Systematic Characterization of the SiC/SiO_2 Transition Layer in NO-Annealed MOSFETs

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Outline

- Introduction, Motivation, Background, Goals
- Experimental Methods
  - EELS, Spectrum Imaging, w_{TL} determination
- Transition layer width results
  - Composition ratios
  - Interdiffusion
  - High-angle annular dark field scanning TEM (HAADF-STEM)
  - Chemical shift
- Correlation with electronic measurements
- Conclusions, Remaining questions, etc.

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Motivation and Background

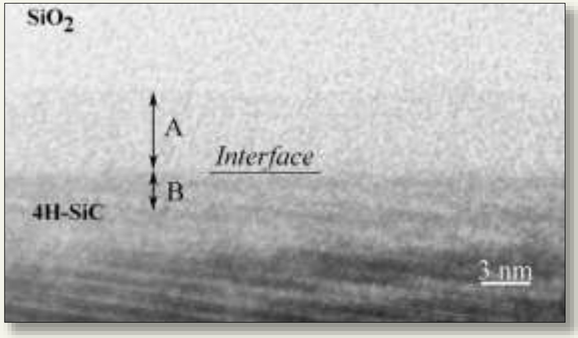
- SiC: Very promising for high temperature, high power, and high radiation environments
  - 4H polytype (bulk):[1] $\boldsymbol{E_g} = 3.23\ \mathrm{eV}$, $\boldsymbol{\mu_e} \approx 850\ \frac{\mathrm{cm}^2}{\mathrm{V\cdot s}}$, $\boldsymbol{\varepsilon} = 10$, $\boldsymbol{\kappa} = 3.7\ \frac{\mathrm{W}}{\mathrm{cm}\cdot{}^\circ\mathrm{C}}$
  - MOSFET devices limited by poor channel carrier mobility and reliability
  - Typical effective device $\boldsymbol{\mu_e}$: SiC ~ $85\ \frac{\mathrm{cm}^2}{\mathrm{V\cdot s}}$; Si ~ $300\ \frac{\mathrm{cm}^2}{\mathrm{V\cdot s}}$
  - Electrically active defects at the SiC/SiO_2 interface inhibit devices during channel inversion
- Possible nature of these defects?

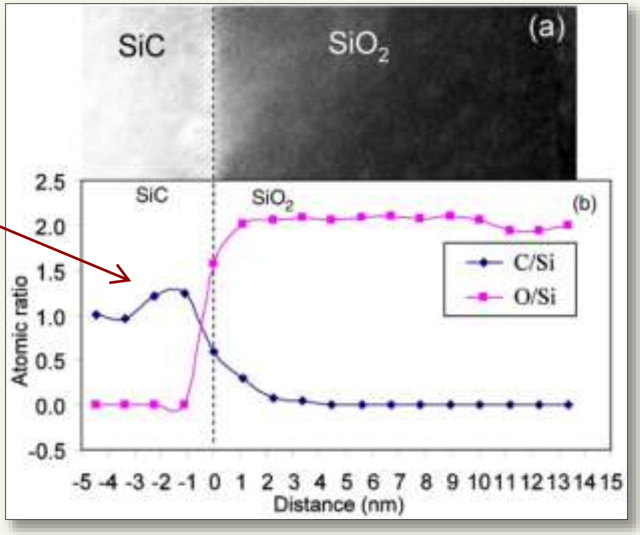
Excess carbon at the interface (perhaps?)	K. Chang, *et al*. J. Electron. Mater. **32**, 464 (2003). X. Shen, *et al*. J. Appl. Phys. **108**, 123705 (2010). Hatakeyama, *et al.* Mater. Sci. Forum **679**, 330 (2010).
3-fold Si and C coordination and C_i	M. Di Ventra, *et al.* Phys. Rev. Lett. **83**, 1624 (1999). S. Pantelides, *et al.* Mater. Sci. Forum **527**, 935 (2006).
V_{Si} and V_o at interface	C. Cochrane, *et al*. Appl. Phys. Lett. **100**, 23509 (2012). J. Rozen, *et al*. J. Appl. Phys. **105**, 124506 (2009).

[1] Semiconductor database: *http://www.ioffe.ru/SVA/NSM/Semicond/SiC/index.html*

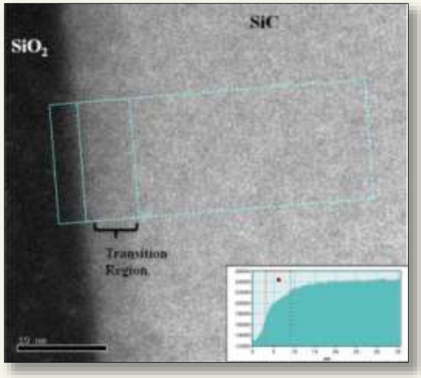
Previous Work

- Transition layer at SiC/SiO_2 interface
  - EELS evidence of enhanced C concentration in SiC at interface
    - T. Zheleva, *et al*. Appl. Phys. Lett. **93**, 022108 (2008).





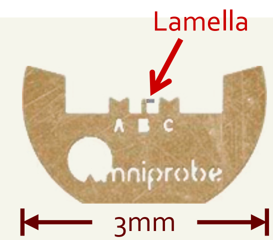
  - Transition layer width (w_{TL}) lowered by NO post-anneal
    - Measured with HAADF-STEM intensity profiles
    - Inverse linear correlation between w_{TL} and mobility
    - T. Biggerstaff, *et al*. Appl. Phys. Lett. **95**, 032108 (2009).



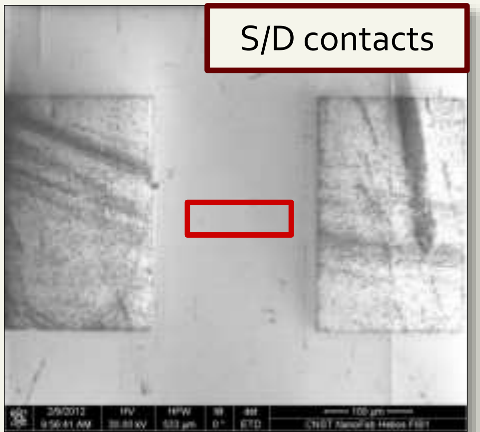
Goals

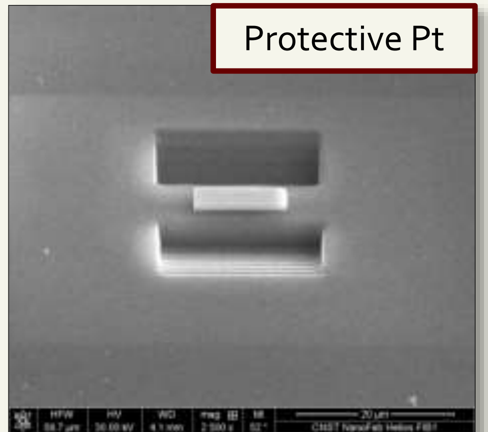
- Previous work lacks systematic investigation of NO-anneal time
- Physically and chemically characterize transition layer as a function of NO post-annealing time
  - Systematic set of SiC MOSFETs that received 0-240 minute post-oxidation anneals at 1175°C
  - Using HRTEM, HAADF-STEM, and EELS
  - Correlate with measured device properties
  - Investigate conflicting claims of excess C at interface
- Develop reliable, objective, and reproducible methods by which to determine w_{TL}
  - For comparison to previous works and future sample sets

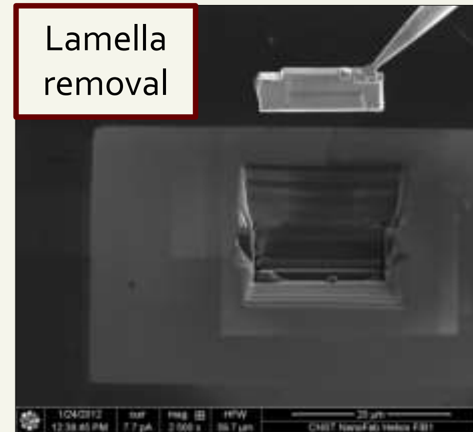
TEM Specimen Preparation

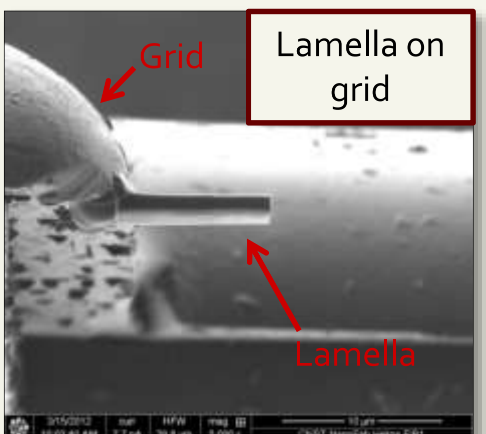


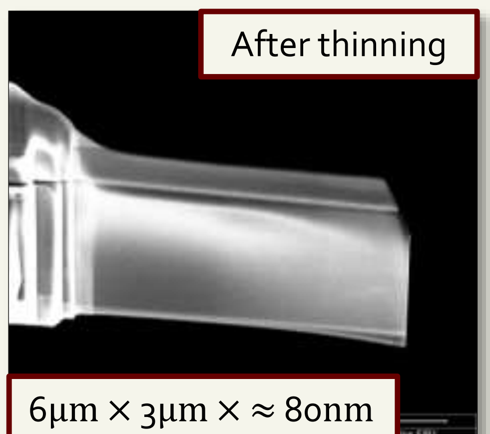
- Cross-sectional TEM specimen prepared with FEI Helios Dual-beam FIB

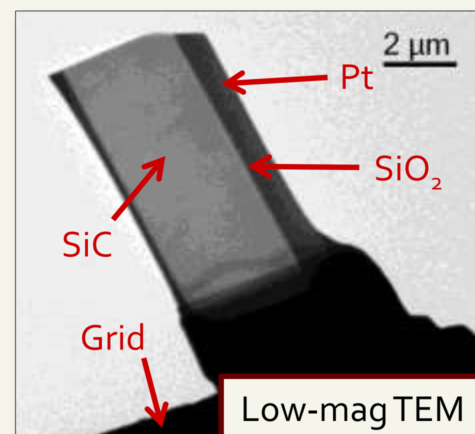




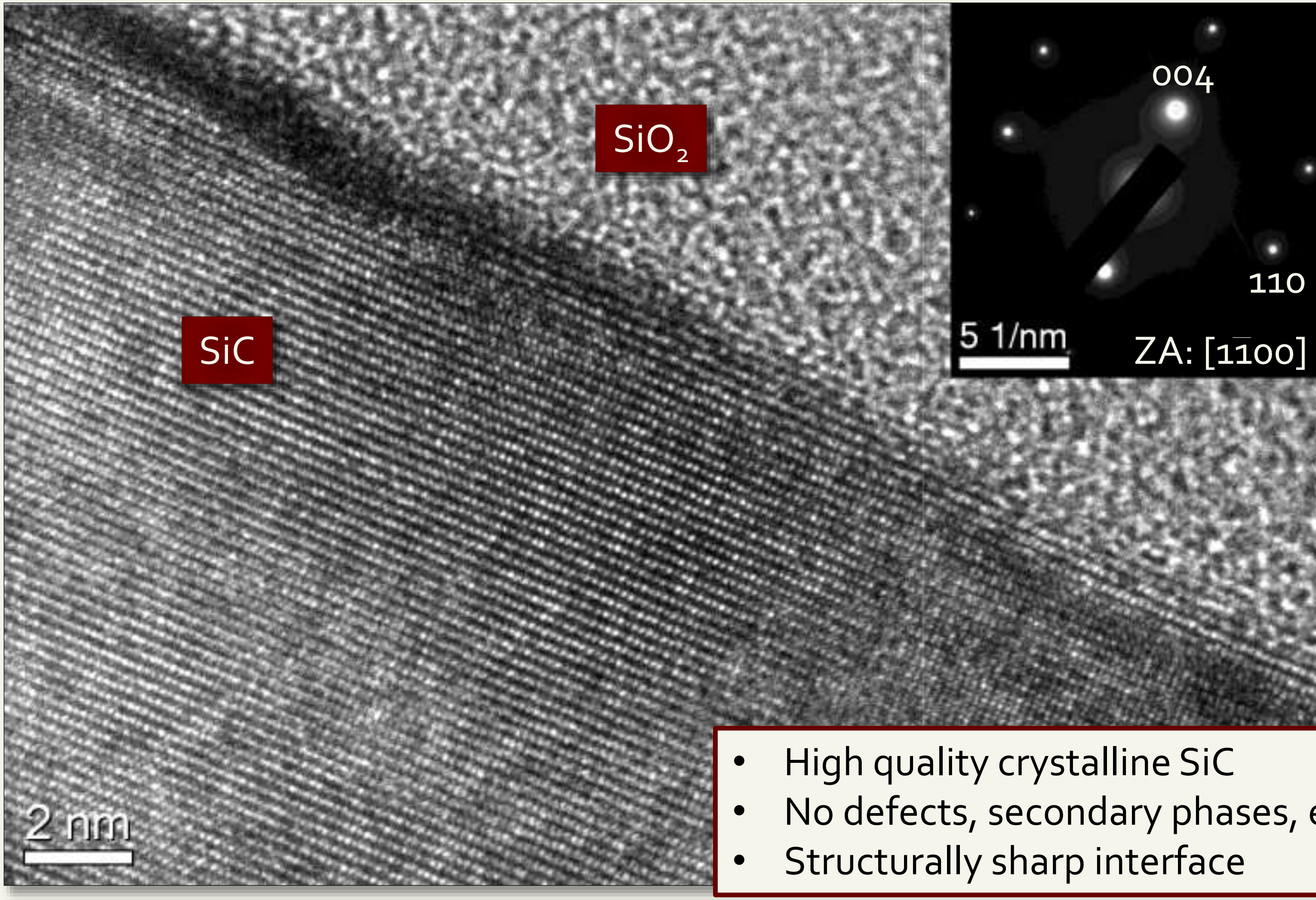








HRTEM of Transition Layer



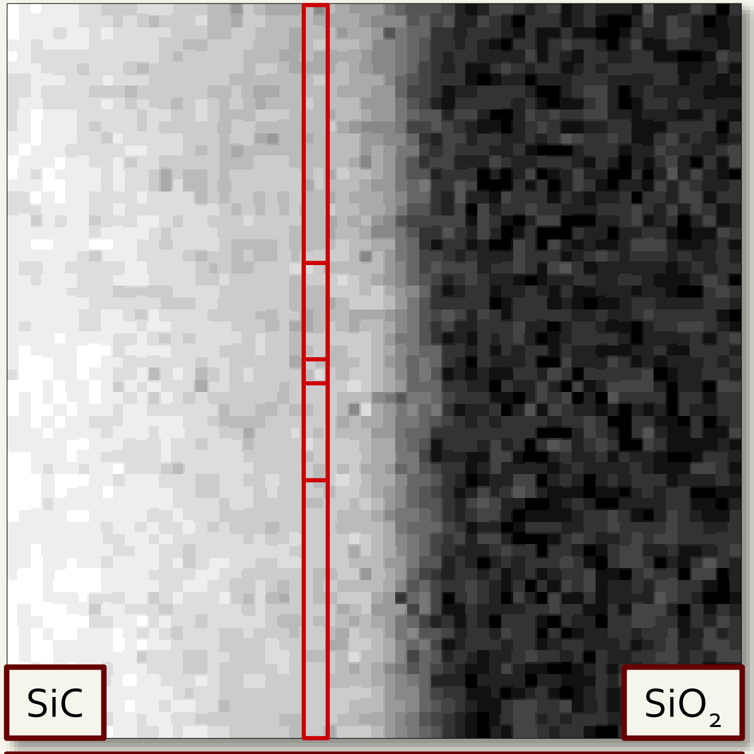
- High quality crystalline SiC
- No defects, secondary phases, etc.
- Structurally sharp interface

Transition Layer Width Measures

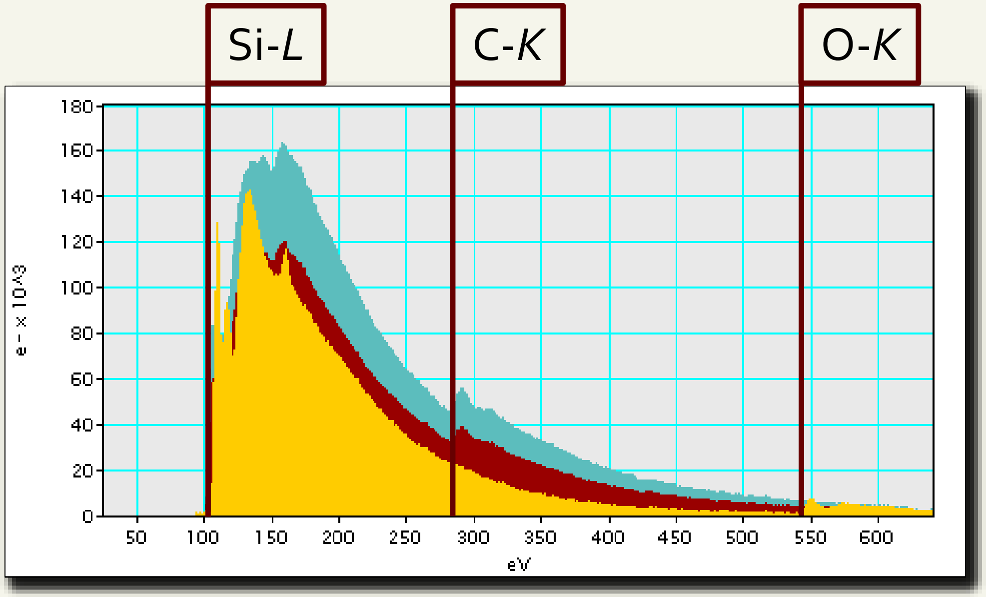
- Relative composition ratios from EELS ($^{\mathrm{C}}/_{\mathrm{Si}}$ and $^{\mathrm{O}}/_{\mathrm{Si}}$)
  - Eliminates many sources of systematic error[1]
- Relative "interdiffusion" of C and O (EELS)
  - C into SiO_2 and O into SiC; which contributes more to w_{TL}?
- HAADF-STEM image intensity profiles
  - HAADF reveals Z-contrast from variations in atomic composition
- Chemical shift of Si-$L_{2,3}$ EELS edge
  - Well-documented shift in edge onset energy (SiC: 100 eV; SiO_2: 104 eV)
    - G. Auchterlonie, *et al.* Ultramicroscopy, **31**, 217 (1989).
  - Reveals information about local Si bonding

[1] R. Brydson and R.M.S. (UK), *Electron Energy Loss Spectroscopy*, Microscopy Handbooks (Bios, 2001).

Spectrum Imaging



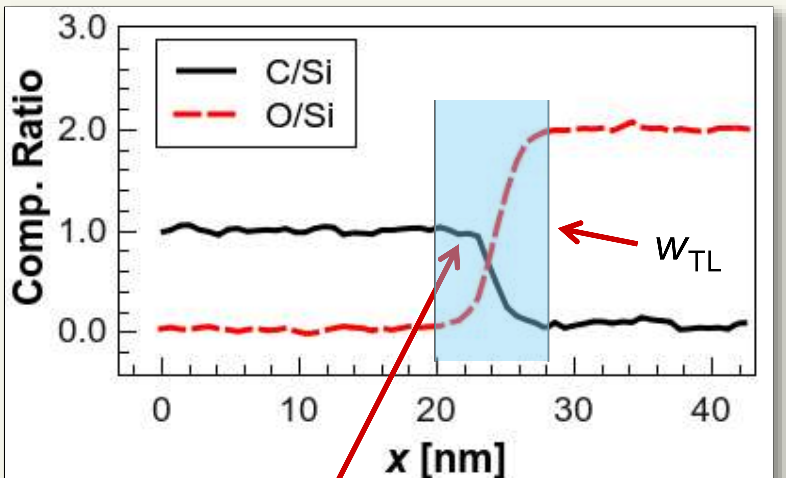
Spectrum Image
(60 minute anneal)



Background-subtracted spectrum
(60 minute anneal)

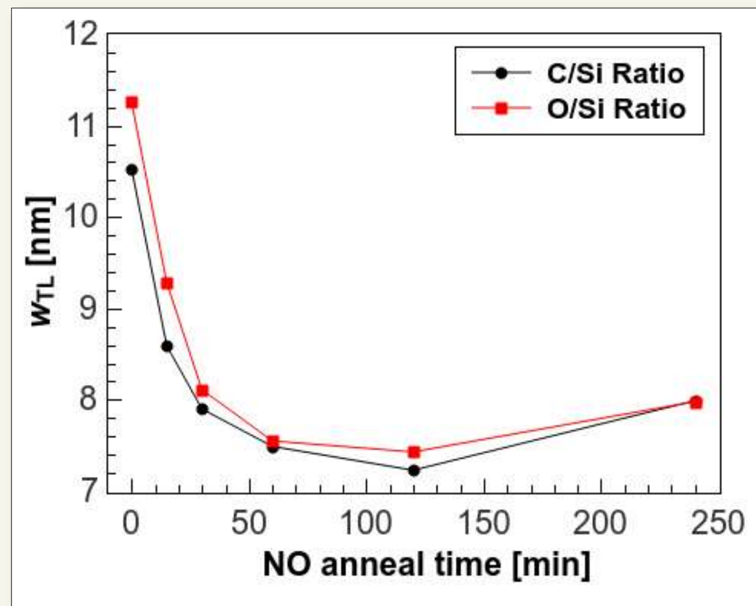
w_{TL} from Composition Ratios

- Profile of atomic ratio maps:



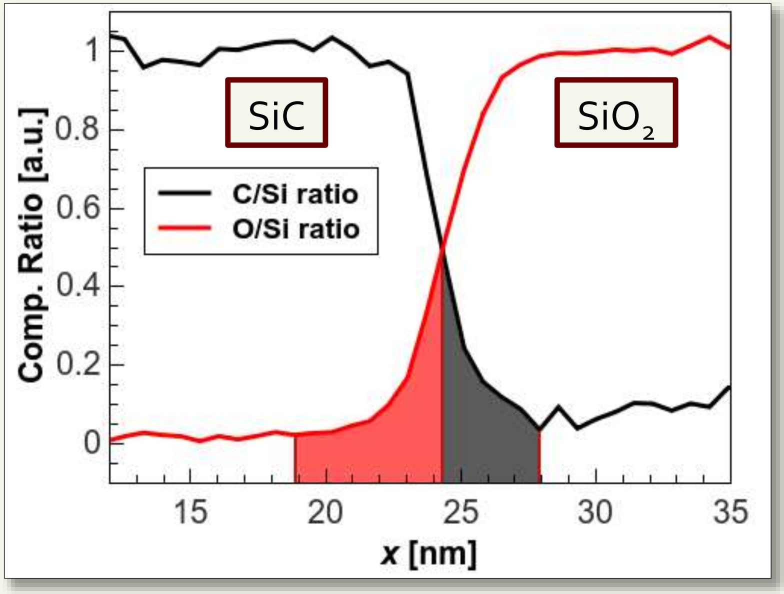
No excess C at interface

- w_{TL} results:
  - NO-anneal shows significant improvement
  - $^{O}/_{Si}$ slightly larger than $^{C}/_{Si}$ always

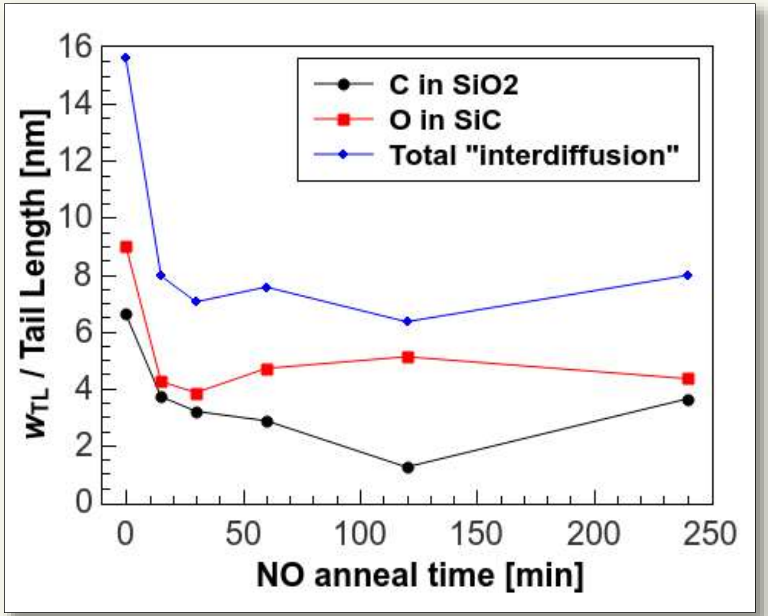


w_{TL} from "Interdiffusion" lengths

- Useful to see tails of C concentration in SiO_2 and O in SiC
  - Normalized bulk concentrations and measured tails with derivative

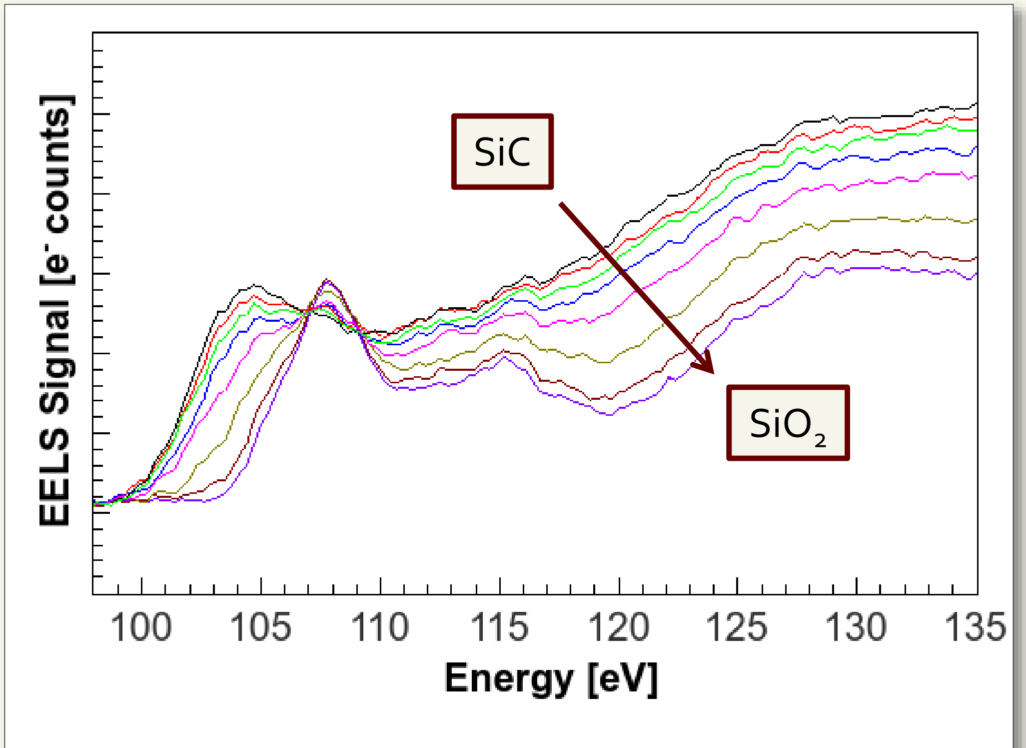


- w_{TL} results:
  - NO-anneal again shows significant improvement
  - O in SiC always larger than C in SiO2
  - Why?
    - C more efficiently removed during oxidation[1]
    - O solubility in SiC very low[2]



[1] M. Di Ventra and S. Pantelides, Phys. Rev. Lett. **83**, 1624 (1999).
[2] M. Di Ventra and S. Pantelides, J. Electro. Mater. **29**, 353 (2000).

Si-$L_{2,3}$ Chemical Shift

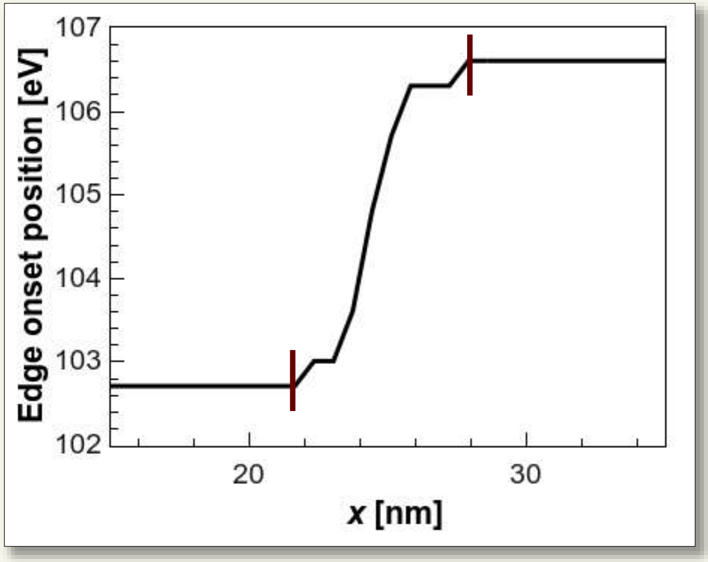


- EELS fine structure (ELNES) reflects local unoccupied density of states
  - Edge onset → minimum energy needed to excite core shell e^-
  - Semiconductor → insulator
  - Band gap widens, core levels depressed relative to E_F[1]
    - Charge transfer from Si → C/O
    - Onset shifts to higher energy

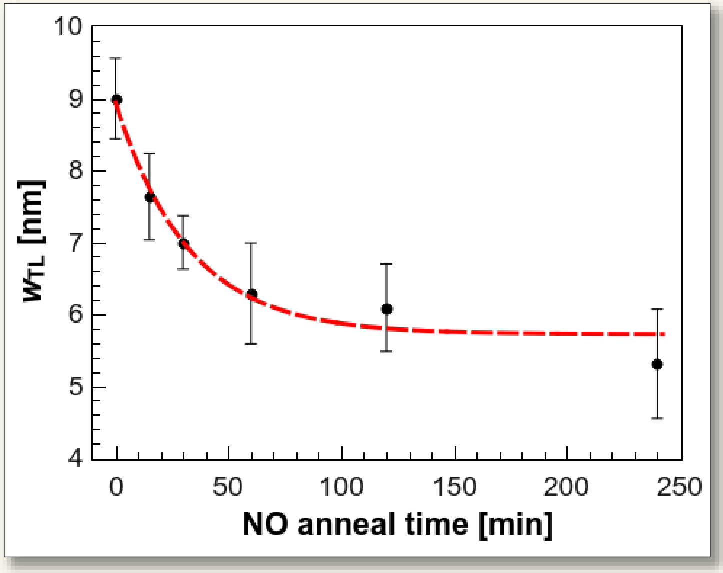
[1] D. Muller, Ultramicroscopy **78**, 163 (1999).

Si-$L_{2,3}$ Chemical Shift

- Track inflection point of edge onset across interface[1]
- Gradual and monotonic shift
  - Bonding changes, possible strain
  - Implies a mix of Si-C and Si-O bonding



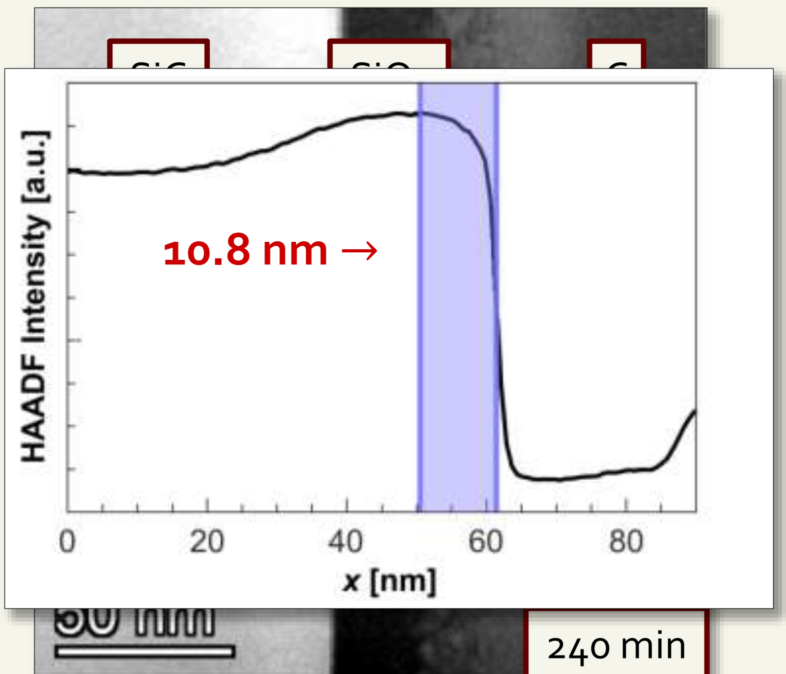
- Significant NO anneal improvement
  - Best method to track transition layer
  - (Relatively) insensitive to spectral noise
- Characterizes bonding instead of composition



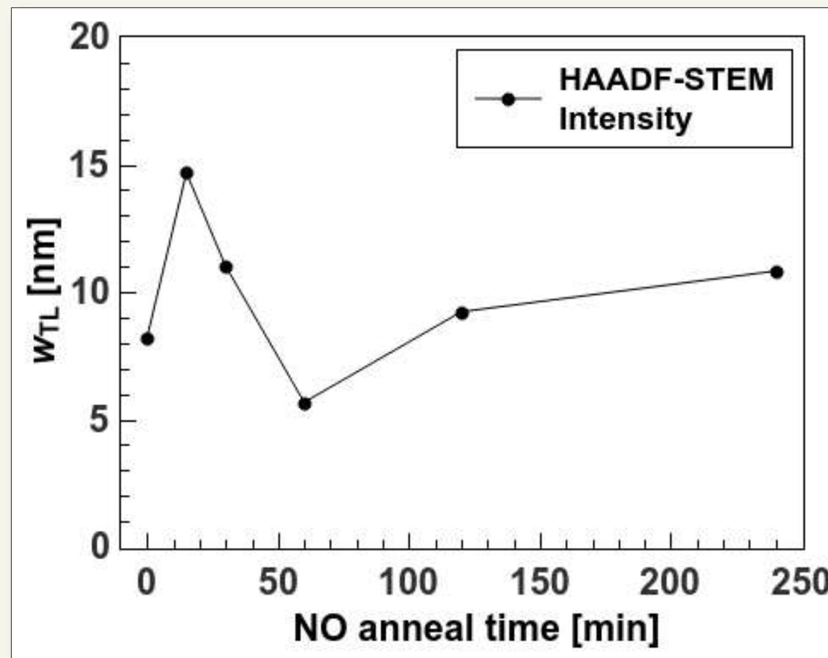
[1] D. Muller, P. Batson, and J. Silcox, Physical Review B **58**, 11970 (1998).

HAADF-STEM Image Intensity[1]

- Z-contrast from enhanced scattering cross-sections of heavier elements
  - w_{TL} defined as width between peak and inflection point



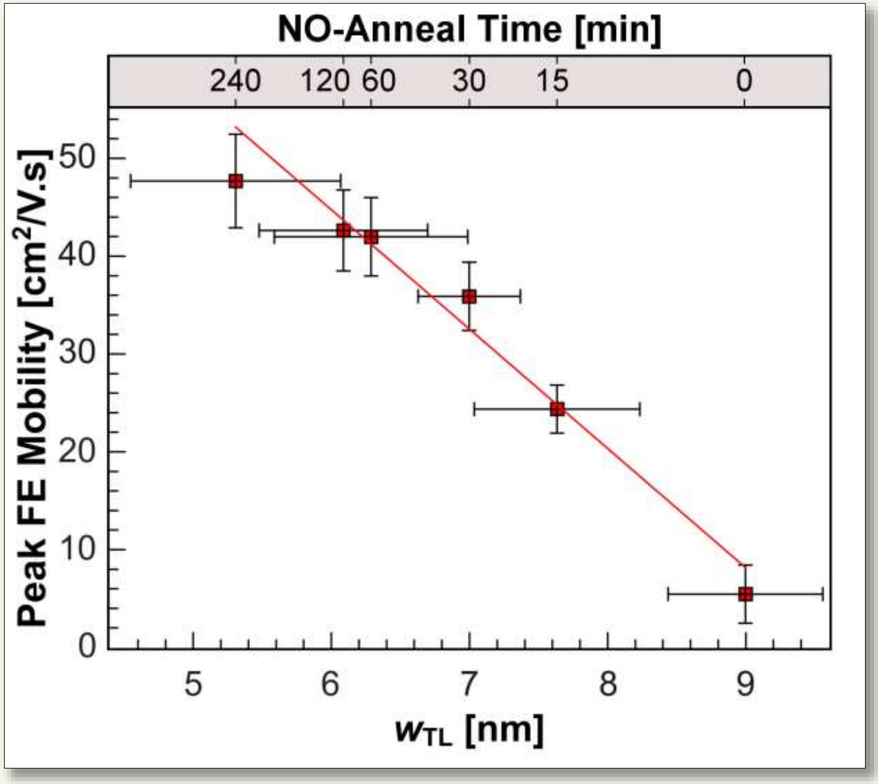
- w_{TL} results:
  - Poorer trend in w_{TL}
  - HAADF images varied between samples
  - No excess C, but bright intensity line (like [1])
    - Reason: thickness variations due to preferential milling?



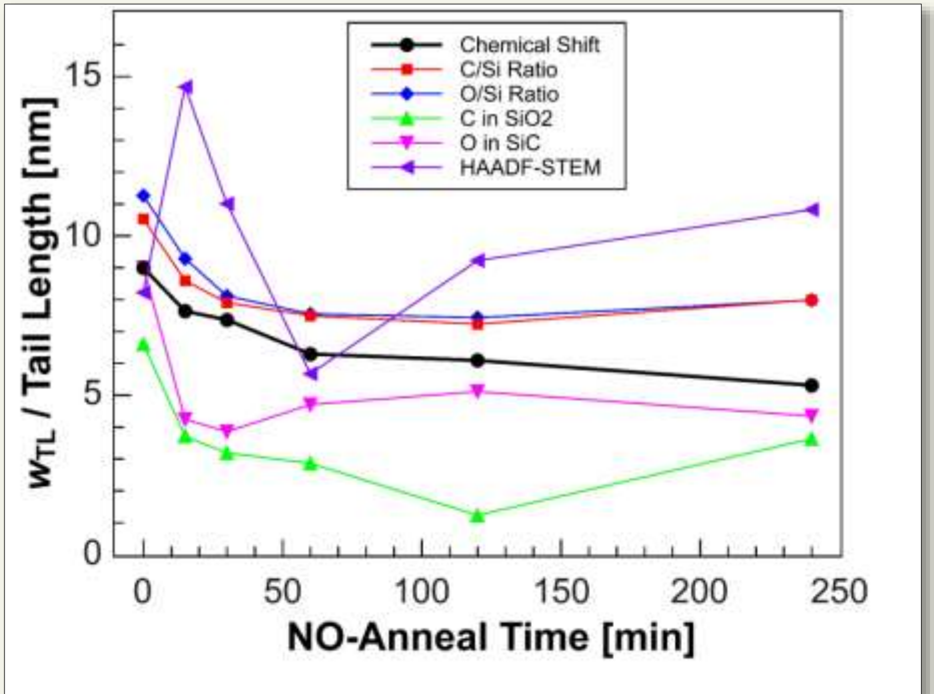
[1] After: T. Biggerstaff, *et al*. Appl. Phys. Lett. **95**, 032108 (2009).

Electronic Measurements

- Data taken by J. Rozen
  - J. Rozen, *et al.* IEEE Trans. Electron. Dev. **58**, 3808 (2011).
  - J. Rozen, *et al.* J. Appl. Phys. **105**, 124506 (2009).
- w_{TL} correlates inverse-linearly μ_{FE}
  - Confirming previous work results
- NO-anneal removes mobility-limiting defects
- Theoretical limit of effect:
  - $\mu_e \sim 120 \frac{\text{cm}^2}{\text{V}\cdot\text{s}}$



Conclusions



- w_{TL} decreases with increasing NO anneal time
  - Chemical shift of Si-$L_{2,3}$ edge onset was most reliable method
  - No excess C on either side of interface
- Smallest transition region for 4hr anneal → w_{TL} = 5.3 nm
- Developed w_{TL} determination method for future comparison

Acknowledgements

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THANK YOU

Questions and comments?