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Wide Bandgap Nitrides for Efficiency: Doping and Defects

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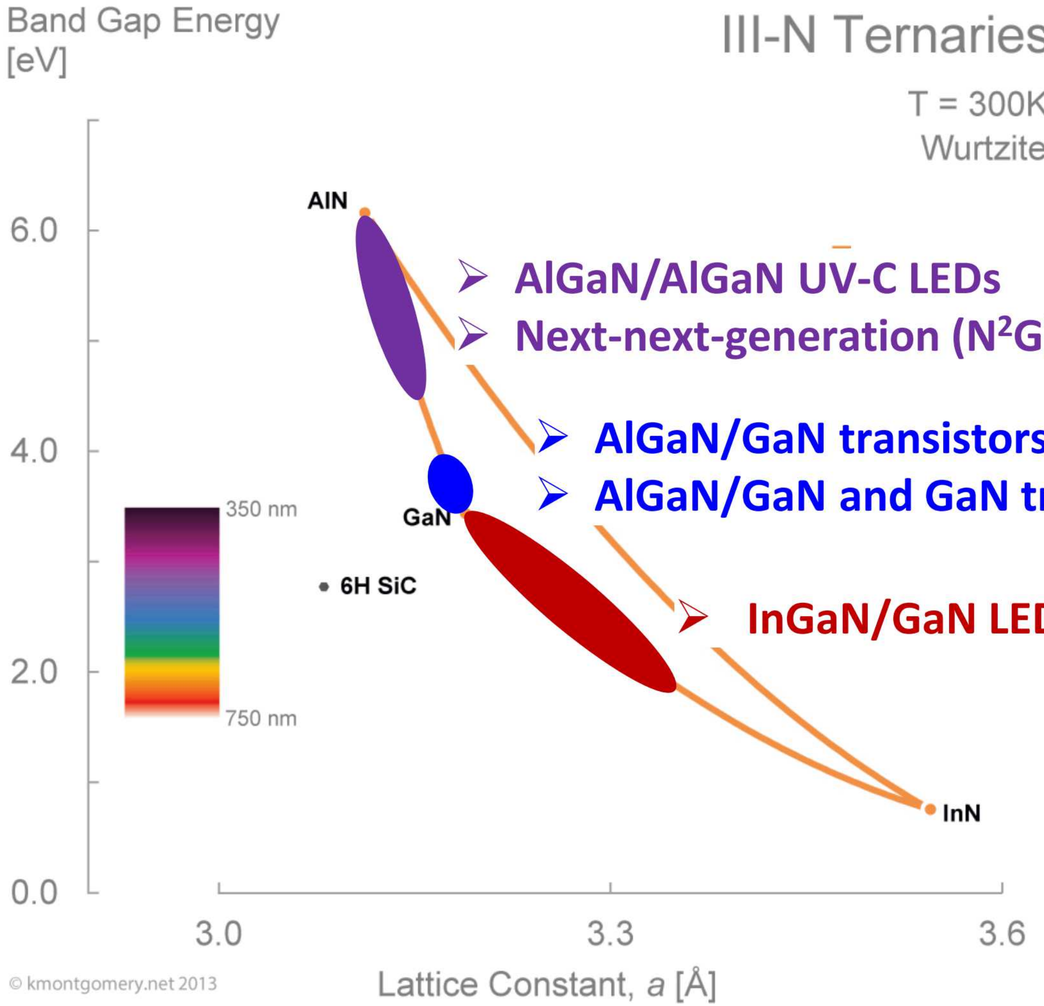
Why III-N's?



- AlGaN/AlGaN UV-C LEDs
- Next-next-generation (N^2G) power electronics
- AlGaN/GaN transistors for RF electronics
- AlGaN/GaN and GaN transistors for power electronics
- InGaN/GaN LEDs for solid-state lighting

- **Persistent III-N challenges: doping and defects**

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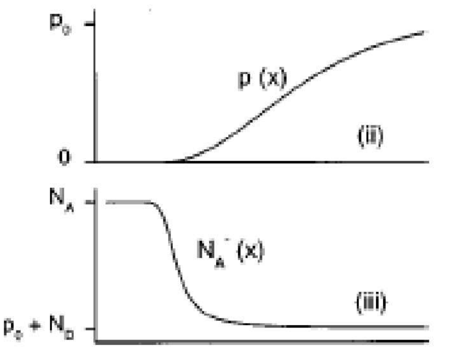
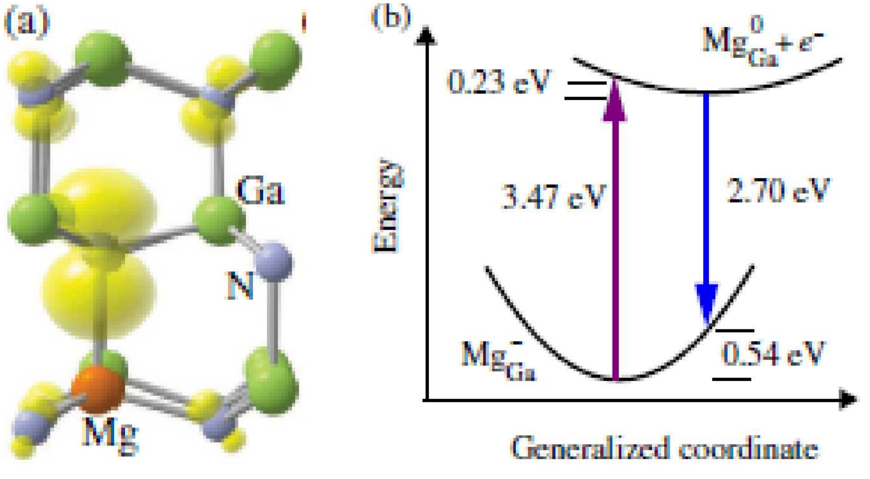
P-type Mg dopant in GaN is actually a deep level

- E_a for Mg_{Ga} ~ 200 meV from E_v
- $p < 5 \times 10^{17}$ cm^{-3} << [Mg] in quasi-neutral region
  - Serious limitation for bipolar devices (LEDs, LDs, BJTs, PV)
- $p << N_A^-$ near depletion region
  - Invalidates depletion approximation
- *p*-GaN behaves as a heavily doped junction and lightly doped bulk



Kozody *et al.* JAP 87 770 1999

- Mg_{Ga} is not hydrogenic but more like an *AX* center
- "Shallow" acceptor gives rise to broad, deep level luminescence



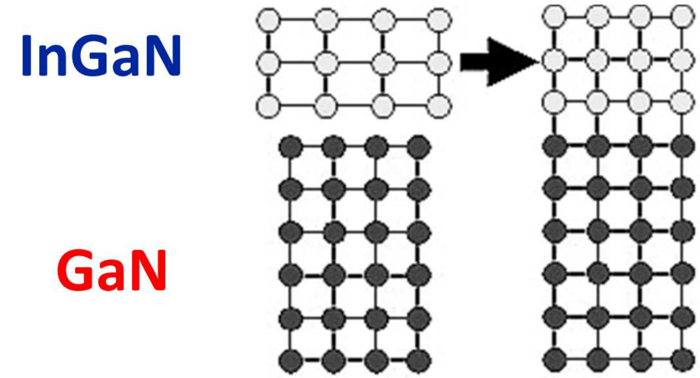
Lyons *et al.* PRL 108 156403 2012

Crystal defects limit InGaN/GaN LED efficiency

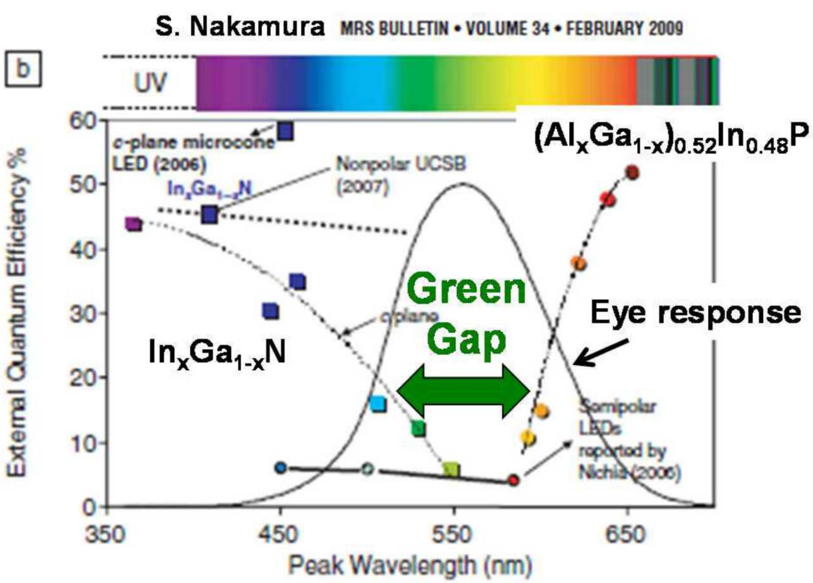
<u>Defects incorporate with large density in InGaN/GaN</u>

- **Highly mis-matched epitaxy and extended defects**
- **Growth conditions tradespace and impurities**
- **Likely contributor to InGaN/GaN "green-yellow gap"**

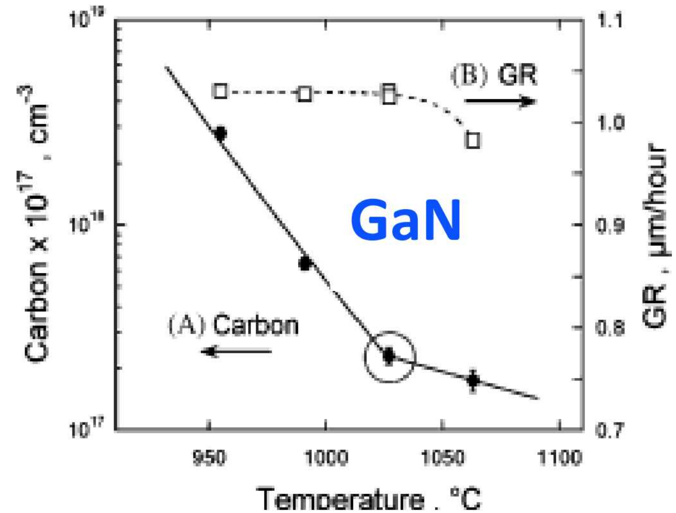
Mis-matched epitaxy and strain



Radiative efficiency InGaN/GaN LEDs



Non-ideal growth conditions



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

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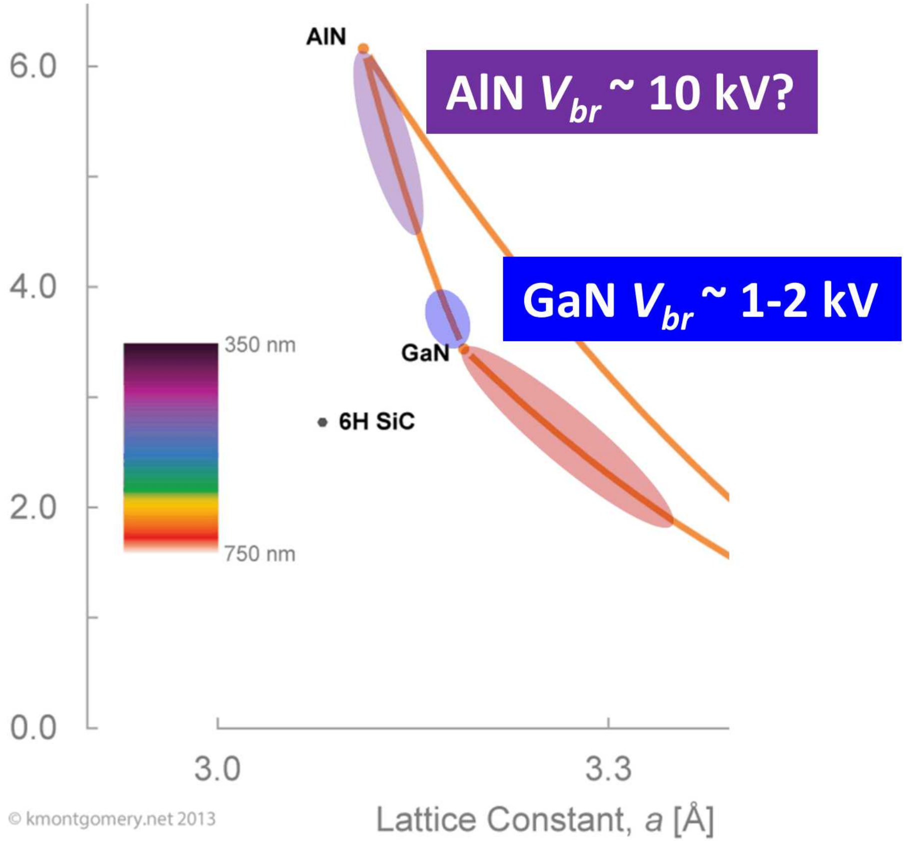
Ultra-wide band gaps: Next frontier of power electronics

Breakdown Voltage (V_{br}) ~ $E_g^{7.5}$



- ➢ **<u>Killer App:</u> Ultra-wide band gap (UWBG) semiconductors (E_g > 4 eV) could dramatically improve SWaP-C in high power systems**
- ➢ **Problems of doping and defects are fundamentally linked in UWBGs**

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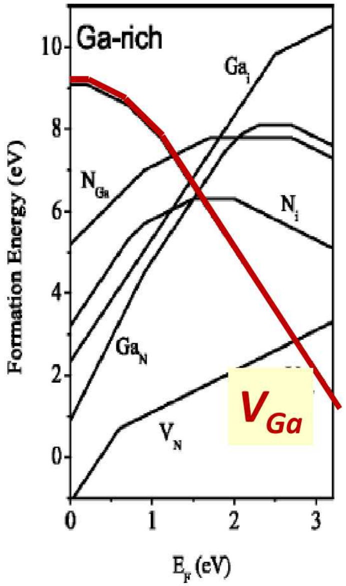
Theory: UWBGs self-compensate by native defect formation

GaN defect formation

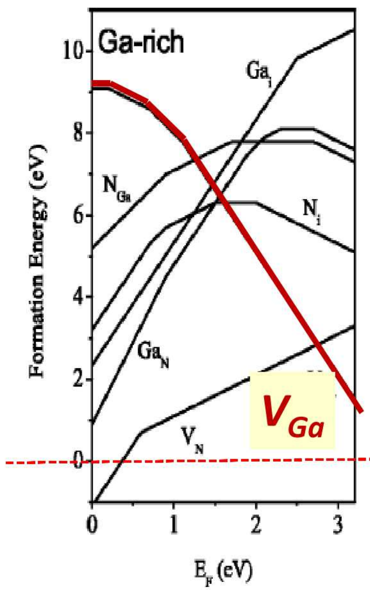


Appl. Phys. Rev.: C. G. Van de Walle and J. Neugebauer

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

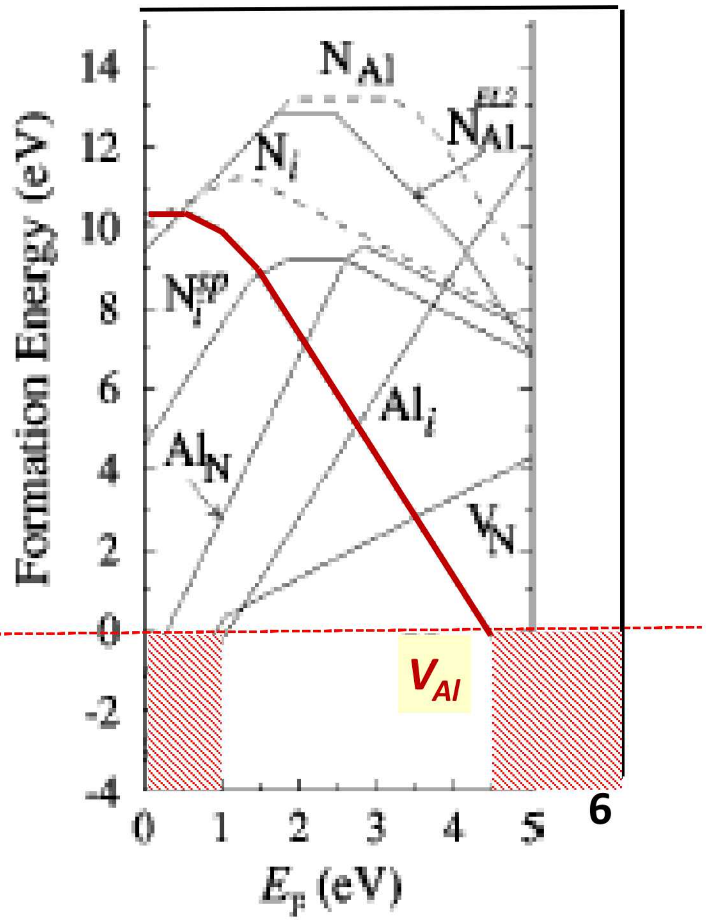
Theory: UWBGs self-compensate by native defect formation

GaN defect formation



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

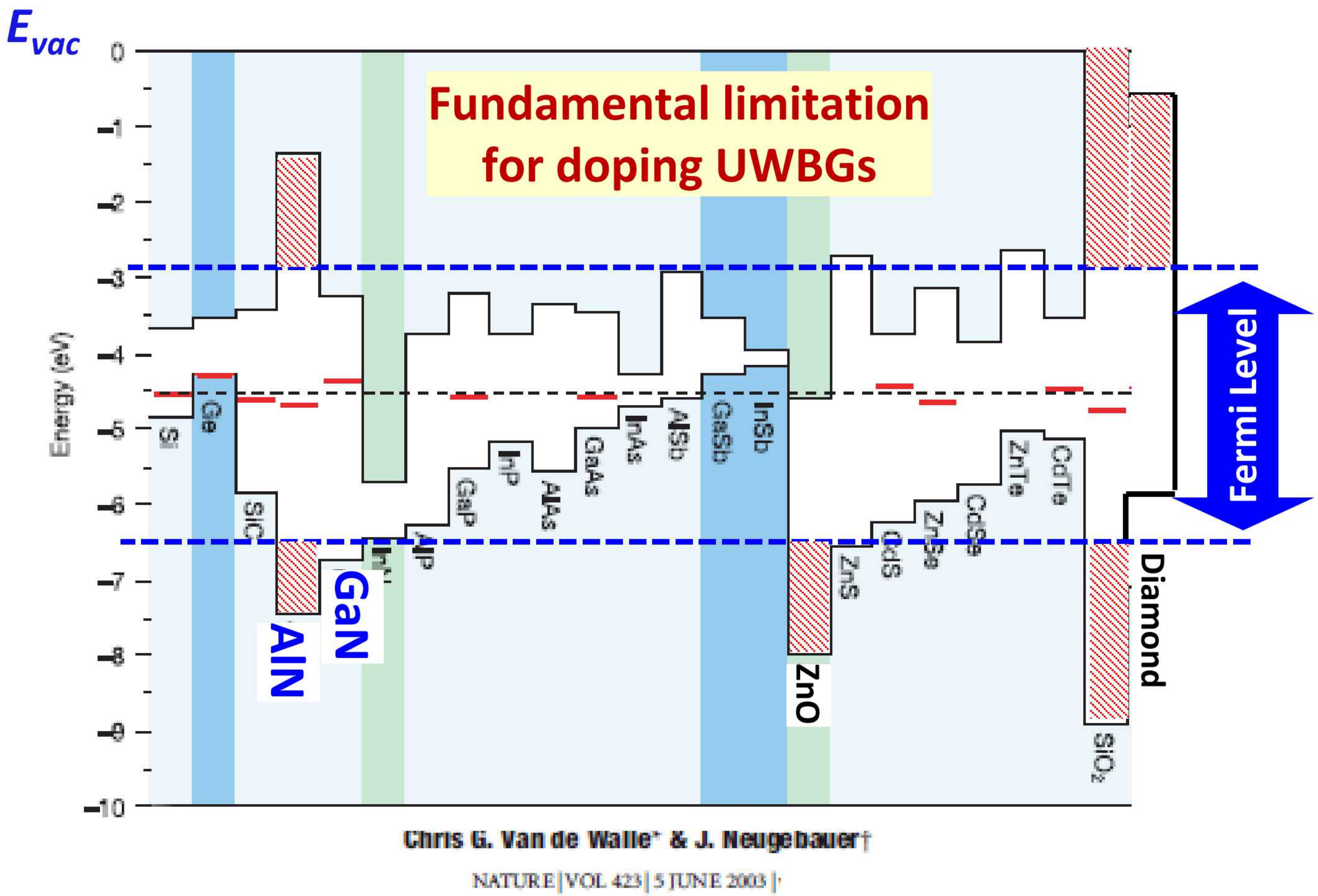
AlN defect formation



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**

Inefficacious doping in UWBGs is a universal problem



- Fermi Level bound within ~2 eV of the charge neutrality level (E_{vac} – 4.5eV)[1,2]
- Explains UWBG doping asymmetry or inefficacy
- At what Al composition does AlGaN cease to be a semiconductor?
- Why? Rampant defect formation? Deep dopants? Both?

1. Zhang *et al.*, JAP 83 3192 1998

2. Walukiewicz, Physica B 302-303 123 2001