LEAP® Tomography and the Rapidly Expanding World of Microelectronic Applications

Thomas F. Kelly

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www.imago.com

EXTREME METROLOGY AT THE NANO-SCALE®

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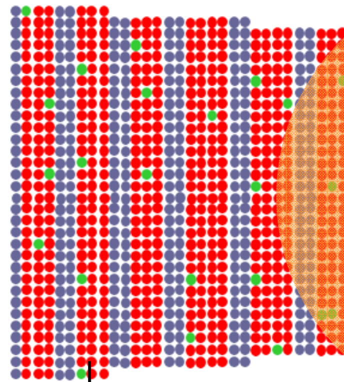
Description of Atom Probe Operation

Atom Probe = Point projection imaging time-of-flight mass spectrometer

~50nm tip → 50mm detector = 10^6 magnification

Needle-Shaped Specimen
50nm radius at apex



Evaporation initiated by:
- Field Pulsing
- or Thermal Pulsing (laser)

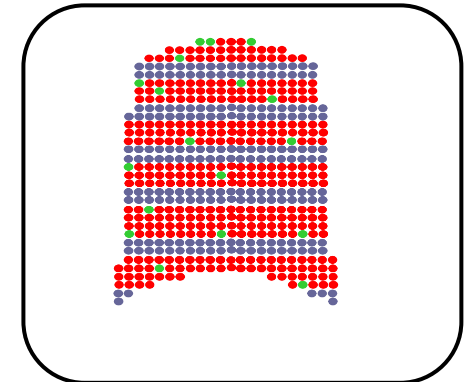
Time of Flight (TOF) identifies mass
TOF~500 ns for LEAP, ΔTOF < 1 ns

\+ High Voltage ~10 kV -

2D Detector

Determines x,y coordinates of atom

Data are collected and interpreted



3-Dimensional Reconstructed Model of Specimen

z is determined from sequence of evaporation events

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Application Spaces

Electrical Conductivity

Metals

Synthetic Organics

Semiconductors and Ceramics

Biological materials

Voltage Pulsing

Laser Pulsing

Thermal Diffusivity

Finer laser focus

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The Strengths of Atom Probe Tomography

Quantitative 3-D Compositional Imaging at the Atomic Scale with High Sensitivity

Atom Probe Tomography is the highest spatial resolution analytical characterization technique

Spatial Resolution	0.4 nm laterally, < 0.2 nm depth (0.06 nm demonstrated laterally)
Sensitivity	~10 appm

- **Compositional Imaging**
  – Buried interfaces
    - Thin film interfaces, precipitates, grain boundaries
- **Structural Imaging**
  – number density, size distribution, …

3D Image

- **Mass Analysis**
  – Phase formation and composition identification

Mass Spectrum

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LEAP® 3000X™

2004 Winner !
2006 Winner !

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Specimen Preparation

Microtips™ and the Lift-Out Method

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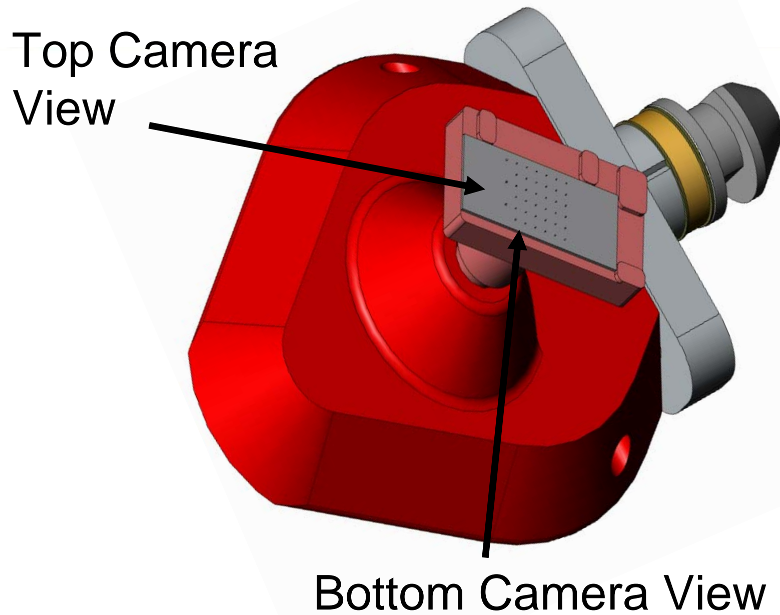
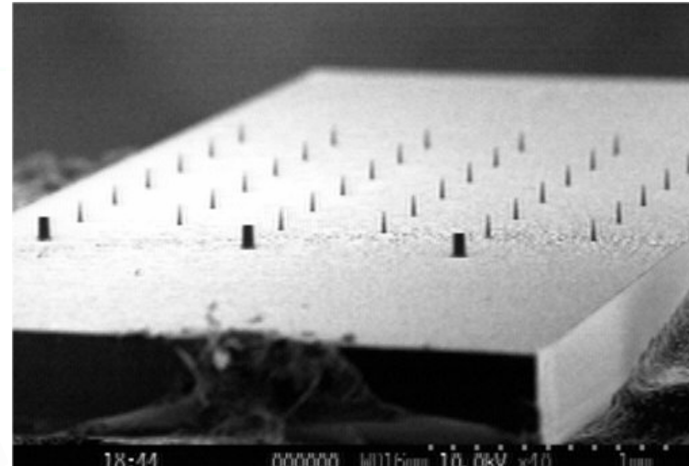
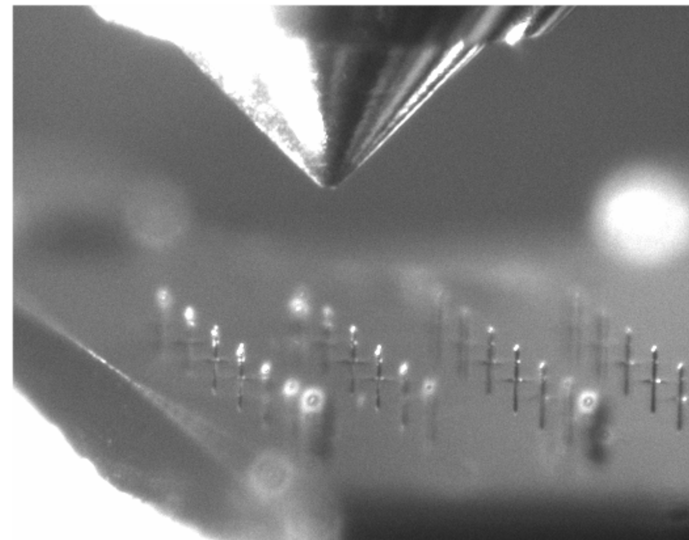
Microtips in the LEAP®







- Two types:
  - Pre-sharpened
  - Flat top
- Uses:
  - Depositions (thin films, organics)
  - Receptacle for liftout

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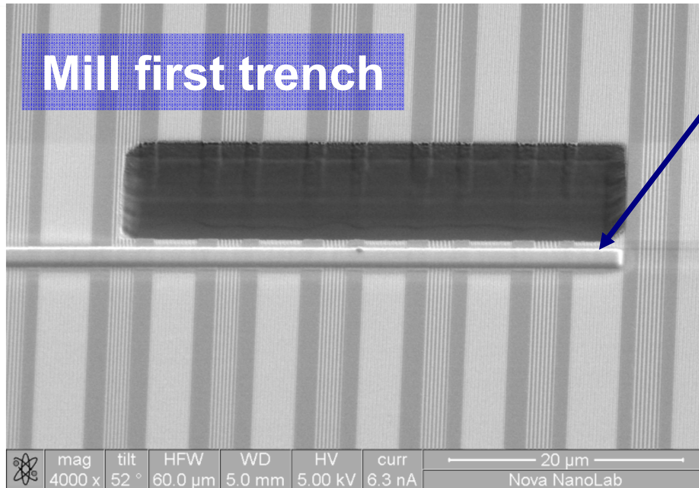
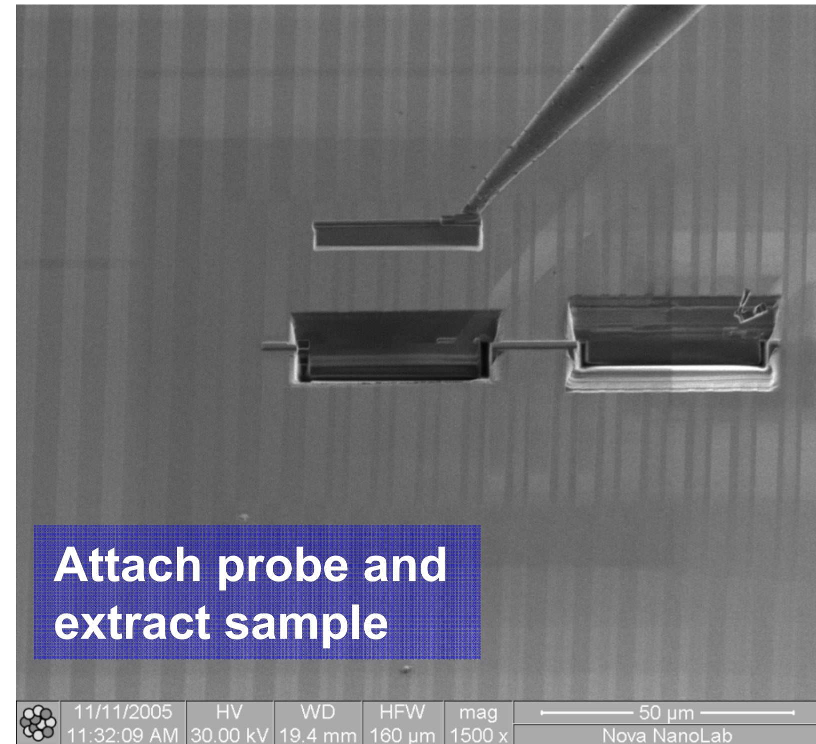
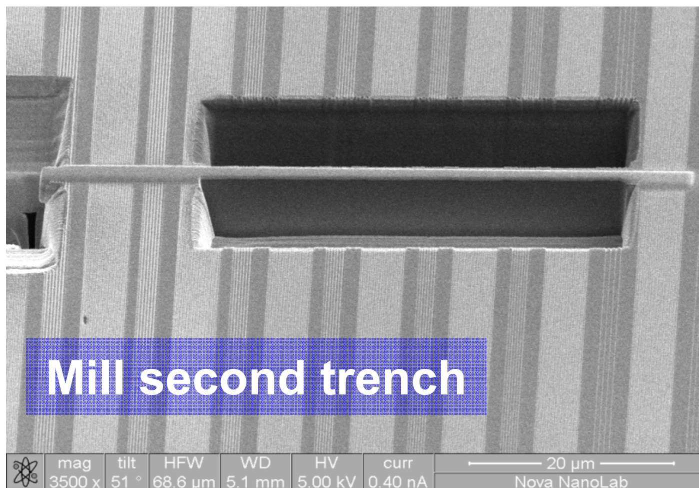
Extracting Specimens with FIB

Step 1 - Extract the Coupon

Deposit Pt







Images courtesy of Brian Gorman

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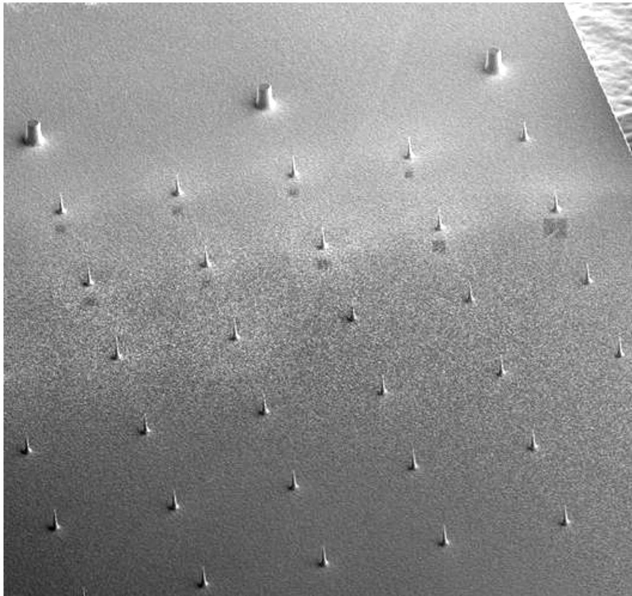
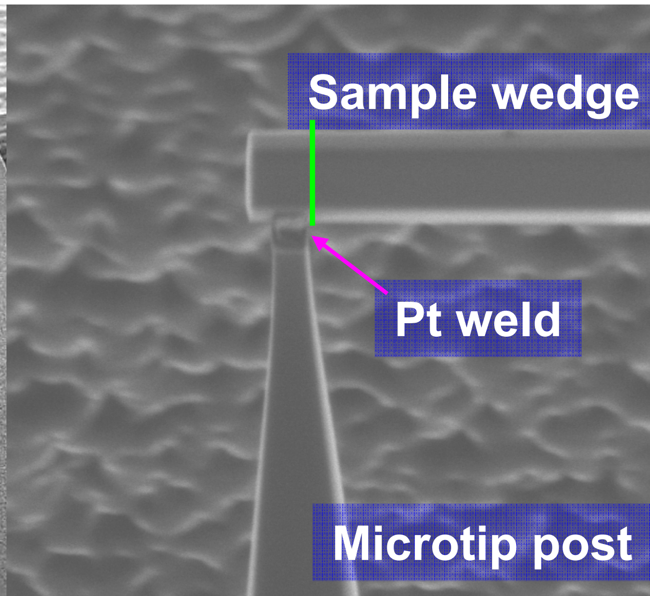
Extracting Specimens with FIB

Step 2 - Attach Sample Wedge to LEAP Microtip

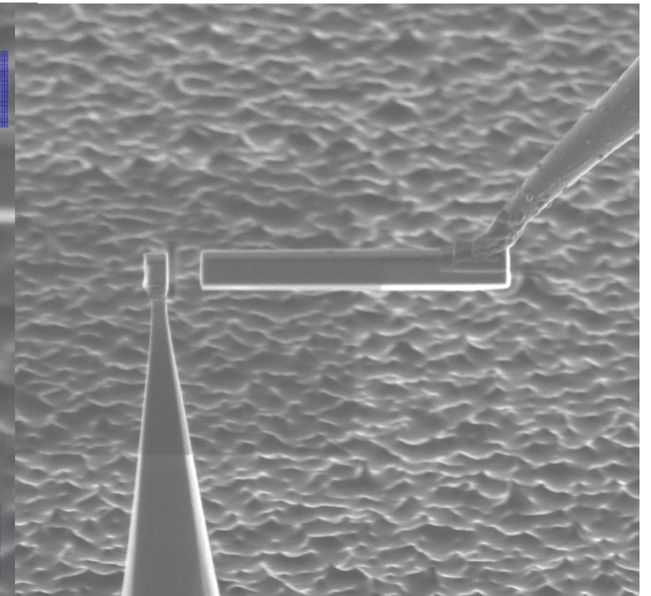
Perspective view of LEAP microtip coupon



Attach sample to wedge



Remainder of wedge is retracted



With J. Sam Moore and Kevin Jones, University of Florida,
Brian Gorman, University of North Texas

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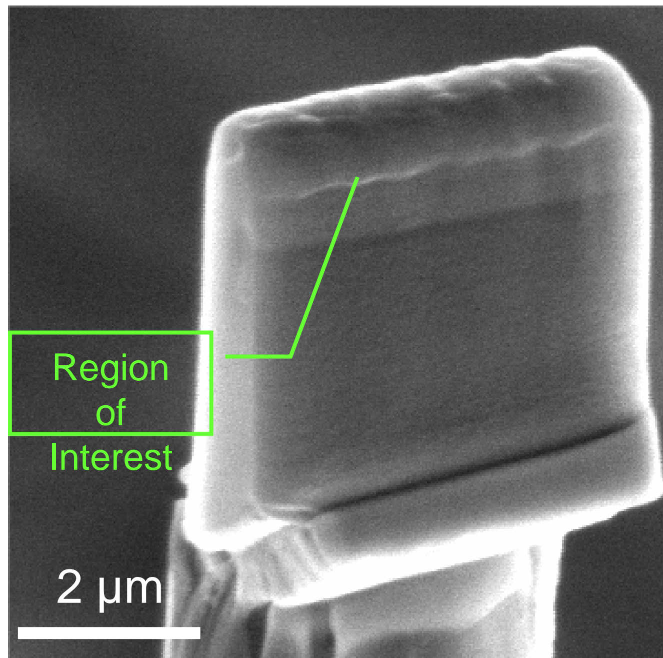
Extracting Specimens with FIB

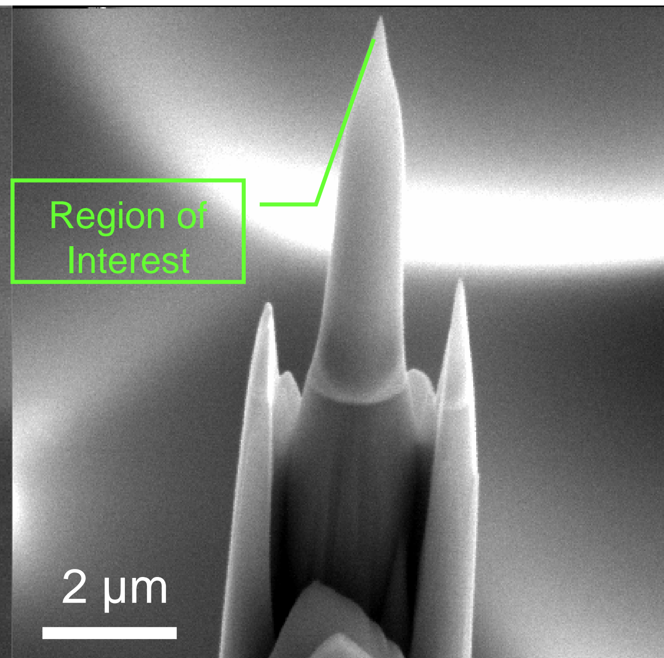
Step 3 - Final Preparation of Tip

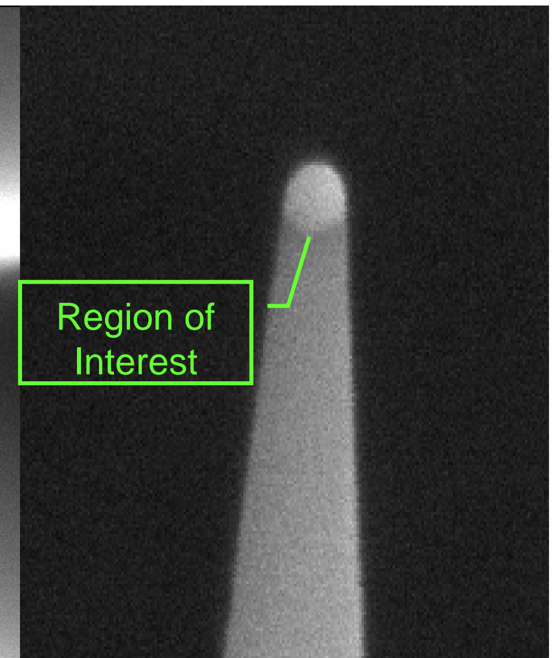
Coupon Mounted on Microtip

Sharpened Tip

Region of Interest







With J. Sam Moore and Kevin Jones, University of Florida,
Brian Gorman, University of North Texas

Total time: 4 hours per 20 specimens

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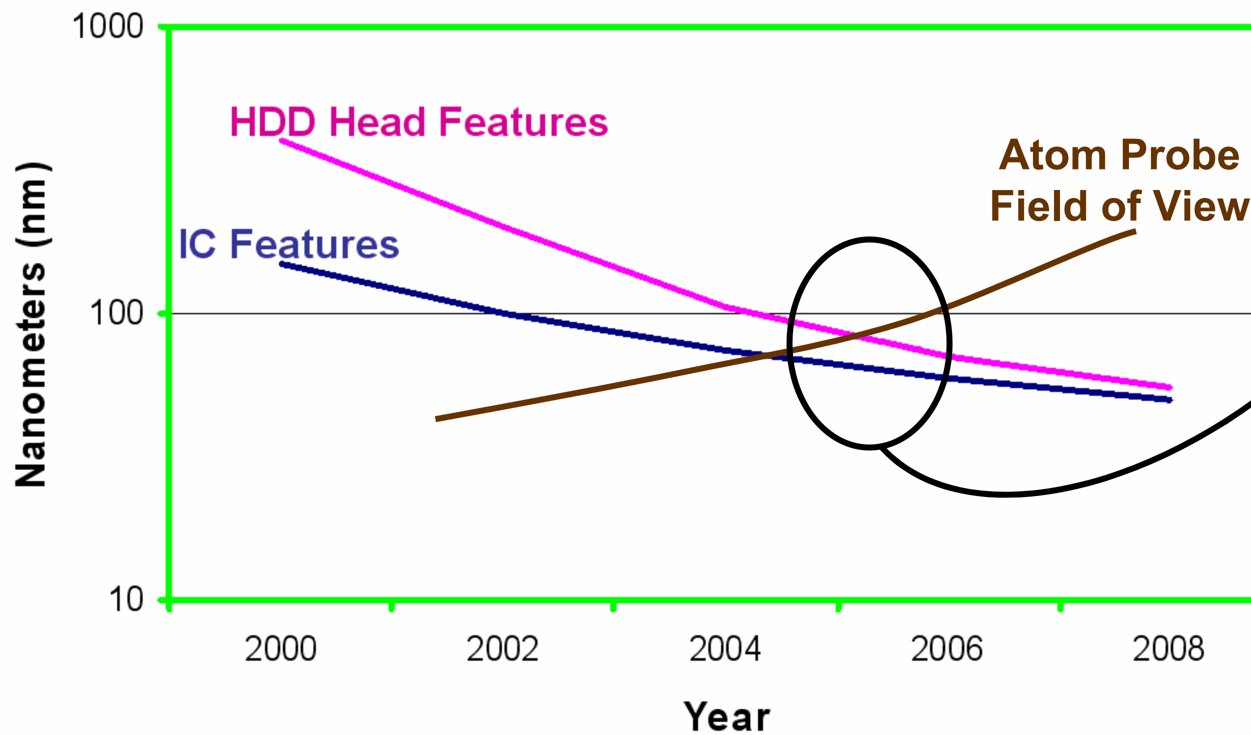
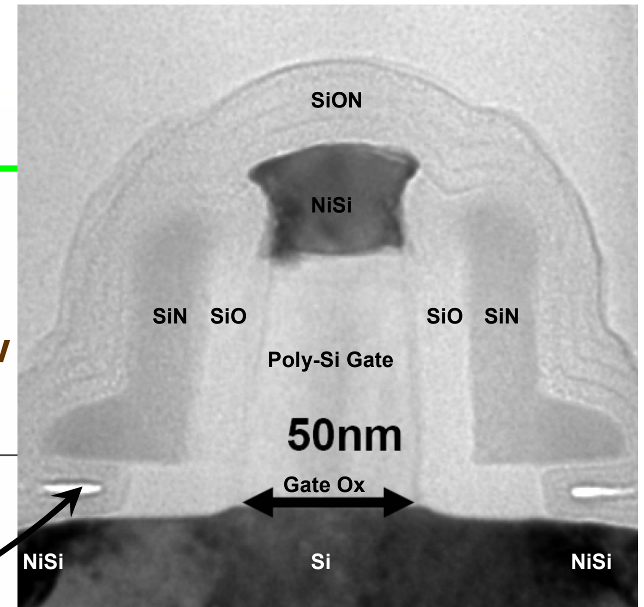
Lithographic Critical Features vs. AP Field of View





Opening the door to full device analysis

At the atomic level!!!

Source: SIA ITRS and Hitachi Global Storage website

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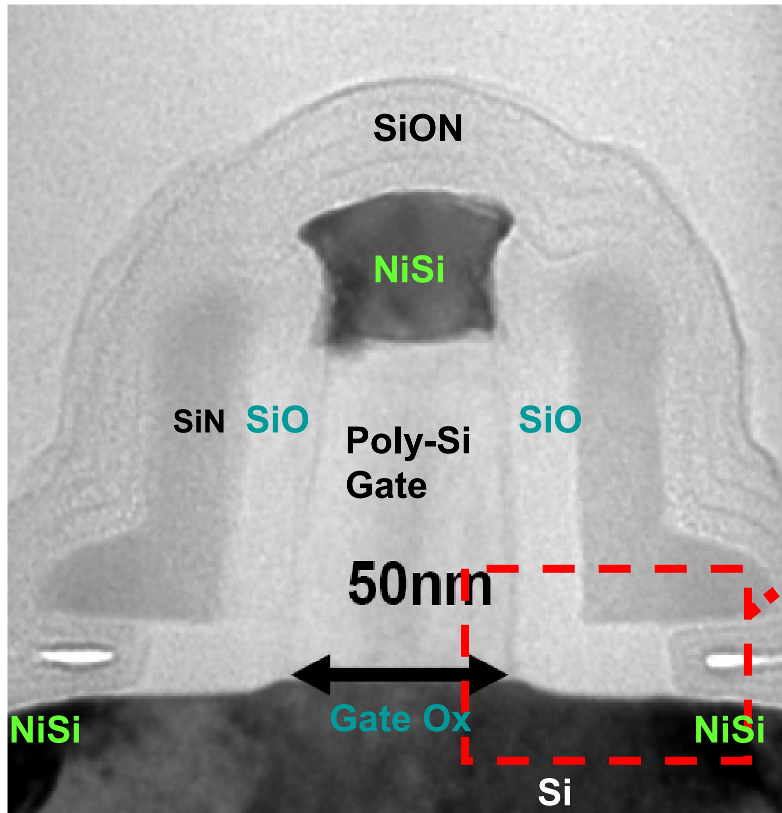
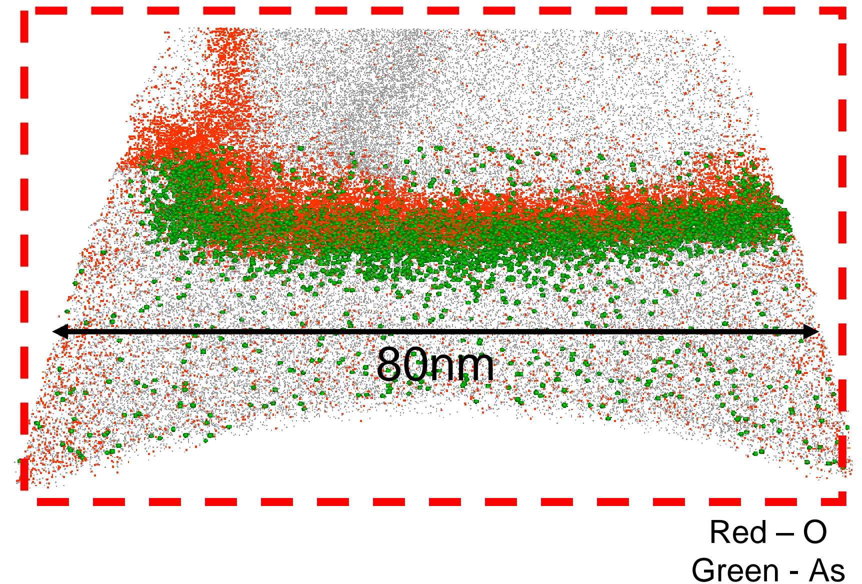
Analysis Volume Approaches Transistor Dimensions



TEM next-generation transistor

LEAP 3000XSi™ with DT200



Red – O
Green - As

LEAP reveals dopant distributions

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Verification

- **Compositional**
  - Compare with known standards
  - e.g., NIST Standard Reference Material (SRM 2137)
- **Spatial**
  - Spatial Distribution Maps™ (SDM™)

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National Institute of Standards & Technology (NIST) Standard Reference Material (SRM)

National Institute of Standards & Technology

Certificate of Analysis

Standard Reference Material 2137

Boron Implant in Silicon Standard
for Calibration of Concentration in a Depth Profile

Serial No.__________

This Standard Reference Material (SRM) is intended for use in calibrating the secondary ion response to minor and trace levels of boron in a silicon matrix by the analytical technique of secondary ion mass spectrometry (SIMS). SRM 2137 consists of a single crystal silicon substrate with a surface rendered disordered by silicon ion implantation. The substrate is ion-implanted with the isotope ^{10}B at a nominal energy of 50 keV.

SRM 2137 is certified for the retained dose of ^{10}B atoms by neutron depth profiling. The dose is expressed in units of ^{10}B mass per unit area. Noncertified information about the concentration of ^{10}B atoms as a function of depth below the surface is provided by SIMS.

Dave Simons, NIST

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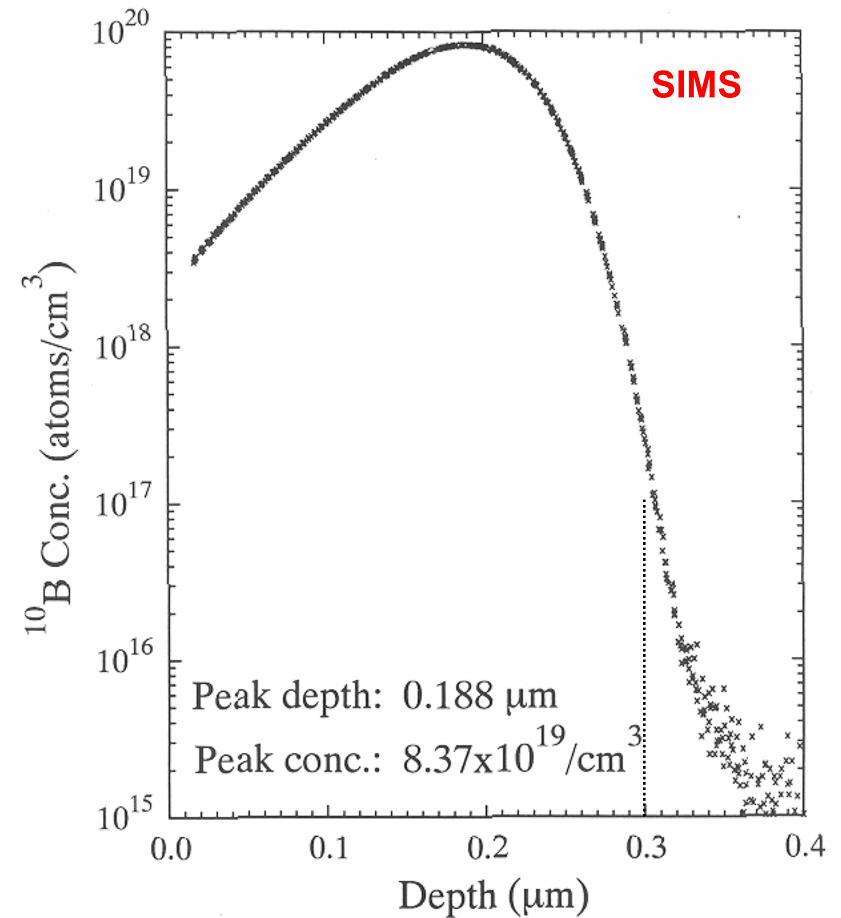
National Institute of Standards & Technology Standard Sample - Boron Implant

Depth (μm)	^{10}B Conc. (atoms/cm^3)	Depth (μm)	^{10}B Conc. (atoms/cm^3)
0.020	3.90×10^{18}	0.175	8.05×10^{19}
0.025	4.50×10^{18}	0.180	8.23×10^{19}
0.030	5.17×10^{18}	0.185	8.34×10^{19}
0.035	5.86×10^{18}	0.190	8.36×10^{19}
0.040	6.63×10^{18}	0.195	8.27×10^{19}
0.045	7.53×10^{18}	0.200	8.11×10^{19}
0.050	8.49×10^{18}	0.205	7.83×10^{19}
0.055	9.59×10^{18}	0.210	7.43×10^{19}
0.060	1.08×10^{19}	0.215	6.93×10^{19}
0.065	1.22×10^{19}	0.220	6.33×10^{19}
0.070	1.36×10^{19}	0.225	5.68×10^{19}
0.075	1.54×10^{19}	0.230	4.98×10^{19}
0.080	1.71×10^{19}	0.235	4.28×10^{19}
0.085	1.91×10^{19}	0.240	3.57×10^{19}
0.090	2.14×10^{19}	0.245	2.91×10^{19}
0.095	2.38×10^{19}	0.250	2.29×10^{19}
0.100	2.65×10^{19}	0.255	1.76×10^{19}
0.105	2.93×10^{19}	0.260	1.30×10^{19}
0.110	3.24×10^{19}	0.265	9.25×10^{18}
0.115	3.56×10^{19}	0.270	6.37×10^{18}
0.120	3.90×10^{19}	0.275	4.20×10^{18}
0.125	4.28×10^{19}	0.280	2.65×10^{18}
0.130	4.67×10^{19}	0.285	1.61×10^{18}
0.135	5.08×10^{19}	0.290	9.25×10^{17}
0.140	5.49×10^{19}	0.295	5.01×10^{17}
0.145	5.90×10^{19}	0.300	2.70×10^{17}
0.150	6.32×10^{19}	0.305	1.34×10^{17}
0.155	6.72×10^{19}	0.310	6.87×10^{16}
0.160	7.11×10^{19}	0.315	3.26×10^{16}
0.165	7.48×10^{19}	0.320	1.69×10^{16}
0.170	7.79×10^{19}		



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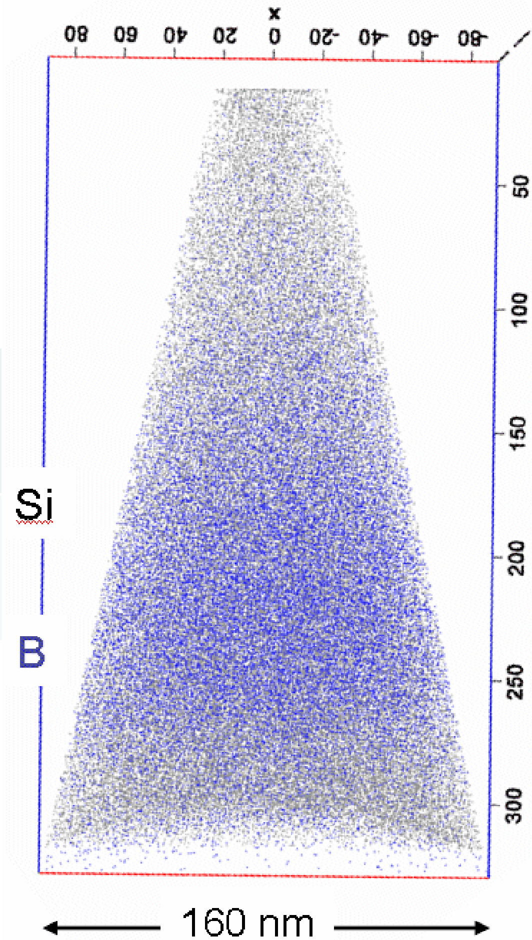
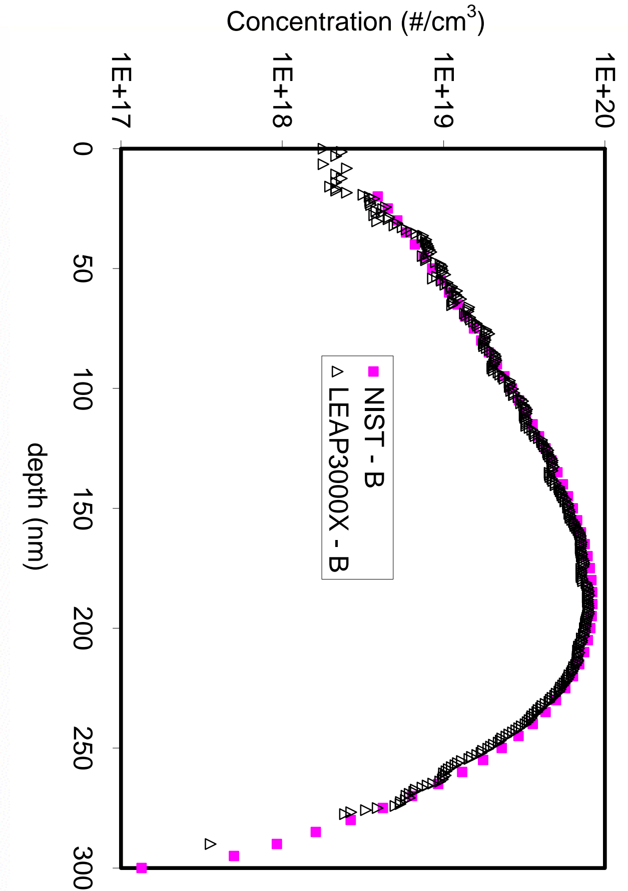
NIST Standard Reference Material – Boron Implant

10 B implant in Si

Sensitivity of ~1 x 10^{18} cm^{-2} is demonstrated

NIST Total Dose	1 x 10^{15} cm^{-2}
LEAP Total Dose	9 x 10^{14} cm^{-2}





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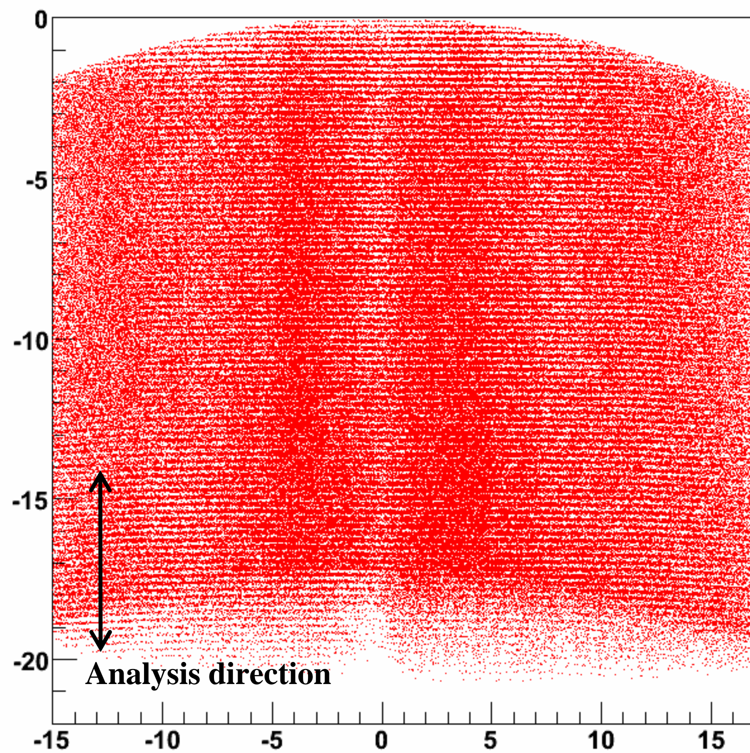
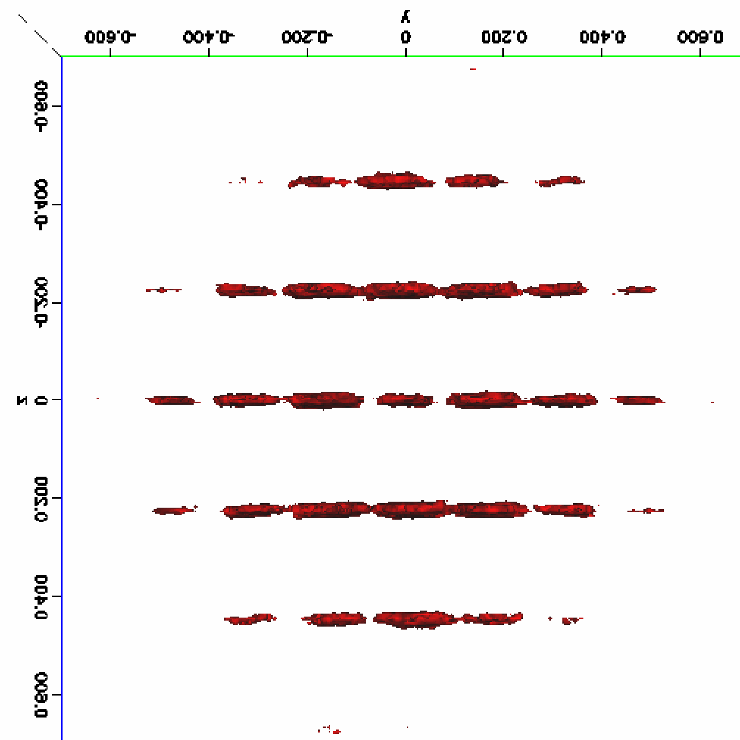
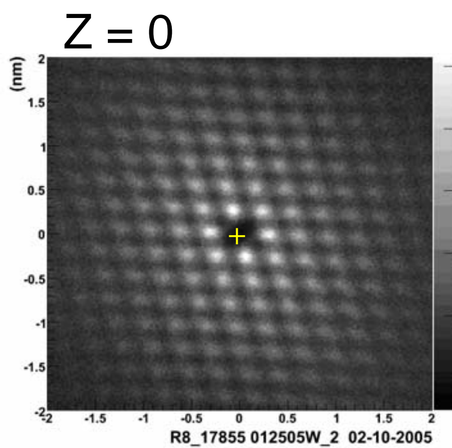
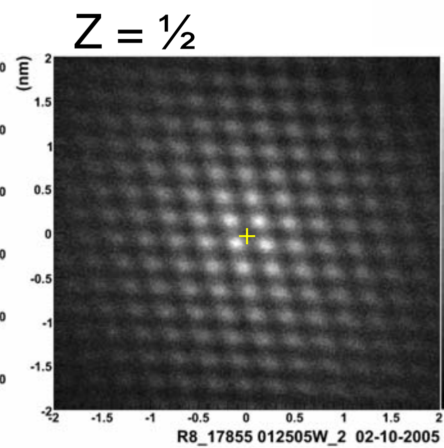
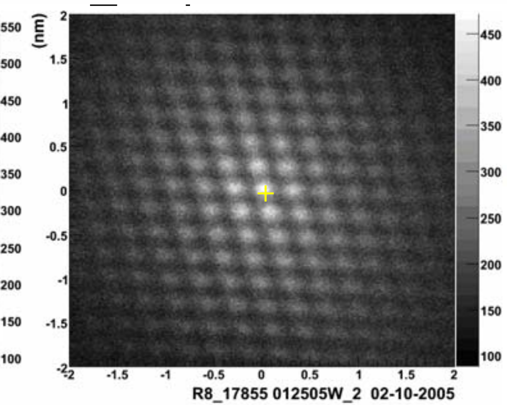
Spatial Distribution Maps™





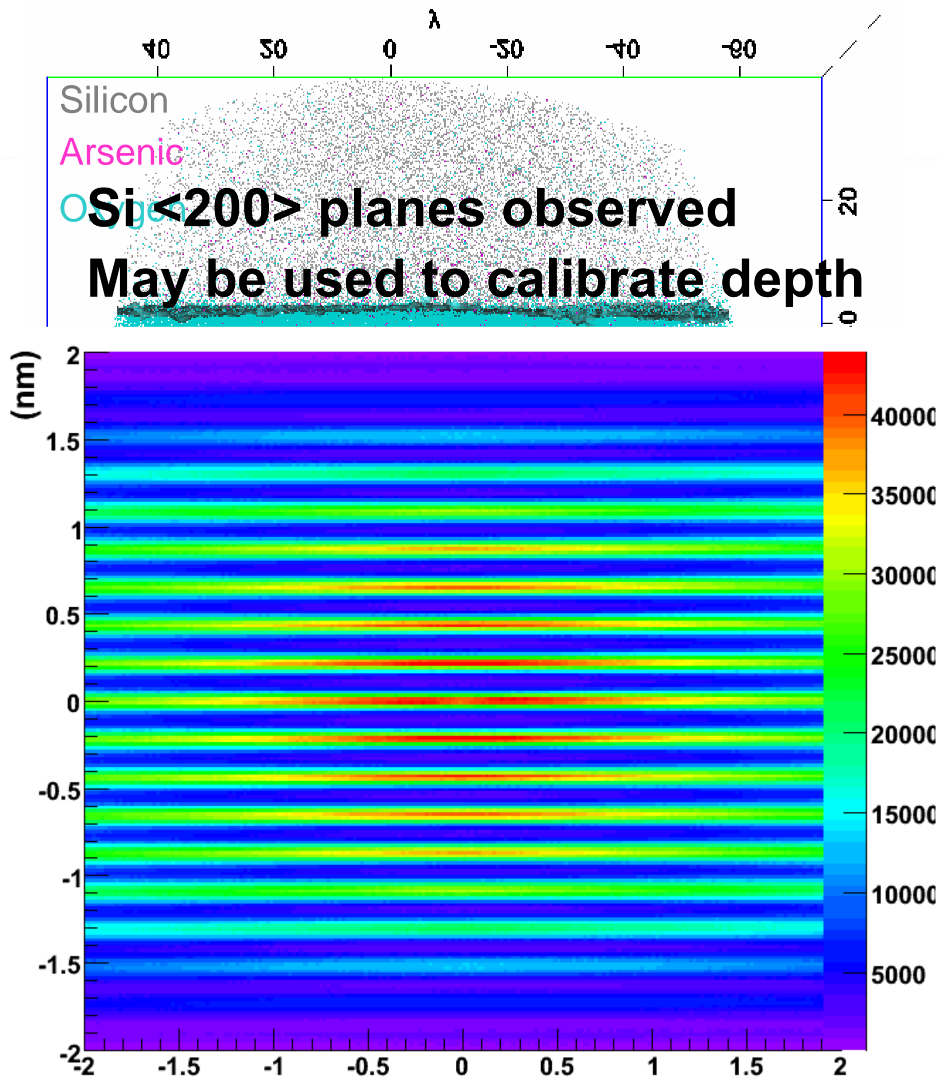






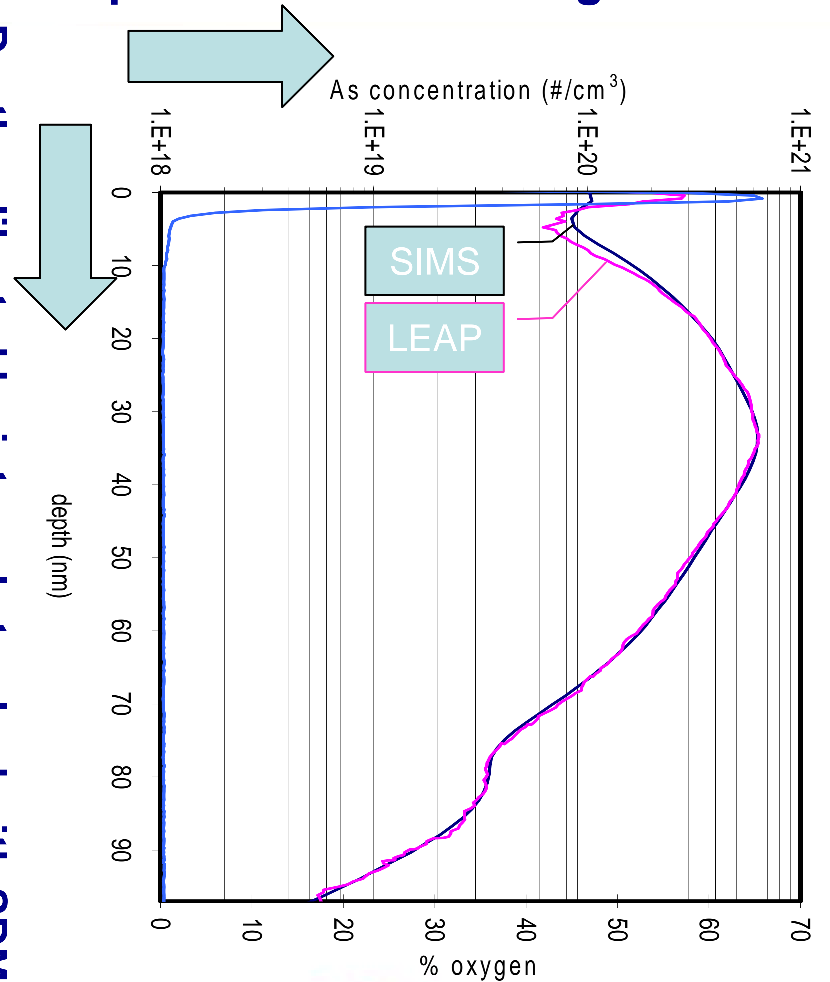
Tungsten bcc lattice observed Brian Geiser, Imago

Compositional and Spatial Verification



Depth calibrated by internal standard with SDM™

Composition calibrated against SIMS



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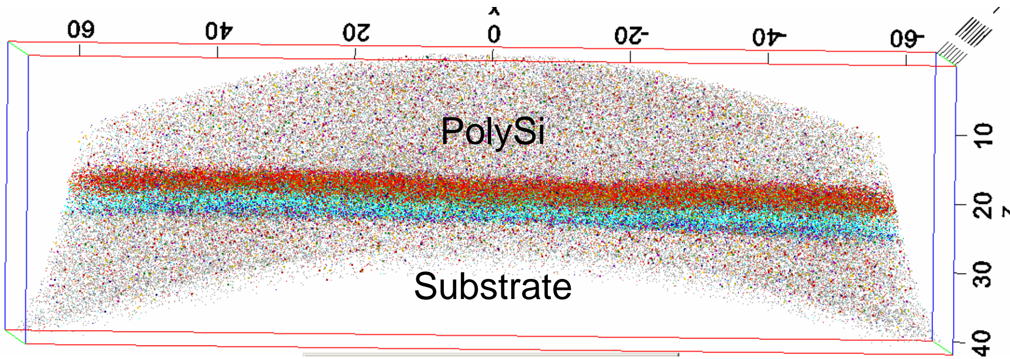
PolySi/Hafnia High-k Dielectric Stack



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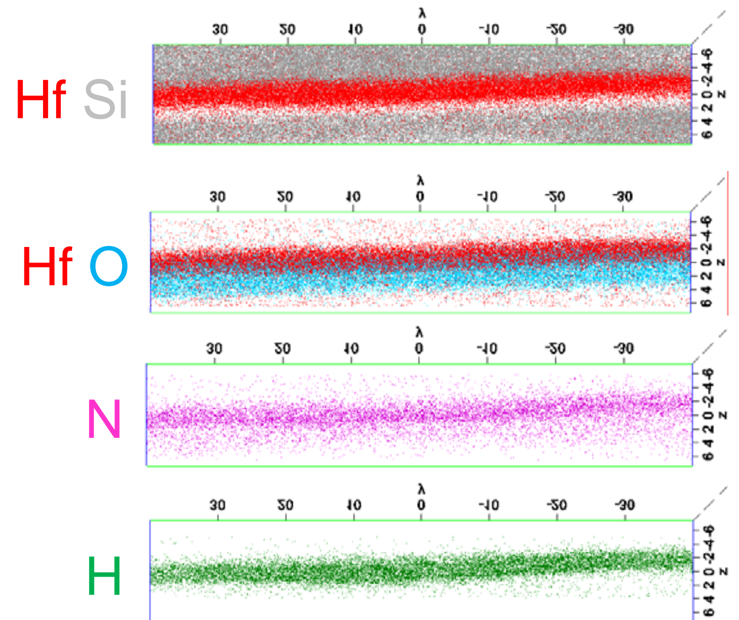
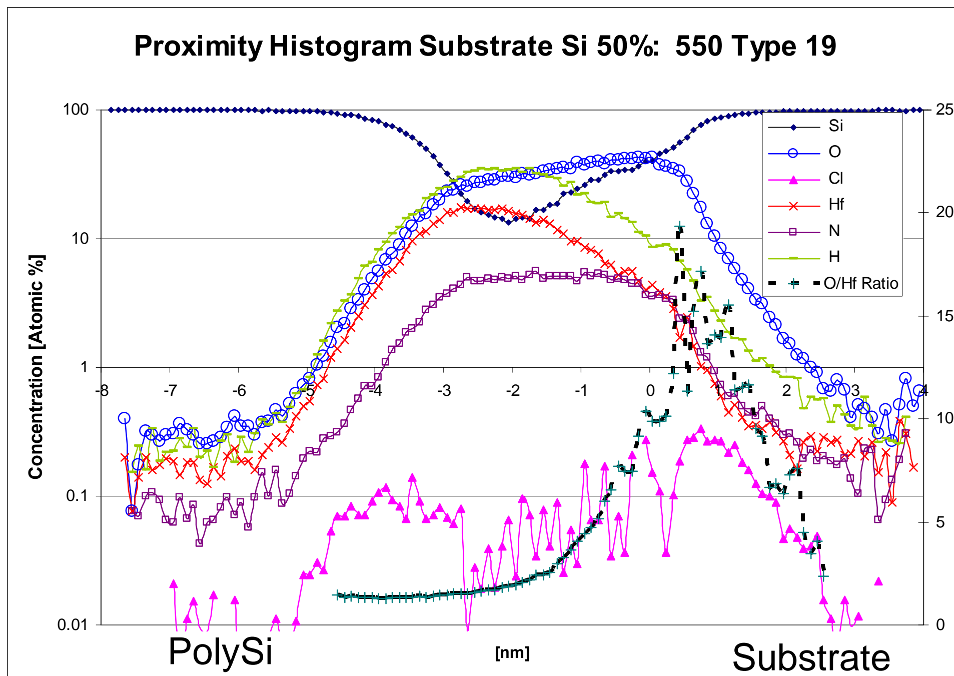
- Keith Thompson, Imago
- Rob Ulfig, Imago





Dielectric thickness
O FWHM = 3.7nm, Peak 43 at.%
Hf FWHM = 2.5nm

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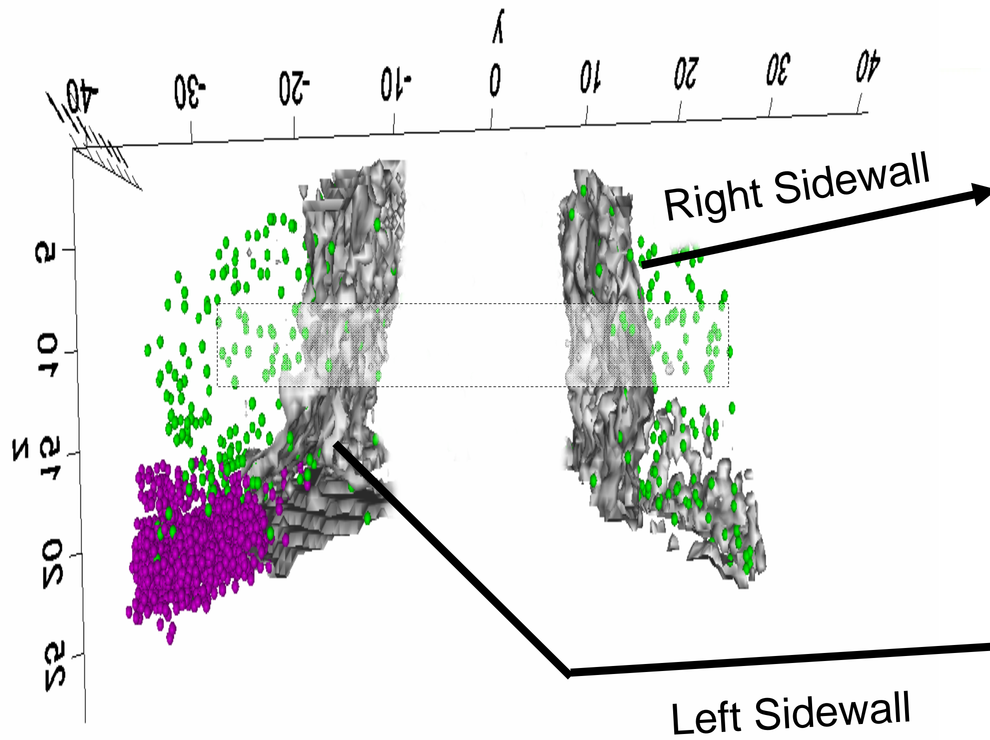
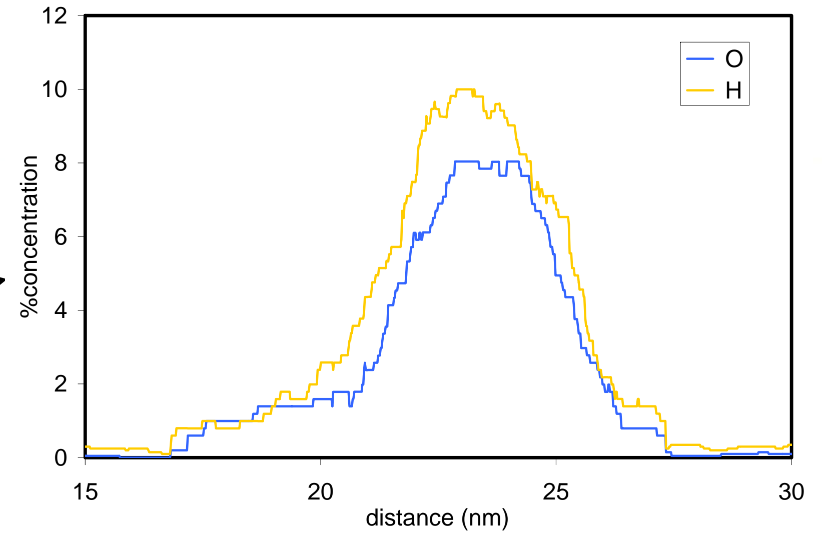
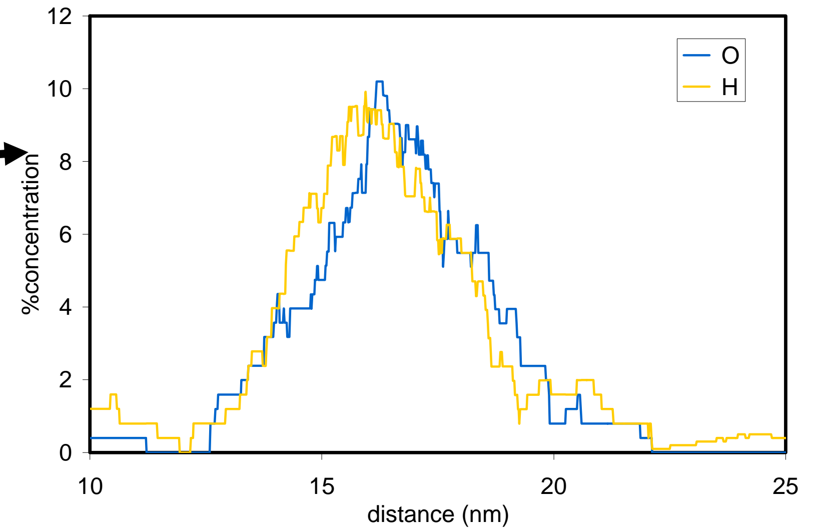
Poly-Si Gate Analysis







Kevin S. Jones and John S. Moore, University of Florida
Sean Corcorran, Intel and coworkers
Keith Thompson and Imago personnel

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Compound Semiconductor Nanostructures

All atoms

As atoms

In, P atoms

%Concentration

depth (nm)

P
As
Ga
In

%Concentration

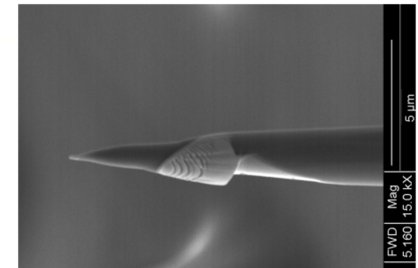
depth (nm)

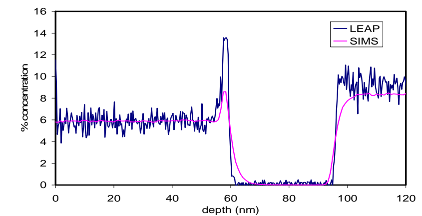
Brian Gorman, University of North Texas, LEAP 3000X

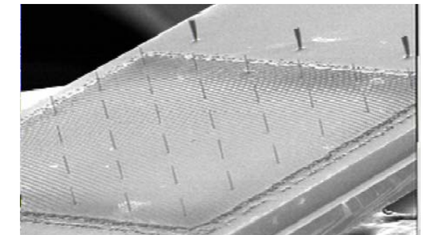
UNT Materials Science and Engineering

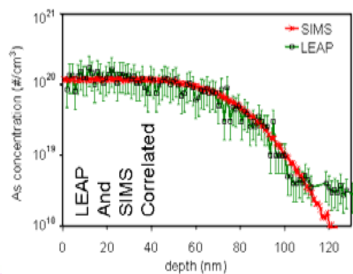
Summary

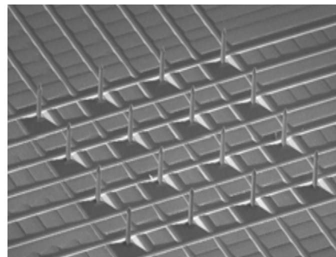
- **Atom probe tomography provides *atomic-scale compositional* characterization at *high sensitivity* in *3D***
  - This is especially useful for characterization of ***buried interfaces***
- **Specimen preparation is similar to TEM**
  - Local electrode enables rapid preparation of multiple samples
- **Site-specific Lift-out enables many new applications**
  - Semiconductor device development
  - Failure analysis
  - Competitive analysis

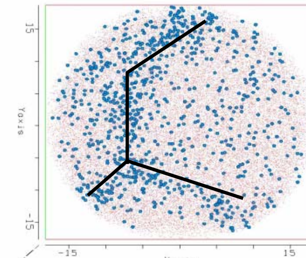


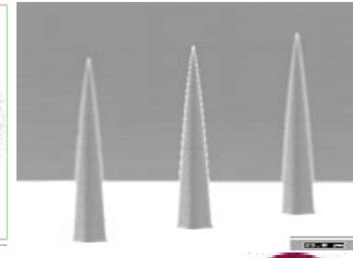


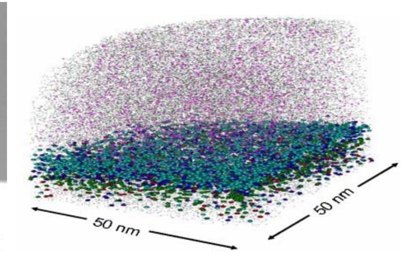












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