Analytical Electron Microscopy of Interfacial States in 4H-SiC/SiO$_2$ MOS Devices

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Why silicon carbide (SiC)?

Projected SiC + GaN revenues 17x to $2.5B by 2023

(Semiconductor Today, 2016)

- Wide bandgap
- Good properties
- Native SiO$_2$
- More efficient than Si at high voltage

Efficiency comparison of SiC vs. Si
(Adapted from Rozen, 2012)
Unresolved problems

- **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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Specific effects investigated

- For NO-annealed devices:
  - Does the orientation of the substrate affect incorporation of nitrogen?
  - Why such a drastic improvement on the $a$-face?

<table>
<thead>
<tr>
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<th>Peak $\mu_{FE}$ (cm$^2$/V s)</th>
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<tbody>
<tr>
<td>$a$-face</td>
<td>83</td>
</tr>
<tr>
<td>Si-face</td>
<td>42</td>
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Mobility of $a$-face vs. Si-face with NO post-anneal
(Liu, 2013)

- Next-generation processing
  - Analysis of phosphorus and boron incorporation
  - How do these passivations 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

SiC

SiO$_2$

10 nm

EELS spectrum collected at each point

Intensity (log scale)

Energy (eV)

Zero-loss peak

Plasmon interaction losses

Si-$L_{23}$

C-K

O-K

Background subtracted Si-$L_{23}$ edge
What is at the interface?

SiC | Int. | SiO₂

EELS Spectrum Image

Linear combination? Or something more?

Si-L₂₃ ELNES signal
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
Unmixing of C-K EELS signal

NO Anneal

- 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

Relative energy loss (eV)

a-face on-axis
Unmixing of O-K EELS signal

- Only sample with interfacial component was α-face with NO anneal
- Interface has edge onset 2-3 eV lower than SiO₂
  - Reduced bandgap
  - Increased dielectric constant
  - Enhanced mobility
- Likely part of the drastically enhanced mobility on the α-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
Individual contributions

• Essentially all work except for device fabrication
  - TEM lamellae preparation
  - TEM/EELS imaging
  - Data processing

• Many more experiments performed
  - Spin-etch XPS depth profiles
  - Devising method to measure $w_{\text{TL}}$
  - SiC work about $\frac{1}{2}$ of overall PhD work

• Open-source software contributor
  - HyperSpy data analysis package
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.