SAND2014-15505PE

Strong sensitivity of Si doping efficiency and deep level formation on growth temperature for *n*-type $Al_{0.7}Ga_{0.3}N$

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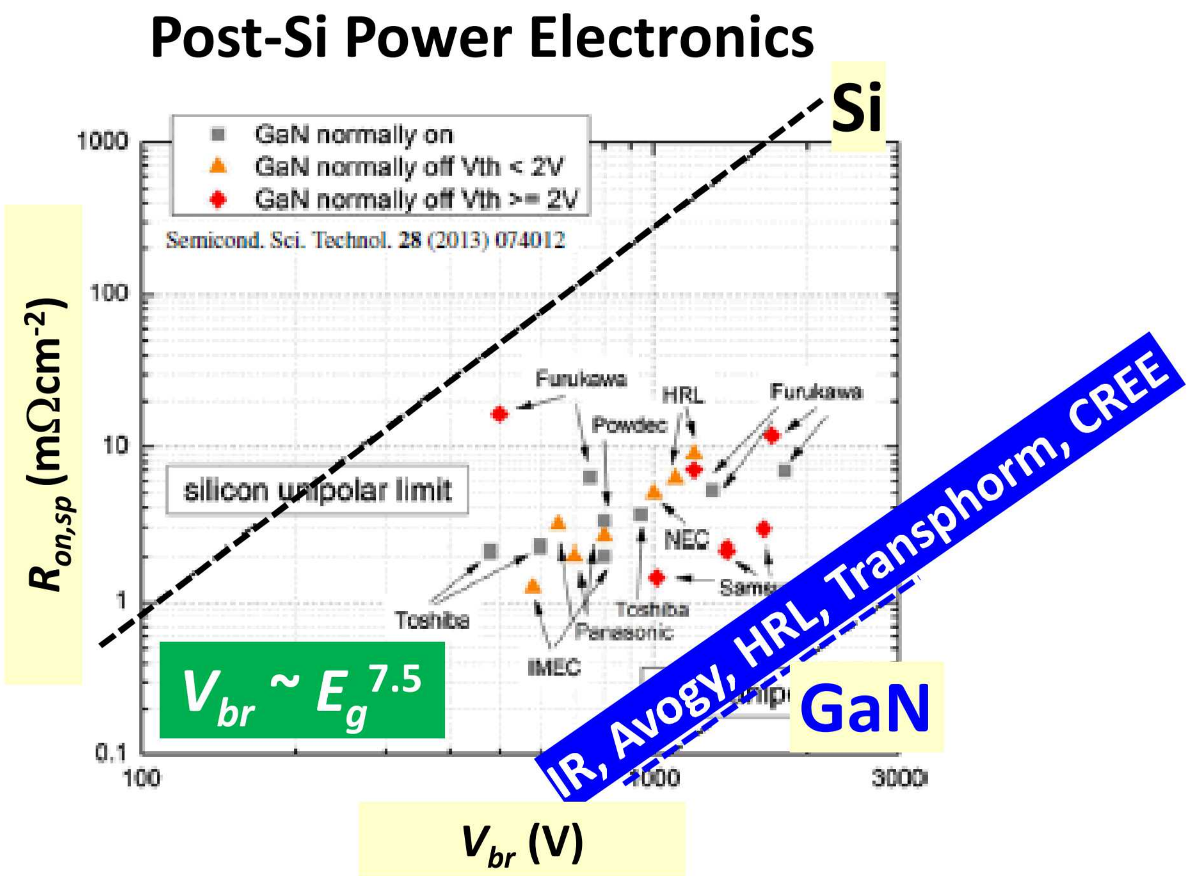
Ultra-wide band gaps: Next frontier of power electronics



➢Wide band gaps (WBGs) GaN and SiC displacing Si for power electronics

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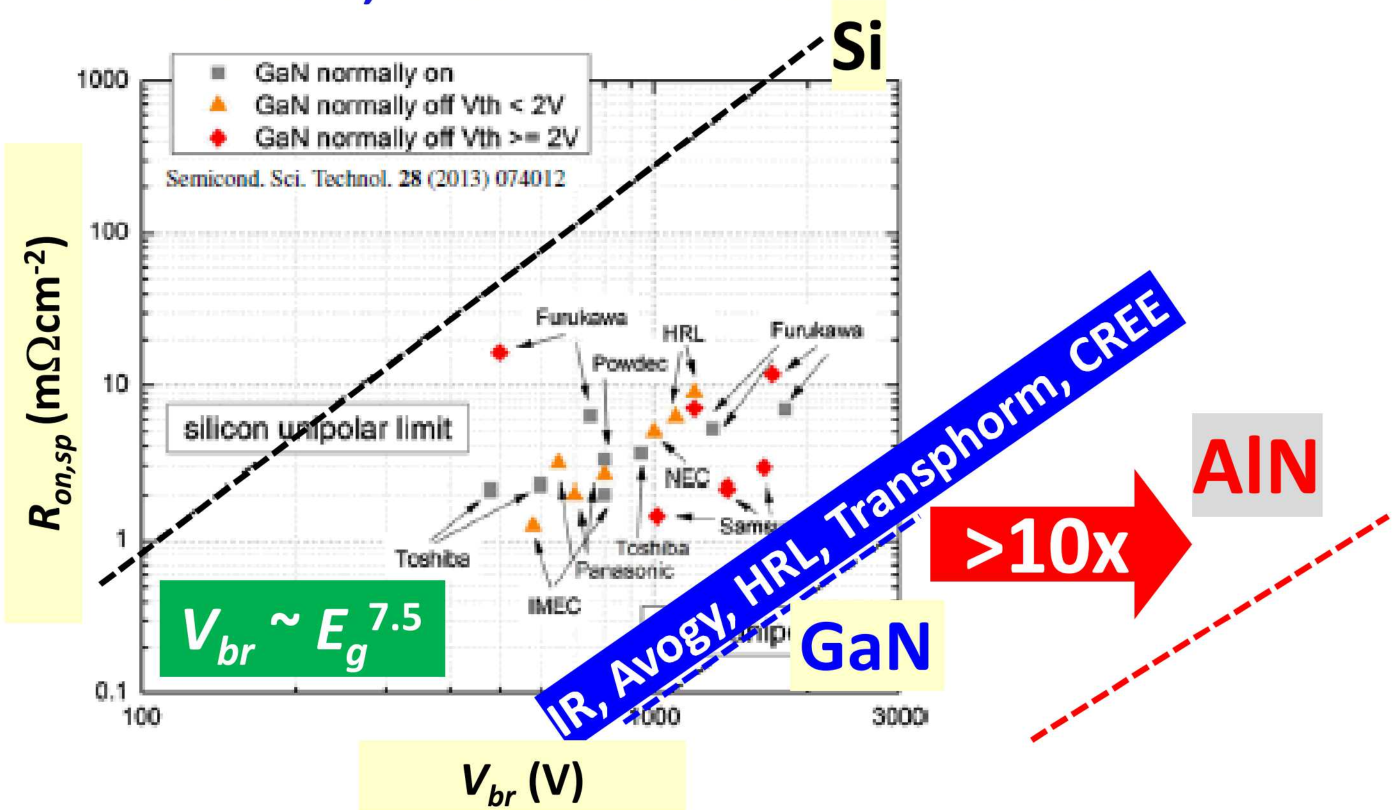
Ultra-wide band gaps: Next frontier of power electronics

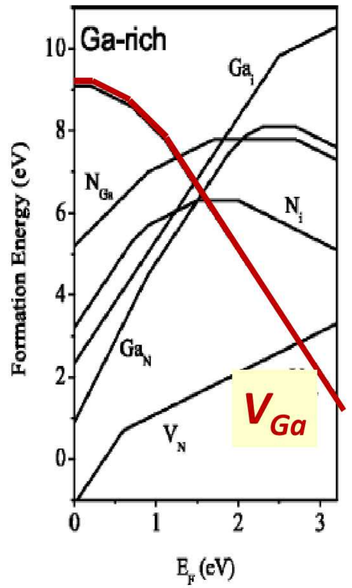
Post-SiC, Post-GaN Power Electronics



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

Theory: UWBGs self-compensate by native defect formation

GaN defect formation

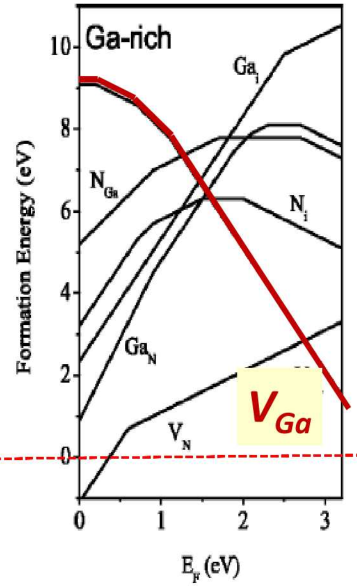


Appl. Phys. Rev.: C. G. Van de Walle and J. Neugebauer

- **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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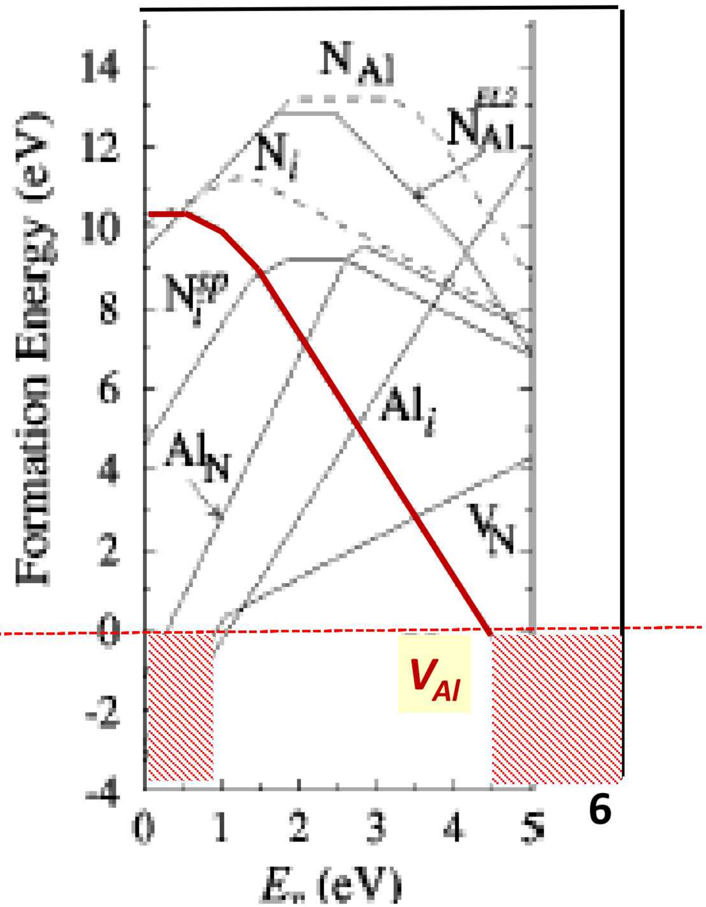
AlN defect formation

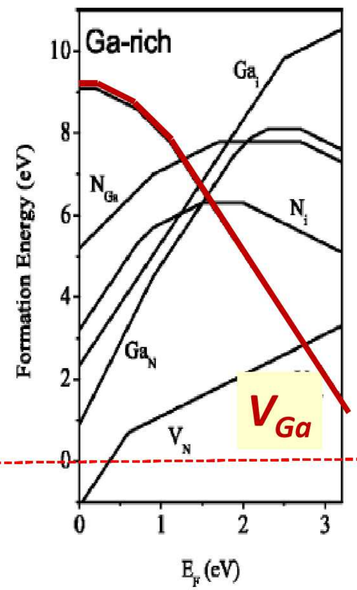


C. Stampfl[1] and C. G. Van de Walle[2]
PHYSICAL REVIEW B, VOLUME 65, 155212

- Vacancy formation energy becomes negligibly small for UWBGs
- Autonomic defect formation pins E_f and completely compensates dopants

Theory: UWBGs self-compensate by vacancy formation

GaN defect formation



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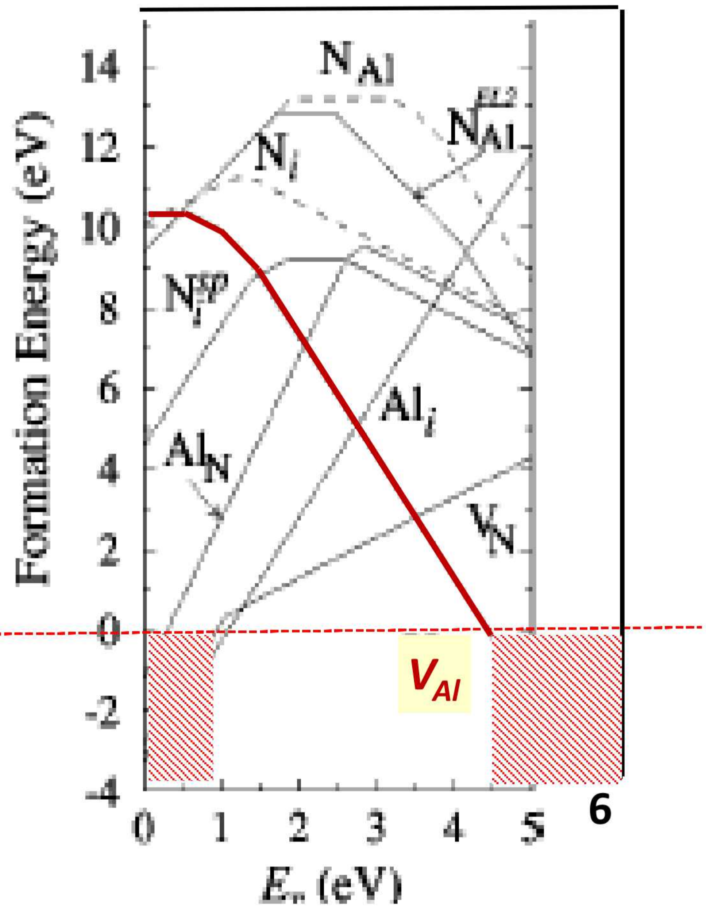
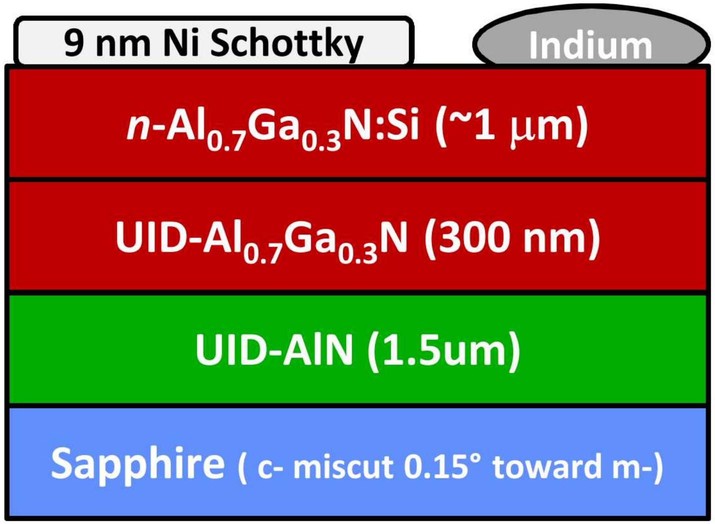
AlN defect formation



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

- 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 ~ $1 – 3 \times 10^9$ cm^{-2}

1. Cantu *et al.* APL 82, 3683 (2003).

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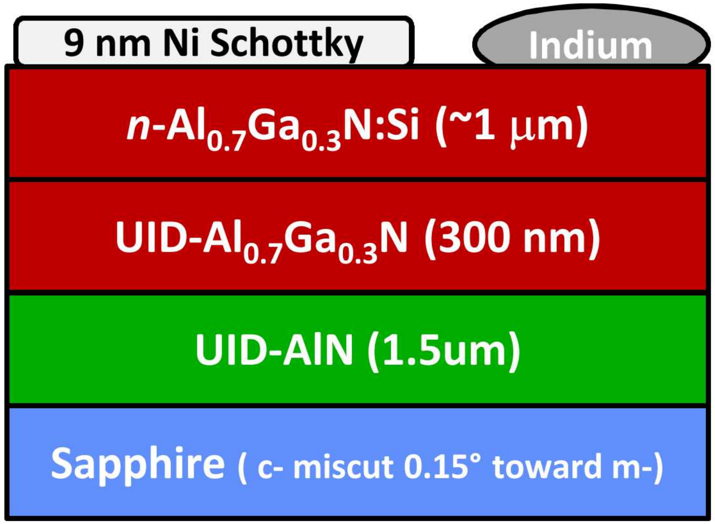
Study interplay of defects and doping in *n*-$Al_{0.7}Ga_{0.3}N$



- Growth temperature (T_g) range of 1060 - 1160 °C
  - Si flow rate constant
  - Increased TMGa flux (2x) to maintain x_{Al} = 0.7
  - Growth rate (μm/hr): 0.25 (1160 °C), 0.38 (1060 °C)
- Higher T_g improved surface morphology and likely reduced impurities[1]

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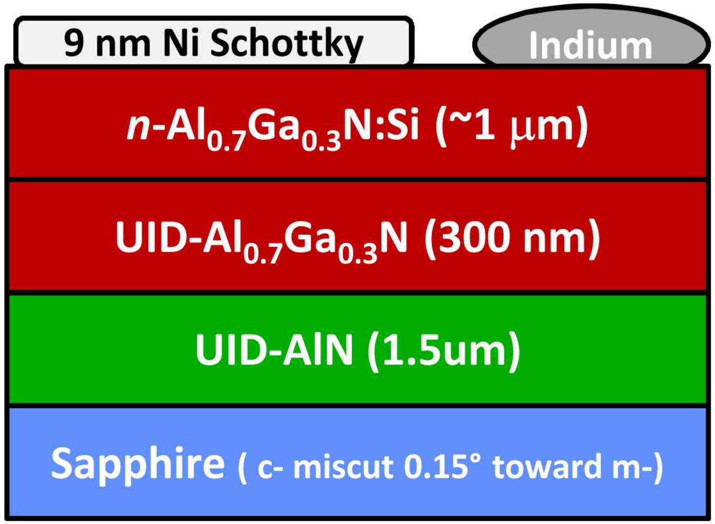

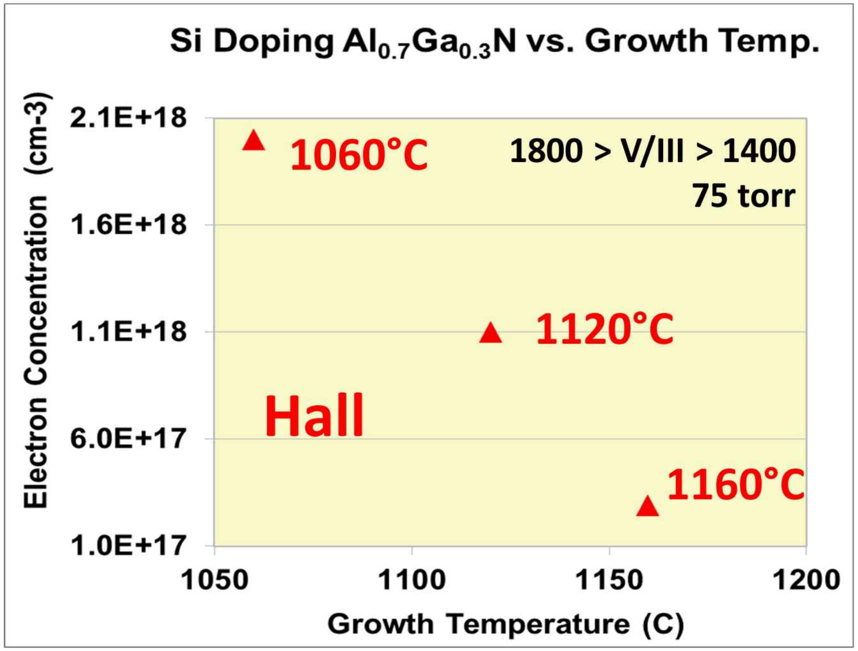

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- **$Al_{0.7}Ga_{0.3}N$ dopant efficacy 20x lower with higher T_g[1]**

1. Cantu *et al.* APL 82, 3683 (2003).

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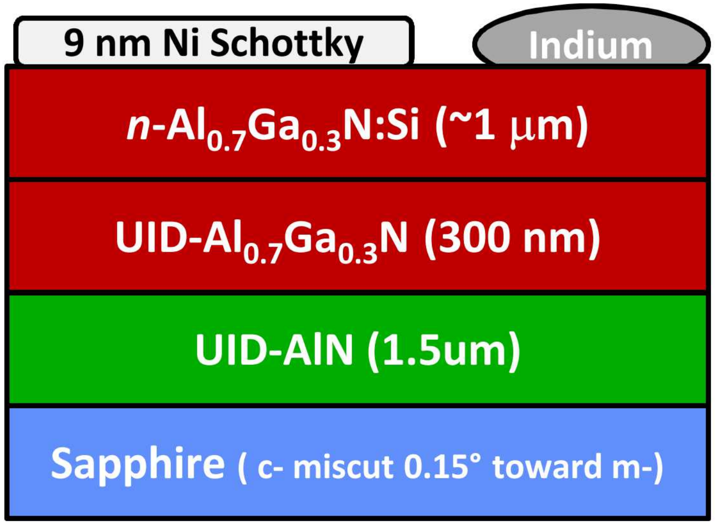
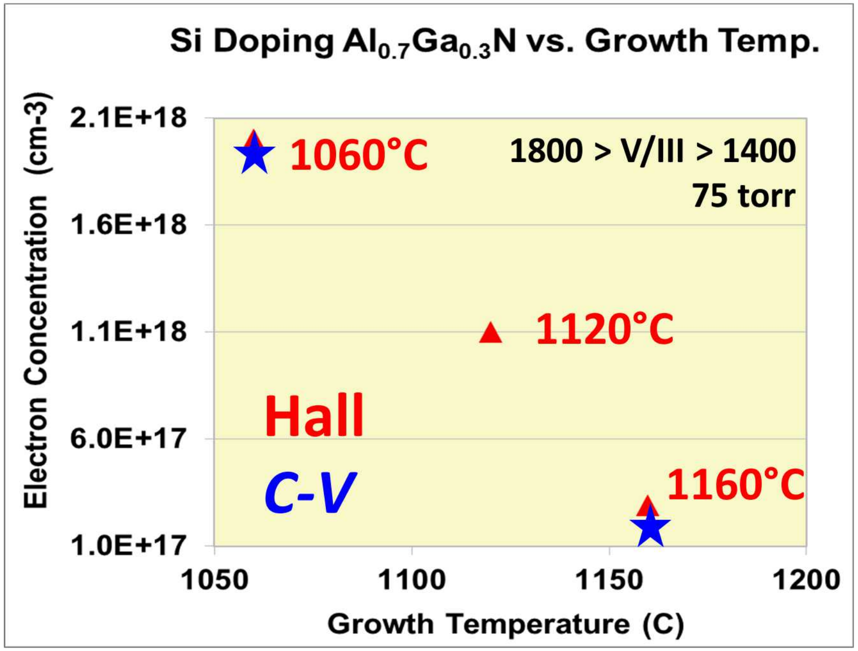
Study interplay of defects and doping in n-$Al_{0.7}Ga_{0.3}N$





- *C-V* and Hall show Si dopant remained shallow
- Decrease in *n* due to deep level defect compensation

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

1. Cantu *et al.* APL 82, 3683 (2003).

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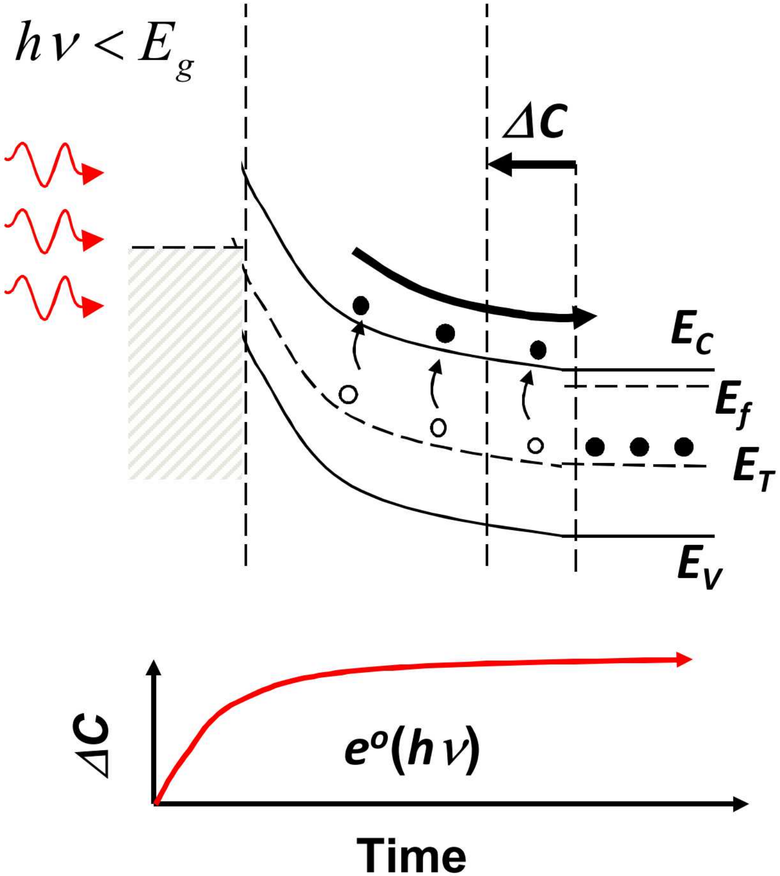
Deep Level Optical Spectroscopy

Deep Level Optical Spectroscopy (DLOS)[1]

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



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

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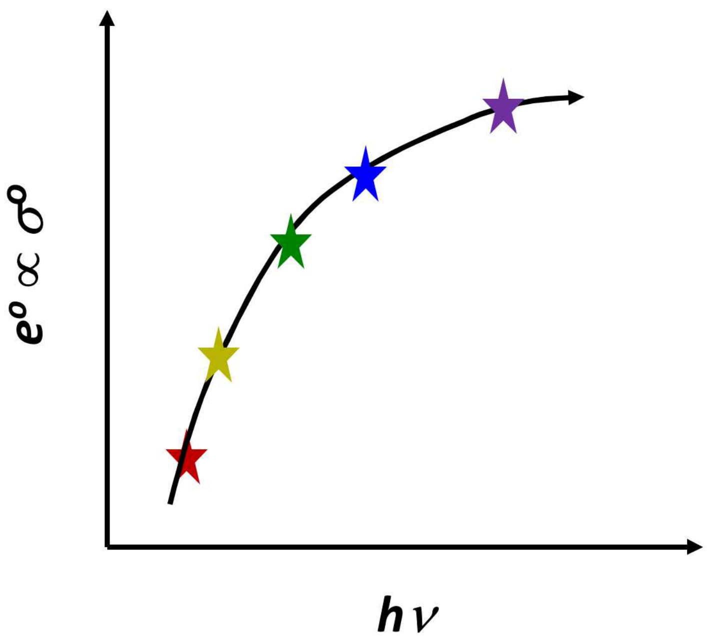
Deep Level Optical Spectroscopy

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

- **Fundamental physics from optical cross-section: $\sigma^o(h\nu) = e^o(h\nu)/\phi(h\nu) = \alpha/N_t$**
- **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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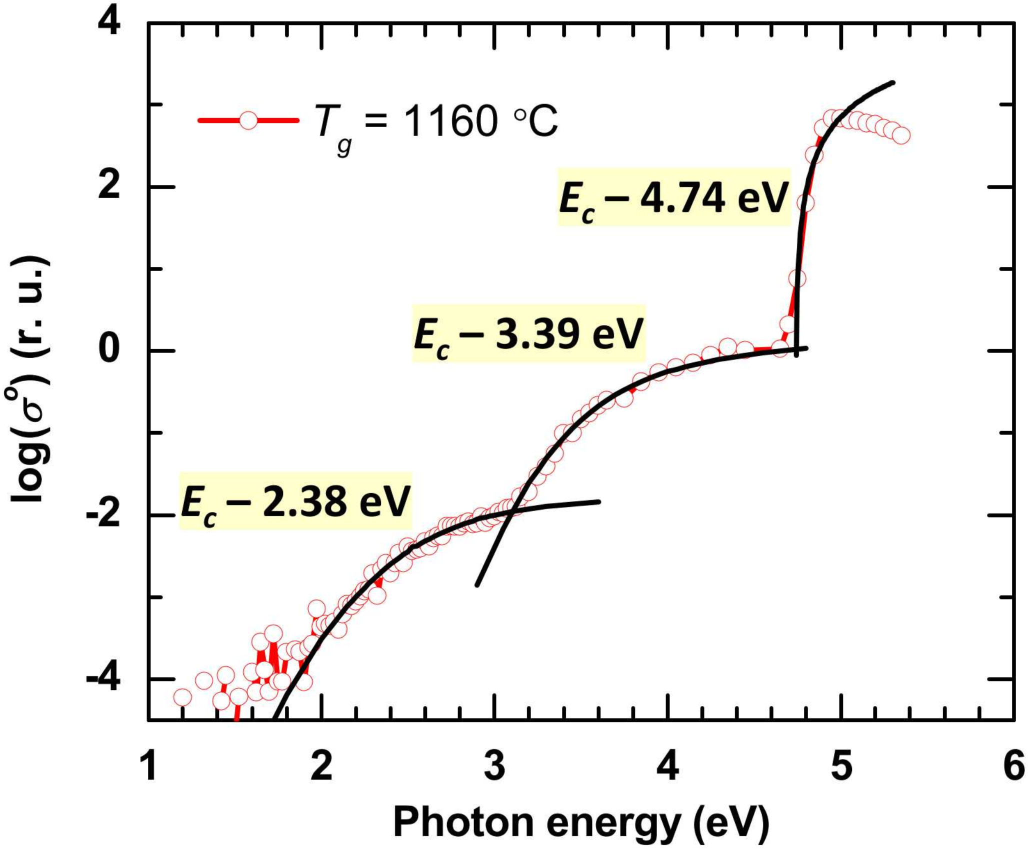
DLOS identifies $Al_{0.7}Ga_{0.3}N$ deep levels

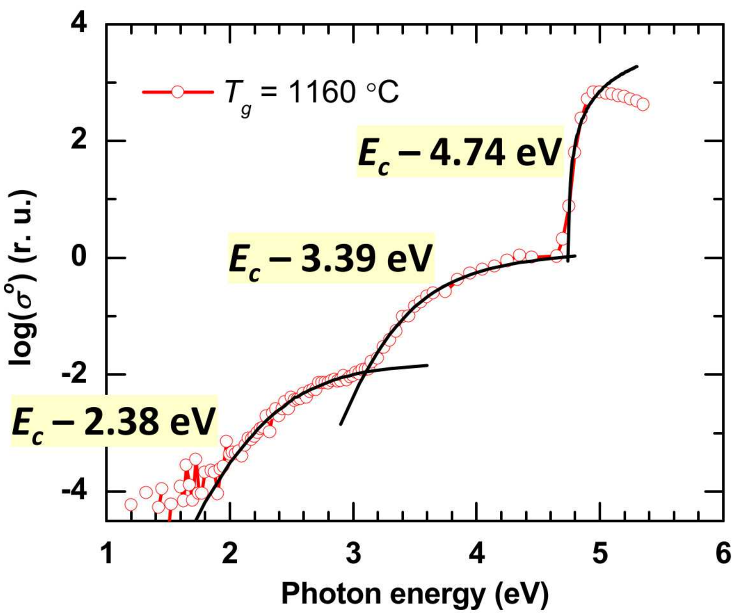
DLOS of *n*-$Al_{0.7}Ga_{0.3}N$ for T_g = 1160 °C



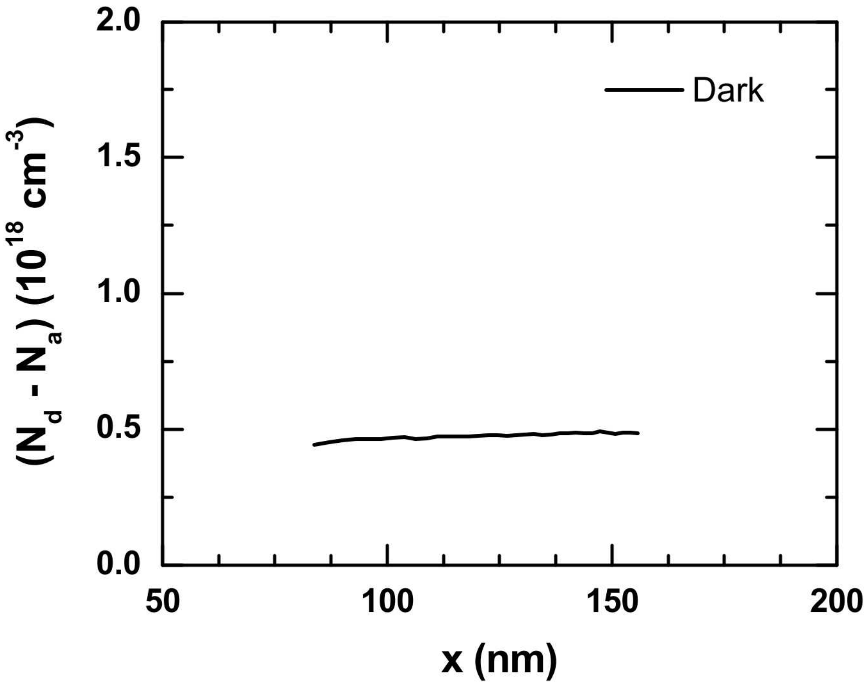
- **Observe three deep level defects**
- **DLOS spectra *does not* convey defect density information**

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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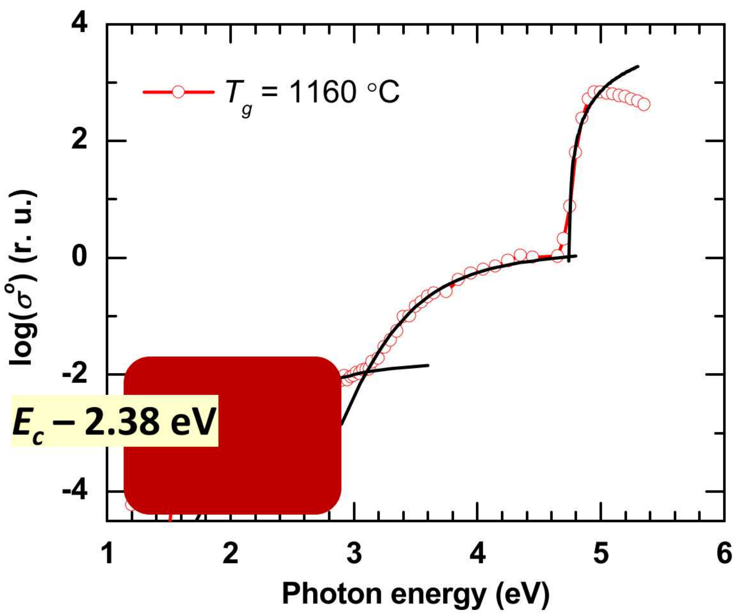
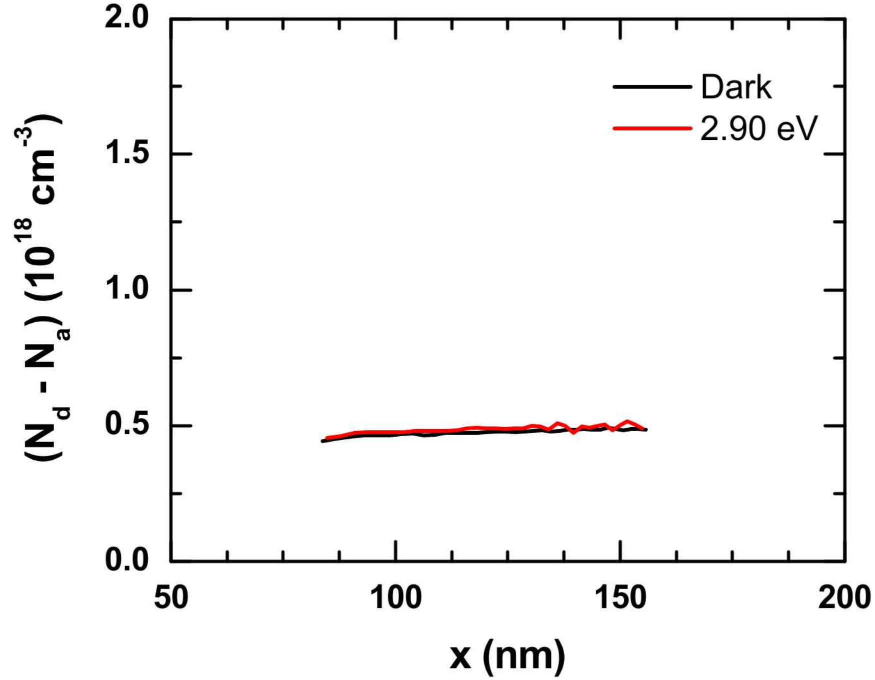
Lighted Capacitance-Voltage identifies compensators

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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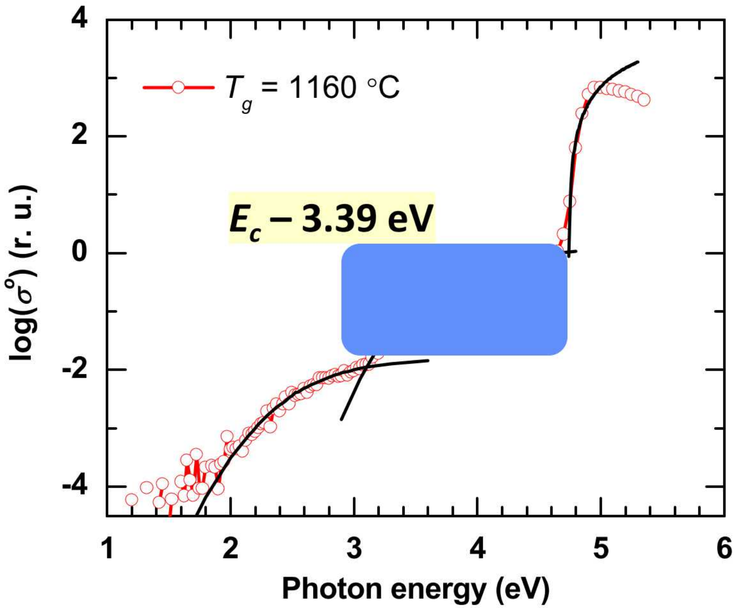
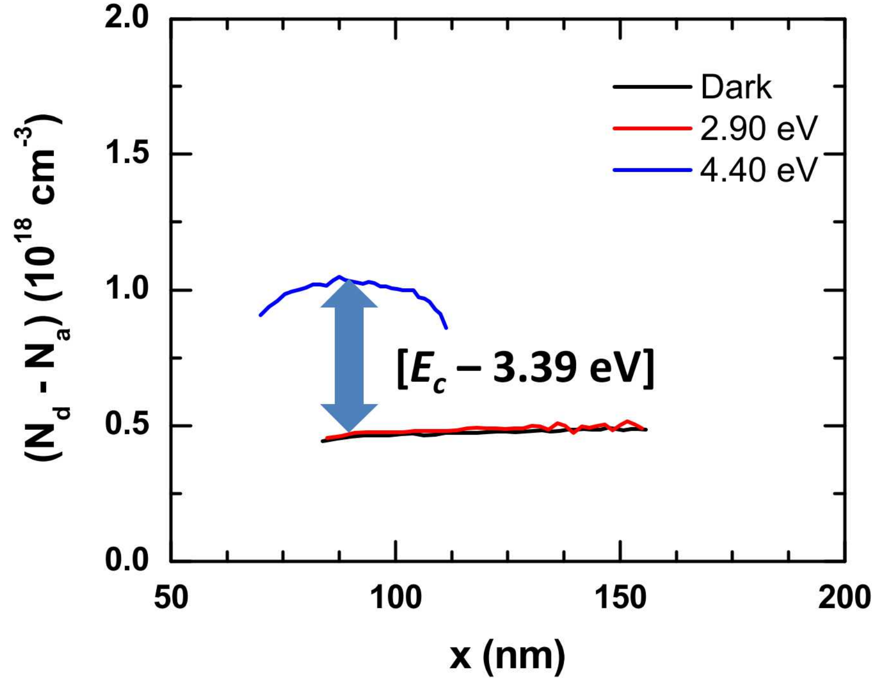
Lighted Capacitance-Voltage identifies compensators

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



LCV for VNA4153A



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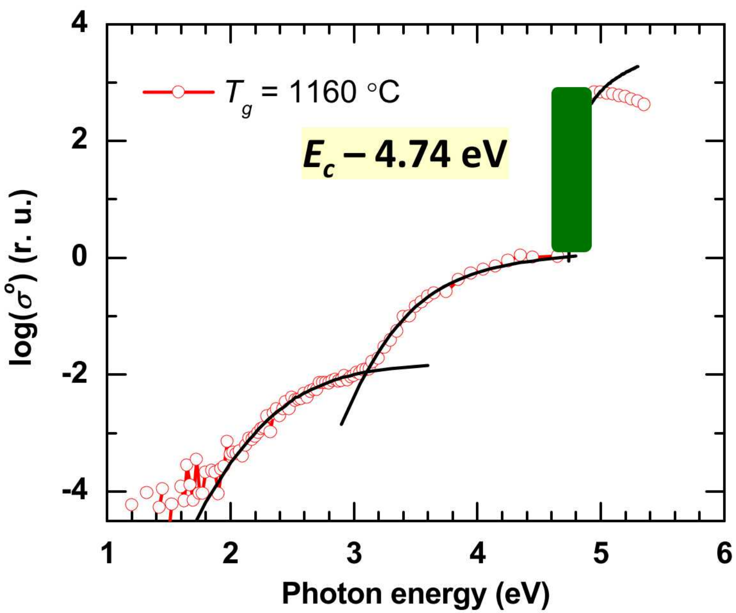
Lighted Capacitance-Voltage identifies compensators

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



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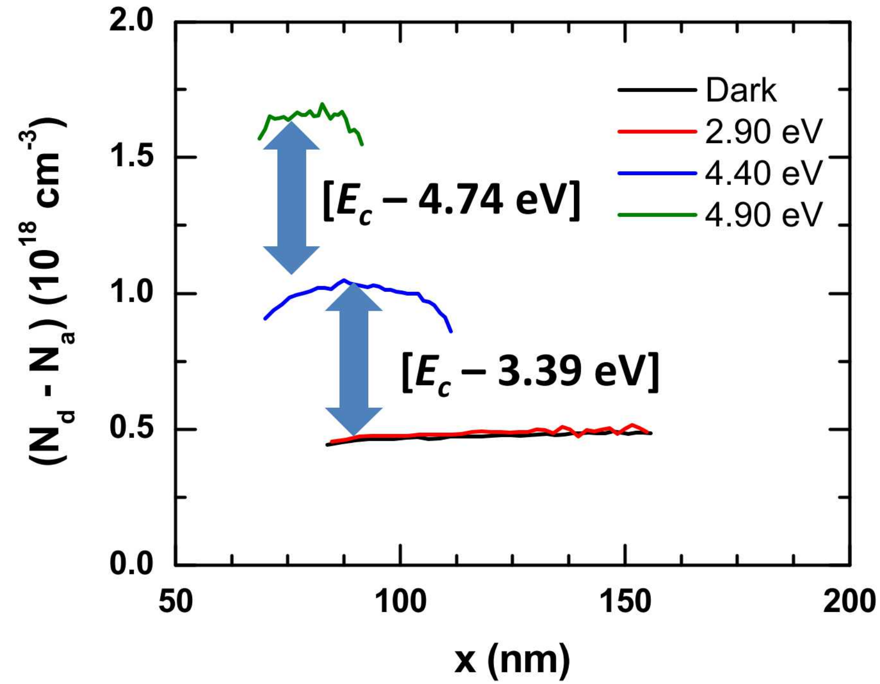

➢ E_c – 3.39 eV and E_c – 4.74 eV defects are dominate compensating centers

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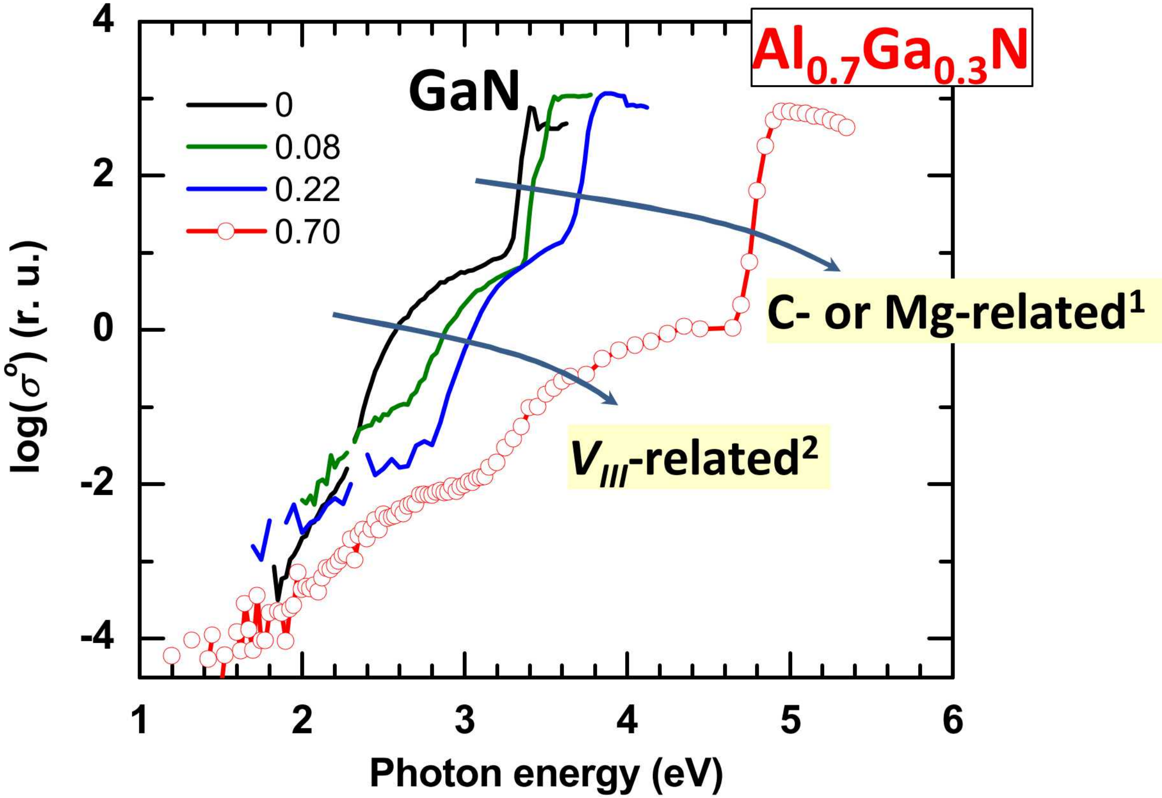
Identify physical origin from DLOS alloying study

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



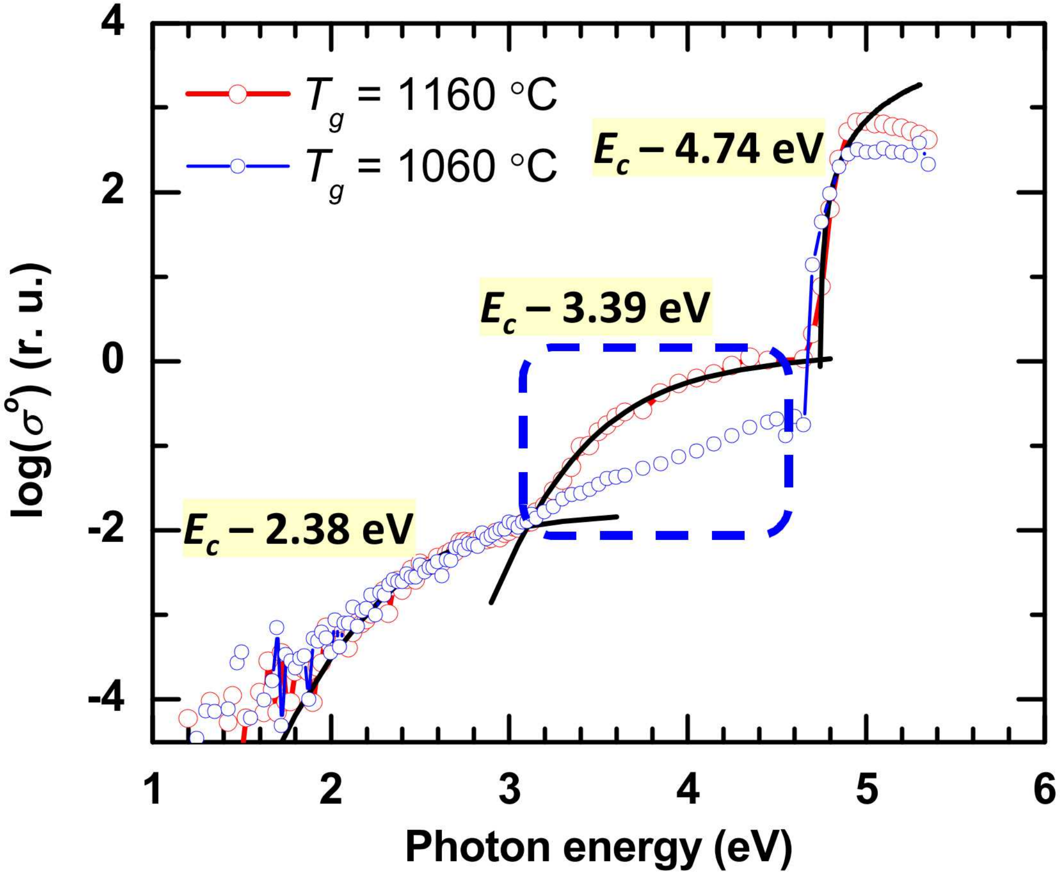
- Systematic evolution suggests similar defect origins for GaN & $Al_{0.7}Ga_{0.3}N$
- Attribute E_c – 4.74 eV level to C or Mg impurities[1]
- Attribute E_c – 3.39 eV level to V_{III}-related defect[2]

1. Armstrong et al, APL 84, 374 (2004)

2. Hierro, *et al.*, Appl. Phys. Lett. 77, 1499 (2000)

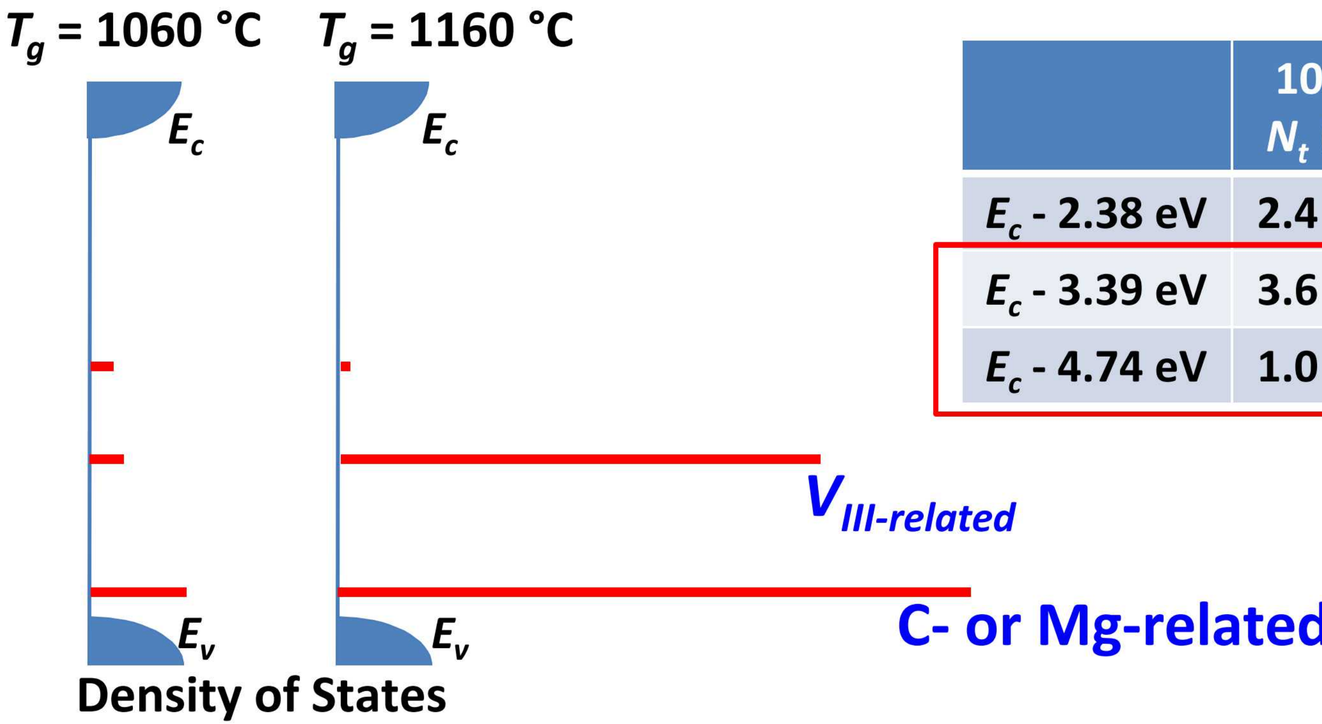
Lower $Al_{0.7}Ga_{0.3}N$ T_g suppresses defect formation

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

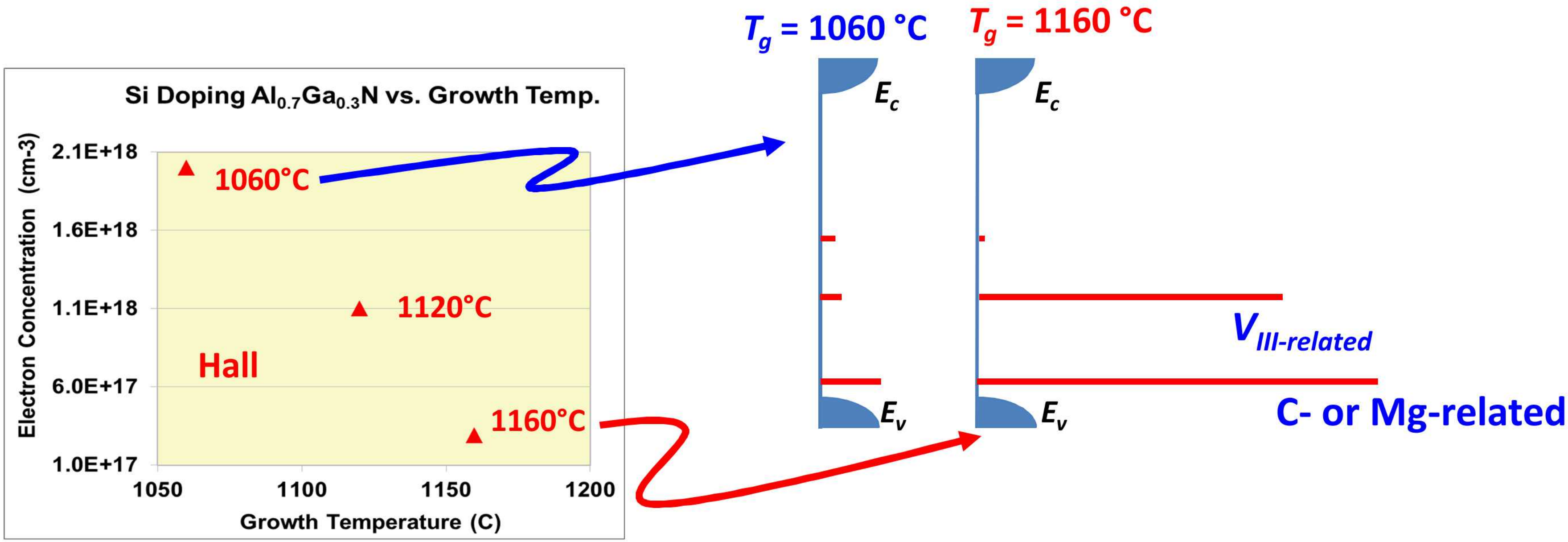
Lower $Al_{0.7}Ga_{0.3}N$ T_g suppresses defect formation



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

- **Net 10x reduction in V_{III} and impurity defects with lower T_g → Unexpected**

Summary and Conclusions



- Si dopant compensation strongly dependent on $Al_{0.7}Ga_{0.3}N$ T_g
- Lower T_g reduced compensating V_{III} and impurity defects by 10x
- Lowering T_g may inhibit the very strong thermodynamic drive to form compensating point defects in UWBGs like Al-rich AlGaN
- Maintaining electrical quality of $Al_xGa_{1-x}N$ ($x > 0.7$) at $T_g > 1100$ °C could require intricate balance of growth conditions

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