Semicon West - Junction Technology Session

Advanced Metrology Solutions

7/11/13

LEAP 4000X-Si
3D Atom Probe

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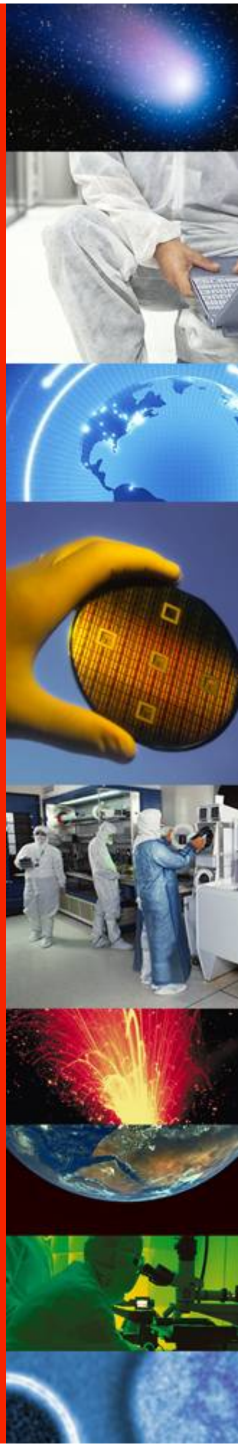
MATERIALS ANALYSIS DIVISION



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A strongly Differentiated Company with Innovative Designs and Clear Technical Roadmap

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World Leader in Elemental & Isotopic Microanalysis

Multiple Products over 3 Method Types:

LEAP 4000-HR, 4000X-HR, 4000X-Si
« APT »

Atom **P**robe **T**omography

Pulsed HV Field or Focused Laser In / Ions Out

IMS Wf, IMS 7f-Auto, IMS 1280-HR, Quad-4550, NanoSIMS 50L
« SIMS »

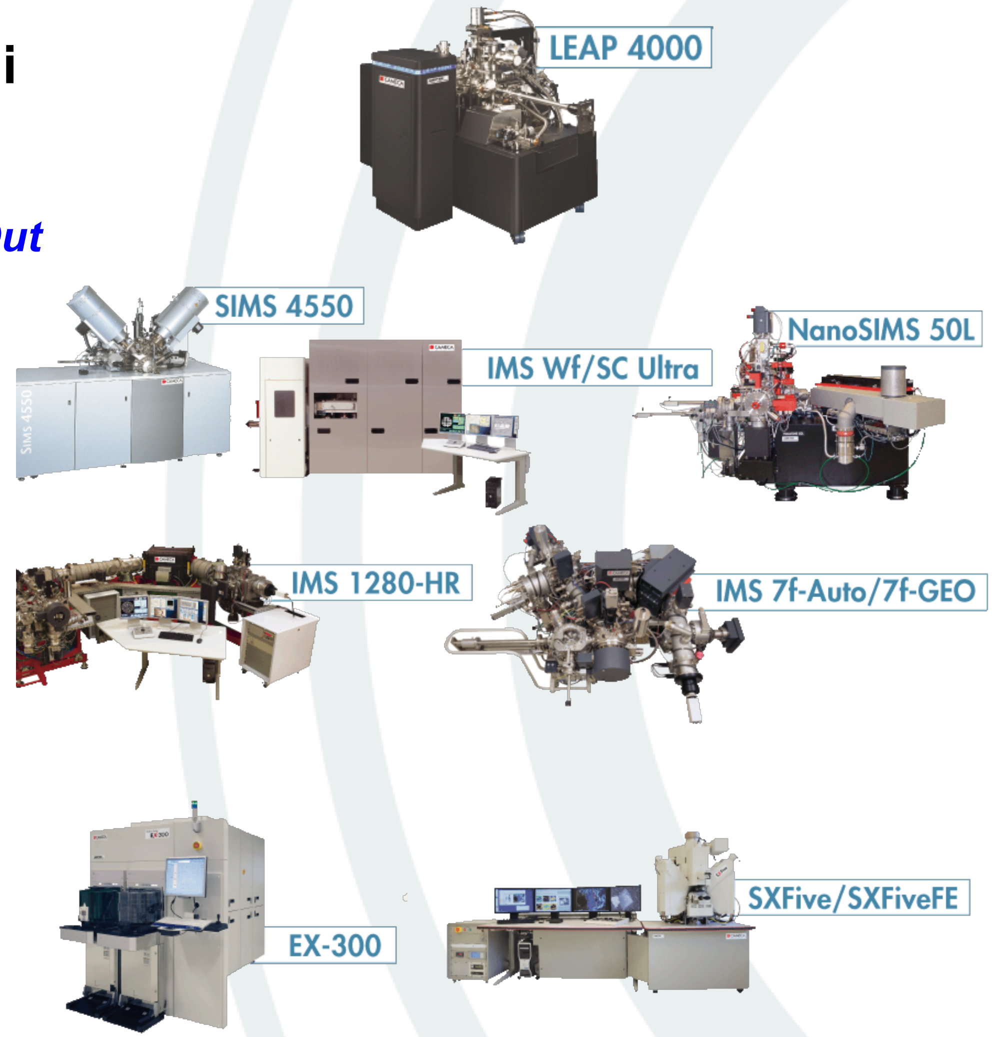
Secondary **I**on **M**ass **S**pectrometry

Ions In / Ions Out

SXFive, EX-300
« EPMA » « LEXES »

Electron **P**robe **M**icro**A**nalysis; **L**ow **E**nergy **X**-ray **E**mission **S**pectroscopy

Electrons In / X-rays Out



Several CAMECA Product Lines Have Been Optimized for Semiconductor Applications

SIMS (Secondary Ion Mass Spectrometry)

- CAMECA SIMS instruments are recognized throughout the international IC community as best in class for investigation on new materials and devices. They are also used as near-the-line tools for automated in-line process control
- Extreme Sensitivity, High Mass Resolution, High Dynamic Range, Low Detection Limits and High Analysis Throughput
- Our SIMS line for Semiconductor applications includes:
  - The ***IMS Wf***: optimized for trace element depth profiling of ultra-thin structures at Extremely Low Impact Energy (EXLIE).
  - The ***IMS 7f***: depth profiling with high sensitivity (down to ppb atomic concentration) and 2D or 3D imaging of trace elements.
  - The ***SIMS 4550***: Quadrupole SIMS for Ultra Low Energy profiling with unsurpassed ease of use, flexibility and insulator analysis.

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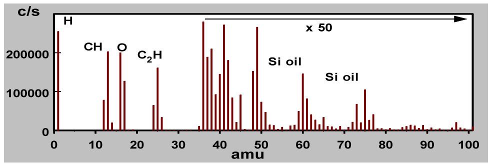
SIMS Analytical Outputs

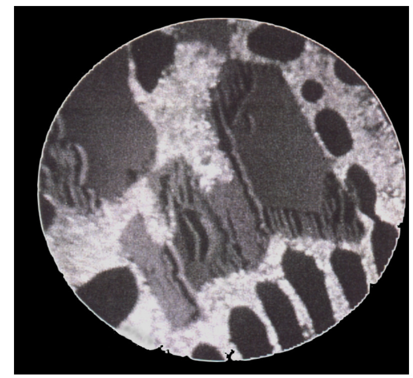


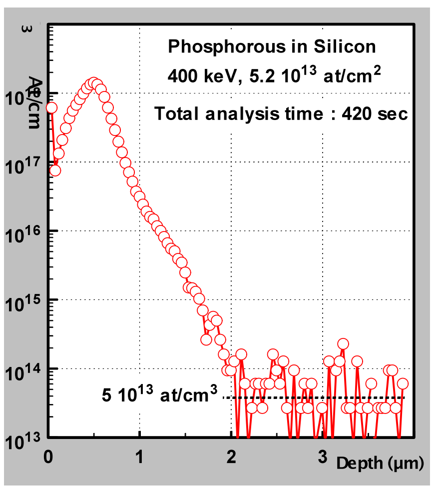
- **Mass spectrum**

Obtained by scanning the mass analyser and recording the mass filtered secondary ion intensities

- **2D & 3D image**

Obtained whether by a direct mass filtered stigmatic microscope image or by scanning a focused ion beam over the sample and recording the intensity of selected secondary ions for each pixel.



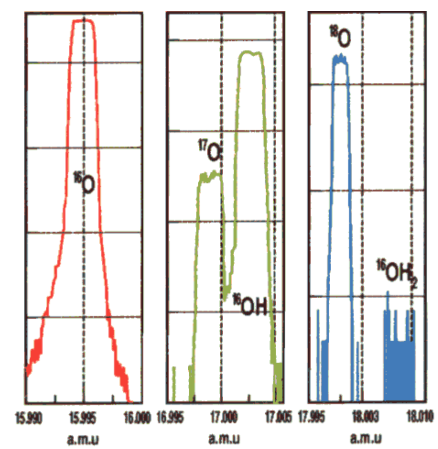


- **Depth profile**

Obtained by sputtering the sample and recording a few selected mass filtered secondary ion intensities versus time (=depth).

- **Isotopic ratio**

Obtained by recording the mass filtered secondary ion intensity at the different isotope peak positions



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Several CAMECA Product Lines Have Been Optimized for Semiconductor Applications

*LEXES based In-Line Metrology Tools

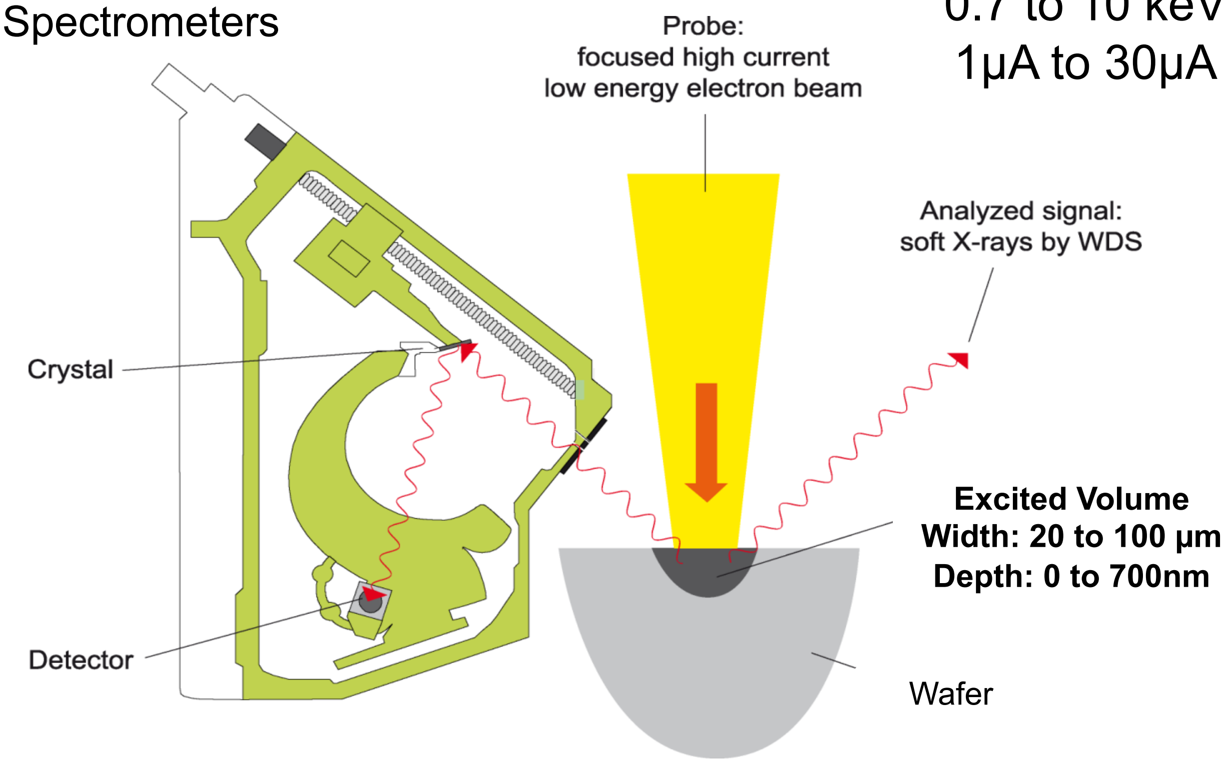
- The ***Shallow Probe EX-300*** is CAMECA's flagship tool for composition and thickness measurements of ultra-thin structures.
- The non-contact, non-destructive LEXES technique is a unique solution for direct measurement of the chemical composition at the surface and near surface.
- The ***EX-300*** offers a panel of complementary capabilities enlarging the domains of classical metrology to current challenging processes:
  - **Ultra shallow implants:** Monitoring of low energy, high concentration implants.
  - **Strained silicon process control:** Chemical composition and thickness in epitaxial layers such as **B:SiGe** and **P:SiC**, with no limitation in the layer composition.
  - **HKMG metrology:** Both the oxides and the metal are controlled by one single ***EX-300*** platform.
- The ***EX-300*** is designed to accelerate the time to market of advanced logic & memory devices while achieving high production yield.

*****L**ow energy **E**lectron induced **X**-ray **E**mission **S**pectrometry

Shallow Probe is based on LEXES:
Low energy Electron induced X-ray Emission Spectrometry

Detection
3 Wavelength
Dispersive Spectrometers

0.7 to 10 keV
1µA to 30µA



LEXES Shallow Probe EX-300

FRONT-END COMPOSITIONAL METROLOGY

- *Fully compatible for fab*
- *200 / 300 mm wafer*
- *Comply to SEMI standards*

Key Strengths

Non-destructive
Non-contact
Lateral mapping
Patterned wafers (30 by 30µm pads)
Buried layers
Analysis range: surface to 800 nm depth
Cover all elements heavier than Be

Targeted Capabilities

Light elements
B, N, C

OxidesThin
(HKMG & memories)
Thick
(Memories)

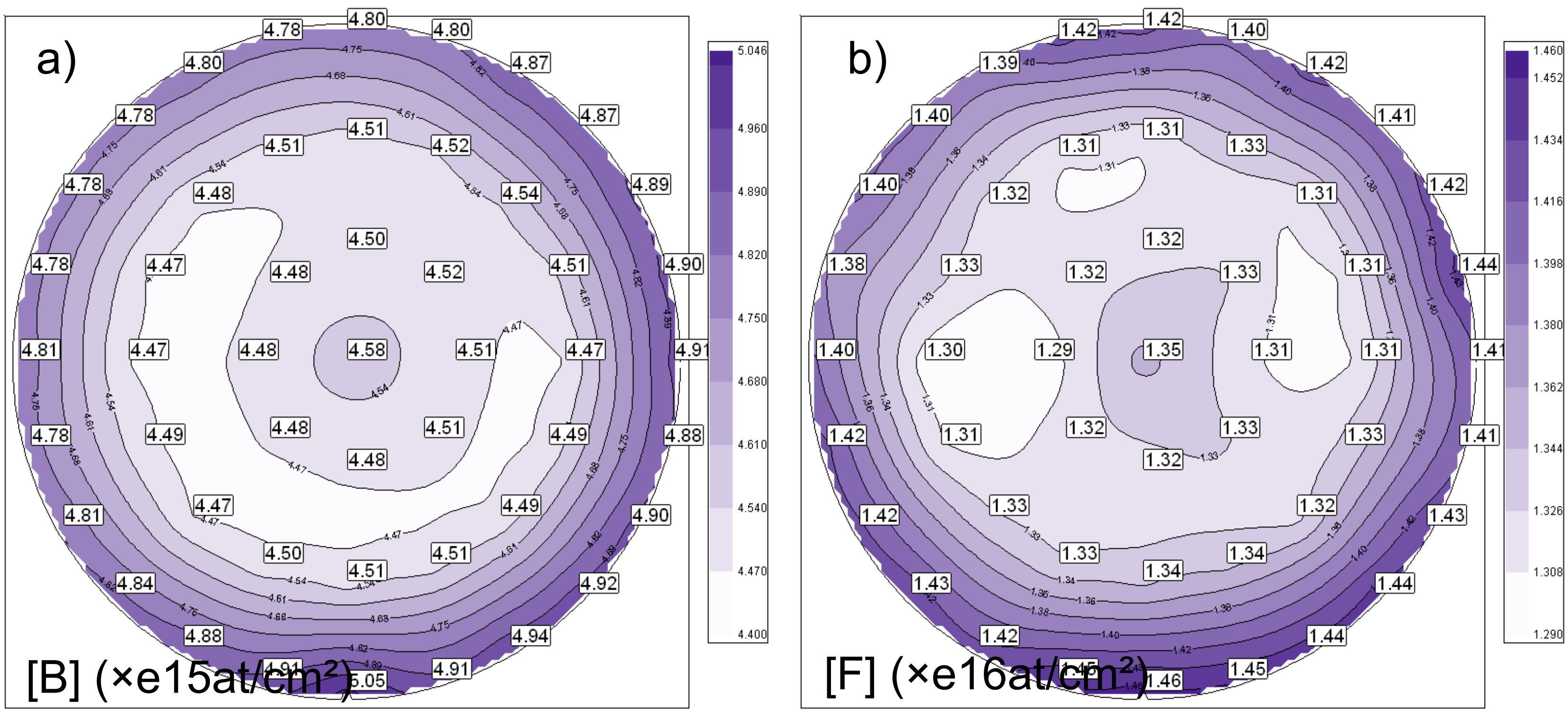
Epitaxial Layers
Ge, P

EX-300: Boron measurements in implants

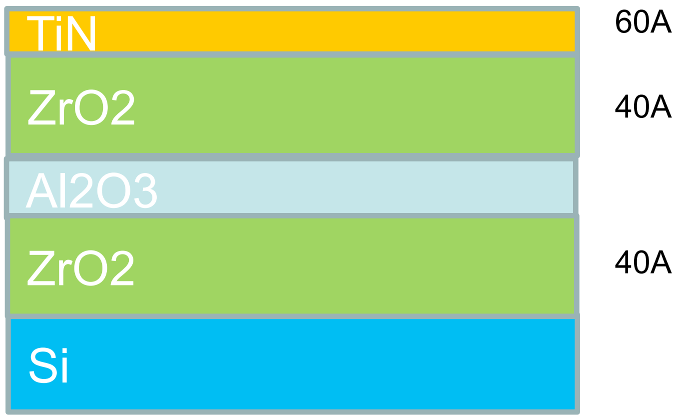
BF3 implants for BPLAD

B average dose 4.6e15 at/cm²	**[B] non-uniformity** 4.04 %
F average dose 1.38e16 at/cm²	**[F] non-uniformity** 3.88 %
Average ratio F/B	3

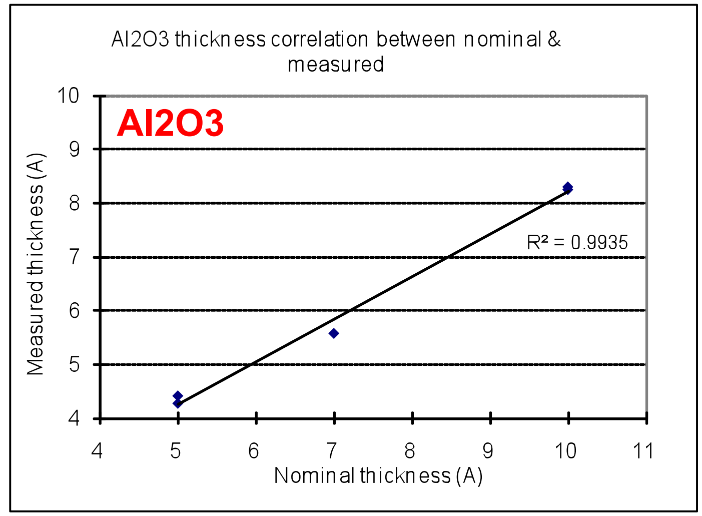
49-points mapping for BF_3 wafer



EX-300: Metal and Multi-oxide layers monitoring



Nominal thickness and SP measurement for all layers w/ or w/o TiN



5 wafers analyzed and all elements Ti, N, Zr and Al have been monitored to follow-up process variation in buried Al_2O_3 layer

Layers parameter and variation among wafers
Shallow Probe precision better than 1% for all parameters

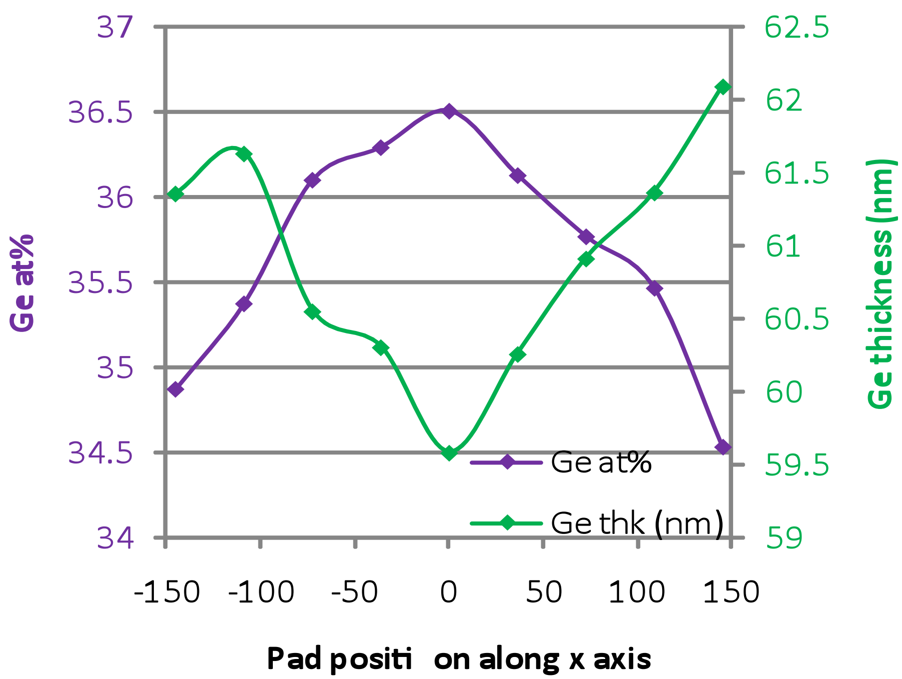
TiN thickness	TiN Ratio	ZrO2 thickness
57.8 A 1.5% variation among wafers	1.29 2% variation among wafers	81.9 A 1.2 % variation among wafers

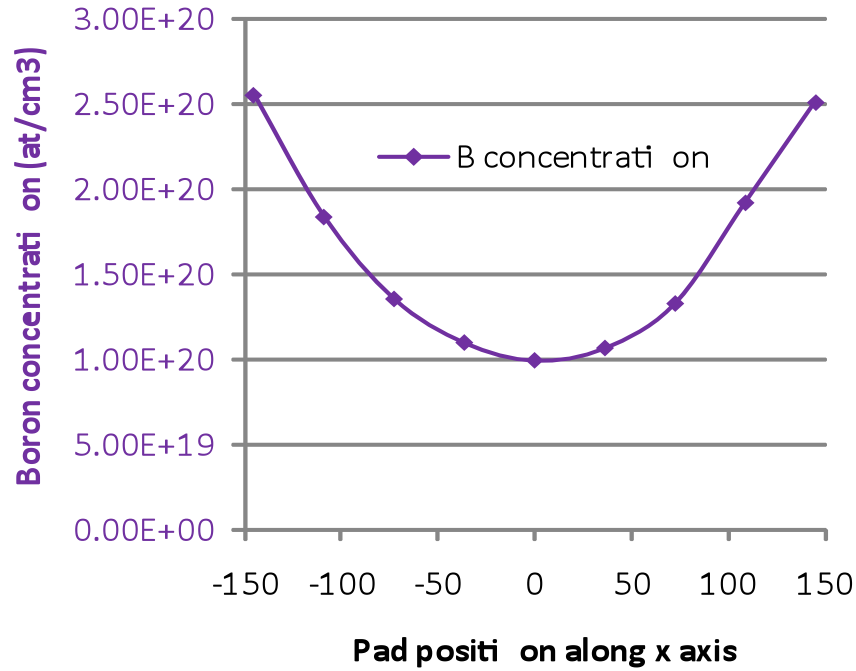
Epitaxial -layers

B and Ge in B: SiGe CVD wafers

Global non-uniformity across 300 mm wafers

Each measurement performed in a pad (60 by 60 µm)





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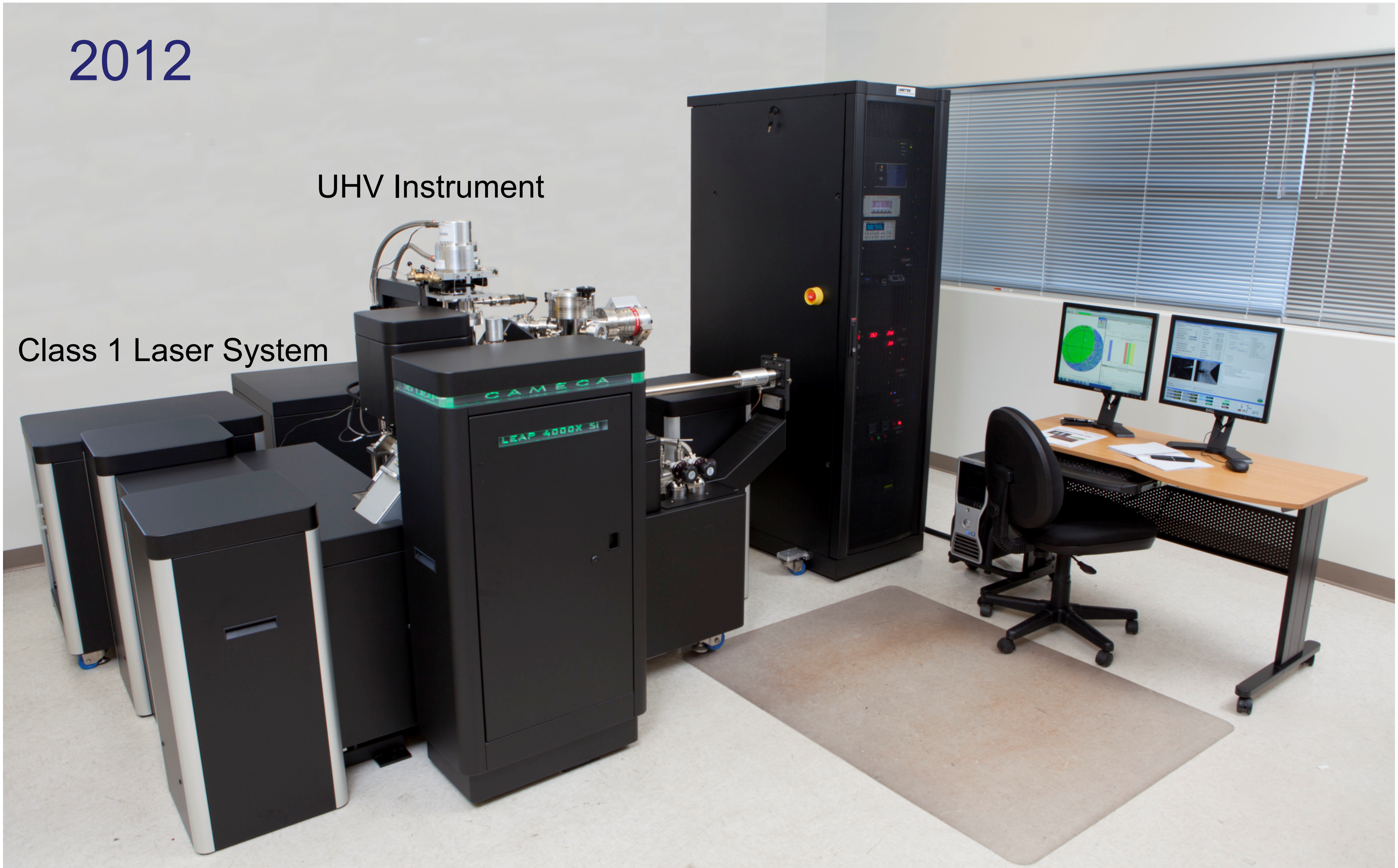
Several CAMECA Product Lines Have Been Optimized for Semiconductor Applications

LEAP (Local-Electrode Atom Probe) 4000X Si

- The ***LEAP 4000X Si***^{TM} is a high performance 3D Atom Probe microscope providing Nano-Scale surface, bulk and interfacial materials analysis of simple and complex structures with atom-by-atom identification and **unique spatial positioning data**.
- Atom Probe Tomography (APT) is the only material analysis technique offering extensive capabilities for **BOTH** 3D imaging and chemical composition measurements at the atomic scale (~ 0.1-0.3 nm resolution depth and ~ 0.3-0.5 nm laterally).
- The system works by using the principle of field evaporation, whereby a strong electric field applied to the specimen is sufficient to cause removal of atoms by ionization. Atom removal is triggered either via a voltage or laser pulse applied to the sample.
- APT adoption is now well underway in both Memory and Logic application spaces.

The LEAP 4000X-Si



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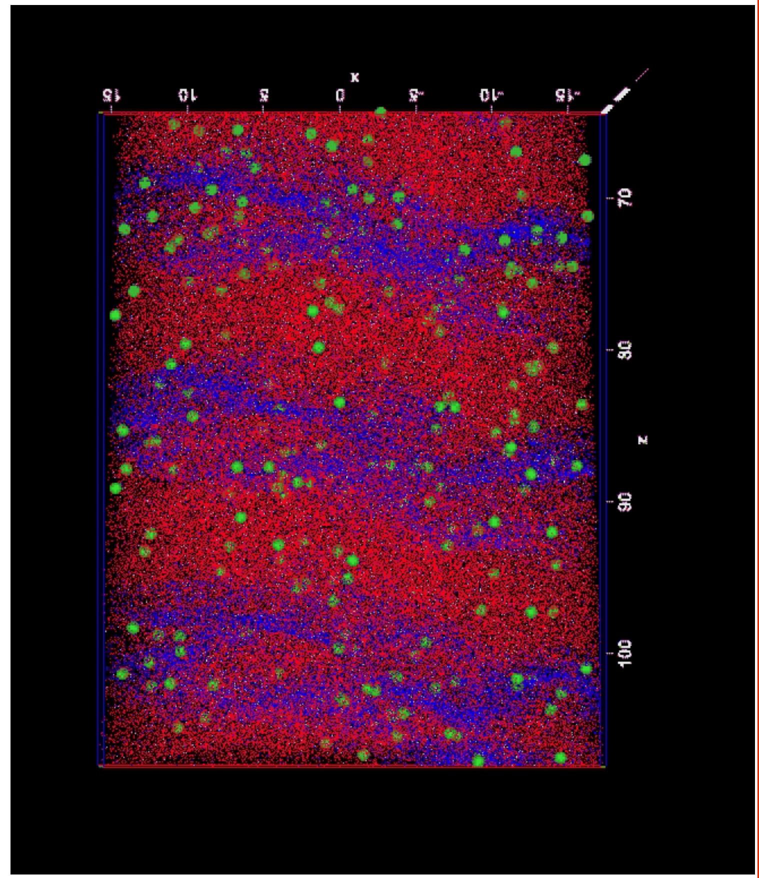
Description of an Atom Probe

- A <u>projection microscope</u> that uses <u>time-of-flight spectroscopy</u> to identify single atoms or small molecular fragments

Key Facts

- Specimen held at ~50K
- Time of flight, t, gives m/n
- Charge state, n, can be 1 to 4
- Flight times ~1 μs (⇨1MHz repetition rate)
- Pulsed field evaporation (δt<1 ns)
  - Field pulsing
  - Thermal pulsing (laser)
- Projection magnification ~10^6X
  - 0.2 nm ⇨ 0.2 mm at detector
- 100% ionization
- 55% detection efficiency independent of m/n



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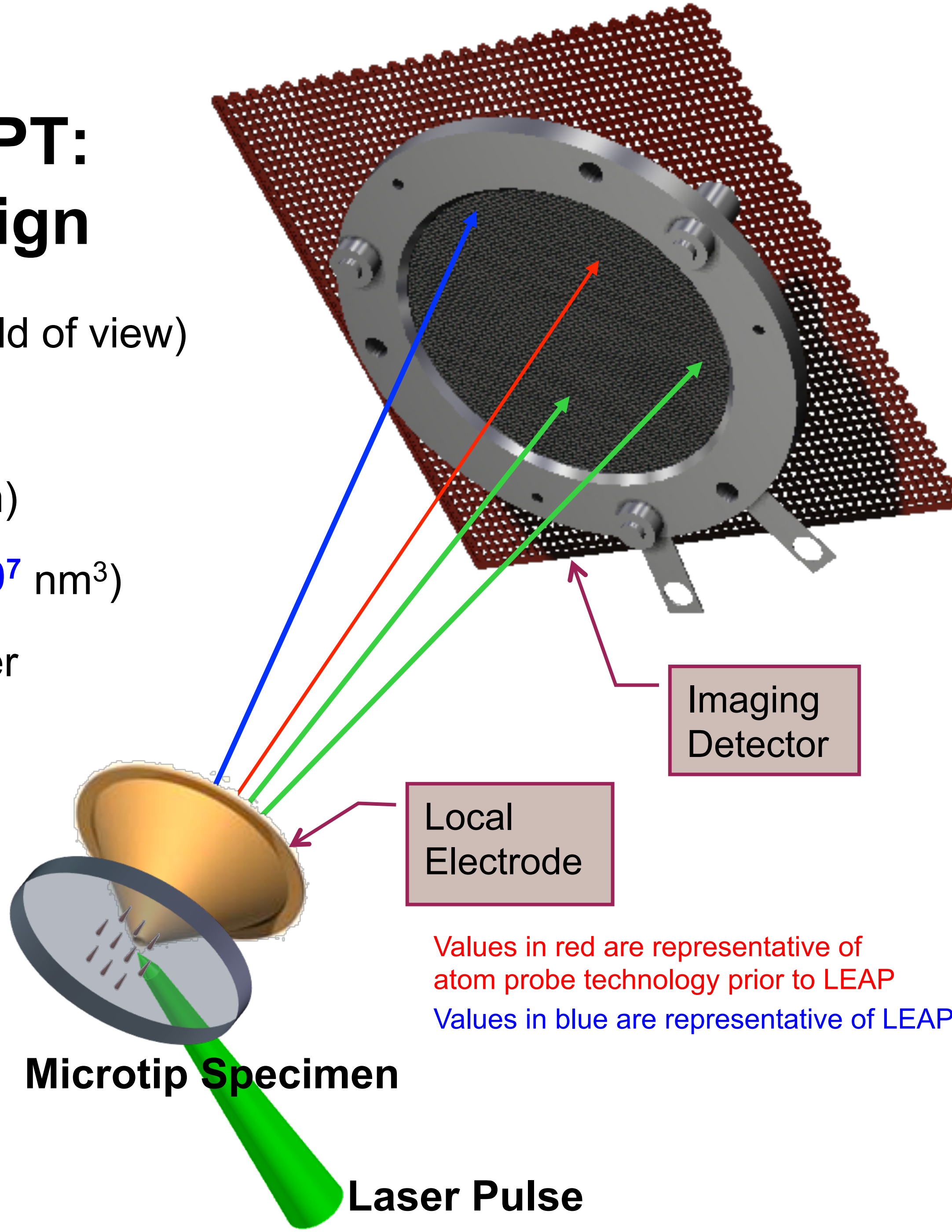
Revolution in APT: LEAP™ Design

1. Large Solid Angle (>150 nm field of view)
2. High speed (>10^8 atoms/hour)
   - High sensitivity (~1 appm)
   - Large analyzed volume (10^7 nm^3)
3. Very good mass resolving power
   - Better than 1000
   - Field and laser pulsing
4. Works on microtip arrays (50 µm tall)
   - Specimen prep simplified
   - Specimen lift out facilitated



Values in red are representative of atom probe technology prior to LEAP
Values in blue are representative of LEAP

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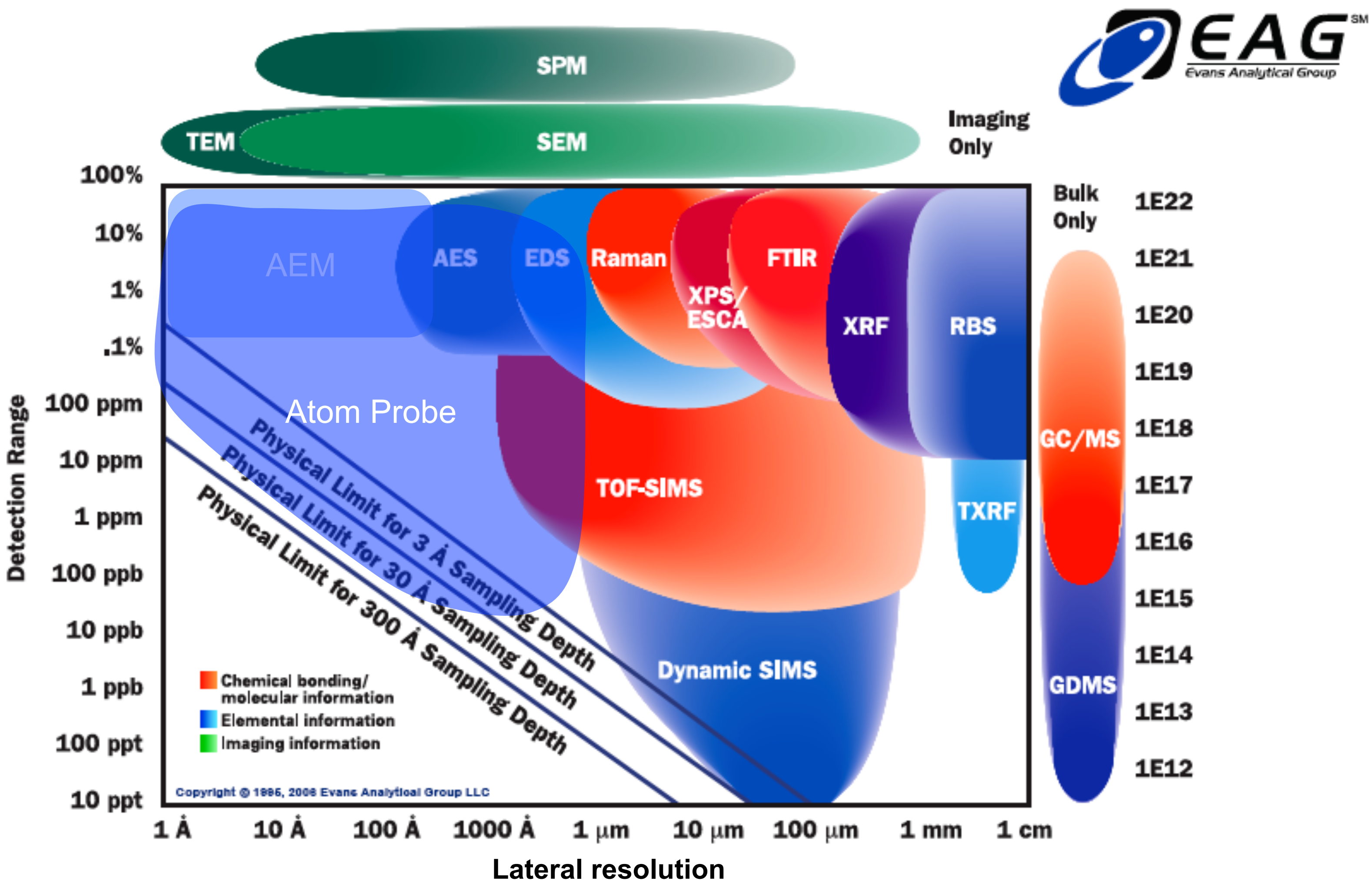
The Atom Probe provides unique Analysis Capability



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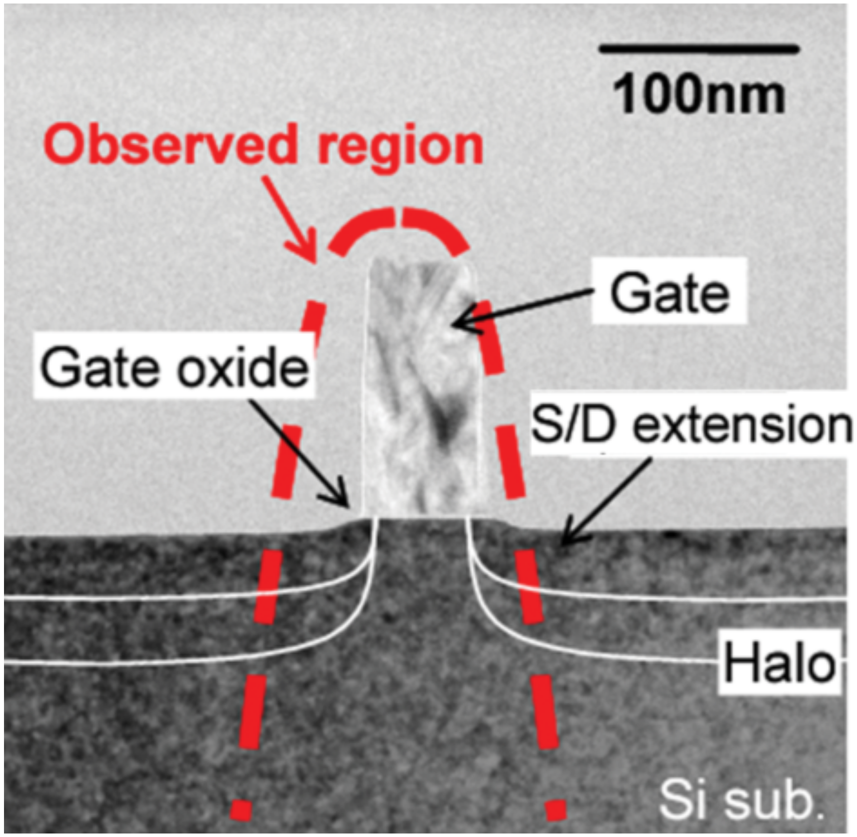
LEAP Capable of Analyzing Device Structures

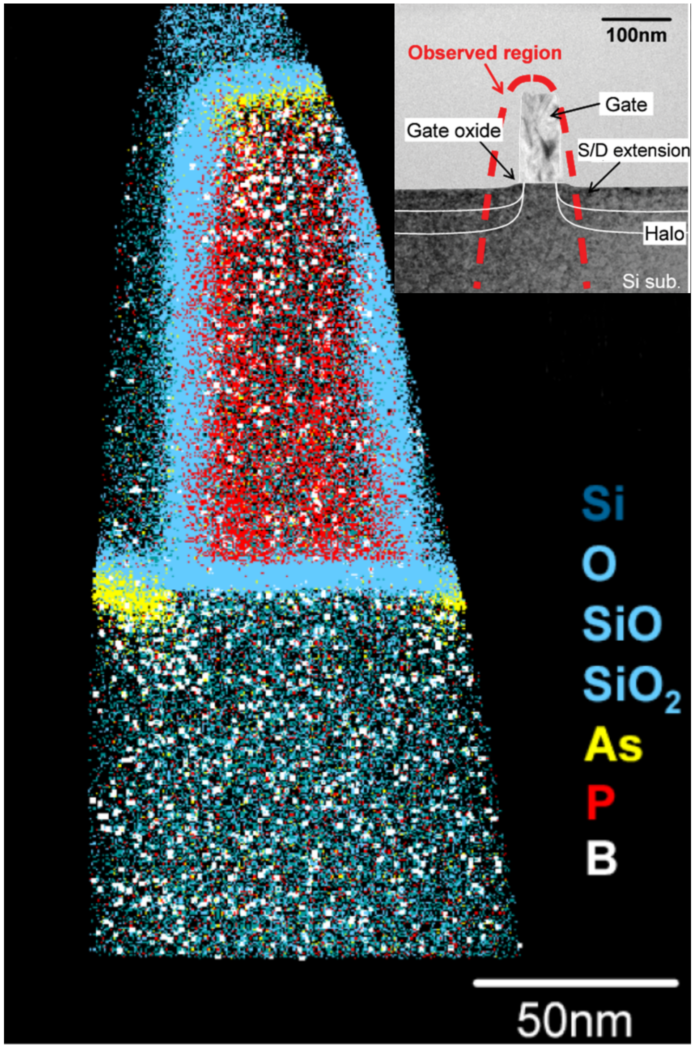
- This (and the following two slides) show published literature examples of both planar and post-planar device structure analysis.
- One significant goal in the application of LEAP to microelectronic structures has been the analysis of devices, especially the entire device structure, not just a small portion of a device.
- The confluence of the downscaling of devices (and the reduction of source/drain junction depths to avoid short channel effects) and the increased field of view now available in modern atom probes now makes the analysis of entire device structures a reality
- Several researchers have used LEAP in the analysis of portions of device patterned structures[1-3] and more recently three have succeeded in analyzing entire devices[4-6]
- Two examples of such device analysis, from a standard transistor and from a fin-style transistor are presented here



1. Moore, J. S., 3-D Analysis of Semiconductor Dopant Distributions in a Patterned Structure using LEAP. *Ultramicroscopy* **2008,** *108*, 536–539.
2. Inoue, K., Monolayer Segregation of As Atoms at the Interface between Gate-Oxide and Si Substrate in a p-MOSFET by 3D Atom-Probe Technique. *Appl. Phys. Letters* **2008,** *92*, 103506/1-3.
3. Inoue, K., Dopant distribution in gate electrode of n- and p-type metal-oxidesemiconductor field effect transistor by laser-assisted atom probe. *Applied Physics Letters* **2009,** *95*, 043502.
4. Inoue, K., Dopant distributions in n-MOSFET structure observed by three dimensional atom probe microscopy. *Ultramicroscopy* **2009,** *109* (12), 1479-1484.
5. Kambham, A. K., Atom-Probe for FinFET dopant Characterization. *Ultramicroscopy* **2010,** *in press*.
6. Lauhon, L. J., Atom-Probe Tomography of Semiconductor Materials and Device Structures. *MRS Bulletin* **2009,** *34* (10), 738-743.

LEAP Analysis of Device Structures – Cont'd

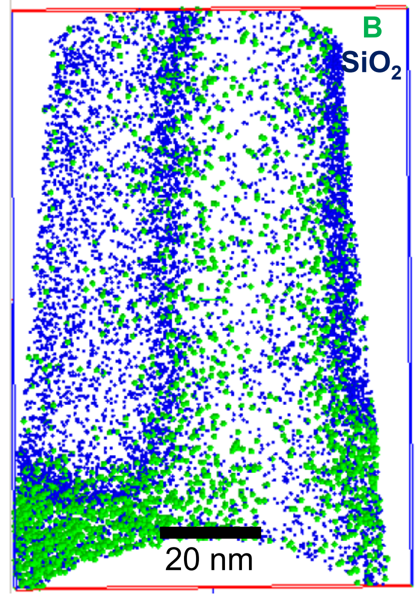
- Inoue et al.[1] have investigated 3D dopant distributions in an n-MOSFET
- Regions of the device analyzed include the gate, gate oxide, channel, source/drain extension, and halo,
  - The atom map to the right shows the data set along with a TEM image of the analyzed region of the transistor (inset)
- Arsenic atoms are visible in the source/drain extension and on top of the gate electrode
  - The As concentration in the source/drain extension was $2x10^{21}$ cm^{-3} with As atoms being detected to a depth of ~10nm from the implanted Si surface
- B atoms can be seen in the Si substrate (channel and halo extension regions),
  - The boron concentration in the channel region was measured to be $1x10^{18}$ cm^{-3}
- P atoms were segregated on the grain boundaries of the poly-Si gate and at the interface between the gate and gate oxide
  - Phosphorus concentration at poly-Si grain boundaries were measured to be $5x10^{20}$ cm^{-3}
  - Phosphorous concentration at the gate/gate oxide was measured to be $2x10^{21}$ cm^{-3}

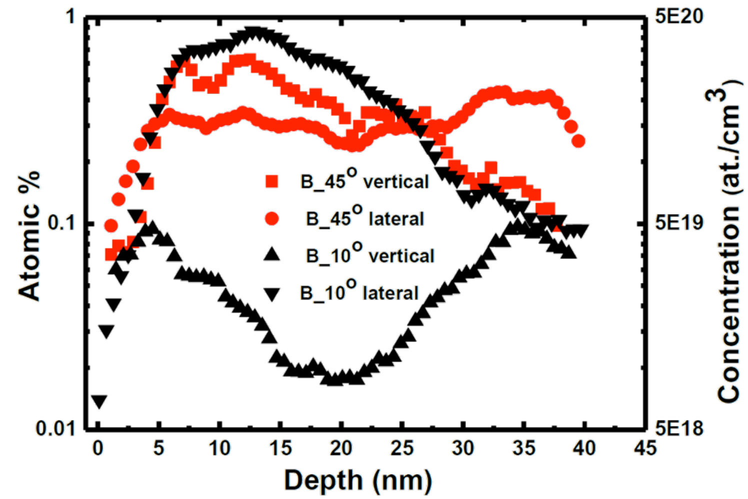


1. Inoue, K., Dopant distributions in n-MOSFET structure observed by three dimensional atom probe microscopy. *Ultramicroscopy* **2009,** *109* (12), 1479-1484.

LEAP Analysis of Device Structures – Cont'd

- In fin-transistors (FINFETs), device performance is reduced if an inhomogeneous distribution of dopants exists in the source/ drain extensions
- Recently, Kambham et al.[1] have analyzed the conformality of boron (BF_2) implantation in FINFET structures as a function of implantation angle (10° and 45°)
- An atom map from the FINFET implanted with B at 10° (top, right) qualitatively shows B pile-up at the sidewall surface
- The sidewall and top doping profiles were obtained from both sample types and plotted for comparison (bottom, right)[1]
  - For the 45° implantation the top (vertical) peak concentration is twice as compared to lateral profile peak concentration
  - In the 10° implantation, the dopants are shallower and significantly reduced in concentration; the result is a high non-conformality of the dopants with the sidewall dose only being 10% of the top dose
- These observations were compared favorably with modeling results from Vandervorst et al.[2]





1. Kambham, A. K., Atom-Probe for FinFET dopant Characterization. *Ultramicroscopy* **2010,** *in press*.
2. Vandervorst, W., *Journal of Vacuum Science & Technology B* **2008,** *26*, 396.

Thank You!