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Nanometer-scale imaging and metrology, nano-fabrication with the Orion Helium Ion Microscope

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National Institute of Standards and Technology (NIST)

Helium Ion Microscope (HeIM)

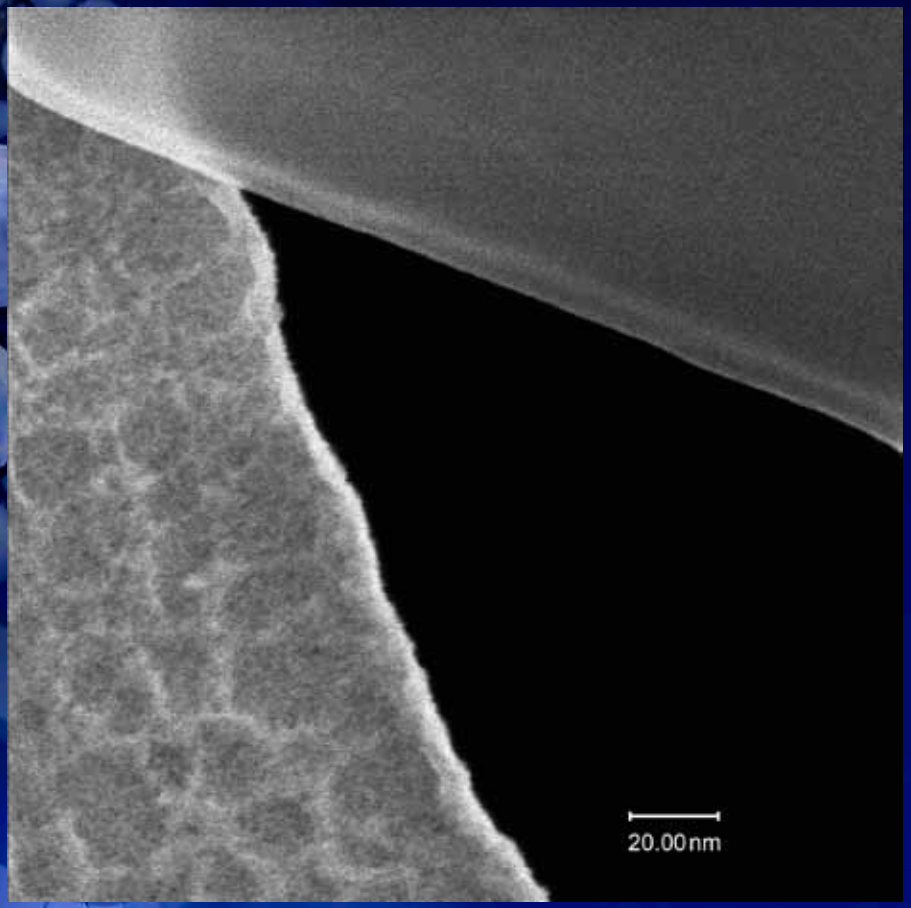
- First of this new type of instrument has been installed at NIST within the *Manufacturing Engineering Laboratory, Precision Engineering Division*
- In place of electrons, helium ions (He^+) are generated and used to irradiate the sample
- Theoretically expected to be 0.25 nm or 4 times better than the best of current large sample SEMs
- Potential applications in patterning at the nanometer scale.

The HeIM 2009 – ORION | Plus ..... Spec's

- Resolution
  - Base System ≤ 0.75 nm
  - Enhanced Resolution ≤ 0.35 nm (optional)
- Accelerating Voltage
  - 30±5 kV fixed
- Beam Current
  - 1fA - 25pA
  - Typically 0.5-1 pA for Highest Resolution
- Detectors
  - Everhart Thornley for Secondary Electrons
  - MCP for Rutherford Backscattered Ions
- Charge Control
  - Electron Flood Gun

Helium Ion Microscopy for IC Industry

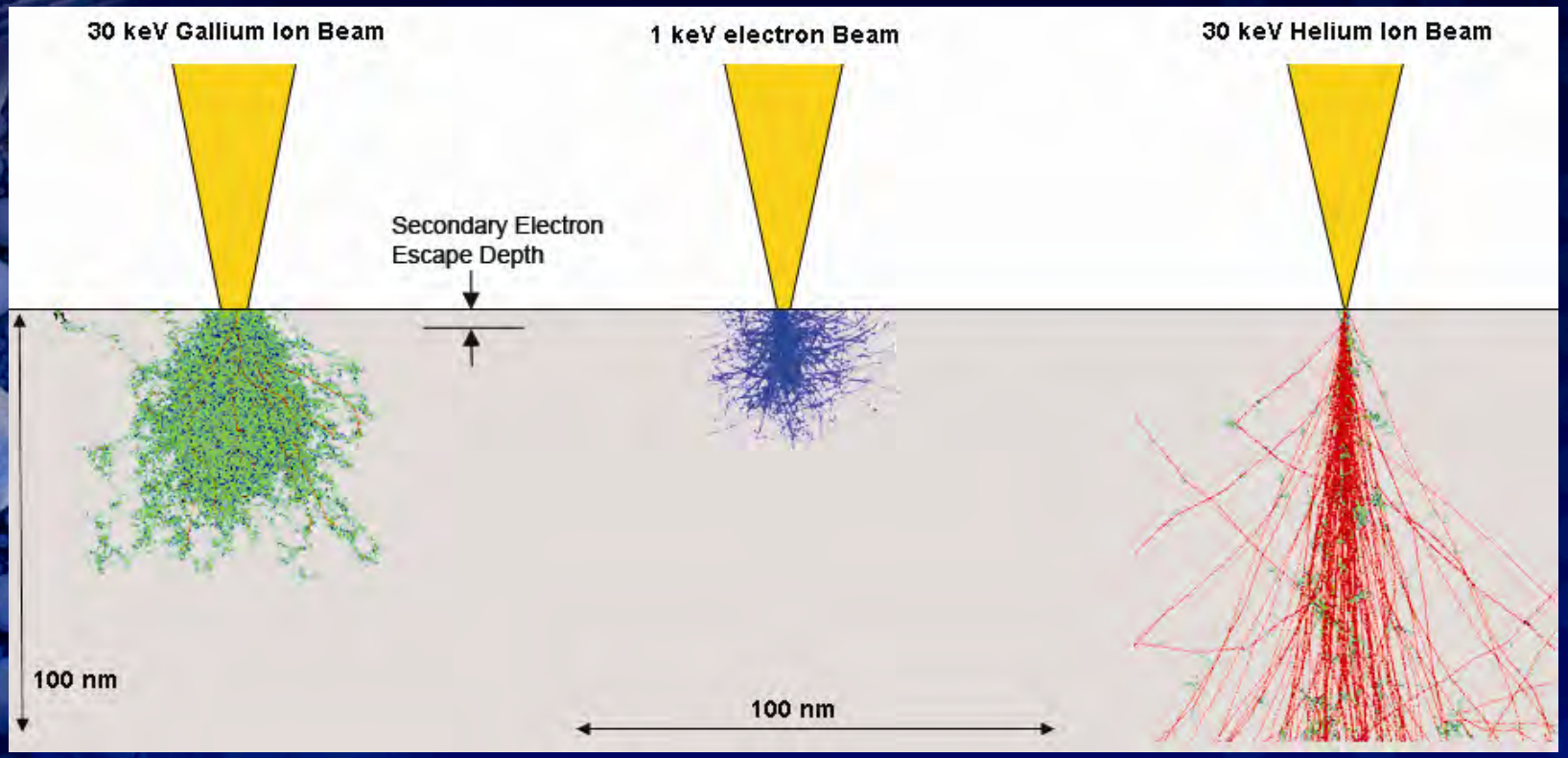
- 0.21 nm resolution/focusing ability has been claimed by vendor



25 % - 75 % signal transition-based resolution (spot size) measurement on an asbestos fiber on a thin holey carbon foil sample. The quoted resolution is 0.21 nm on an image taken on Orion Plus HeIM. The field-of-view is 200 nm (courtesy of Carl Zeiss SMT).

- At this point close to 1 nm resolution is typical

HeIM – Beam Sample Interaction

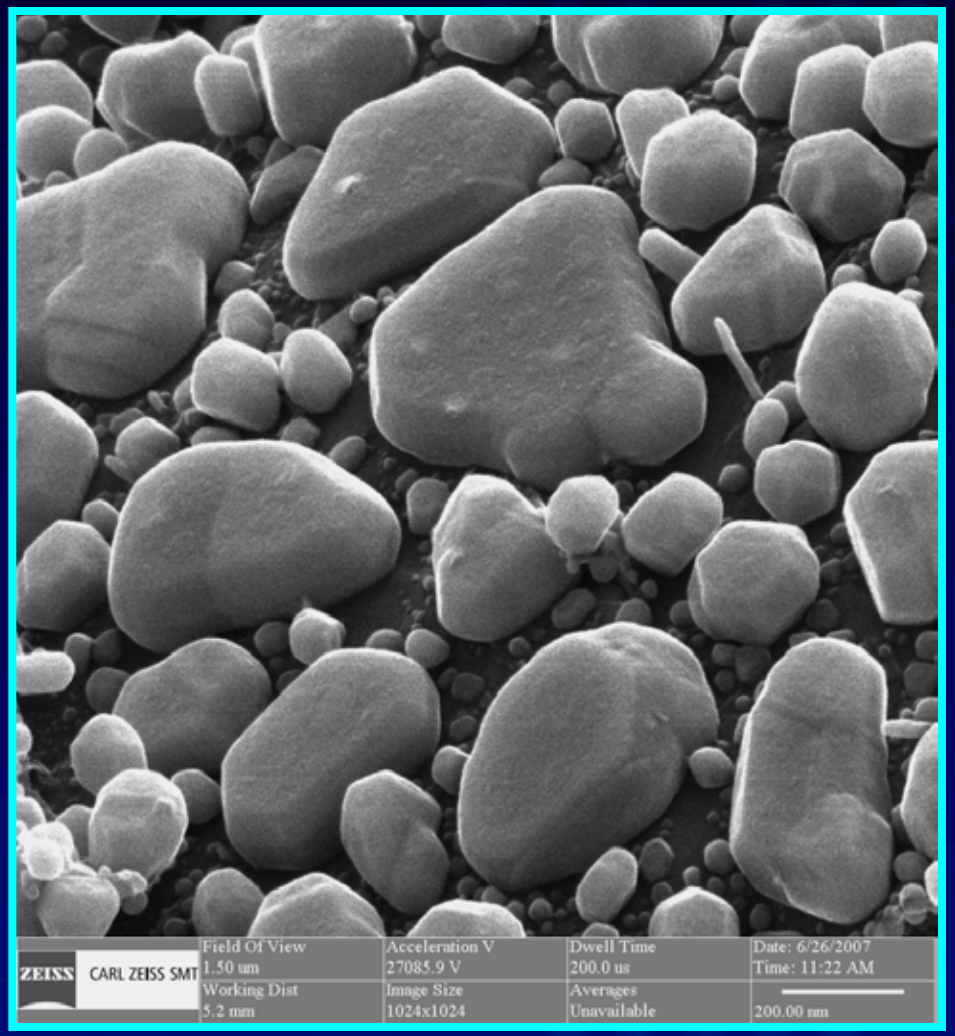


- 1 keV electron beam has a larger interaction volume resulting in SE_1 and SE_2
- 30 kV He beam is still collimated well below the SE escape depth and there is minimal signal contribution from recoil
- HeIM images have a better resolution than a high keV SEM and a smaller sample interaction volume than a low keV SEM

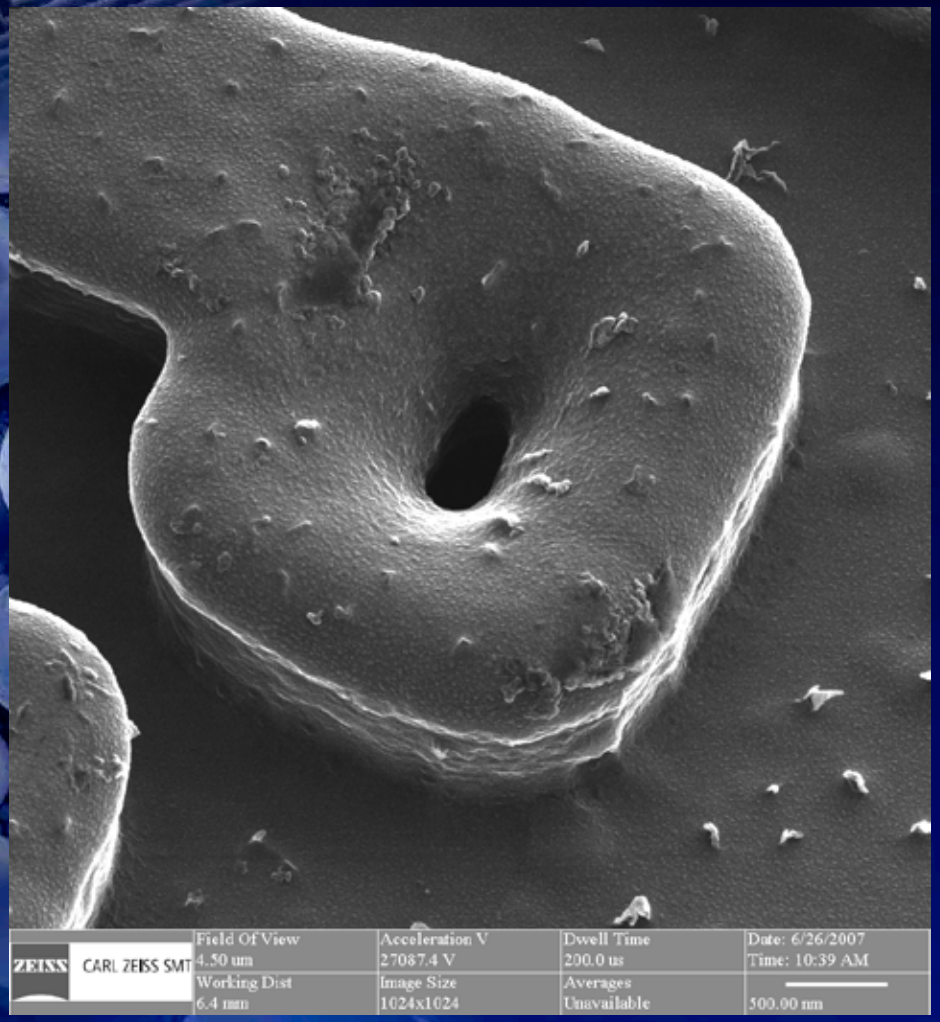
Simulation results from TNO-TU Delft

Helium Ion Microscope (HeIM)

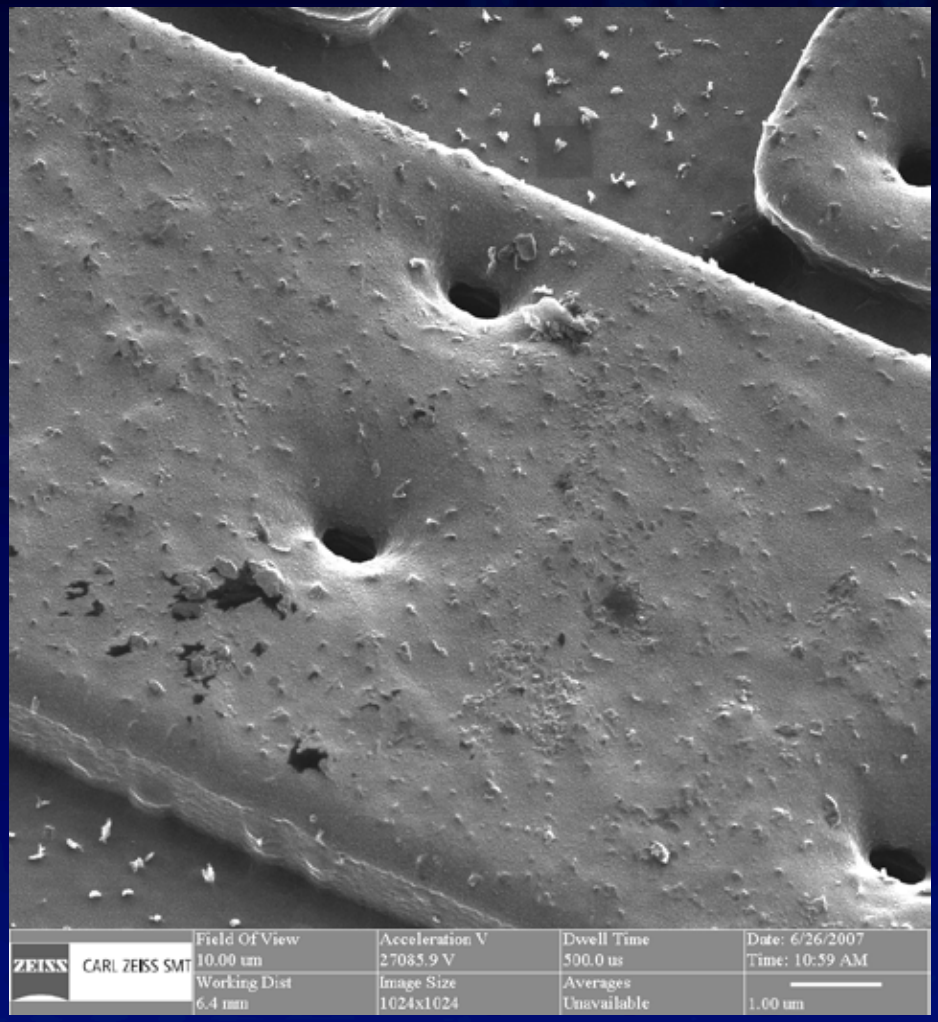
- He^+ beam produces both secondary electrons (SE) and backscattered ions
- SE yield is large, so low beam currents work well
- Interaction volume of He+ beam near the surface is thought to be considerably smaller than that of an SEM
- The excited volume is restricted and SE generation is near the surface
- At the same energy, the wavelength of the He ions is much smaller than that of the electrons



HeIM Image: High Surface Sensitivity

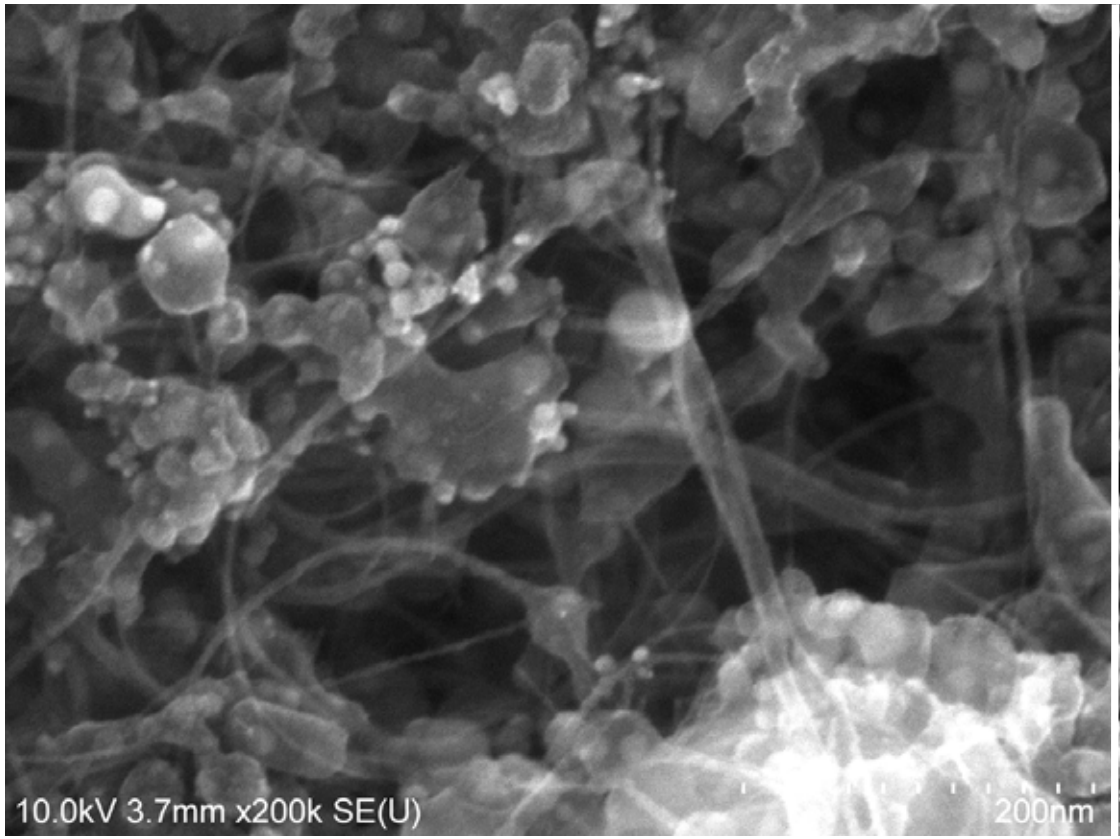


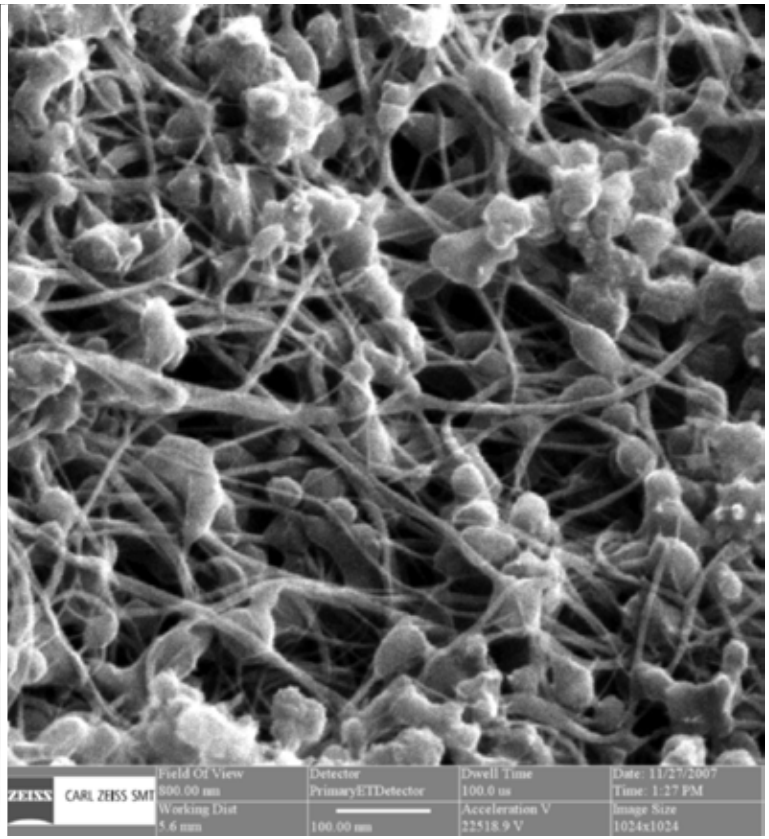
field of view = 4.5 micrometers



field of view = 10.0 micrometers

Comparison of carbon nanotube imaging

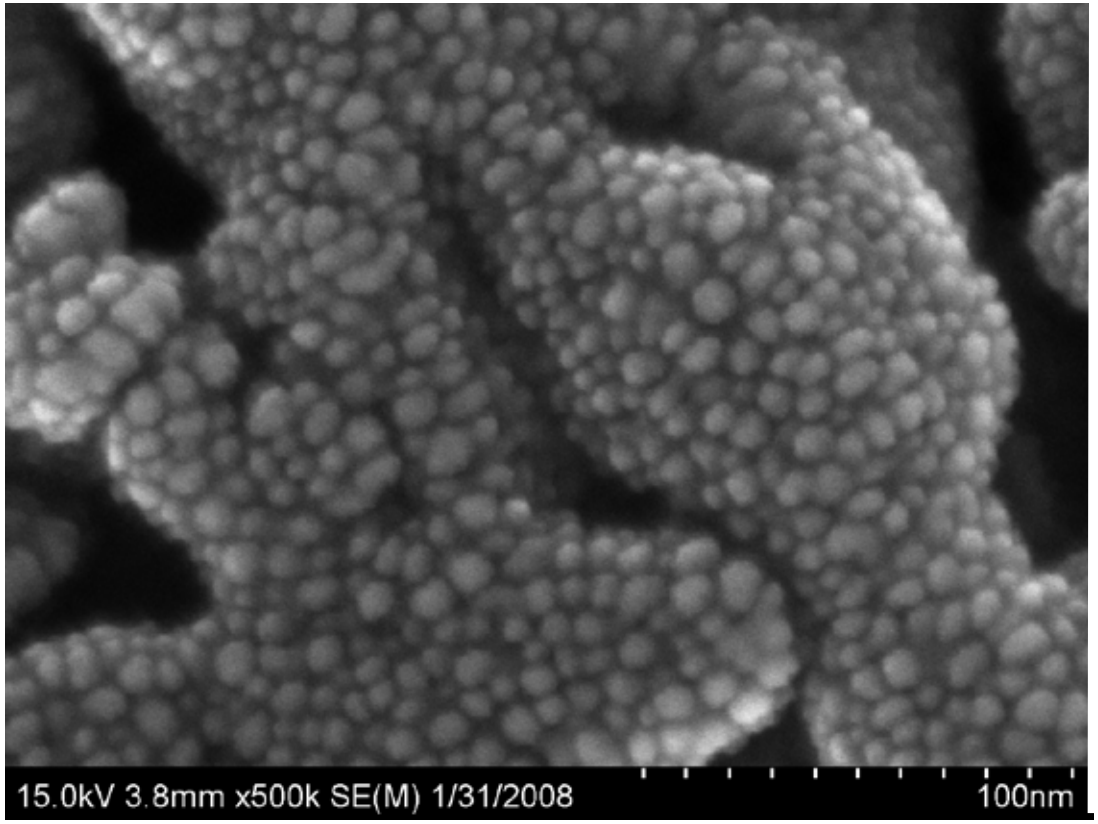




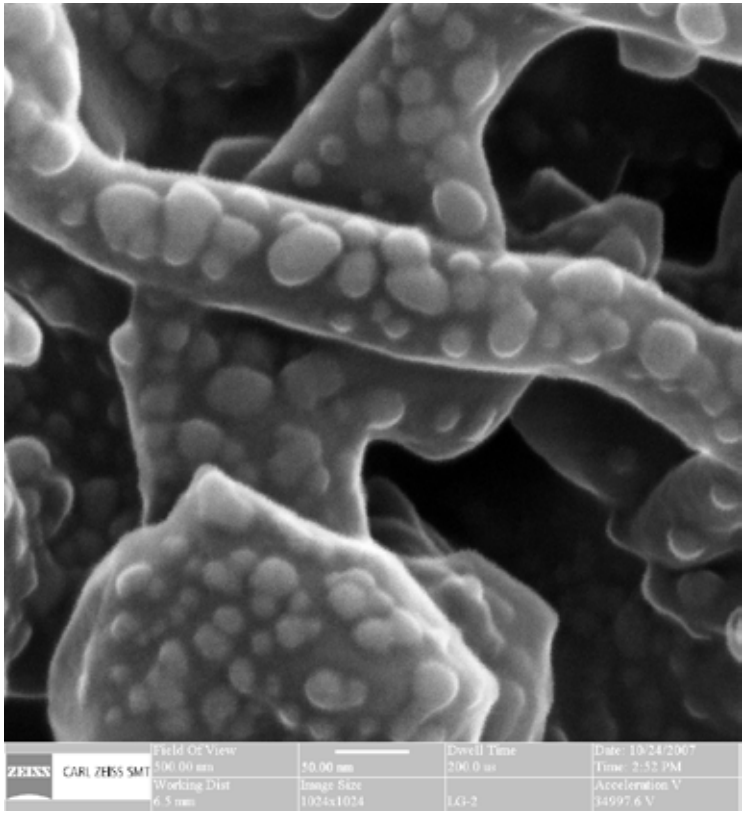
SEM image
field of view = 630 nm

HeIM image
field of view = 800nm

Comparison of magnetic tape resolution sample images



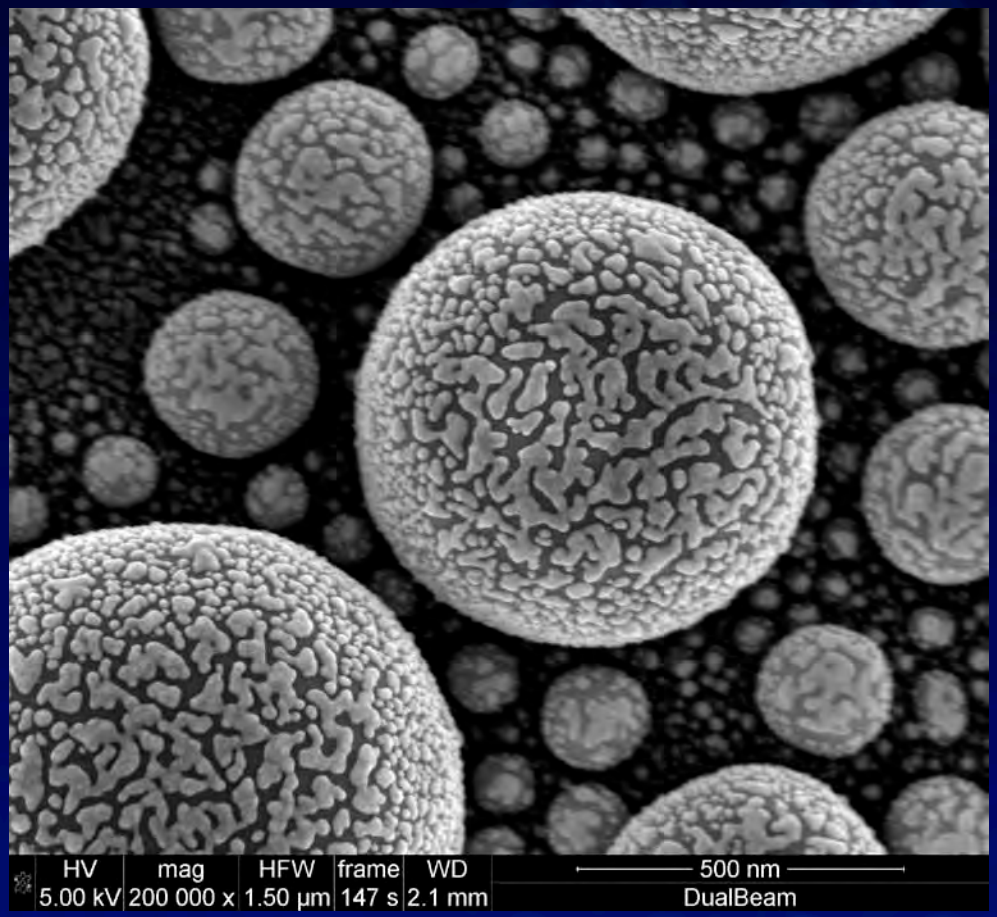
SEM image
field of view = 260 nm



HeIM image
field of view = 500nm

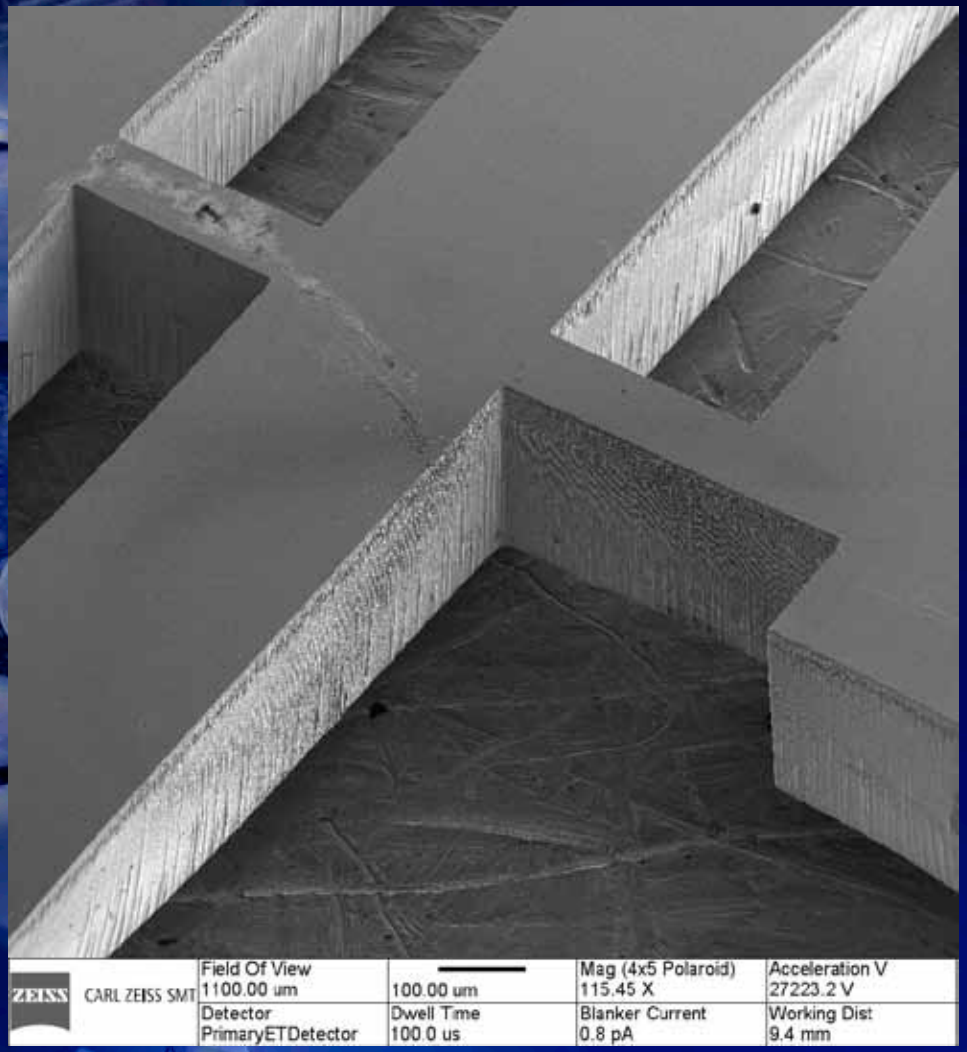
HeIM and SEM Depth of Field

High vacuum, high landing energy helium ion microscope (HeIM) image of Au-decorated tin ball resolution sample. 1.5 mm field of view

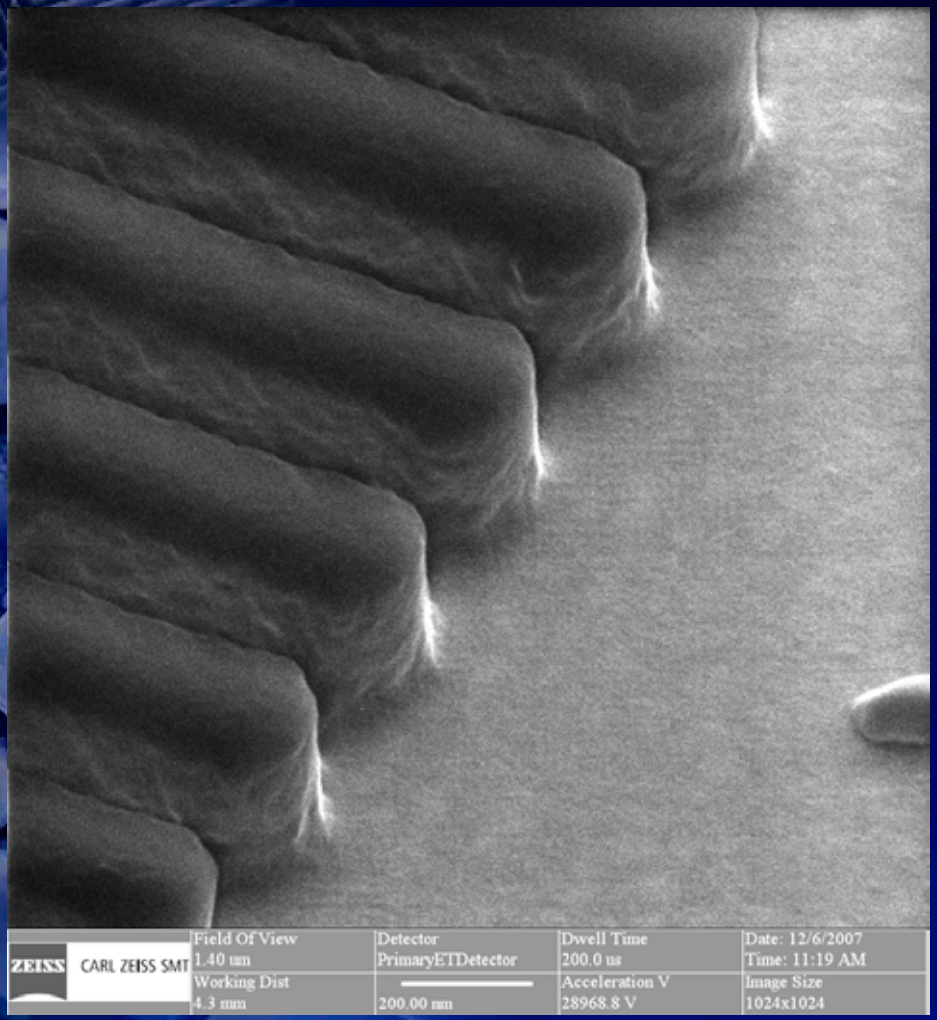


High vacuum, medium landing energy SEM image of Au-decorated tin ball resolution sample. 1.5 mm field of view

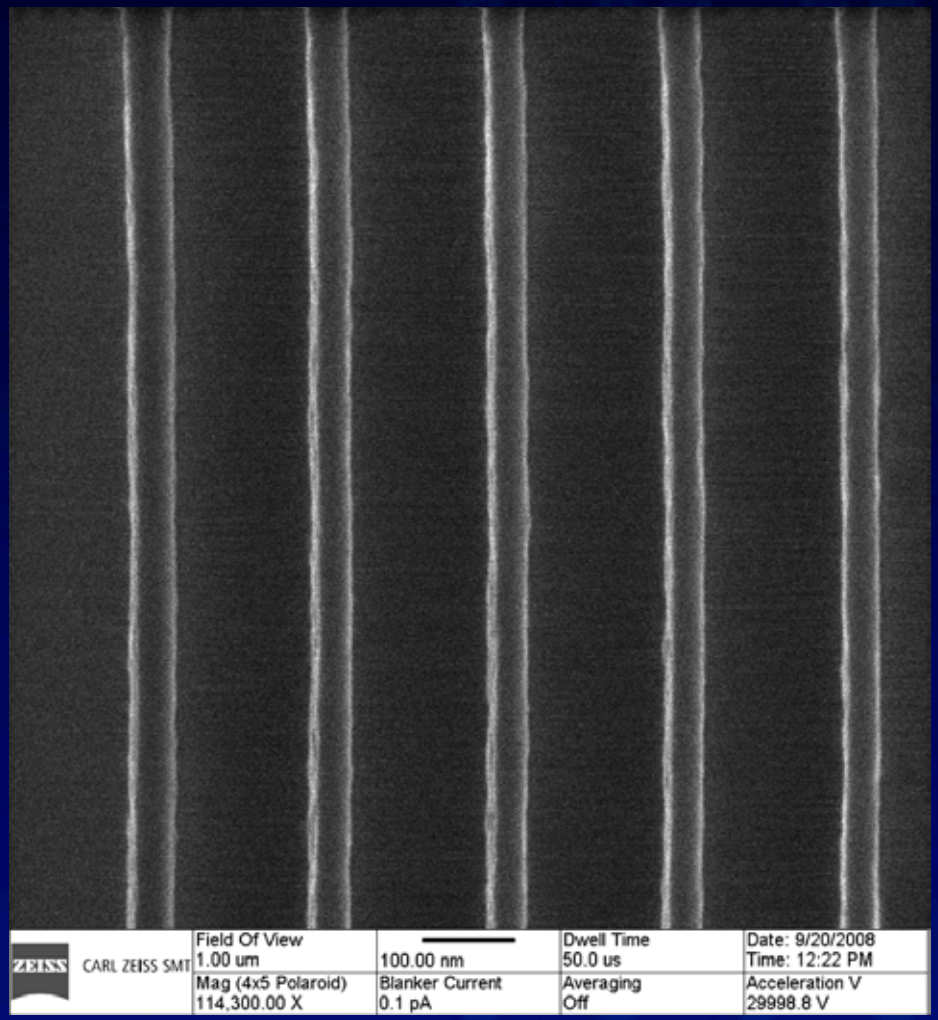
HeIM Depth of Field for large samples



HeIM imaging of Resist Samples

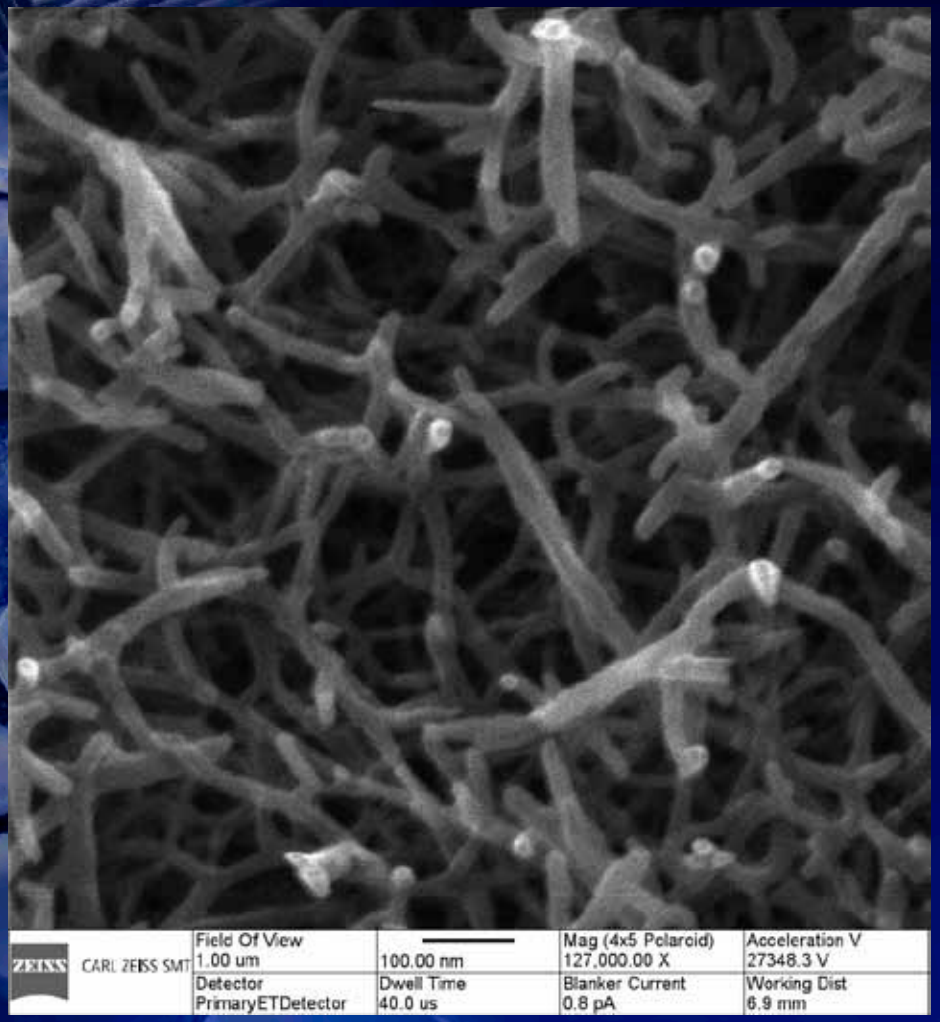


Tilted view of resist wide lines on Si, 1.4 mm field of view.



40 nm wide resist patterns showing wall roughness, 0.1 pA beam current, 1 mm field of view.

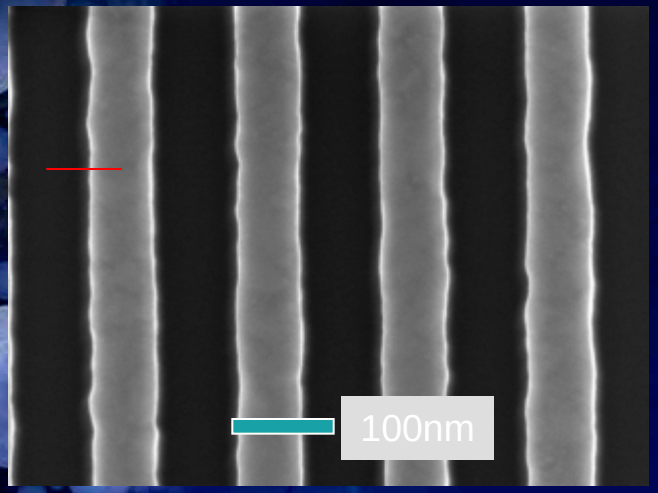
HeIM Imaging of Organic Materials

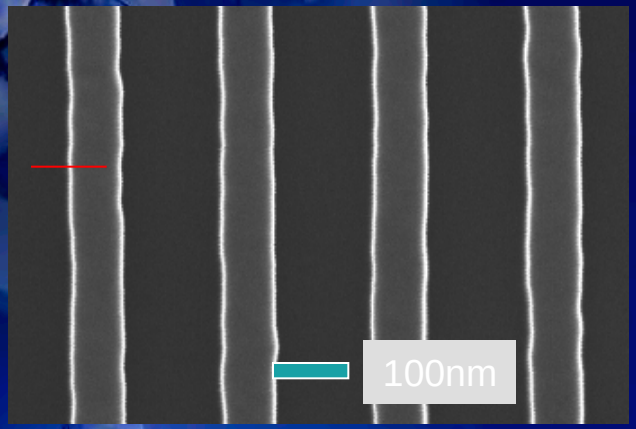


Cellulose Nanocrystal fibers

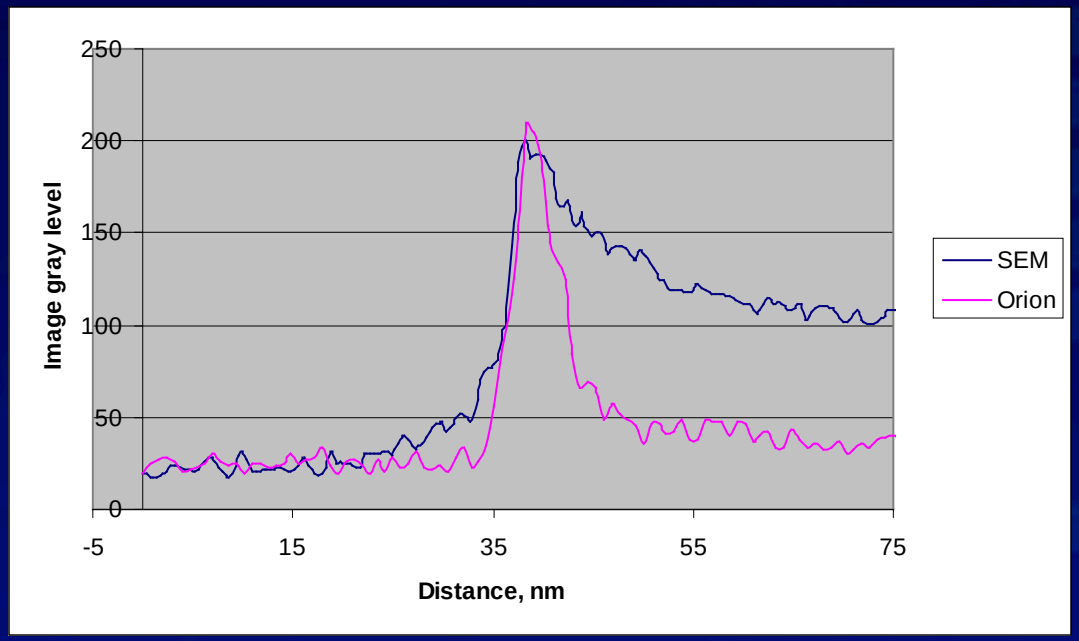
Cross Sectional View of Mesoporous Silica

Metrology Example: Poly Line-Space Array

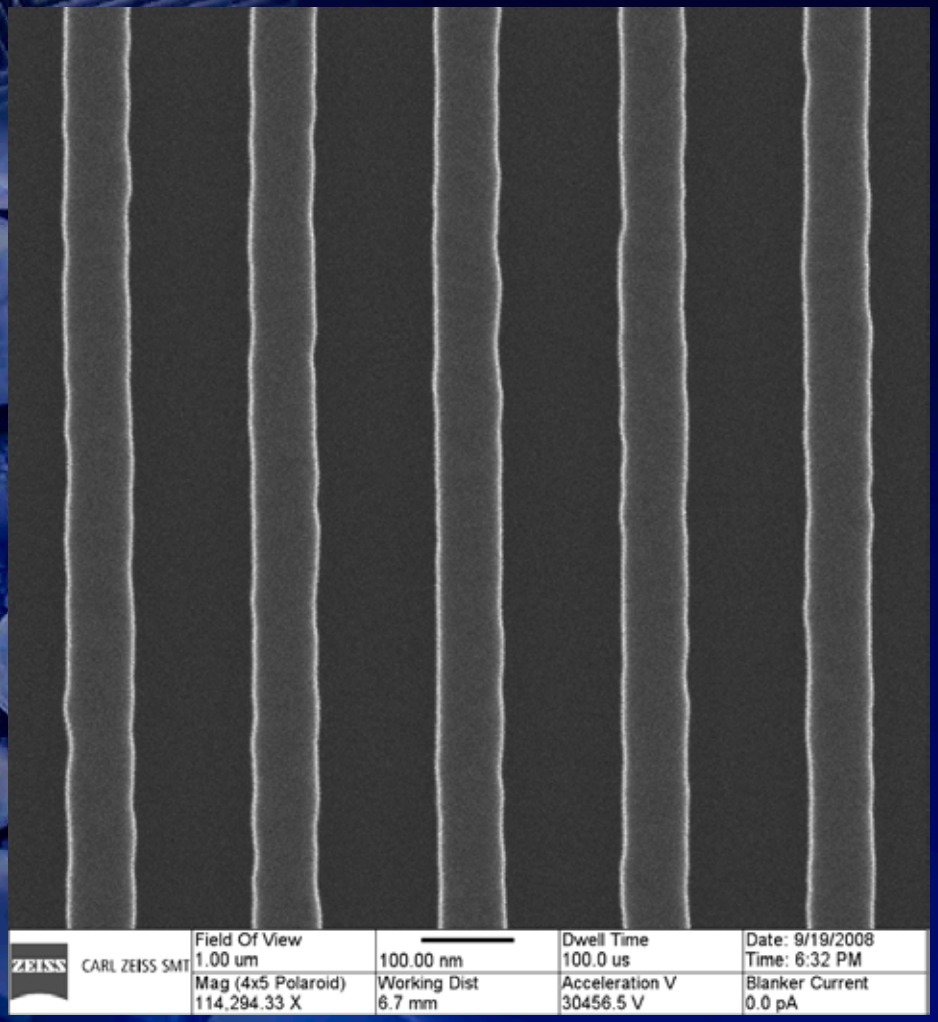




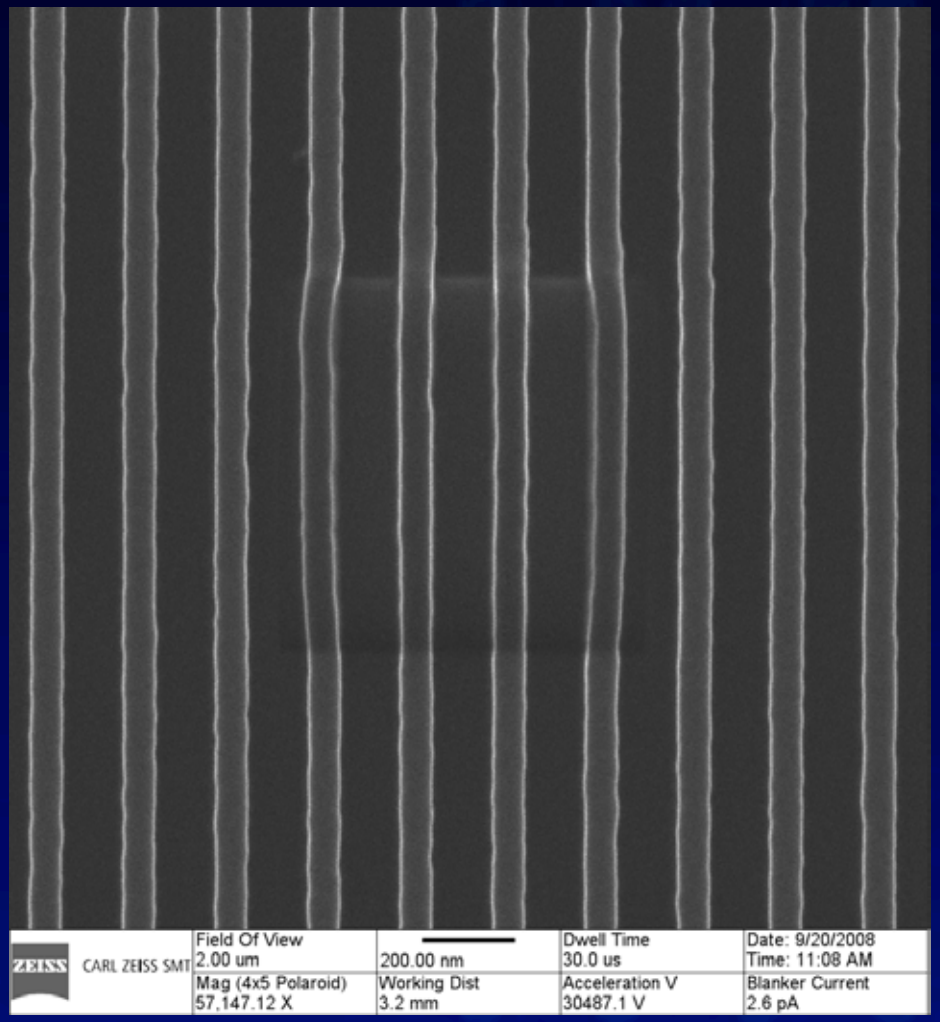
- Sub-100nm lines
- Single line scans at positions indicated
- HeIM line scan shows extremely sharp drop to substrate signal level.



HeIM imaging of Amorphous Si

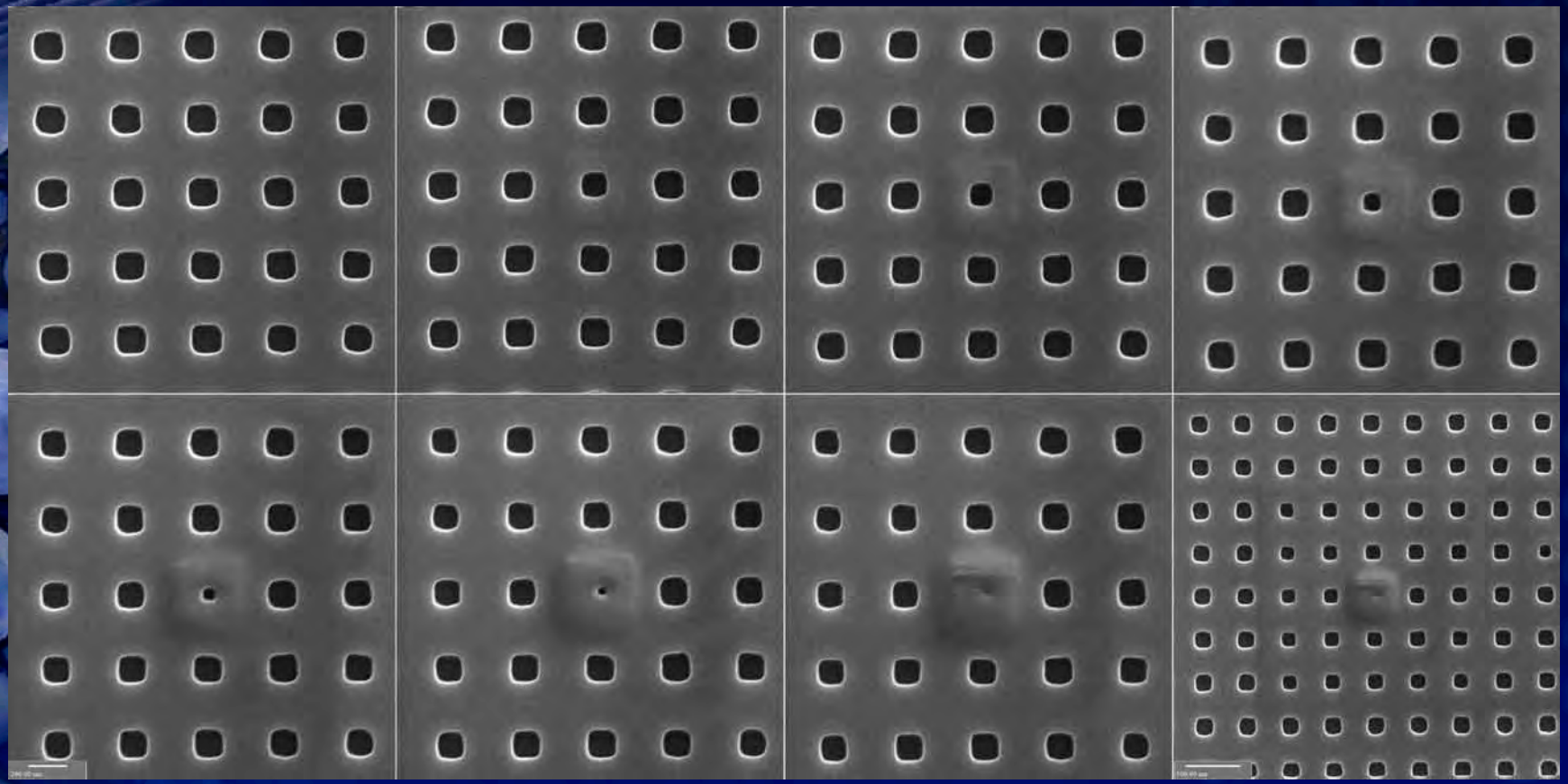


65 nm wide amorphous Si lines on Si, 1 ㎛ field of view.



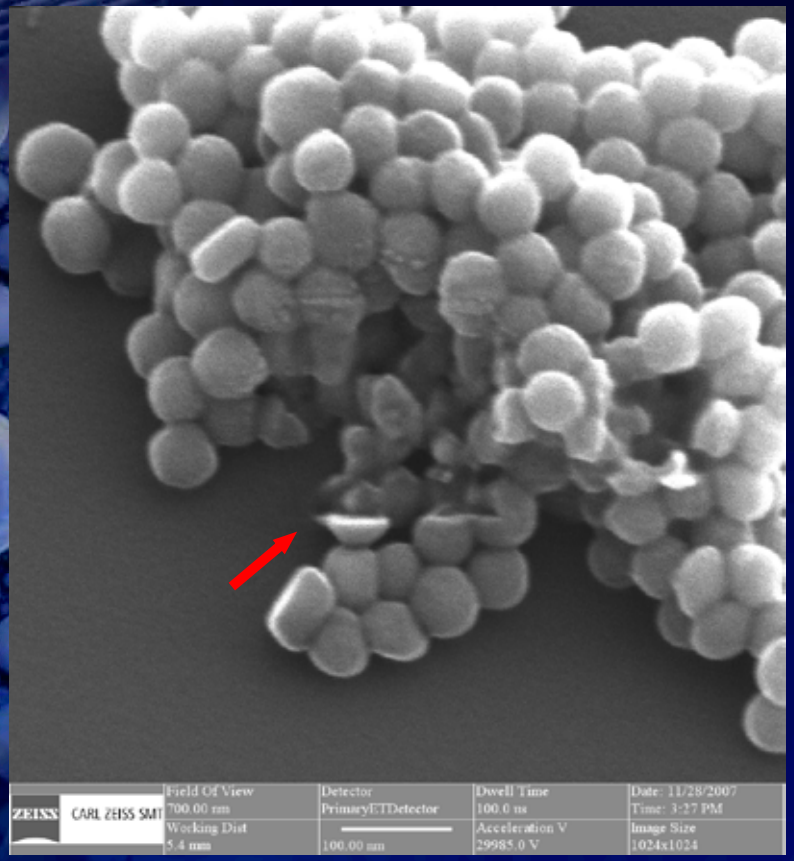
Amorphous Si on Si sample showing swelling due to He ion irradiation. 2 pA beam current, 2 ㎛ field of view.

HeIM imaging of an EUV Mask

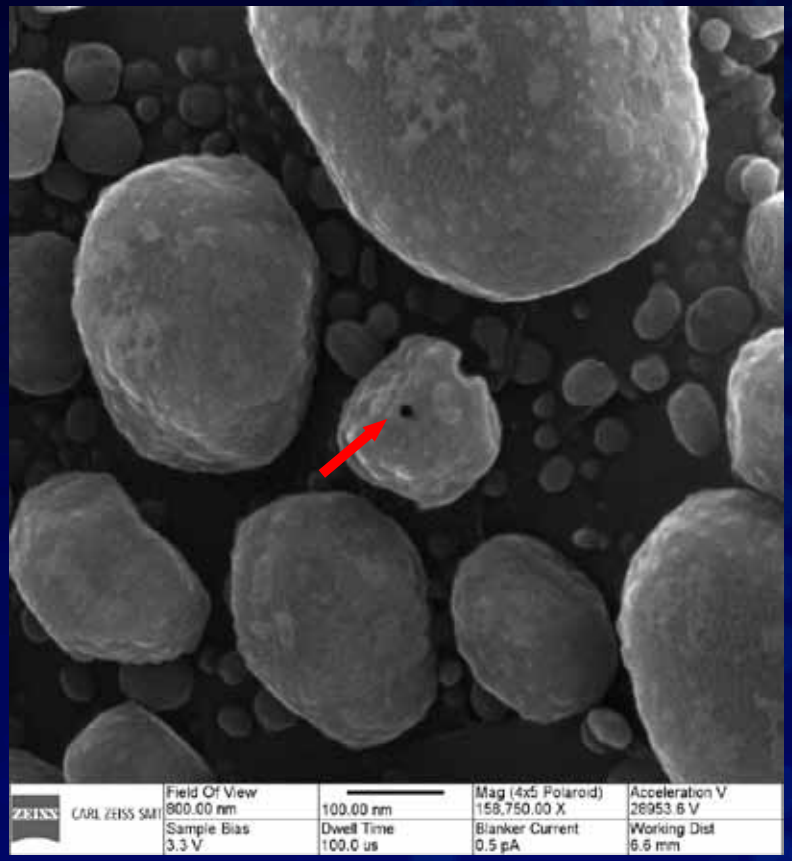


HeIM SE images of an EUV mask. The central contact hole gradually closed during the repeated He ion bombardment (The field of view is 2 mm for most images). The lower right corner image shows that all holes that were irradiated by the He ion beam got somewhat smaller. 2 pA beam current and approximately 15 minutes overall irradiation time (The field of view is 3.5 mm)

HeIM Nano-Milling

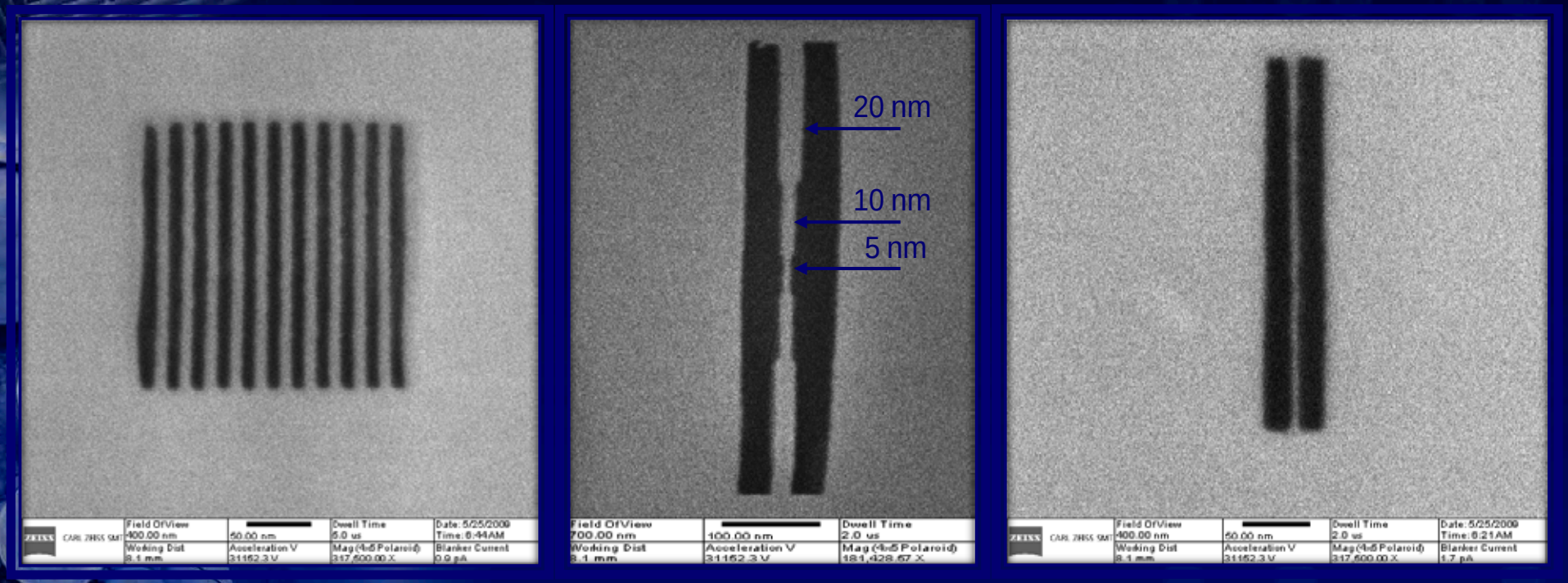


- HeIM SE image of 30 nm Au particle sample after nano-milling. 700 nm field of view



- An aperture of 10 nm size created by HeIM nano-milling. 800 nm field of view

HeIM Nano-Milling on Graphene



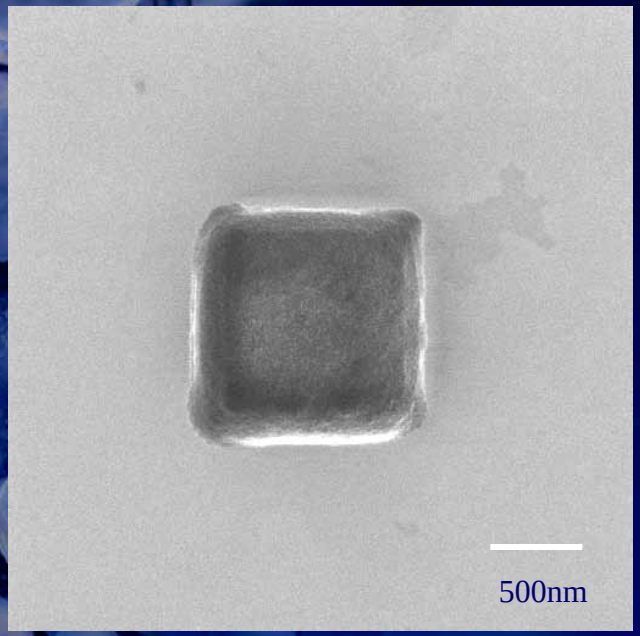
HIM SE images of patterns produced by He beam nano-milling of 1 to 3 atom thick suspended graphene layer.

Left: 10 nm dense lines and spaces, middle: ribbon linewidth control, right: 300 nm long 5 nm wide ribbon. FOW 400 nm, 700 nm, and 400 nm, respectively

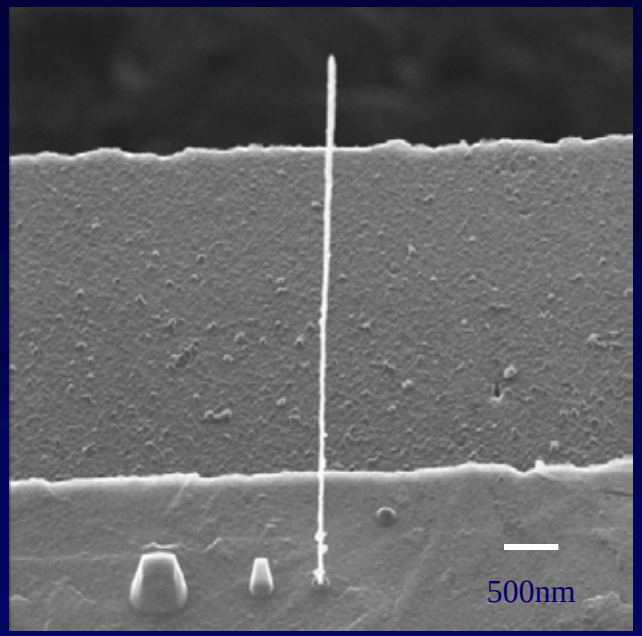
Images of Dr. Daniel Pickard National University of Singapore

HeIM Nano-Manufacturing

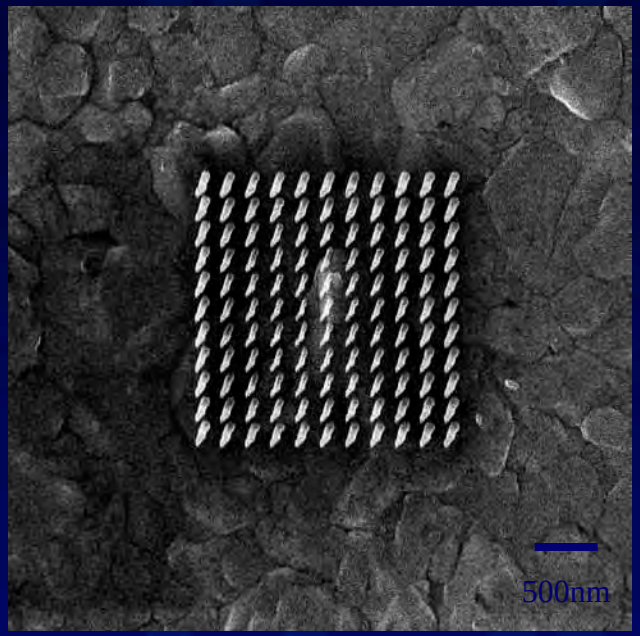
Gas-Induced Etching and Deposition



Si etch with XeF_2



Tungsten needle
45 nm wide, 7.9 um high

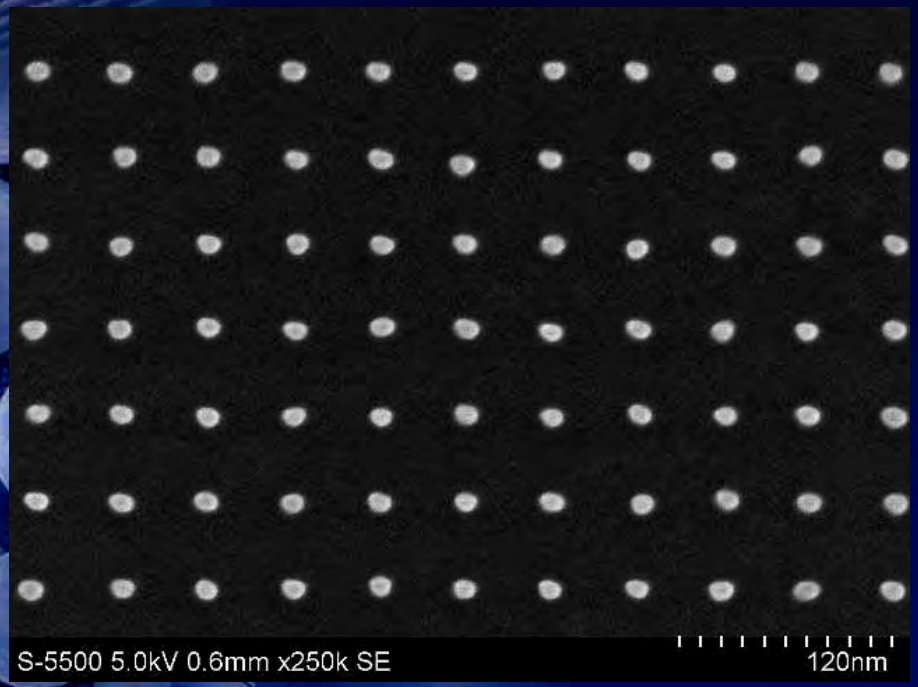


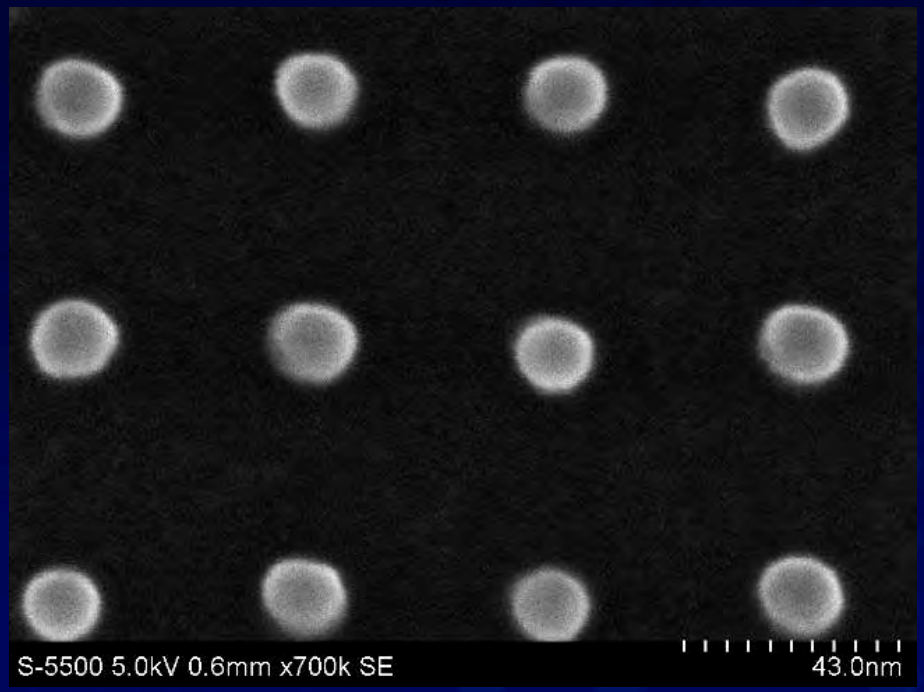
20 nm tungsten pillars

- Small probe size, small interaction volume, and an efficient interaction between helium beam and chemical precursors make the HeIM an ideal tool for nano-manufacturing applications

Courtesy of Carl Zeiss SMT

High-Throughput Helim Ion Lithography

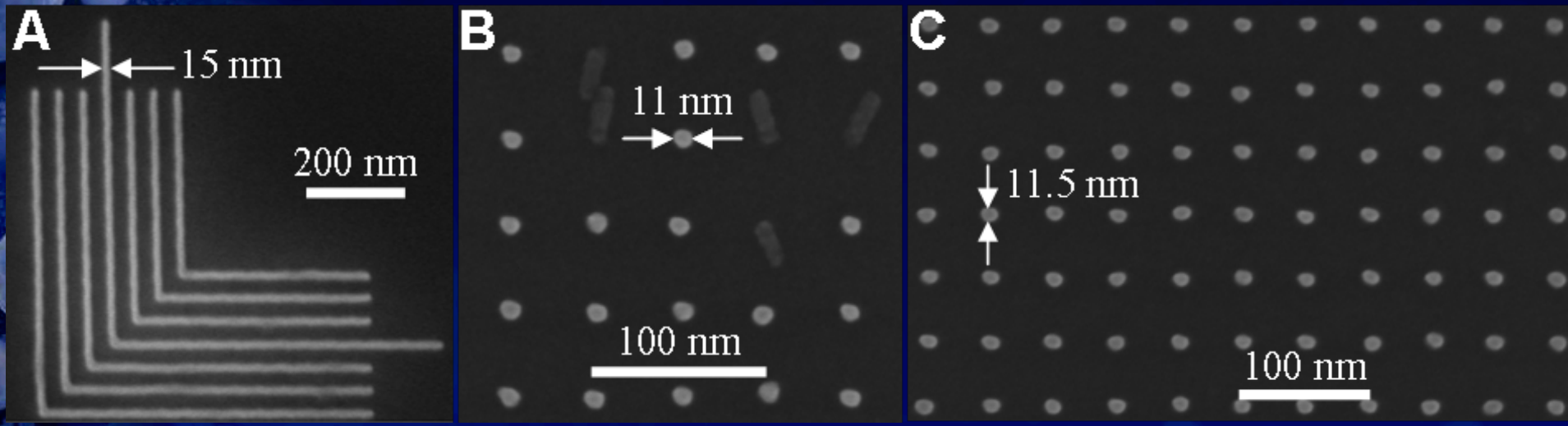




Dense array of 15 nm hydrogen silsesquioxane (HSQ) resist posts generated by He ion lithography 500 nm field of view (left) and 180 nm field of view (right).

- Very low dose is enough to expose resist
- 1000 fold speed advantage over e-beam litho might be possible

High Aspect Ratio Patterning by Helium Ion Lithography



Scanning Electron Microscope	Helium Ion Microscope
Penetration effects limit surface detail	Excellent surface detail
Positive and negative electron charging possible	Positive charging possible but can be eliminated by electron flood gun
High beam currents might result in sample damage	High beam currents/doses result in sample damage (milling, swelling)
X-ray analysis possible	Other analytical modes need to be pursued
Surface contamination possible but masked by high kV operation	Surface contamination can be a bigger problem
Electromagnetic fields are likely to limit operation	Electromagnetic fields are less likely to limit operation
Mechanical vibration limits high-resolution operation	Mechanical vibration is a serious limit to high-resolution operation
Established and relative mature emitter technology	Emitter technology is still in development
Source demagnification at sample 100-12,000 x depending on column design	Source demagnification ~3-50 x
Lithography, material deposition possible	Nano-milling, lithography and material deposition possible

Helium Ion Microscopy

- The helium ion microscope (HeIM) is reaching a stage of maturity. It's highly desirable to explore what this technology could bring to the various industries.
- Foreseeable applications include
  - Dimensional metrology of resist and developed wafers
  - Dimensional metrology of traditional and advanced masks
  - Ion beam lithography (very high sensitivity/throughput)
  - Mask fabrication and repair
  - Nano-etching, nano-scale deposition
  - Direct device fabrication/alteration
  - Particle composition analysis at the nm scale
- Useful simulation modeling software package is available already.

HeIM and FIB

- FIB and HeIM
  - Each has unique advantages/strengths
  - Remain complimentary
- As a revolutionary technology, HeIM is forging new ground for both imaging and patterning at the nanoscale.