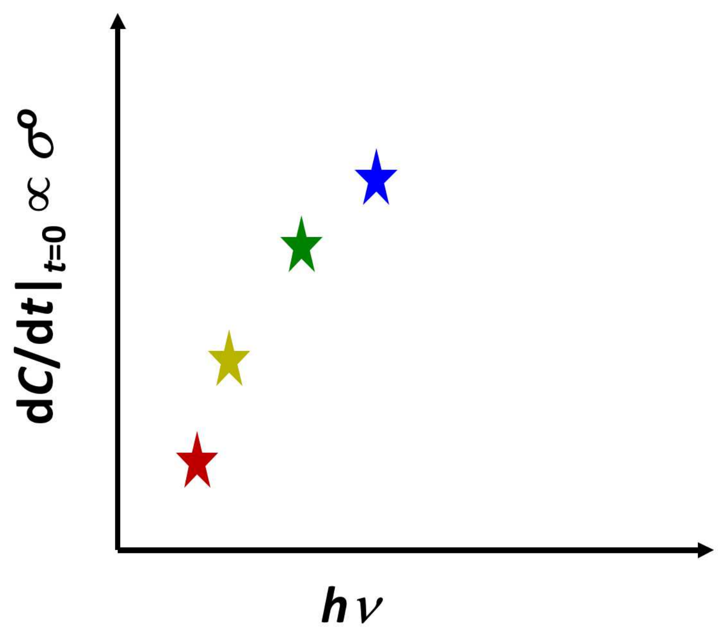

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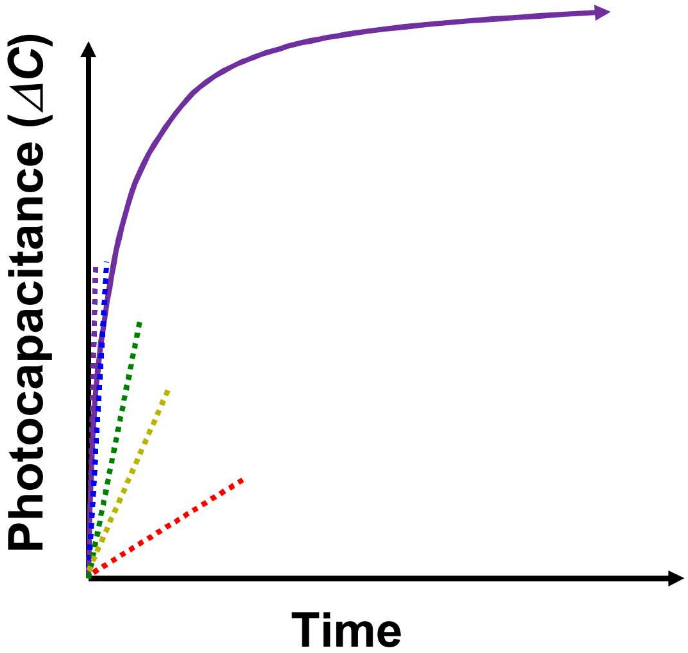

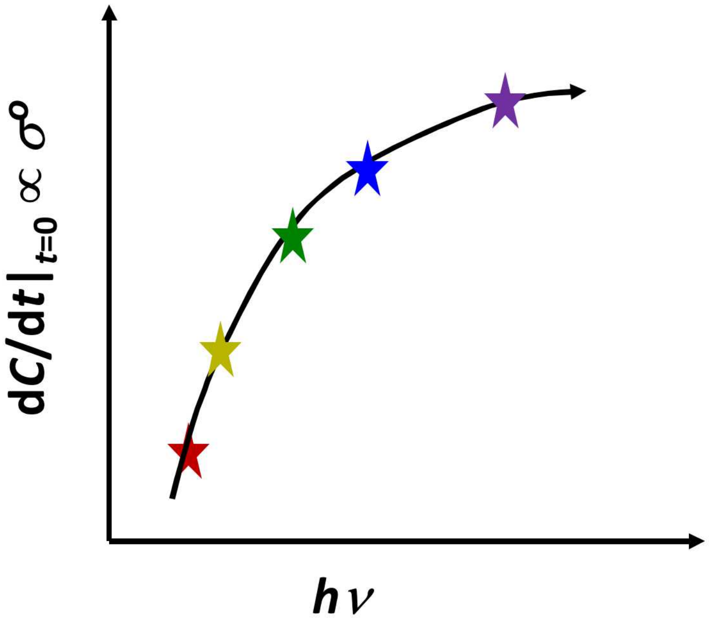

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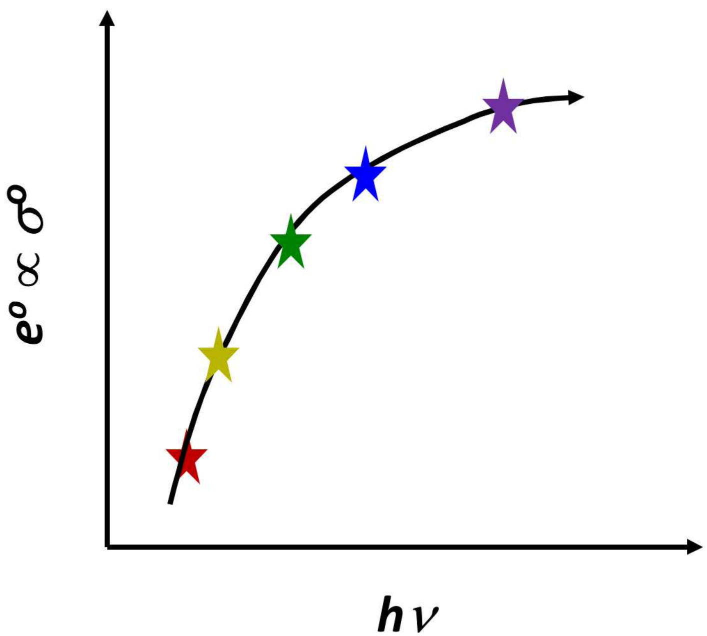
Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

- **Determine deep level energy E_o from lineshape of $\sigma^o(h\nu)$**
- **Discuss defect density later…**

Optical analog of Arrhenius plot



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

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

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

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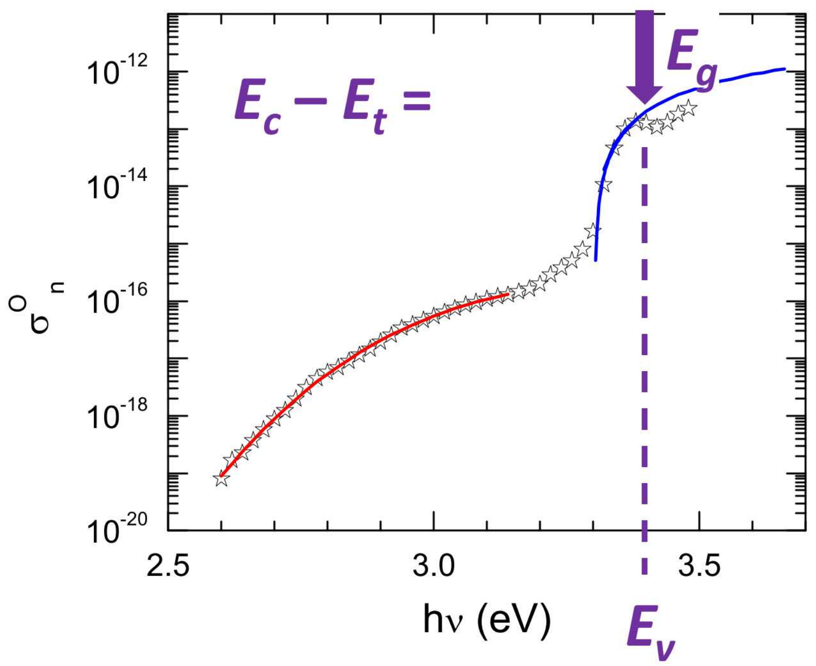
Interpretation of DLOS spectra

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)

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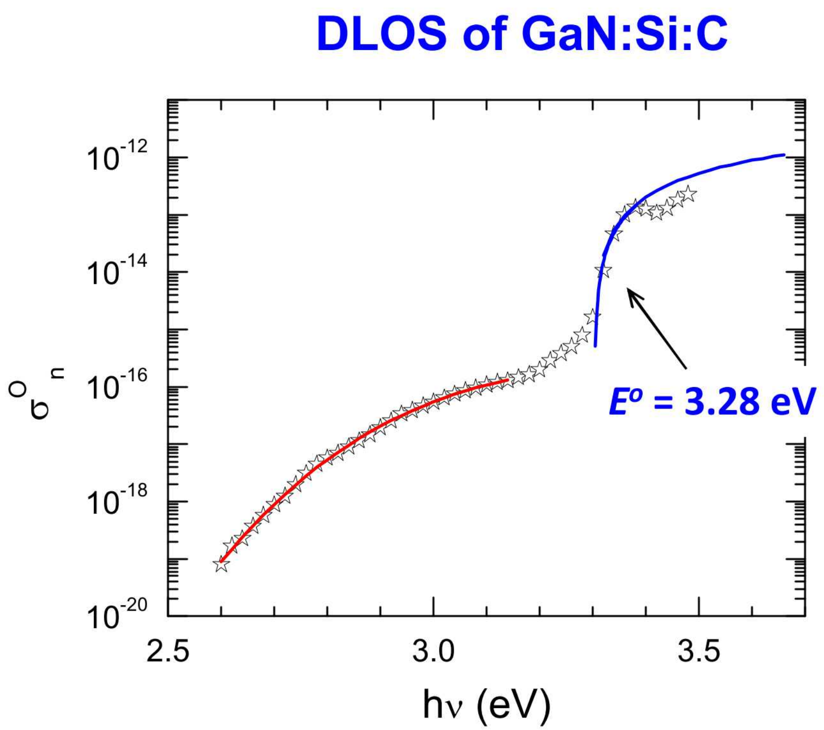

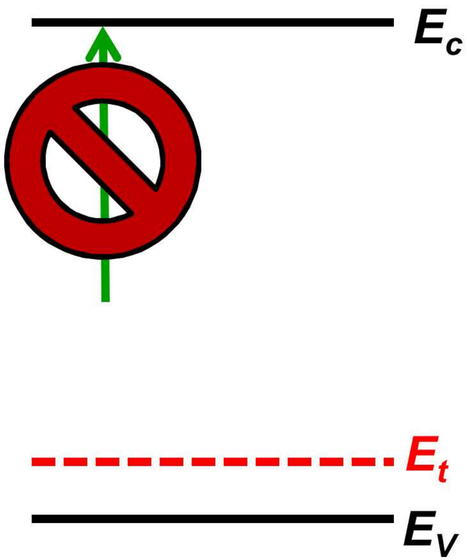

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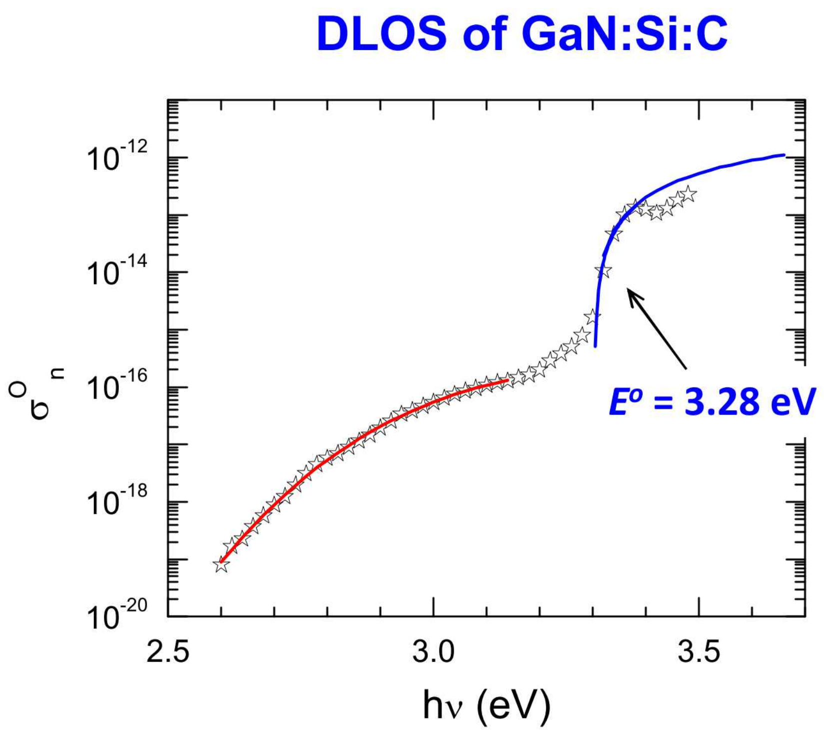

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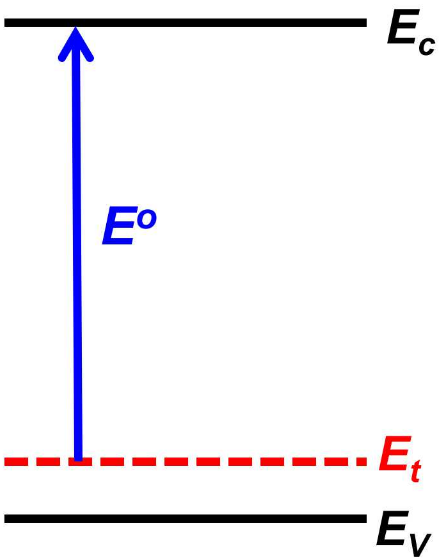

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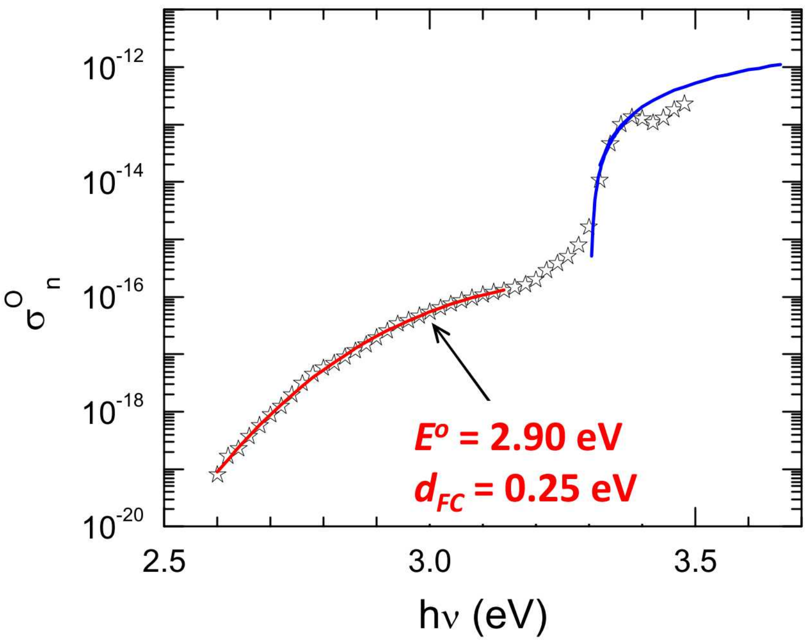

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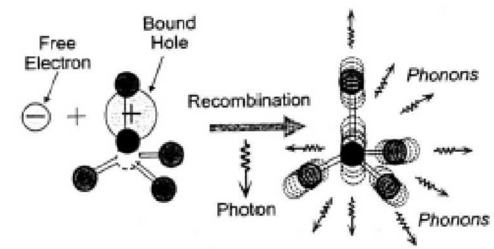
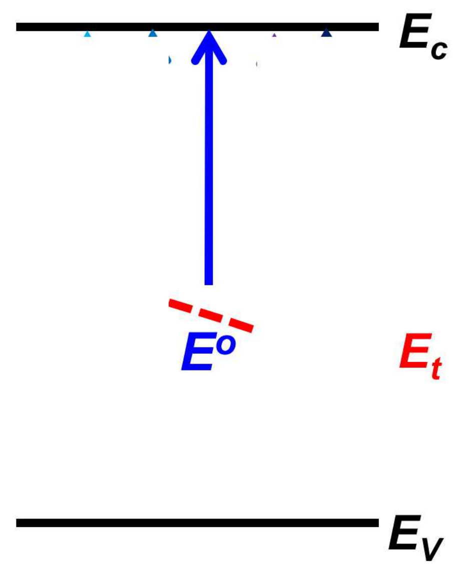


M. A. Reshchikov JAP 97 061301 2005



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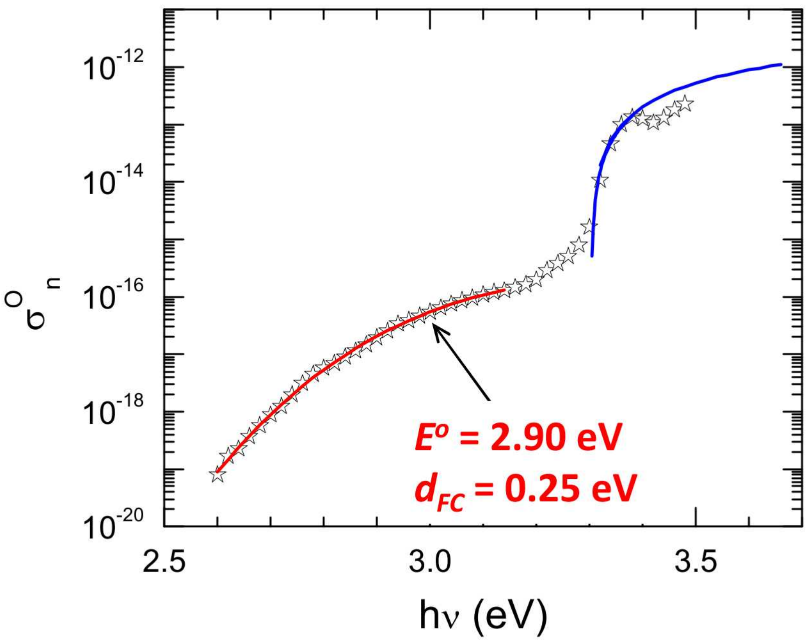

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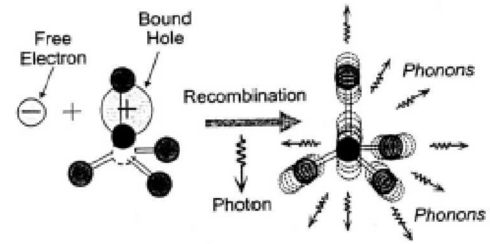

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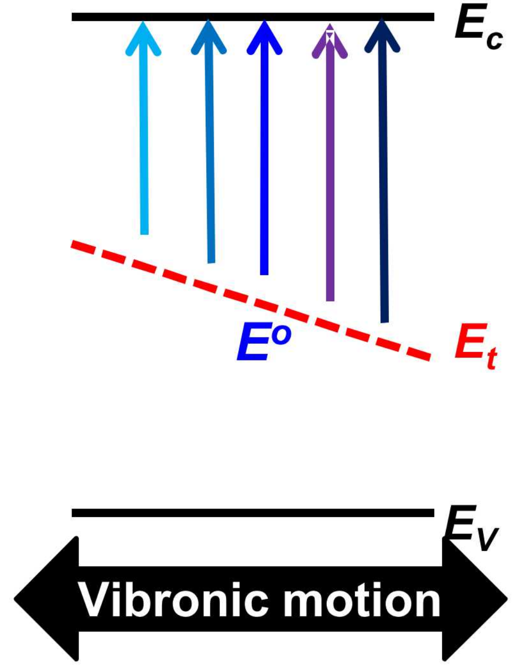

Quantify E^o for sharp and broad defect absorption spectra

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

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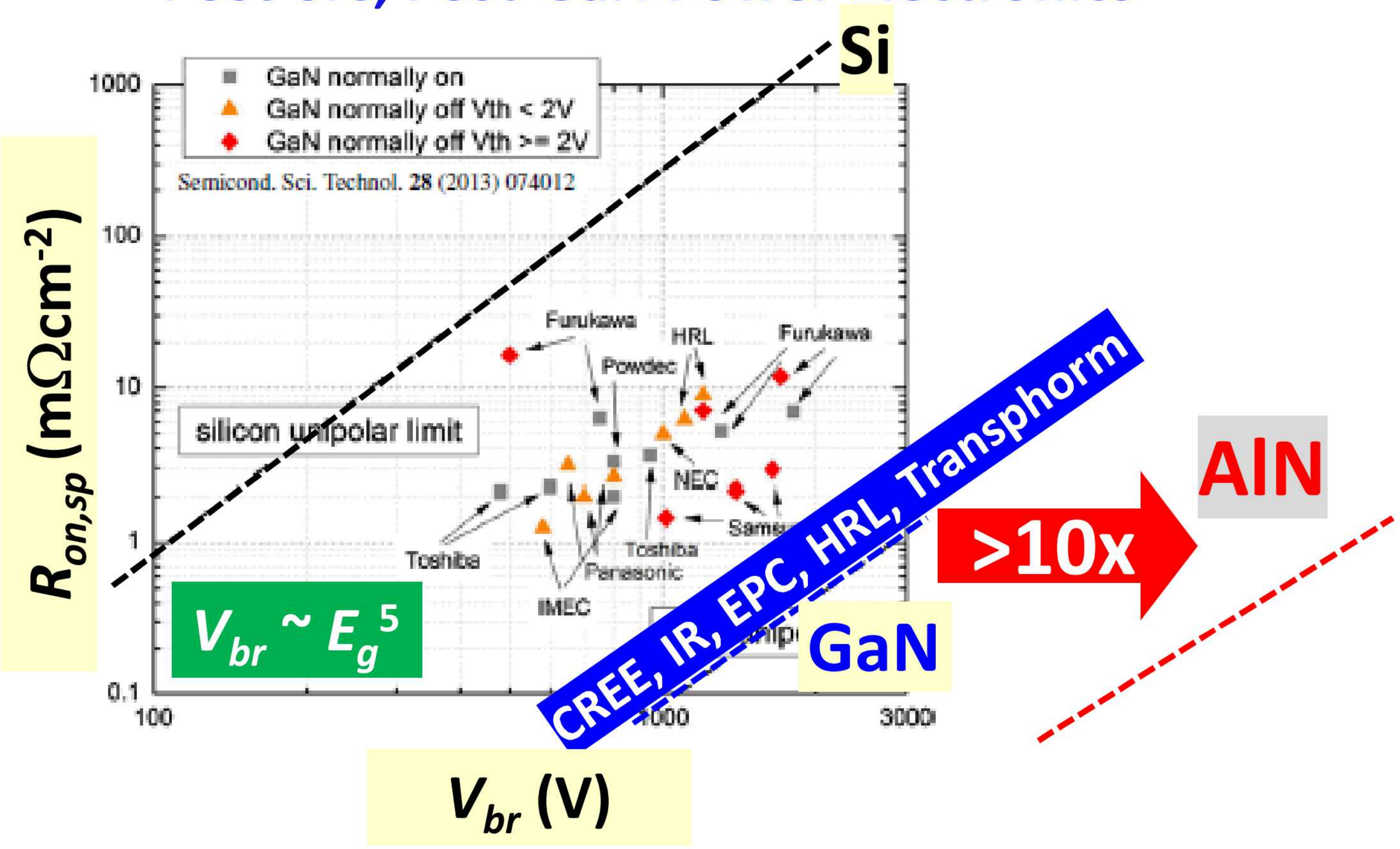
Ultra-wide band gaps: Next frontier of power electronics

Post-SiC, Post-GaN Power Electronics



- ➢Ultra-wide band gap (UWBG) semiconductors (E_g > 4 eV) have potential for dramatic increase in breakdown voltage (V_{br})
- ➢Must understand fundamental relationship between UWBG doping and defects

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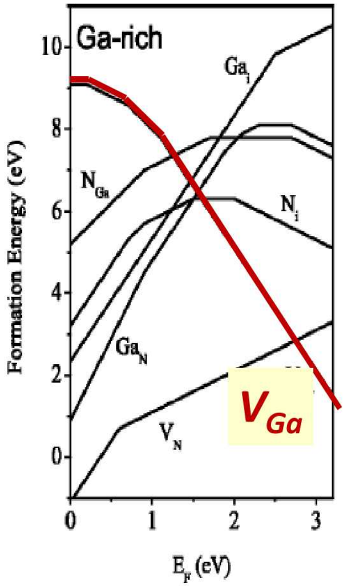
Theory: UWBGs self-compensate by native defect formation

GaN defect formation

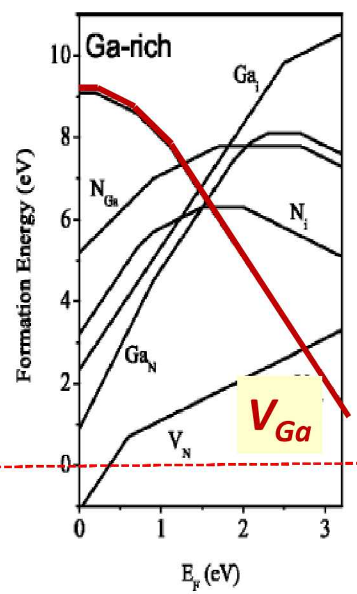


Appl. Phys. Rev.: C. G. Van de Walle and J. Neugebauer

- **Compensating defects become more favorable with increasing E_g**
- **Carrier capture reduces defect formation energy by ~ E_g**

Theory: UWBGs self-compensate by vacancy formation

GaN defect formation



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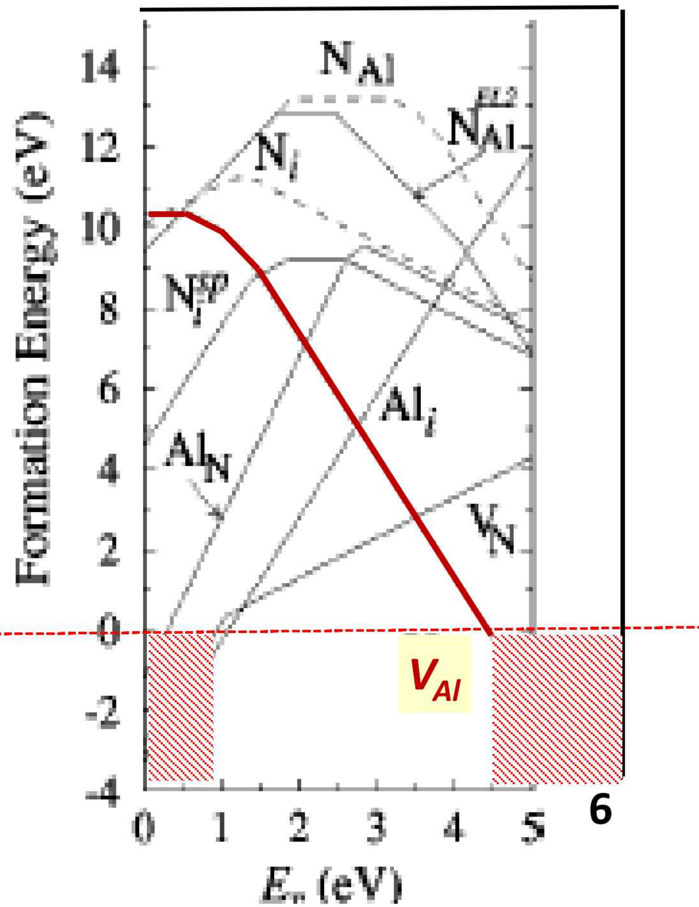
AlN defect formation



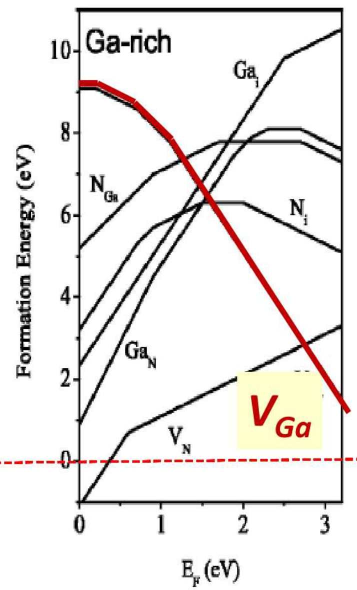
C. Stampfl[1] and C. G. Van de Walle[2]
PHYSICAL REVIEW B, VOLUME 65, 155212

- ➢ **Vacancy formation energy becomes negligibly small for UWBGs**
- ➢ **Defect formation pins E_f and completely compensates dopants**

Theory: UWBGs self-compensate by vacancy formation

AlN defect formation

GaN defect formation



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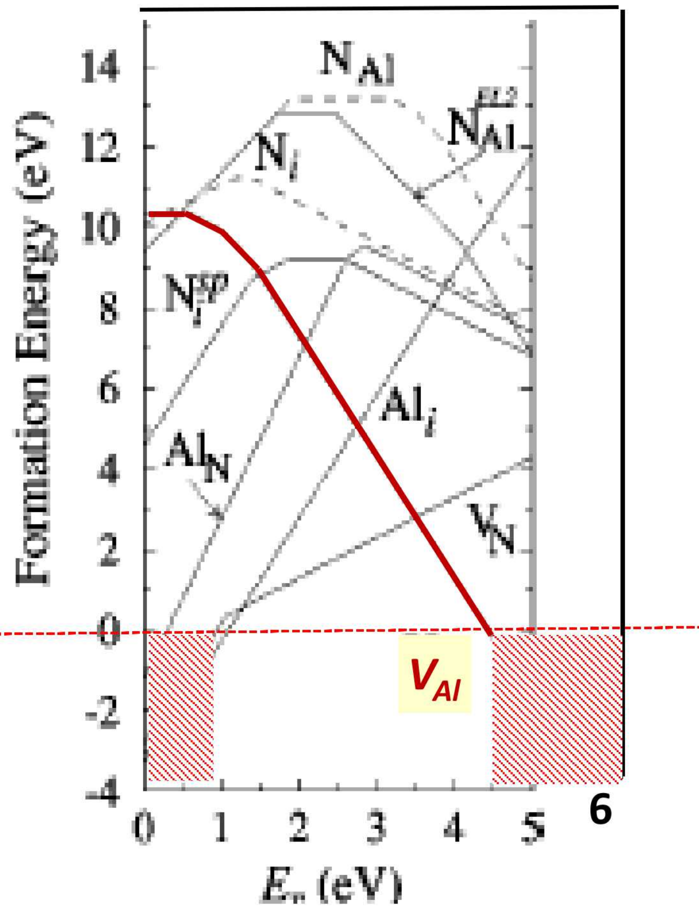
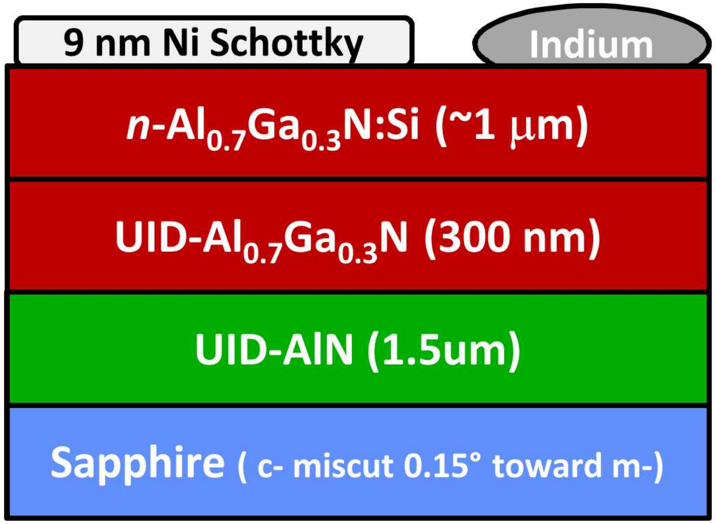


C. Stampfl[1] and C. G. Van de Walle[2]
PHYSICAL REVIEW B, VOLUME 65, 155212

- **Do compensating defects limit *n*-type doping in Al-rich AlGaN?**
- **If so, what are the physical origin of the defects?**
- **How can they be controlled?**

Study interplay of defects and doping in *n*-$Al_{0.7}Ga_{0.3}N$



- $Al_{0.7}Ga_{0.3}N$ grown by metal-organic vapor phase epitaxy (MOVPE)
- TDD ~ 1 – 3 × 10^9 cm^{-2}
- Growth temperature (T_g) of 1160 °C or 1060 °C
- Increased TMGa flux (2x) to maintain x_{Al} = 0.7
- Growth rate (μm/hr): 0.25 (1160 °C), 0.38 (1060 °C)

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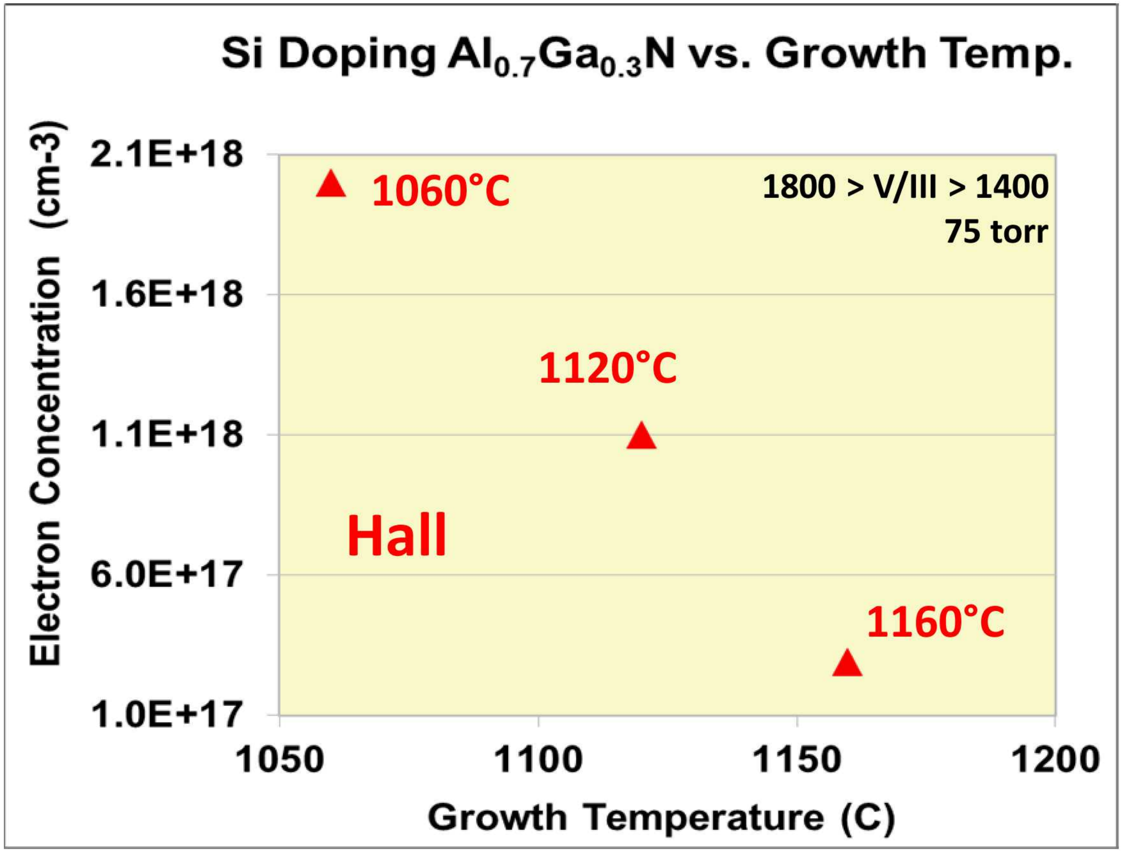
$Al_{0.7}Ga_{0.3}N$ dopant efficacy depends strongly on T_g



➢ ~4x decrease in free carrier concentration with increasing T_g

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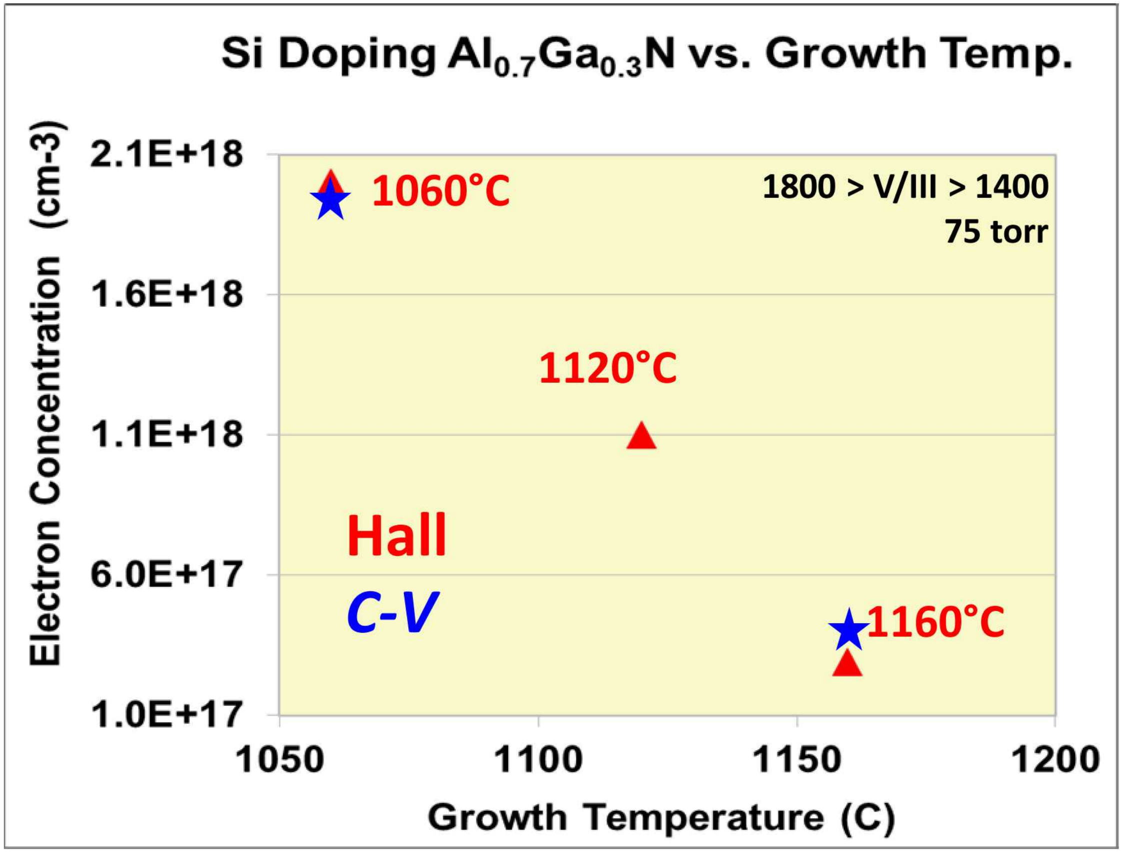
$Al_{0.7}Ga_{0.3}N$ dopant efficacy depends strongly on T_g



- **Agreement of Hall and *C-V* confirms Si dopant remains shallow**
- **Carrier concentration decreases due to compensation by defects**

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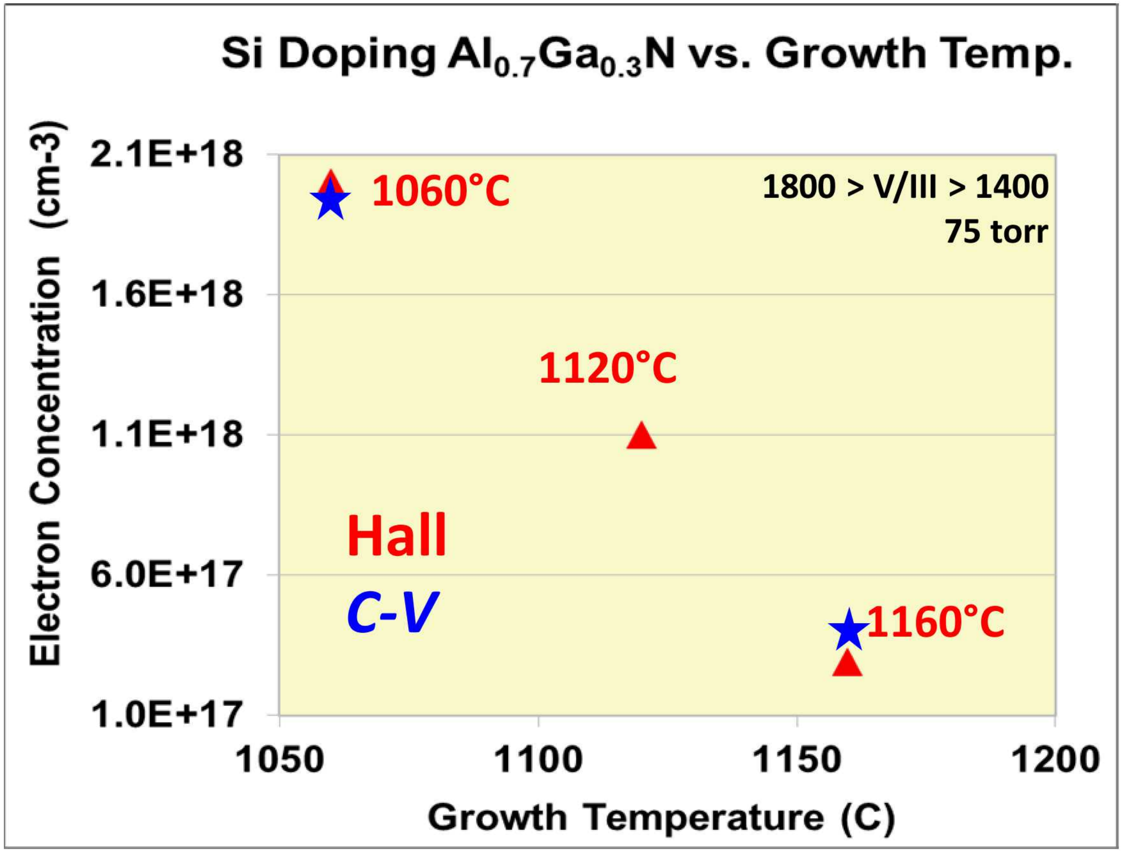
$Al_{0.7}Ga_{0.3}N$ dopant efficacy depends strongly on T_g



- Use deep level optical spectroscopy (DLOS) to understand how T_g mediates defects and doping in *n*-$Al_{0.7}Ga_{0.3}N$

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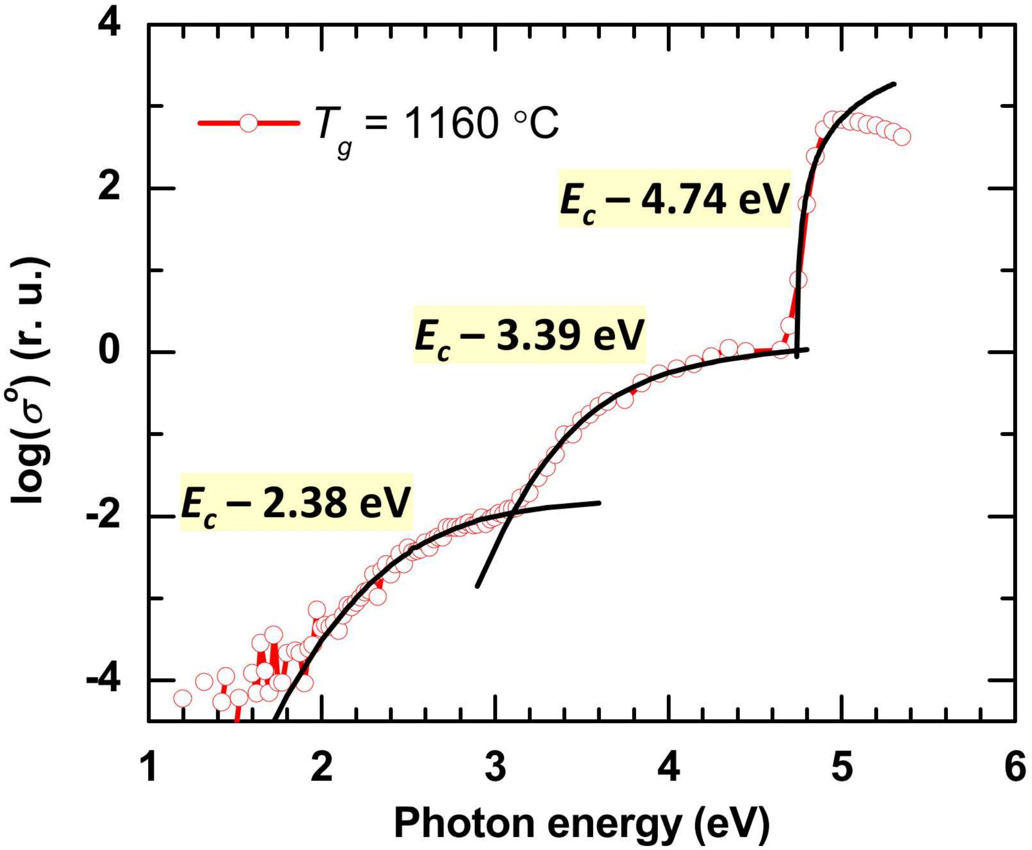
DLOS identifies $Al_{0.7}Ga_{0.3}N$ deep levels

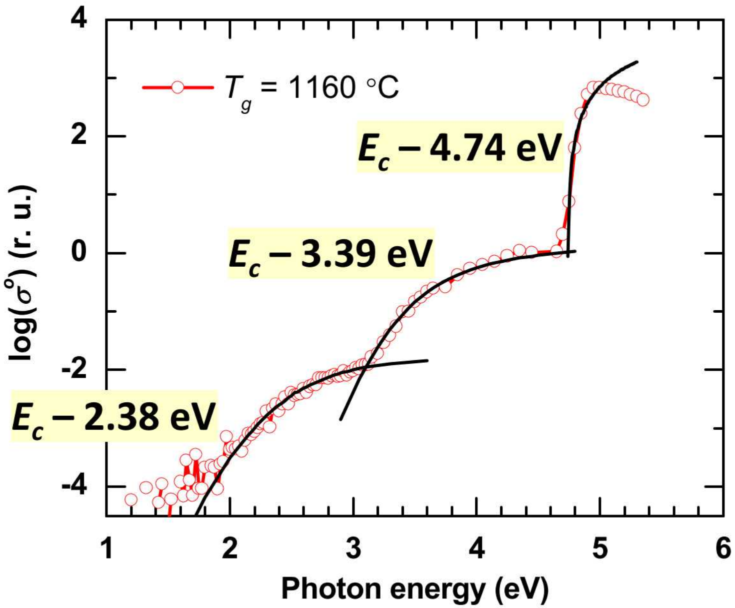
DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



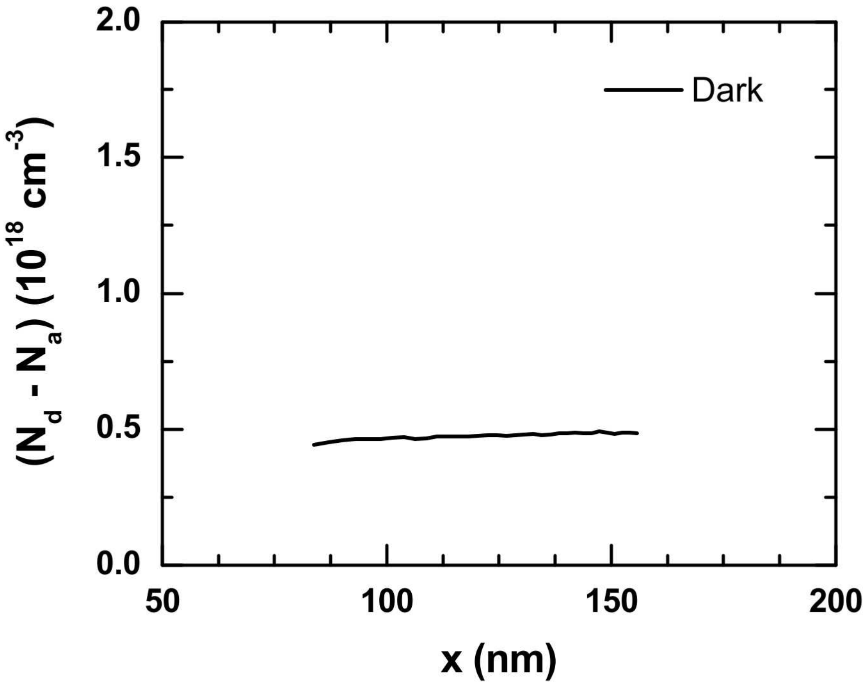
- Observe three deep level defects
- DLOS spectra ***does not*** convey defect density information

Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



- Lighted Capacitance-Voltage (LCV) measures defect density (N_t)
- $N_t = \Delta(N_d - N_a)$ measured by CV under sub-gap, monochromatic illumination

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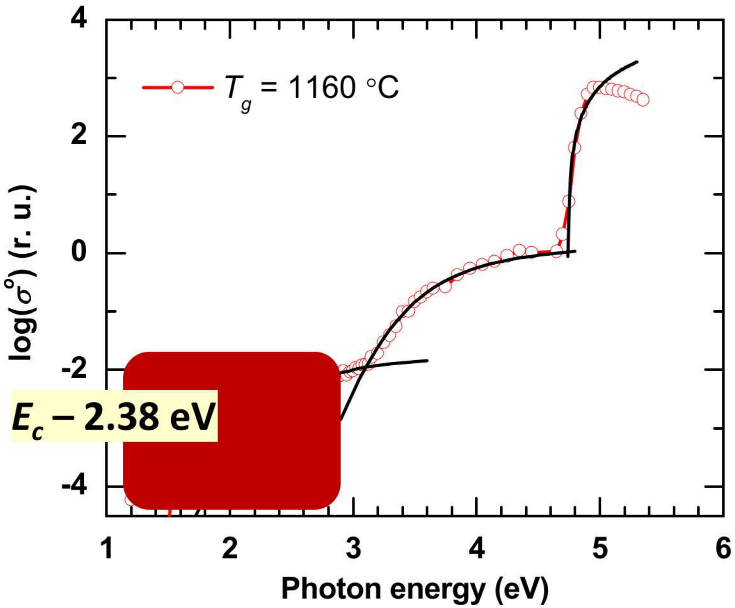
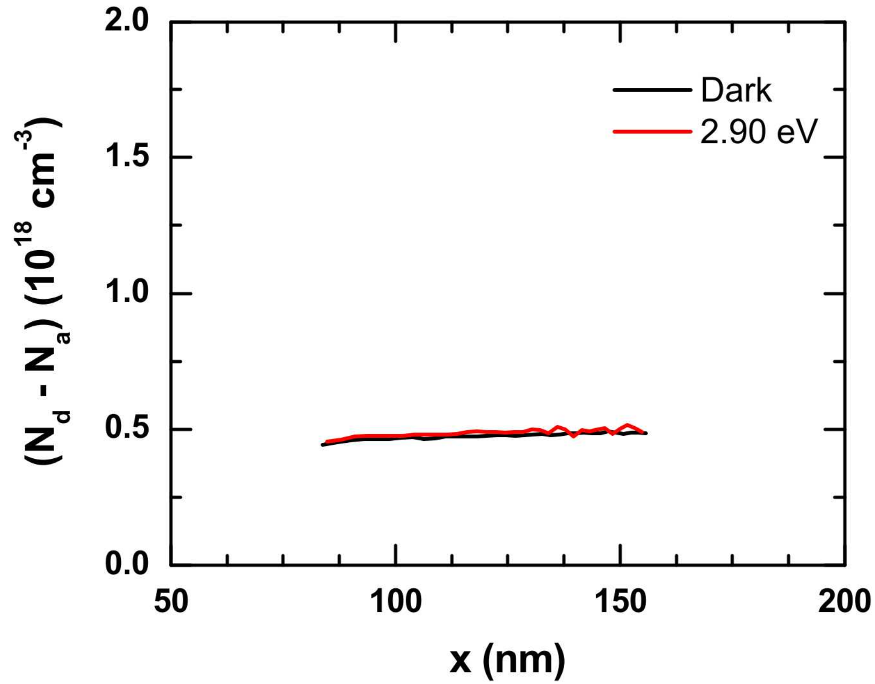
Lighted Capacitance-Voltage identifies compensators

DLOS of *n*-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV for VNA4153A



➢ ***E_c* – 2.38 eV level is not a strong compensation center**

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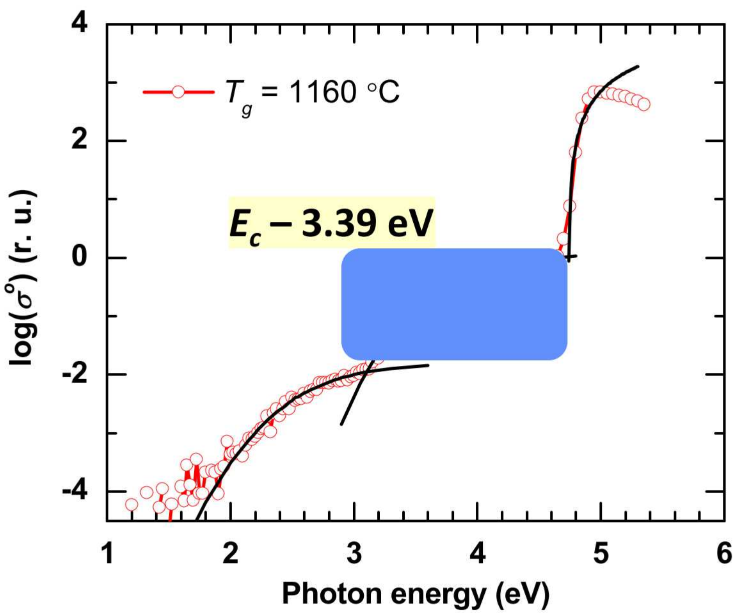
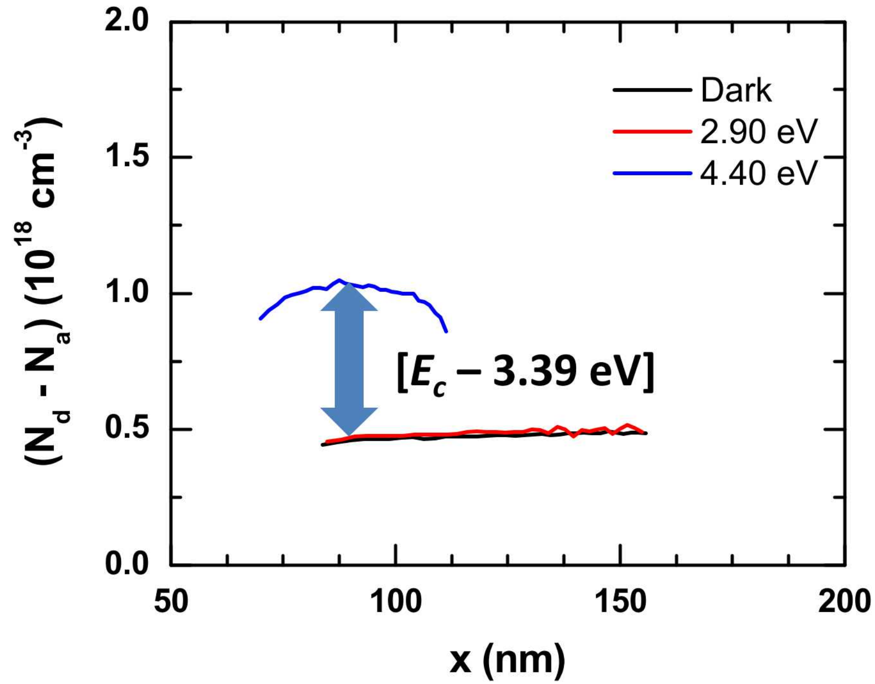
Lighted Capacitance-Voltage identifies compensators

DLOS of n-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV for VNA4153A



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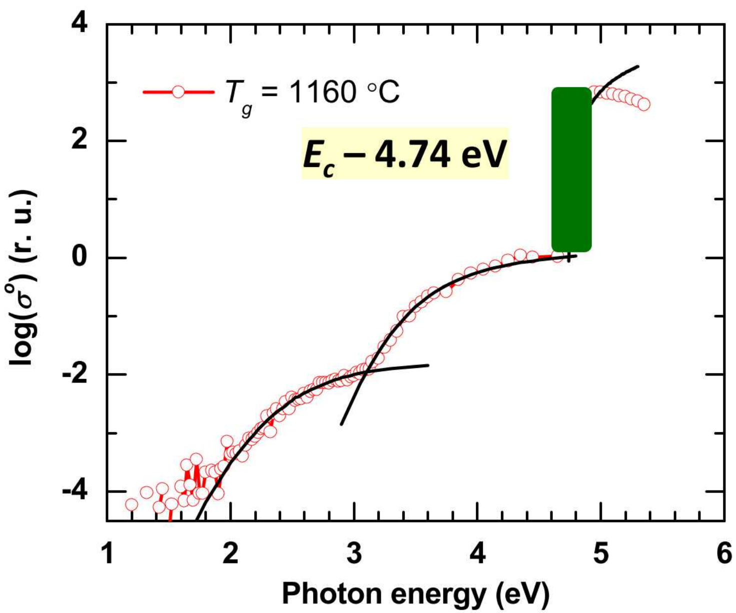
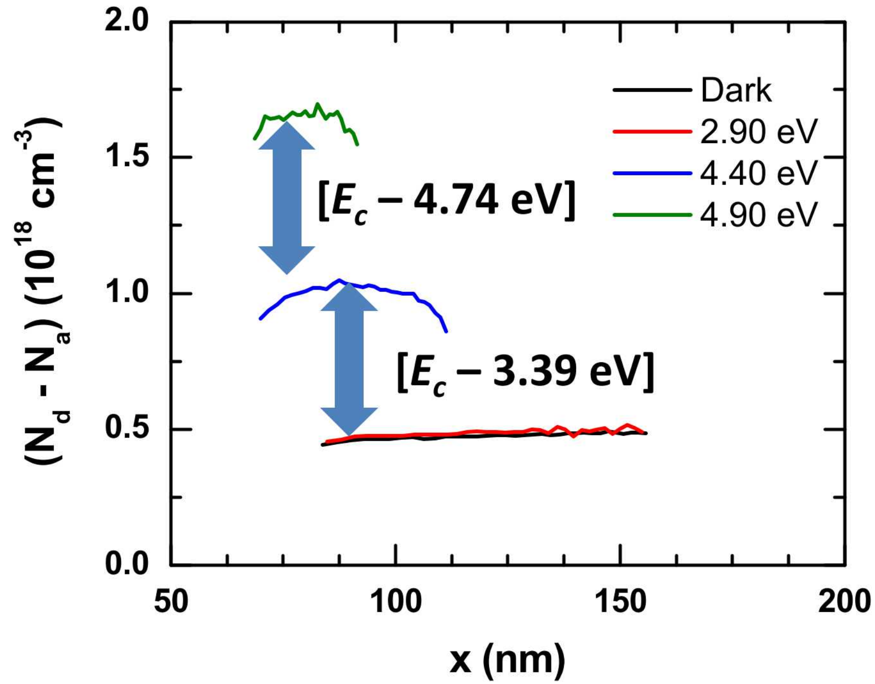
Lighted Capacitance-Voltage identifies compensators

DLOS of *n*-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



LCV for VNA4153A



➢ ***E***E_c – 3.39 eV and E_c – 4.74 eV defects are dominate compensating centers

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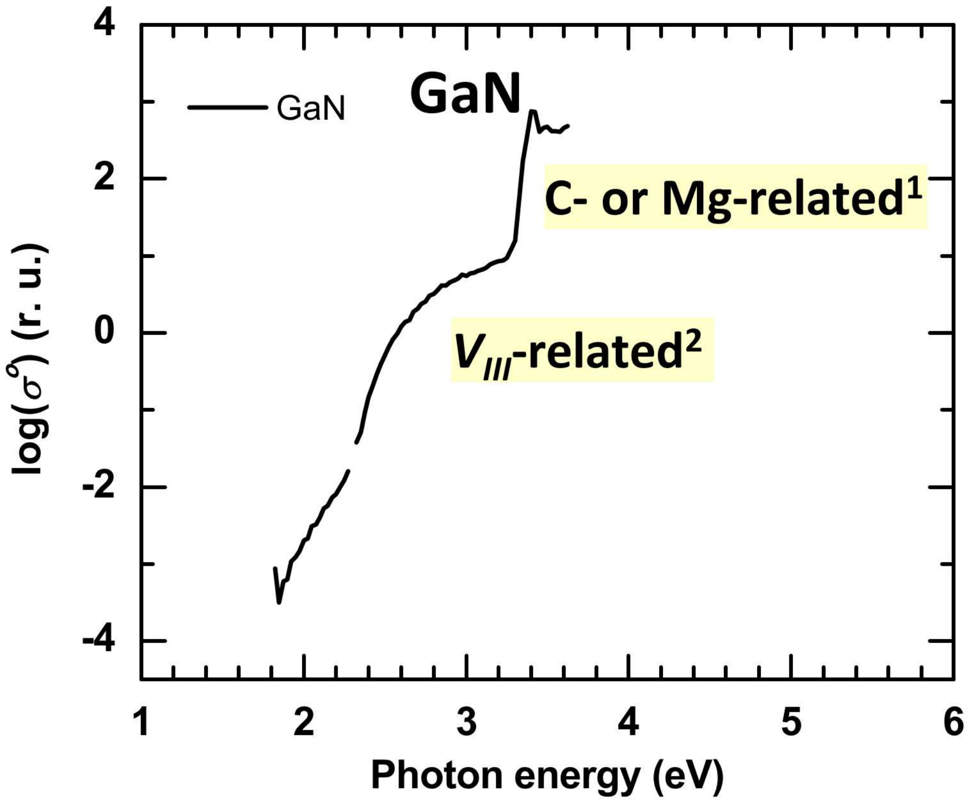
Identify physical origin from DLOS alloying study

DLOS of (Al)GaN *vs.* Al mole fraction



1. Hierro et al. APL 76 3064 2000
2. Hierro et al. APL 77 1499 2000

T. A. Henry, A. Armstrong,[a] A. A. Allerman, and M. H. Crawford
APPLIED PHYSICS LETTERS 100, 043509 (2012)

Identify physical origin from DLOS alloying study

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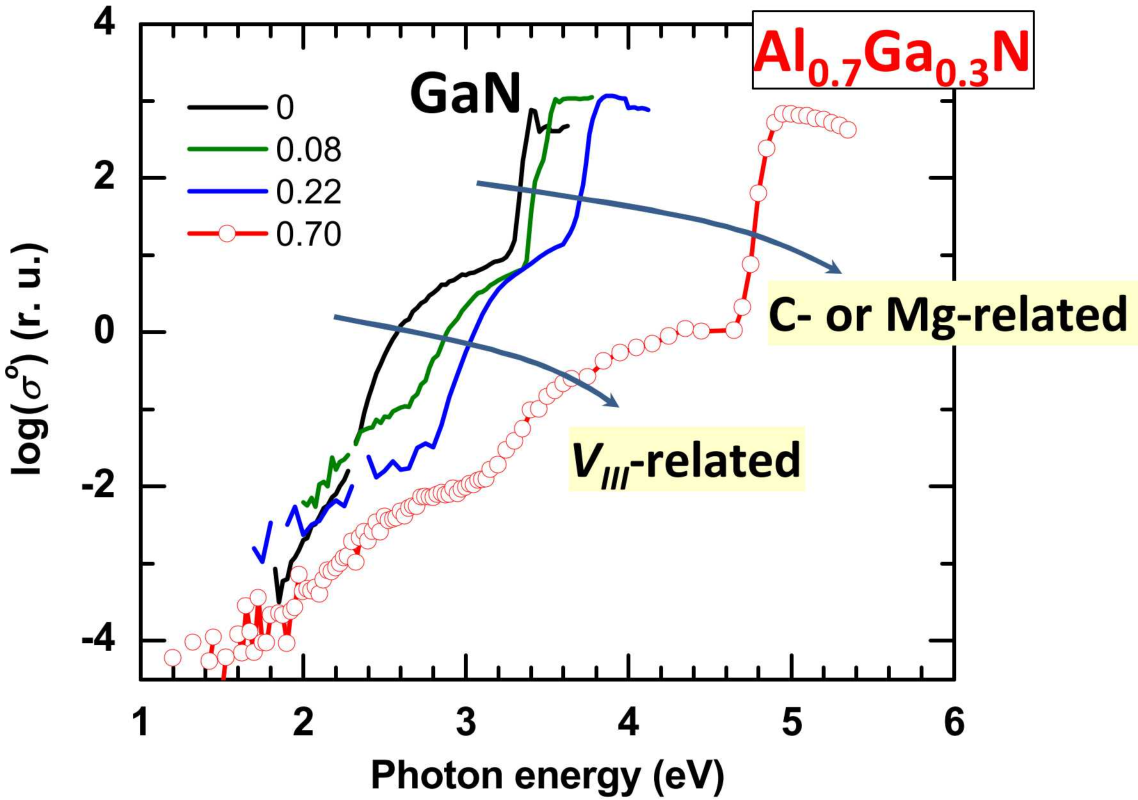

- **Deep level evolution with alloying suggests similar defect origins**
- **Attribute E_c – 4.74 eV level to C or Mg impurities**
- **Attribute E_c – 3.39 eV level to V_{III}-related defect**

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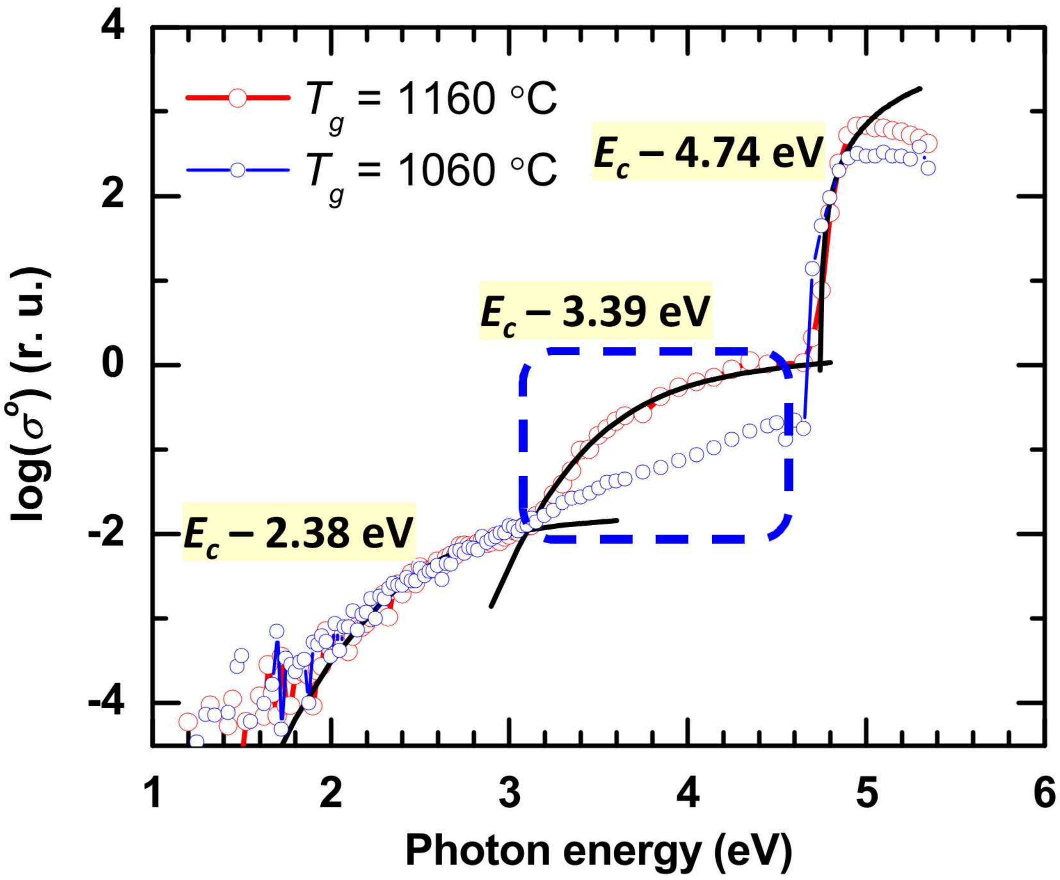
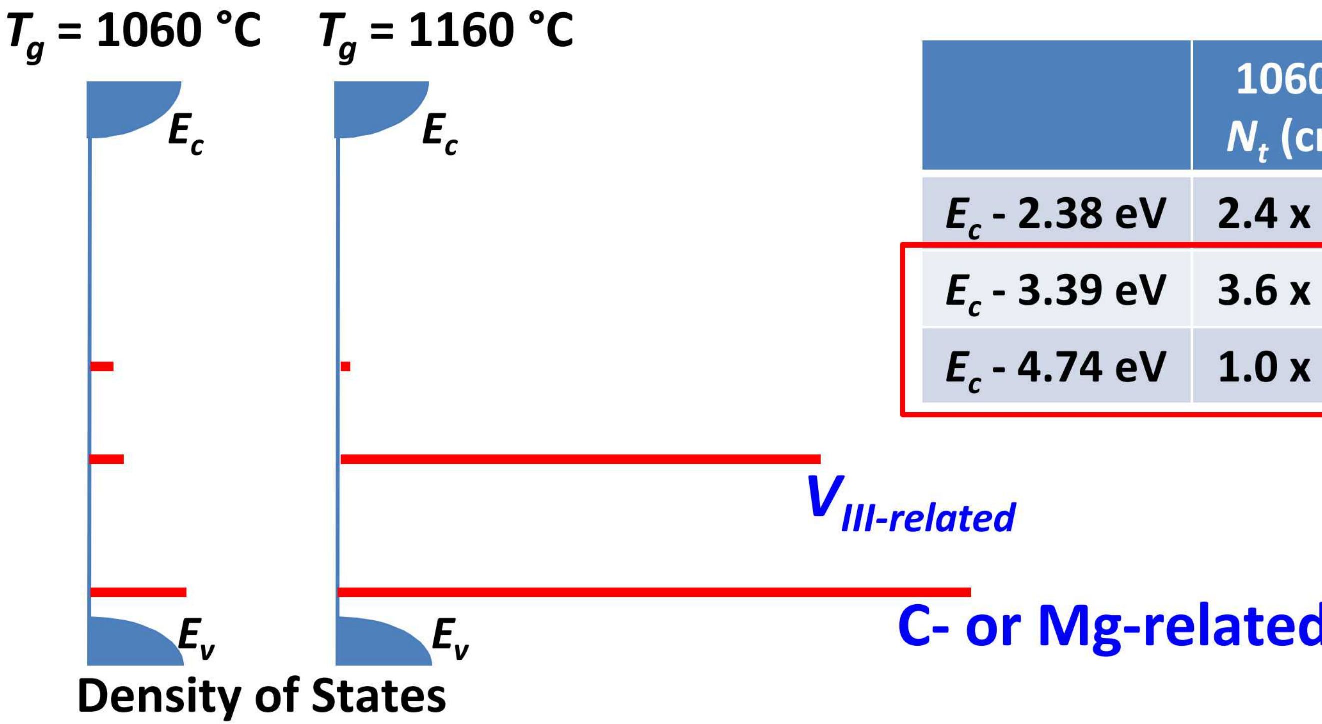
Lower $Al_{0.7}Ga_{0.3}N$ T_g suppresses defect formation

n-$Al_{0.7}Ga_{0.3}N$ DLOS spectra *vs.* T_g



- ➢ **V_{III}-related E_c – 3.39 eV deep level defect weakly evident for T_g = 1060 °C**
- ➢ **Qualitative evidence for reduced defect density**

Lower $Al_{0.7}Ga_{0.3}N$ T_g suppresses defect formation



	1060 °C N_t (cm^{-3})	1160 °C N_t (cm^{-3})	ΔN_t
E_c - 2.38 eV	2.4×10^{16}	1×10^{16}	0.4x
E_c - 3.39 eV	3.6×10^{16}	5.1×10^{17}	14x
E_c - 4.74 eV	1.0×10^{17}	6.6×10^{17}	6.6x

- Net 10x reduction in V_{III} and impurity defects with lower T_g → Unexpected
- Lower T_g may inhibit the very strong thermodynamic drive to form compensating point defects in UWBGs
- Complex tradespace among structural and electrical quality general to UWBG film epitaxy not encountered in conventional semiconductors

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