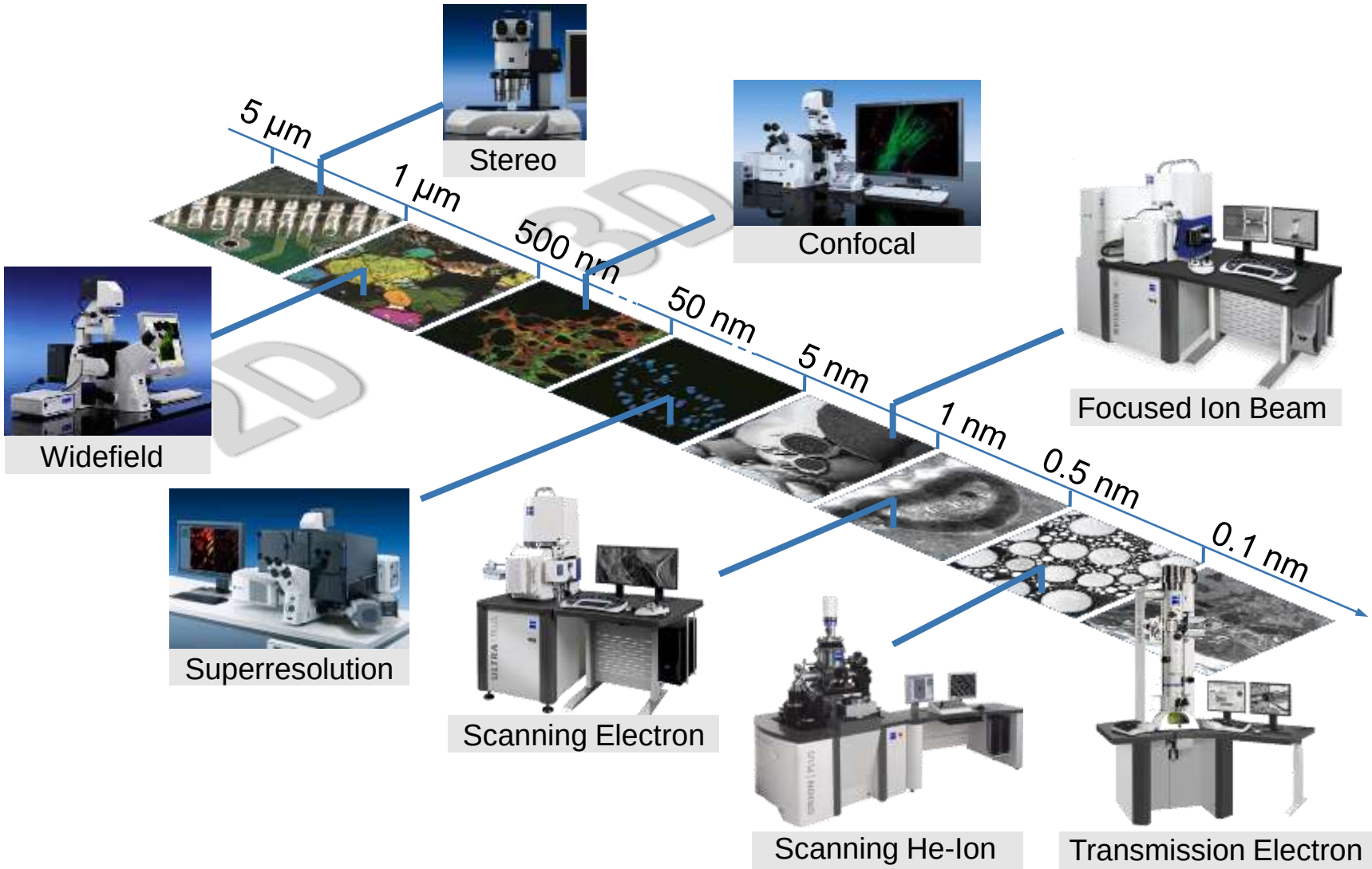
Helium Ion Microscopy

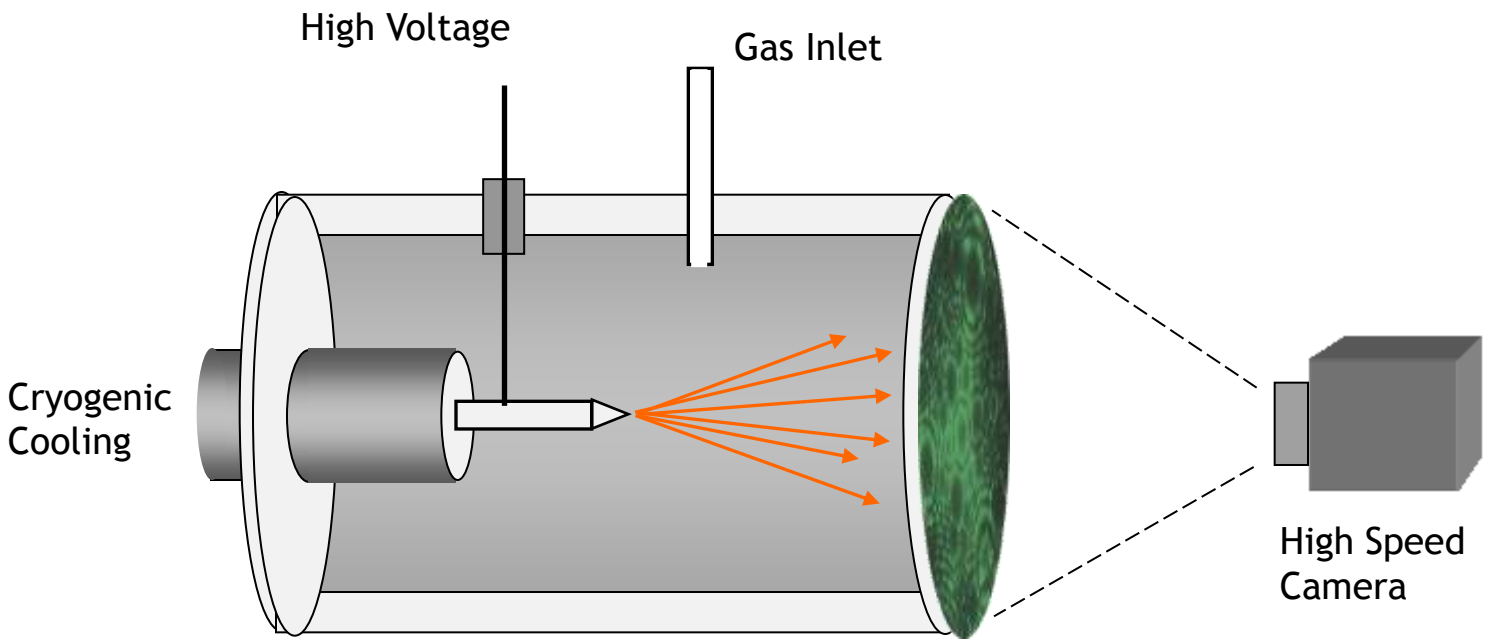
Peter Gnauck

Technology to cover all scales
Carl Zeiss Microscopy Portfolio



Field Ion Microscope (FIM) Basics

(Erwin Müller in 1955)

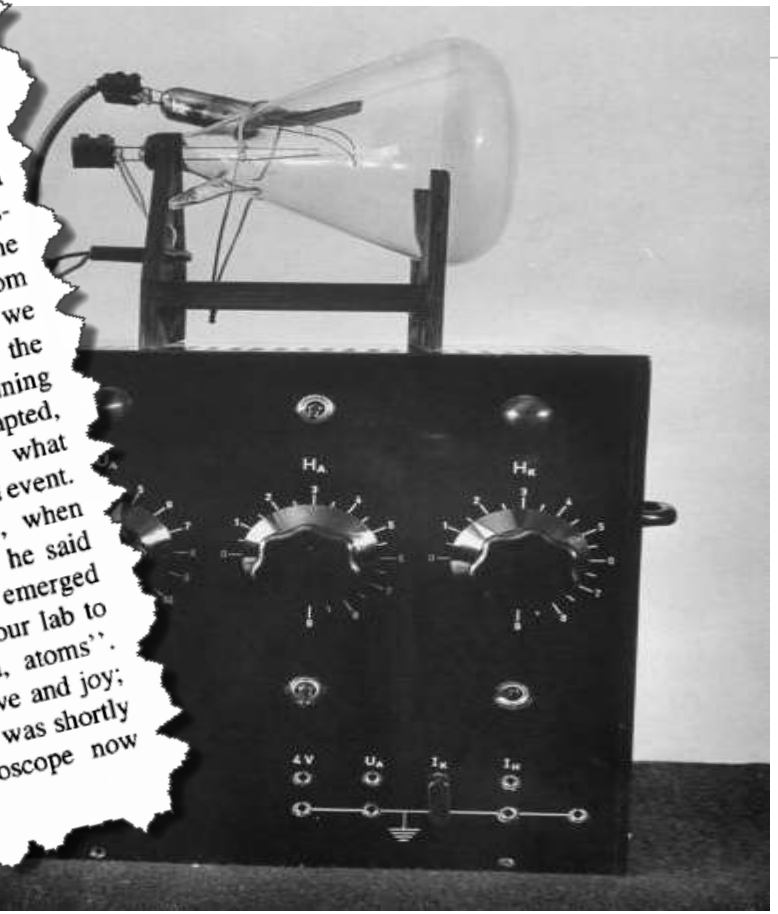


The first person to *directly* see atoms

Erwin Müller
1911 to 1977

6. October 11, 1955

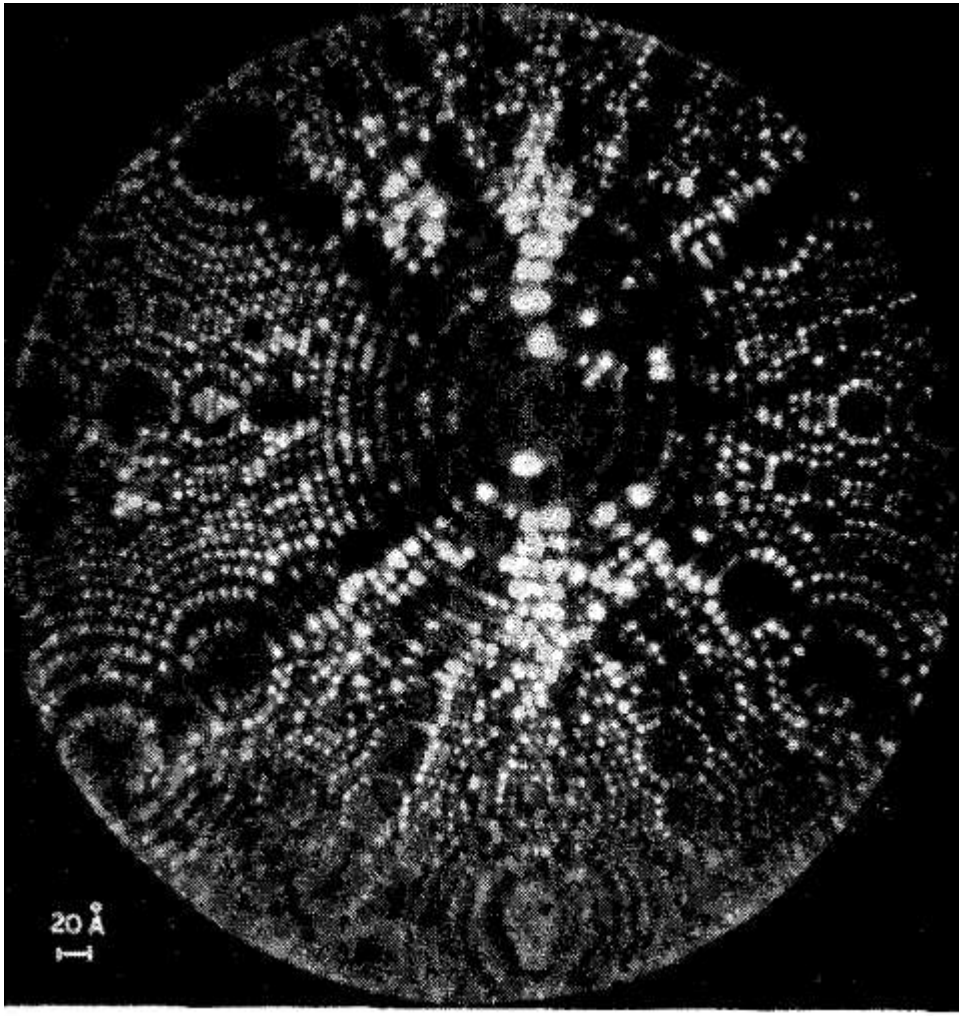
The day of October 11, 1955 was a day long to be remembered by those of us who were in the laboratory. Bahadur had built the FIM to re-test the hypothesis that cooling the tip was worthwhile, and had gotten the experiment going. Now, he called Professor Müller into his laboratory room to show him the 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.



Allan J. Melmed, "Recollections of Erwin Müller's Laboratory: The Development of the FIM (1951-1956)", Applied Surface Science (1996).

Adobe Acrobat Document

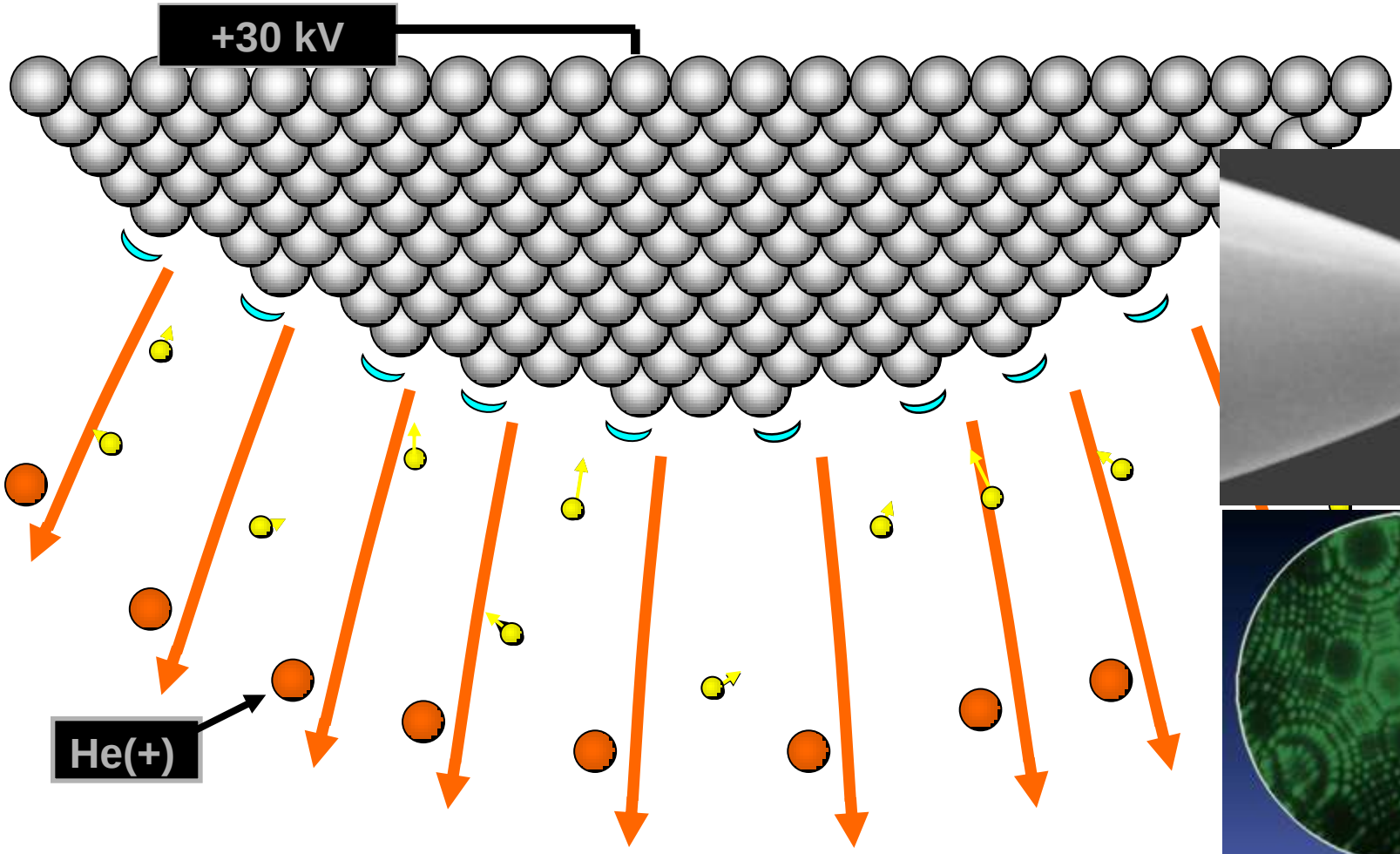
First direct observation of atoms by Müller October 11, 1955

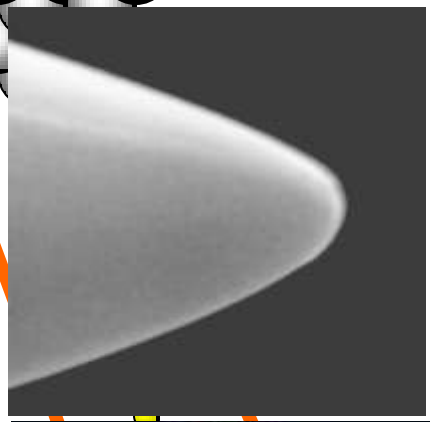


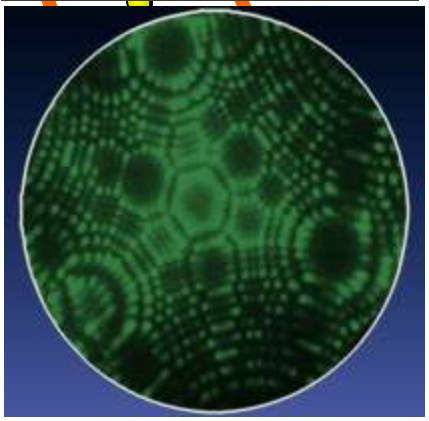
E. W. Müller, J. Appl. Phys. ***27,*** *474 (1956)*

Unsharpened Orion Helium Ion Source
and Its FIM Image

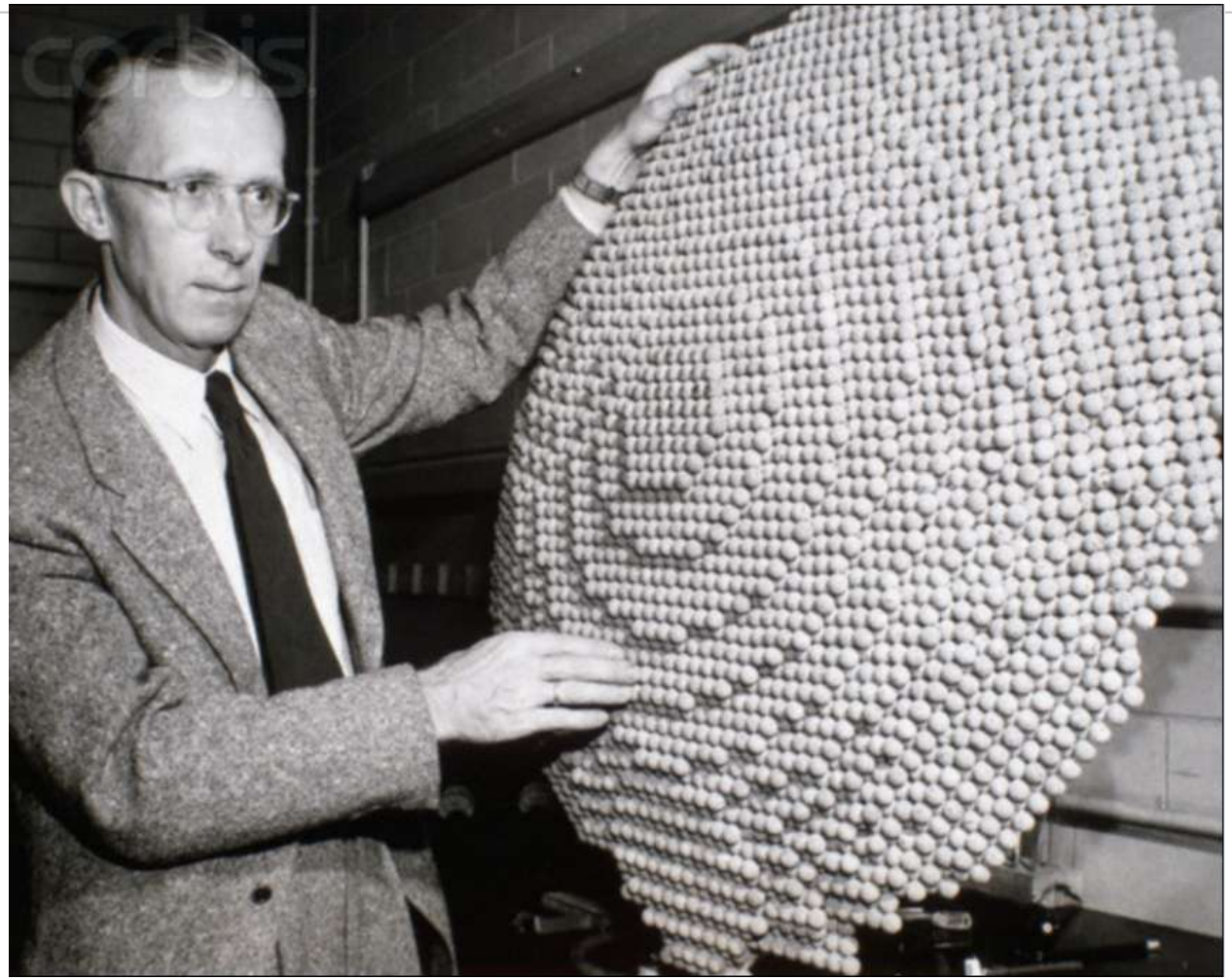
Unsharpened tip





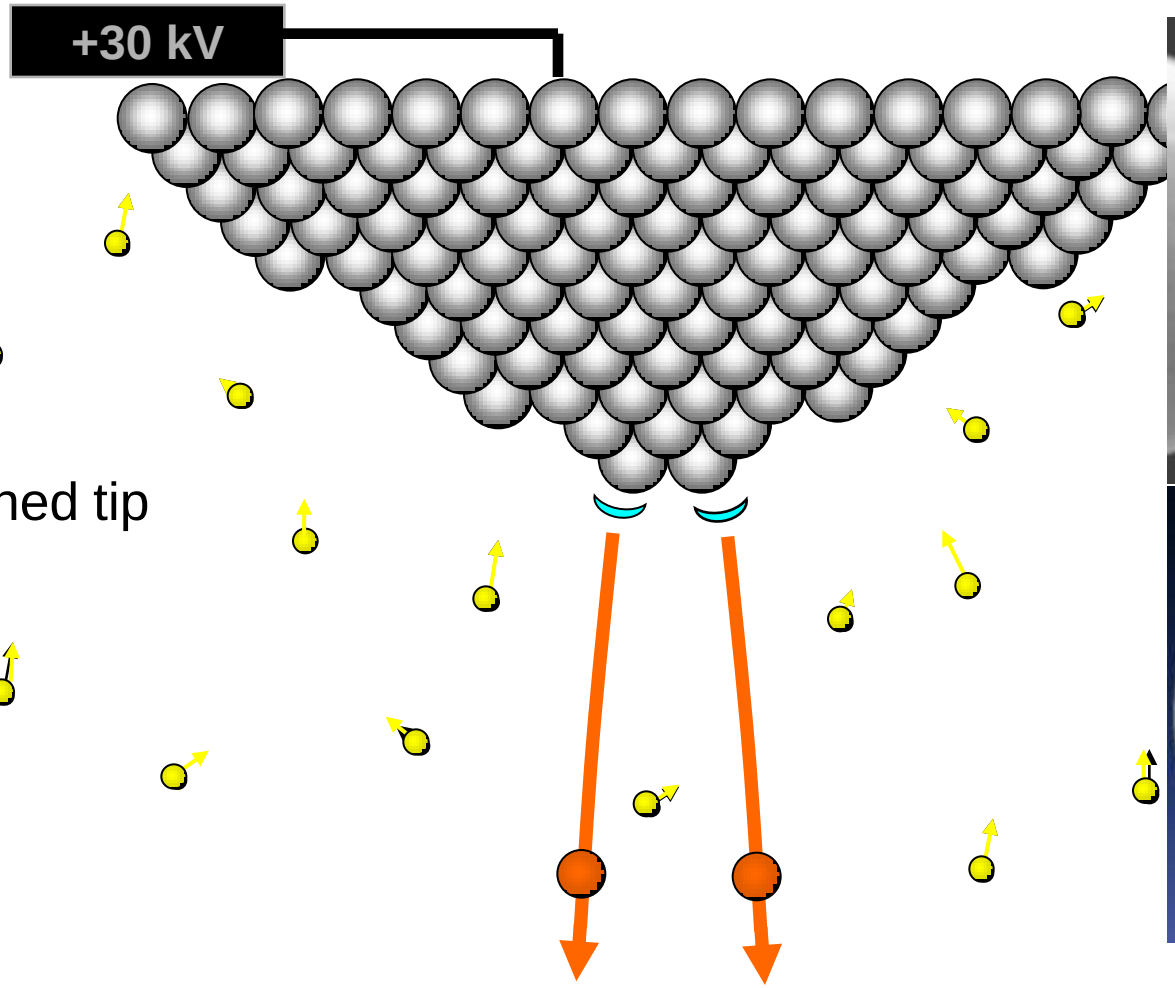


The Field Ion Microscope (FIM) and the Gas Field Ion Source (GFIS

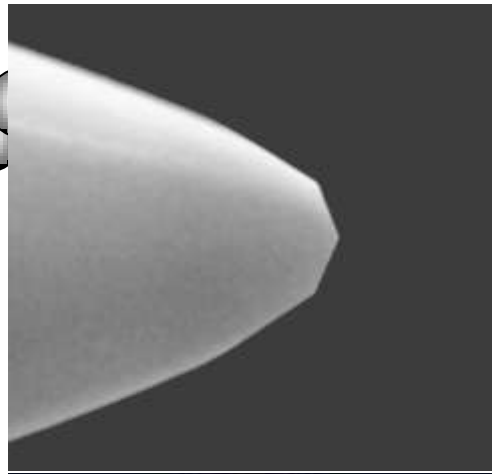


From TIME-LIFE photo archives

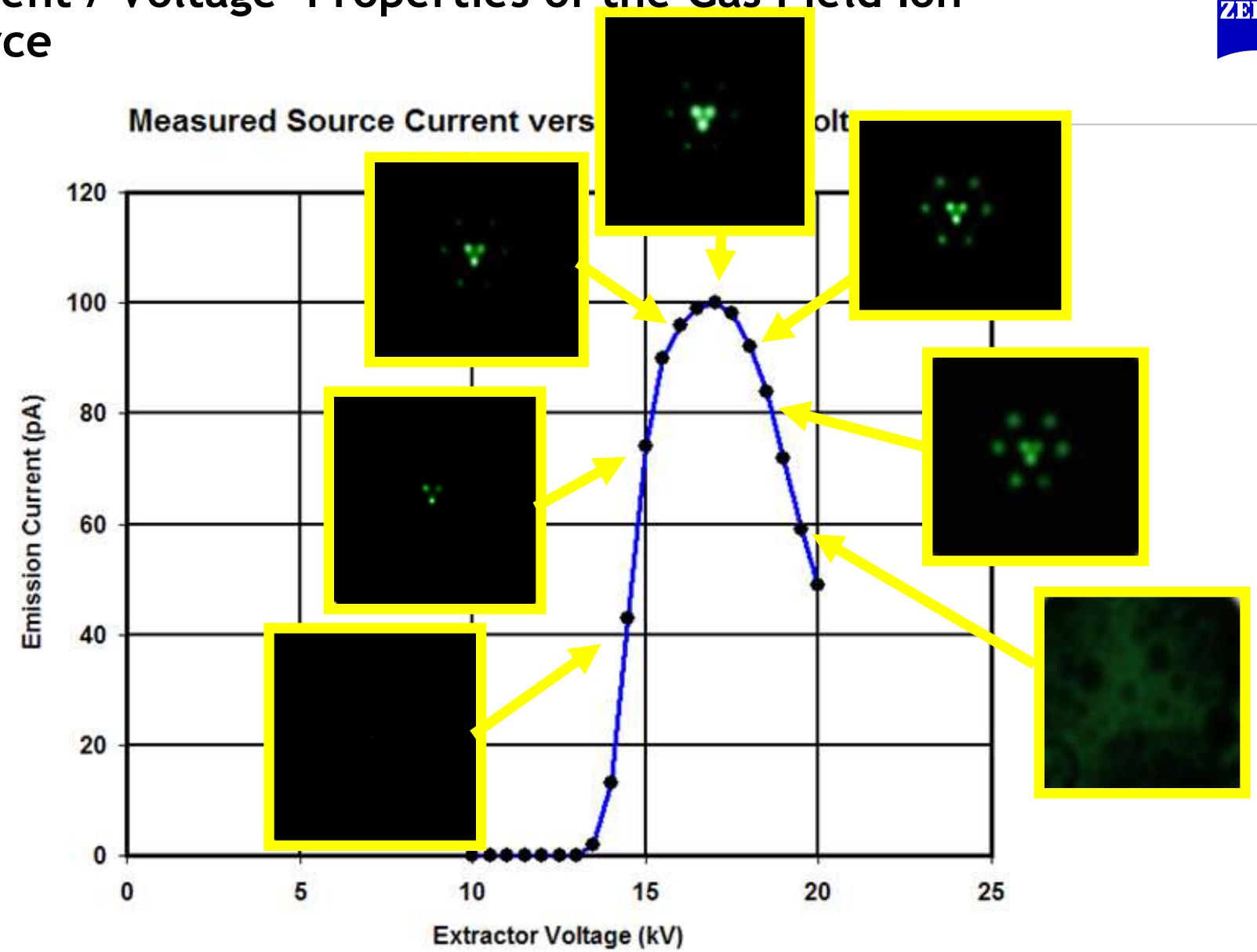
Final Helium Ion Source
3 Atom Cluster - And Associated FIM Image



Sharpened tip

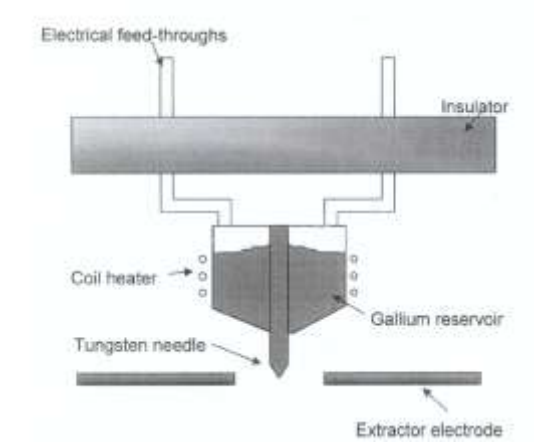


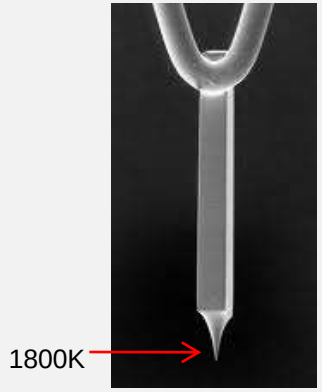
Current / Voltage Properties of the Gas Field Ion Source

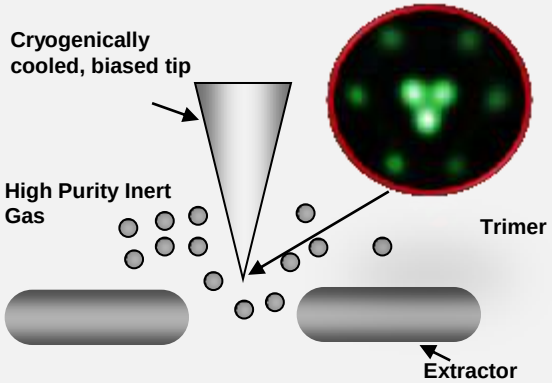


Source Technologies

Focused Ion Beam	Scanning Electron Microscope	Helium Ion Microscope
Liquid Metal Ion Source	**Schottky Field Emitter**	**Gas Field Ion Source**



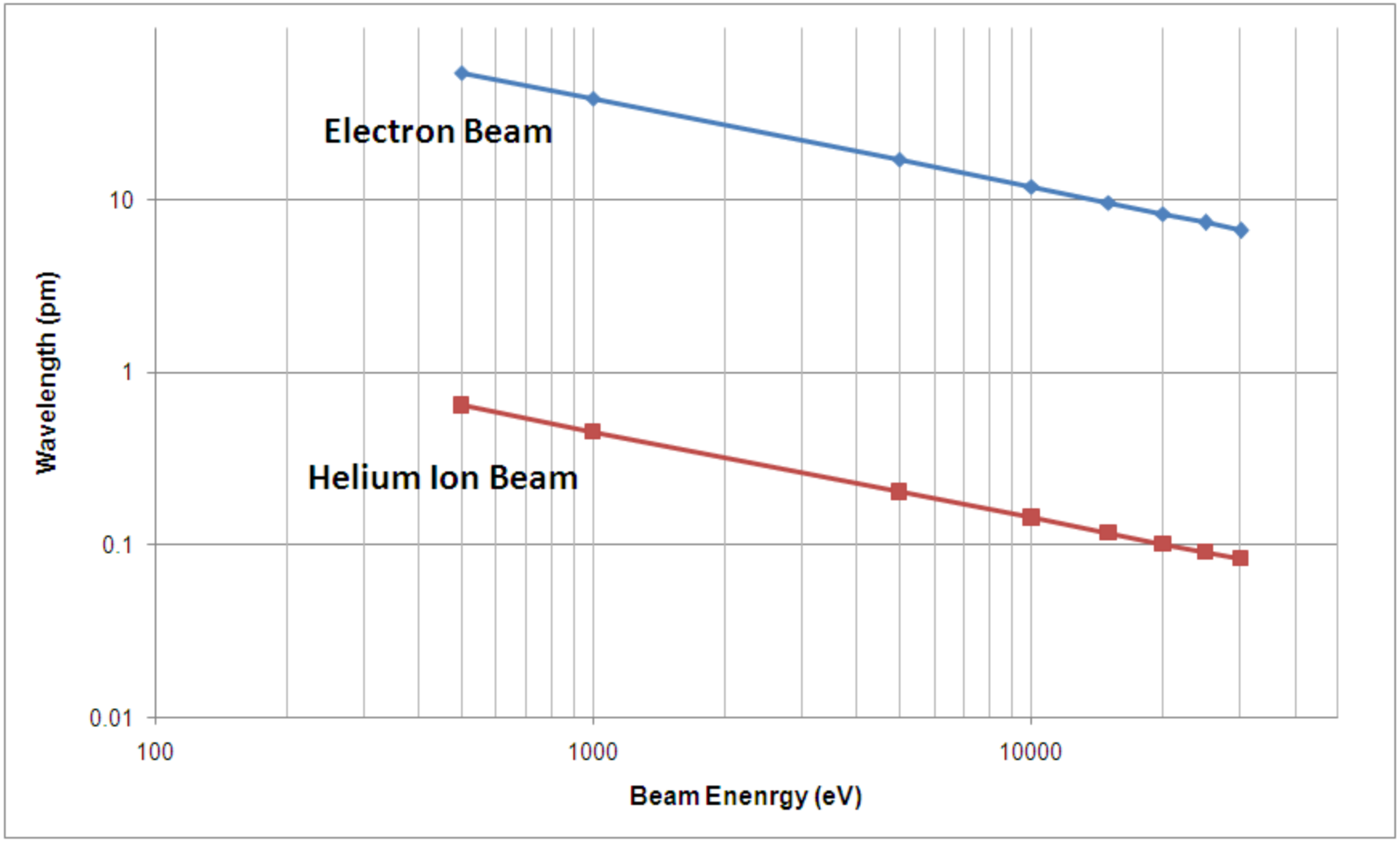




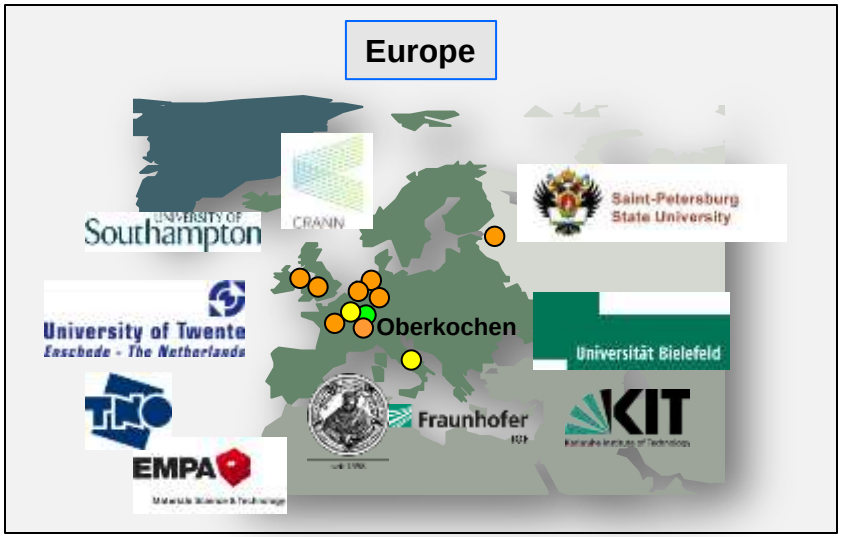
Probe Size ~5nm	Probe Size ~0.8nm	Probe Size ~0.35nm ✓
Brightness ~$3X10^6$ A/cm^2.sr	Brightness ~$5X10^8$ A/cm^2.sr	Brightness ~$5X10^9$ A/cm^2.sr ✓

Scanning probe with the highest brightness and smallest probe size

Benefits of GFIS – Resolution and Probe Size



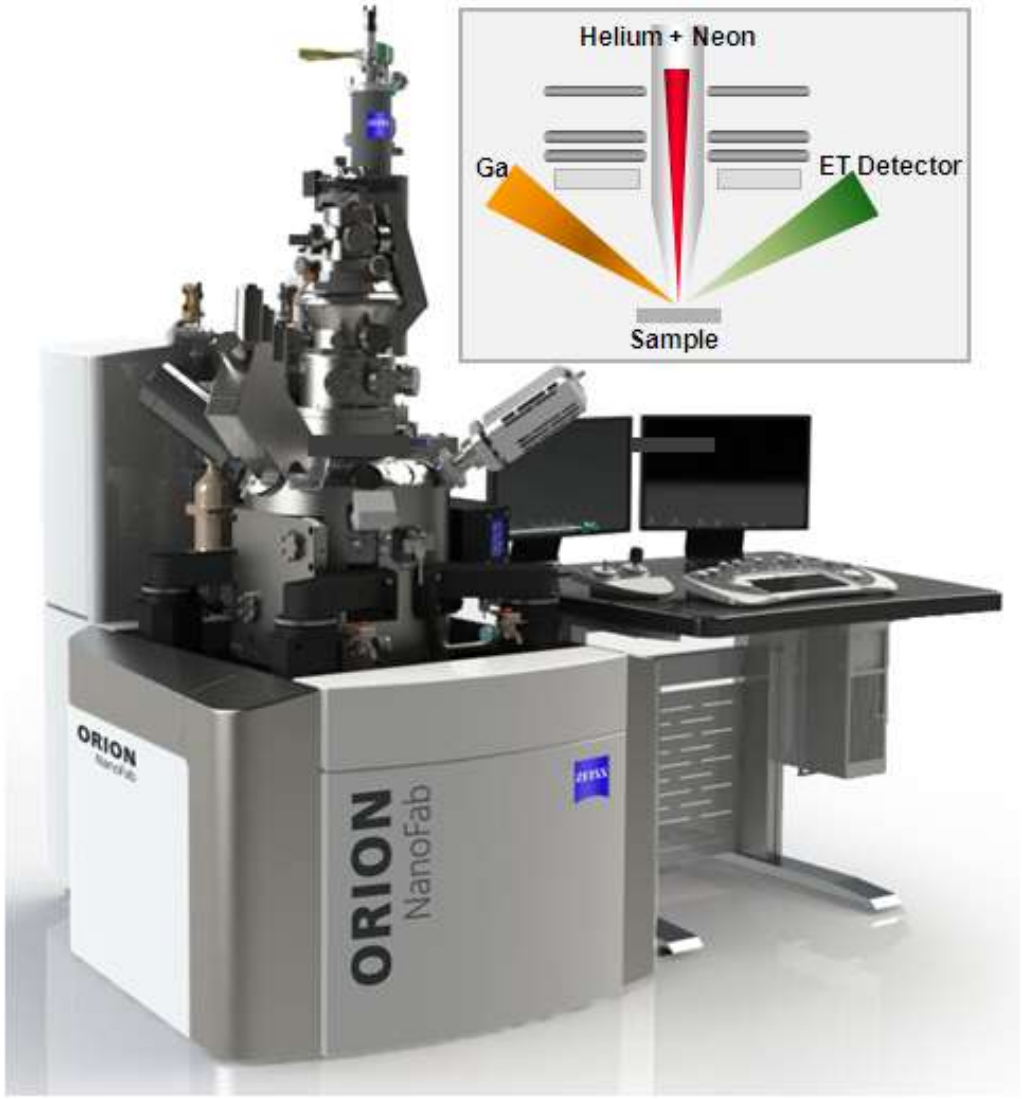
Helium Ion Microscope – Current Status



Momentum building…

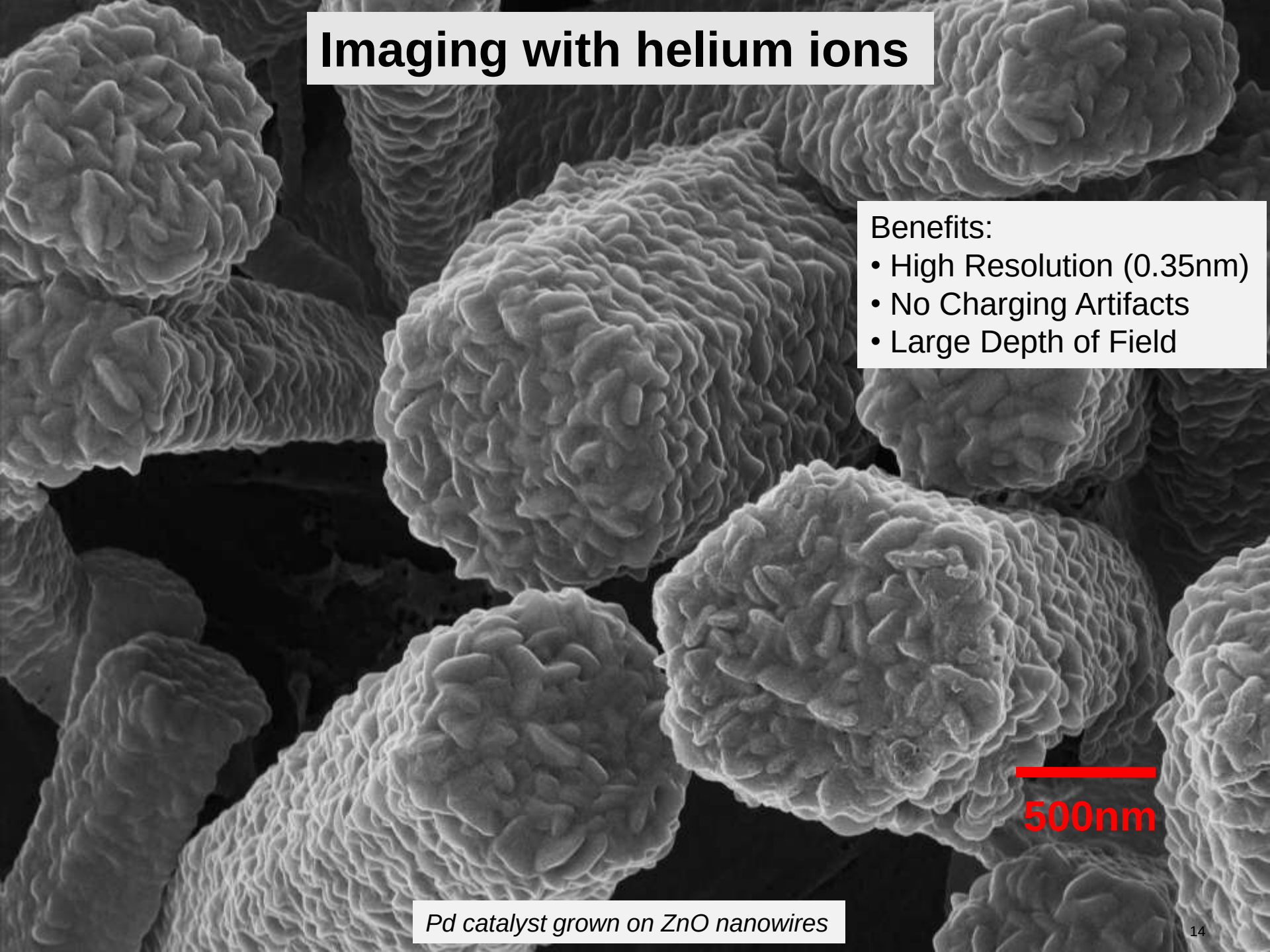
- User base growing (25 installed systems)
- Over 100 publications with HIM and chapters in 3 microscopy books
- Dedicated HIM sessions at major conferences (M&M, EIPBN, AVS)

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.

Imaging with helium ions

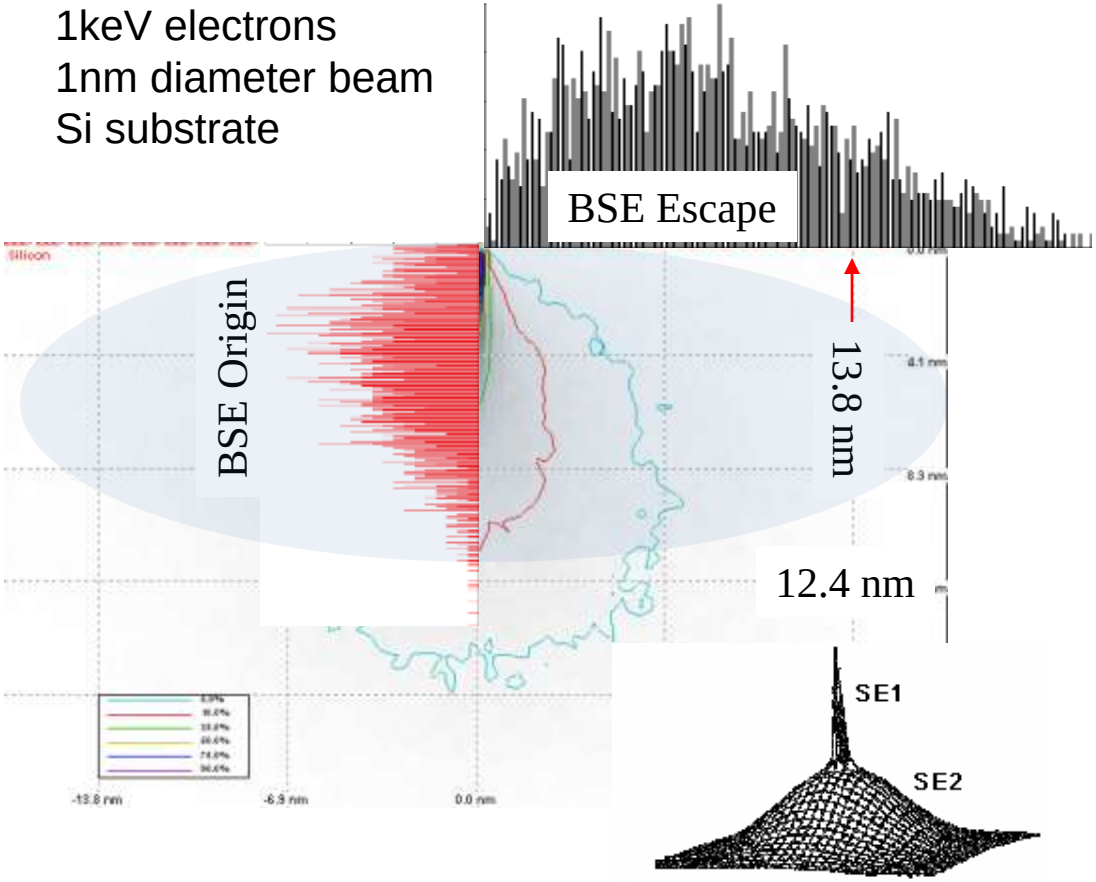


Benefits:
- High Resolution (0.35nm)
- No Charging Artifacts
- Large Depth of Field

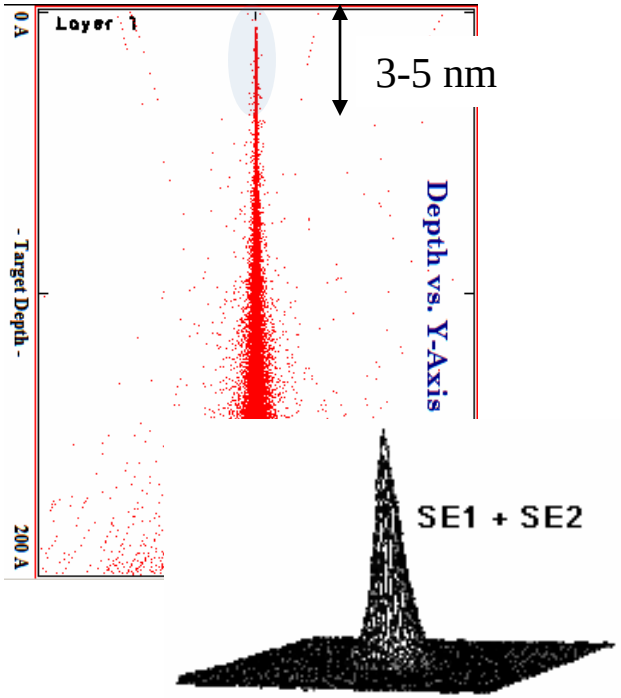
Pd catalyst grown on ZnO nanowires

Surface Sensitivity

CASINO simulation
1keV electrons
1nm diameter beam
Si substrate

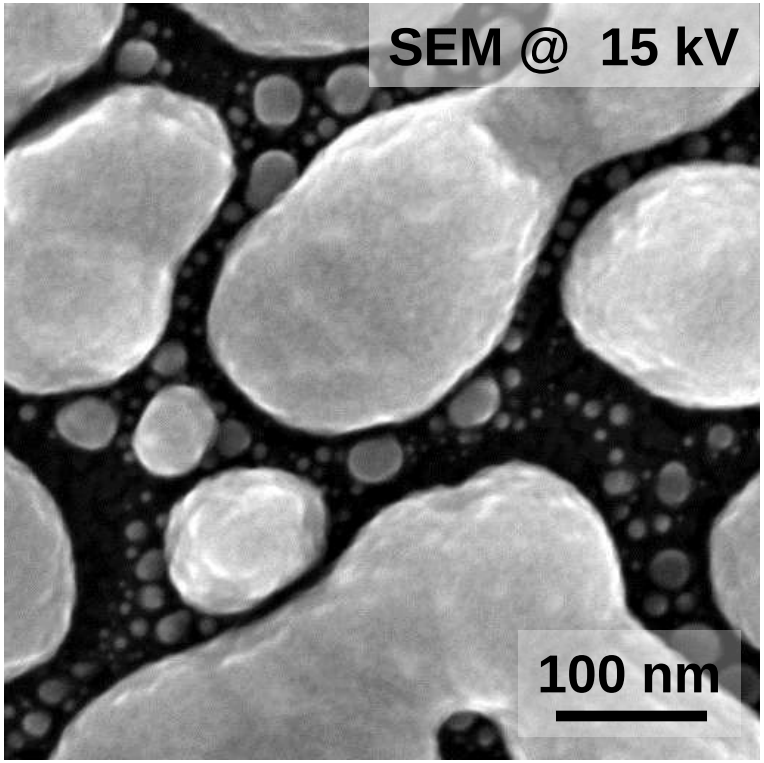


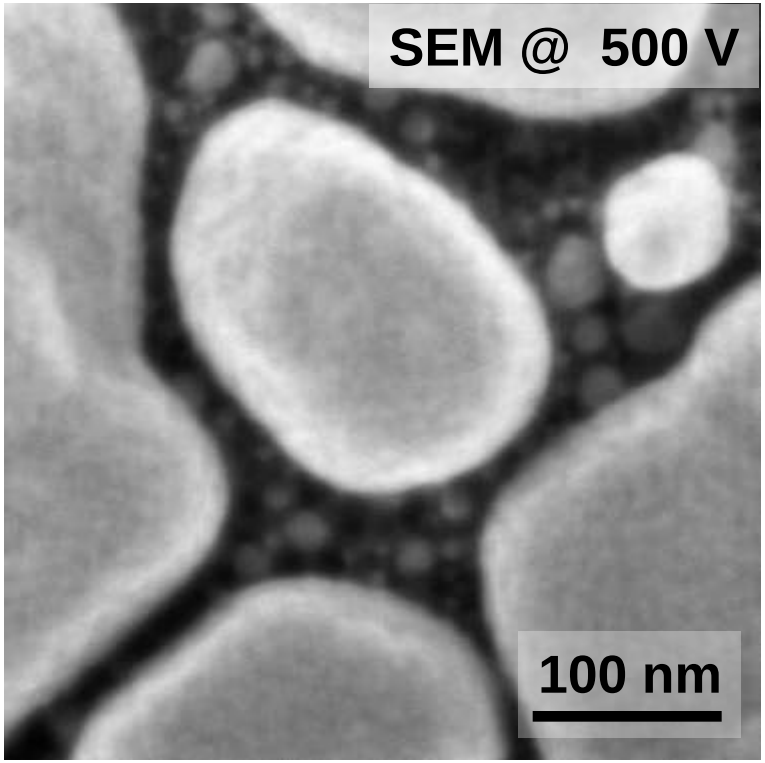
TRIM simulation
30keV He+
Point beam
Si substrate



SEM images are produced by SE1 and SE2 electrons while the HIM image is primarily due to SE1 electrons

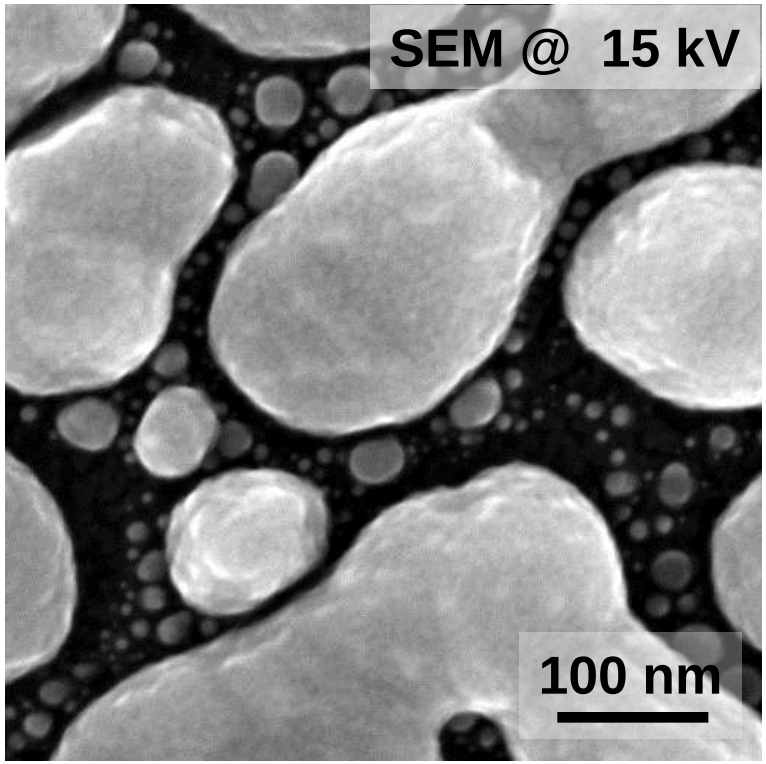
Coated AuC (big Au islands)



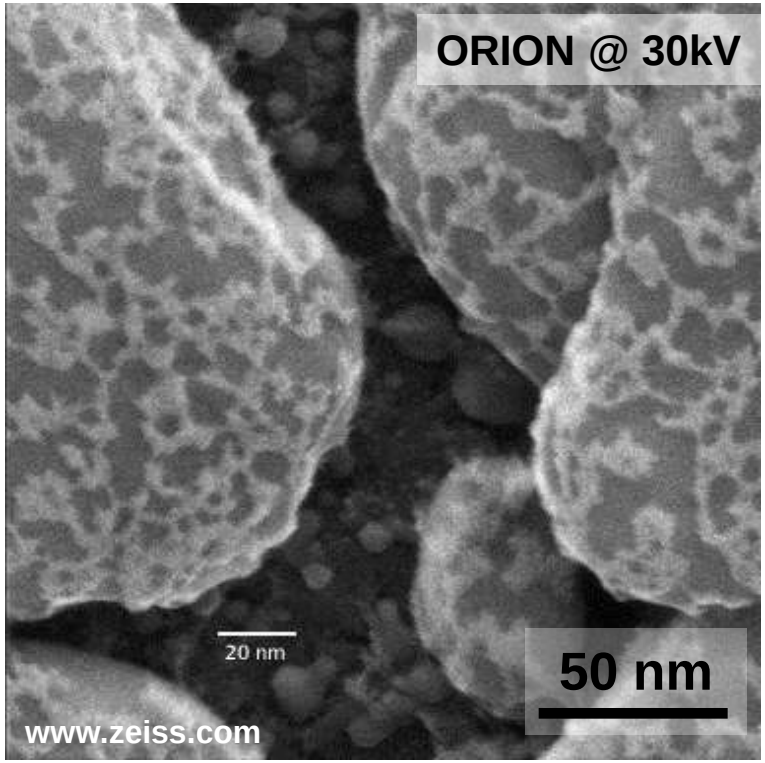


sample courtesy of Al Lysse, Carl Zeiss SMT Inc., US

Coated AuC (big Au islands)

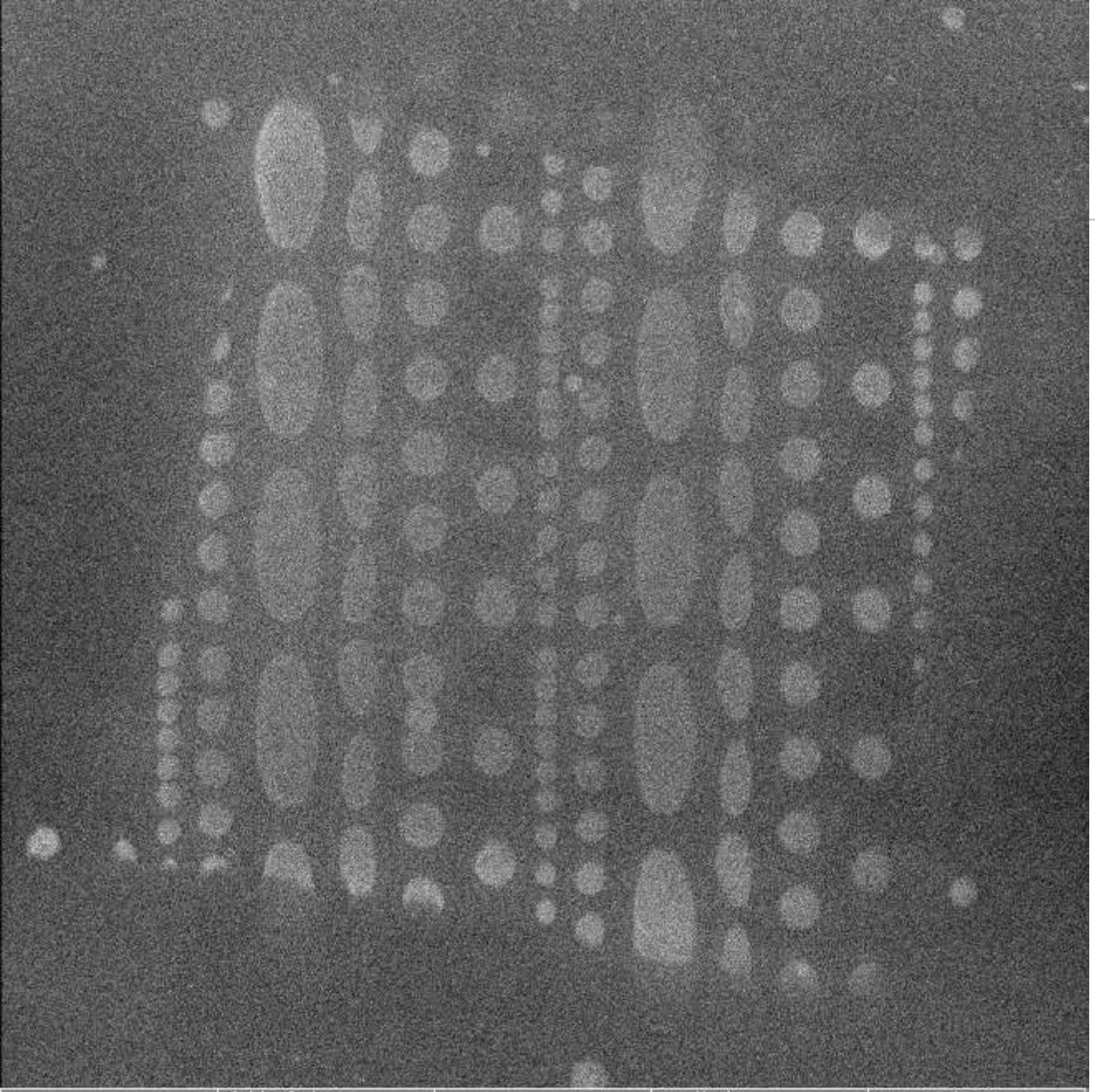


- good SNR
- high contrast between Au and C



- high surface sensitivity

…surface details that could not be seen become visible



ZEISS CARL ZEISS SMT	Field Of View 55.00 um	5.00 um	Dwell Time 1.0 us	Date: 3/6/2008 Time: 10:40 AM
	Working Dist 9.9 mm	Blanker Current 1.5 pA	Line Averaging 128	Acceleration V 28021.2 V

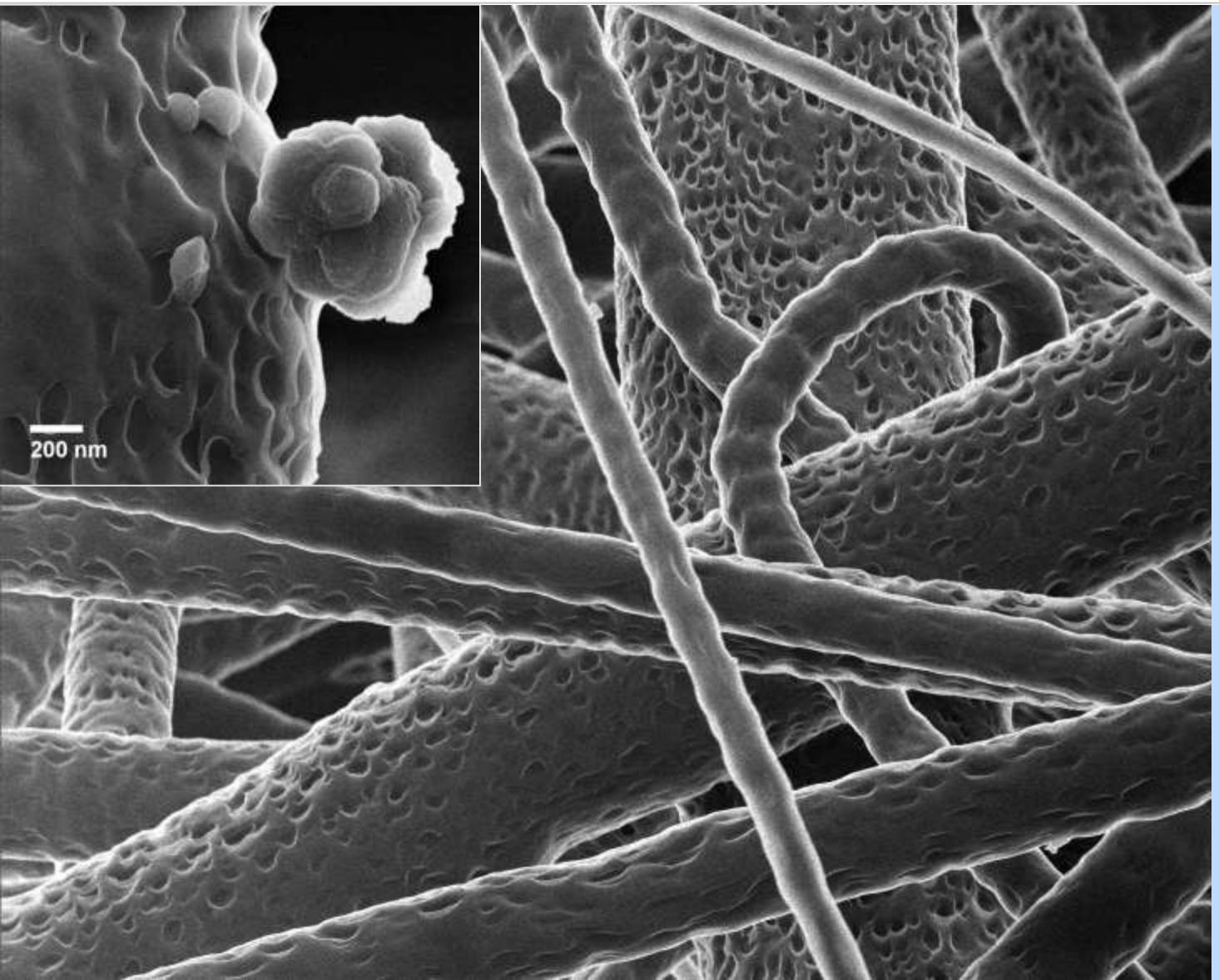
Surface Detail

- Helium beam generates contrast from atomically thin layers as well as chemical contrast (light grey is –NH2 and dark grey is -NO2)

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

Materials Imaging – Polymer Engineering
Hydroxyapatite grown on PLLA Fibers



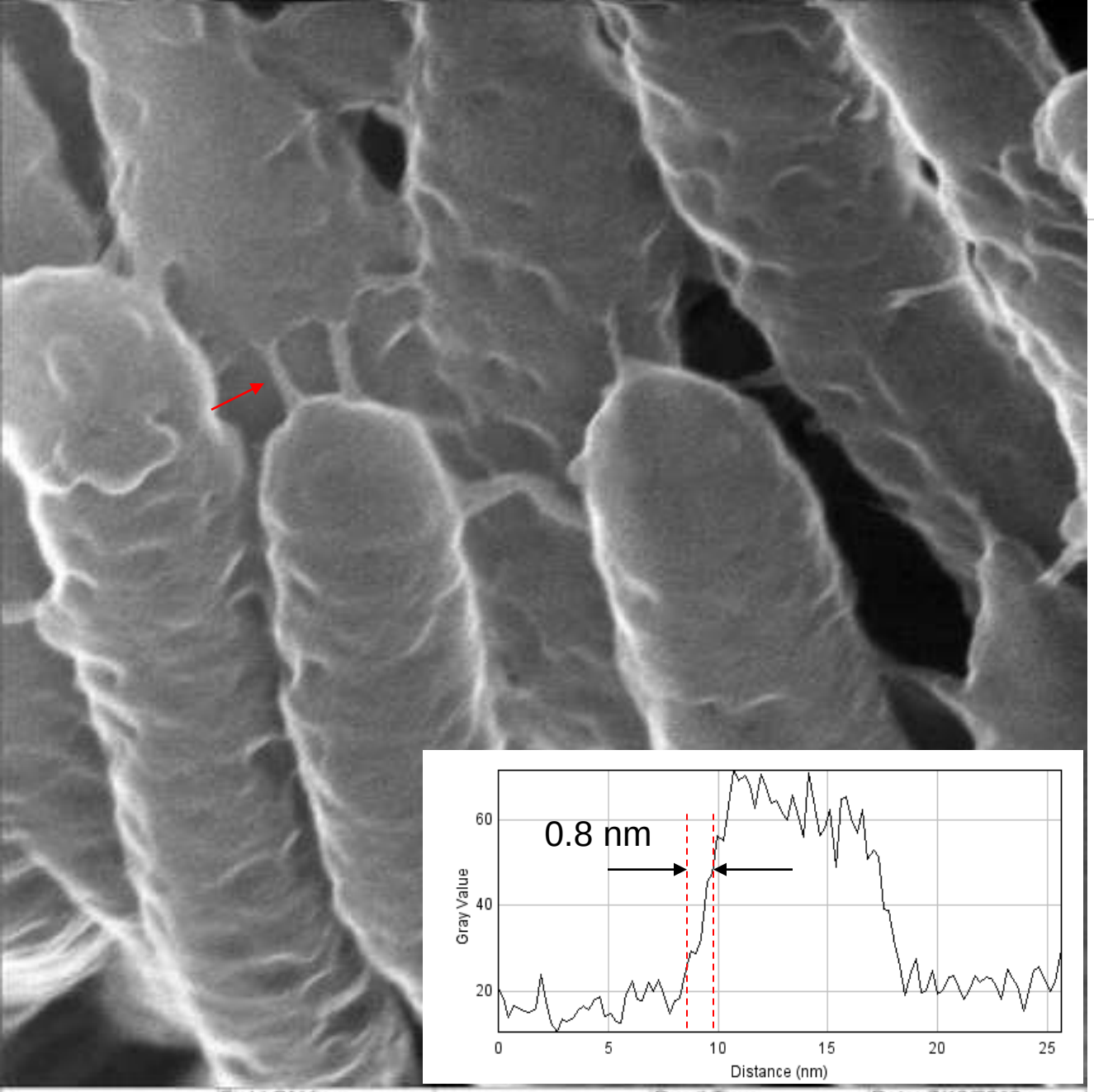
HIM image of Hydroxyapatite grown on Poly (L-Lactide) spun fibers. PLLA acts as a scaffold for growing Hydroxyapatite which is bone mineral. Inset image shows Hydroxyapatite nucleation sites at high resolution.

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



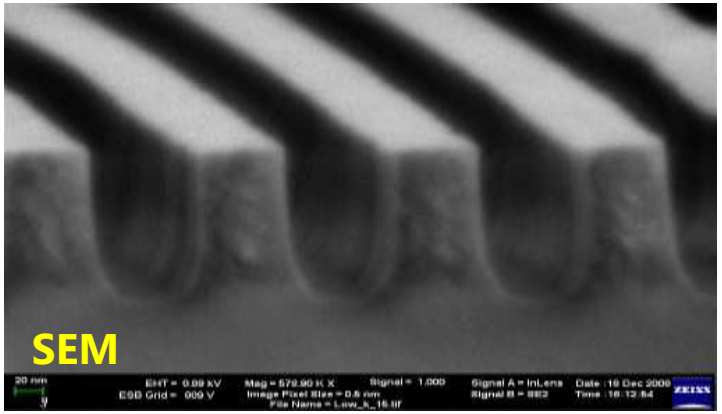
CARL ZEISS SMT	Field Of View 500.00 nm	50.00 nm	Dwell Time 0.2 us	Date: 7/13/2010 Time: 5:41 PM
	Mag (4x5 Polaroid) 228,600.00 X	Blanker Current 0.4 pA	Line Averaging 128	Acceleration V 38.0 kV

Stereocilia in the Inner Ear

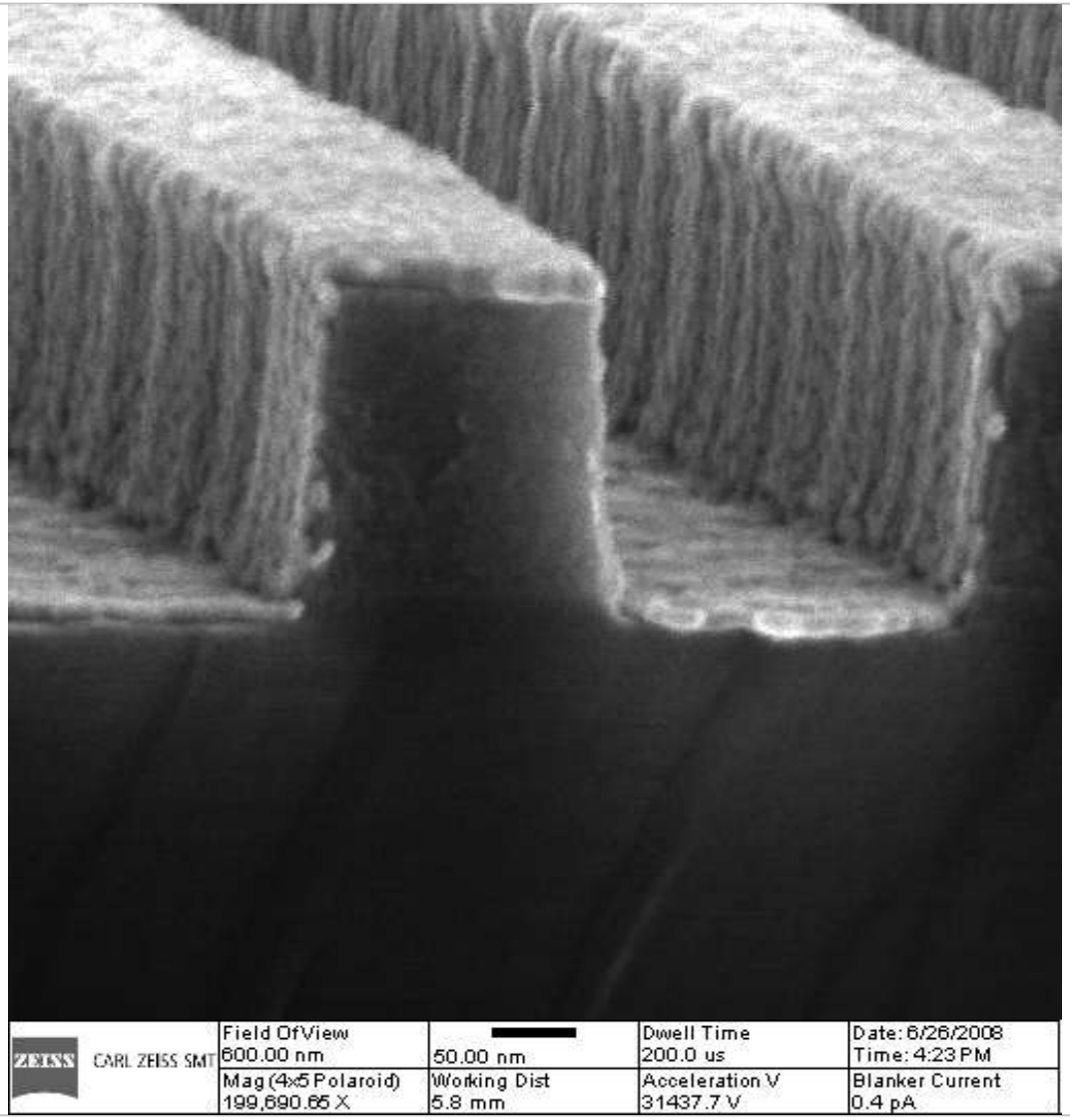
Sample courtesy of NIH

Imaging Examples
Resist

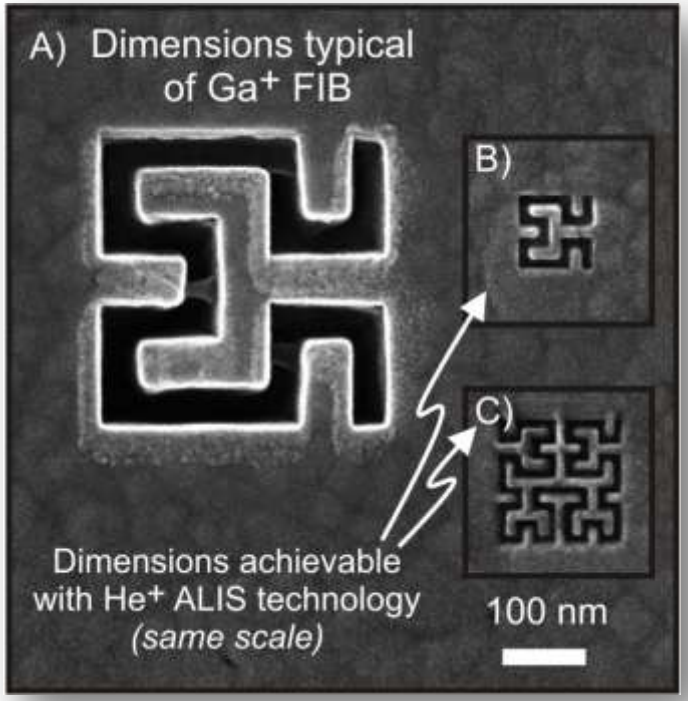
Resist lines after development. The materials is Si-CH3 enriched MSQ polymer.
The SEM images were of limited value due to charging artifacts.

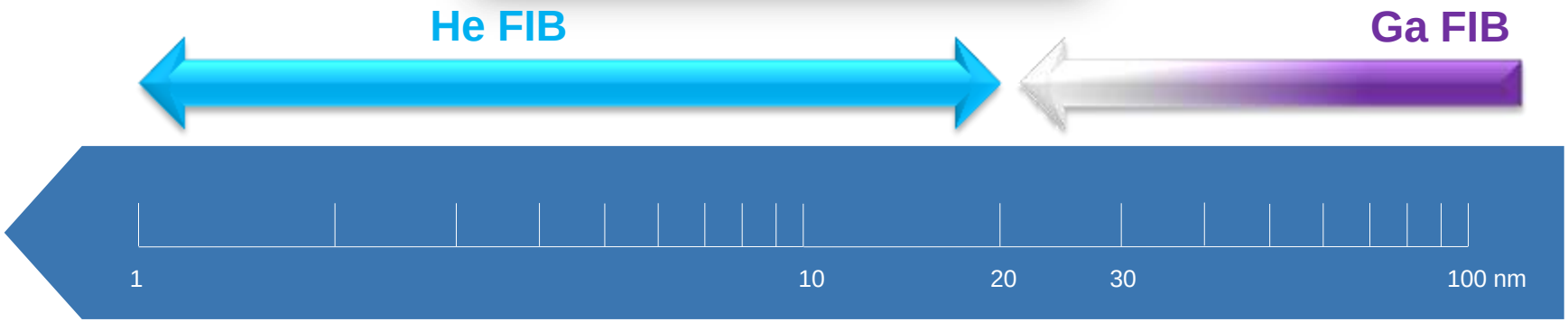


Sample courtesy of SELETE



Ion Beam Milling
Technology Comparison • *Ga FIB vs. Helium Ion Beam*





** Courtesy: Dan Pickard, NUS*

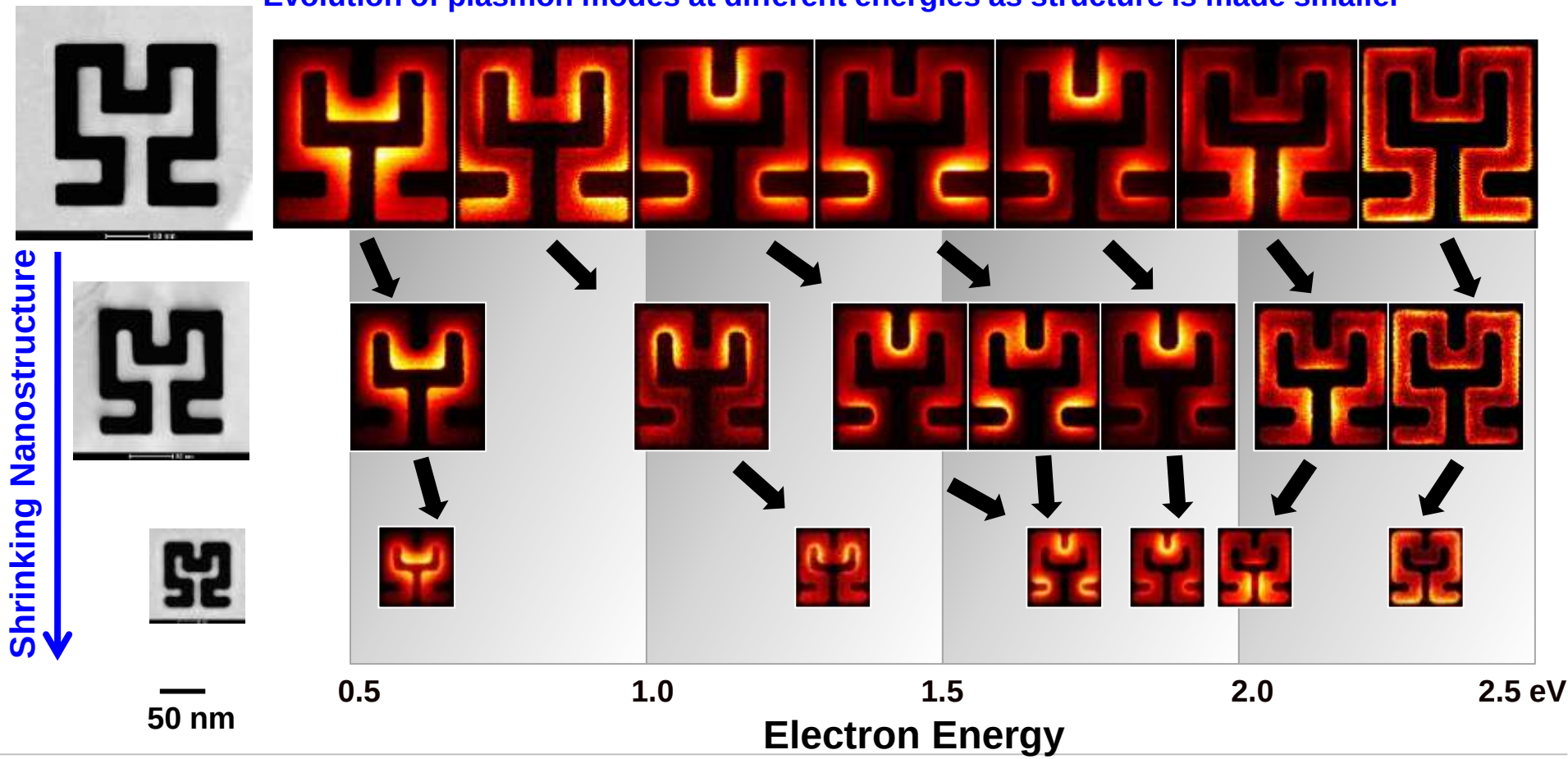
Ion Beam Milling

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

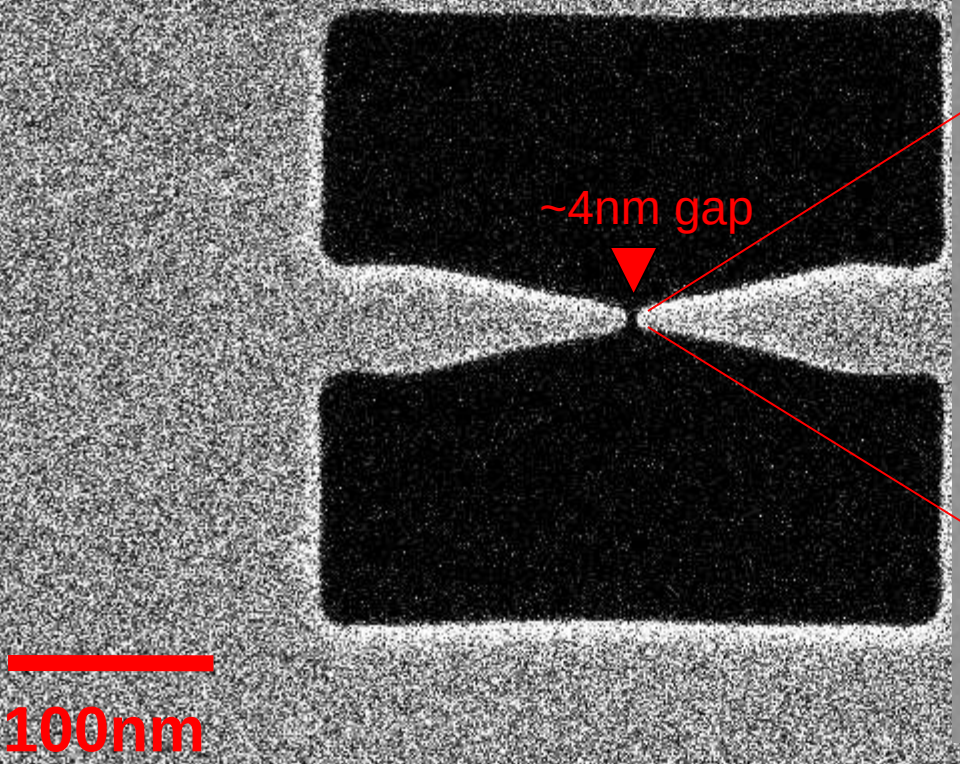


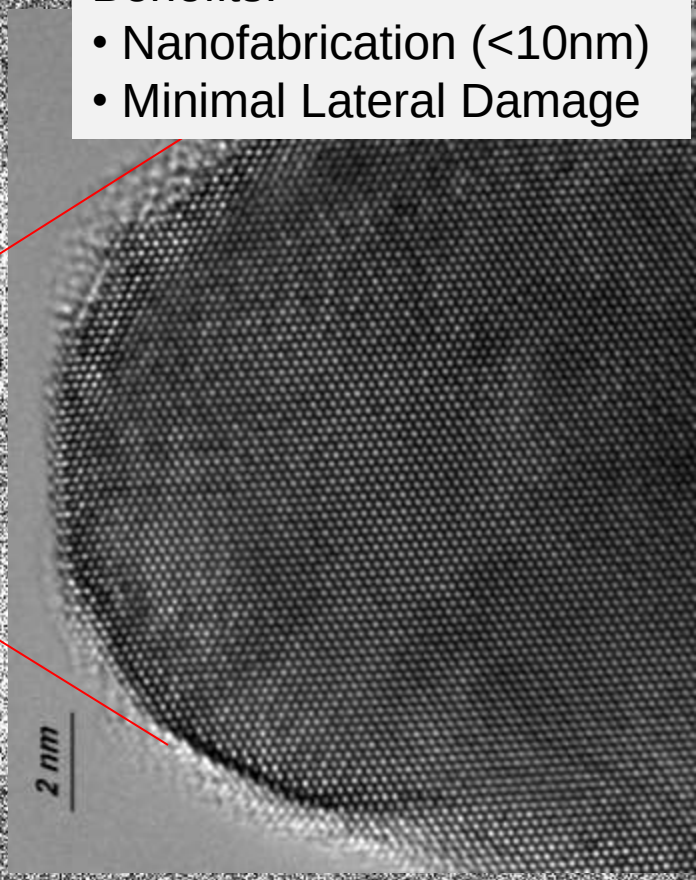
** Courtesy: Dan Pickard, NUS*

Machining with helium ions

Benefits:

- Nanofabrication (<10nm)
- Minimal Lateral Damage





TEM Image

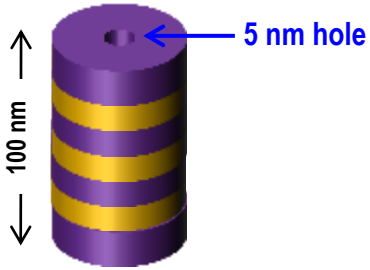
Ion Beam Milling
Application • *DNA Transistor at IBM*

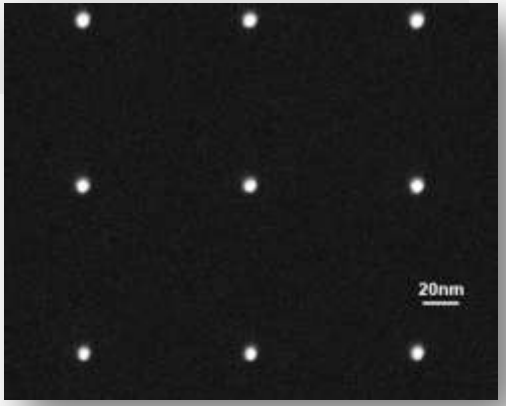
Research Area	DNA sequencing
Challenge	How to make 5 nm holes in 7 layer metal-dielectric sandwich film?
Conventional Method	TEM at high energy

Transmission Electron Microscope

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 (± 1nm variability).**





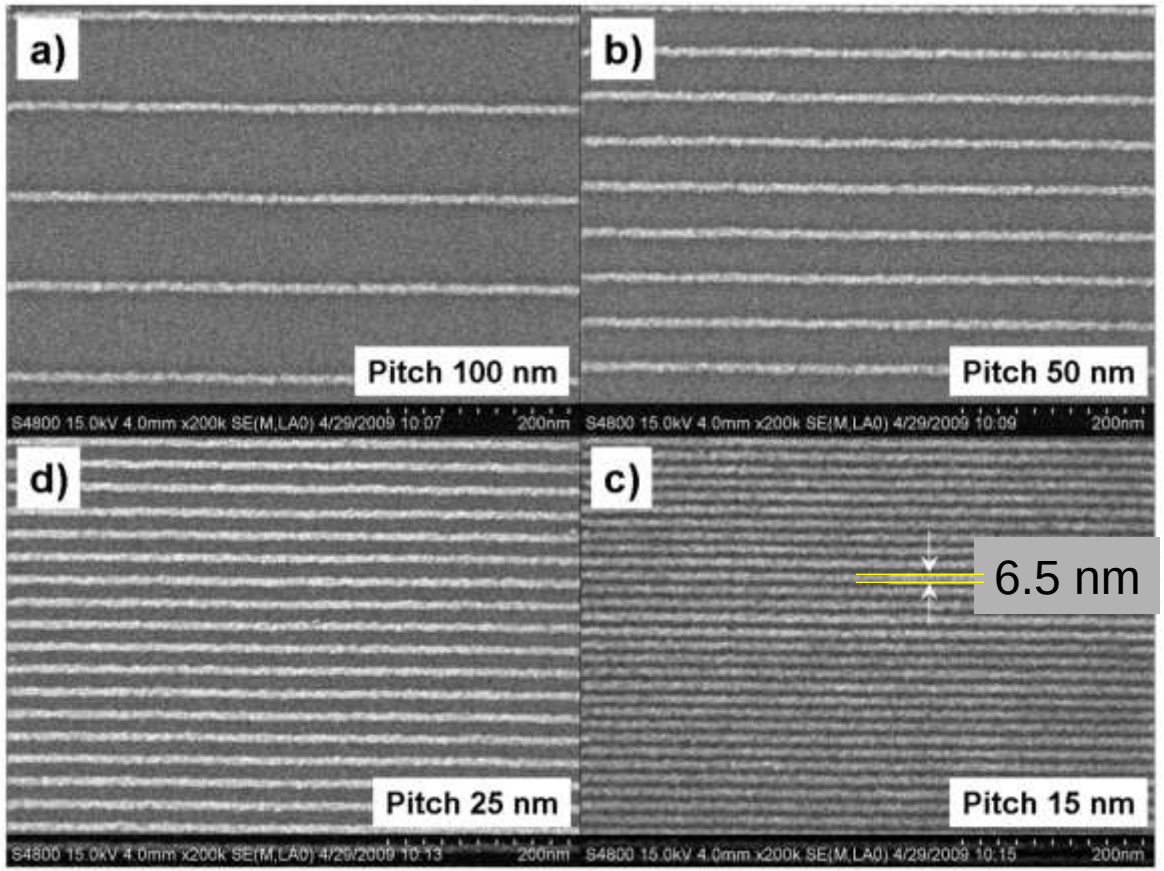
Nano Structuring
Early results Lithography (SHIBL)

Experiment

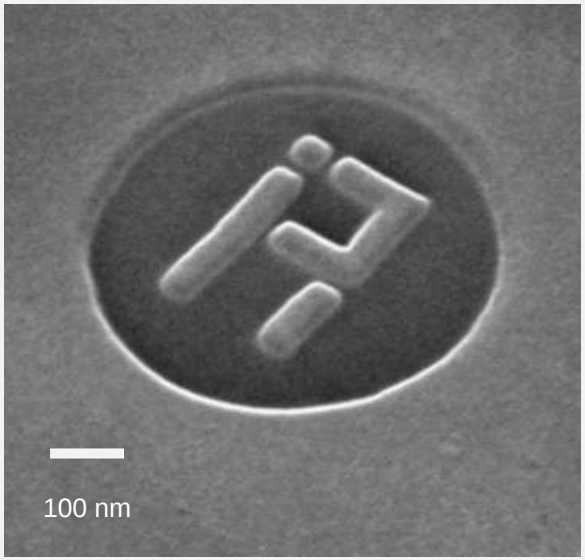
- Lines written in HSQ resist

Results

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

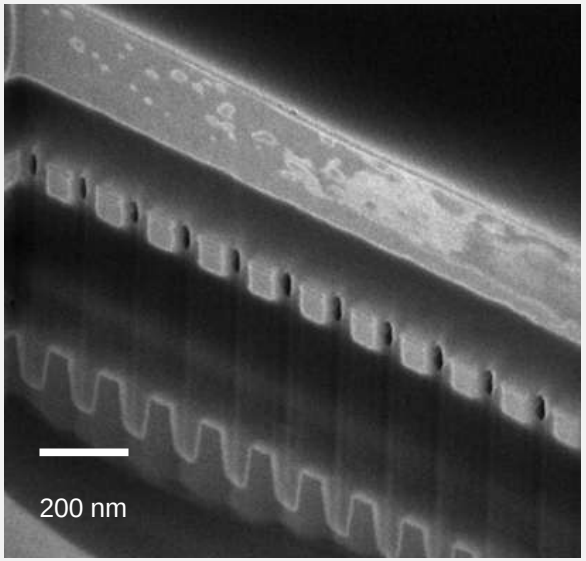


Early Neon Results



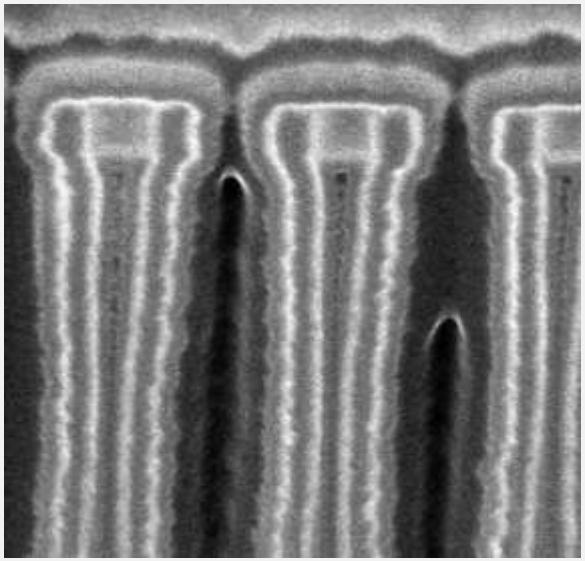
Si sputtering

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



Thinned section

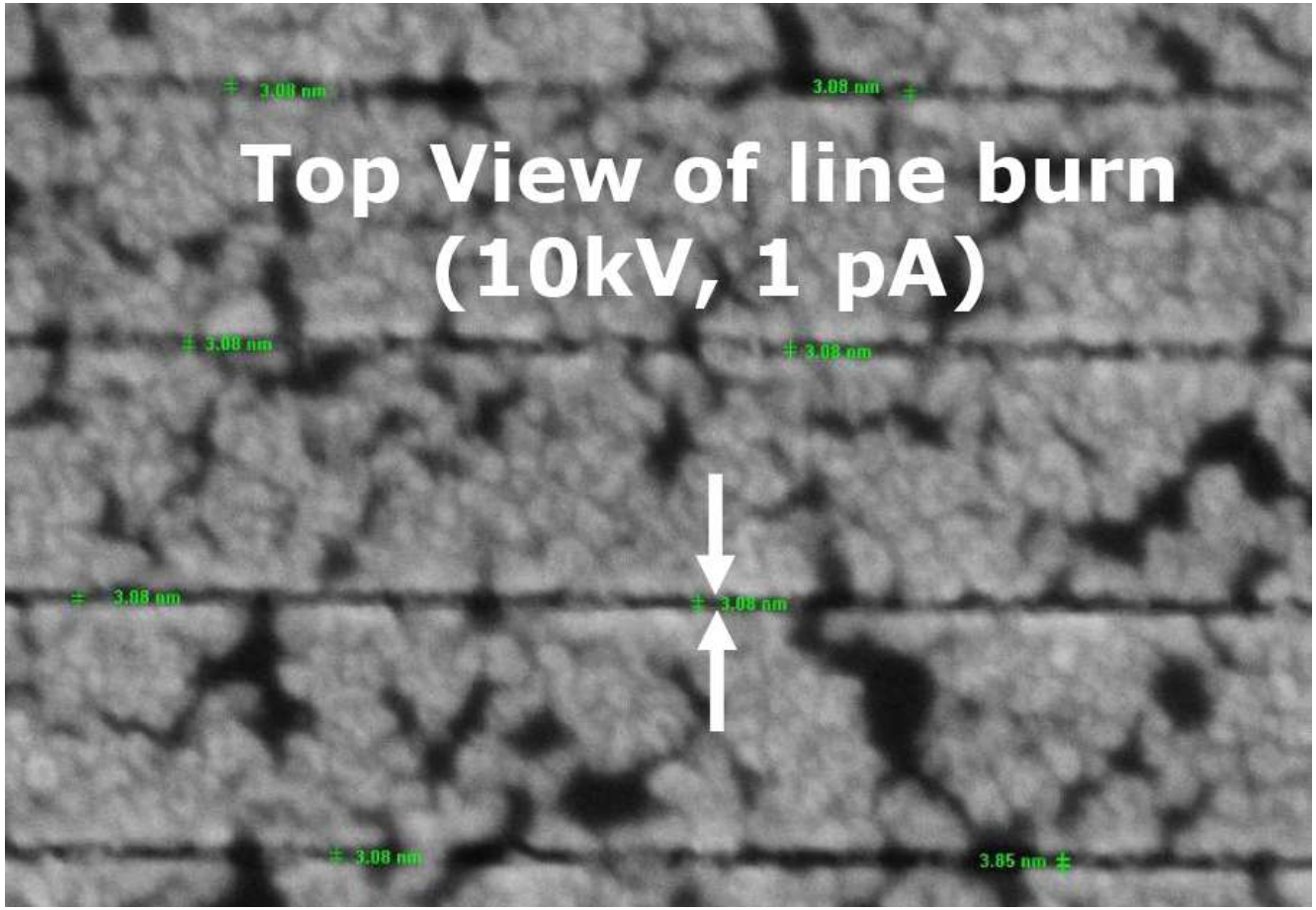
Material removal with Ne on sample backside followed by imaging with He.



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.

S Tan, R Livengood, D Shima, J Notte, S McVey, "Gas Field Ion Source and Liquid Metal Ion Source Charged Particle Material Interaction Study for Semiconductor Nanomachining Applications", Journal of Vacuum Science & Technology B, 28(6), C6F15 (2010).

ZEISS

We make it visible.