Analytical Electron Microscopy of Interfacial States in 4H-SiC/SiO_2 MOS Devices

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2016 Fall MRS
GSA Finalist Talk
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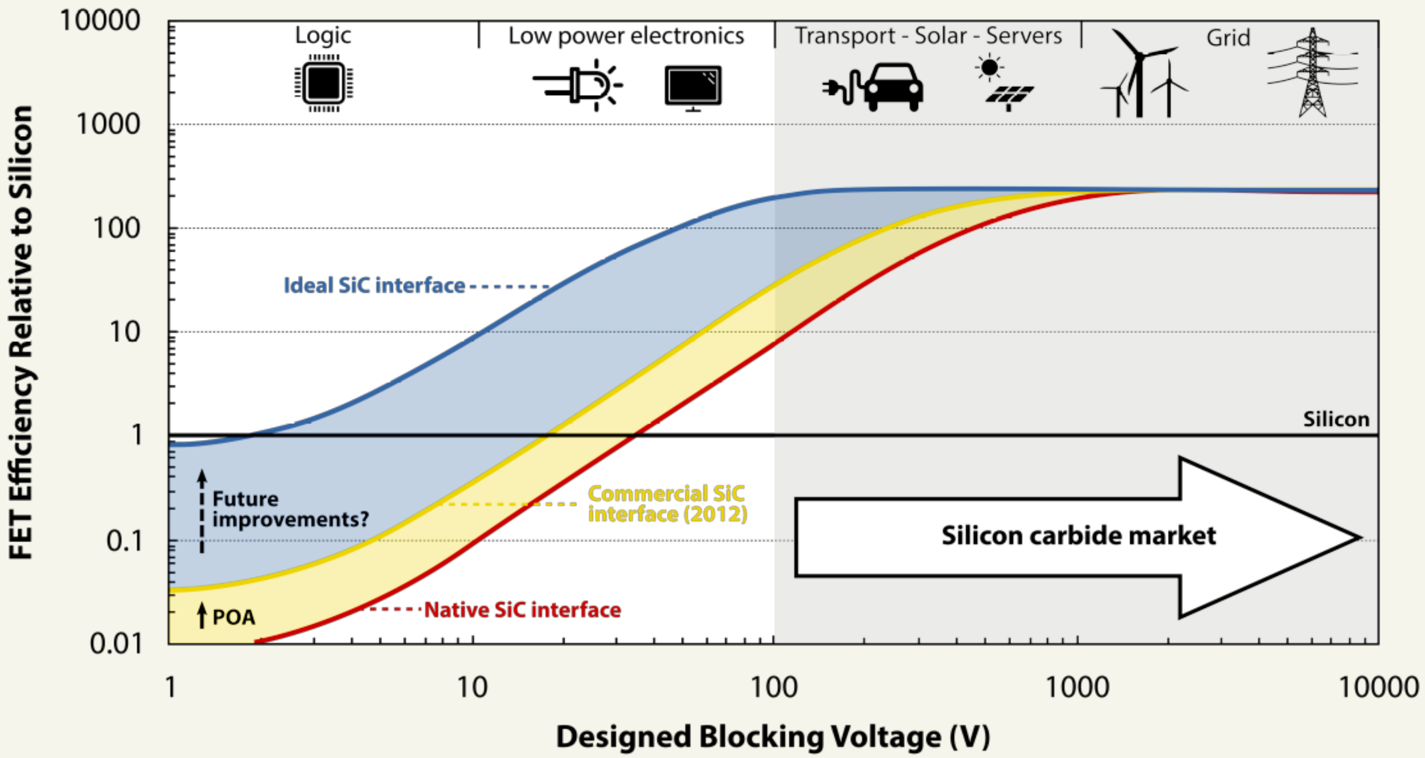
Why silicon carbide (SiC)?

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

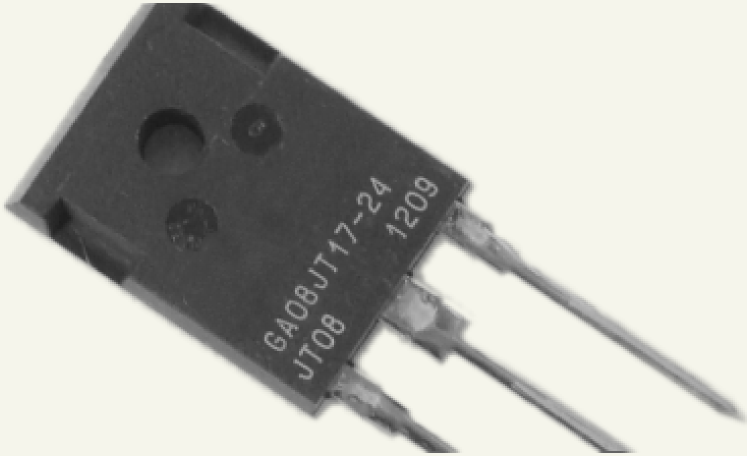
(Semiconductor Today, 2016)



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

- **Wide bandgap**
- **Good properties**
- **Native SiO_2**
- **More efficient than Si at high voltage**

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]

[1] J. Taillon, L. Salamanca-Riba, et al., J. Appl. Phys. 113, 044517 (2013).
[2] K. C. Chang, et al. *J. Appl. Phys.* **97**, 104920 (2005).
[3] H. Watanabe, et al., *Appl. Phys. Lett.*, **99**(2), 021907 (2011).
[4] X. Zhu, et al., *Appl. Phys. Lett.*, **97**(7), 071908 (2010).

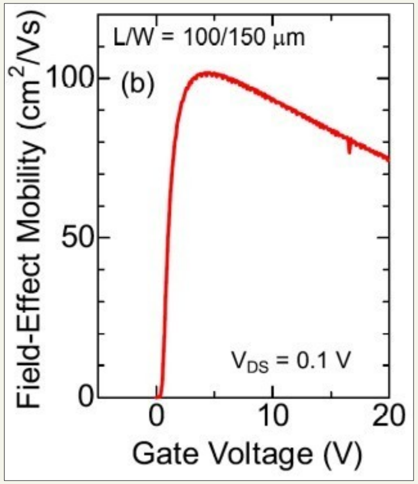
Specific effects investigated

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

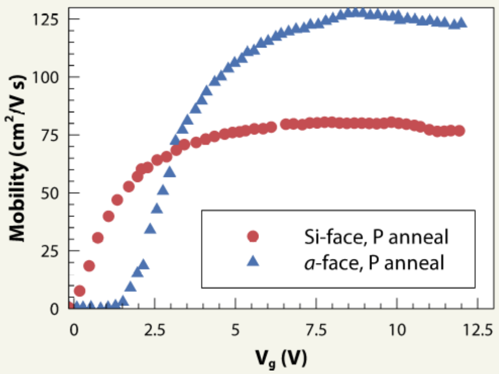
	Peak μ_{FE} (cm²/V s)
***a*-face**	83
Si-face	42

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?



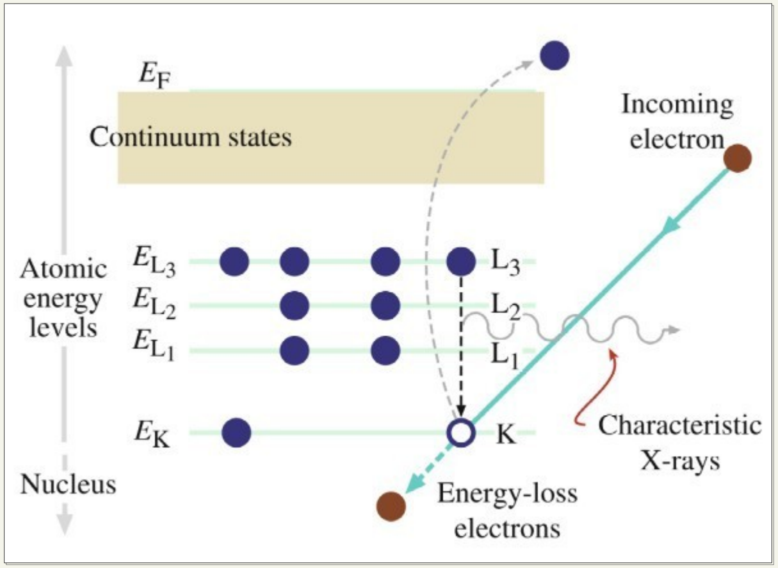
High µ in B-passivated device
(Okamoto, 2014)



High µ in P-annealed devices
(Liu, 2013)

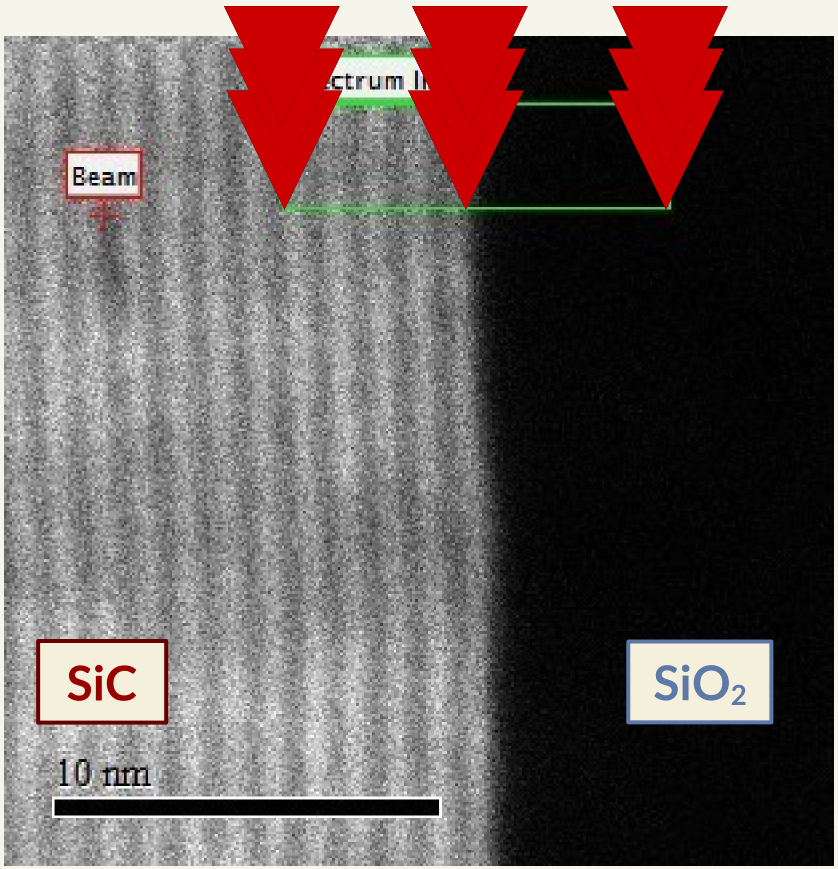
(Very) Brief introduction to TEM-EELS

Electron
Energy
Loss
Spectroscopy



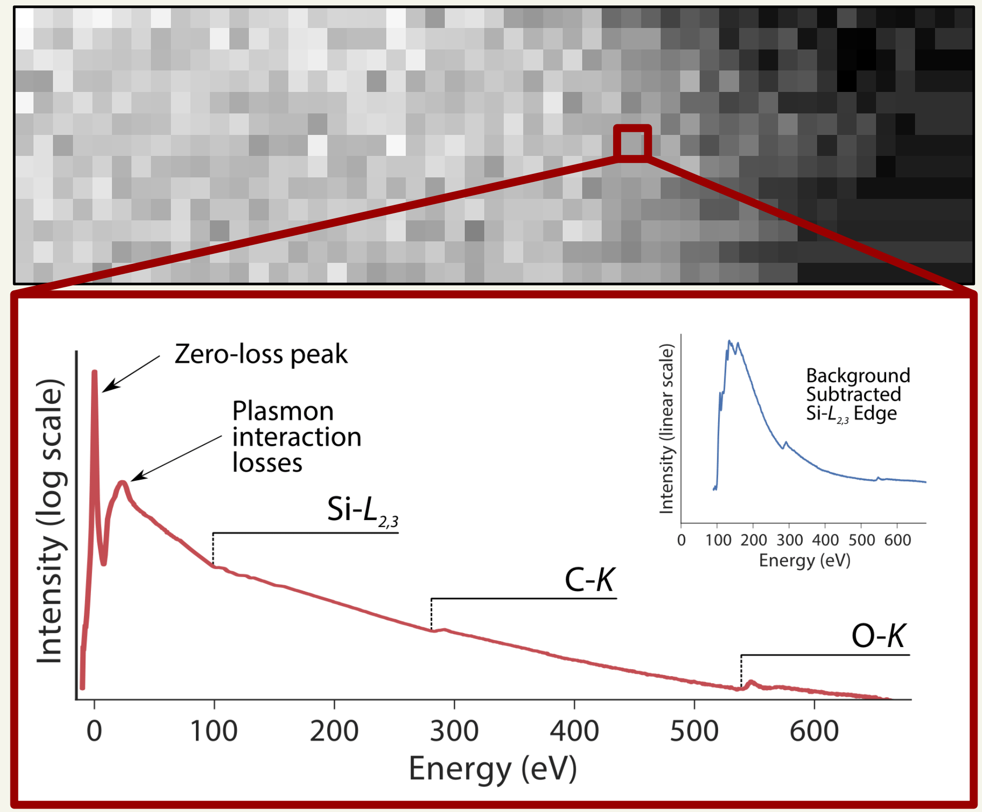
EELS energy band schematic
(*Williams and Carter, 2009*)

EELS Spectrum Imaging

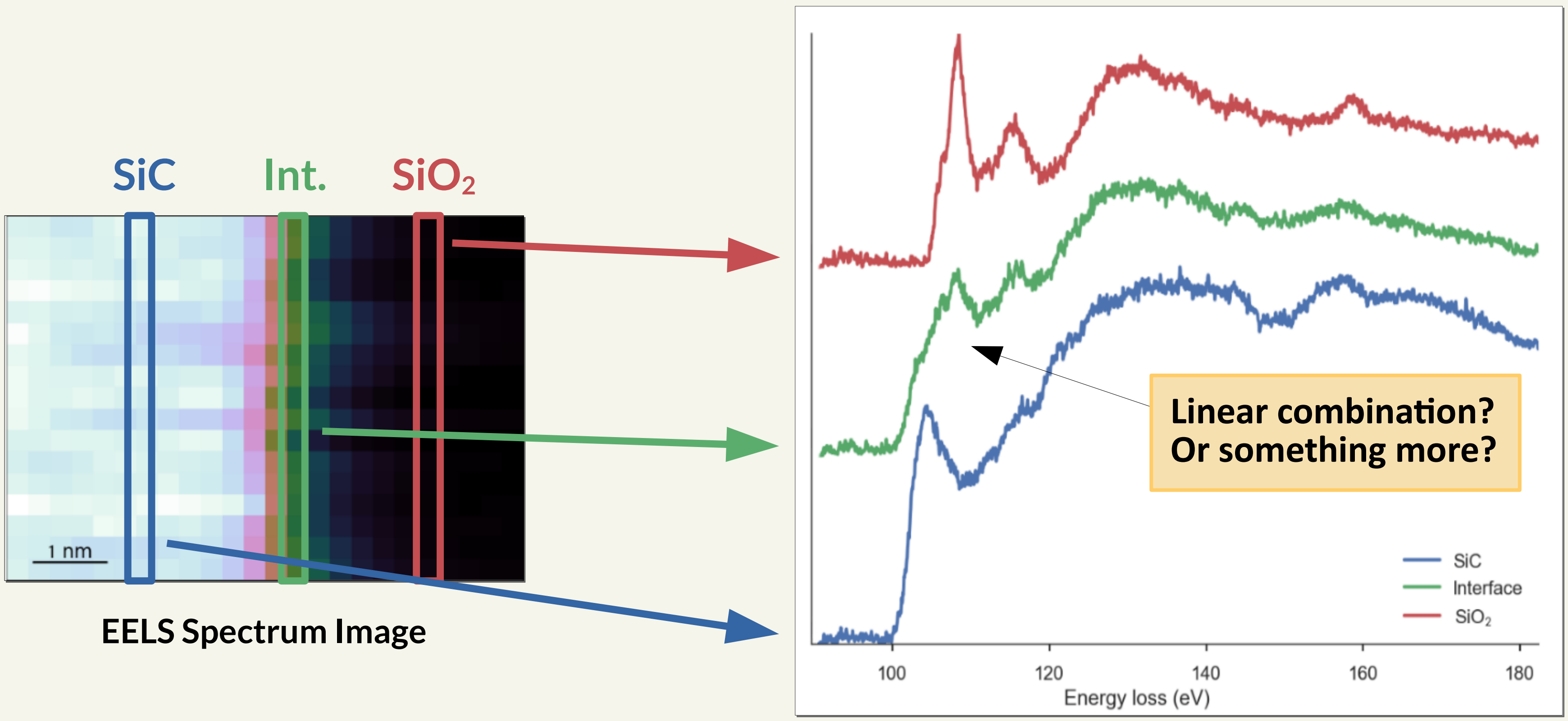


STEM survey image at interface

EELS spectrum collected at each point



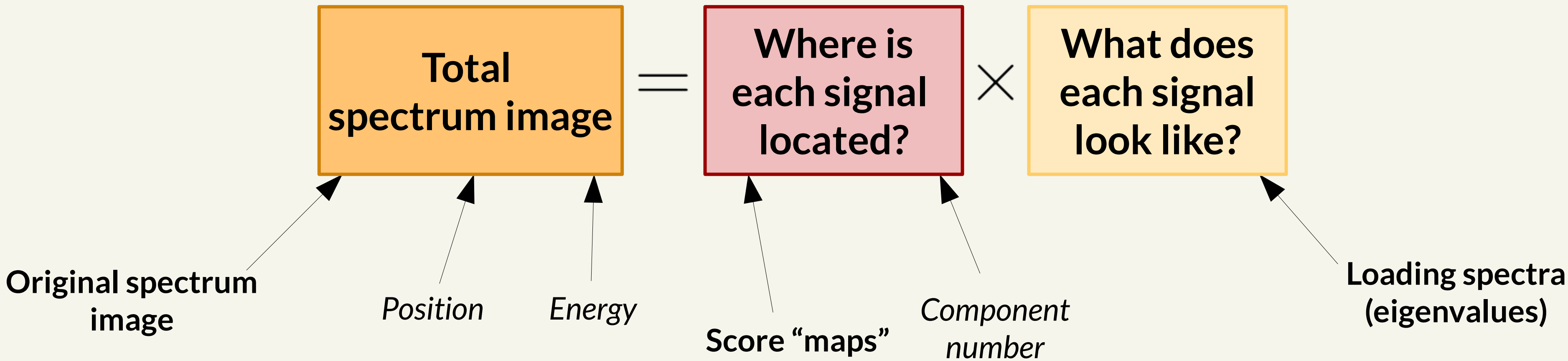
What is at the interface?



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

Hyperspectral decomposition (or unmixing)

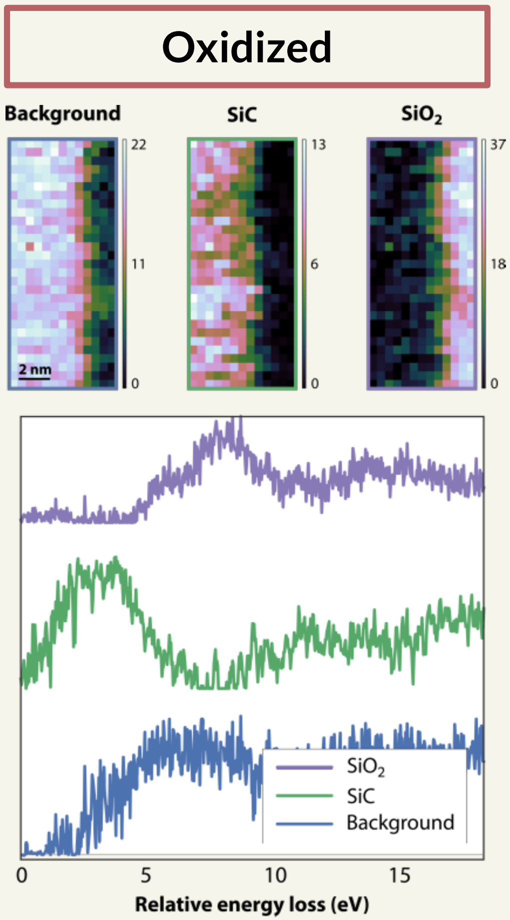
- **Technique to recover multiple unknown signals from a spectrum image**
- **Consider a spectrum image as a matrix, and use matrix decomposition:**



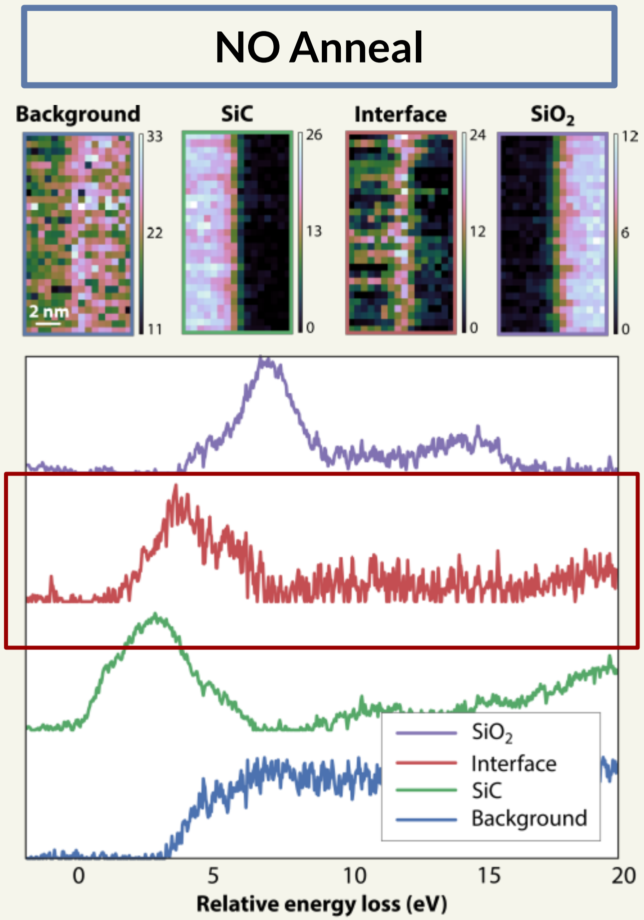
- **Any number of decomposition strategies can be used**
  - Non-negative Matrix Factorization (NMF) is very suitable for EELS data
  - Unbiased; unsupervised; only assumption is positivity of data

Unmixing of Si-$L_{2,3}$ EELS signal

5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007
13 Al Aluminum 26.981	14 Si Silicon 28.085	15 P Phosphorus 30.974



a-face on-axis



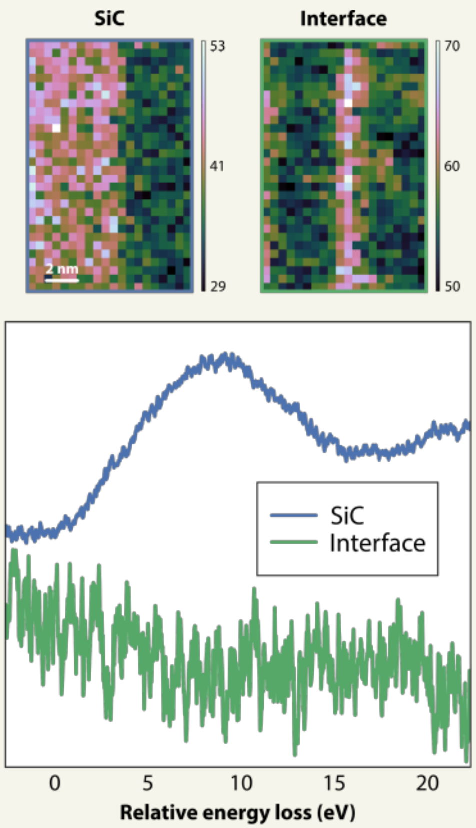
a-face on-axis

- **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_3N_4 signal

Unmixing of C-*K* EELS signal

5 **B** Boron 10.811	6 **C** Carbon 12.011	7 **N** Nitrogen 14.007
13 **Al** Aluminum 26.981	14 **Si** Silicon 28.085	15 **P** Phosphorus 30.974

NO Anneal

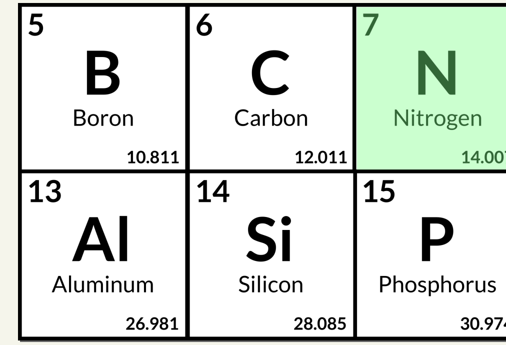


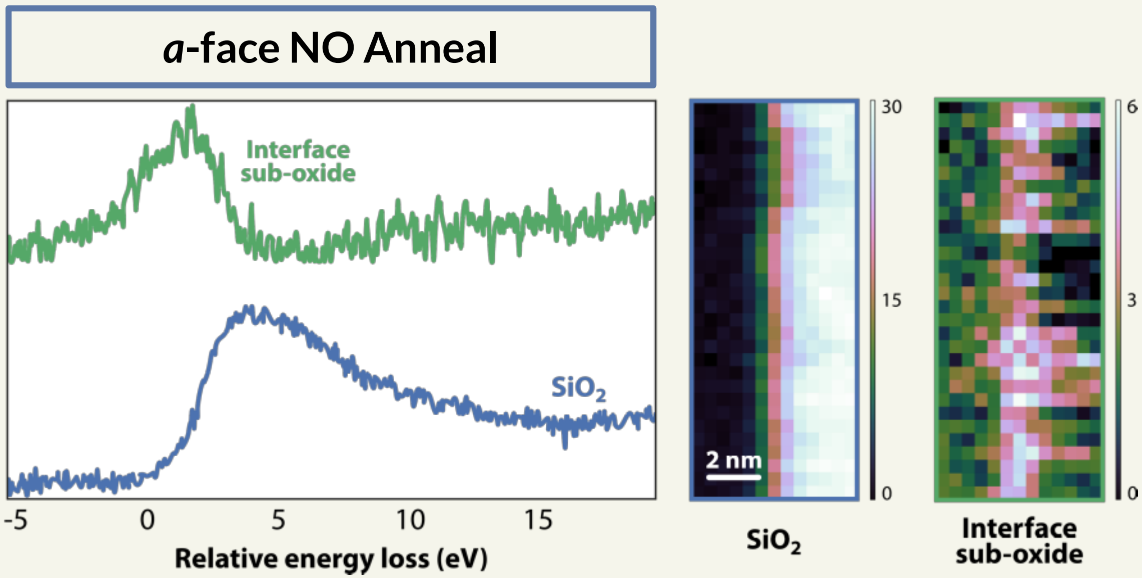
a-face on-axis

- **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



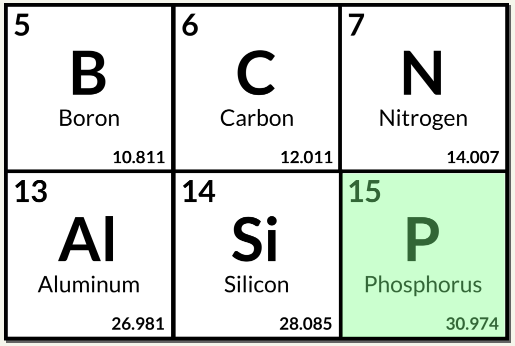


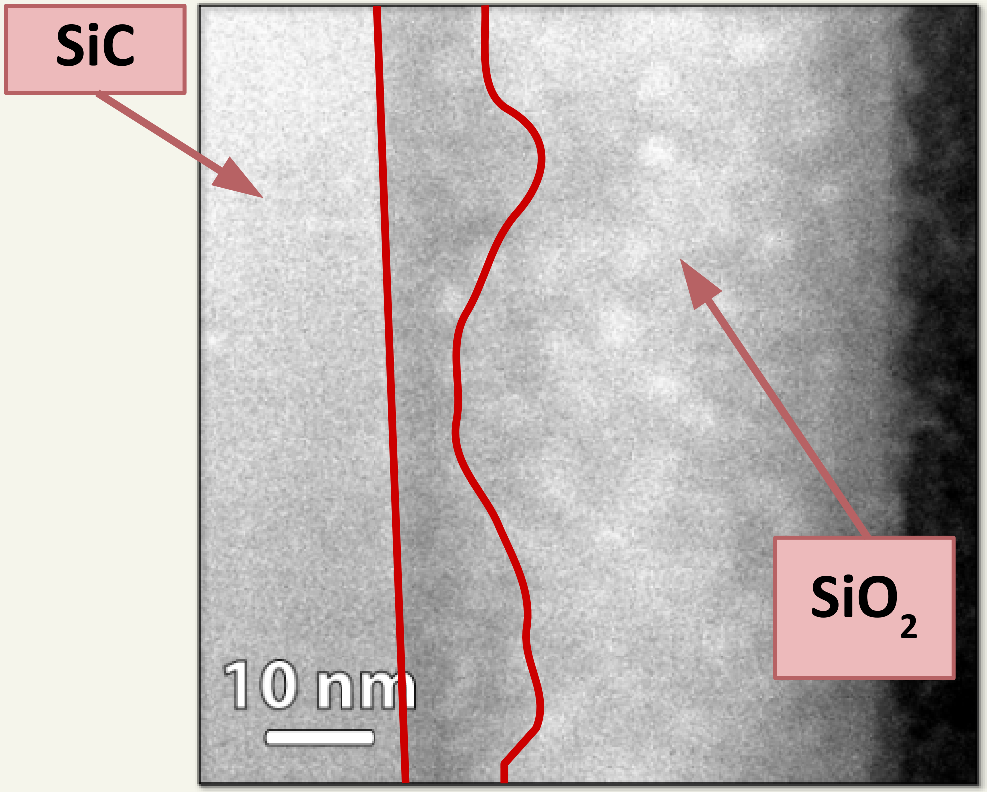
- **Only sample with interfacial component was *a*-face with NO anneal**
- **Interface has edge onset 2-3 eV lower than SiO_2**
  - Reduced bandgap
  - Increased dielectric constant
  - Enhanced mobility
- **Likely part of the drastically enhanced mobility on the *a*-face**
  - Silicon/carbon oxynitride configuration

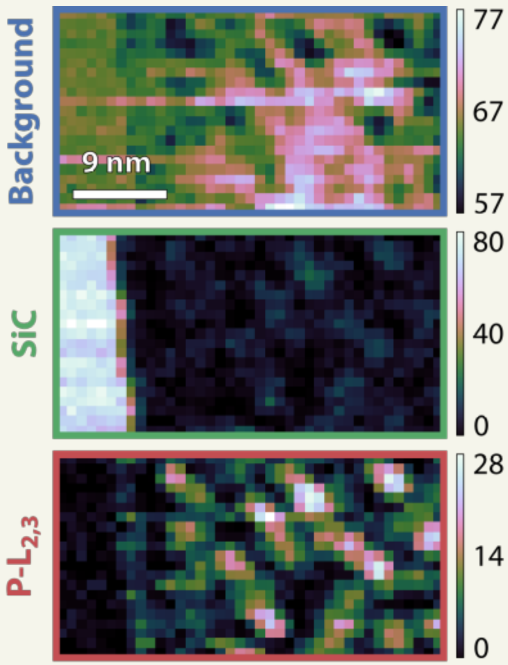
Summary of crystallographic orientation effects

- **Confirmation of Si_3N_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





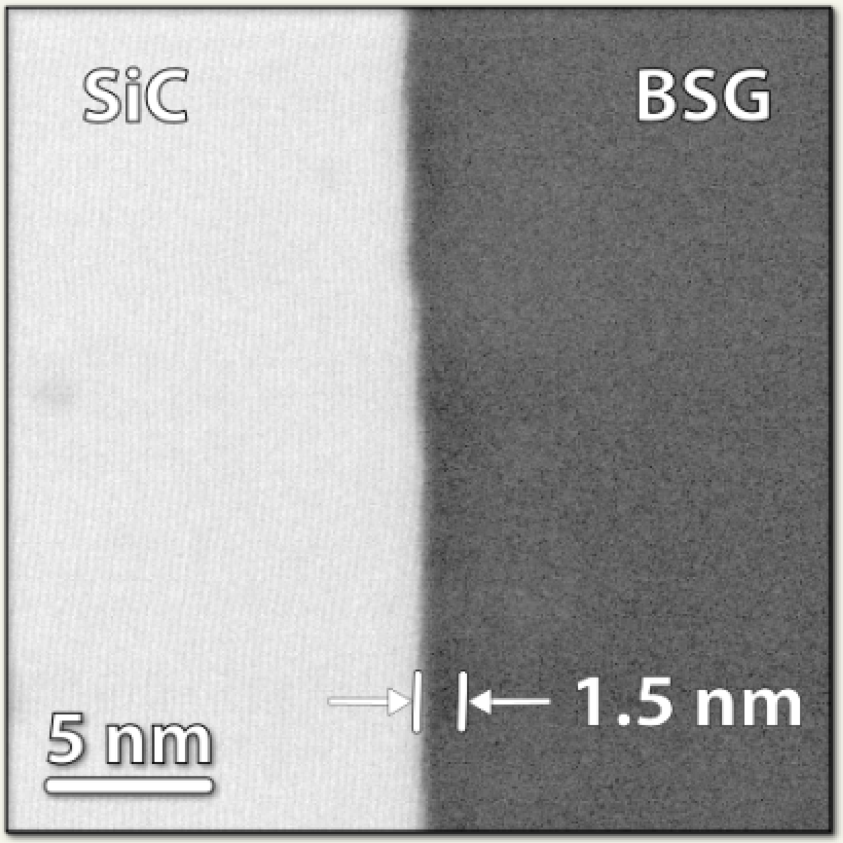


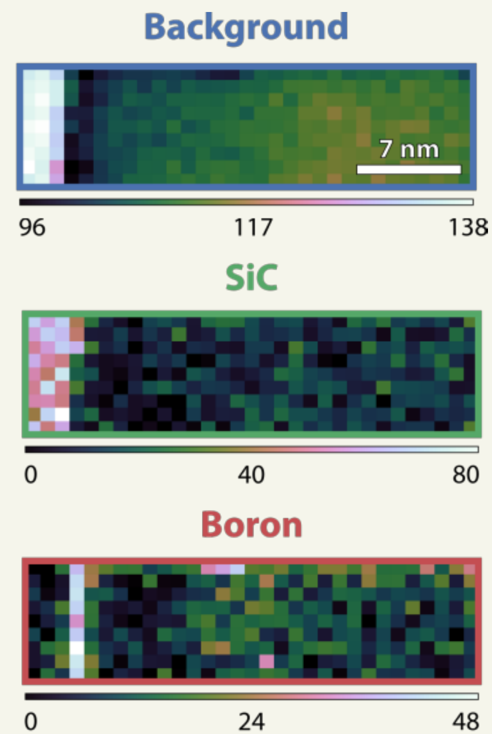
- **HAADF-STEM (Z-contrast) shows significant difference in oxide quality**
  - Bright spots correspond to higher mass
  - Non-uniformly distributed; lighter atomic mass layer 5 – 10 nm in thickness at interface

- **EELS shows P-rich clusters**
  - 3.6 ± 0.8 nm in diameter

Boron anneal imaging results

5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007
13 Al Aluminum 26.981	14 Si Silicon 28.085	15 P Phosphorus 30.974





- **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_{TL}
  - SiC work about ½ of overall PhD work
- **Open-source software contributor**
  - HyperSpy data analysis package

Acknowledgments

Funding/Support

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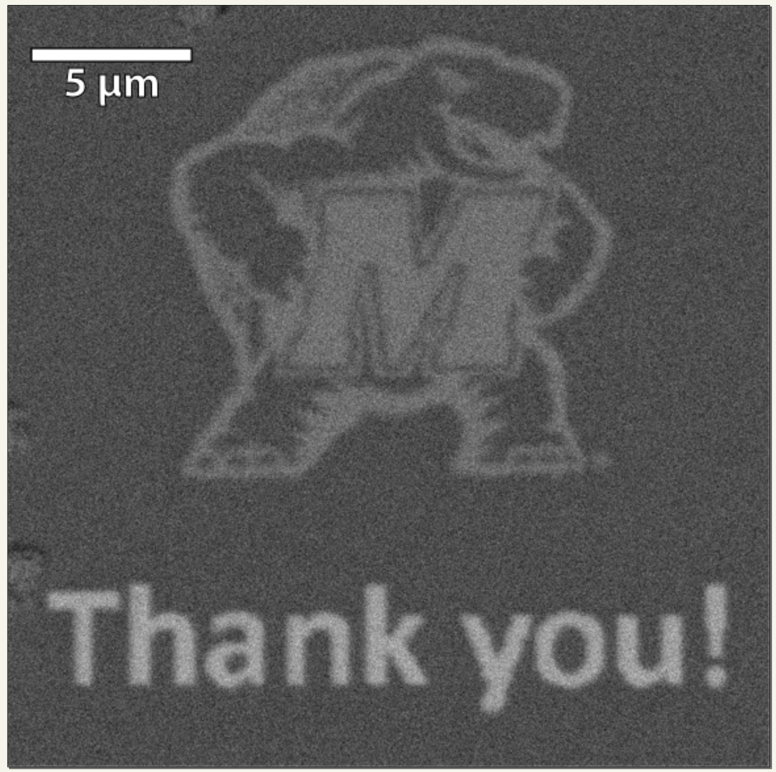

Backscatter electron image of PSG on SiC, after 2 minutes of patterning with the Gaia FIB (20pA current).
Image contrast arises from the mass difference caused by Ga implantation into the sample

Facilities/Assistance

UNIVERSITY OF MARYLAND

MARYLAND NANOCENTER AIMLAB
ADVANCED IMAGING & MICROSCOPY LABORATORY

NIST

CNST
Center for Nanoscale Science & Technology

Joshua Schumacher