3D characterization of semiconductor interfaces using aberration-corrected STEM

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Motivation

Richard F. Feynman
1918-1988

- ***"What good would it be to see individual atoms distinctly?"***
- ***"Another direction of improvement is to make physical machines three dimensional [...]."***

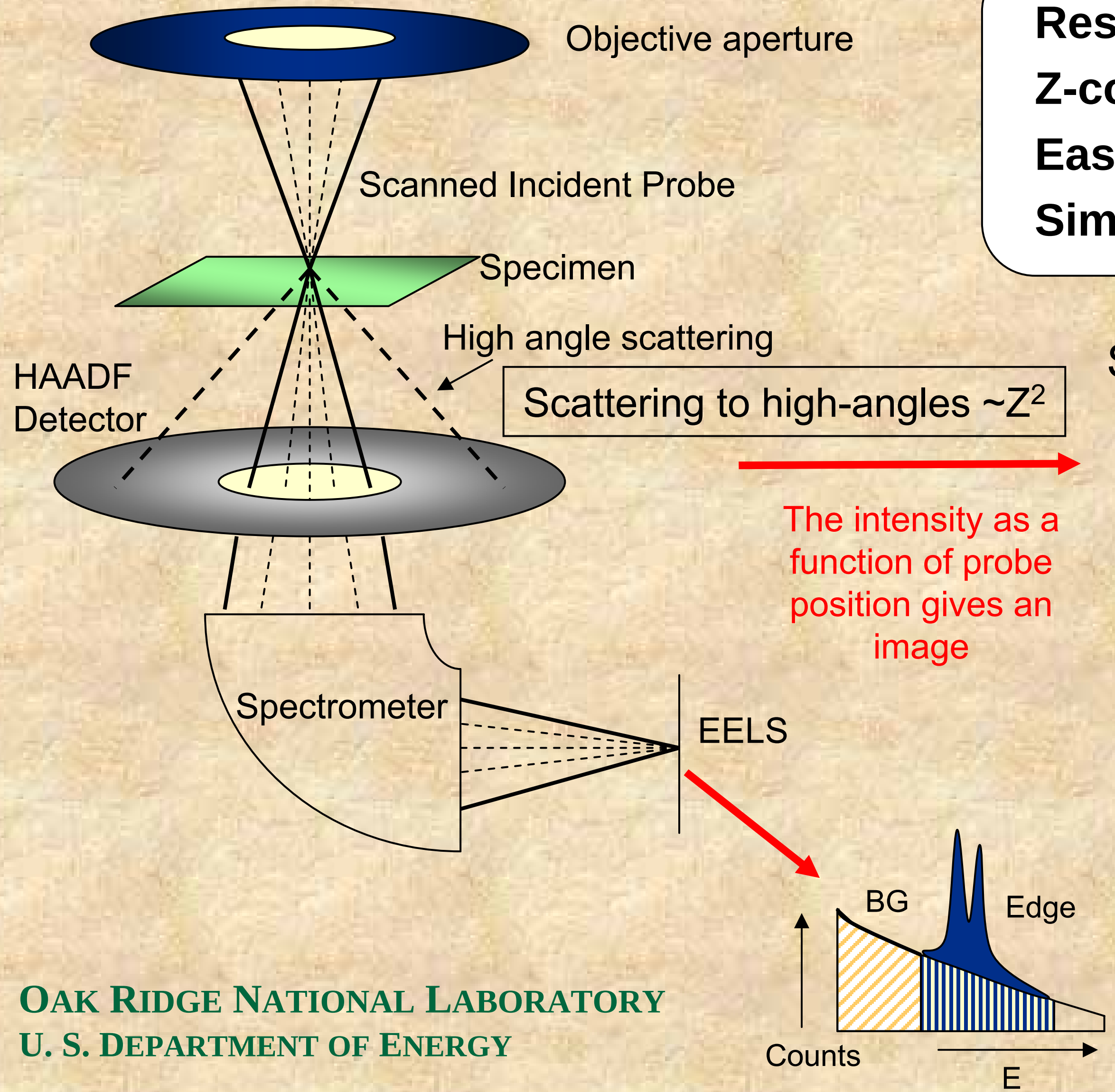
STEM Z-contrast imaging

Resolution = probe size

Z-contrast ~Z^2

Easy image interpretation

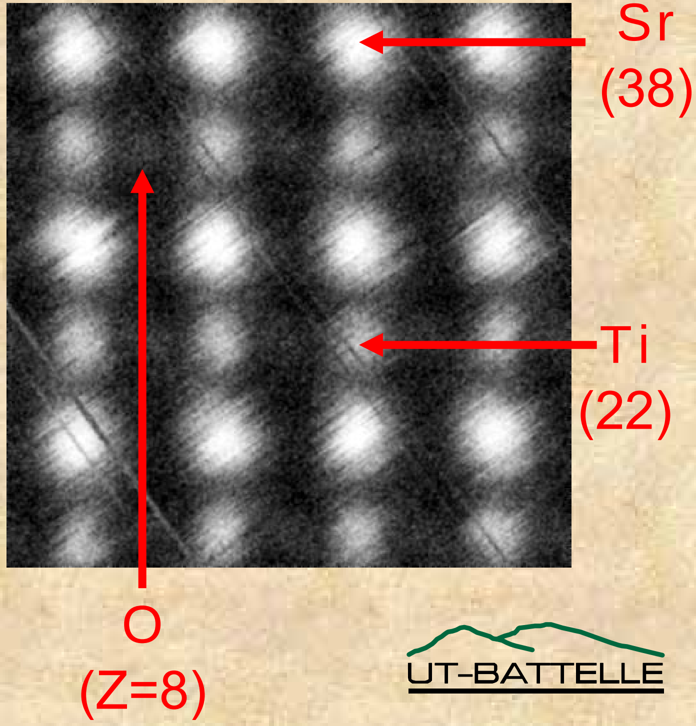
Simultaneous EELS



Scattering to high-angles ~Z^2

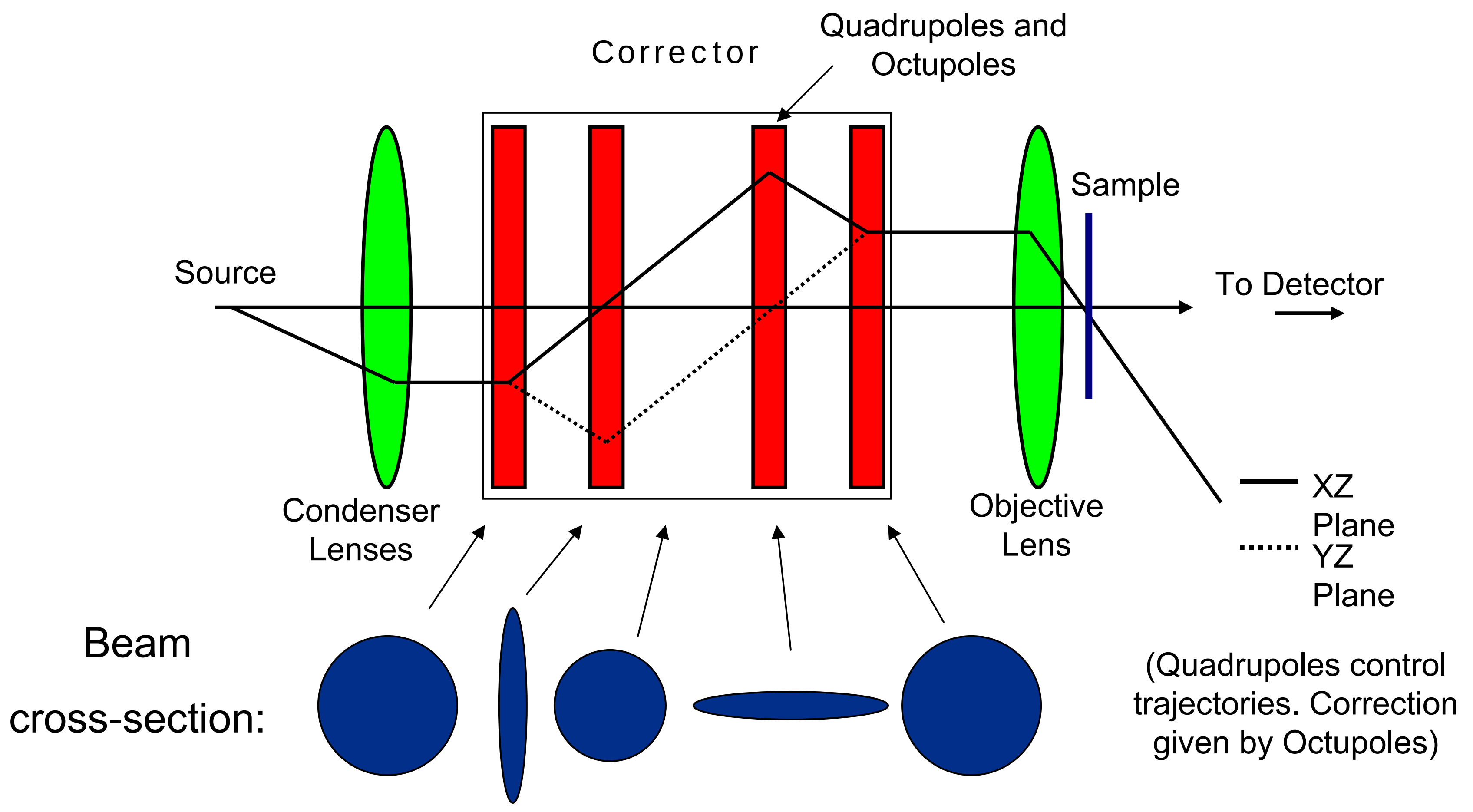
The intensity as a function of probe position gives an image

SrTiO$_3$ [110] HAADF image



Aberration Correction in STEM

Nion aberration corrector



(Quadrupoles control trajectories. Correction given by Octupoles)

Aberration corrected probe

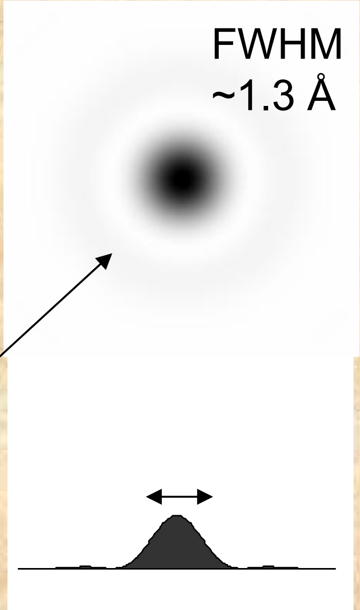
VG Microscope's HB603U, 300 kV

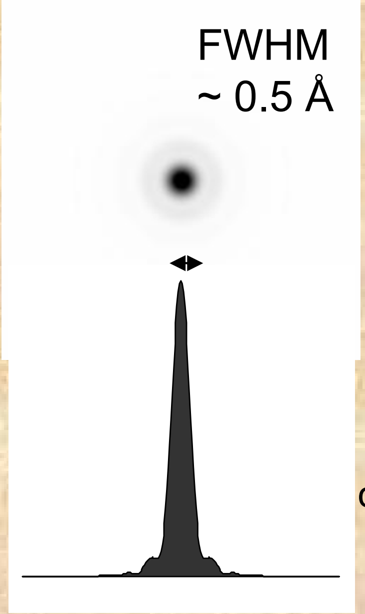
Aberration limited

C_s= 1.0 mm

C_c=1.0 mm

Significant current is lost in probe "tails"





No spherical aberration

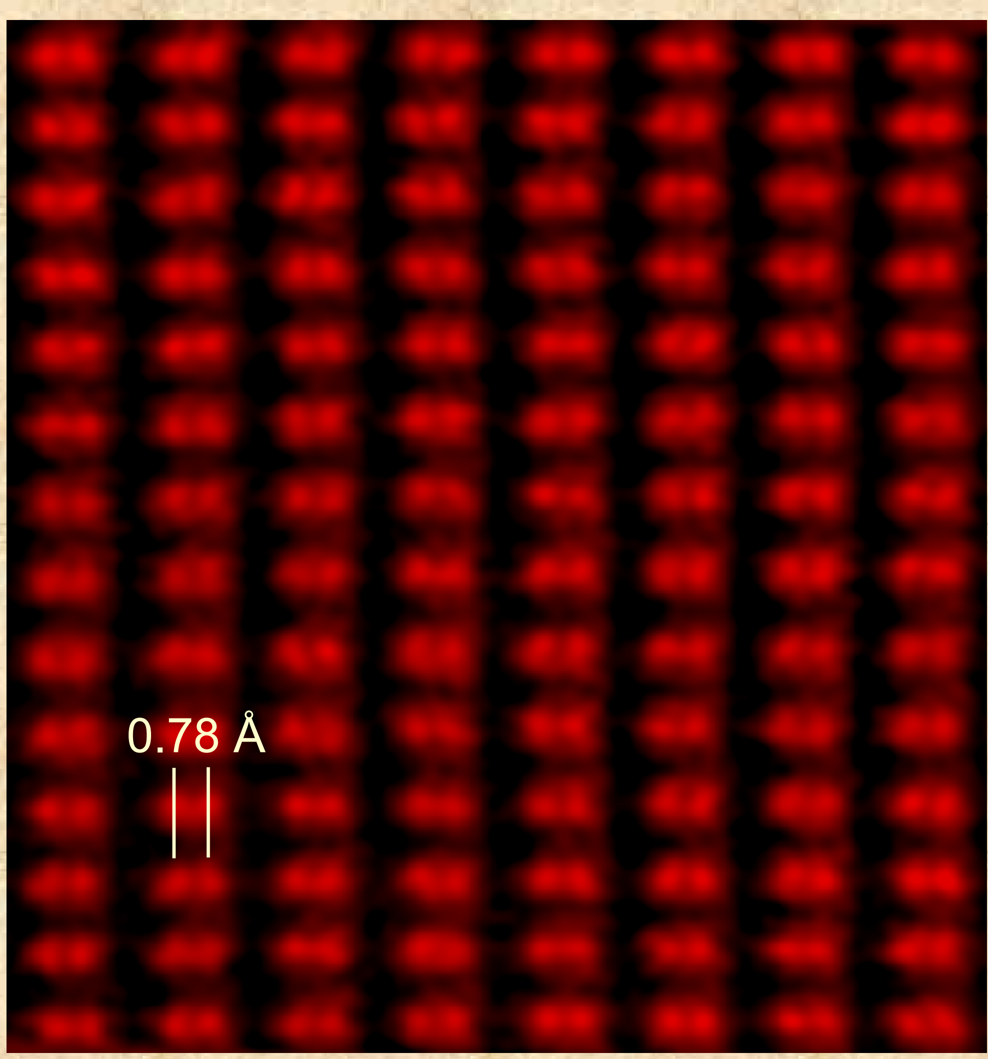
Current density is concentrated into central maximum

(Normalized to same total current)

Aberration correction ⇒ "smaller " and "brighter" probe

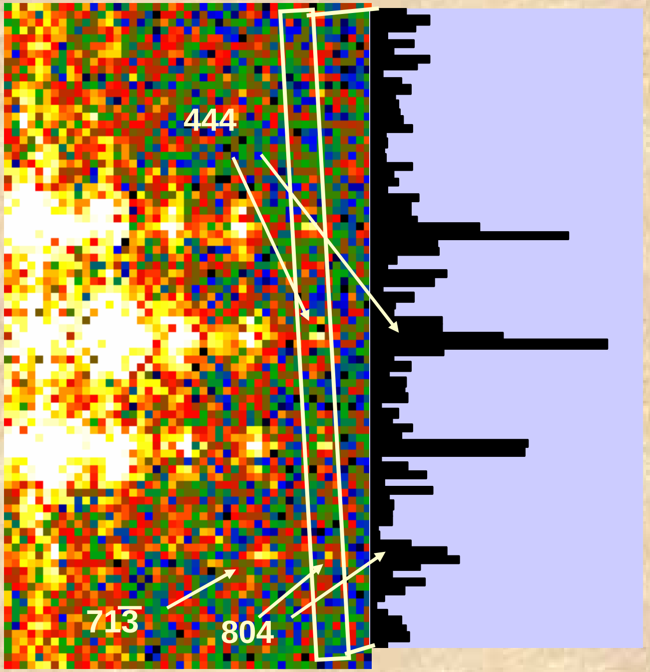
Critical for single atom sensitivity

Pico-scale Z-contrast Imaging:



Information transfer to 0.607 Å

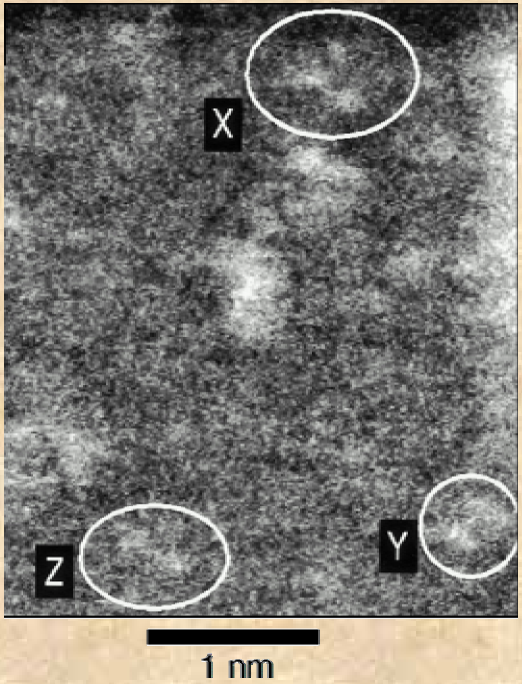
(61 pm)



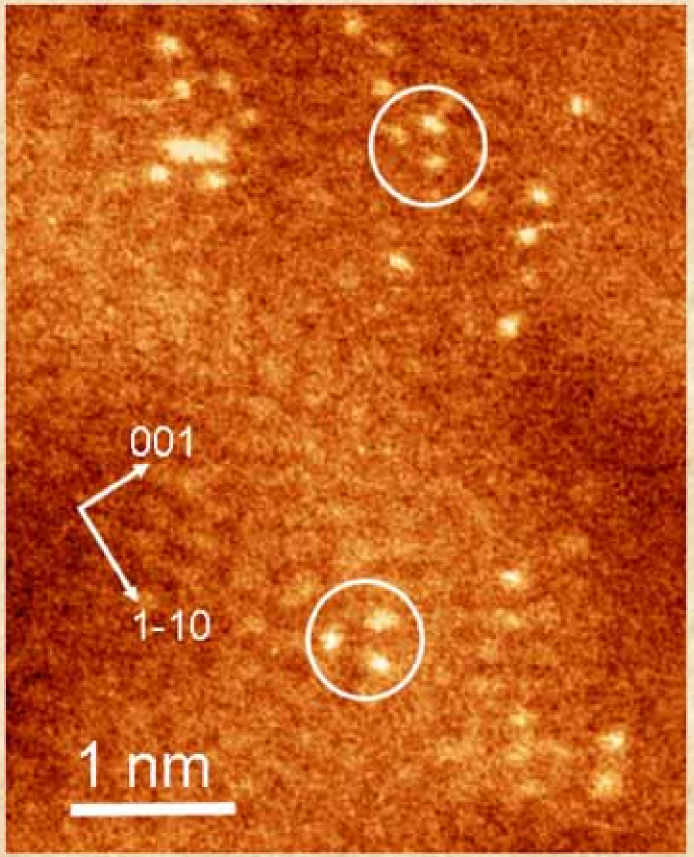
P.D. Nellist et al.,
Science **305**, 1741(2004)

Si ⟨112⟩ Direct Image
Resolution at 0.78 Å

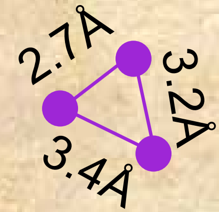
The form of Pt on the γ-Al_2O_3 (110C) Surface

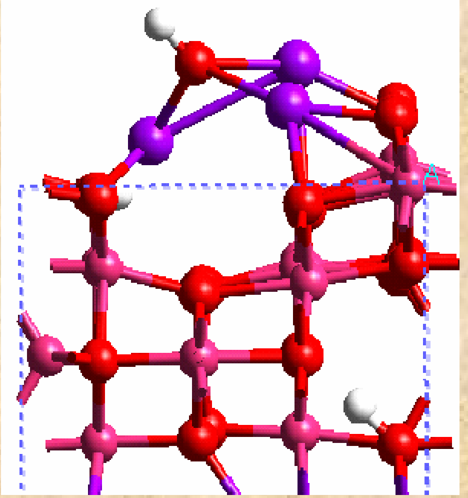


P.D. Nellist 1996



A.Y. Borisevich 2004



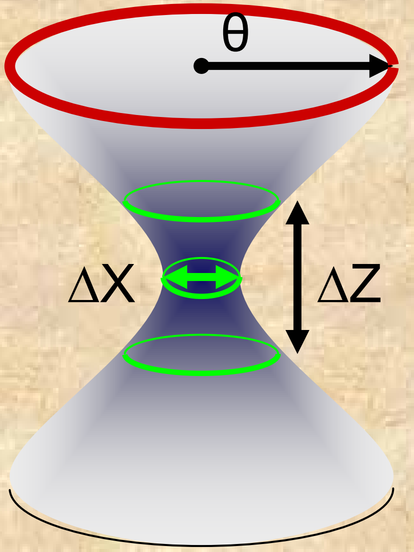


With OH-cap Pt spacings match calculations
Pt atoms change from electron-rich to electron-poor
- good Lewis acid sites - Sohlberg et al, ChemPhysChem 5, N 12, 1893-1897 (2004).

Unexpected Benefit of Aberration Correction

$$\Delta X \approx \lambda / \theta$$

$$\Delta Z \approx \lambda / \theta^2$$



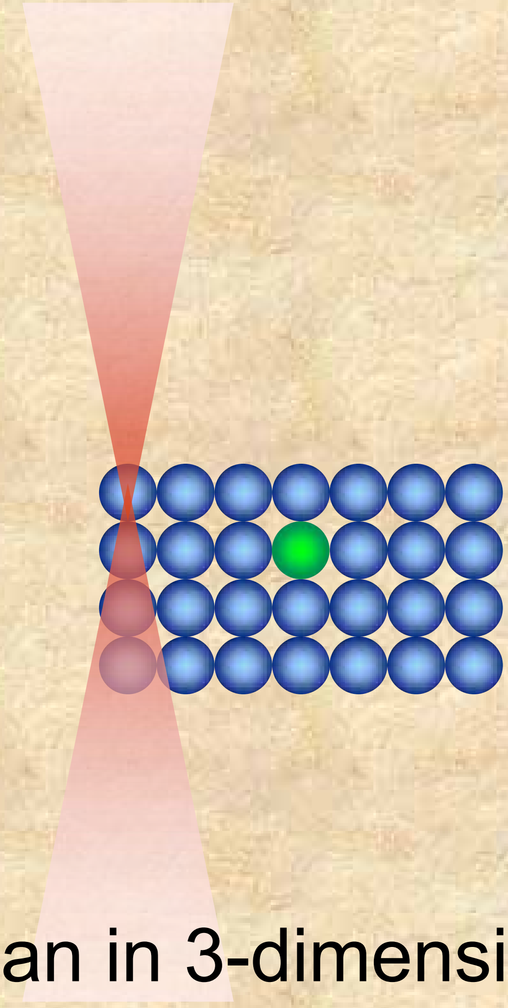
Corrected 200kV “UltraSTEM”:

$\theta = 50$ mrad

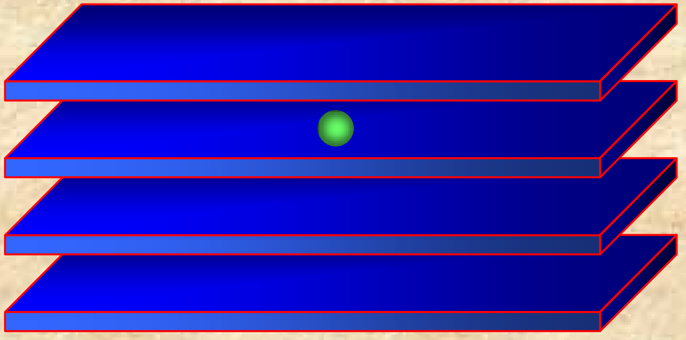
$\Delta X \approx 0.05$ nm

$\Delta Z \approx 1$ nm

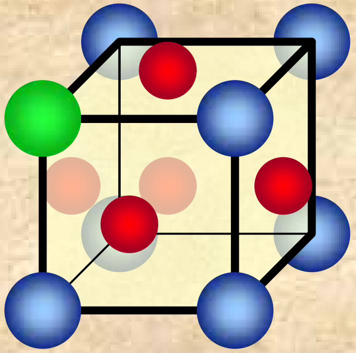
3D concept



Scan in 3-dimensions

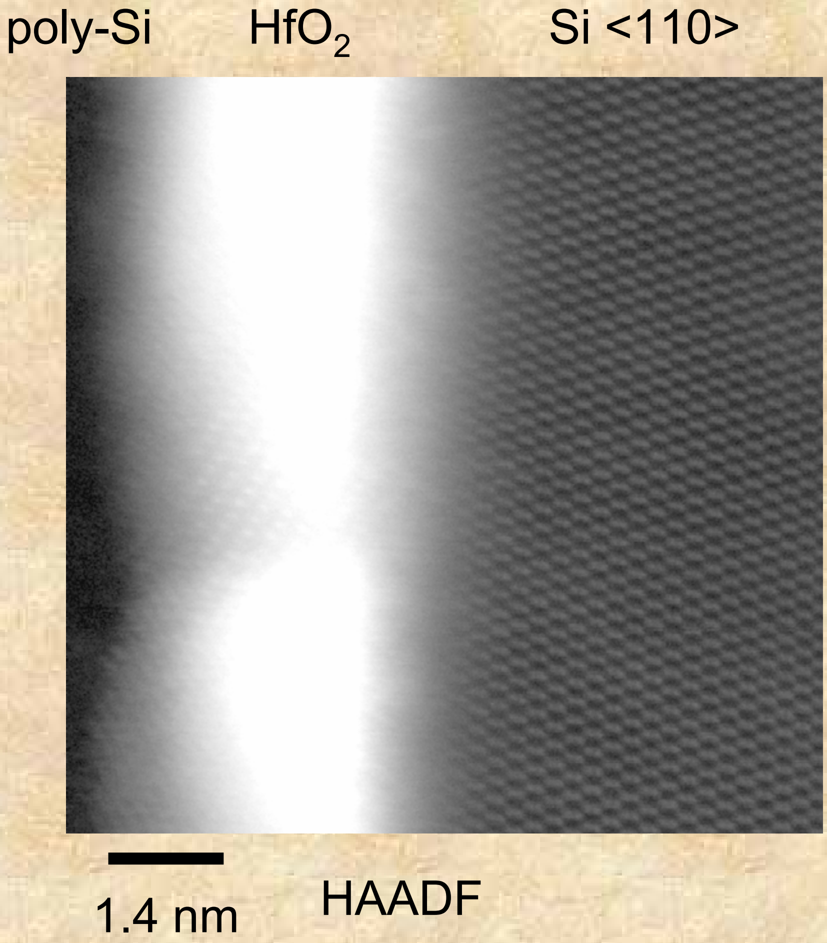


Build 3D dataset by slices

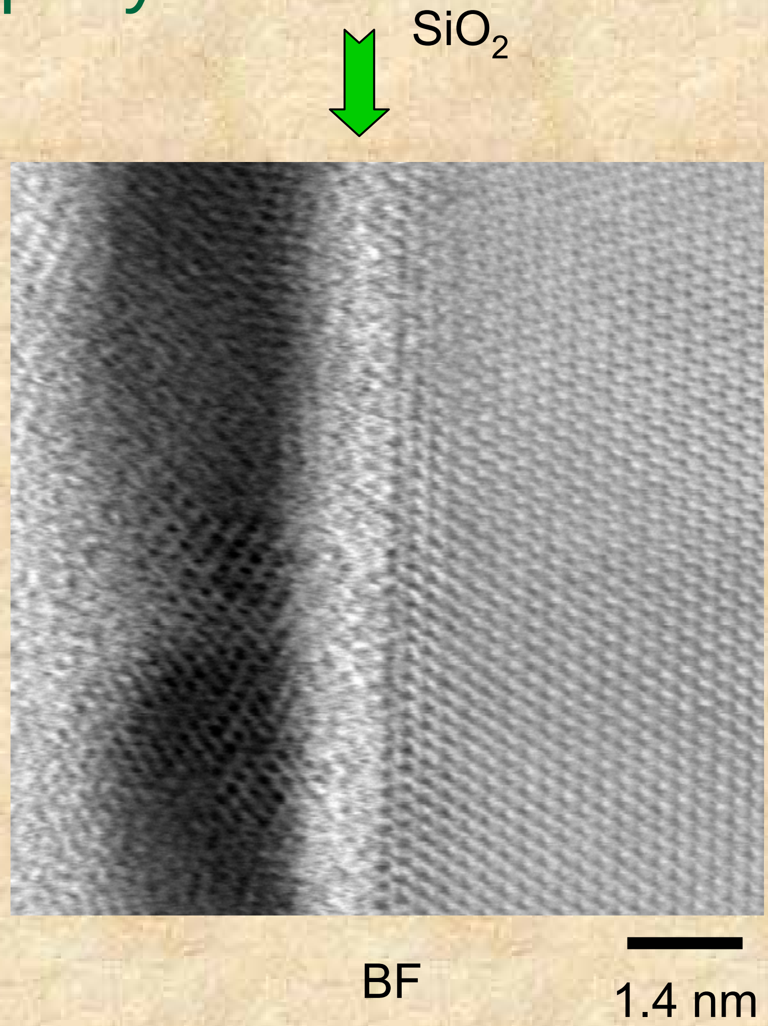


Build and Analyze 3D Model

Si/HfO_2/poly-Si



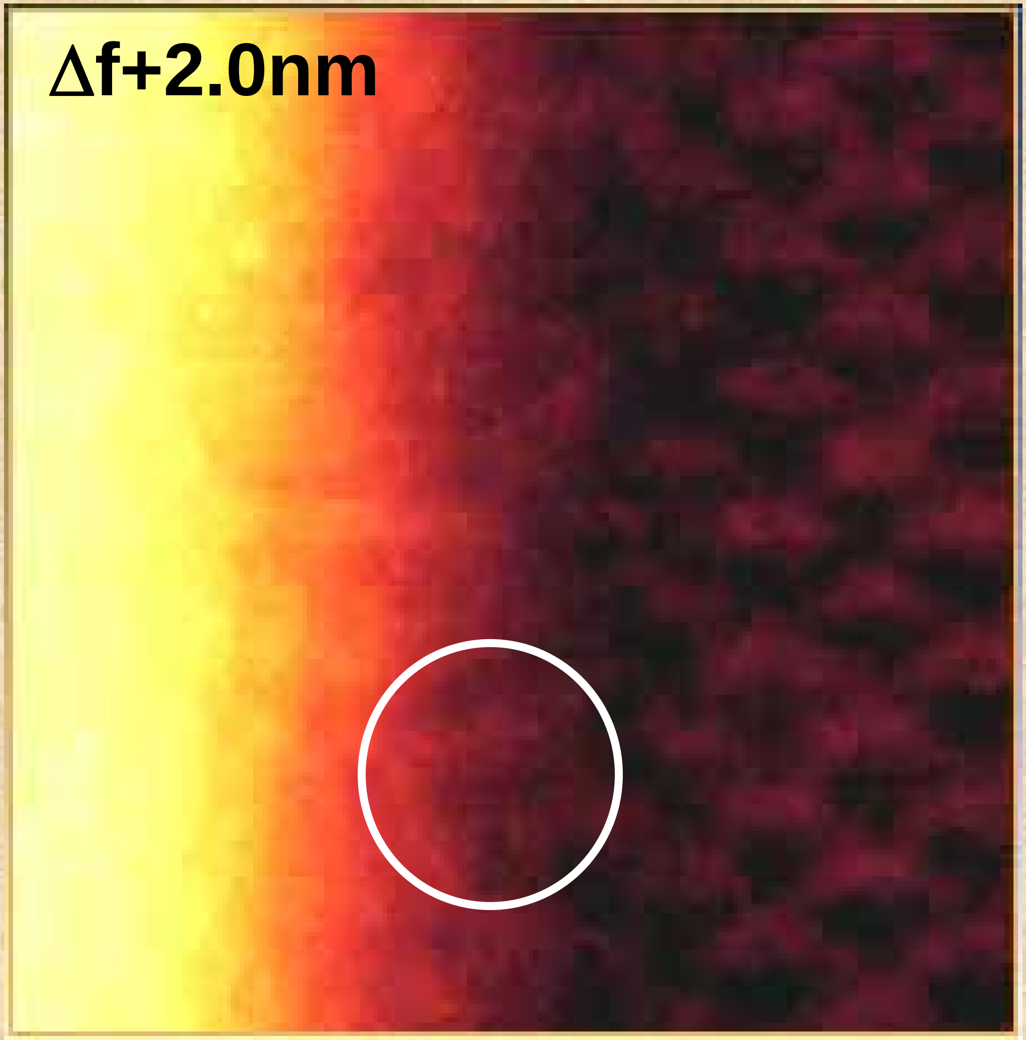
HAADF



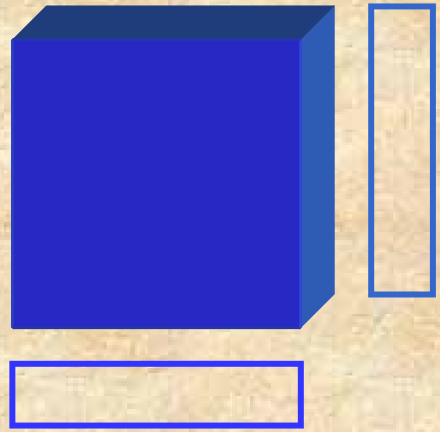
BF

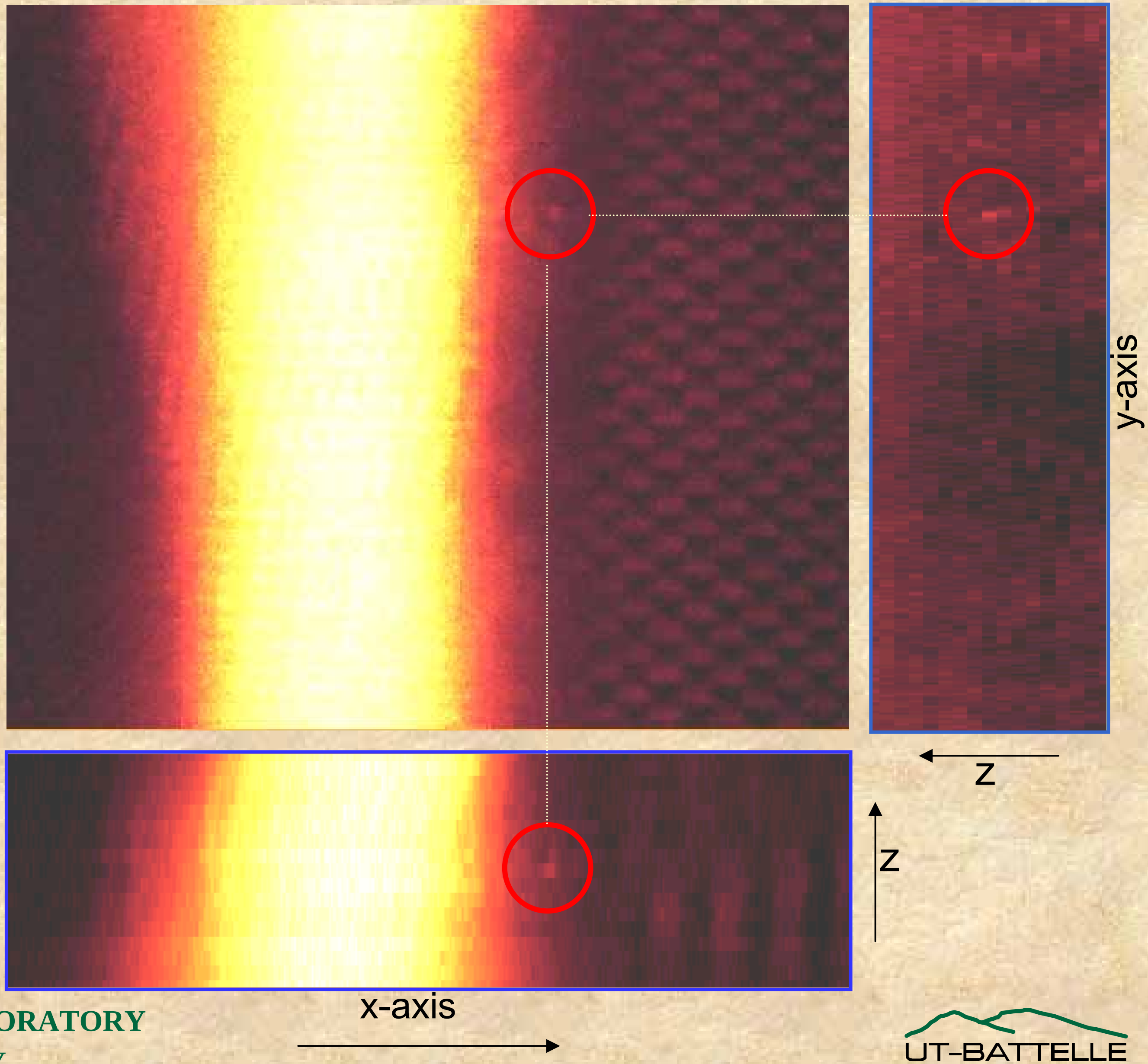
- *Atomic layer deposition*
- *Substrate temperature 320°C*
- *Annealing at 950°C for 30sec. In N_2*

3D Analysis of Semiconductors

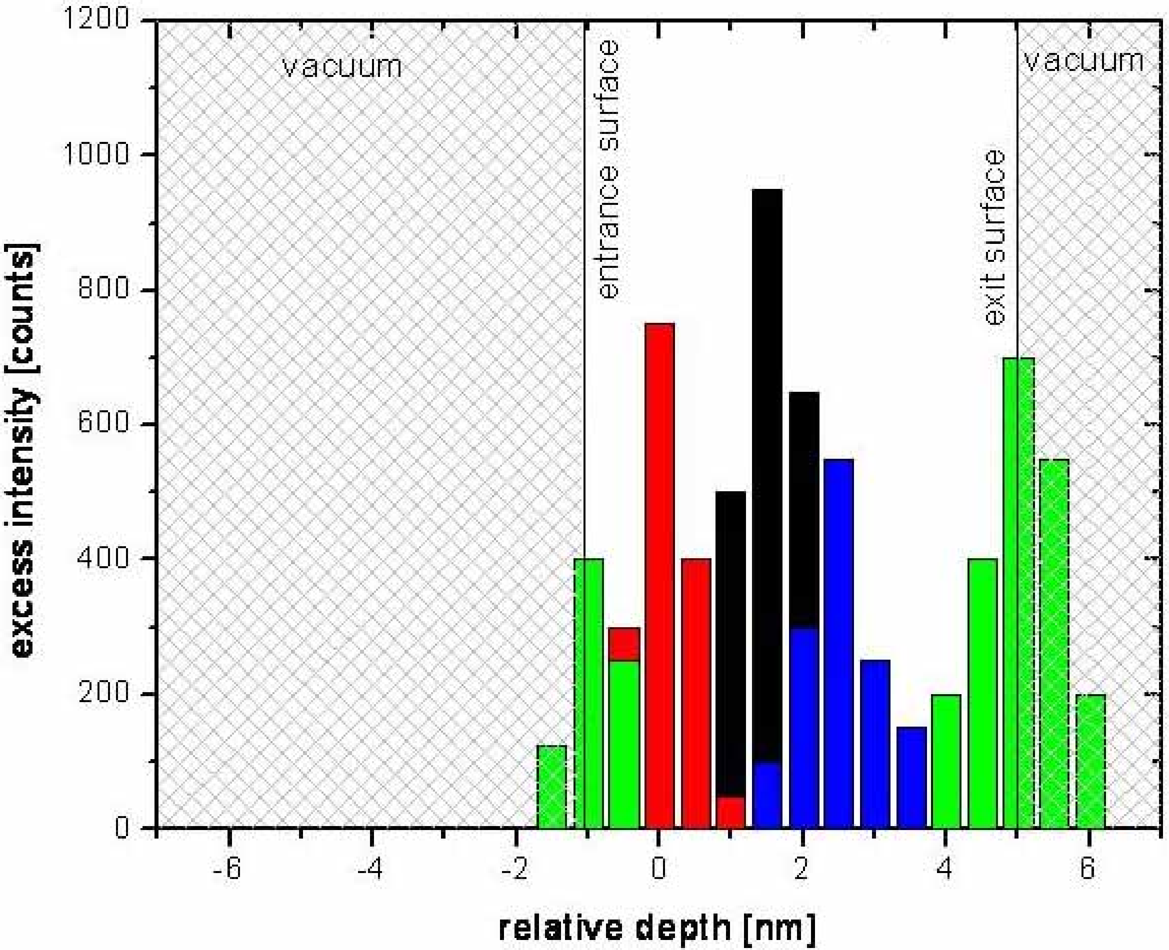


Slice View

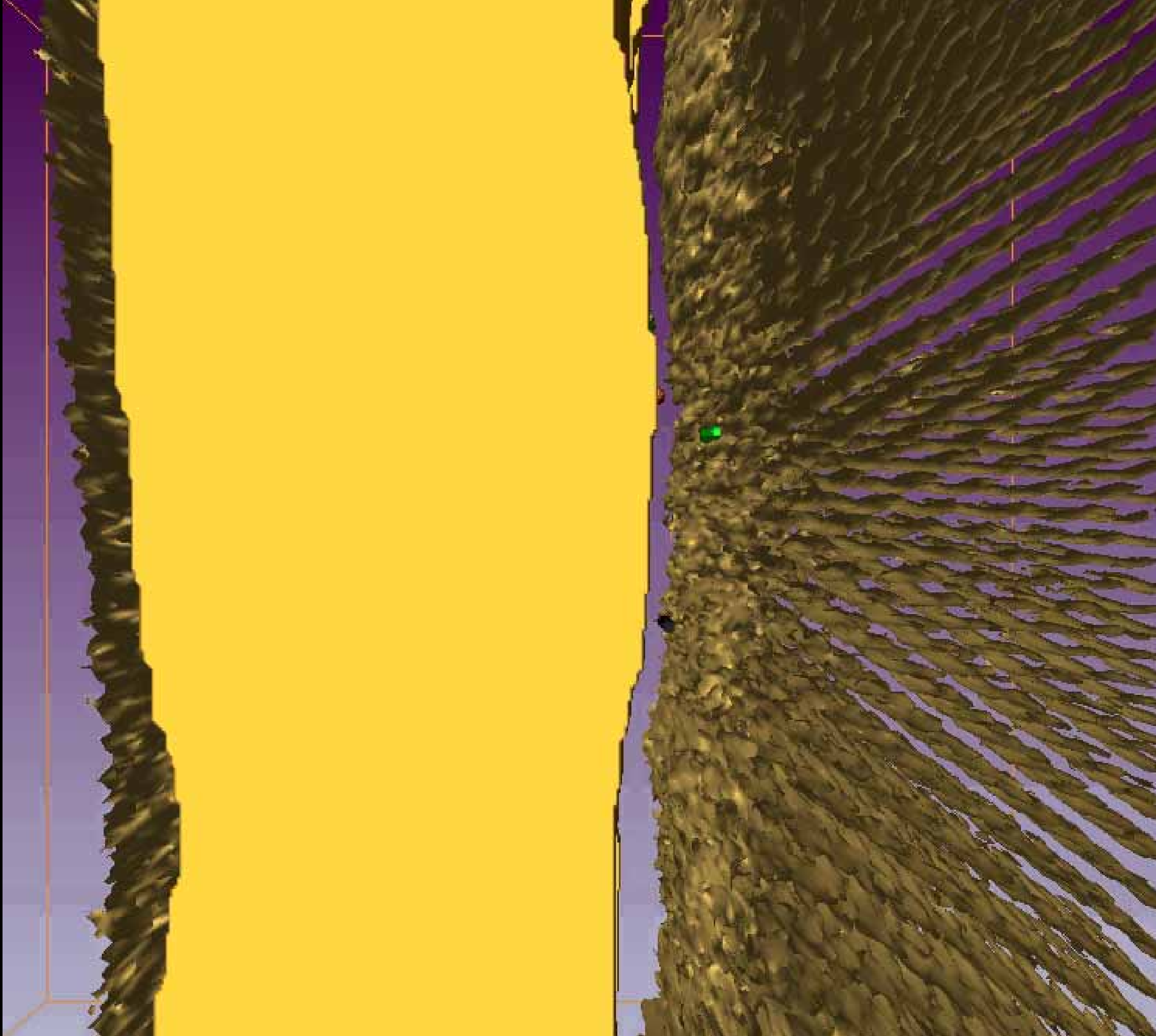




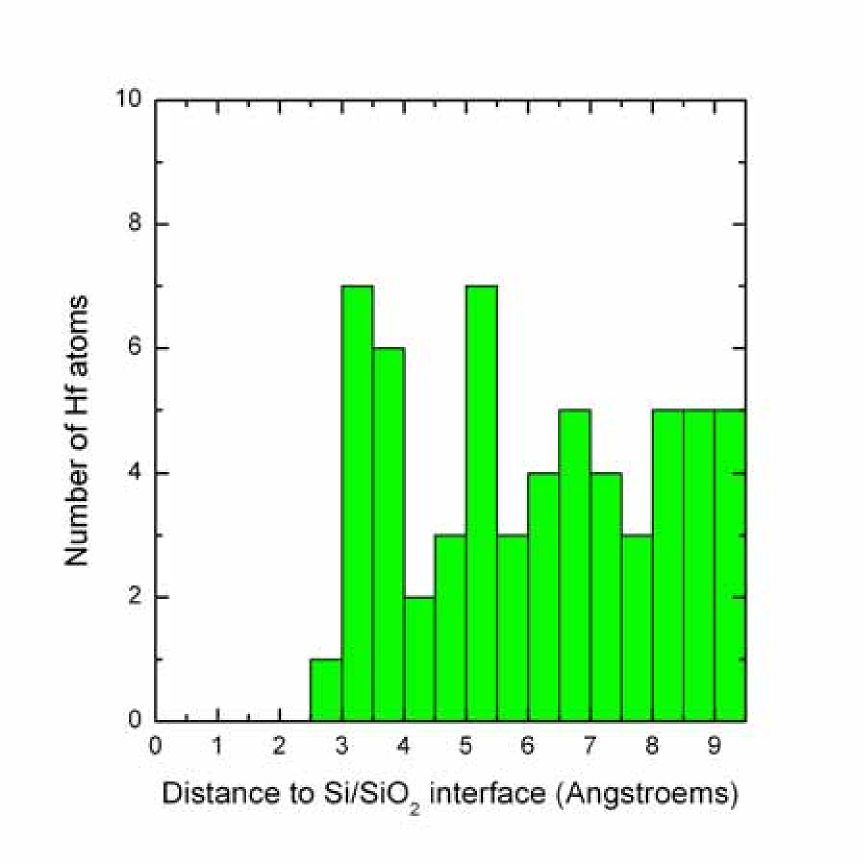
Vertical position of Hf atoms

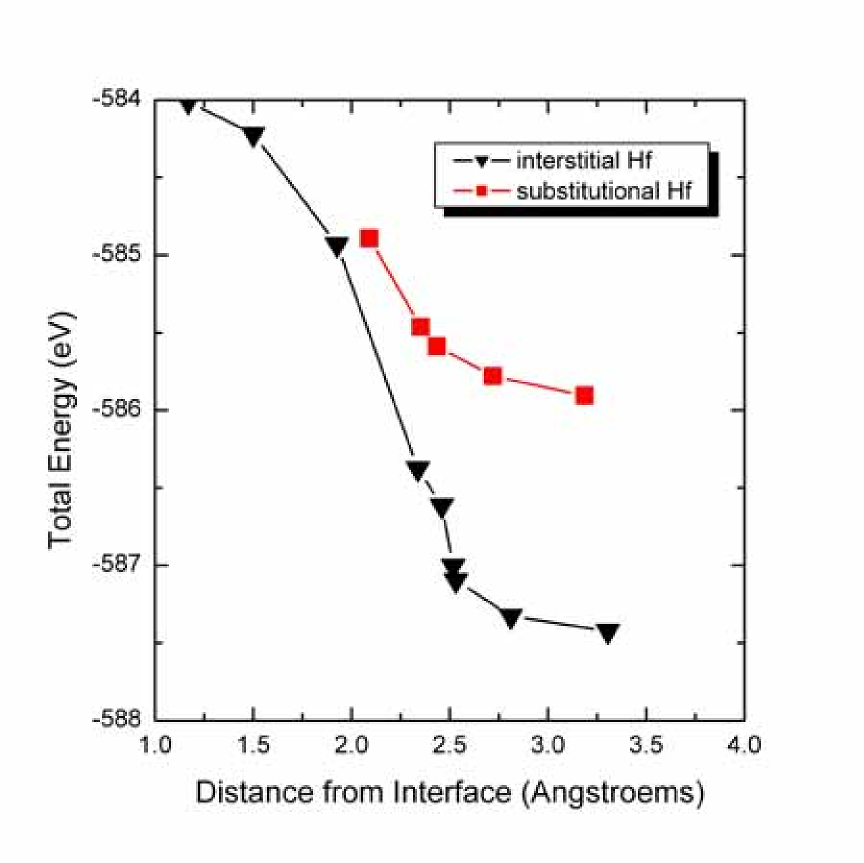


- **Atoms located inside the device**
- **Sample thickness 6±1 nm**



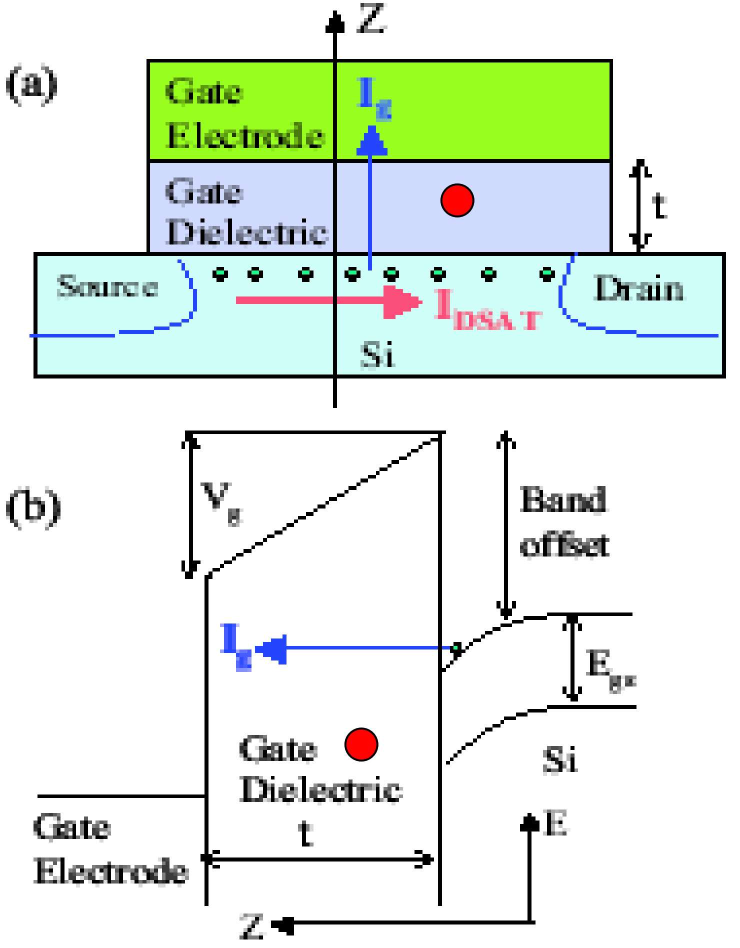
Hf atom distribution in SiO_2



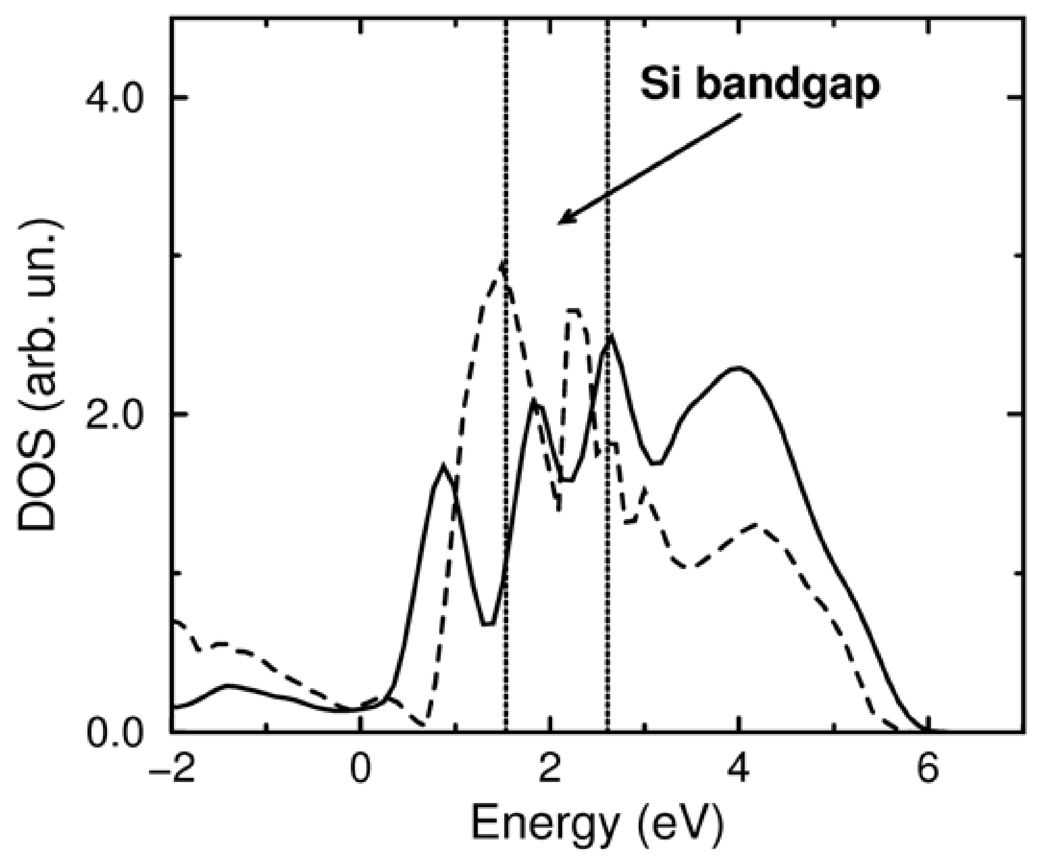


S.J. Rashkeev (2004)

Leakage current related to individual Hf atoms in SiO_2 films



From: G. Bersuker, P. Zeitzoff, G. Brown, and H. R. Huff, Materials Today, January 2004, p.26

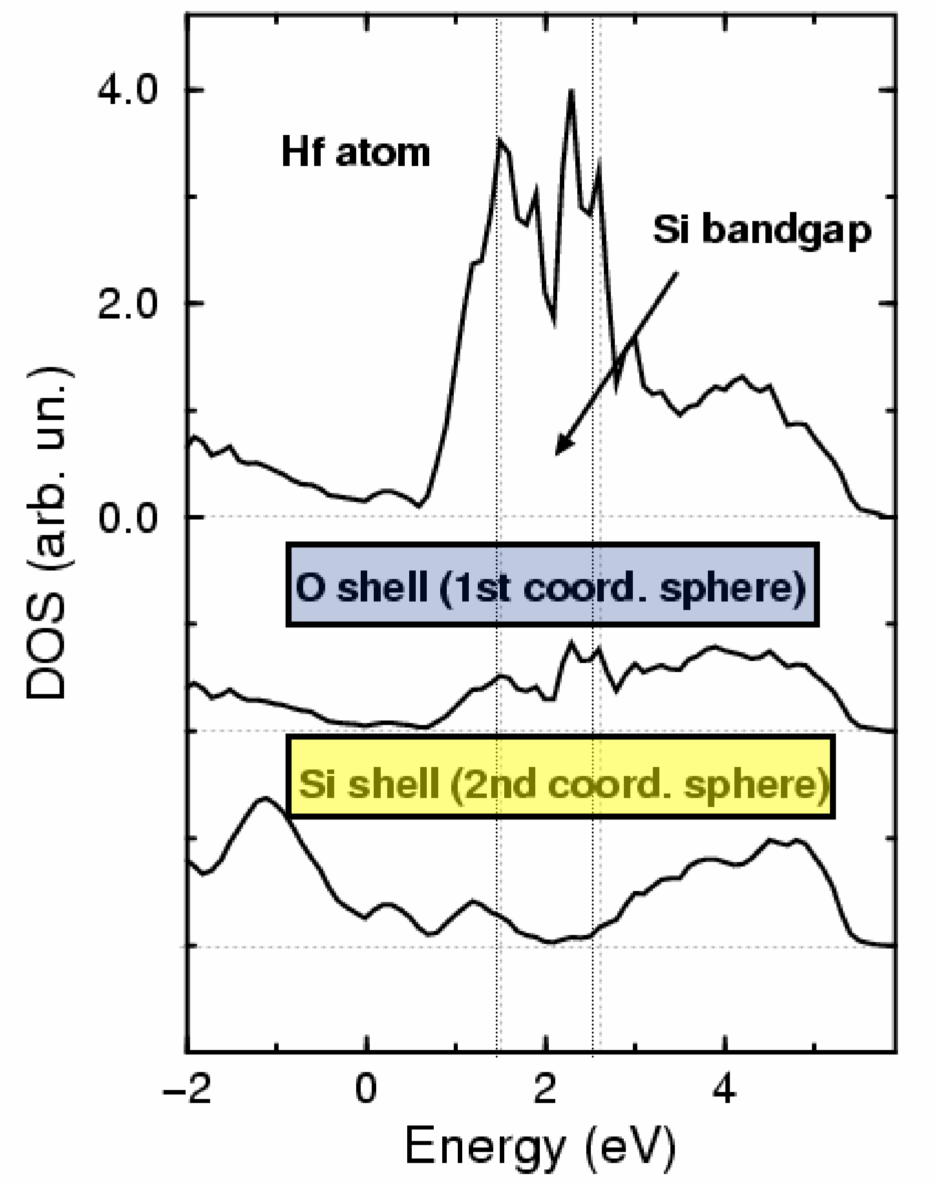


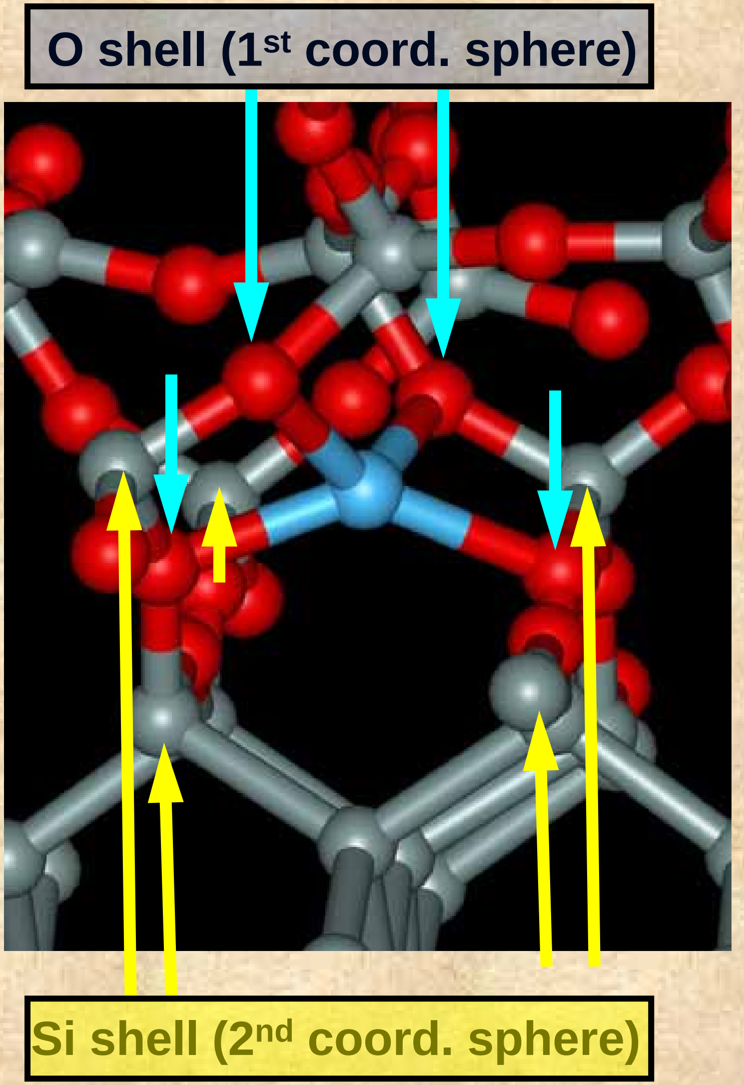
Hf can act as a leakage current center

S.N. Rashkeev (2004)

UT-BATTELLE

Other atoms involved in leakage current



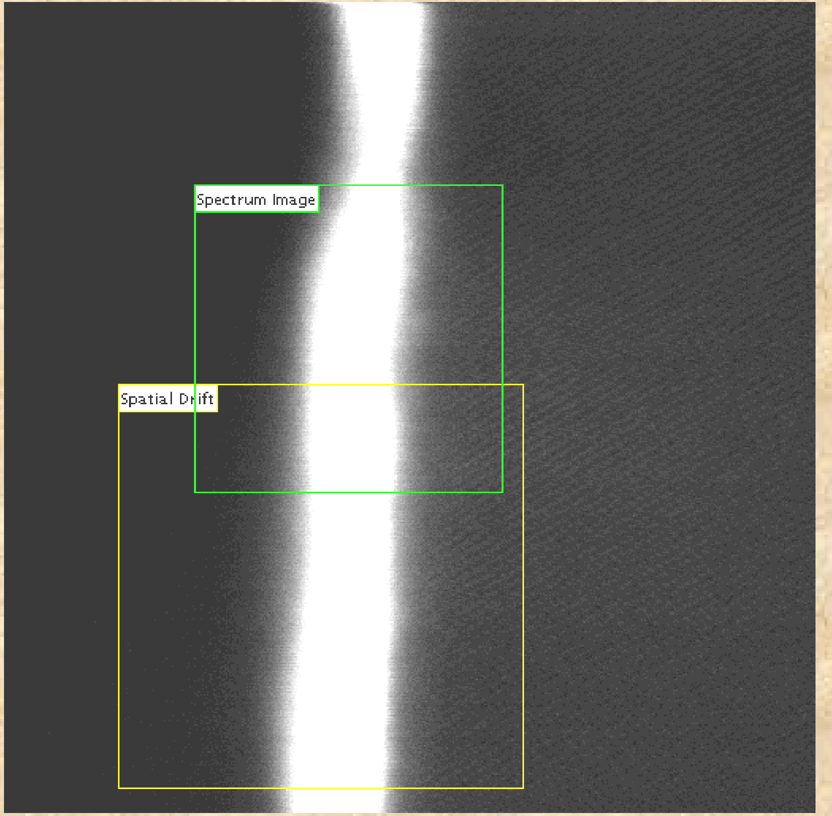


O shell (1st coord. sphere)

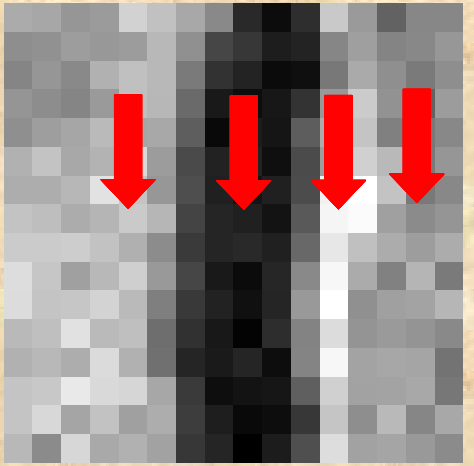
Si shell (2nd coord. sphere)

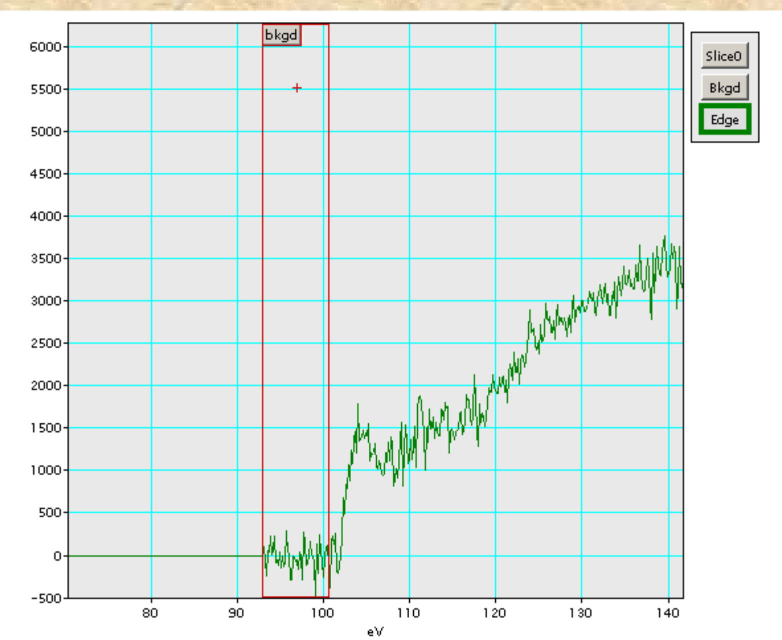
S.N. Rashkeev (2004)

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

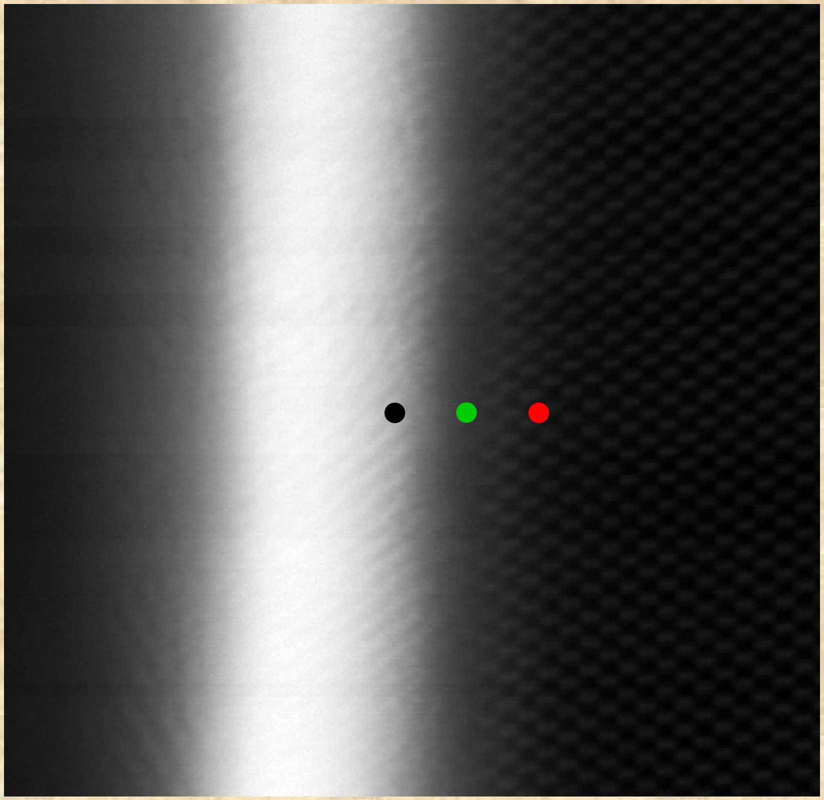


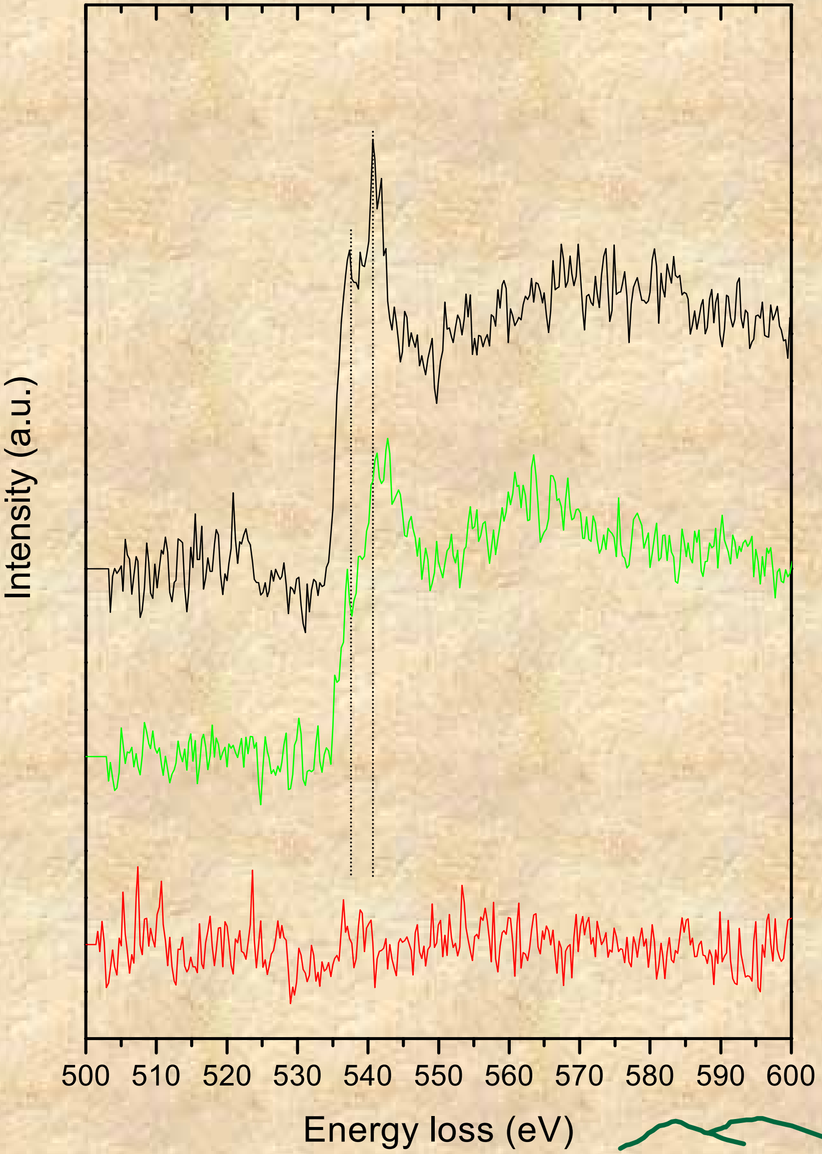
p-Si HfO_2/SiO_2 Si<110>



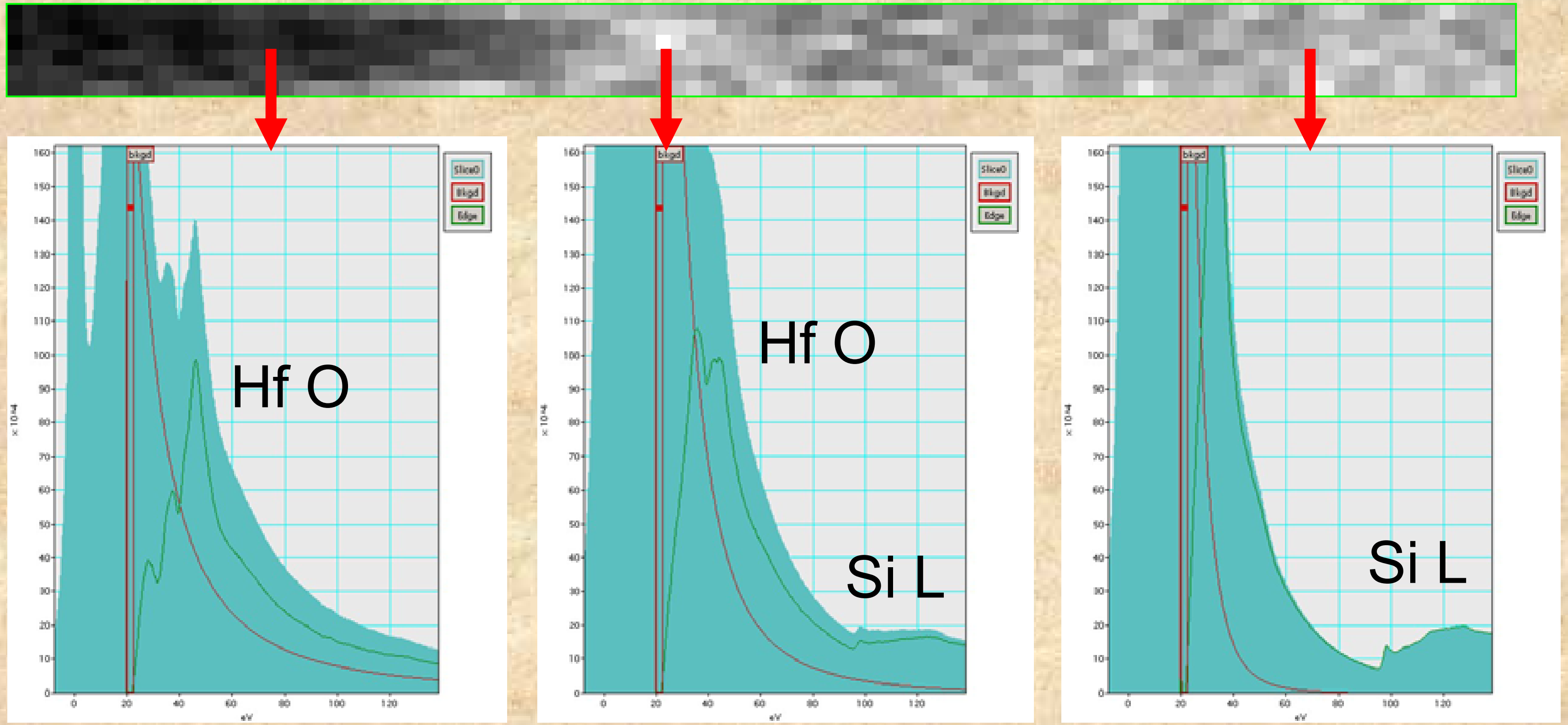


Spot Analysis: O K edge



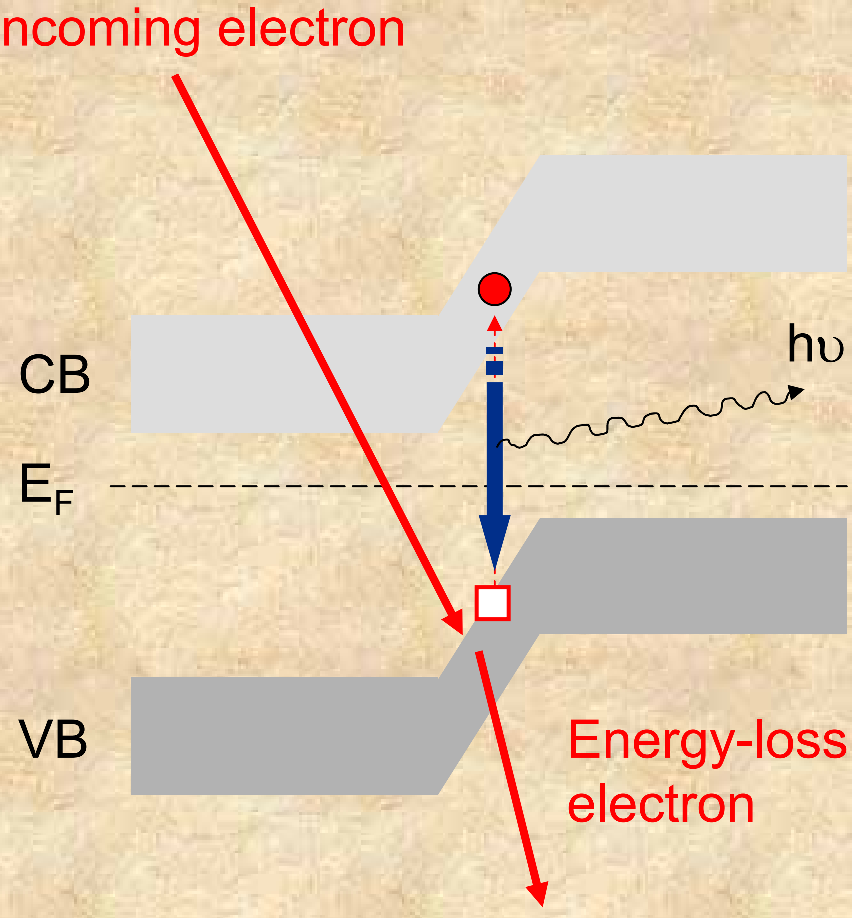


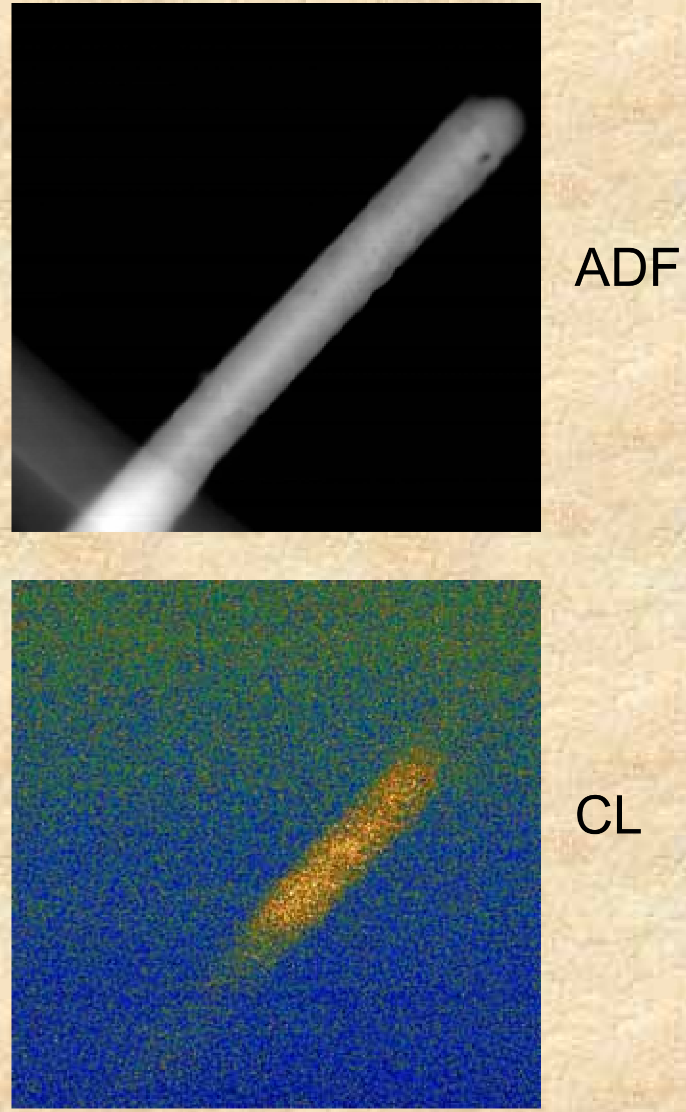
Valence EELS = VEELS



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

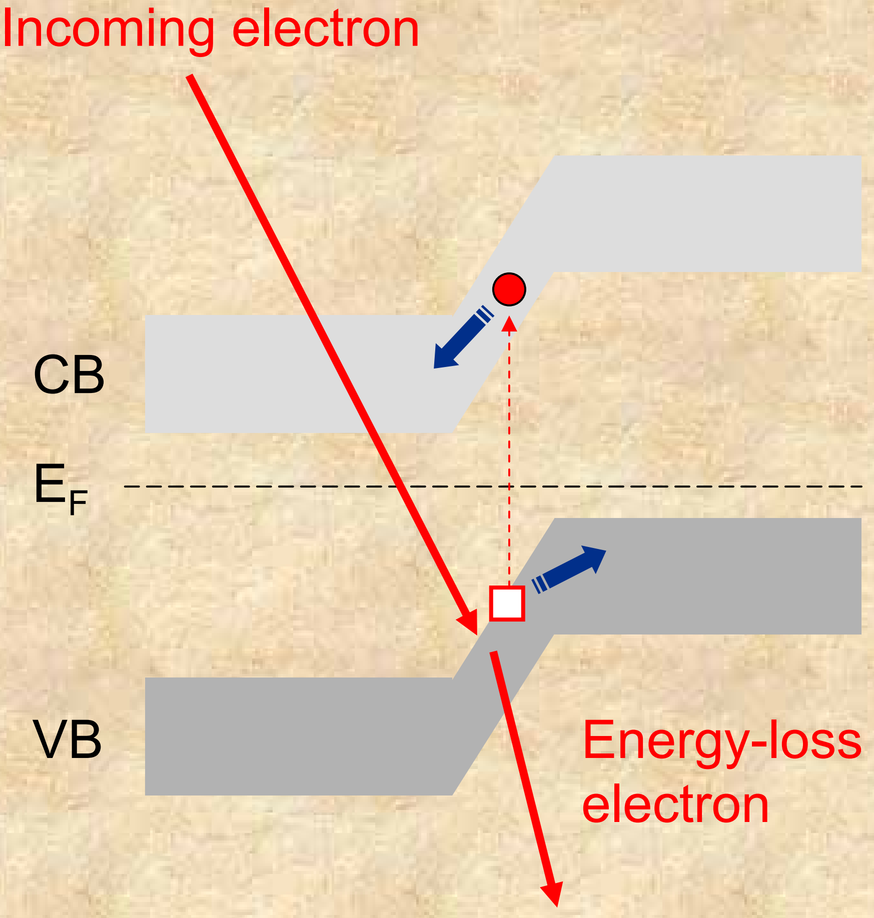
Cathodoluminescence





ZnO(Mg) nanorods

Electron Beam Induced Current

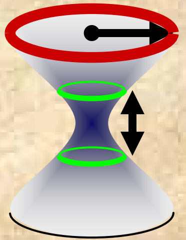


EBIC

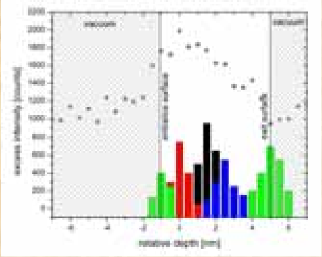
Detectable w/ and w/o applied potential

→Imaging contrast
→Charge Collection Microscopy (CCM)
→ 3D-CCM

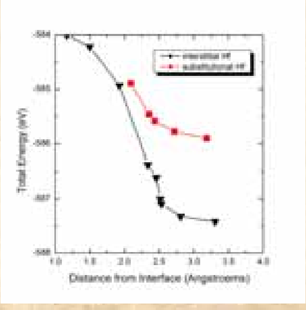
Conclusions



- Volume resolution better than 0.1 x 0.1 x 6 nm^3
- Single atom sensitivity in 3D

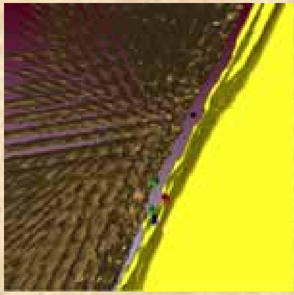


- Direct proof that dopant atoms are located inside the device



- 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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