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.
Motivation and Background

• SiC: Very promising for high temperature, high power, and high radiation environments
  • 4H polytype (bulk):\[ E_g = 3.23 \text{ eV}, \mu_e \approx 850 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}, \varepsilon = 10, \kappa = 3.7 \frac{\text{W}}{\text{cm} \cdot ^\circ \text{C}} \]
  • MOSFET devices limited by poor channel carrier mobility and reliability
  • Typical effective device $\mu_e$: SiC $\approx 85 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$; Si $\approx 300 \frac{\text{cm}^2}{\text{V} \cdot \text{s}}$
  • Electrically active defects at the SiC/SiO$_2$ interface inhibit devices during channel inversion

• Possible nature of these defects?


\(^1\) 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

- Transition layer width ($w_{TL}$) lowered by NO post-anneal
  - Measured with HAADF-STEM intensity profiles
  - Inverse linear correlation between $w_{TL}$ and mobility
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

- Lamella on grid: 6 μm × 3 μm × ≈ 80 nm

- Low-mag TEM
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 ($\frac{C}{Si}$ and $\frac{O}{Si}$)
  - 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)
    - Reveals information about local Si bonding

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Spectrum Imaging

Spectrum Image (60 minute anneal)

SiC

SiO₂

Background-subtracted spectrum (60 minute anneal)

Si-L

C-K

O-K
$w_{\text{TL}}$ from Composition Ratios

- Profile of atomic ratio maps:

- $w_{\text{TL}}$ results:
  - NO-anneal shows significant improvement
  - $O_{\text{Si}}$ slightly larger than $C_{\text{Si}}$ always

No excess C at interface
\( w_{\text{TL}} \) from “Interdiffusion” lengths

- Useful to see tails of C concentration in \( \text{SiO}_2 \) and O in SiC
  - Normalized bulk concentrations and measured tails with derivative

- \( w_{\text{TL}} \) results:
  - NO-anneal again shows significant improvement
  - O in SiC always larger than C in \( \text{SiO}_2 \)
  - Why?
    - C more efficiently removed during oxidation
    - O solubility in SiC very low

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

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

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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

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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?

Electronic Measurements

• Data taken by J. Rozen

• $w_{TL}$ correlates inverse-linearly $\mu_{FE}$
  - Confirming previous work results

• NO-anneal removes mobility-limiting defects

• Theoretical limit of effect:
  - $\mu_e \sim 120 \frac{cm^2}{V \cdot s}$
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 $\rightarrow w_{TL} = 5.3$ nm
• Developed $w_{TL}$ determination method for future comparison
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Questions and comments?