Reliable High-Performance Gate Oxides for Wide Band Gap Devices

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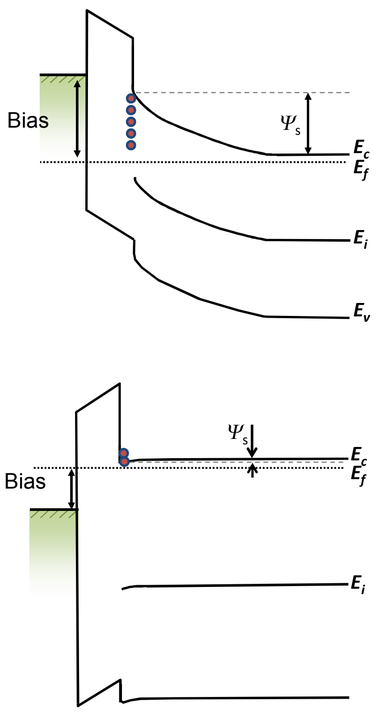
Jon Ihlefeld,[1] Elizabeth A. Paisley,[1] Michael Brumbach,[1] Adam Morgan,[1,2] Christopher T. Shelton,[2] Robert Kaplar,[1] Andrew Allerman,[1] Christina Rost,[2] Jon-Paul Maria,[2] and Stanley Atcitty[1]
[1] Sandia National Laboratories, [2] North Carolina State University
Contact Information: jihlefe@sandia.gov or satcitt@sandia.gov



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Motivation

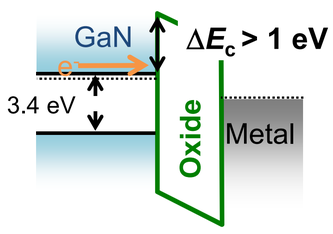
- Wide band gap semiconductor devices can improve the performance of energy conversion systems
- Voltage control, normally-off devices based on GaN have seen limited deployment
- Lack of deployment stems from issues related to switching stability/repeatability/reliability and conduction
- All of these issues are related to defects in the insulating component of the device (gate oxide/passivation layer)

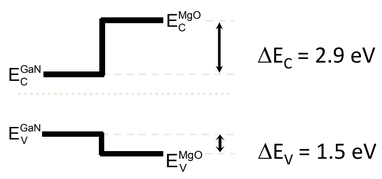
FY16 Activities

1. Quantify GaN defect/composition effects on MgO/GaN electronic structure
2. Quantify and verify interface trap density at MgO/GaN
3. Prepare lattice matched MgO-CaO alloys on GaN
4. Establish collaboration with external industrial partner

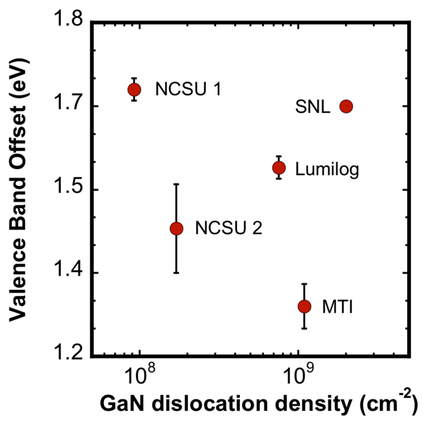
GaN Defect Effects on Electronic Structure

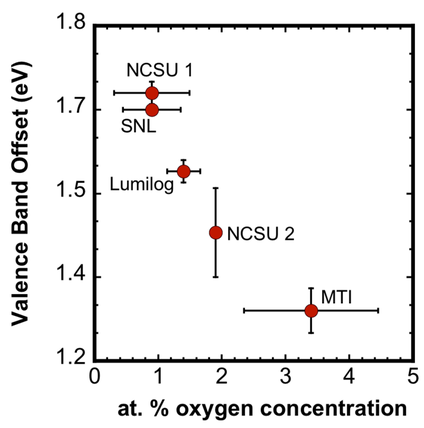
- Band offsets are an important factor in device design
  - Insulation resistance
  - Threshold voltage
- Typically require ≥ 1 eV at both conduction and valence band

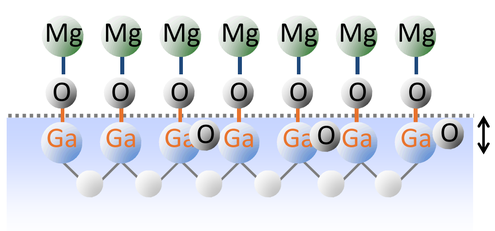




- Band structure measured using X-ray photoelectron spectroscopy (XPS) in molecular-beam grown MgO/GaN
- Surface oxygen content measured with XPS
- Dislocation density measured with X-ray diffraction
- Several sources of GaN were investigated to identify design principles needed for different GaN device manufacturers







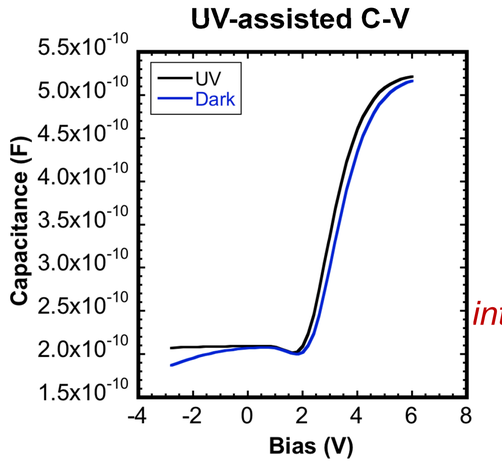
Sub-surface oxygen content (due to growth impurities) impact device electronic structure

- GaN dislocation density does not strongly impact band offsets
- GaN near-surface oxygen impurity content strongly affects band offsets
- ***Source of GaN material will strongly impact device performance***
- ***GaN properties must be known prior to device design***

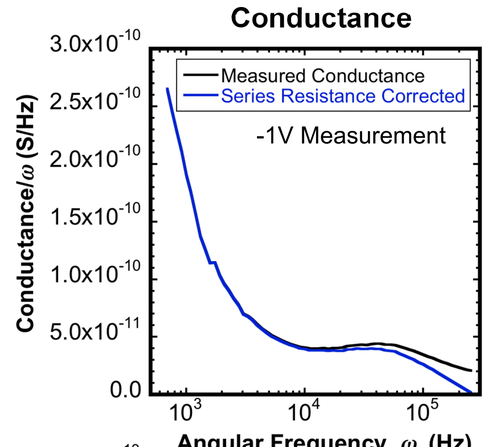
Electronic Properties: MgO/GaN

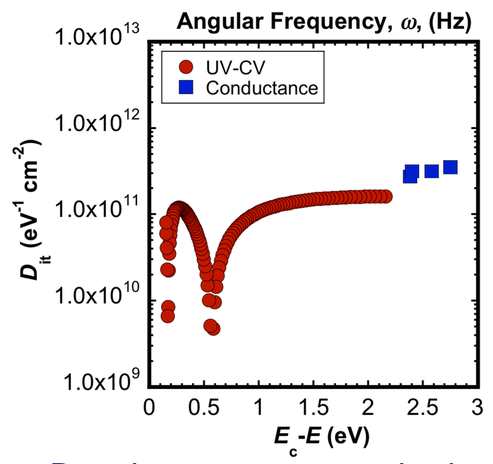
- MgO (18 nm)/GaN (N_d≅2×10^{18} cm^{-3}) devices prepared and C-V and conductance characteristics measured
- UV-assisted C-V technique utilized
  - Provides one of the most conservative and complete measures for D_{it}

UV-assisted C-V



Conductance





Average D_{it} across band gap:

$$D_{it} = \frac{C_{ox}}{qA}\left(\frac{\Delta V}{E_g}\right)$$

MgO D_{it}: 1.5 x 10^{11} eV^{-1} cm^{-2}

This is a very low (and promising) interface state density number. Such a low value requires verification by another technique

D_{it} at each bias/position in band gap:

$$D_{it} = \frac{2.5}{qA} * \left[\frac{G}{\omega}\right]_{max}$$

MgO D_{it}: 3 x 10^{11} eV^{-1} cm^{-2}

Conductance technique verifies low interface state density values at MgO/GaN interface

Dielectric | GaN	D_{it} (eV^{-1} cm^{-2})	Reference
La_2O_3	8 x 10^{11}	SNL
MgO	**3 x 10^{11}**	**SNL**
CaO	**3 x 10^{11}**	**SNL**
Ga_2O_3	4.2 x 10^{11}	[4]
Si_3N_4	5 x 10^{12}	[5]
Al_2O_3	3 x 10^{12}	[6]
Al_2O_3	5 x 10^{11}	[7]
SiO_2	2 x 10^{11*}	[8]

[7]Wu, Y., Appl. Phys. Lett., **90**, 2007
[8]Sawada, T., Appl. Surf. Sci., **159-160**, 2000
*Measured using Terman method

[4]Chiou, Y., Semicond. Sci. Technol. **25**, 2010.
[5]Mishra, U., J. Appl. Phys., **106**, 2009
[6]Ostermaier, C., Phys. Status Solidi C, **5**, 2008

- D_{it} values are among the lowest reported for a gate insulator on GaN and verified by 2 measurement methods
- Positive threshold voltages observed
  - Implications for safe (enhancement mode, normally off) operation

FY16 Publications and Impact

- Developing a new understanding of surface chemistry and impact on device properties (band offsets)
- Research presented at 2 conferences and 2 invited colloquia
- E.A. Paisley, M. Brumbach, A. Allerman, A. Armstrong, R. Kaplar, A. Baca, S. Atcitty, and J.F. Ihlefeld, "Spectroscopic investigations of band offsets of MgO|AlGaN heterostructures with varying AlN content," Applied Physics Letters, **107**, 102101 (2015)
- 2 publications in preparation
- *Have shown and verified that MgO on GaN have among the lowest reported interface defect state densities*
  - *Will minimize issues resulting in performance limitations in GaN enhancement-mode devices.*

FY17 Goals and Milestones:

- Complete D_{it} study for lattice matched MgO-CaO on GaN and SiC
- Prepare lattice matched alloys on SiC and pursue device development with industrial partner

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