Helium Ion Microscopy

Peter Gnauck
Technology to cover all scales
Carl Zeiss Microscopy Portfolio

Widefield
Stereo
Confocal
Focused Ion Beam
Superresolution
Scanning Electron
Scanning He-Ion
Transmission Electron
Field Ion Microscope (FIM) Basics
(Erwin Müller in 1955)
The first person to directly see atoms

6. October 11, 1955

The day of October 11, 1955 was a day long to be remembered by those of us who were in the laboratory. Bahadur had built the FIM to re-test the hypothesis that cooling the tip was worthwhile, and had gotten the experiment going. Now, he called Professor Müller into his laboratory room to show him the result. Russell Young and the author shared the room between Bahadur’s room and Müller’s office, and we watched Müller enter Bahadur’s lab and close the door. We waited outside quite anxiously, imagining Müller waiting for his eyes to become dark adapted, in order to see the image, and wondering what Müller’s reaction would be to this long-awaited event.

Inside, Bahadur has related to the author, when Müller saw the low temperature He image, he said something like “This is it!” When Müller emerged from the room, he walked quickly across our lab to his office muttering simply, “Atoms, ja, atoms.” For us, it was a time of unprecedented awe and joy; we thought that a Nobel Prize for Müller was shortly forthcoming. After all, Müller’s microscope now made it possible to see atoms.

First direct observation of atoms by Müller
October 11, 1955

E. W. Müller, J. Appl. Phys. 27, 474 (1956)
Unsharpened Orion Helium Ion Source
and Its FIM Image

Unsharpened tip

He(+) +30 kV

Unsharpened Orion Helium Ion Source
and Its FIM Image
The Field Ion Microscope (FIM) and the Gas Field Ion Source (GFIS)
Final Helium Ion Source
3 Atom Cluster - And Associated FIM Image

Sharpened tip
Current / Voltage Properties of the Gas Field Ion Source
Source Technologies

Focused Ion Beam
- Probe Size: ~5nm
- Brightness: \( \sim 3 \times 10^6 \text{ A/cm}^2 \cdot \text{sr} \)

Scanning Electron Microscope
- Probe Size: ~0.8nm
- Brightness: \( \sim 5 \times 10^8 \text{ A/cm}^2 \cdot \text{sr} \)

Helium Ion Microscope
- Probe Size: ~0.35nm
- Brightness: \( \sim 5 \times 10^9 \text{ A/cm}^2 \cdot \text{sr} \)

Scanning probe with the highest brightness and smallest probe size
Benefits of GFIS – Resolution and Probe Size

Graph showing the relationship between beam energy (eV) and wavelength (pm) for Electron Beam and Helium Ion Beam.
Helium Ion Microscope – Current Status

Momentum building…
- User base growing (25 installed systems)
- Over 100 publications with HIM and chapters in 3 microscopy books
- Dedicated HIM sessions at major conferences (M&M, EIPBN, AVS)
The ORION NanoFab Platform

- **3D Nanofabrication** of sub-10nm structures.
- **High Resolution Imaging** (0.35nm) ideal for nanoscale research.
- **Precise Machining** with He/Ne beams and **Rapid Prototyping** with Ga beam – only platform offering unique combination of ion beams.
- **Configurable** architecture to address specific imaging and nanofabrication applications.
Benefits:
- High Resolution (0.35nm)
- No Charging Artifacts
- Large Depth of Field

Imaging with helium ions

Pd catalyst grown on ZnO nanowires
Surface Sensitivity

CASINO simulation
1keV electrons
1nm diameter beam
Si substrate

TRIM simulation
30keV He+
Point beam
Si substrate

SEM images are produced by SE1 and SE2 electrons while the HIM image is primarily due to SE1 electrons.
Coated AuC (big Au islands)

sample courtesy of Al Lysse, Carl Zeiss SMT Inc., US
Coated AuC (big Au islands)

- good SNR
- high contrast between Au and C

...surface details that could not be seen become visible

- high surface sensitivity

SEM @ 15 kV

ORION @ 30 kV

www.zeiss.com
Self Assembled Monolayer of 4-nitro-1,1-biphenyl-4-thiol (NBPT) exposed with E-beam Lithography which modifies the terminal group from NO$_2$ (dark grey) to NH$_2$ (light grey)

Sample courtesy of University of Bielefeld
Hydroxyapatite grown on PLLA Fibers

HIM image of Hydroxyapatite grown on Poly (L-Lactide) spun fibers. PLLA acts as a scaffold for growing Hydroxyapatite which is bone mineral. Inset image shows Hydroxyapatite nucleation sites at high resolution.

**HIM Advantages**
- High resolution imaging of charging materials without the use of conductive coating or gas.
- Details on fiber surface clearly visible.
- Large depth of field keeps all of field of view in focus.
- Beam sensitive material like PLLA and Hydroxyapatite can be observed without damage which is difficult to achieve at high resolution in FESEM.
High Resolution Imaging

- Imaging tip links between Stereocilia in the inner ear
- Can accurately measure the diameter of the tip links without coating

Stereocilia in the Inner Ear

Sample courtesy of NIH
Resist lines after development. The materials is Si-CH3 enriched MSQ polymer. The SEM images were of limited value due to charging artifacts.
Ion Beam Milling
Technology Comparison • Ga FIB vs. Helium Ion Beam

* Courtesy: Dan Pickard, NUS
Ion Beam Milling
Application • *Plasmon Response with Nanostructure Miniaturization*

**EELS Response**
Electron energy loss spectroscopy allows nanometer scale spatially resolved visualization of plasmon modes at nanostructures

Evolution of plasmon modes at different energies as structure is made smaller

* Courtesy: Dan Pickard, NUS

Electron Energy

50 nm

0.5  1.0  1.5  2.0  2.5 eV

Shrinking Nanostructure
Benefits:
- Nanofabrication (<10nm)
- Minimal Lateral Damage

Machining with helium ions

TEM Image
Ion Beam Milling
Application • DNA Transistor at IBM

<table>
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<tr>
<th>Research Area</th>
<th>DNA sequencing</th>
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<td>Challenge</td>
<td>How to make 5 nm holes in 7 layer metal-dielectric sandwich film?</td>
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<tr>
<td>Conventional Method</td>
<td>TEM at high energy</td>
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Zeiss Solution
Helium Ion Beam Milling, 400X faster

- 15s to drill a single hole (400X faster than TEM).
- Hole uniformity much better than any other technique (± 1 nm variability).
Nano Structuring
Early results Lithography (SHIBL)

Experiment
- Lines written in HSQ resist

Results
- 6.5 nm lines created
- Line width is independent of pitch – No proximity effect!
- Dot exposures also free of cross-talk
Early Neon Results

Si sputtering

Neon ion beam sputters Si more effectively than He and has better machining fidelity than Ga

Thinned section

Material removal with Ne on sample backside followed by imaging with He.

Cross section

Polishing of sample frontside with Ne followed by imaging with He.
Helium Ion Microscope for NanoFabrication: Direct Sputtering by Neon

Finely sputtered lines in thin metal coatings reveal the fidelity of the neon beam. Imaging type analysis suggests a probe size of ~2 nm.

We make it visible.