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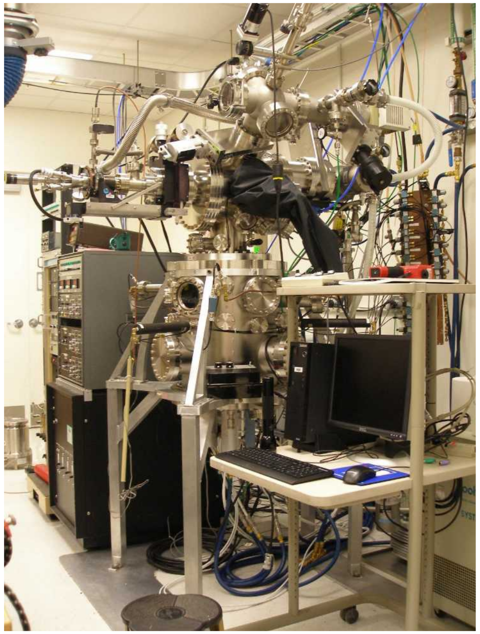

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Reliable High-Performance Gate Oxides for Wide Band Gap Devices

25 October 2013

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Project Overview

	Silicon	4H-SiC	GaN
Bandgap (eV)	1.1	3.2	3.4
T_{max} (°C)	300°C	600°C	700°C
Mobility (cm^2/Vs)	1500	260	1500
Breakdown Field (MV/cm)	0.3	3.5	2.0

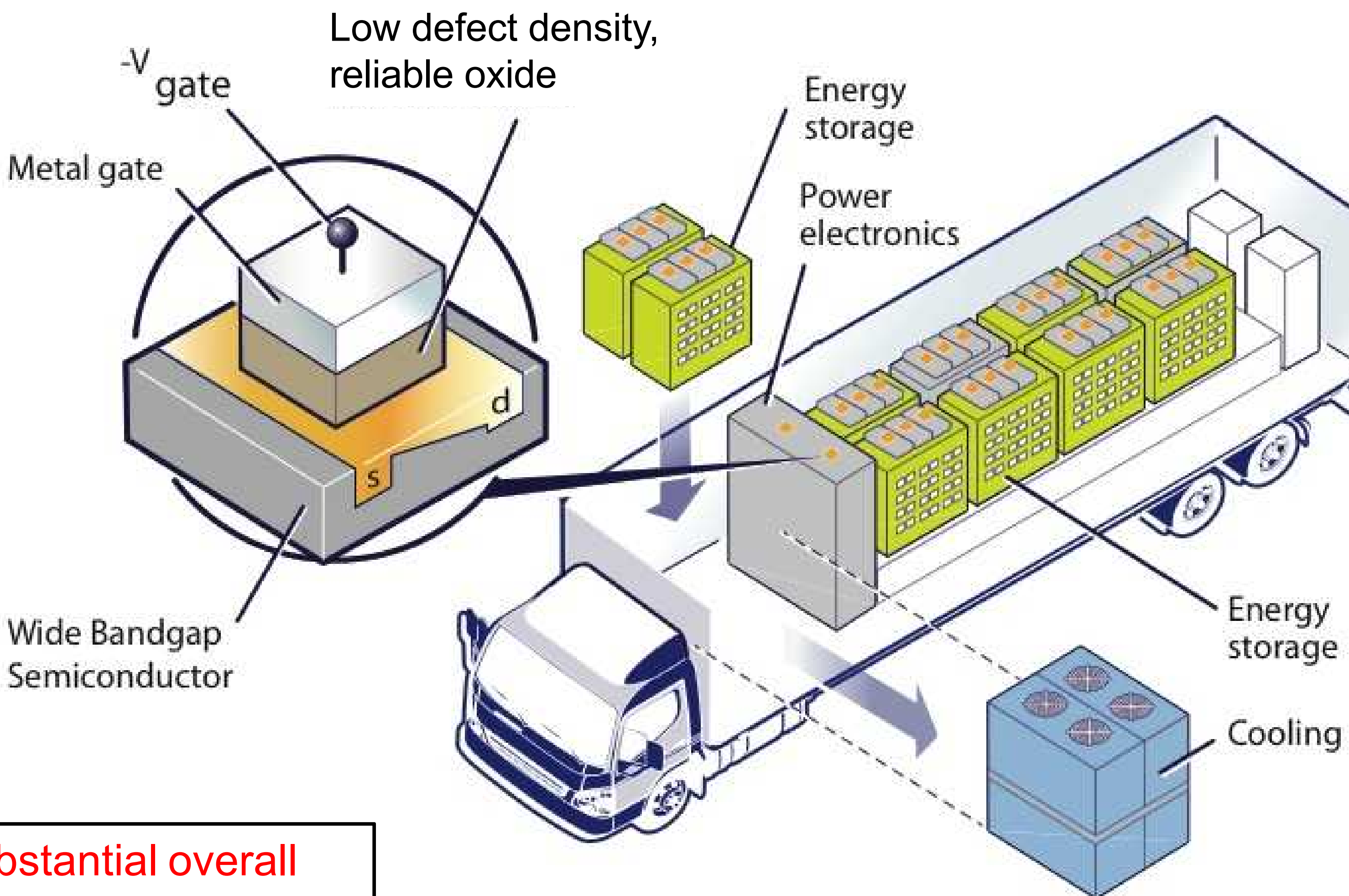
- Leading technology today is Si-based IGBTs
  - Si-based devices are limited in operating temperature
- Costs and low mobility associated with SiC technology makes GaN devices attractive
  - Particularly useful for 600 V applications
- Voltage controlled devices (such as MOSFETs) based on GaN have seen limited deployment owing to issues with the insulating switch

Data adapted from: R.S. Pengelly, *et al. IEEE Trans. M.T.T.*, **60** (6) (2012)

Project Overview

- Oxide materials are critical components of metal-oxide semiconductor (MOS) devices
  - The oxide is a dielectric layer that allows a semiconductor switch to open and close
- Wide bandgap semiconductor (WBG) MOS power transistors have seen limited deployment owing to key technological issues ***all related to oxide defects***:
  - Low channel mobility → poor switch conduction
  - Threshold voltage instability → unpredictable switch performance
  - High drain resistance → poor switch conduction
- *Preparation of low defect density gate insulators is vital to alleviating these issues and realizing efficient, reliable, and high-performance devices*
- ***This project focuses on the preparation of reliable gate oxides on WBG semiconductors***

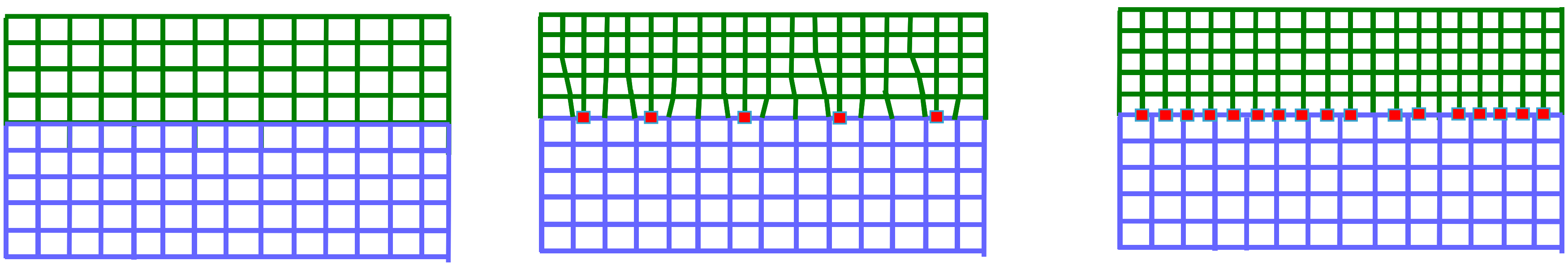
Wide Band Gap Switch Needs for ESS



Substantial overall efficiency improvement

Oxide/GaN Strain States – Controlling Threading Defects and Interface States

0% Strain Coherent Interface Satisfied Bonds	~< 10% Strain Pseudomorphic With Dislocations	~>10% Strain Incoherent With Dislocations



Ln_2O_3	La	Nd	Sm	Gd	Dy	Ho	Er	Tm	Yb	Lu
ε_{cub}	0.7%	-10%	-3%	-4%	-5.4%	-5.9%	-6.4%	-6.9%	-7.4%	-7.7%
ε_{hex}	19.1 %	16.9 %								

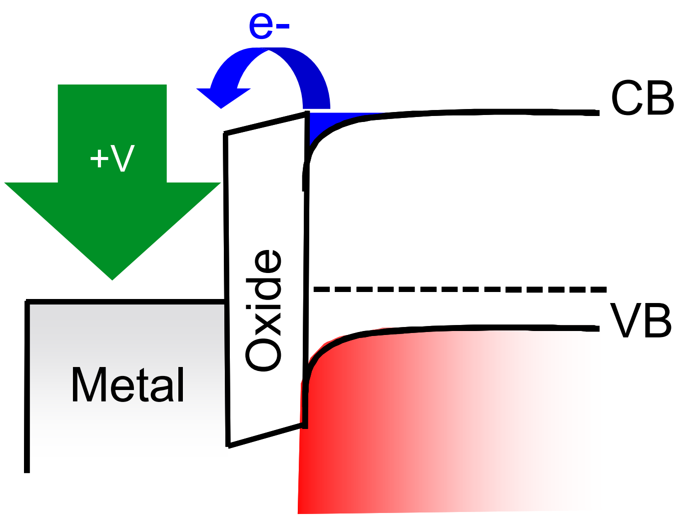
- If cubic, alloy to minimize strain → Minimize Dislocations
- Hexagonal structure likely to be too high of strain

Data from: G-Y. Adachi and N. Imanaka, *Chem. Rev.* (1998)

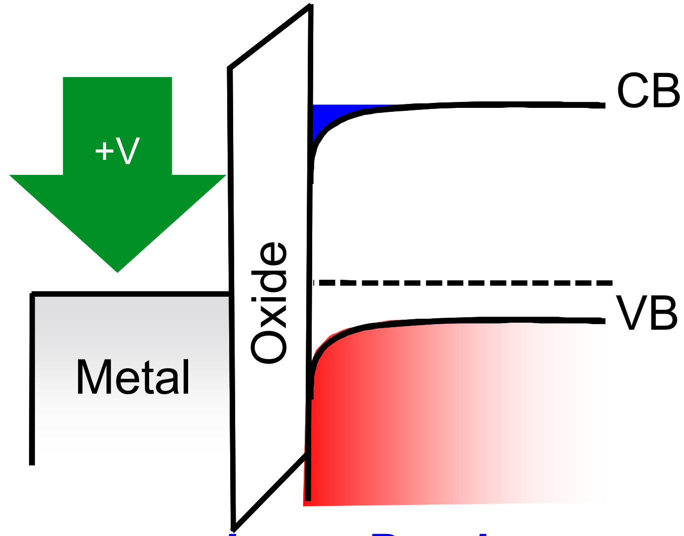
Oxide Electronic Properties: Importance of Band Gap

E_g^{GaN}=3.4 eV

Ln_2O_3	La	Nd	Sm	Gd	Dy	Ho	Er	Tm	Yb	Lu
E_g	5.5	4.7	5.0	5.4	4.9	5.3	5.3	5.4	4.9	5.5
κ	20-30	10	11	12	12	12	14		13	9



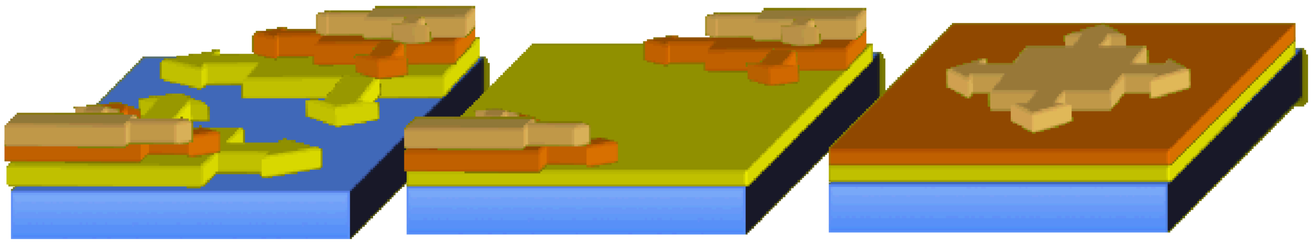
Low Bandgap
Low Band Offsets
Low Efficiency

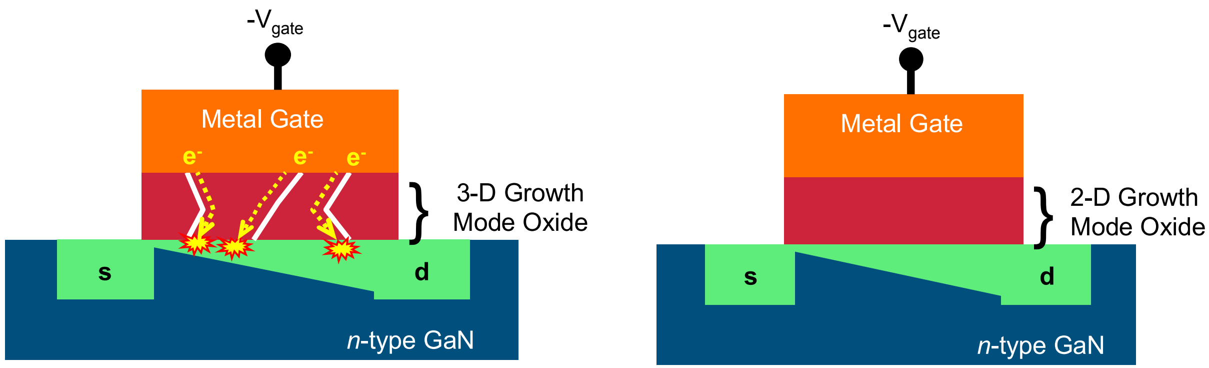


Large Bandgap
Potentially Large Band Offsets

Data from: J-P. Maria in *High Dielectric Constant Materials* (2005).

Oxide/GaN Growth and Structural Issues



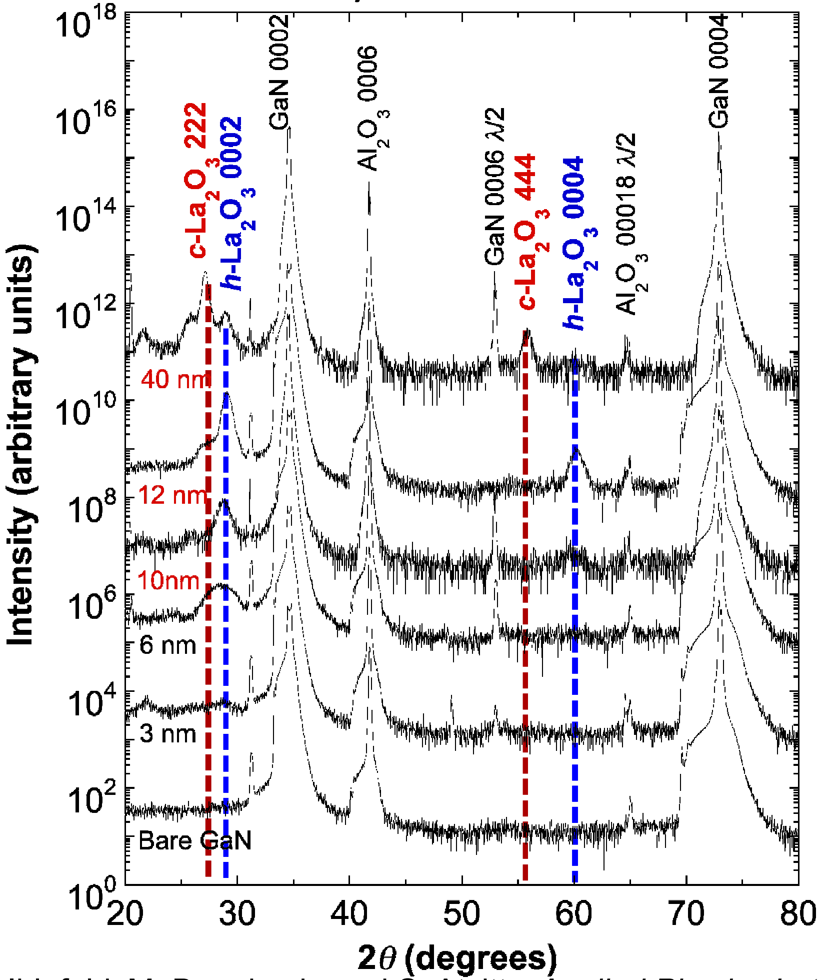


- Rough growth results in grain boundaries that act as defect sources for gate leakage ➔ poor performance
- Smooth growth should have fewer threading defects ➔ greater reliability and performance
- ***Amorphous oxides (e.g. SiO_2) do not work well for WBG gates owing to poor interface bonding***

First Step: La_2O_3 Growth Characteristics

- Hexagonal growth observed for thicknesses of ≤ 6nm
- Transitions to rough cubic phase for thicknesses > 6nm

X-ray Diffraction



J.F. Ihlefeld, M. Brumbach, and S. Atcitty, *Applied Physics Letters*, **102**, 162903 (2013)

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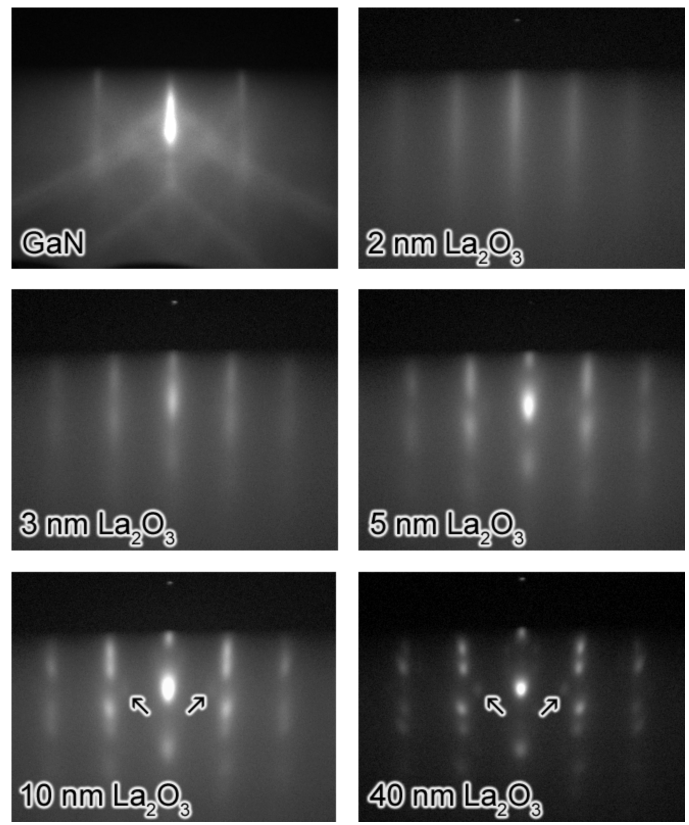
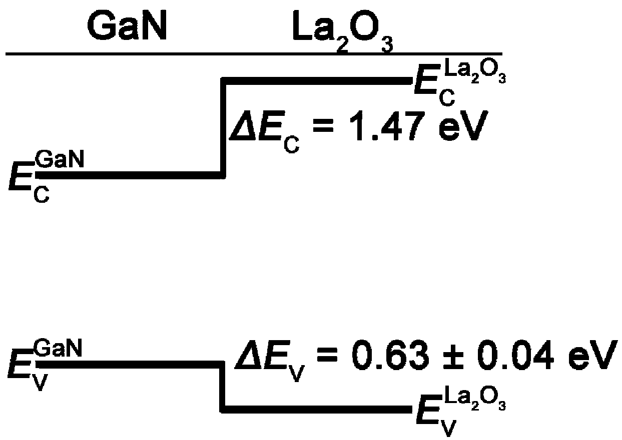
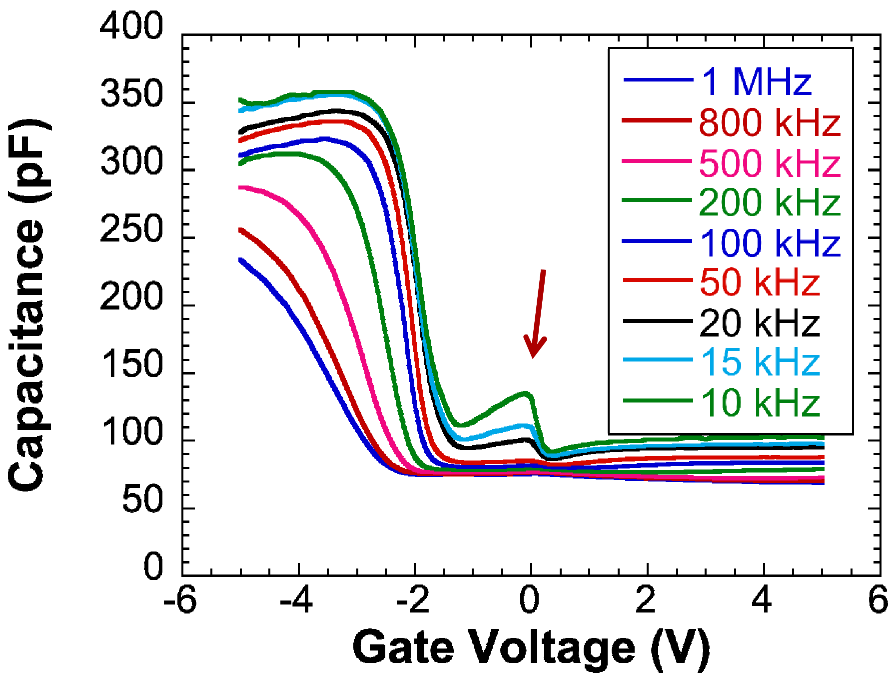


Streaks Good

Spots Bad

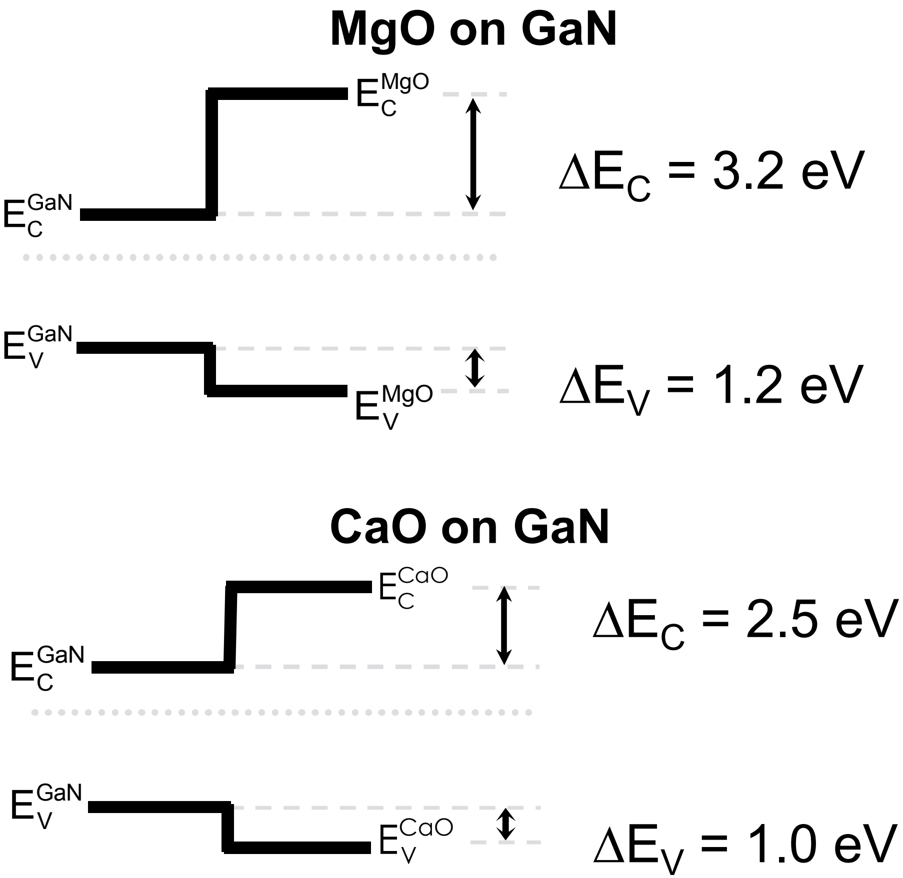
Second Step: Band Alignments and Electronic Properties



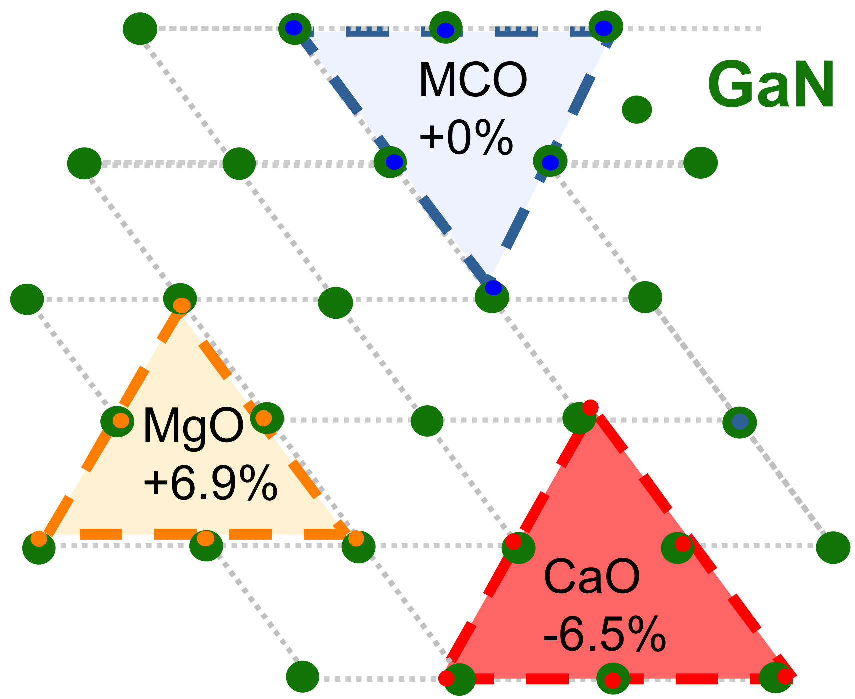


- Ideally want band offsets >1 eV to maximize performance and reliability
  - Valence band offset of 0.63 eV
  - Conduction band offset of 1.47 eV
- C-V curves enable identification of interface defects
  - Low frequency peak (red arrow) indicates presence of interface trap states
- **La_2O_3 looks great on paper, but is not a good option**

Must Improve Morphology and Offsets: MgO-CaO alloys



- MgO-CaO alloys can be grown with 0% strain
- Band offsets ≥ 1 eV at both bands for both materials

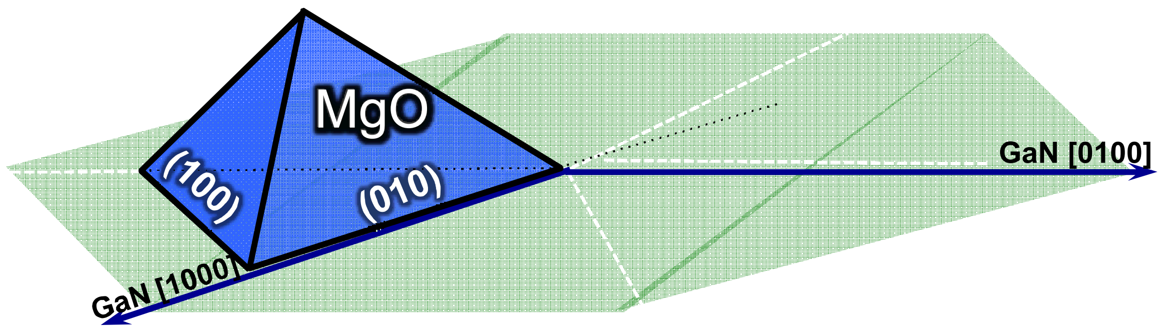


The MgO-CaO system is a viable solution to the threading defect and trap issue

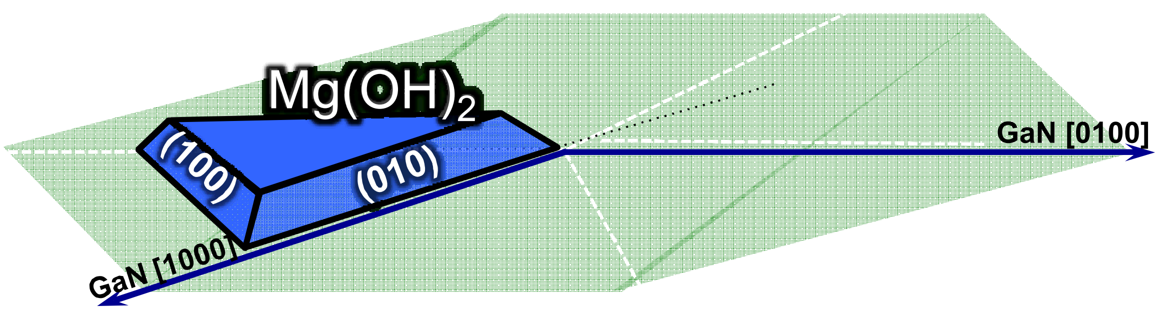
In collaboration with Prof. Jon-Paul Maria at North Carolina State University

Controlling Growth for Smooth Surfaces

Conventional Growth



H_2O-Assisted Growth



- MgO and CaO want to grow as 3-D pyramids on GaN
  - Rough growth
  - Threading defects
  - Poor performance and reliability
- A $AE(OH)_2$ surfactant on MgO or CaO would result in a smooth surface
  - Minimal threading defects
  - Greatly improved performance and reliability

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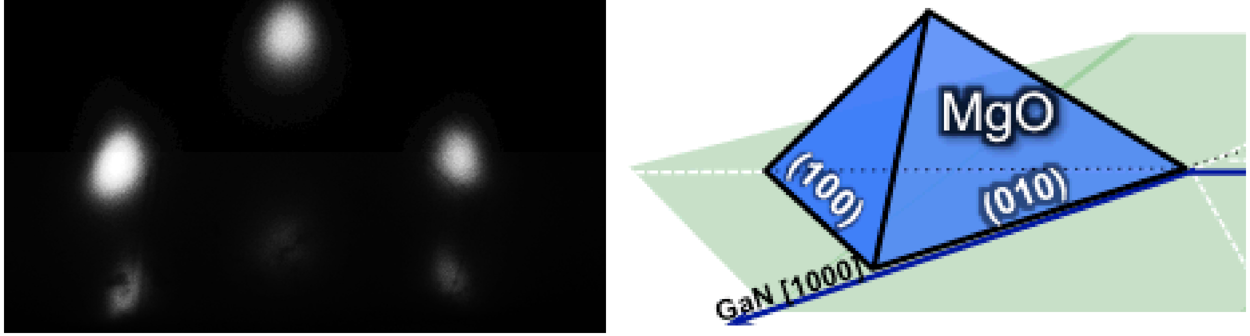
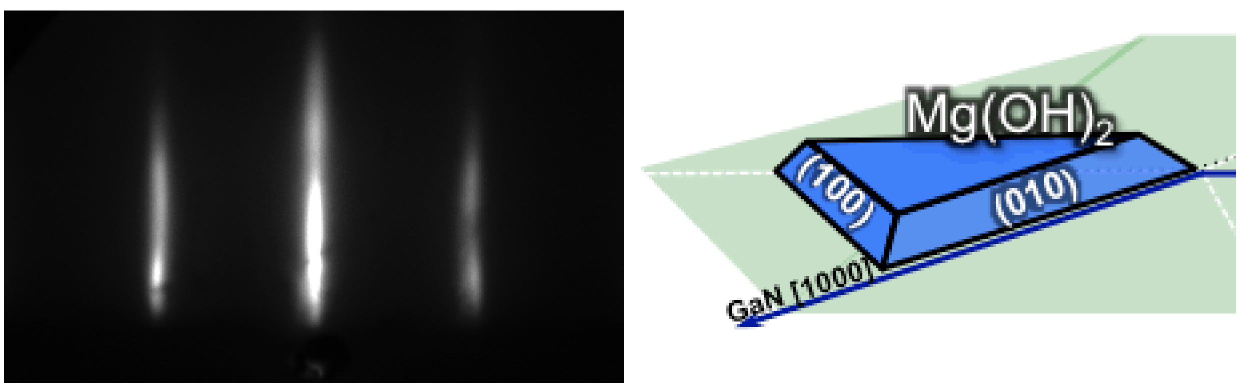
Controlling Growth for Smooth Surfaces

MgO-Conventional Growth



MgO-H_2O Surfactant



- Conventional O_2 growth results in rough surface
  - Similar to cubic La_2O_3
  - Likely high threading defect concentration
- **H_2O-assisted growth results in a smooth growth surface**
  - Minimizes threading defects
  - Potentially improved performance

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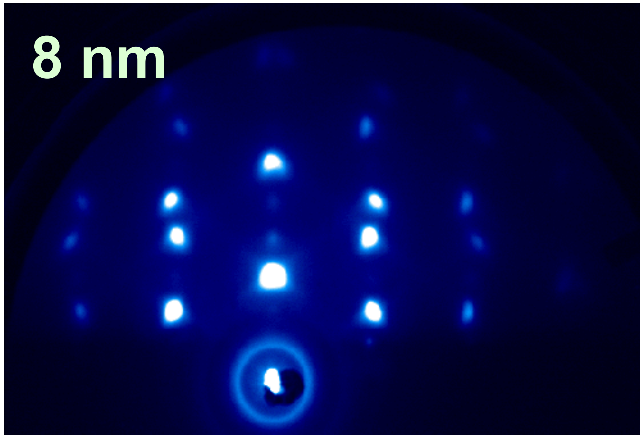
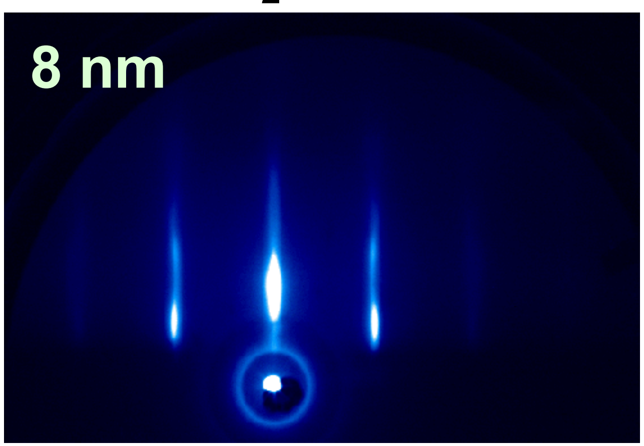
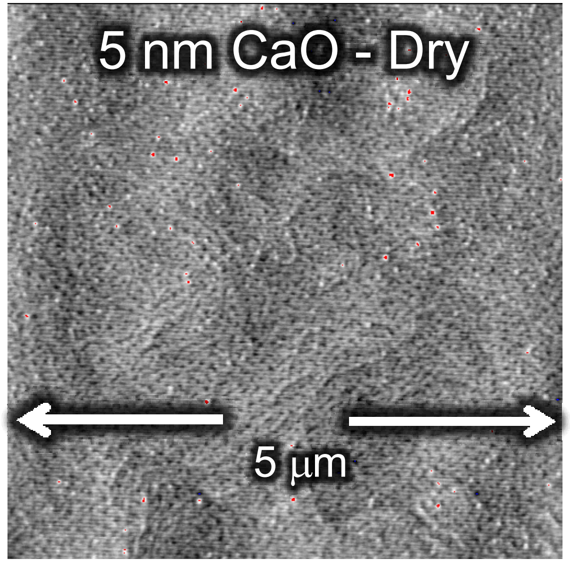
Controlling Growth for Smooth Surfaces

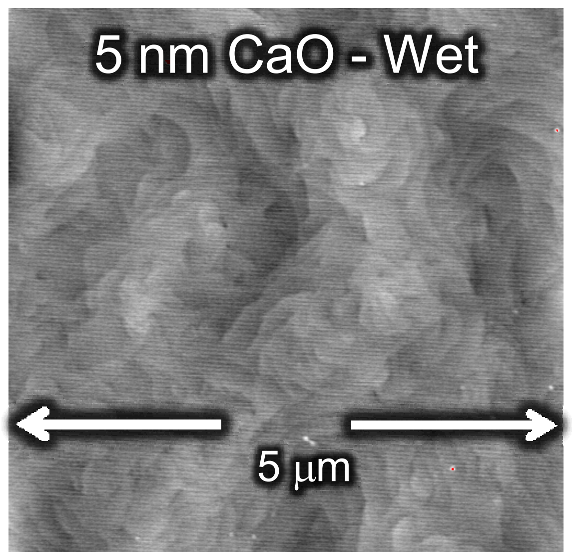
CaO-Conventional Growth



CaO-H_2O Assisted







- Conventional O_2 growth results in rough surface
  - Similar to cubic La_2O_3
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- **H_2O-assisted growth results in a smooth growth surface**
  - Minimizes threading defects
  - Potentially improved performance

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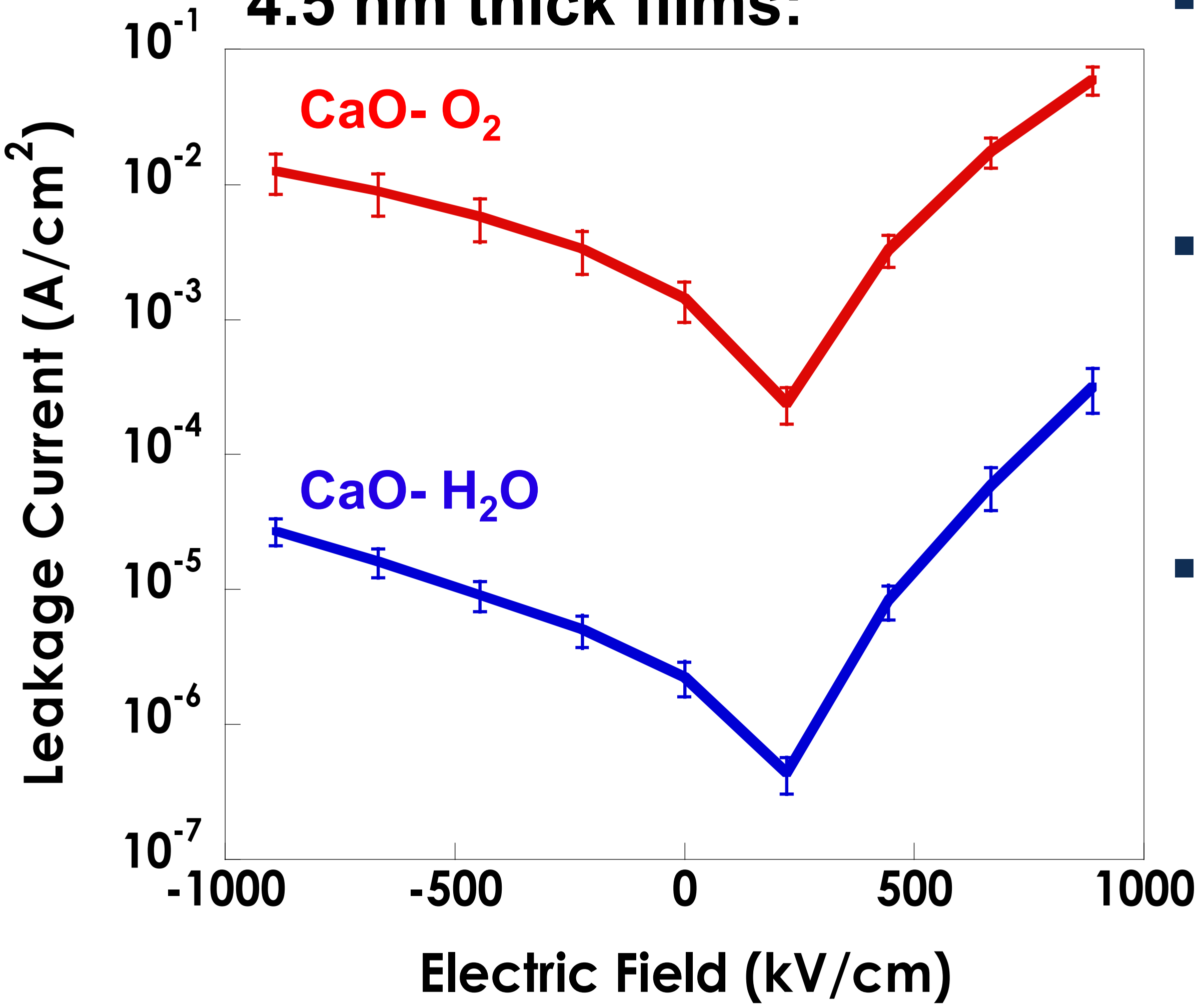
Controlling Growth for Smooth Surfaces

4.5 nm thick films:



- Smooth film has 10^2-10^3 decrease in dielectric leakage
- Substantial improvement over conventionally prepared gate dielectrics
- **H_2O-assisted growth results in greatly improved structural and electrical properties**

In collaboration with Prof. Jon-Paul Maria at North Carolina State University

FY13 Summary

- FY13 Milestones:
  - Characterize growth of lanthanide oxides on GaN
    - ✓ Completed; hexagonal phase unavoidable; grows as rough cubic phase
  - Measure band offsets of lanthanide oxides on GaN and electrical response
    - ✓ Completed; ~0.63 eV valence band offsets measured; electrically active defects identified in capacitance-voltage analysis
  - Upfit growth instruments to enable surfactant-enhanced growth
    - ✓ Initiated and ongoing; surfactant growth established at SNL
  - Establish collaboration with NCSU to optimize surfactant-enhanced growth technique
    - ✓ Initiated; technology and samples transferred to Sandia for analysis
  - Submit manuscripts for publication in peer-reviewed journal
    - ✓ 1 papers already published
    - J.F. Ihlefeld, M. Brumbach, and S. Atcitty, "Band offsets of La_2O_3 on (0001) GaN grown by reactive molecular-beam epitaxy," *Applied Physics Letters*, **102**, 162903 (2013)

FY14 Milestones

- Develop process to prepare strain-free alloys on GaN
- Fully characterize physical and electrical defects
  - High temperature measurements to explore reliability
- Investigate passivation anneal effects on MOSCap performance
- Develop understanding of GaN surface quality role on oxide growth, performance and reliability
- Submit ≥1 manuscript for publication in peer-reviewed journals
- **Explore partnership with commercial manufacturer(s)**

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