Analytical Electron Microscopy of Interfacial States in 4H-SiC/SiO₂ MOS Devices

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Outline

- Motivation
- Introduction to techniques
- SiC MOSFET characterization
  - NO annealing and effects of crystallographic orientation
  - Boron and phosphorus passivations
- Conclusions and Future work
Motivation and background

- **Electrically active defects limit:**
  - Carrier mobility
  - Reliability
  - Device stability

- **SiC: Very promising for high temperature, high power, and high radiation environments**
  - NO post oxidation anneal (POA) drastically improves performance
  - Phosphorus and boron potential next-generation techniques

- **What is the true nature of the interface, and how do our processing techniques really affect it?**
  - Our (and others’) work indicates a distinct transition region (EELS)\(^1\)\(^-2\)
  - Others suggest abrupt transition; only roughness (XPS, MEIS, etc.)\(^3\)\(^-4\)

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Motivation for orientation experiments

- Origins for mobility enhancement on $a$-face are poorly understood
- Does NO anneal operate in a different manner for the $a$-face compared to the Si-face?

SiC crystal face orientations (Adapted from Dhar, 2005)

Mobility of $a$-face vs. Si-face (Liu, 2013)
Next-generation processing

- “Next-generation” passivation techniques are more poorly understood than the NO process

- Phosphorus and boron passivations are particularly promising
  - Only one TEM study of P, and none of B in literature
  - How do they differ from NO-annealing?

High $\mu$ in B-passivated device
(Okamoto, 2014)

High $\mu$ in P-annealed devices
(Liu, 2013)
(Very) Brief introduction to TEM-EELS

Electron Energy Loss Spectroscopy

EELS energy band schematic
(Williams and Carter, 2009)
EELS Spectrum Imaging

STEM survey image at interface

EELS spectrum collected at each point

SiC

SiO$_2$

10 nm

Intensity (log scale)

Energy (eV)

Zero-loss peak

Plasmon interaction losses

Si-$L_{2,3}$

C-K

O-K

Background Subtracted Si-$L_{2,3}$ Edge
What is at the interface?

SiO$_2$ Int. SiC

EELS Spectrum Image

Si-$L_{2,3}$ ELNES signal

Linear combination? Or something more?
Hyperspectral decomposition (or unmixing)

- Technique to recover multiple unknown signals from a spectrum image
- Consider a spectrum image as a matrix, and use matrix decomposition:

  - Any number of decomposition strategies can be used
    - Non-negative Matrix Factorization (NMF) is very suitable for EELS data
    - Unbiased; unsupervised; only assumption is positivity of data
Unmixing of Si-$L_{2,3}$ EELS signal

- No significant variation between different orientations
  - $a$-face results shown

- NO anneal gives rise to interfacial state in all samples
  - No such state in samples only oxidized
  - Very similar to Si$_3$N$_4$ signal
Si-L\textsubscript{2,3} Interface – Evidence of N bonding

Reduced edge onset for $\alpha$-face

Effect of substrate orientation

Comparison to Si\textsubscript{3}N\textsubscript{4} literature (Skiff, 1987)
Unmixing of C-K EELS signal

- NO anneal gives rise to interfacial state in all samples
  - No such state in samples only oxidized
- Pre-edge intensity indicative of $sp^2$ bonding, rather than $sp^3$
  - Often observed in C-N configurations
- Strong presence of N in carbon bonds

Interfacial nitrogen’s effects observed in Si and C signals, in all samples
Unmixing of O-K EELS signal

- Only sample with interfacial component was \(a\)-face with NO anneal
- Interface has edge onset 2-3 eV lower than \(\text{SiO}_2\)
  - Reduced bandgap
  - Increased dielectric constant
  - Enhanced mobility
- Likely part of the drastically enhanced mobility on the \(a\)-face
  - Silicon/carbon oxynitride configuration
Summary of crystallographic orientation effects

- **Confirmation of Si$_3$N$_4$-like bonding, measured at Si-$L_{2,3}$ edge**
  - Further agreement between EELS and XPS results
  - Miscut/roughness alone does not appear to alter chemical states

- **Carbon bonds have $sp^2$ character in NO annealed devices (C-$K$ edge)**
  - Signals the N bonds to both Si and C

- **Distinct oxygen interfacial signal only in NO annealed $a$-face device**
  - $a$-face enables additional bonding configurations that affect the oxide signal
  - Nanometer scale region of reduced bandgap likely origin of enhanced mobility in such orientations
Phosphorus anneal imaging results

- HAADF-STEM (Z-contrast) shows significant difference in oxide quality
  - Bright spots correspond to higher mass
  - Non-uniformly distributed; lighter atomic mass layer 5 – 10 nm in thickness at interface

- EELS shows P-rich clusters
  - $3.6 \pm 0.8$ nm in diameter
Boron anneal imaging results

- EELS matches expectations from HAADF-STEM
  - B-rich region near the interface (about 1.5 nm wide)

- 1.0 nm diffusion of B into SiC substrate
  - $p$-type doping origin of increased $V_{th}$

- HAADF-STEM (Z-contrast) shows more uniformity in oxide
  - Darker layer at interface about 1.5 nm in thickness
  - Corresponds to lighter mass (possibly boron)
Phosphorus and Boron anneal summary

• Both P and B incorporated into gate oxide differently than NO
  - Significantly more oxide impact than observed after nitridation

• Phosphorus distributed into nanometer sized P-rich clusters
  - Likely to have significant impacts on polarization instability
  - Offers opportunities for gate oxide engineering (i.e. can we control phosphorus distribution?)

• Boron segregates preferentially to the SiC/oxide interface
  - Like NO, but with substantially more boron remaining throughout the BSG layer
  - B diffuses into SiC, and distribution throughout oxide is not uniform
Remaining questions for SiC

• Continued investigation of boron and phosphorus annealed oxides
  - Results presented here are just the very surface
  - Can these oxides be tailored to improve performance, and how do the oxide characteristics change?

• Analysis of substrate strain at the interface
  - Could have significant effects on performance of devices, but little is known
  - Do the various processing conditions change the strain substantially?
  - How does $a$-face compare to Si-face?
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Backscatter electron image of PSG on SiC, after 2 minutes of patterning with the Gaia FIB (20pA current).
Image contrast arises from the mass difference caused by Ga implantation into the sample

Facilities/Assistance

Thank you!

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