3D characterization of semiconductor interfaces using aberration-corrected STEM

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Motivation

- “What good would it be to see individual atoms distinctly?”

- “Another direction of improvement is to make physical machines three dimensional […].”

Richard F. Feynman
1918-1988
STEM Z-contrast imaging

Resolution = probe size
Z-contrast ~Z^2
Easy image interpretation
Simultaneous EELS

The intensity as a function of probe position gives an image

SrTiO_3 [110] HAADF image

Sr (38)
Ti (22)
O (Z=8)
Aberration Correction in STEM

Nion aberration corrector

Source → Condenser Lenses → Objective Lens → Sample → To Detector

Quadrupoles and Octupoles

Beam cross-section:

(Qualinopes control trajectories. Correction given by Octupoles)
Aberration corrected probe

VG Microscope’s HB603U, 300 kV

Aberration limited

\[ C_s = 1.0 \text{ mm} \]
\[ C_c = 1.0 \text{ mm} \]

Significant current is lost in probe “tails”

FWHM \~ 1.3 Å

No spherical aberration

Current density is concentrated into central maximum

FWHM \~ 0.5 Å

Aberration correction \implies “smaller” and “brighter” probe

Critical for single atom sensitivity

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Pico-scale Z-contrast Imaging:

Information transfer to 0.607 Å
(61 pm)

P.D. Nellist et al.,

Si \langle 112 \rangle Direct Image
Resolution at 0.78 Å
The form of Pt on the $\gamma$-Al$_2$O$_3$ (110C) Surface

With OH-cap Pt spacings match calculations
Pt atoms change from electron-rich to electron-poor
Unexpected Benefit of Aberration Correction

\[ \Delta X \approx \frac{\lambda}{\theta} \]

\[ \Delta Z \approx \frac{\lambda}{\theta^2} \]

Corrected 200kV “UltraSTEM”:
- \( \theta = 50 \text{ mrad} \)
- \( \Delta X \approx 0.05 \text{ nm} \)
- \( \Delta Z \approx 1 \text{ nm} \)
3D concept

Scan in 3-dimensions

Build 3D dataset by slices

Build and Analyze 3D Model
Si/HfO$_2$/poly-Si

- Atomic layer deposition
- Substrate temperature 320°C
- Annealing at 950°C for 30sec. In N$_2$
3D Analysis of Semiconductors

\[ \Delta f \pm 2.0 \text{nm} \]
Slice View
Vertical position of Hf atoms

- Atoms located inside the device
- Sample thickness 6±1 nm
3D reconstruction of HfO2/SiO2(Hf)/Si

• Localization of single Hf atoms (laterally & vertically)
• Surface roughness
• "Si dumbbell columns"
Hf atom distribution in SiO$_2$

Leakage current related to individual Hf atoms in SiO$_2$ films

Hf can act as a leakage current center


Other atoms involved in leakage current

EELS Spectrum Imaging: Si L$_{2,3}$-edge

p-Si  HfO$_2$/SiO$_2$  Si<110>
Spot Analysis: O K edge
Valence EELS = VEELS

- Local electronic structure (DOS)
- Local dielectric properties ($\varepsilon = \varepsilon_1 + i\varepsilon_2$)
- Leakage paths (in 3D?)
Cathodoluminescence

Incoming electron

\[ E_F \]

\[ h\nu \]

\[ \text{Energy-loss electron} \]

ZnO(Mg) nanorods

ADF

CL
Electron Beam Induced Current

- Incoming electron
- CB
- EF
- VB
- Energy-loss electron
- EBIC
- Detectable w/ and w/o applied potential
- Imaging contrast
- Charge Collection Microscopy (CCM)
- 3D-CCM
Conclusions

- Volume resolution better than $0.1 \times 0.1 \times 6 \text{ nm}^3$
- Single atom sensitivity in 3D
- Direct proof that dopant atoms are located inside the device
- Hf atoms stay away from the Si/SiO$_2$ interface
- Hf atoms occupy “interstitial” sites in SiO$_2$
- Single Atom EELS (in 3D)
- Comparison of DOS and EELS/ELNES data
- VEELS
  - Local dielectric properties
  - Optical properties
- CL & EBIC
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