LEAP® Tomography and the Rapidly Expanding World of Microelectronic Applications

Thomas F. Kelly
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www.imago.com
<table>
<thead>
<tr>
<th>Imago Contributors</th>
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<tbody>
<tr>
<td>Keith Thompson</td>
</tr>
<tr>
<td>David Larson</td>
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<td>Jesse Olson</td>
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<tr>
<td>Joe Bunton</td>
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<td>Roger Alvis</td>
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<td>Rob Ulfig</td>
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<td>Dan Lawrence</td>
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<tr>
<td>Paul Ronsheim, IBM</td>
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<tr>
<td>Brian Gorman, Univ. North Texas</td>
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<tr>
<td>Sean Corcoran, Intel</td>
</tr>
<tr>
<td>Kevin Jones, Sam Moore, Univ. Florida</td>
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<tr>
<td>David Seidman, Northwestern Univ.</td>
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</table>
Description of Atom Probe Operation

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

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

Needle-Shaped Specimen
50 nm radius at apex

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

High Voltage ~10 kV

2D Detector
Determines x,y coordinates of atom

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

3-Dimensional Reconstructed Model of Specimen
z is determined from sequence of evaporation events

Data are collected and interpreted

Evaporation initiated by:

z is determined from sequence of evaporation events
Application Spaces

Electrical Conductivity

Thermal Diffusivity

- Synthetic Organics
- Biological materials
- Semiconductors and Ceramics
- Metals

Voltage Pulsing

Laser Pulsing

Finer laser focus

EXTREME METROLOGY AT THE NANO-SCALE®

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The Strengths of Atom Probe Tomography

<table>
<thead>
<tr>
<th>Quantitative 3-D Compositional Imaging at the Atomic Scale with High Sensitivity</th>
</tr>
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<tbody>
<tr>
<td>Atom Probe Tomography is the highest spatial resolution analytical characterization technique</td>
</tr>
<tr>
<td>Spatial Resolution</td>
</tr>
<tr>
<td>Sensitivity</td>
</tr>
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</table>

- **Compositional Imaging**
  - Buried interfaces
    - Thin film interfaces, precipitates, grain boundaries

- **Structural Imaging**
  - Number density, size distribution, …

- **Mass Analysis**
  - Phase formation and composition identification
Specimen Preparation

Microtips™ and the Lift-Out Method
Microtips in the LEAP®

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

Step 1 - Extract the Coupon

Mill first trench

Deposit Pt

Mill second trench

Attach probe and extract sample

Images courtesy of Brian Gorman
Extracting Specimens with FIB

Step 2 - Attach Sample Wedge to LEAP Microtip

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

Step 3 - Final Preparation of Tip

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

Total time: 4 hours per 20 specimens
Opening the door to full device analysis
At the atomic level!!!

Source: SIA ITRS and Hitachi Global Storage website
Analysis Volume Approaches Transistor Dimensions

TEM next-generation transistor

LEAP 3000XSi™ with DT200

LEAP reveals dopant distributions

SiON
NiSi
Poly-Si Gate
SiN SiO
SiO
SiON
SiN SiO
NiSi
NiSi
50nm
50nm
80nm
80nm

Red – O
Green - As
Verification

- **Compositional**
  - Compare with known standards
  - e.g., NIST Standard Reference Material (SRM 2137)

- **Spatial**
  - Spatial Distribution Maps™ (SDM™)
National Institute of Standards & Technology (NIST) Standard Reference Material (SRM)

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. Nontested information about the concentration of $^{10}$B atoms as a function of depth below the surface is provided by NIST.

Dave Simons, NIST
National Institute of Standards & Technology Standard Sample - Boron Implant

<table>
<thead>
<tr>
<th>Depth (μm)</th>
<th>$^{10}$B Conc. (atoms/cm²)</th>
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<td>$7.48 \times 10^{19}$</td>
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<tr>
<td>0.170</td>
<td>$7.79 \times 10^{19}$</td>
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**SIMS**

Peak depth: 0.188 μm
Peak conc.: $8.37 \times 10^{19}$/cm³
10 B implant in Si
Sensitivity of $\sim 1 \times 10^{18} \text{ cm}^{-2}$ is demonstrated

<table>
<thead>
<tr>
<th></th>
<th>NIST Total Dose</th>
<th>LEAP Total Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 B implant in Si</td>
<td>$1 \times 10^{15} \text{ cm}^{-2}$</td>
<td>$9 \times 10^{14} \text{ cm}^{-2}$</td>
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</table>
Spatial Distribution Maps™

Tungsten bcc lattice observed
Brian Geiser,
Imago
Compositional and Spatial Verification

Si<200> planes observed
May be used to calibrate depth

Composition calibrated against SIMS

Depth calibrated by internal standard with SDM™

LEAP SIMS

Si, Arsenic, Oxygen

1.E+18
1.E+19
1.E+20
1.E+21

0 1 02 03 04 05 06 07 08 09 0

As concentration (#/cm³)

0 10 20 30 40 50 60 70 80 90

Depth (nm)

% oxygen
PolySi/Hafnia High-k Dielectric Stack

- Paul Ronsheim, IBM
- Keith Thompson, Imago
- Rob Ulfig, Imago

Dielectric thickness
O FWHM = 3.7 nm, Peak 43 at.%
Hf FWHM = 2.5 nm
Poly-Si Gate Analysis

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

Brian Gorman, University of North Texas, LEAP 3000X
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