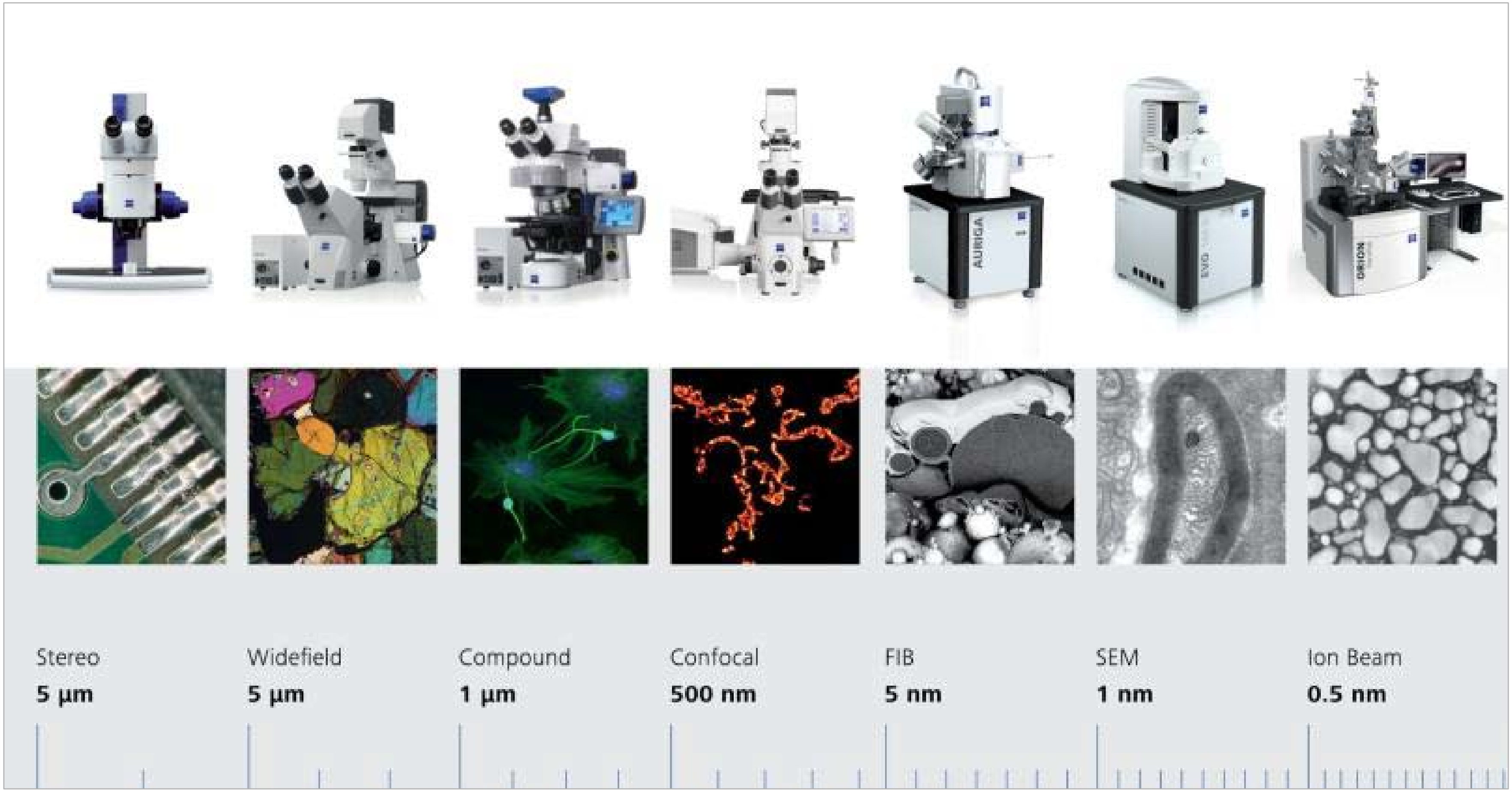
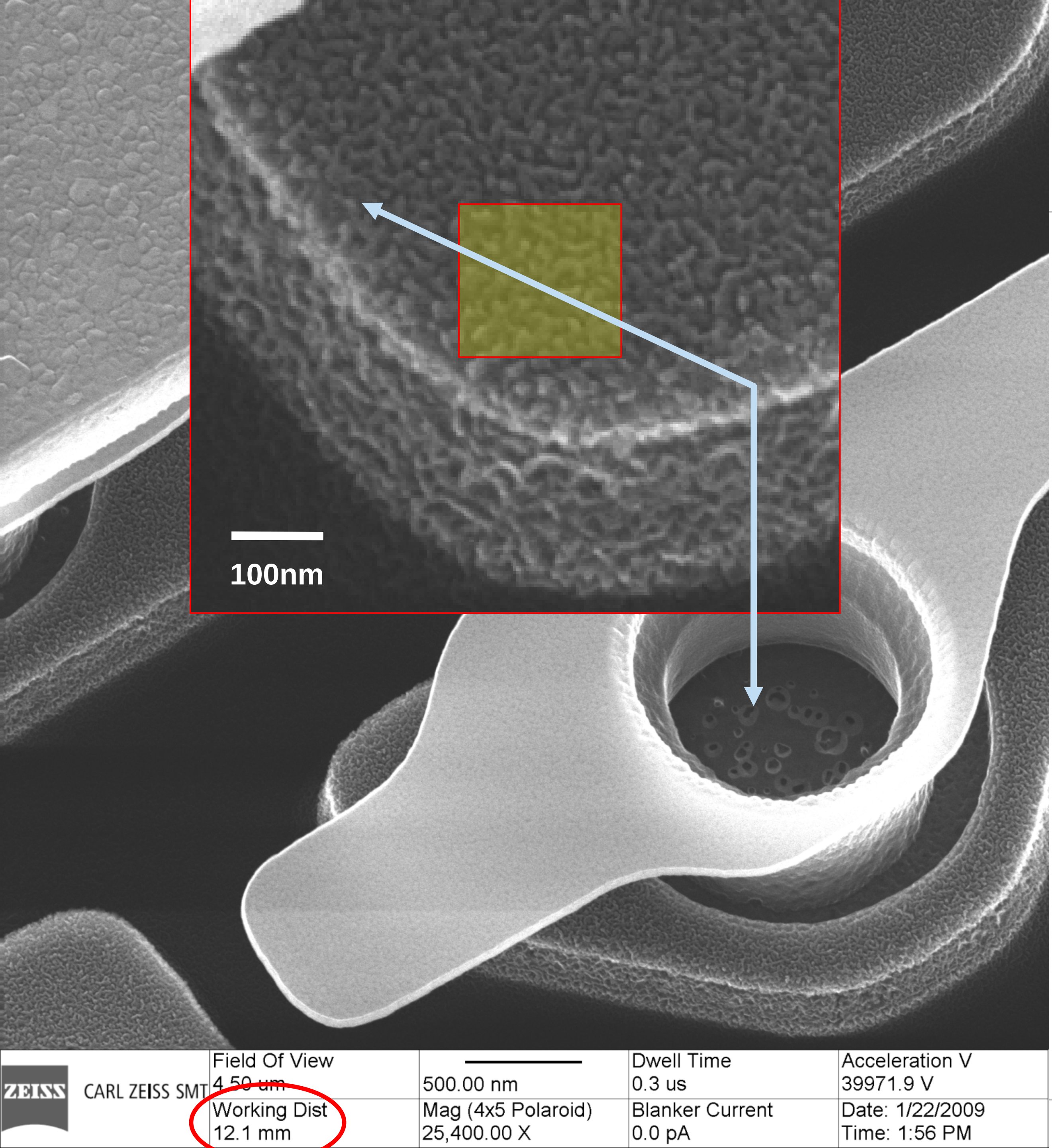
Helium Ion Microscopy:
High Resolution Imaging and sub-10 nm Nanostructuring

Peter Gnauck

Microscopy Landscape



From the micrometer to the sub-nanometer scale…



CARL ZEISS SMT	Field Of View 4.50 um	500.00 nm	Dwell Time 0.3 us	Acceleration V 39971.9 V
	Working Dist 12.1 mm	Mag (4x5 Polaroid) 25,400.00 X	Blanker Current 0.0 pA	Date: 1/22/2009 Time: 1:56 PM

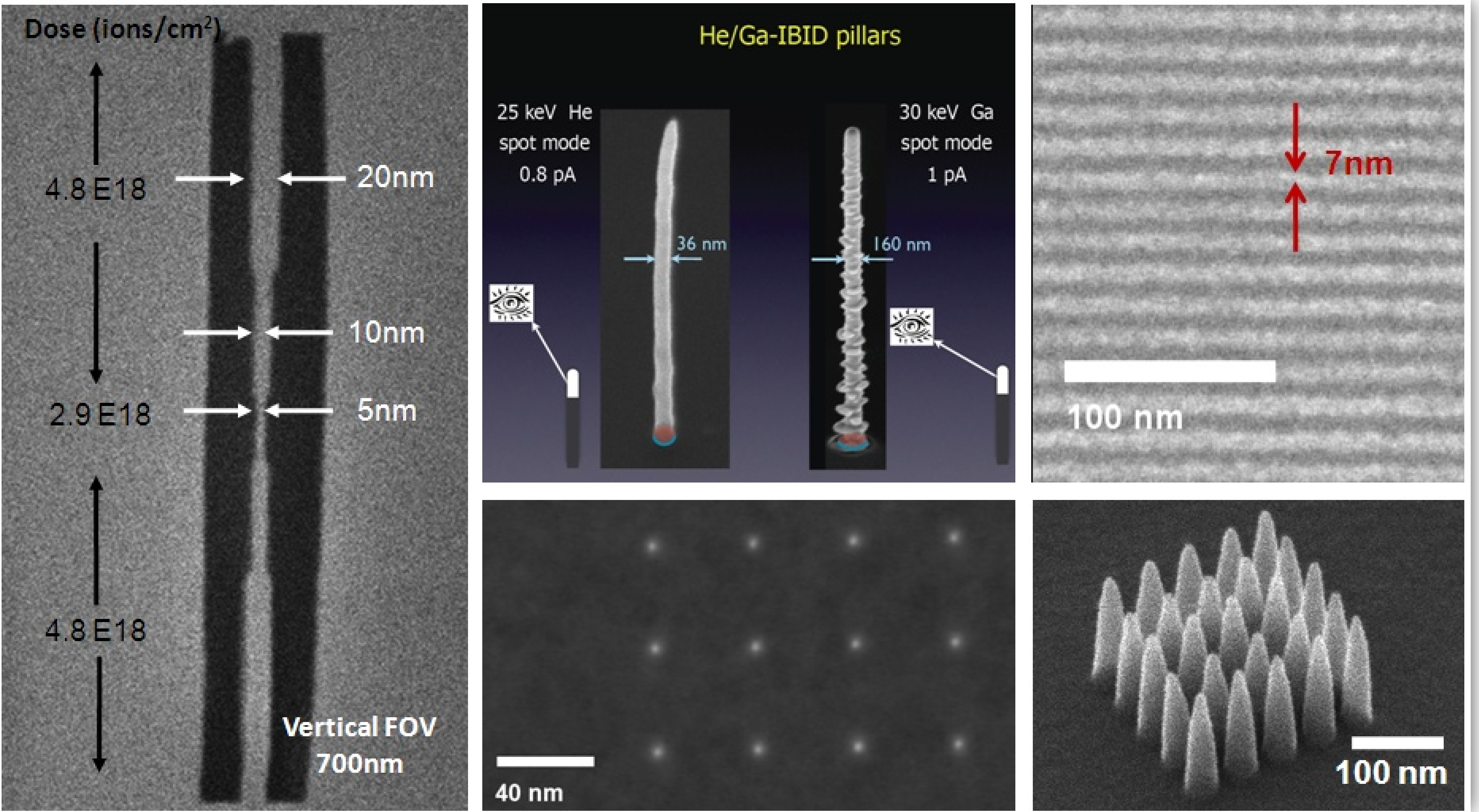
Imaging

- **High lateral resolution**
- **Surface sensitivity**
- **Large depth of field**
- **No charging**

Top and bottom of a processed DLP chip

sample courtesy of TI

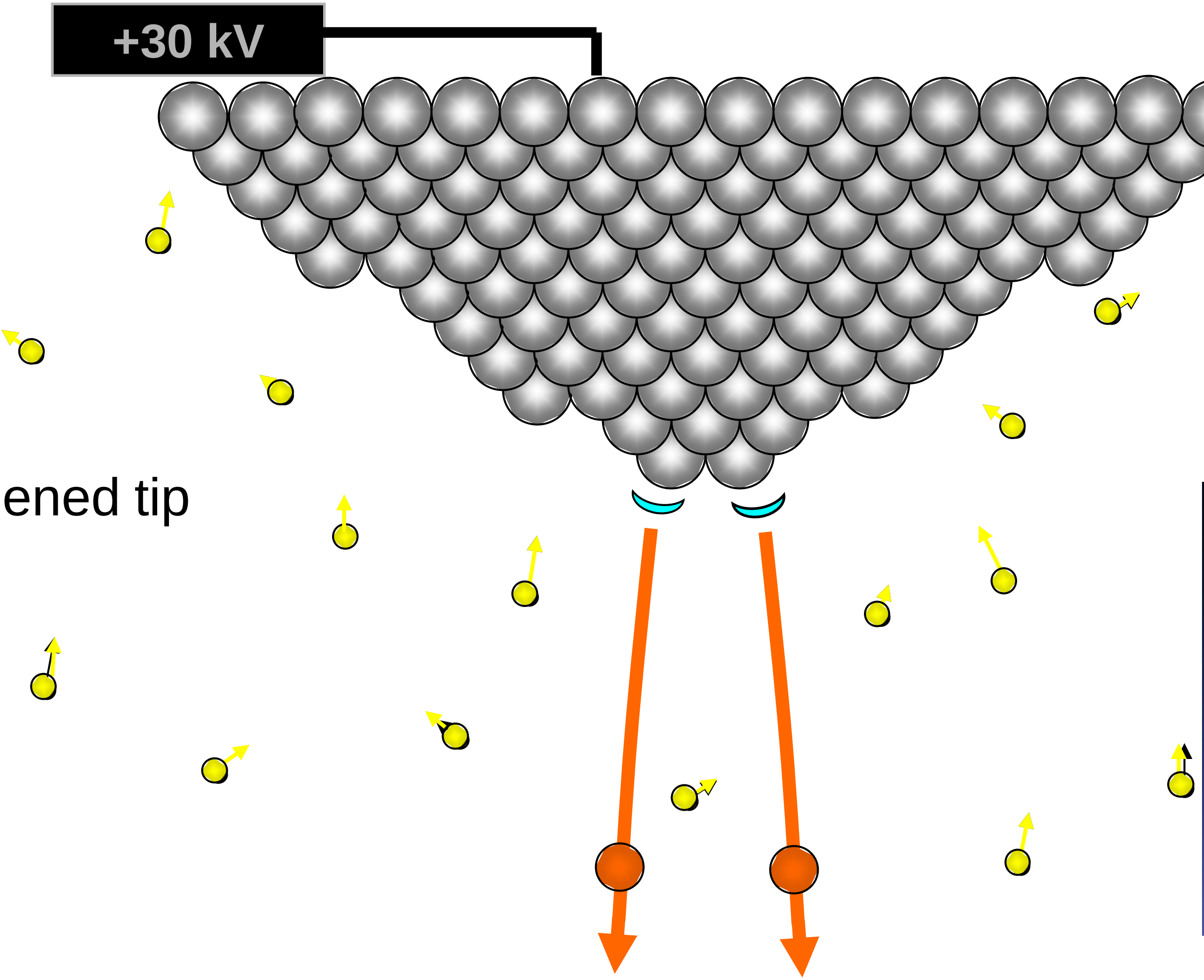
3D Nanofabrication



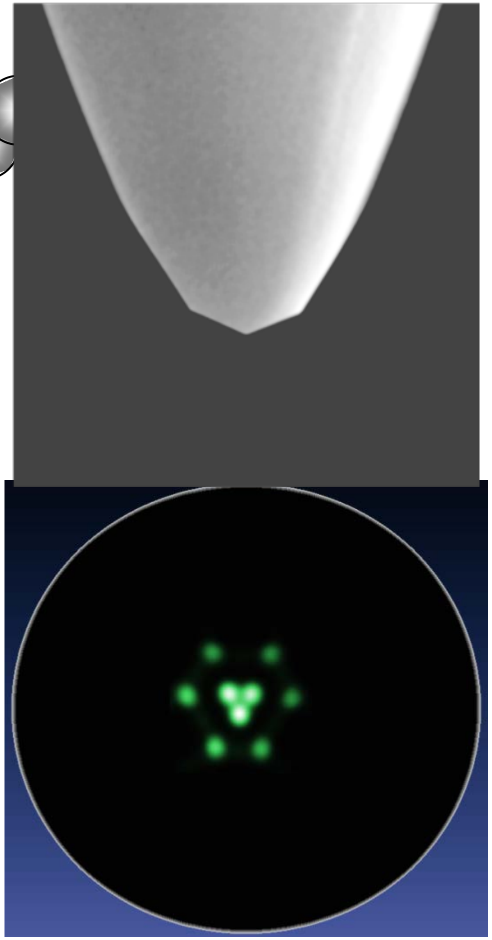
- **Precise and Controlled Nanofabrication**

Final Helium Ion Source

3 Atom Cluster - And Associated FIM Image



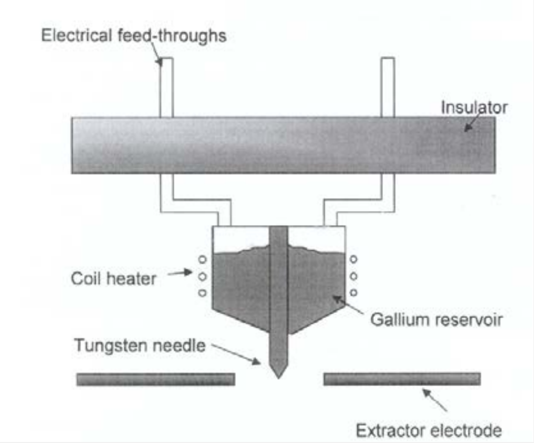
Sharpened tip



Source Technologies

Focused Ion Beam

Liquid Metal Ion Source



Probe Size ~5nm
Brightness ~3X10^6 A/cm^2.sr

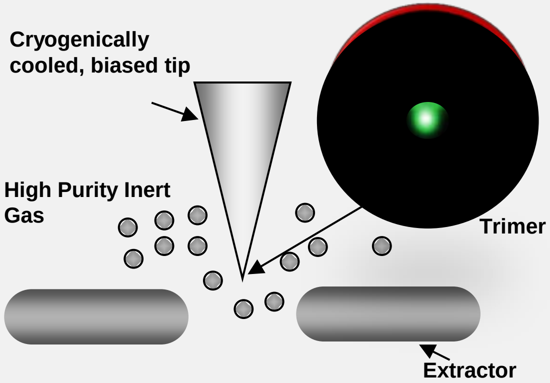
Scanning Electron Microscope

Field Emitter

Probe Size ~0.8nm
Brightness ~5X10^8 A/cm^2.sr

Helium Ion Microscope

Gas Field Ion Source



Probe Size ~0.35nm ✓
Brightness ~5X10^9 A/cm^2.sr ✓

Scanning probe with the highest brightness and smallest probe size

Resolution and Probe Size

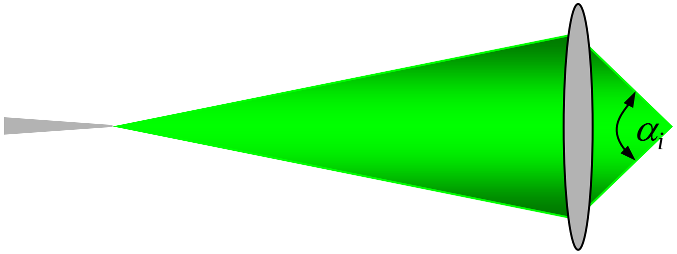
Probe Size: $d_P = \sqrt{(M \cdot d_g)^2 + d_S^2 + d_C^2 + d_d^2}$

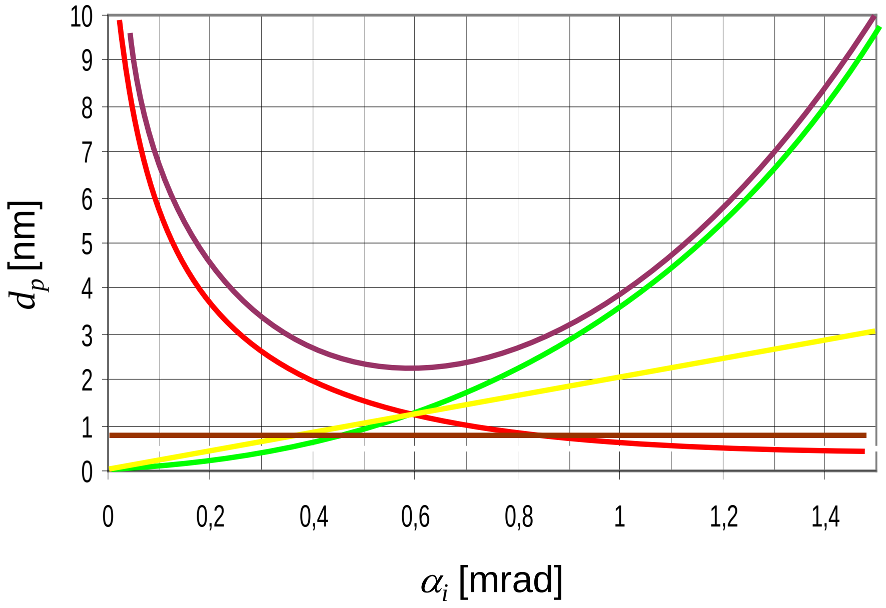
Demagnified source: $d_{So} = M \cdot d_g$

Spherical aberration: $d_S = 0.5 C_S \alpha_i^3$

Chromatic aberration: $d_C = C_C \dfrac{\Delta U}{U} \alpha_i$

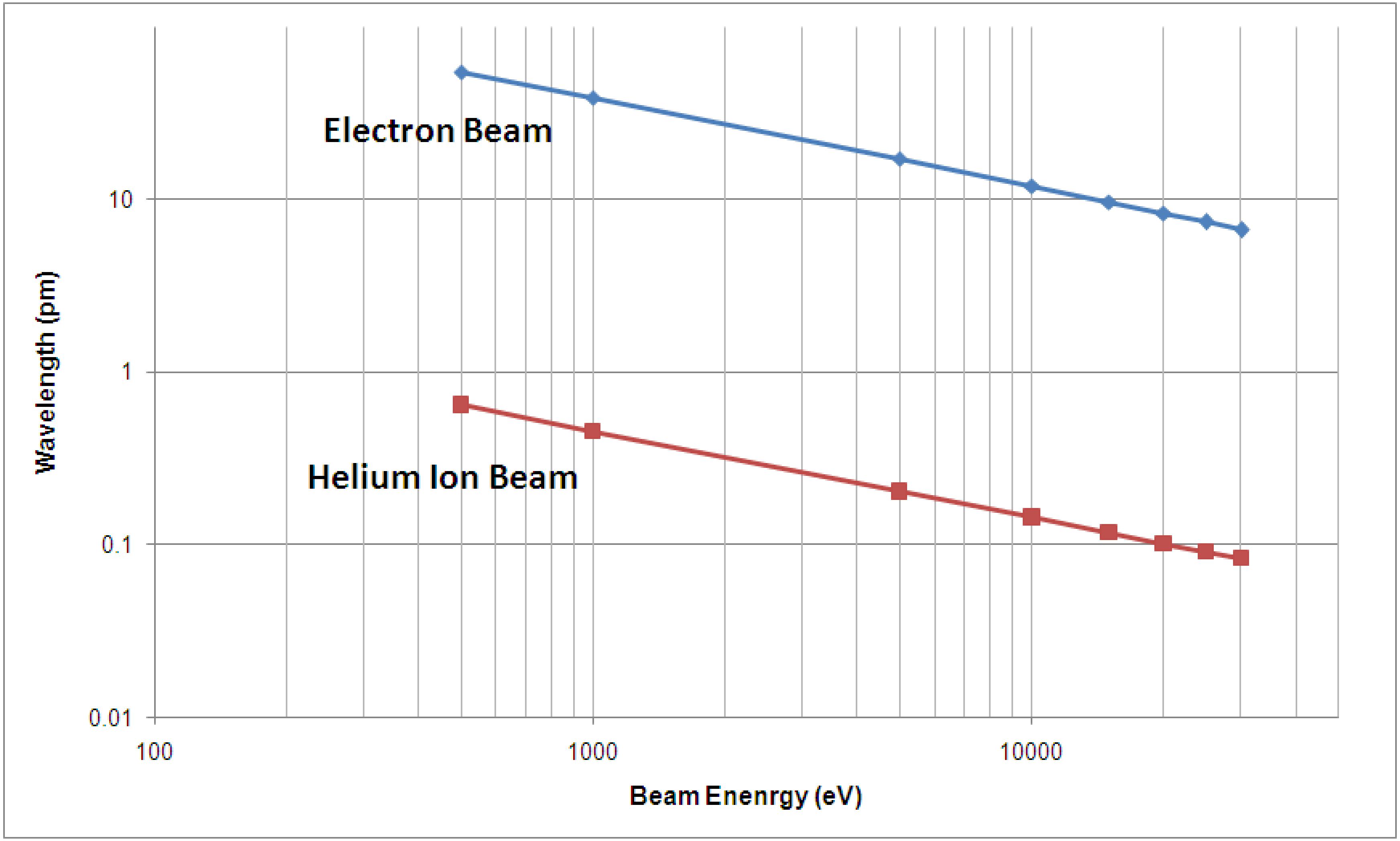
Diffraction Error: $d_d = 0.6 \dfrac{\lambda}{\alpha_i}$





Superposition of the aberration discs

Benefits of GFIS – Resolution and Probe Size



Resolution and Probe Size

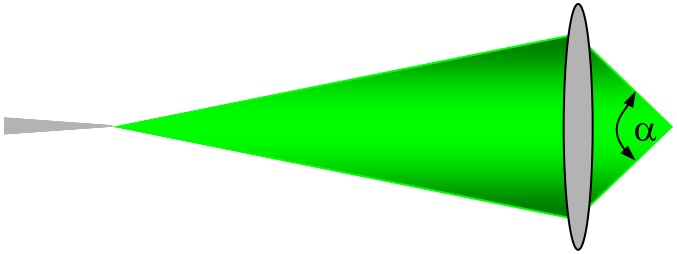
Probe Size: $$d_P = \sqrt{(M \cdot d_g)^2 + d_S^2 + d_C^2 + d_d^2}$$

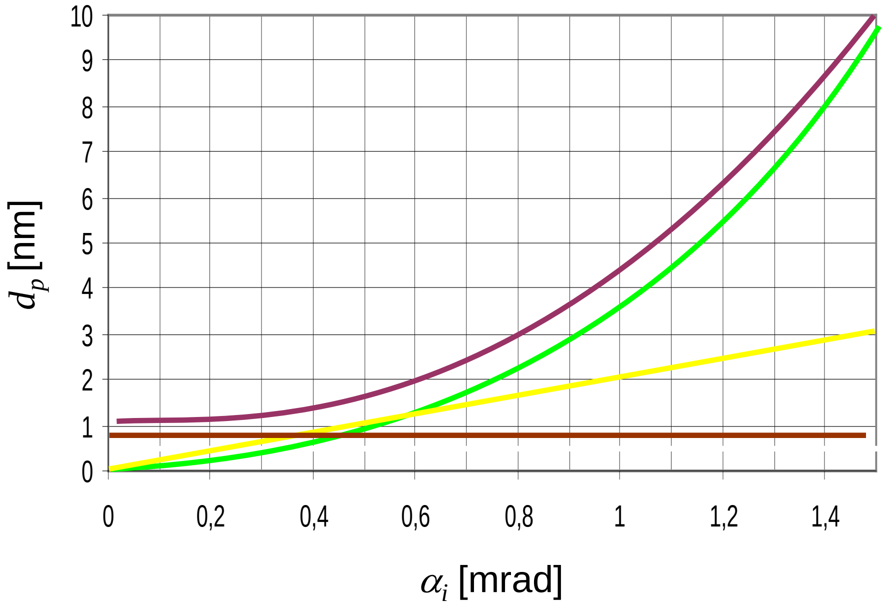
Demagnified source: $$d_{So} = M \cdot d_g$$

Spherical aberration: $$d_S = 0.5 C_S \alpha_i^3$$

Chromatic aberration: $$d_C = C_C \frac{\Delta U}{U} \alpha_i$$

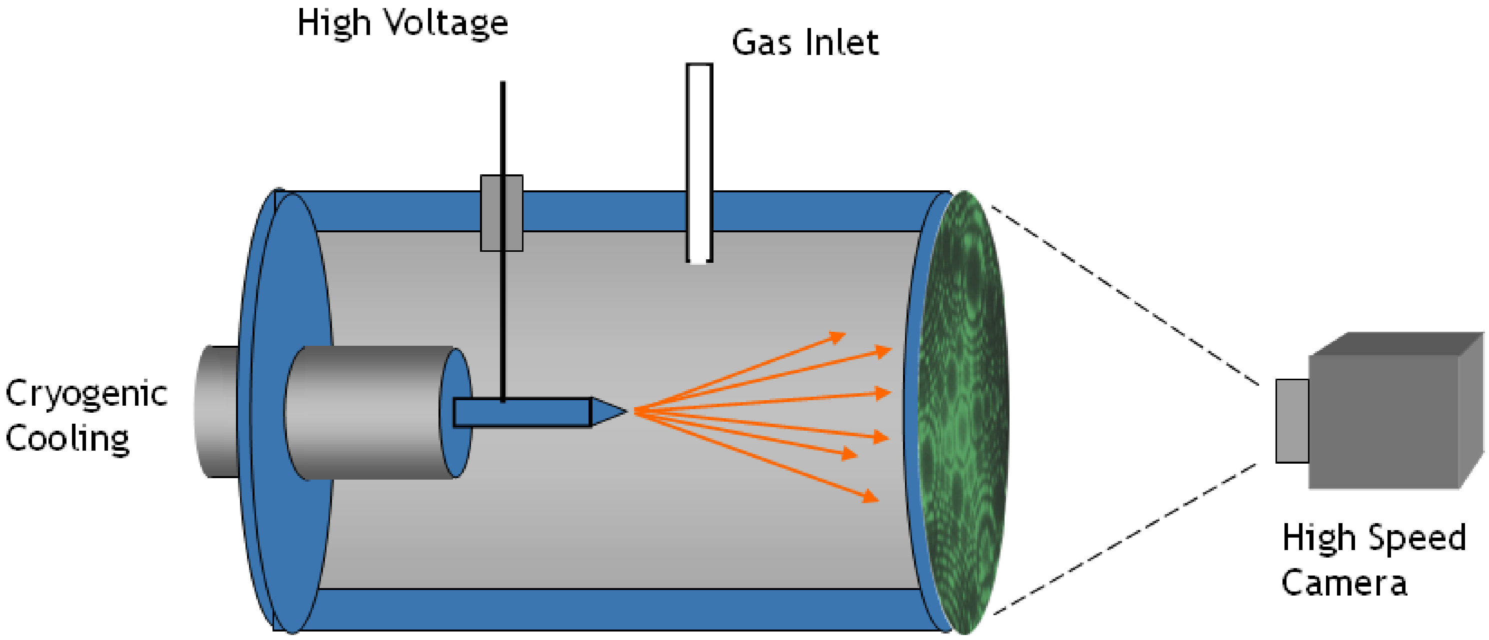
~~*Diffraction Error:*~~ $$\cancel{d_d = 0.6 \frac{\lambda}{\alpha_i}}$$



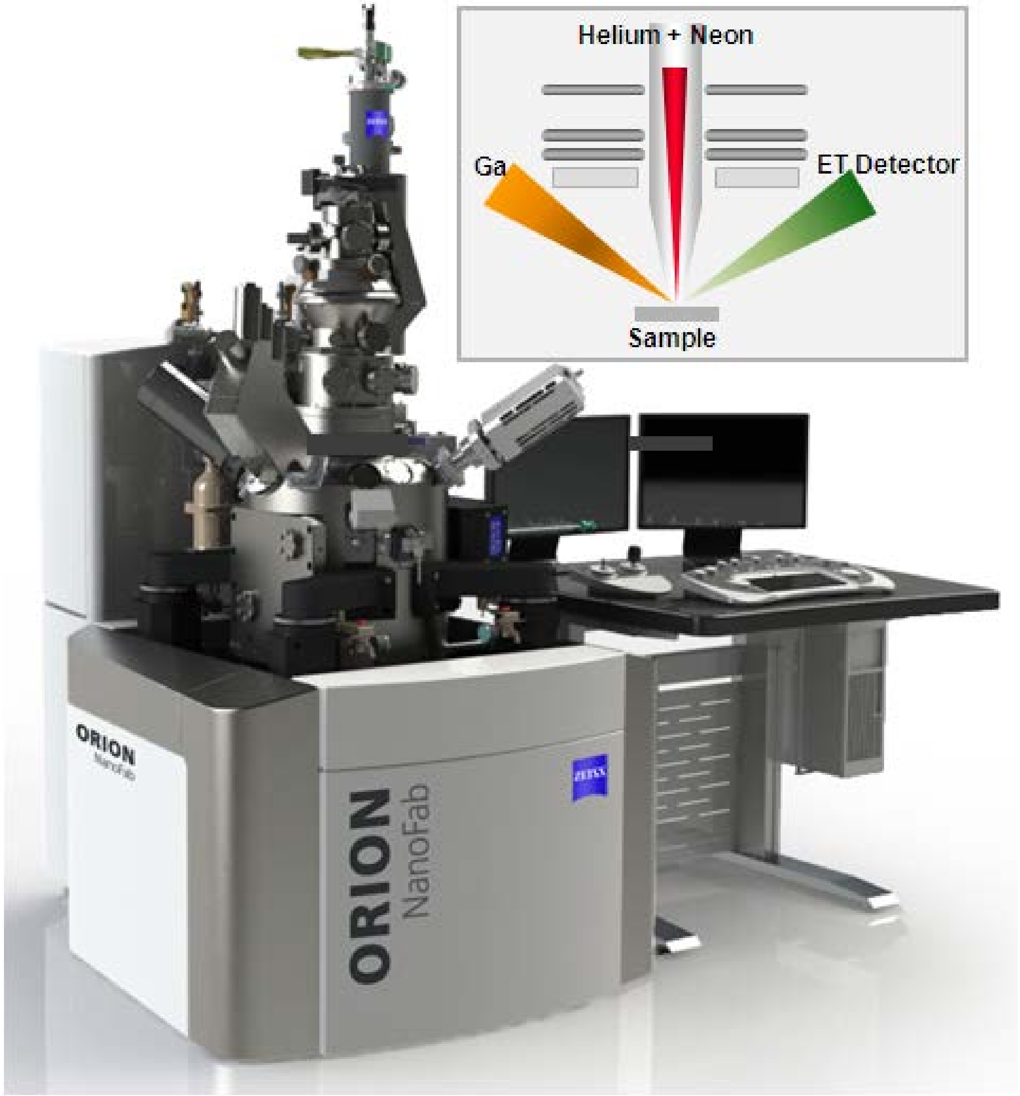


Superposition of the aberration discs

Ion Optics
The GFIS Source

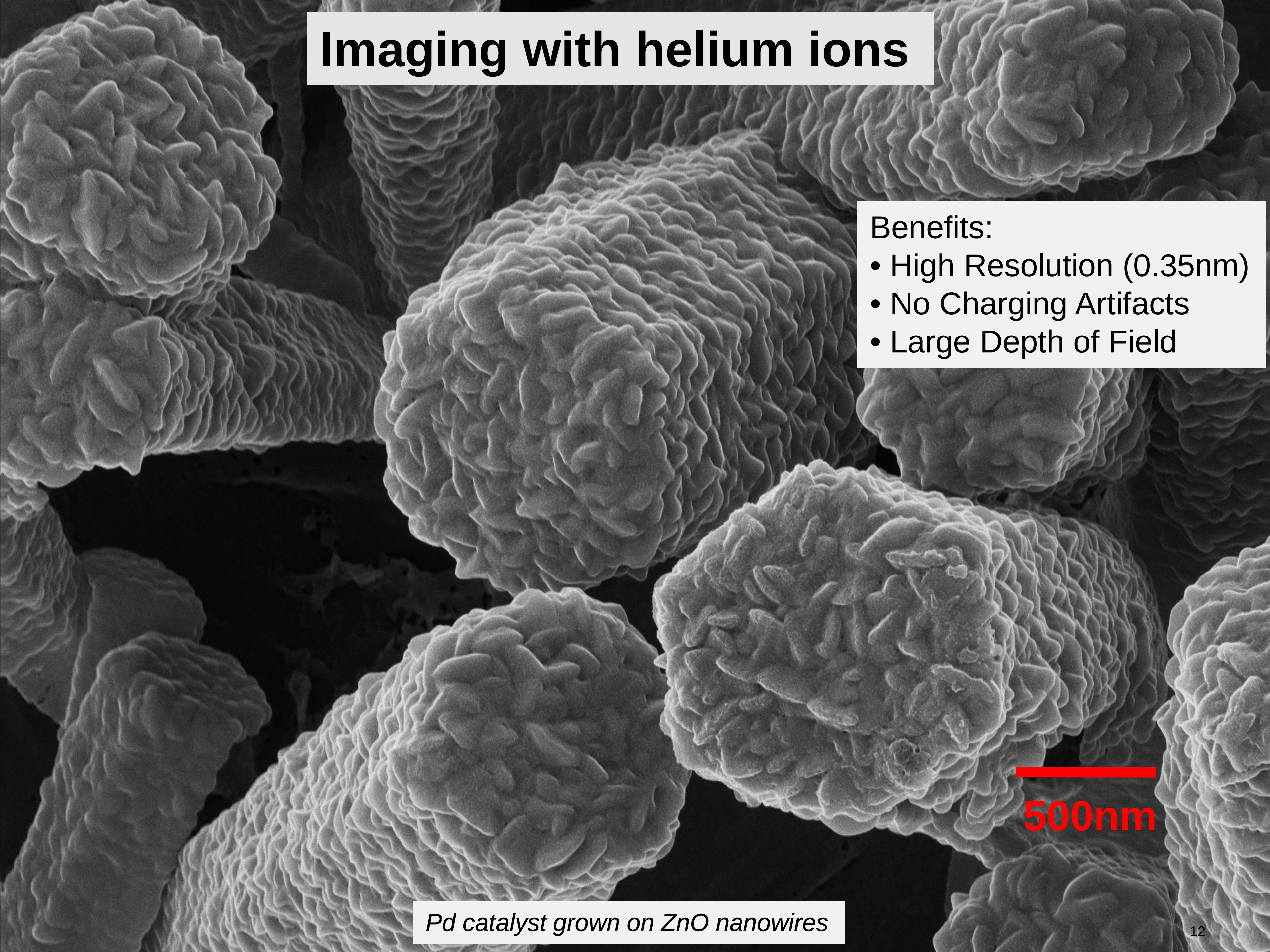


The ORION NanoFab Platform



- **3D Nanofabrication** of sub-10nm structures.
- **High Resolution Imaging (<0.5nm)** 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

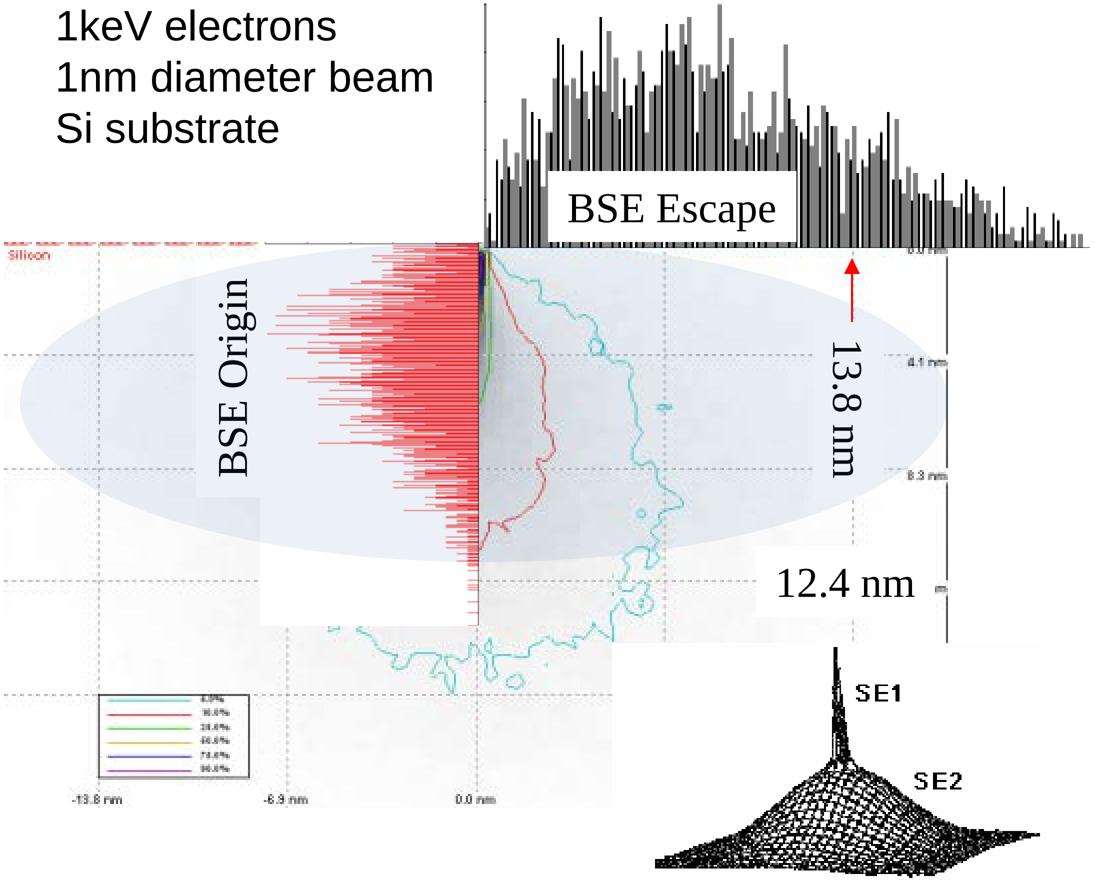


Benefits:
- High Resolution (0.35nm)
- No Charging Artifacts
- Large Depth of Field

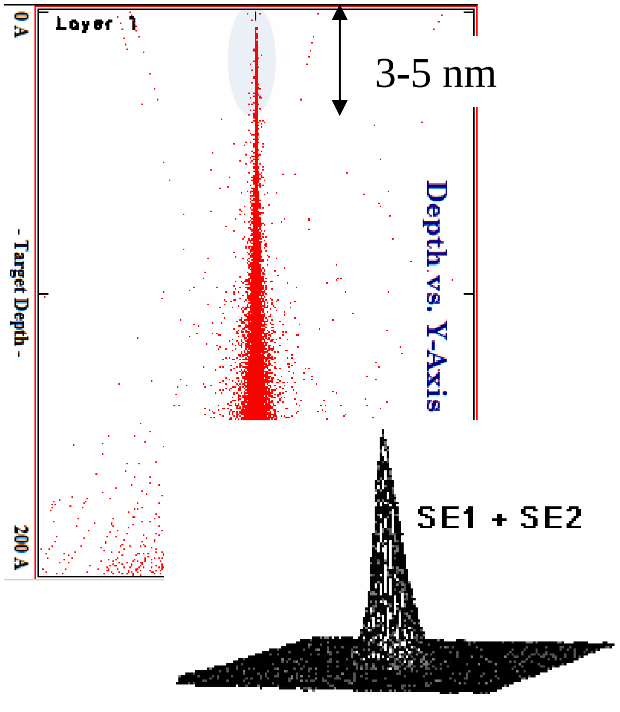
Pd catalyst grown on ZnO nanowires

Surface Sensitivity

CASINO simulation
1keV electrons
1nm diameter beam
Si substrate

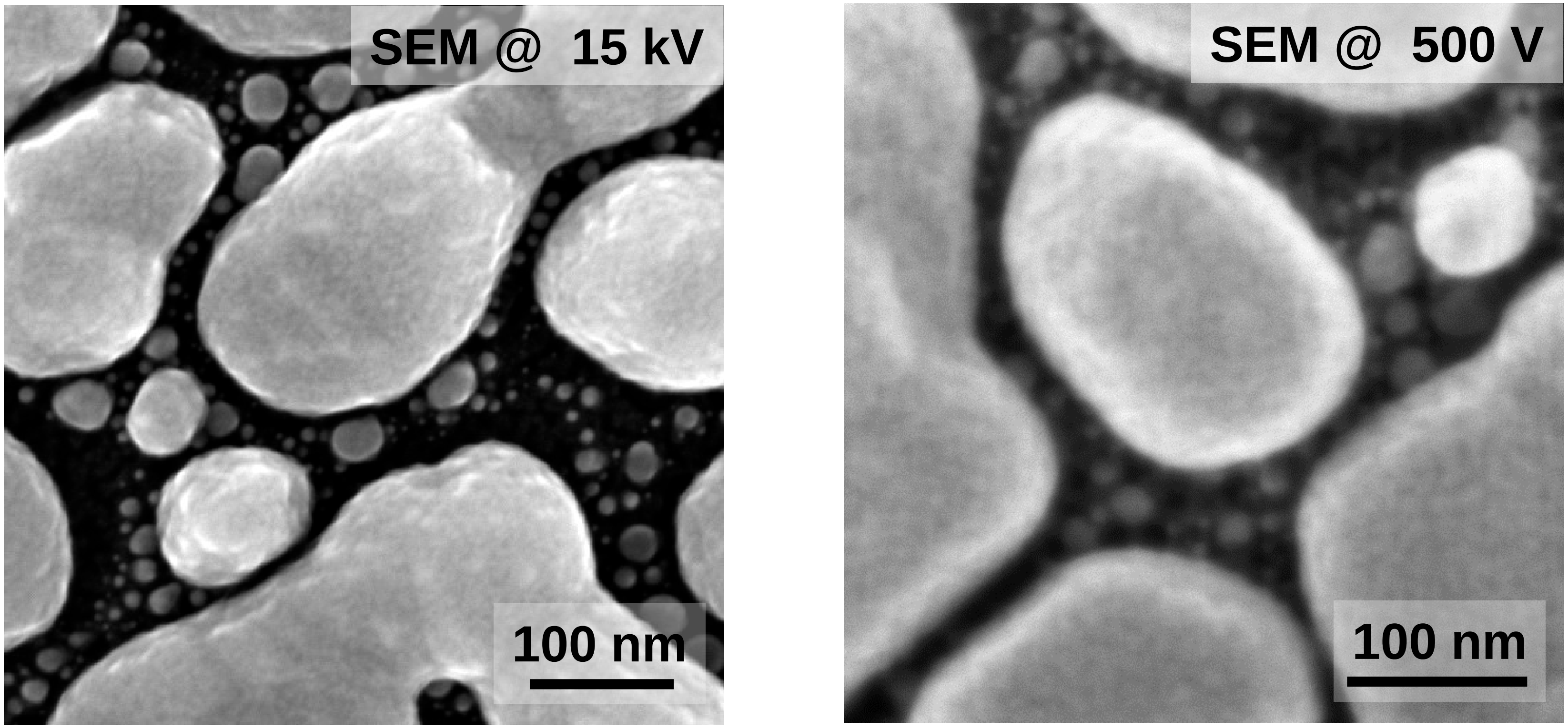


TRIM simulation
30keV He+
Point beam
Si substrate



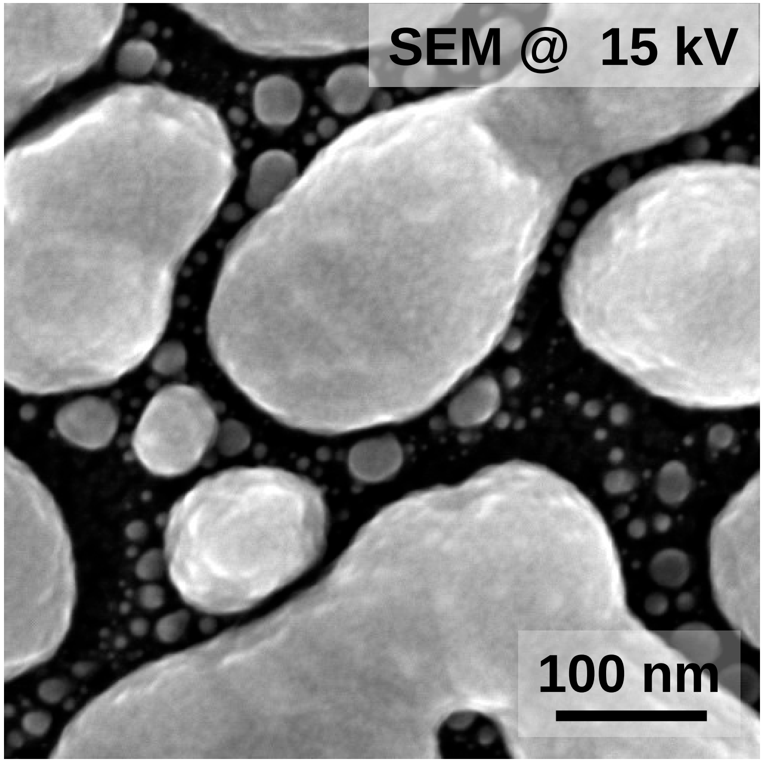
SEM images are produced by SE1 and SE2 electrons while the HIM image is primarily due to SE1 electrons

Coated AuC (big Au islands)

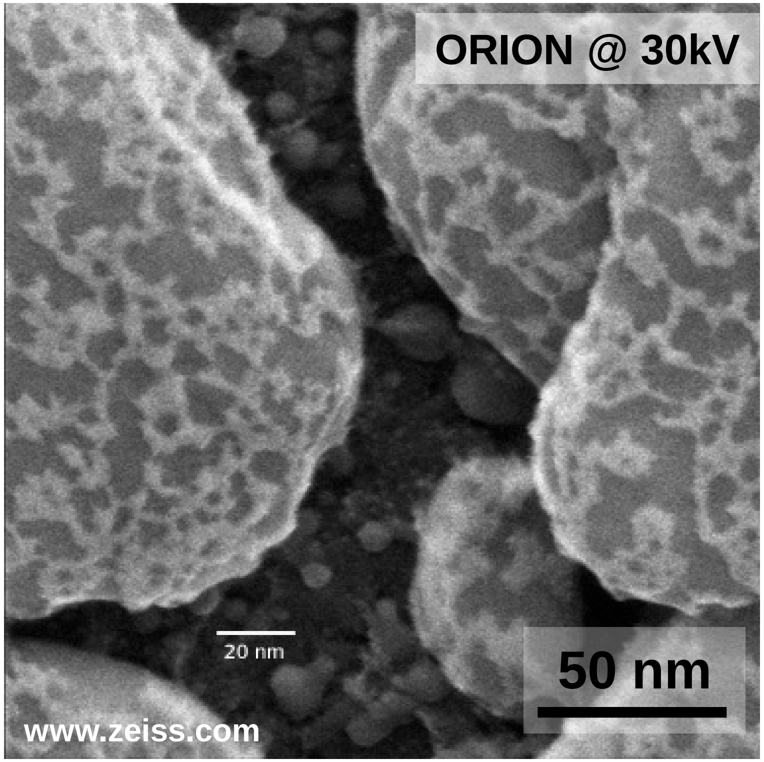


sample courtesy of Al Lysse, Carl Zeiss SMT Inc., US

Coated AuC (big Au islands)



- good SNR
- high contrast between Au and C

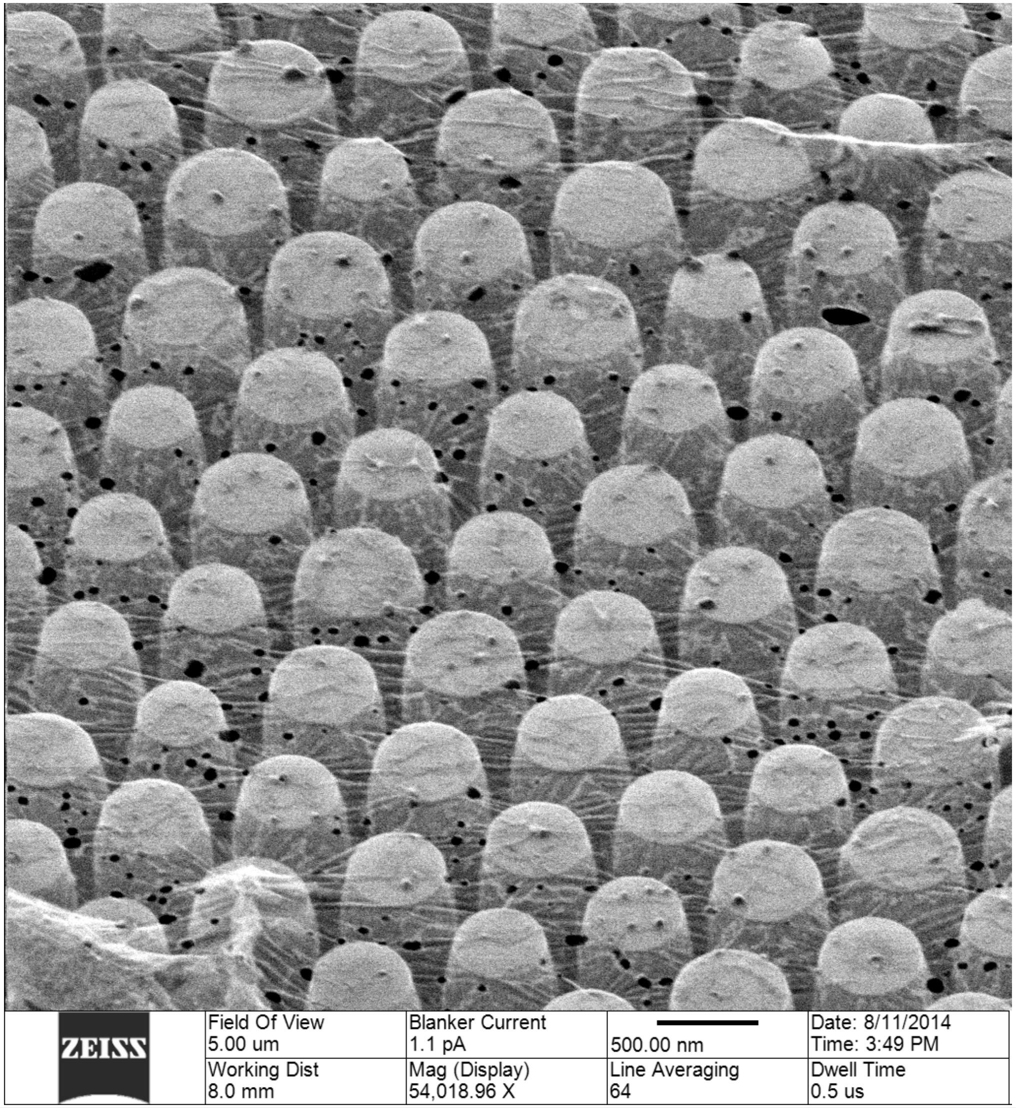


- high surface sensitivity

…surface details that could not be seen become visible

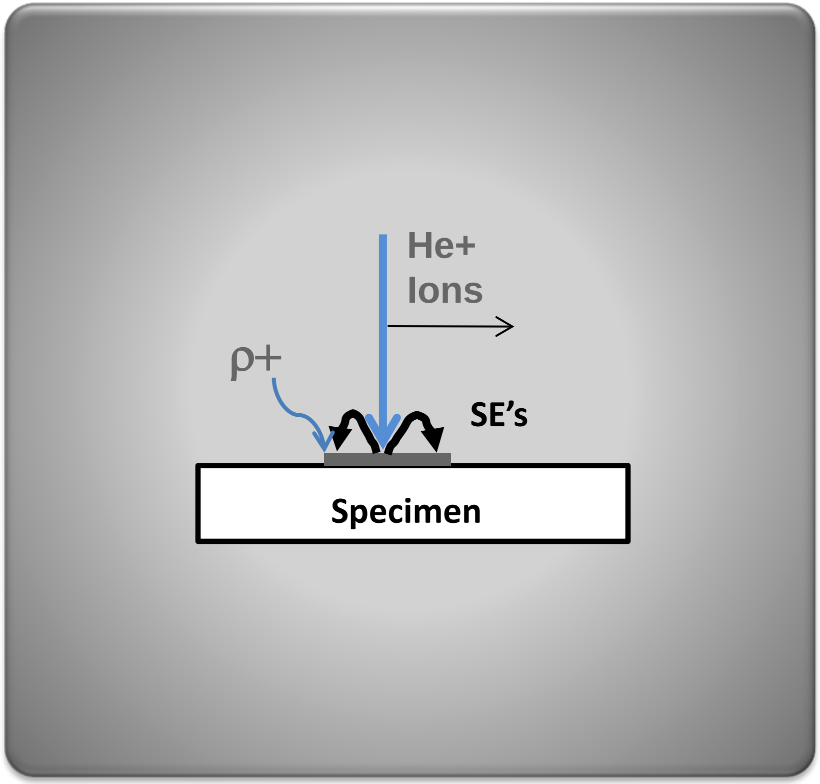
Imaging of Graphene

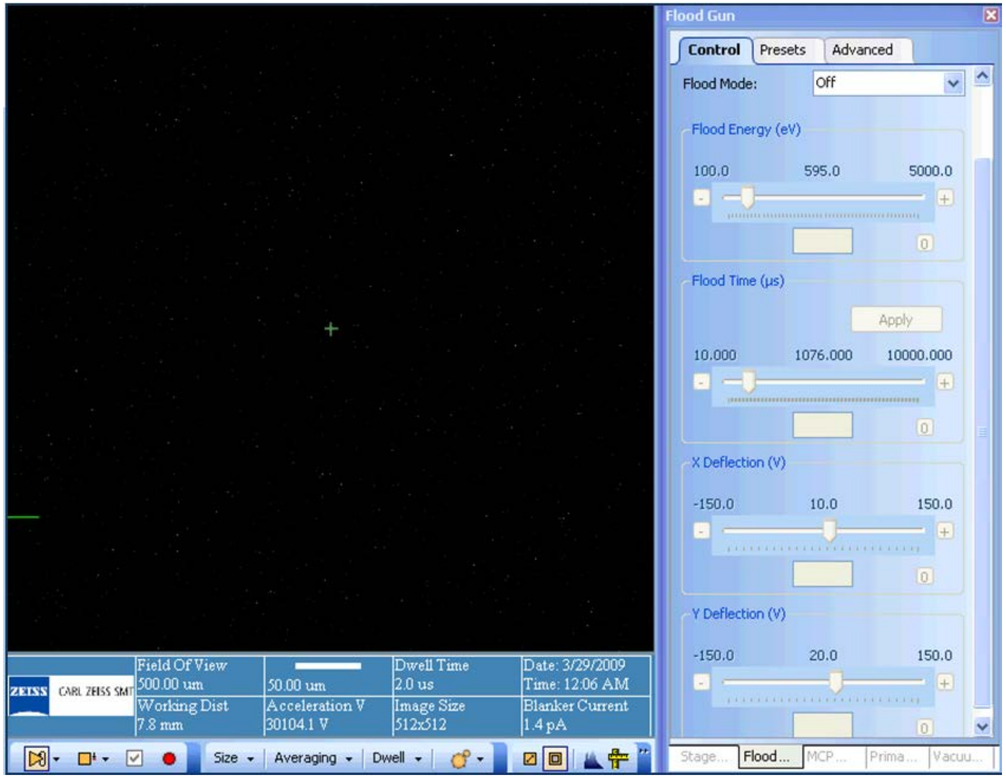
Single sheet graphene flakes on GaN poles



Sample courtesy of S. Christiansen, MPI Erlangen

Charging due to the helium ion beam



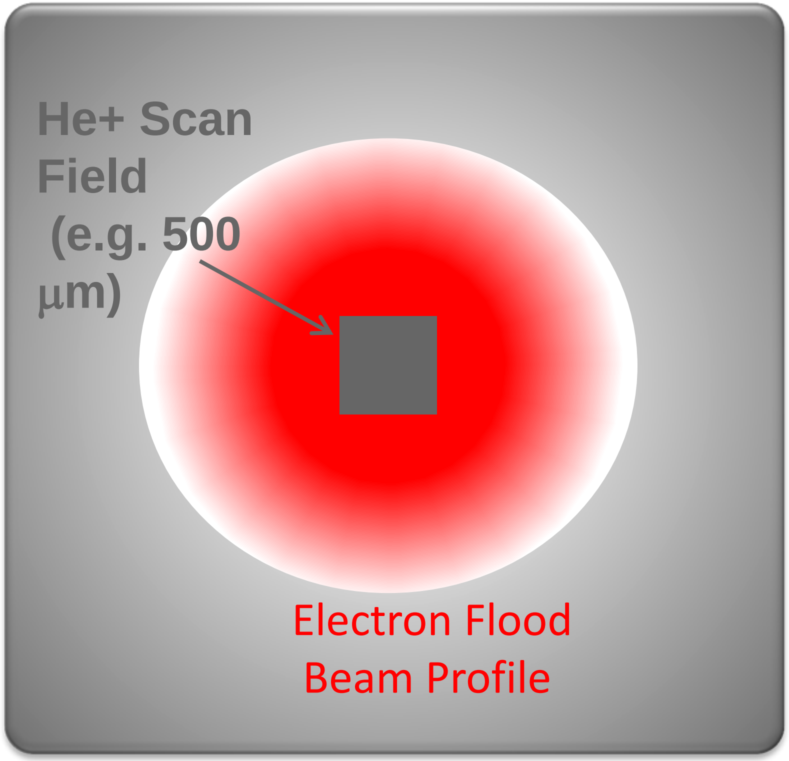

Field Of View 500.00 um
50.00 um
Dwell Time 2.0 us
Date: 3/29/2009
Time: 12:06 AM
Working Dist 7.8 mm
Acceleration V 30104.1 V
Image Size 512x512
Blanker Current 1.4 pA

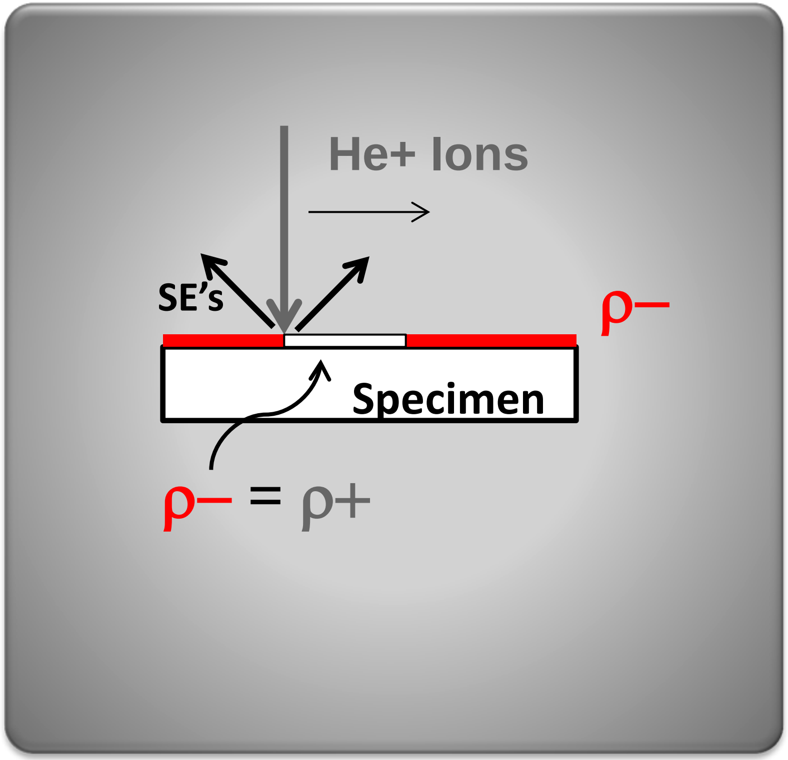
Flood Gun
Flood Mode: Off
Flood Energy (eV): 100.0 595.0 5000.0
Flood Time (µs): 10.000 1076.000 10000.000
X Deflection (V): -150.0 10.0 150.0
Y Deflection (V): -150.0 20.0 150.0

Helium ions always cause a net positive charge in the sample (ions implanted, electrons emitted)

For insulating samples, the positive charge density accumulating on the surface causes secondary electrons to return to the sample resulting in a dark image

Charge neutralization with an electron flood gun

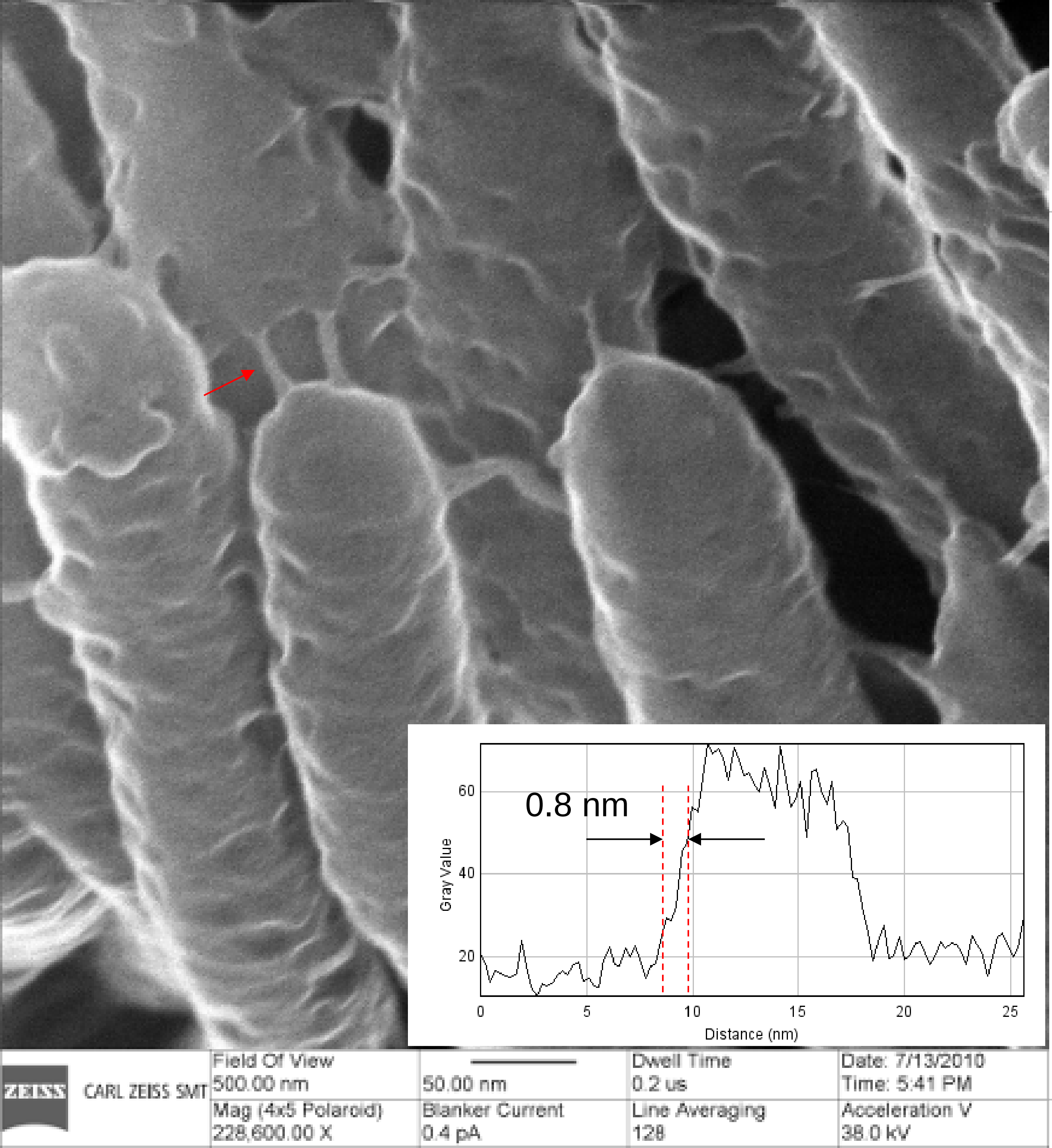




An electron flood beam is multiplexed with the helium imaging beam to neutralize the positive charge on the sample surface and produce a charge neutral image.

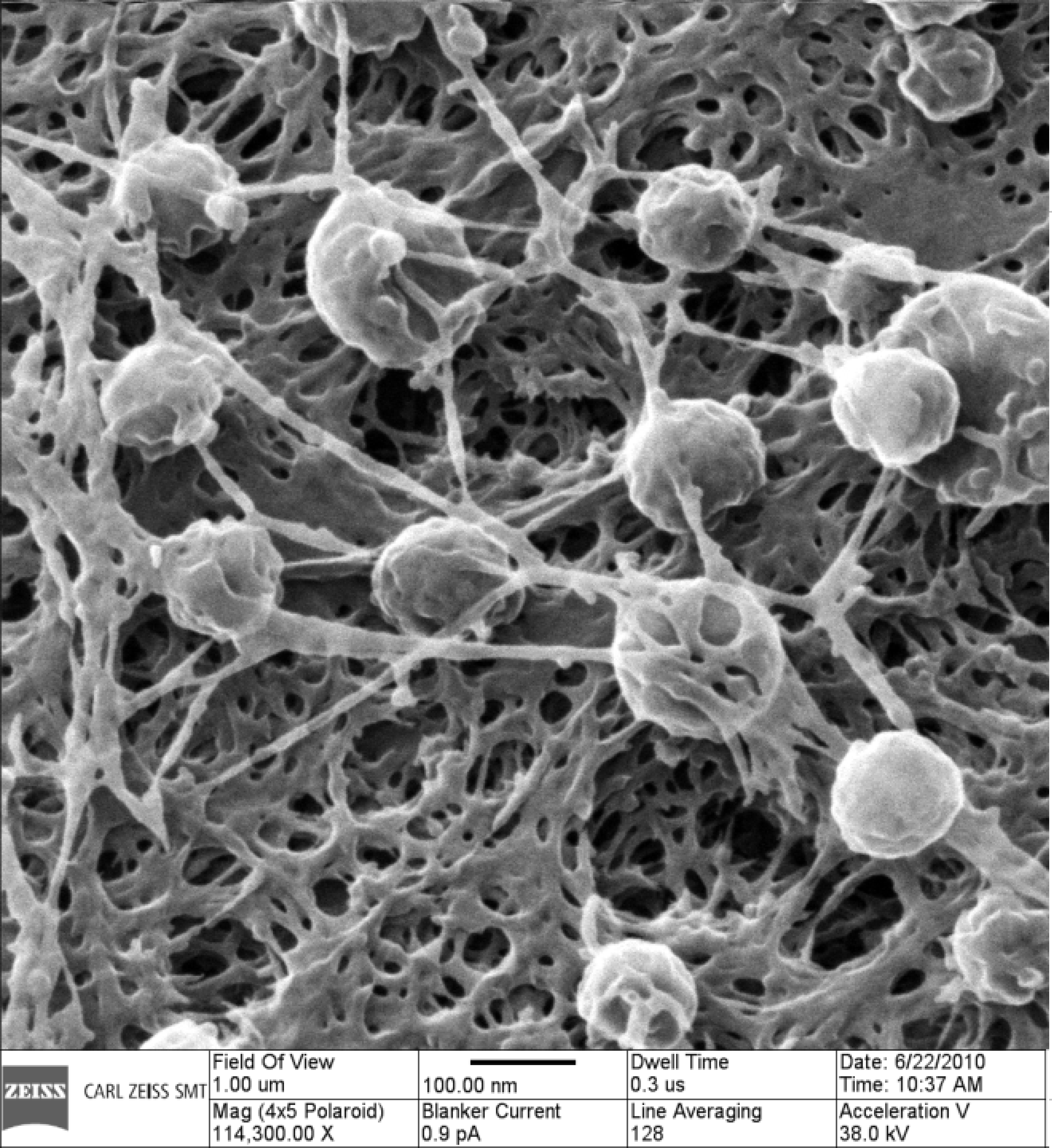
High Resolution Imaging

- 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



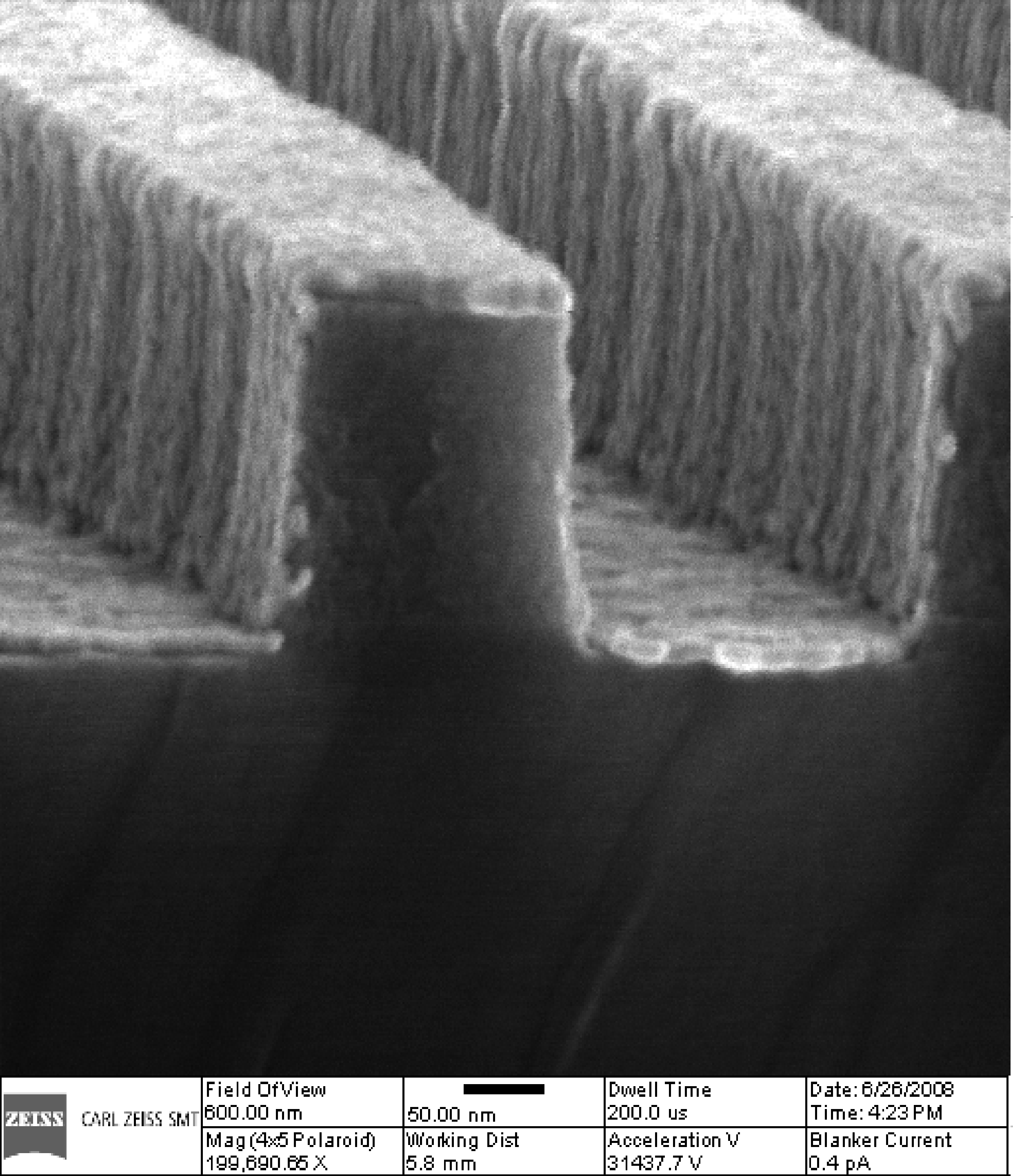
CARL ZEISS SMT	Field Of View 1.00 um	100.00 nm	Dwell Time 0.3 us	Date: 6/22/2010 Time: 10:37 AM
	Mag (4x5 Polaroid) 114,300.00 X	Blanker Current 0.9 pA	Line Averaging 128	Acceleration V 38.0 kV

Charge Neutralization

- High resolution imaging of an uncoated sample showing virus particles entering a cell
- Instrument resolution not compromised by charge neutralization using the electron flood gun

Virus particles entering a cell

sample courtesy of Dr. Paul Walther, Univ. of Ulm



CARL ZEISS SMT

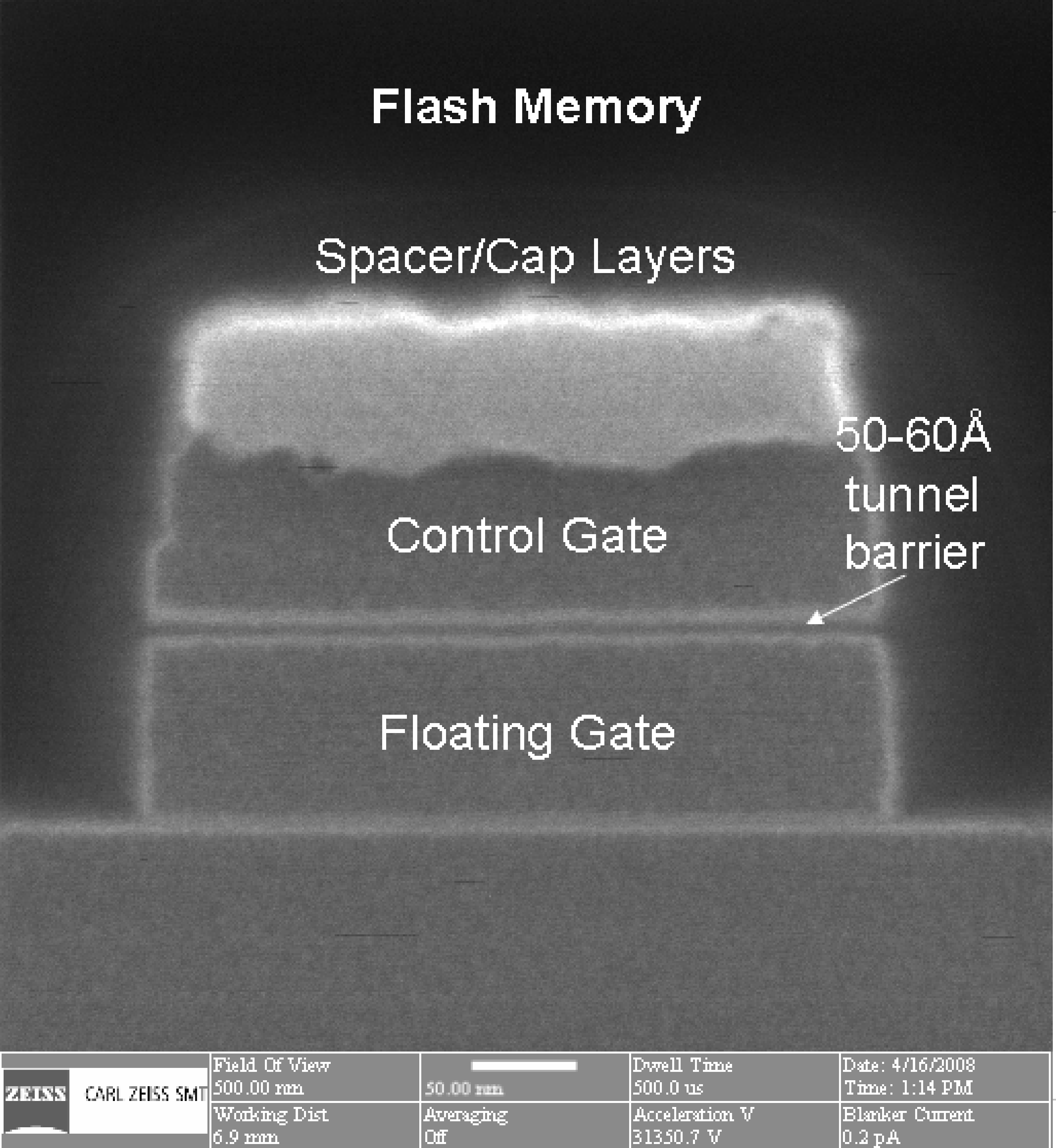
Field Of View 600.00 nm	50.00 nm	Dwell Time 200.0 us	Date: 6/26/2008 Time: 4:23 PM
Mag (4x5 Polaroid) 199,690.65 X	Working Dist 5.8 mm	Acceleration V 31437.7 V	Blanker Current 0.4 pA

Low Beam Damage

- High resolution surface detail with minimal sample modification due to the helium beam

SiCOH low K dielectric

Sample courtesy of AIST-Selete



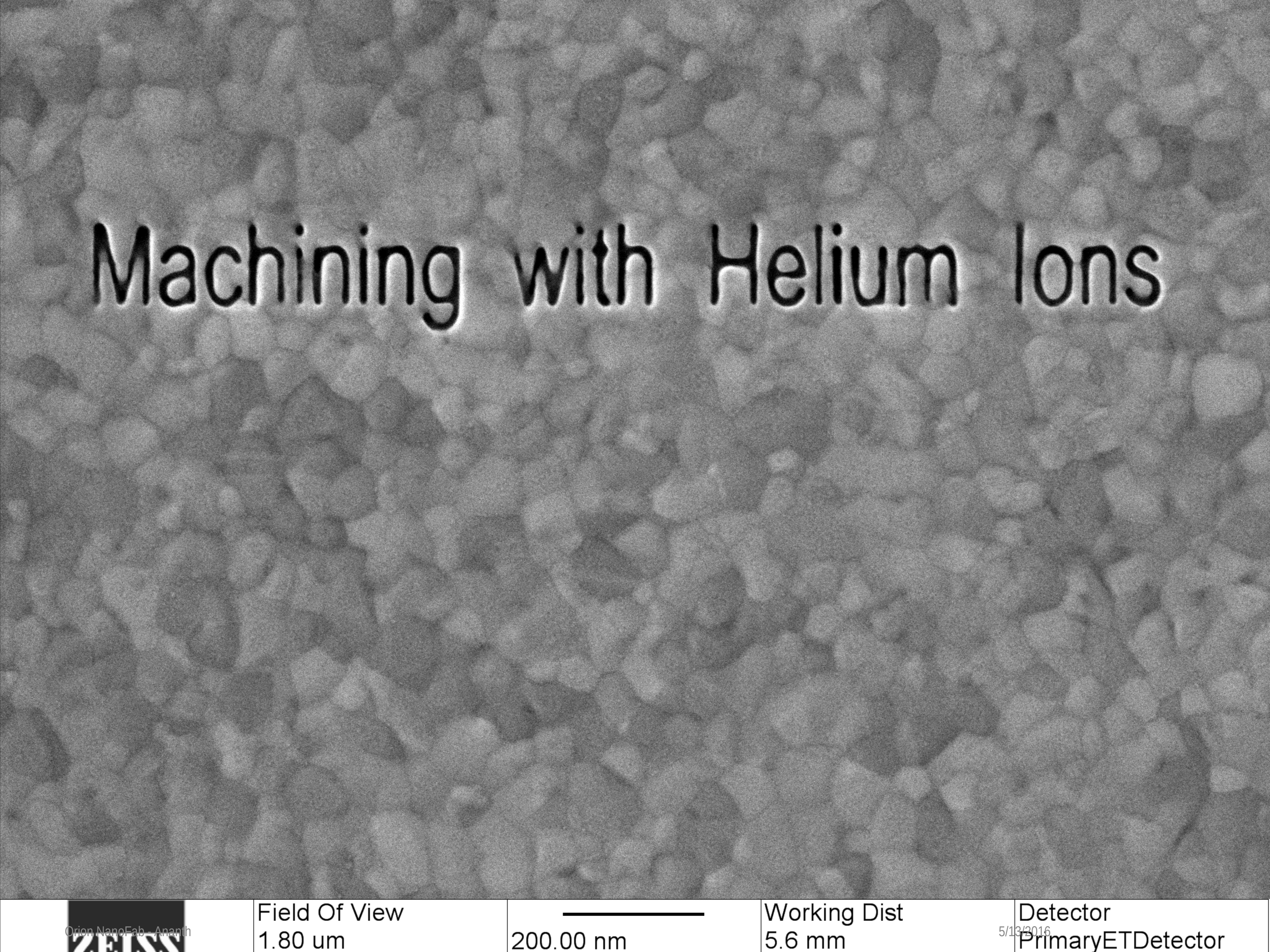
Field Of View 500.00 nm
Working Dist 6.9 mm
Averaging Off
Dwell Time 500.0 us
Acceleration V 31350.7 V
Date: 4/16/2008
Time: 1:14 PM
Blanker Current 0.2 pA

Material Contrast

- Ability to view tunneling barrier due to surface sensitivity and material contrast

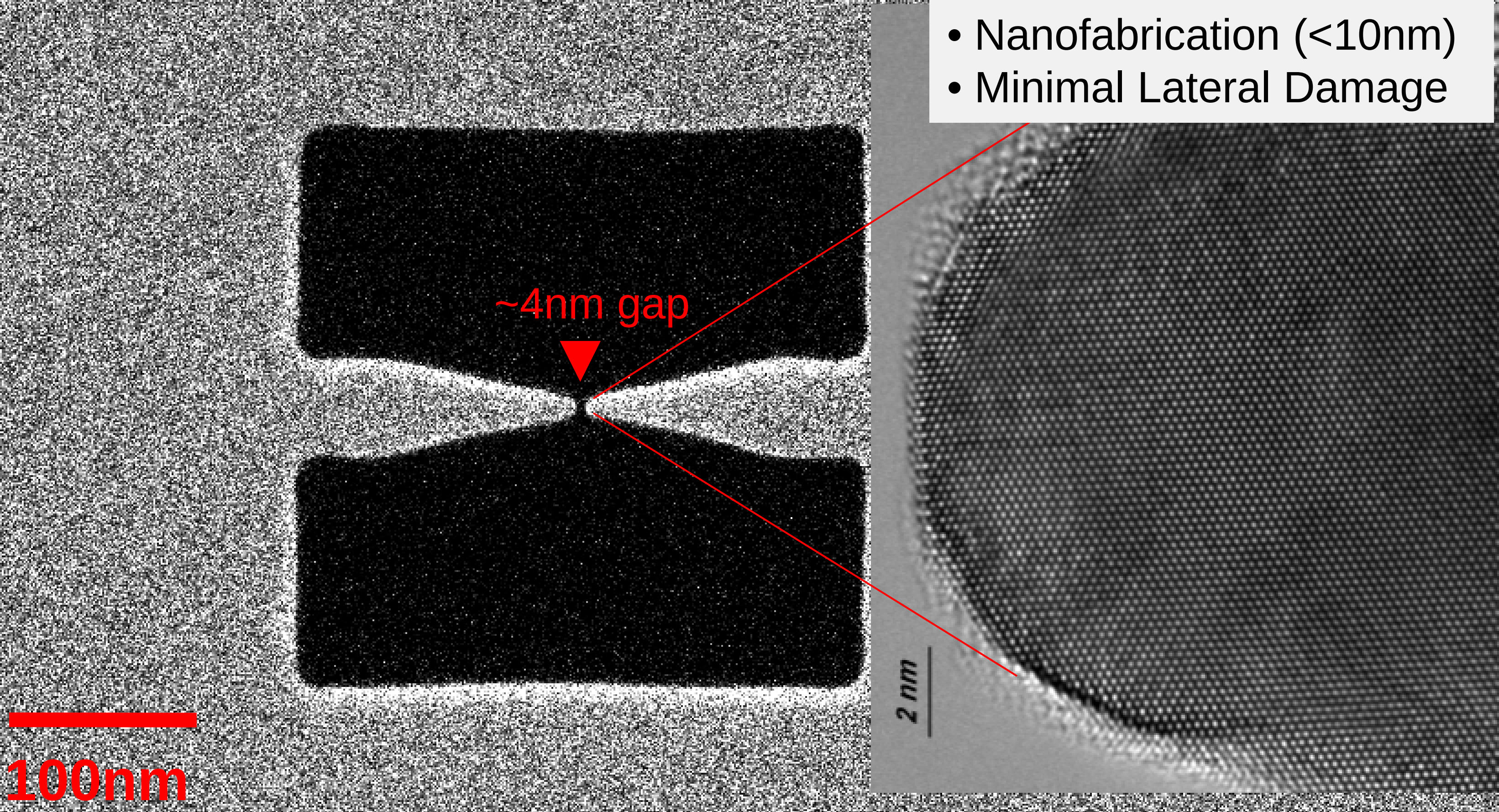
Samsung Flash Memory

sample courtesy of Chipworks


Machining with Helium Ions
ZEISS
Field Of View
1.80 um
200.00 nm
Working Dist
5.6 mm
Detector
PrimaryETDetector

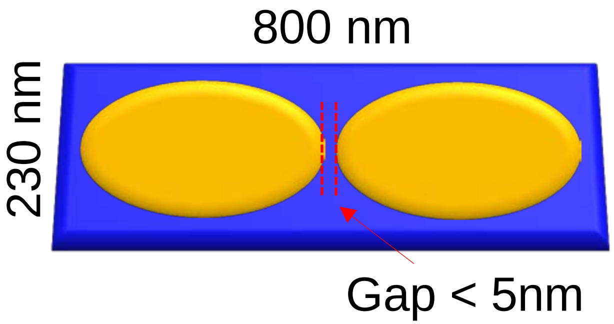
Machining with helium ions

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

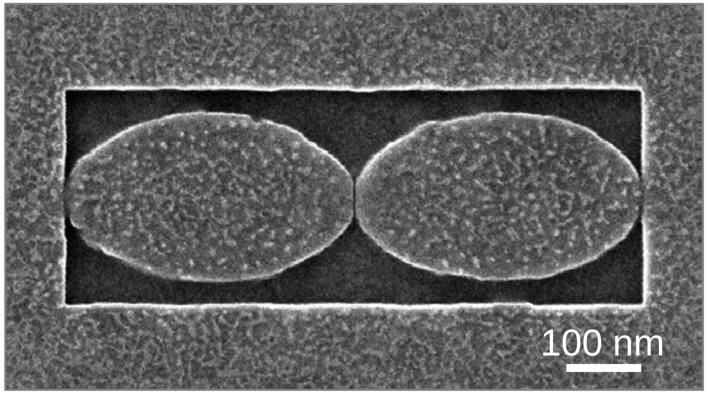


TEM Image

Nanofabrication: He ion beams

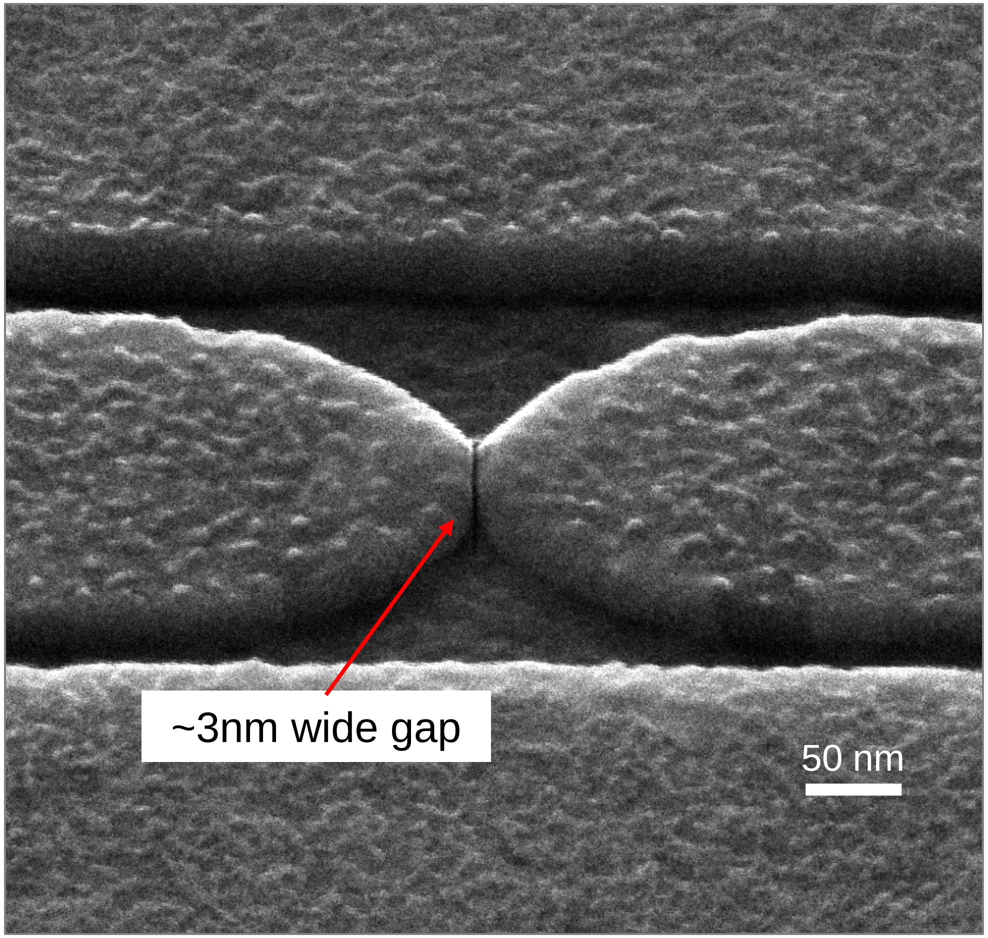


Top down view



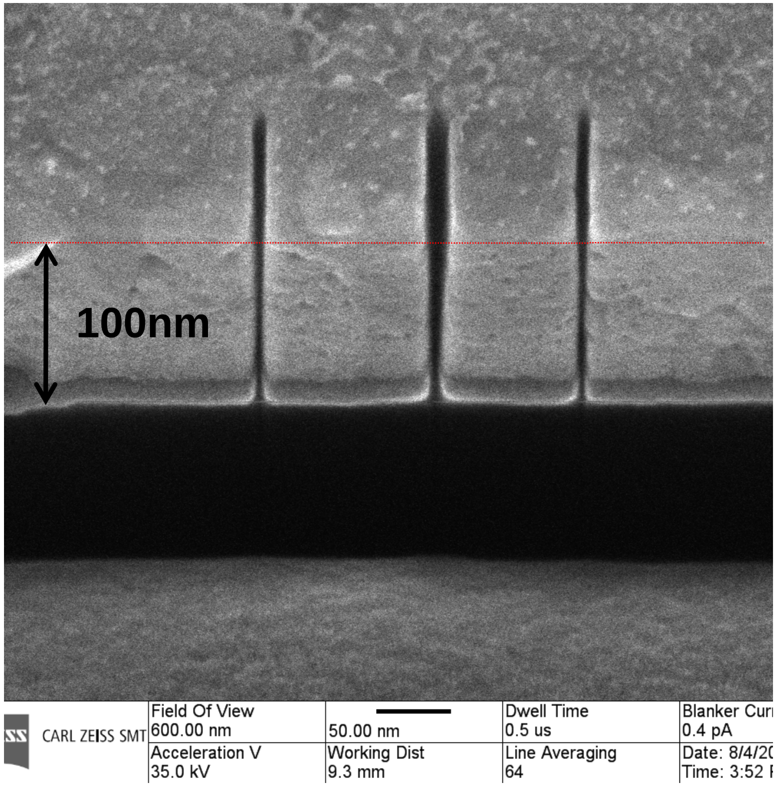
Two Step Milling with He ion beam

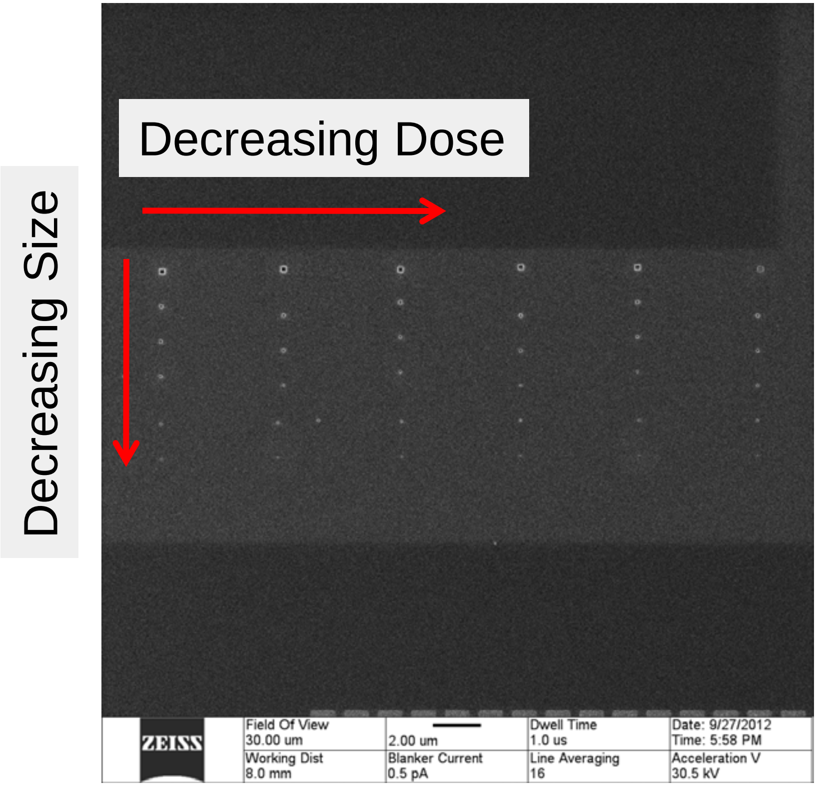
- All gold removed with He ion beam
- Final line cut with He ion beam



45° tilt view

Via Milling – Aspect Ratio





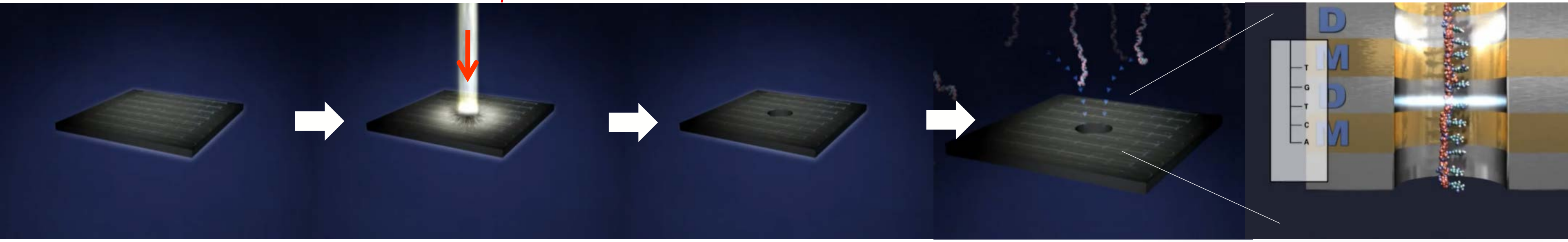
- High Aspect Ratio via milling in gold
- 5nm wide slots machined into a 100nm thick film (20:1)
- Nearly vertical sidewalls (~89°)

- Dose array in SiCOH over M1
- Box size decreasing from 200nm to 25nm (top to bottom)
- Dose decreasing from 2nC/um^2 to 0.75 nC/um^2 (left to right)

Ion Beam Milling
Application • *DNA Transistor at IBM*

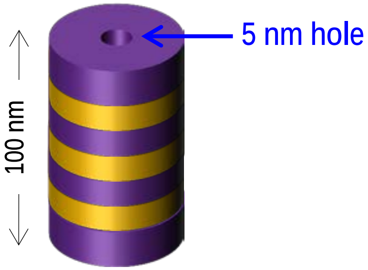
Research Area	DNA sequencing
Challenge	How to make 5 nm holes in 7 layer metal-dielectric sandwich film?
Conventional Method	TEM at high energy

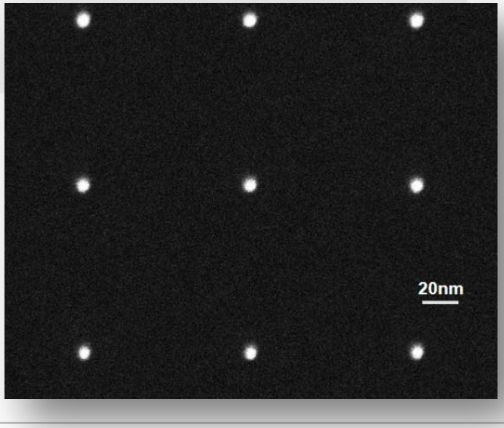
Transmission Electron Microscope



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).**





He Ion Beam Milling
Graphene Research

Research Area

Graphene is a flat monolayer of carbon atoms tightly packed into a two-dimensional (2D) honeycomb lattice, and is a basic building block for graphitic materials. It has extraordinary properties:

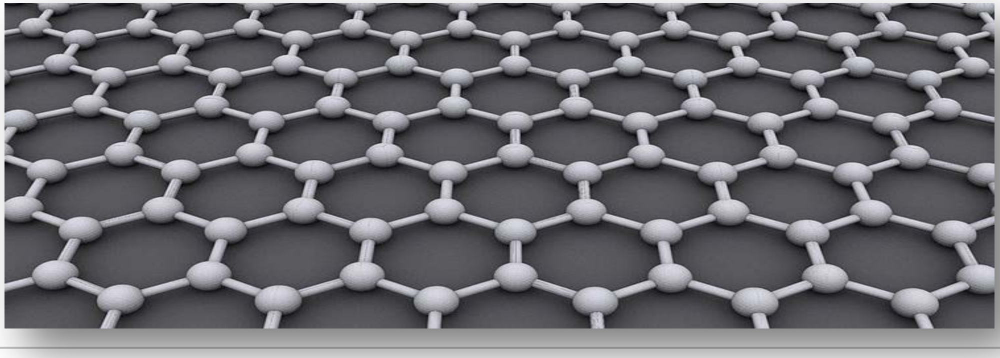
(1) Electronic (2) Optical (3) Thermal (4) Mechanical

2010 Nobel Prize in Physics awarded for groundbreaking experiments with graphene

Research Applications

- Nanoribbons
- Transistors
- Optical modulators
- Integrated circuit
- Transparent electrodes
- Ultracapacitor
- Chemical and electrical sensors

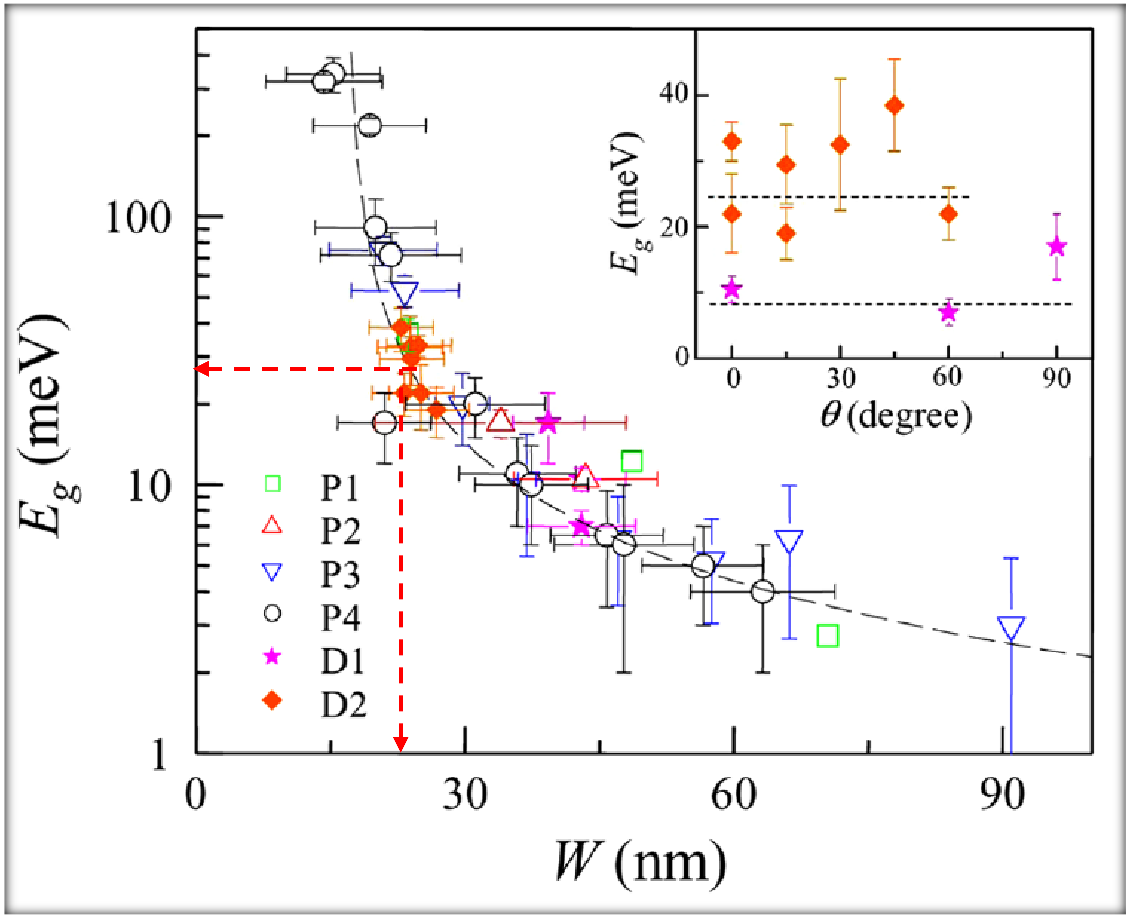
Structure



Graphene Machining for Quantum Confinement

The bandgap in a graphene ribbon increases as the ribbon width decreases

In order to increase bandgap above room temperature thermal energy (25 meV), confinement of ribbon to less than 20 nm is desired.

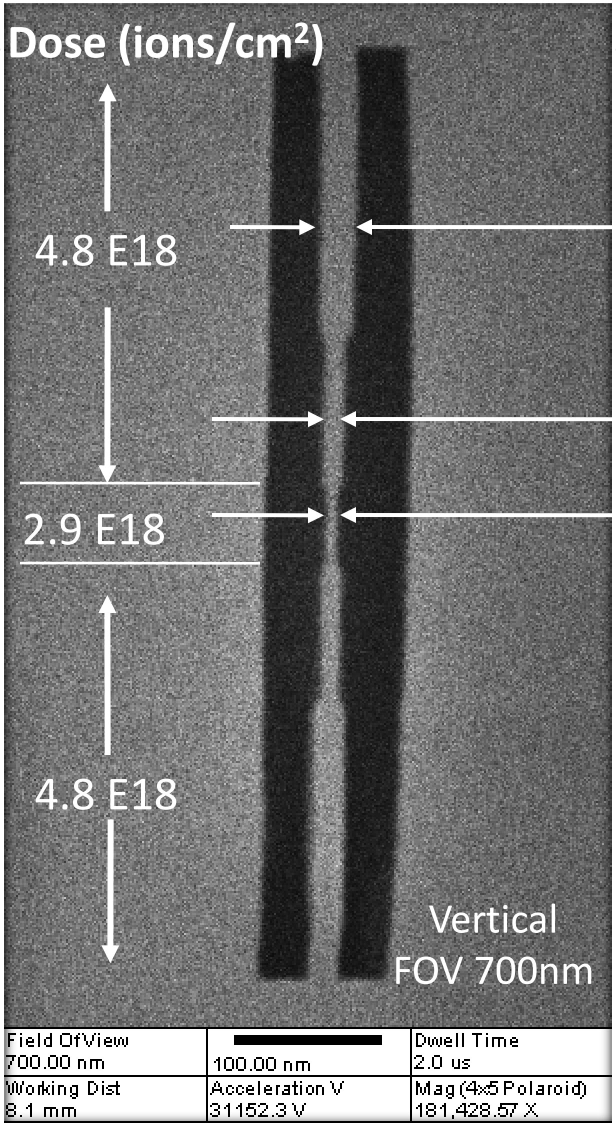


Graphene nanoribbons bandgaps can be modulated

M. Han, B. Özyilmaz , Y. Zhang., P Kim, Phys; Phys. Rev. Lett. 98 (2007) 206805

Direct Patterning of Graphene: Ribbon Width Control

- Pattern generator (Nabity) used to define milling structures
- External control of column
- 700 nm vertical field of view
- Milling proceeded simultaneously down both sides of ribbon to maintain strength



Field Of View 700.00 nm | 100.00 nm | Dwell Time 2.0 us

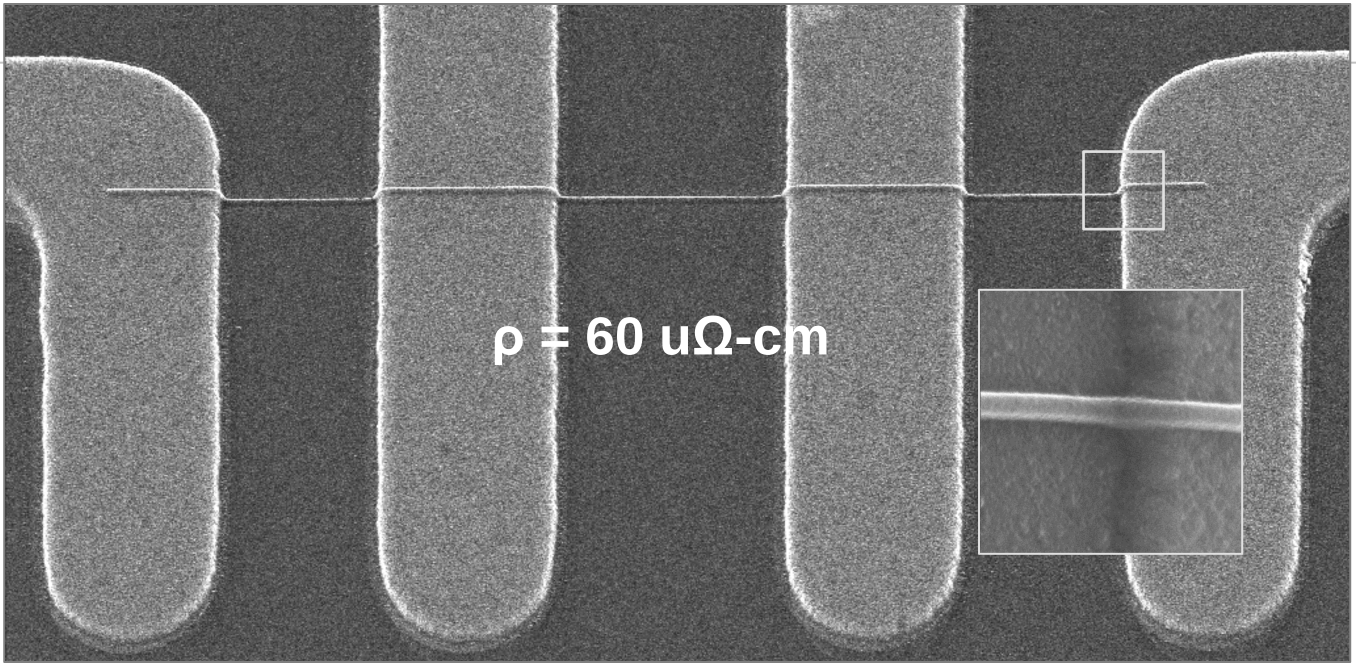
Working Dist 8.1 mm | Acceleration V 31152.3 V | Mag (4x5 Polaroid) 181,428.57 X

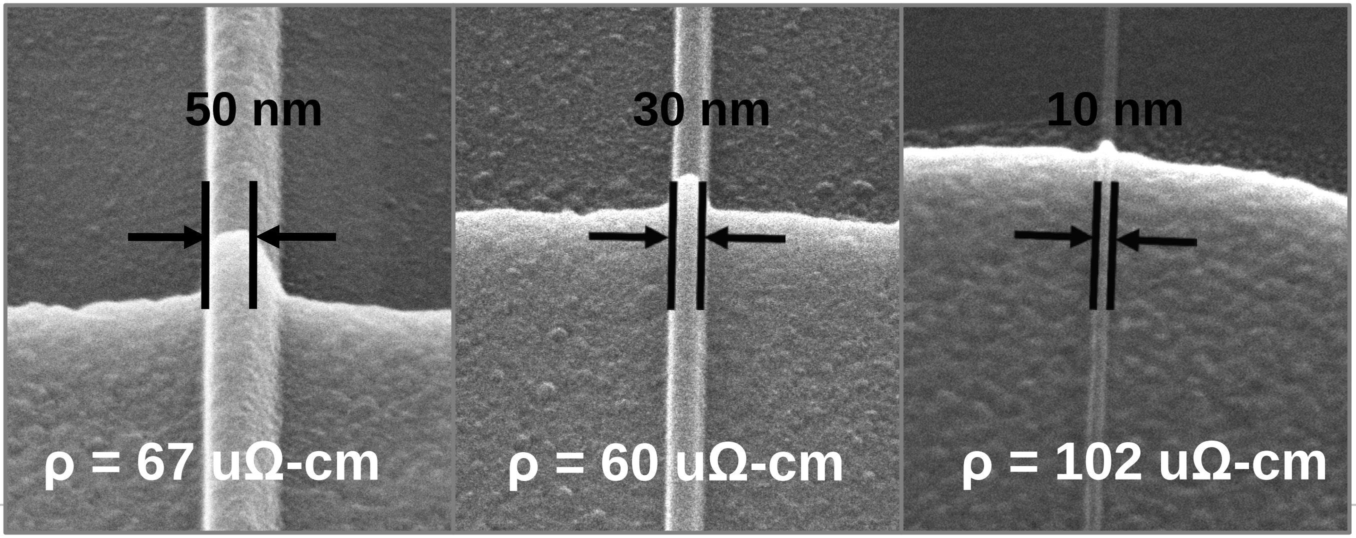
20nm width

10nm width

5nm width

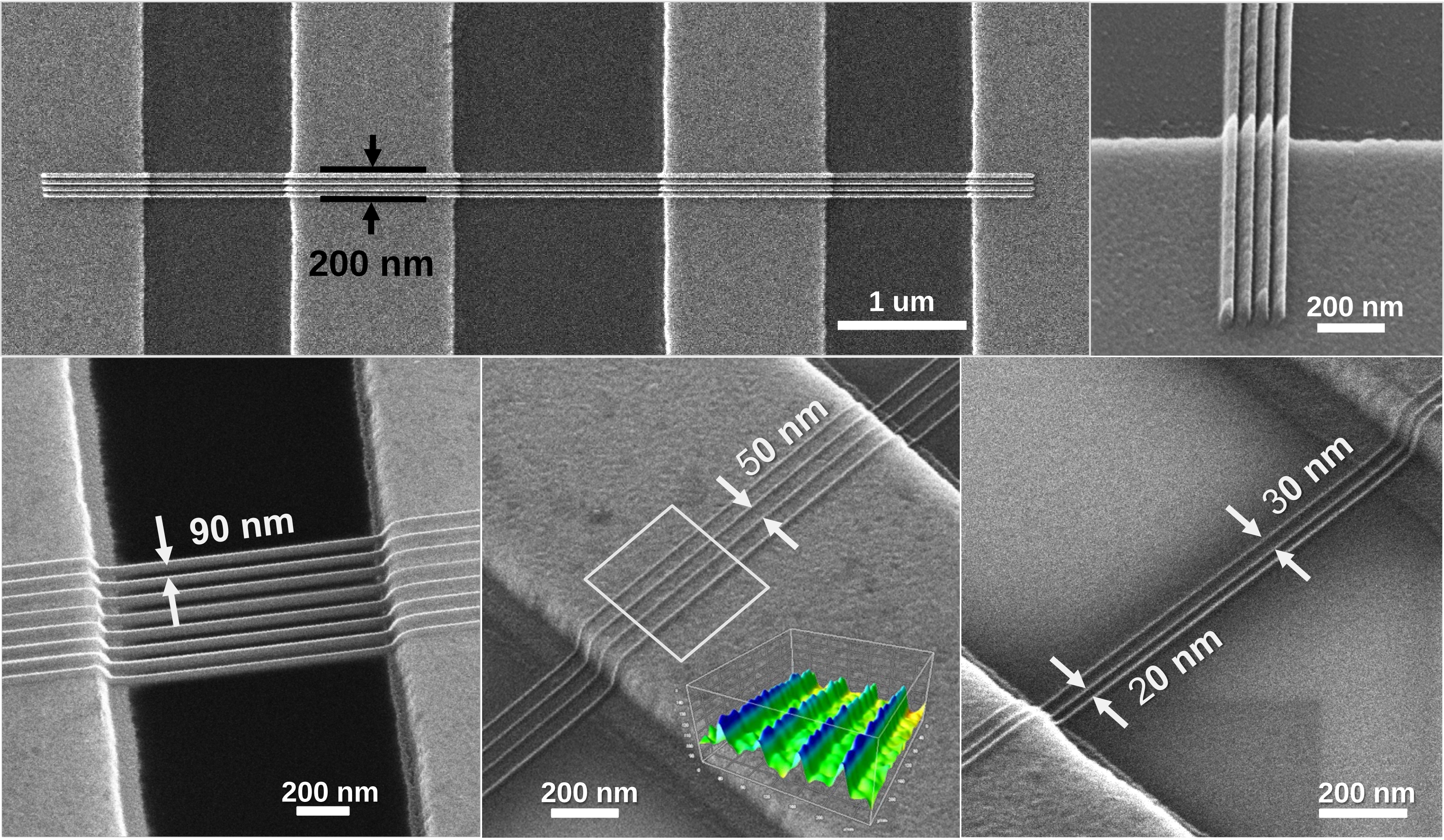
Metal Deposition
Cobalt Single Line Deposition





- Good step coverage
- Nanoscale deposition
- ρ < 100 uΩ-cm (width >20 nm)

Multiple Line Cobalt Deposition



Resistivity 50~120 µΩ-cm

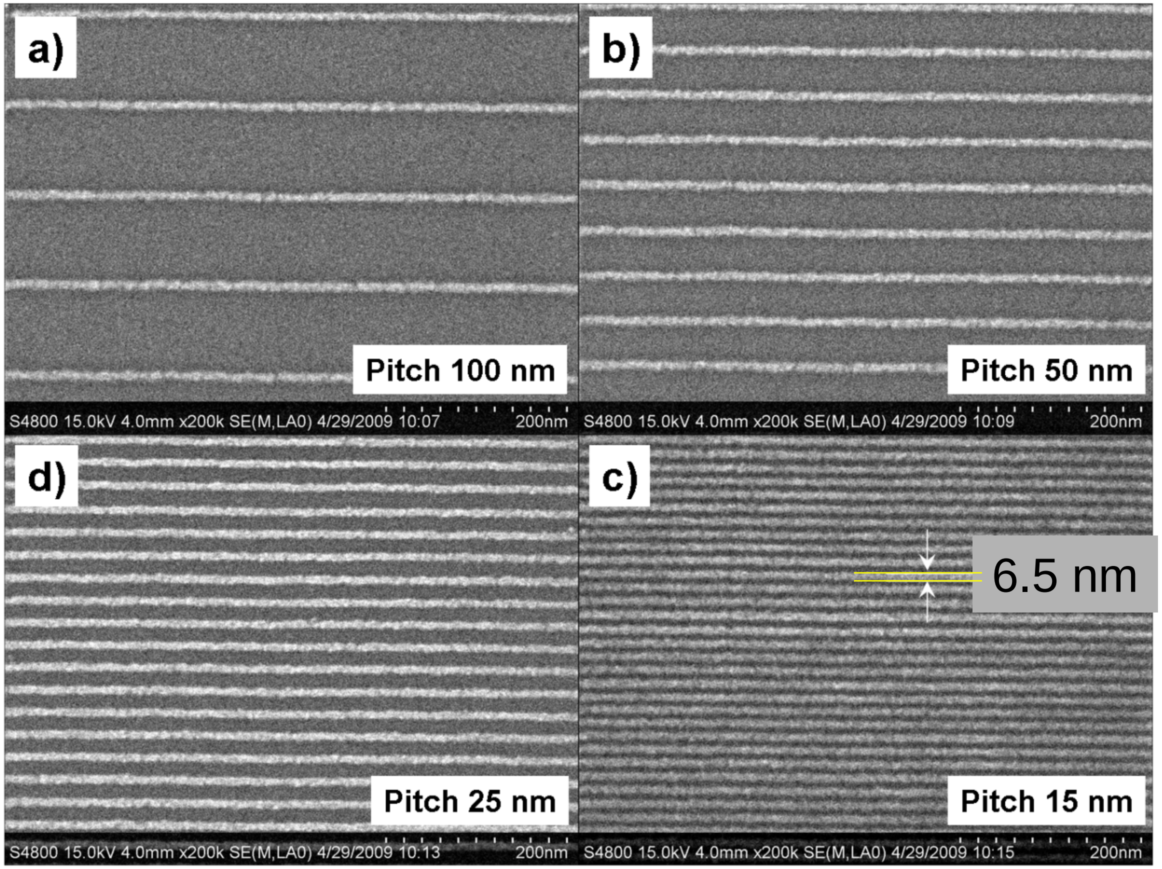
Nano Structuring
Early results Lithography (SHIBL)

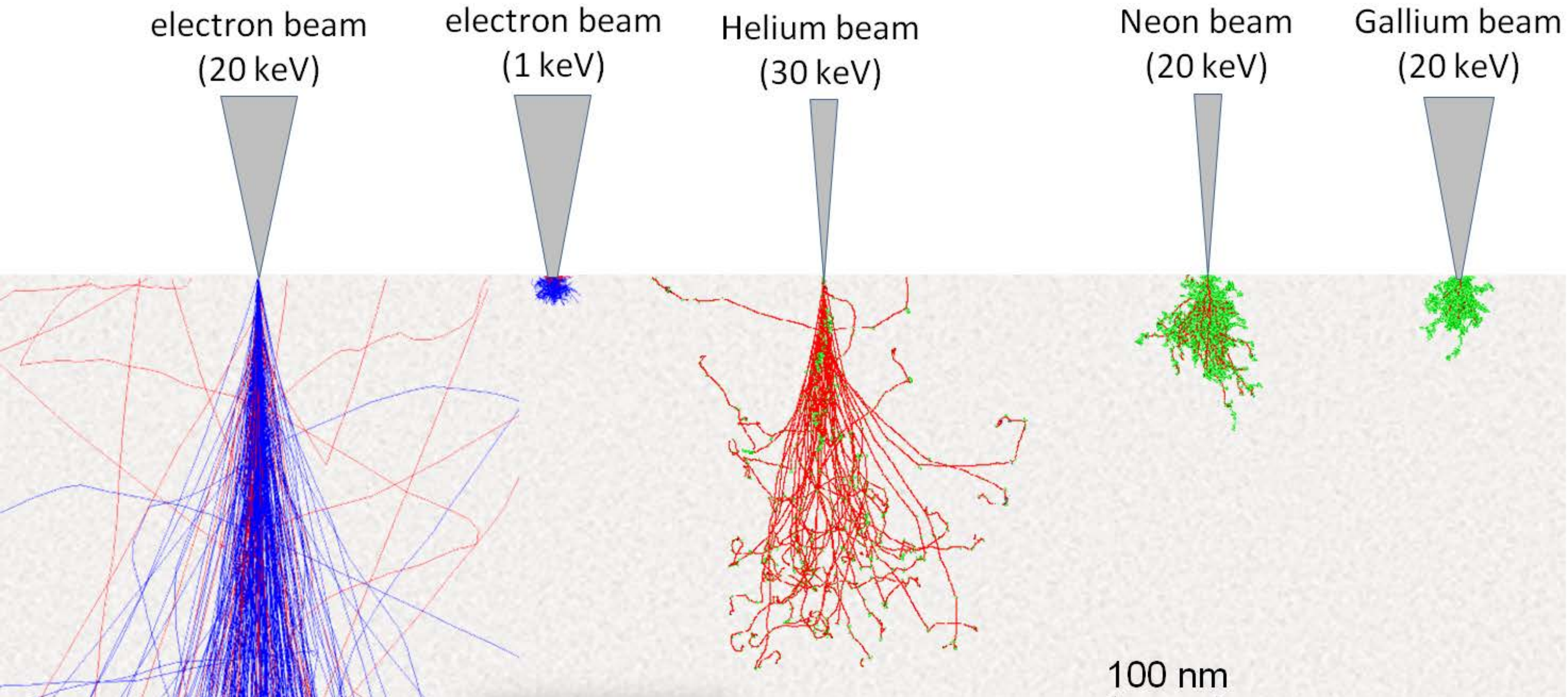
Experiment

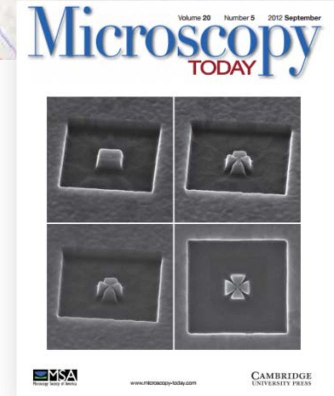
- Lines written in HSQ resist

Results

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






Microscopy TODAY

Volume 20 Number 5 2012 September

MSA

www.microscopy-today.com

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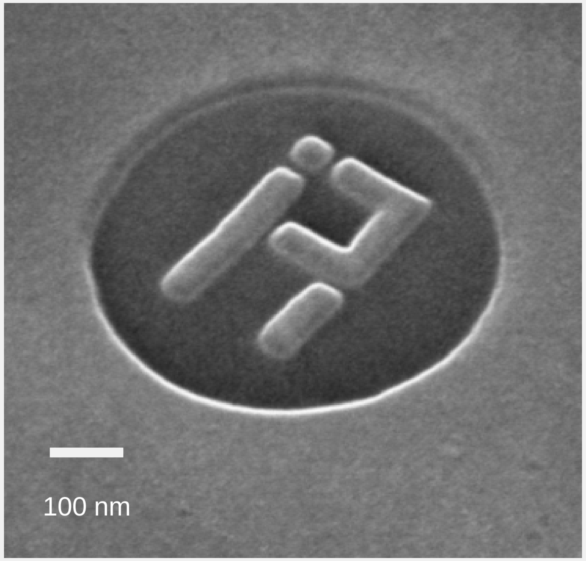
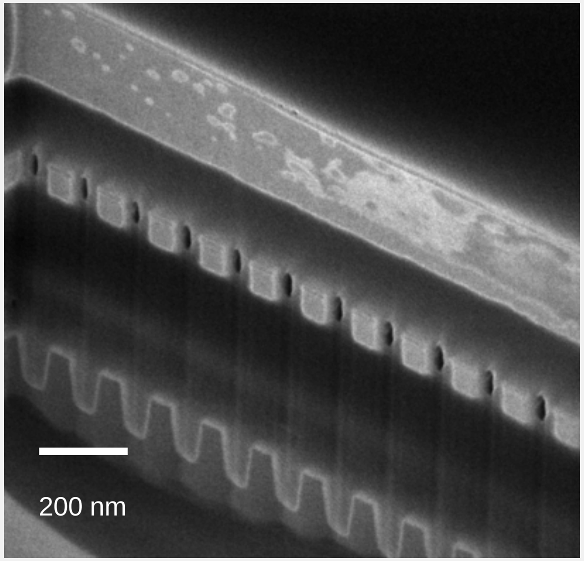
Why Mass Matters, Microscopy Today,
Vol 20, Issue 5, Sept. 2012

Early Neon Results



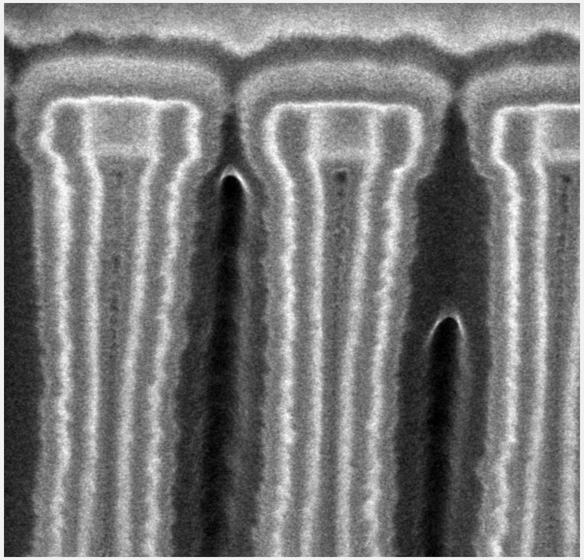
Si sputtering

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.

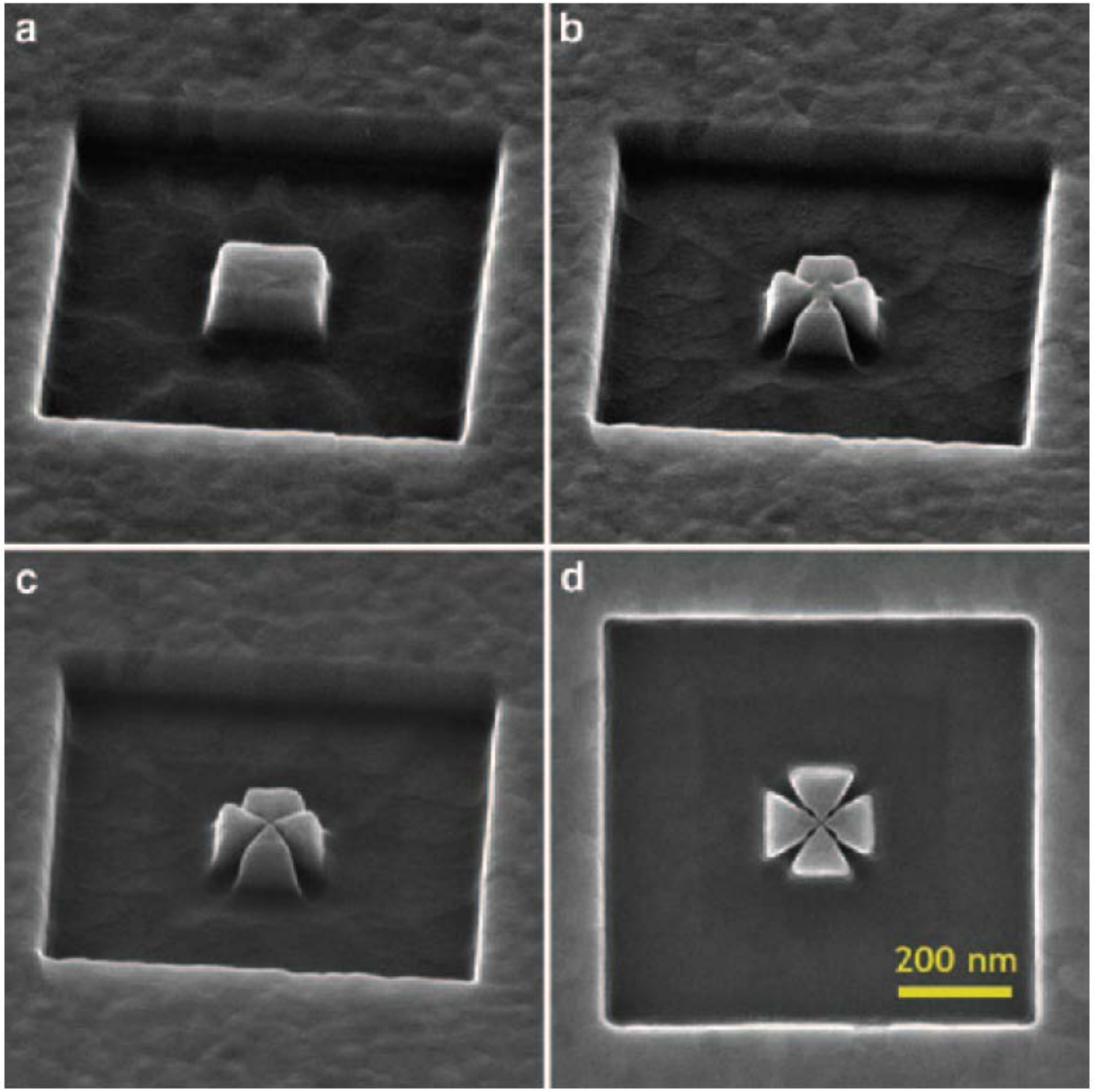


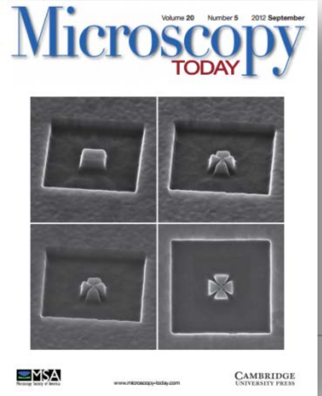
Cross section

Polishing of sample frontside with Ne followed by imaging with He.

Helium Ion Microscope for NanoFabrication: Combining Ga, Ne and He - Beams:

For some samples, the gallium beam is best sited for bulk removal. Then for finer work, where gallium implantation is to be avoided, the neon is used. For the final precision, the helium beam is used.

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