High Resolution Secondary Ion Mass Spectroscopy (SIMS) for Characterization

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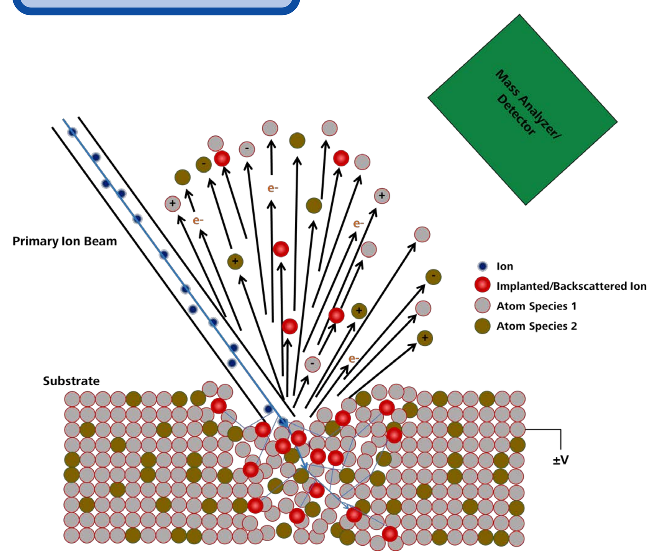
Introduction

Focused helium and neon beams created with the ZEISS ORION NanoFab Gas Field Ion Source (GFIS) have been used in several semiconductor applications including patterning, nanofabrication, and characterization[1-2]. The helium beam is ideal for high resolution imaging with its < 0.5 nm probe size[3]. The neon beam, with a probe size < 2 nm and sputter rate of around 20 times that of helium, is well suited for precise material modification at the nanoscale.[4]

The precise nature of the focused beam makes the GFIS an attractive option for use in high-resolution dynamic SIMS. Conventional dynamic SIMS instruments have demonstrated ultimate lateral resolution of ~50 nm. This resolution is primarily limited by the focused probe size of the primary beam. In contrast, with a Ne^+ probe size of 1.9 nm, the resolution of the SIMS information produced by the ZEISS ORION NanoFab is limited only by beam-sample interactions. As such, the chemical characterization of nanomaterials has the potential to be performed at an unprecedented level. Here we introduce a magnetic spectrometer for semiconductor characterization.

SIMS Basics



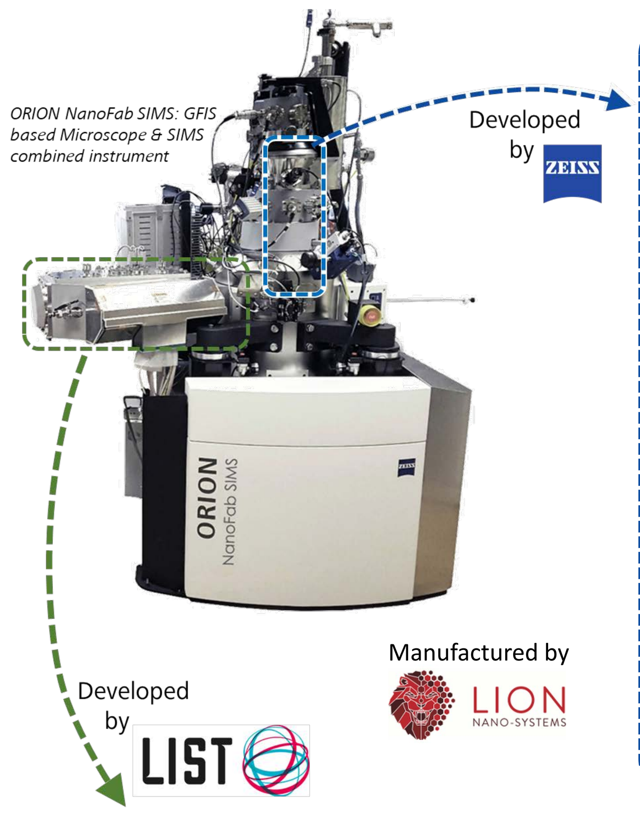
Dynamic Secondary Ion Mass Spectroscopy (SIMS) is performed using a focused energetic ion beam

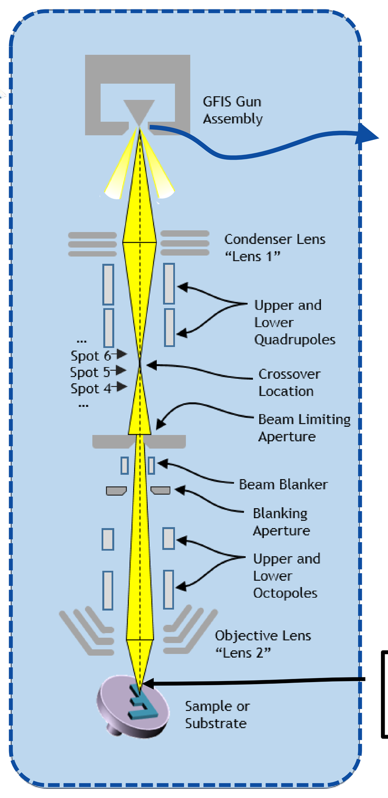
- The bombarding primary beam will sputter particles from the target material
- A certain fraction (Useful Yield) of the sputtered particles are positively or negatively ionized
  - The ionization efficiency is material and matrix dependent
- During bombardment, the produced secondary ions are collected and mass separated to obtain chemical information about the sample

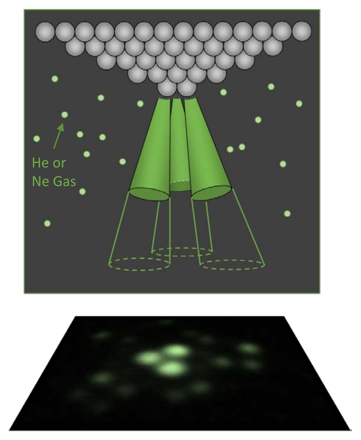
In our case, the primary beam is Ne^+ produced via our GFIS column in the NanoFab

Spectrometer Design

In a joint development between ZEISS, the Luxembourg Institute of Science and Technology, and Luxembourg Ion Optical Nano-Systems, a dynamic SIMS instrument was constructed and mounted on the ZEISS ORION NanoFab[5]. Feasibility and testing of fundamentals was conducted in 2012. LIST addressed the instrumental aspects, focusing in particular on appropriate extraction optics providing a high extraction efficiency while minimizing the effect on the primary ion beam[6], coupled to an in-house developed double focusing magnetic sector mass spectrometer.

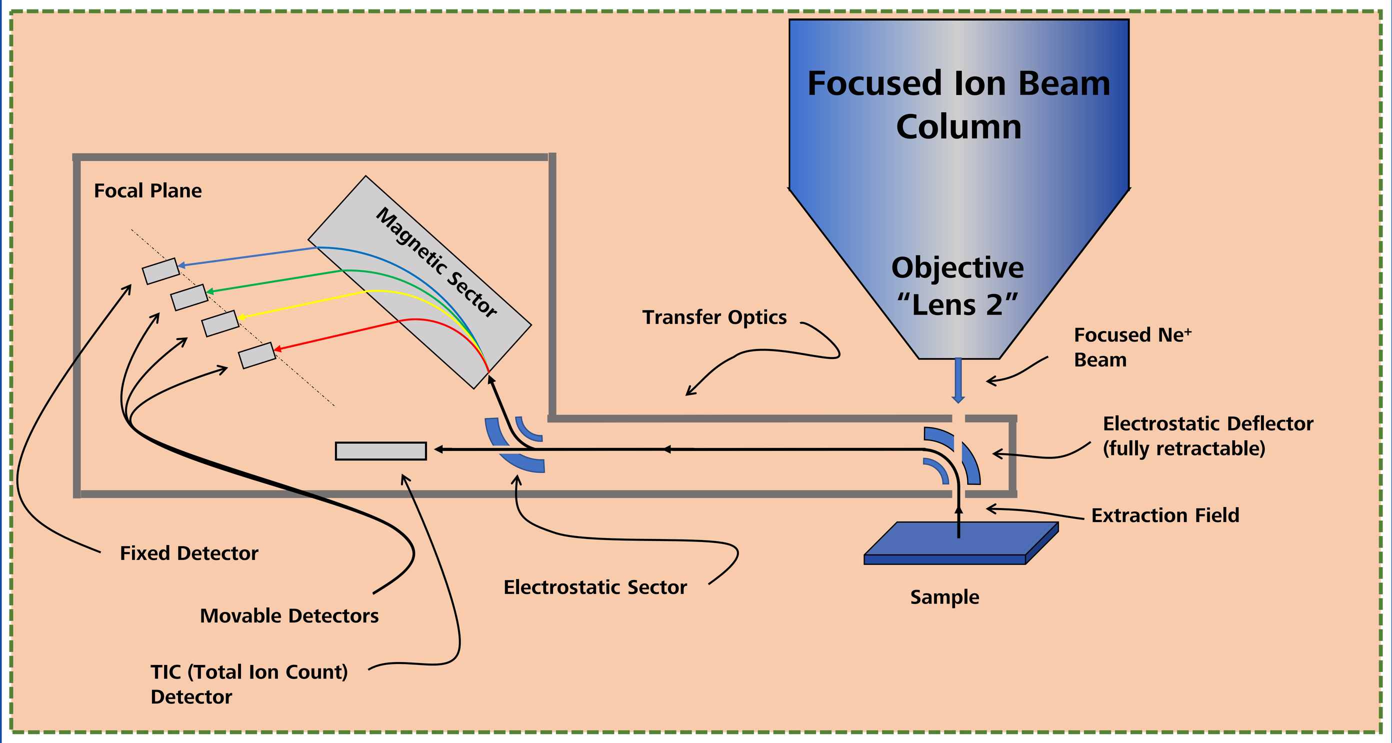






The Gas Field Ion Source (GFIS) generates a probe from a single atom, producing a high brightness, monochromatic, low diffraction ion beam.

He^+ probe size 0.5 nm
Ne^+ probe size 1.9 nm



Notable Specifications:

- Fully retractable extractor
- Double focusing magnetic sector (Mattauch-Herzog design)
- Bipolar fields for detecting both positive and negative ions with minimal re-alignment
- Transmission efficiency: 40%
- 1 TIC detector, 1 fixed detector, and 3 moveable detectors
- Mass resolution (M/ΔM) is 400
- m/z ratio is 1 to 500

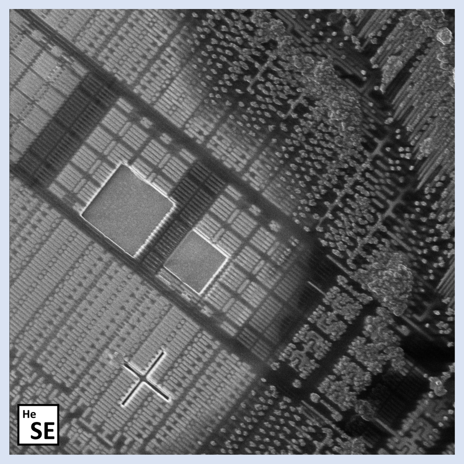
References

[1] Hlawacek, G.; Gölzhäuser, A., Helium Ion Microscopy. Springer: 2016.
[2] Stanford, M. G.; Lewis, B. B.; Mahady, K.; Fowlkes, J. D.; Rack, P. D., Review Article: Advanced nanoscale patterning and material synthesis with gas field helium and neon ion beams. JVST B 2017, 35 (3), 030802.
[3] Ward, B.; Notte, J. A.; Economou, N., Helium ion microscope: A new tool for nanoscale microscopy and metrology. JVST B 2006, 24 (6), 2871-2874.
[4] Tan, S.; Livengood, R.; Shima, D.; Notte, J.; McVey, S., Gas field ion source and liquid metal ion source charged particle material interaction study for semiconductor nanomachining applications. JVST B 2010, 28 (6), C6F15-C6F21
[5] Wirtz, T.; Dowsett, D.; Philipp, P., SIMS on the Helium Ion Microscope: a Powerful Tool for High-Resolution High-Sensitivity Nano-Analytics. In Helium Ion Microscopy, Springer: 2016; pp 297-323.
[6] T. Wirtz, N. Vanhove, L. Pillatsch, D. Dowsett, S. Sijbrandij, J. Notte, Appl. Phys. Lett. 101 (4) (2012) 041601-1-041601-5
[7] Vollnhals, F., J.-N. Audinot, T. Wirtz, M. Mercier-Bonin, I. Fourquaux, B. Schroeppel, U. Kraushaar, V. Lev-Ram, M. H. Ellisman and S. Eswara (2017). "Correlative microscopy combining secondary ion mass spectrometry and electron microscopy: comparison of intensity–hue–saturation and Laplacian pyramid methods for image fusion." Analytical chemistry 89(20): 10702-10710.

Workflow Examples

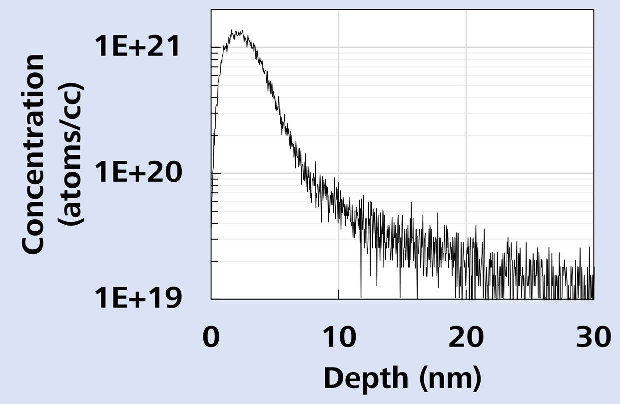
The combination of SIMS analysis on a high resolution imaging platform allows for many capabilities that can be executed in a variety of sequences or "workflows" depending on the application at hand. The basic capabilities are described herein for an sample which is a partly de-processed finFET device.

SE Imaging



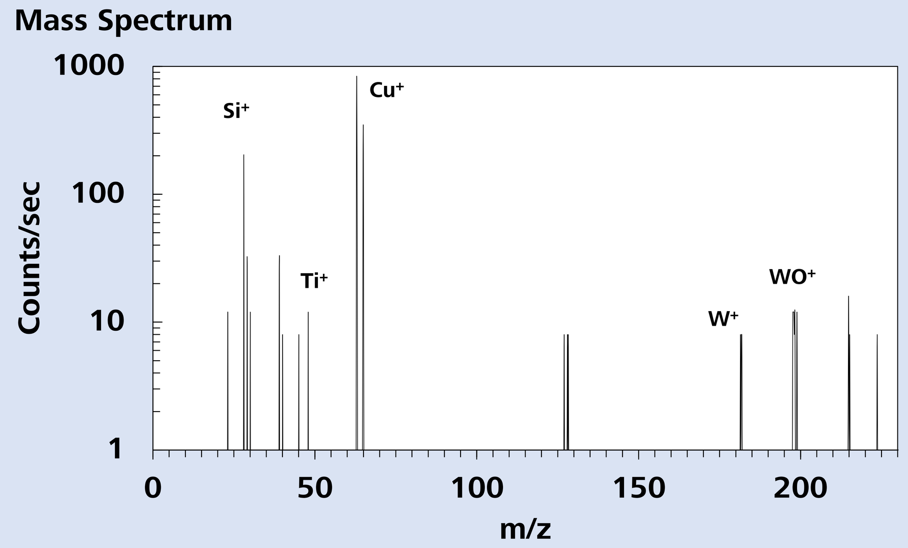
High resolution secondary electron images can be acquired for navigation or to locate a region of interest. Images offer sub-nanometer probe size and surface sensitivity.

Depth Profiling



For applications involving concentration gradients as a function of depth in the sample, the distribution of elements can be visualized as the neon beam sputters collectively over time.

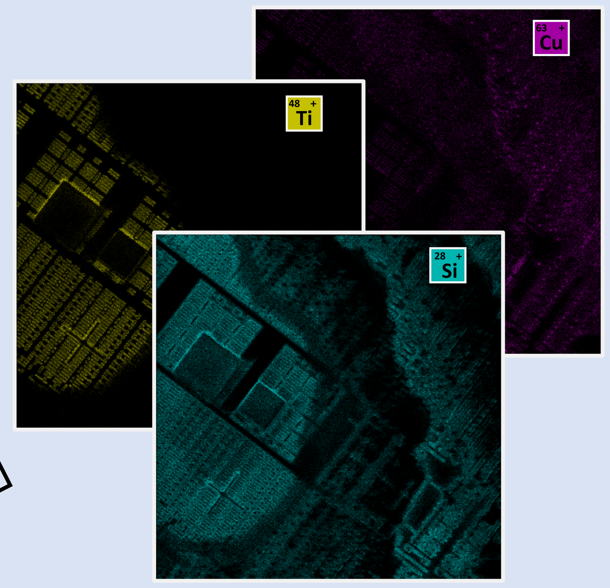
Mass Spectrum

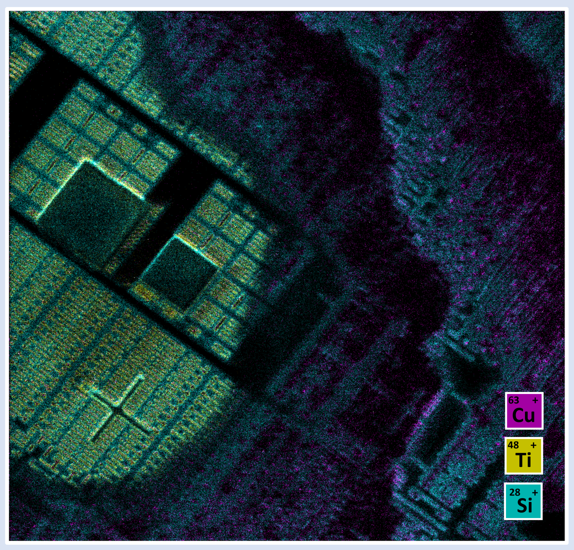


The mass spectra of a sample can be obtained by ramping up the magnetic field while keeping the detector location fixed or, conversely, by sweeping the detectors along the magnetic focal plane via individually actuated piezo motors with a constant magnetic field. In each case the neon beam is responsible for sputtering at the point of interest.

Elemental Imaging / Mapping

The elemental maps shown here were achieved by rastering the primary (neon) beam across the sample, with the detector at a location corresponding to the mass of interest. In this case, the count rate reported by the detector is used to assign a grey level, or color intensity, to each pixel in the image.

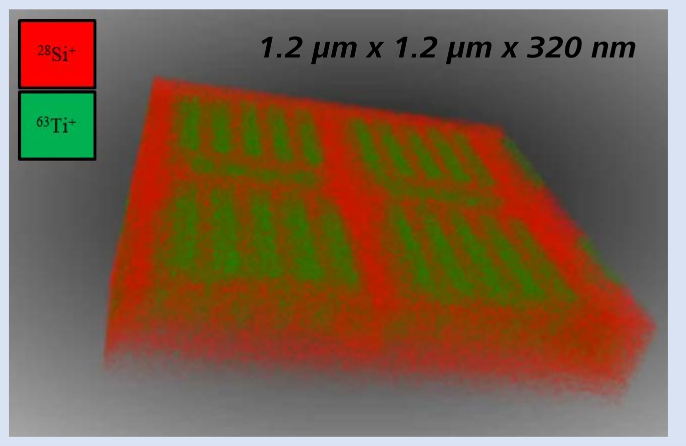




Four detectors can be assigned to individual masses and used simultaneously, enabling the creation of composite images with different elements assigned to different colors for enhanced visualization.

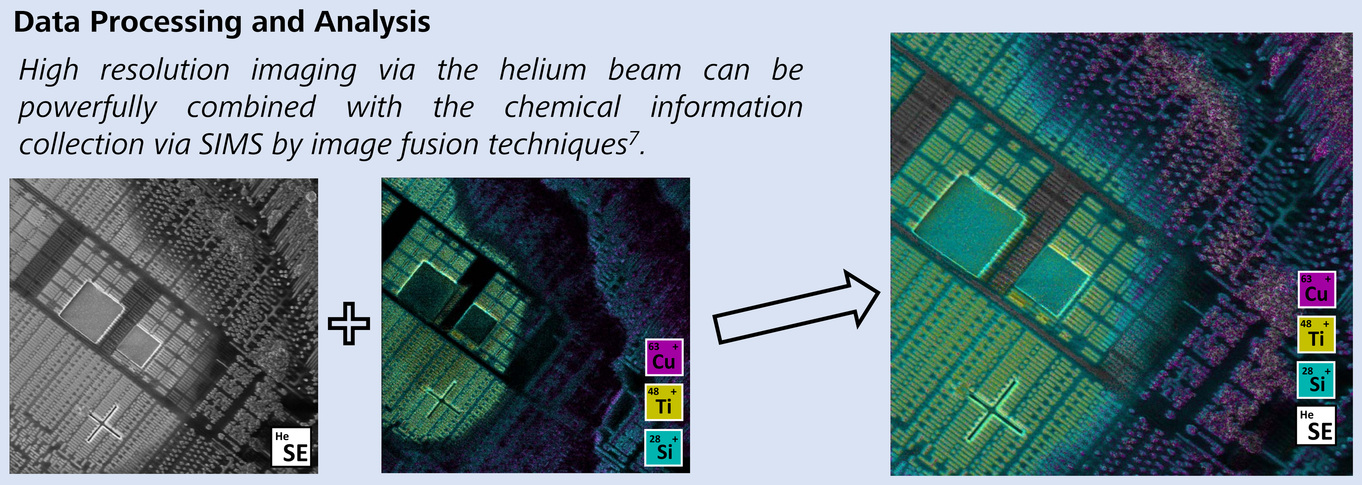
Volumetric Mapping / 3D

Repeated SIMS imaging over a selected area will progressively reveal deeper layers through the sputtering process, thereby providing three-dimensional elemental information. The 3D dataset can then be visually rendered in a variety of ways such as arbitrary cross sectional imaging, segmentation, and by assigning transparency to select elements.

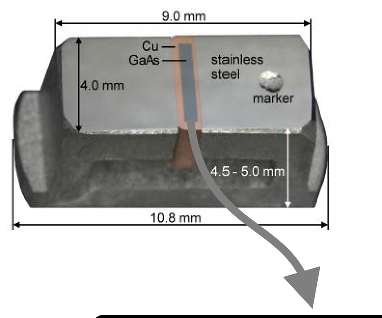


Data Processing and Analysis

High resolution imaging via the helium beam can be powerfully combined with the chemical information collection via SIMS by image fusion techniques[7].

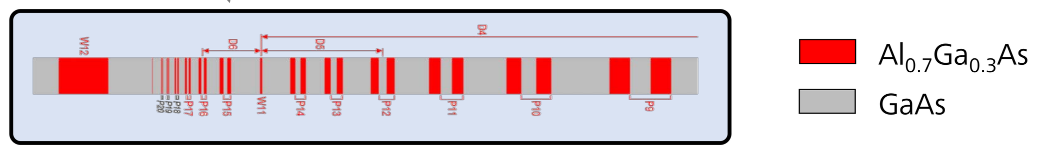


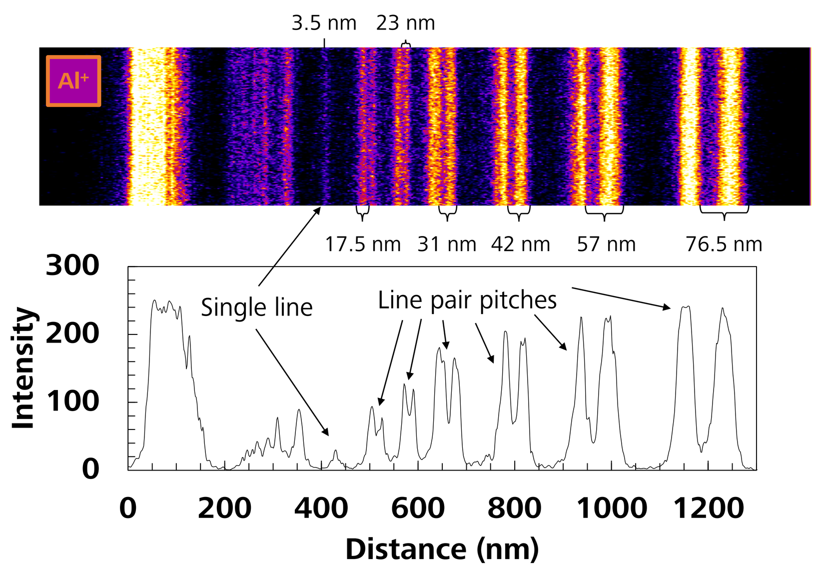
Lateral Resolution



Resolution Standard: To establish the lateral resolution achievable by the NanoFab SIMS instrument, a recognized international standard, the BAM-L200 was chosen

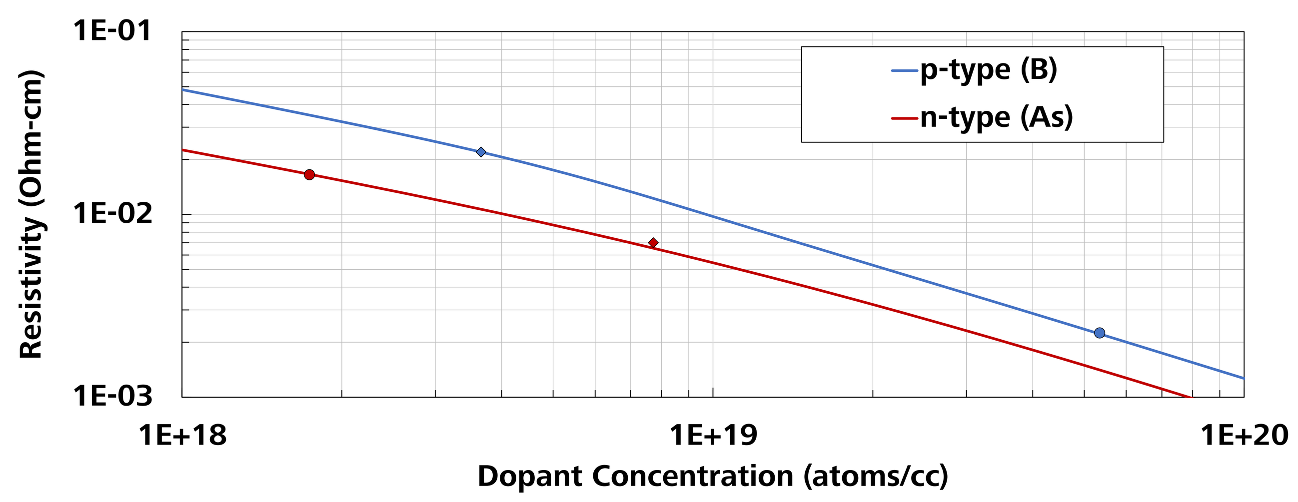
- This sample is a cross section of a stack grown of alternating layers of GaAs and $Al_{0.7}Ga_{0.3}As$
- All layers were grown by metalorganic vapor phase epitaxy, and each layer has had it's thickness measured and certified by TEM





- SIMS Image generated with a 10 keV Ne^+ beam and the spectrometer configured to detect aluminum
- The corresponding line profile through the above image shows the indicated line pairs with their pitch, and a 3.5 nm solitary line
- The lateral spatial resolution of the tool is only limited by the collision cascade of the primary beam, not the focused probe size as in other commercial SIMS instruments

Sensitivity



Dopant	Resistivity (ohm-cm)	Est. Concentrations (PPM)
As	0.006 – 0.008	120.08 – 188.72
B	0.0214 – 0.0225	70.5 – 75.82
B	0.002 – 0.0025	936.2 – 1202.4
As	0.015 – 0.018	29 – 40.52

- Four uniformly doped wafers were analyzed to demonstrate the sensitivity of the NanoFab SIMS
- Resistivity of doped silicon were calculated according to:

$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + \left(\frac{N}{C_r}\right)^{\alpha}} \quad (1)$$

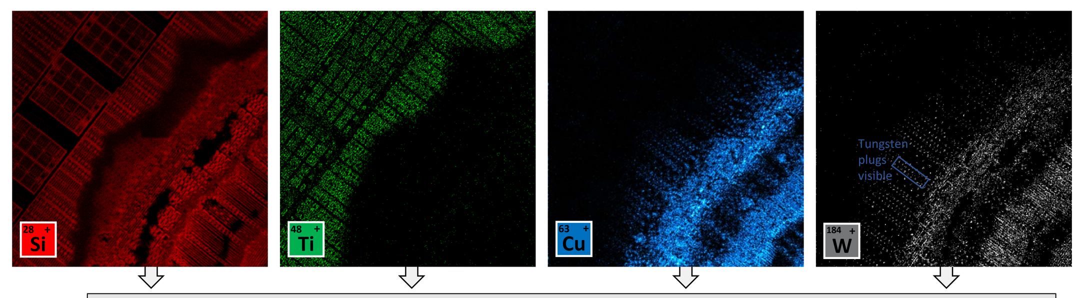
$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} \quad (2)$$

Where: μ_{min}, μ_{max}, α, and C_r are material constants based on the dopant type (B or As in this case). N is the estimated concentration of the dopant. For n-type silicon, electron mobility dominate and for p-type silicon, hole mobility dominates.

- In our case, all dopants were detectable in silicon using a primary ion current of 10 pA with a 5 µm field of view showing a upper limit of better than 75 ppm for boron in silicon and better than 188 ppm for arsenic in silicon

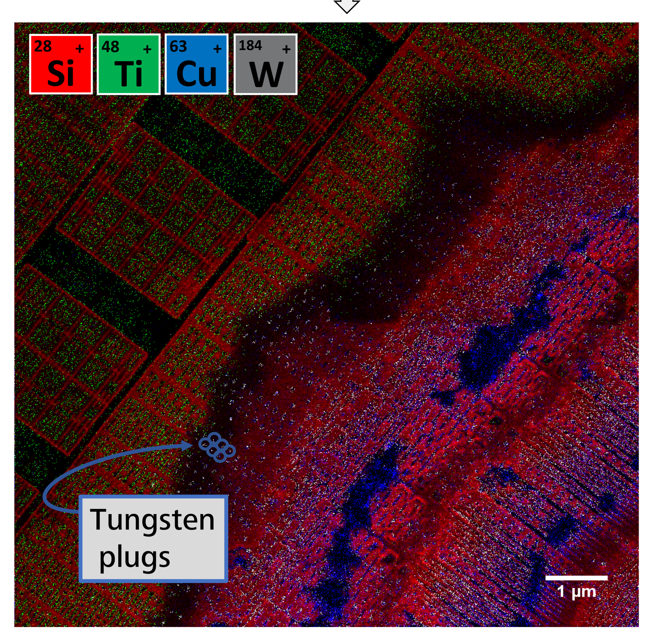
Semiconductor Analysis

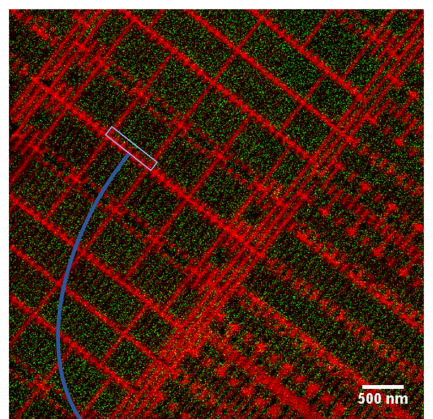
Sample: 22 nm FinFET Device which was de-processed with an Ar^+ beam exposing multiple layers.



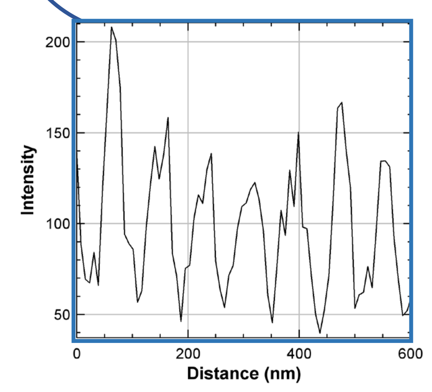
Multiple detectors allow up to four elemental images to be acquired simultaneously

Multiple images are combined into a single multi-element color image.





Higher magnification (smaller pixel size) shows a resolution better than 50 nm.



Line profile extracted from the indicated region of the high magnification image

- Multi element images reveal the relationship between different materials
- SIMS imaging resolves even small features such as tungsten plugs