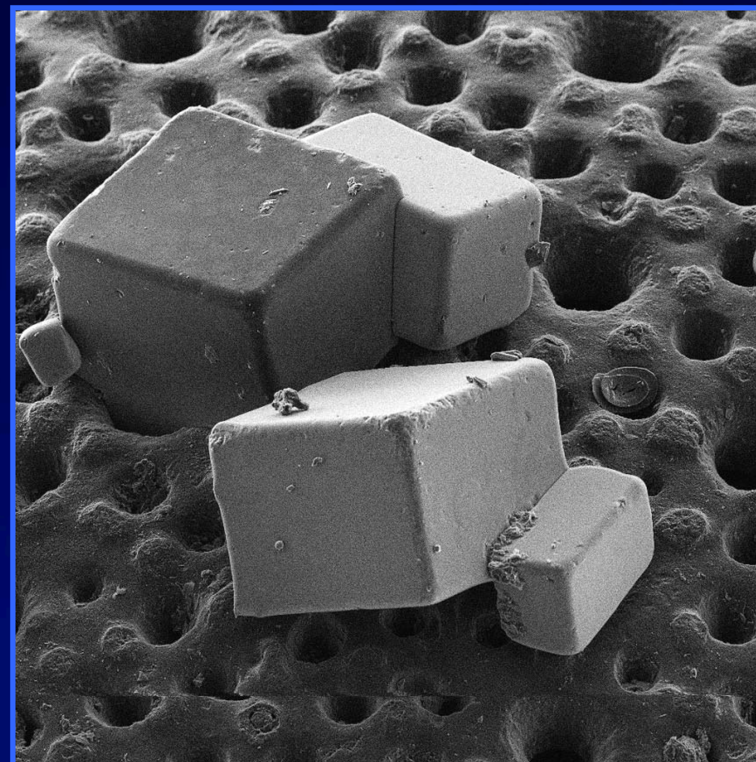
# Understanding Imaging and Metrology with the Helium Ion Microscope


**Michael T. Postek,**

**Andras E. Vladar and Bin Ming**

**National Institute of Standards and Technology**


**Frontiers of Characterization and Metrology for Nanoelectronics**

***CNSE University at Albany***

***May 11-14, 2009***


NIST
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

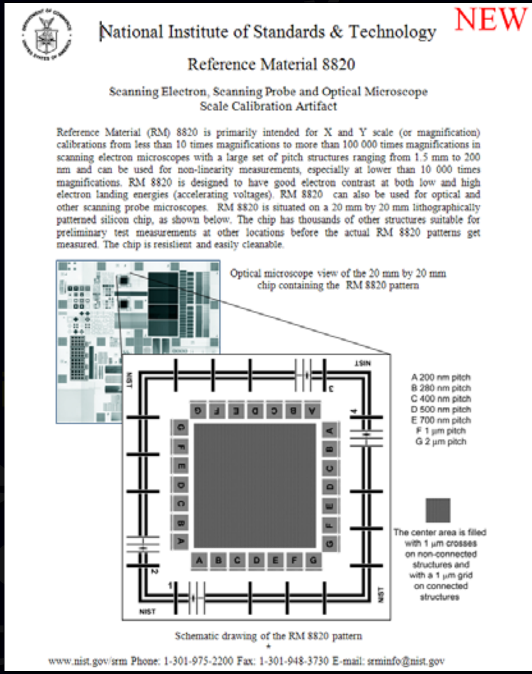
MEL
Innovation & productivity

# Disclaimer

- Certain commercial equipment is identified in this report to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment identified is necessarily the best available for the purpose

# Nanoelectronics Manufacturing

- The helium ion microscope is an exciting new technology for nanotechnology nanomanufacturing.
  - Initially, appears straightforward
  - But, much must be understood
    - Especially to obtain meaningful quantitat
- The NIST Manufacturing Engine Laboratory (MEL) has supporte "**nanomanufacturing**" through t t of measurements and standards since about 1999.



National Institute of Standards & Technology

NEW

Reference Material 8820

Scanning Electron, Scanning Probe and Optical Microscope Scale Calibration Artifact

Reference Material (RM) 8820 is primarily intended for X and Y scale (or magnification) calibrations from less than 10 times magnifications to more than 100 000 times magnifications in scanning electron microscopes with a large set of pitch structures ranging from 1.5 mm to 200 nm and can be used for non-linearity measurements, especially at lower than 10 000 times magnifications. RM 8820 is designed to have good electron contrast at both low and high electron landing energies (accelerating voltages). RM 8820 can also be used for optical and other scanning probe microscopes. RM 8820 is situated on a 20 mm by 20 mm lithographically patterned silicon chip, as shown below. The chip has thousands of other structures suitable for preliminary test measurements at other locations before the actual RM 8820 patterns get measured. The chip is resislient and easily cleanable.

Optical microscope view of the 20 mm by 20 mm chip containing the RM 8820 pattern



Schematic drawing of the RM 8820 pattern

www.nist.gov/srm Phone: 1-301-975-2200 Fax: 1-301-948-3730 E-mail: srminfo@nist.gov

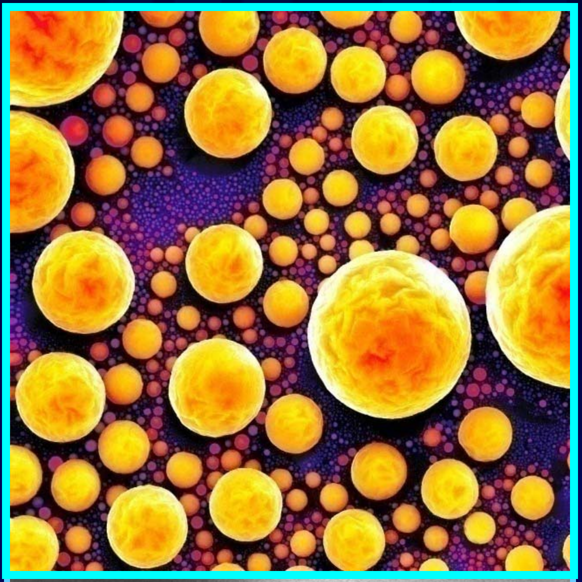
- Semiconductor manufacturing is "**nanomanufacturing**" and MEL has supported SEMATECH since its inception
  - **New magnification calibration sample**

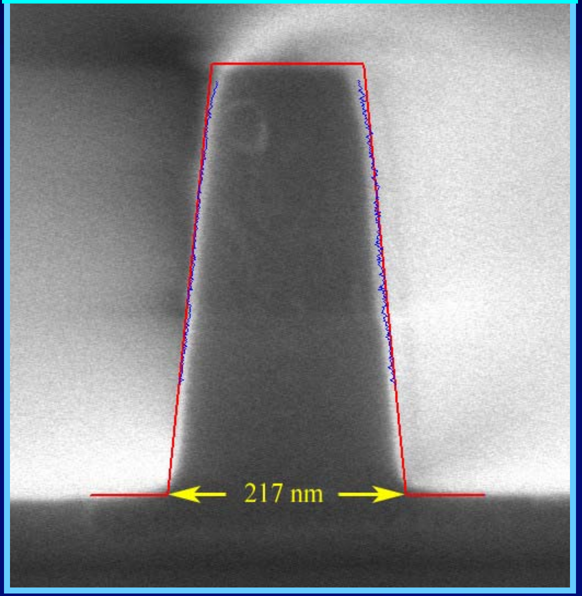
# Nanoelectronics Manufacturing

- Development of successful **nanomanufacturing** is the key link between scientific discovery and commercial products
  - Revolutionize and possibly revitalize many industries and yield many new high-tech products
- Without high-quality imaging, accurate measurements and standards at the sub-nanometer scale, nanomanufacturing cannot succeed

# Imaging and Measurements

- Both nanotechnology and nanomanufacturing require:
  - Atomic level measurement accuracy and repeatability
  - Ability to accurately measure desired performance attributes – at high throughput
  - Commercially viable production costs
- Advanced measurement technology is needed by nanotechnology and nanomanufacturing more than for any other prior technology
  - Avoid past technological problems
    - Asbestos

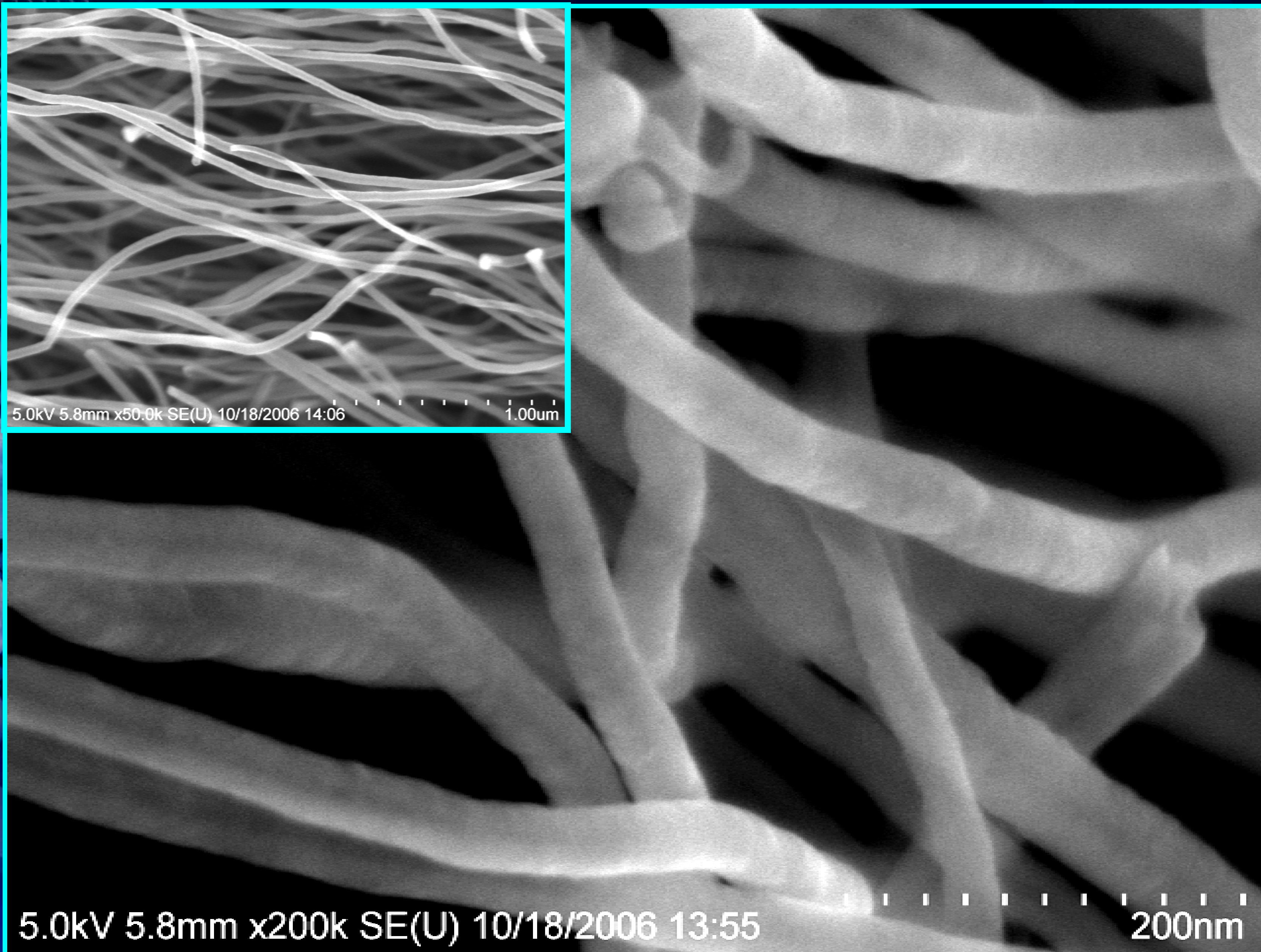





n a n o t e c h n o l o g y

# Nanometrology Challenge

- Much of the measurement infrastructure currently available for nanotechnology and nanomanufacturing is good and getting better but, only evolutionary in nature
  - Optics
  - Transmission Electron Microscope
  - Scanning Probe Microscope
  - Scanning Electron Microscope
- Automated, operator-independent instrumentation adapted to nanomanufacturing must be developed and is indispensable
  - This was one of the key conclusions at the NNI Grand Challenge Workshop on Instrumentation and Metrology and the recent NIST Nanomanufacturing Workshop
- New, potentially revolutionary metrology is needed for many applications
  - Helium Ion Microscope




n a n o t e c h n o l o g y

## Resolution of Scanning Electron and Ion Microscopes in the Precision Engineering Division Labs**

| | Manufacturer Published Specification (nm) | Best Measured (nm) | Median Measured (nm) |
|---|---|---|---|
| Instrument 1 | 0.9 | 0.65 | 0.78 |
| Instrument 2 | 0.4 | 0.38 | 0.42 |
| Instrument 3 | 0.8 | 0.7 | 1.2 |
| Instrument 4 | 1.0 | 0.8 | 0.9 |

** Instrument identification and manufacturer intentionally omitted.

# Nanometrology Challenge

- Much of the measurement infrastructure currently available for nanotechnology and nanomanufacturing is only evolutionary
  - Optics
  - Transmission Electron Microscope
  - Scanning Electron Microscope
  - Scanning Probe Microscope
- Nanomanufacturing requires that automated, operator-independent instrumentation must be developed
  - Instrument operators are the largest source of measurement error
    - This has been well documented by the semiconductor industry
- New, potentially revolutionary metrology is needed for many applications
  - Helium Ion Microscope

# Nanometrology Challenge

- Much of the measurement infrastructure currently available for nanotechnology and nanomanufacturing is only evolutionary
  - Optics
  - Transmission Electron Microscope
  - Scanning Electron Microscope
  - Scanning Probe Microscope
- Automated, operator-independent instrumentation adapted to nanomanufacturing must be developed and is indispensable
  - This was one of the key conclusions at the NNI Grand Challenge Workshop on Instrumentation and Metrology and the recent NIST Nanomanufacturing Workshop
- New, metrology instrumentation and technology is needed for many applications
  - Helium Ion Microscope

# Helium Ion Microscope (HIM)

- First of this new type of instrument was installed at NIST within the *Precision Engineering Division*
- In place of electrons, helium ions ($He^{+}$) are generated and used to irradiate the sample
- HIM resolution is capable of demonstrating 0.25 nm or 3-4 times better than the best current large sample SEMs
  - The need for detail obscuring specimen coating is minimized
  - Surface detail information is enhanced due to physics of signal formation
- Application of NIST (and others) expertise to the study of the physics of this instrument facilitates more accurate measurements and standards development.

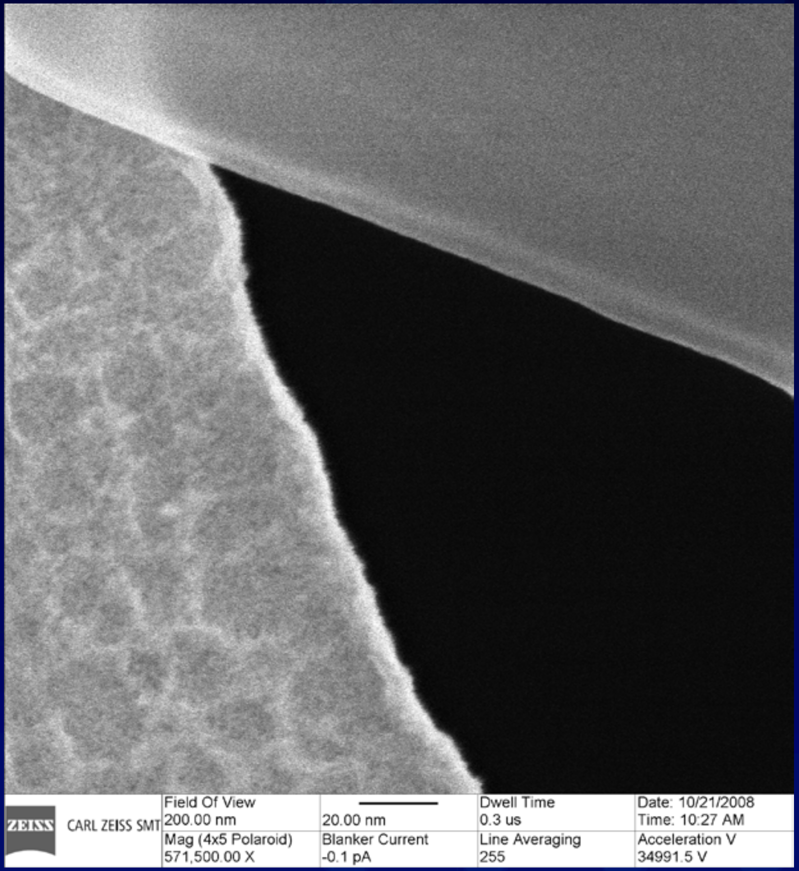
# Helium Ion Microscope (HIM)

- Contender for the next semiconductor production tooling?
- Question needing answers:
  - Imaging mechanisms?
  - What happens with the helium injected into the sample?
  - Currently instrument restricted to high landing energies
  - Throughput (low dose) and effect on S/N
  - Others????
- Exciting to be at the beginning of a new technology

# Helium Ion Microscope Sharpness

**Rapid evolution:**

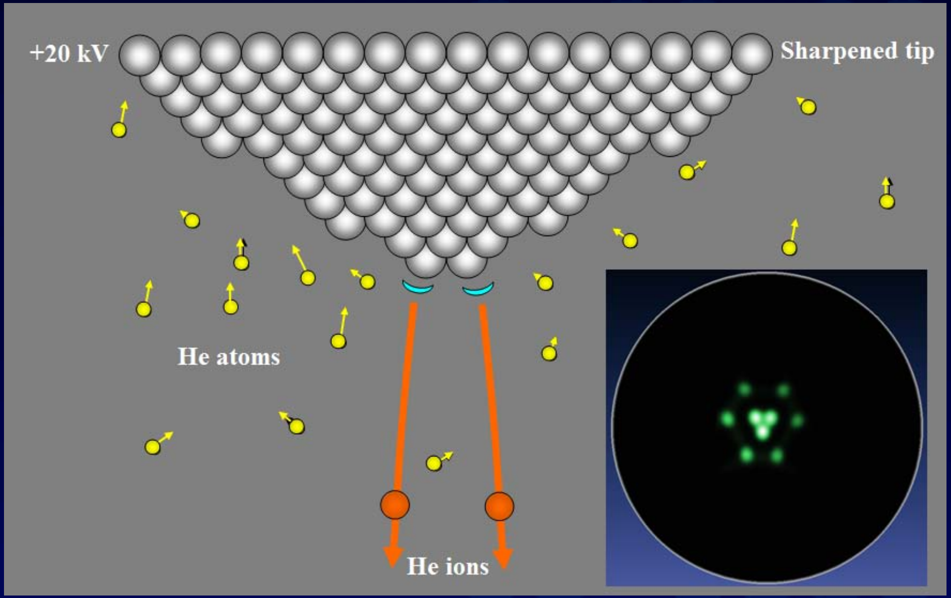
**Recent news release stated:**
**"……a surface resolution of 2.4 Ängstrom (0.24 nanometer) has repeatedly been achieved (25%-75% edge-rise criterion) on various samples."**

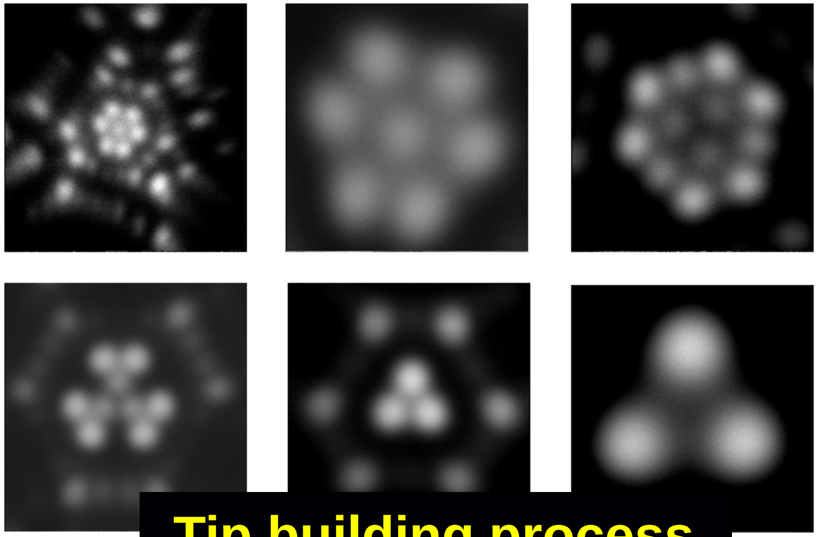



**Zeiss. "Helium Ion Microscopy". Microscopy and Analysis January 2009 p28**
**www.smt.zeiss.com/orion (2009).**

# Helium Ion Emission

- The ion source is cryogenically cooled in a low-pressure helium gas environment.
- Helium ionization takes place at the atomically sharp tip.
- The arriving helium atoms adhere everywhere to the tip
- At the very tip of the pyramid is the electric field high enough for the atoms to ionize accelerate down the column.
- Emitter control and manipulation literally is at the level of a <u>*single*</u> atom.



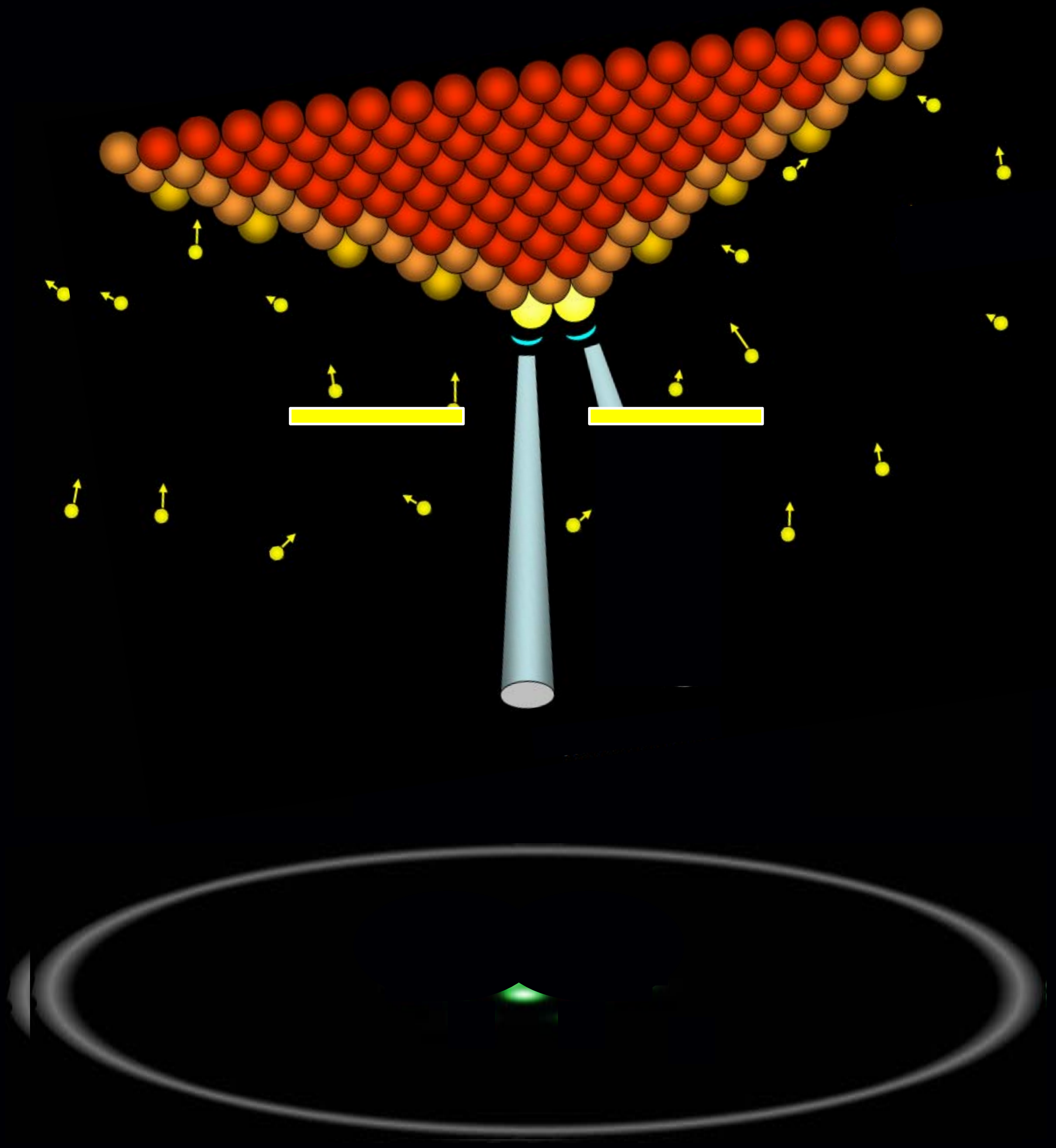



Tip building process

n a n o t e c h n o l o

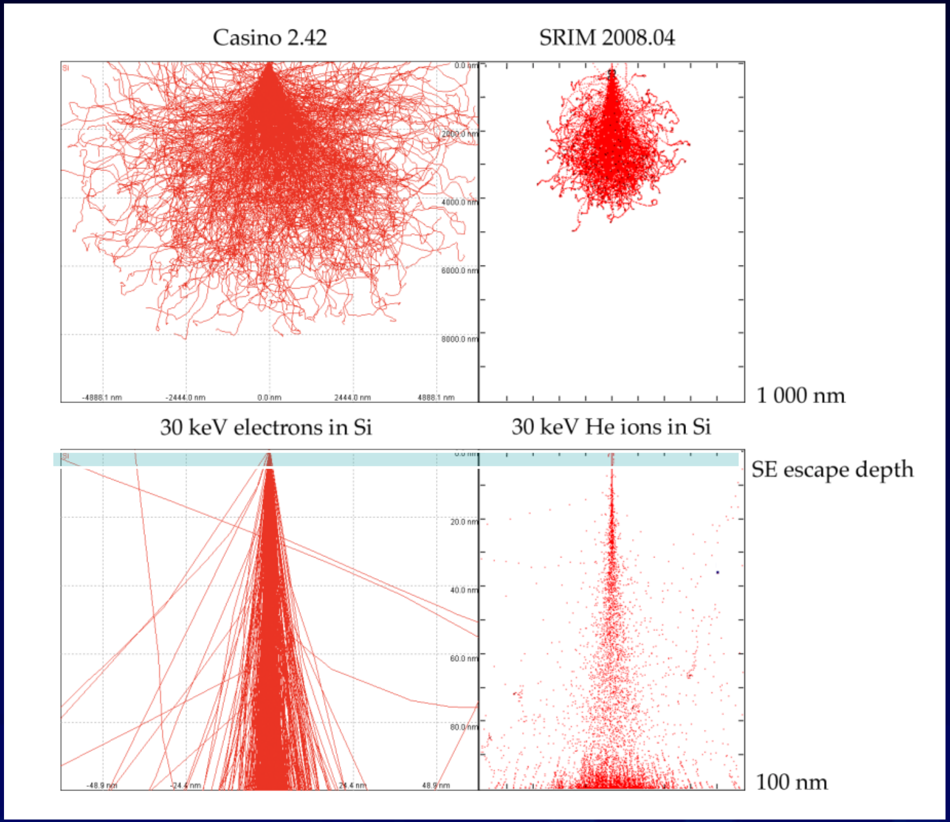
# Alignment to the brightest atom

- **Under normal operating conditions the ion current from a single atom of a three-atom cluster (trimer) is selected by tilting the gun and using a beam limiting aperture.**
  - **This permits a smaller source size, but at the expense of lower beam current.**



# Helium Ion Microscope (HIM)

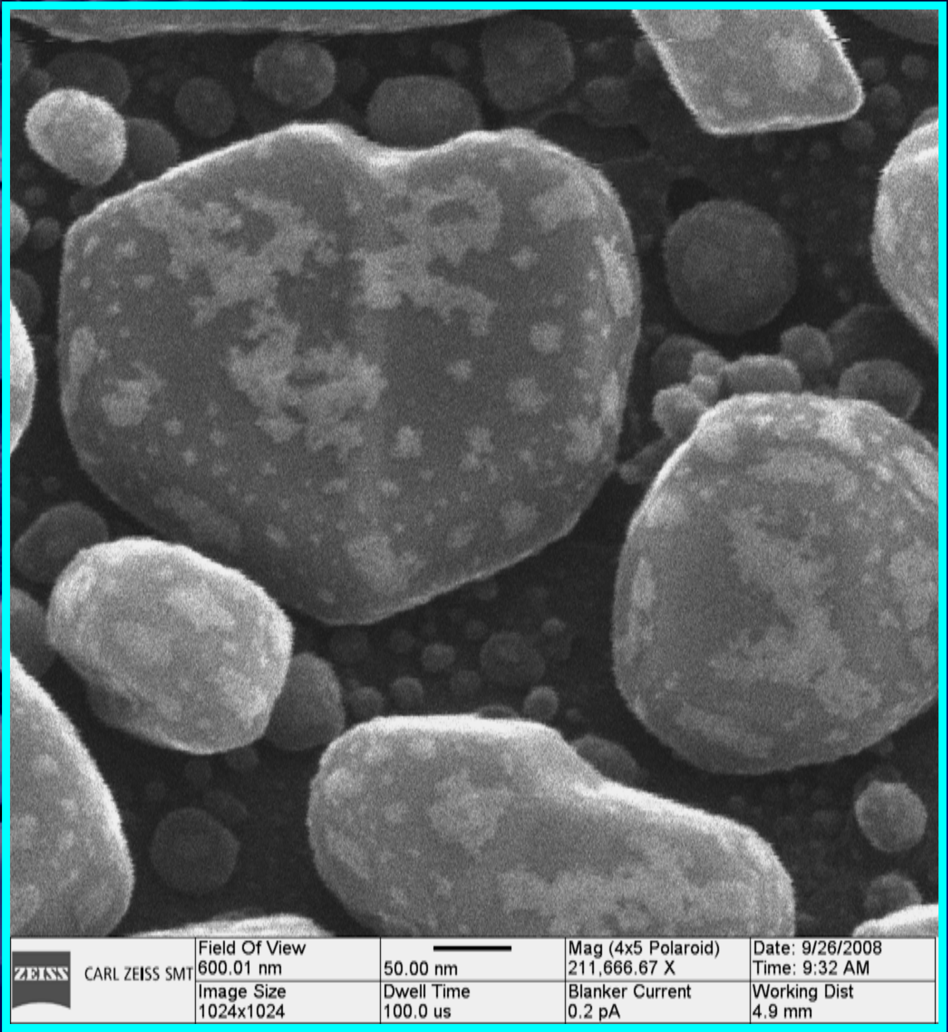
- Interaction volume of the He+ beam near the surface is considerably smaller than that of an SEM
- $He^{+}$ beam produces both secondary electrons (SE) and scattered $He^{+}$ ions
- Ratio of SE 1 yield to SE 2 and SE 3 yield is much better than the SEM
- The excited volume is buried deep in the sample and SE generation is localized near the surface

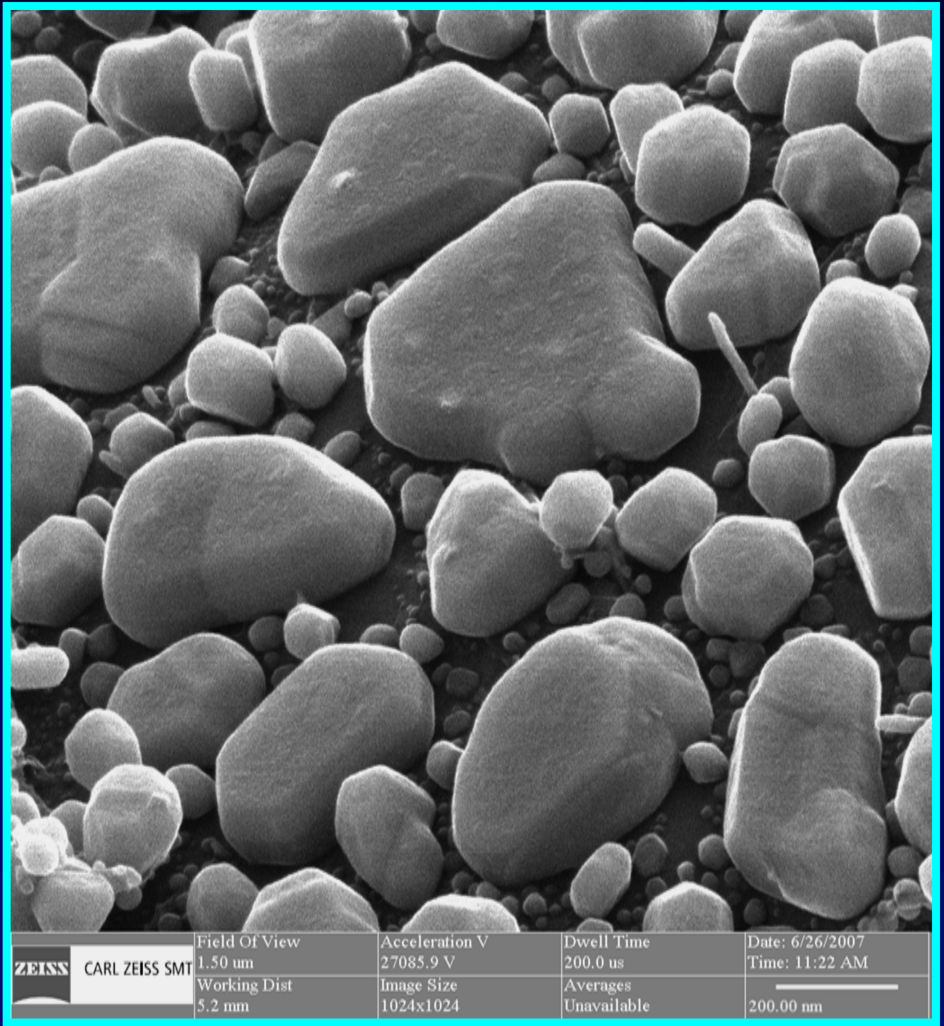



Modeled interaction volumes for electron and He ion excitation

- Positive performance dominated by the demagnified source size and the shallow SE generation (fundamentally all SE-1)
- Major limitations to the performance are other instrument issues (e.g., vibration) which can be overcome with engineering solutions.

# Primary beam interactions

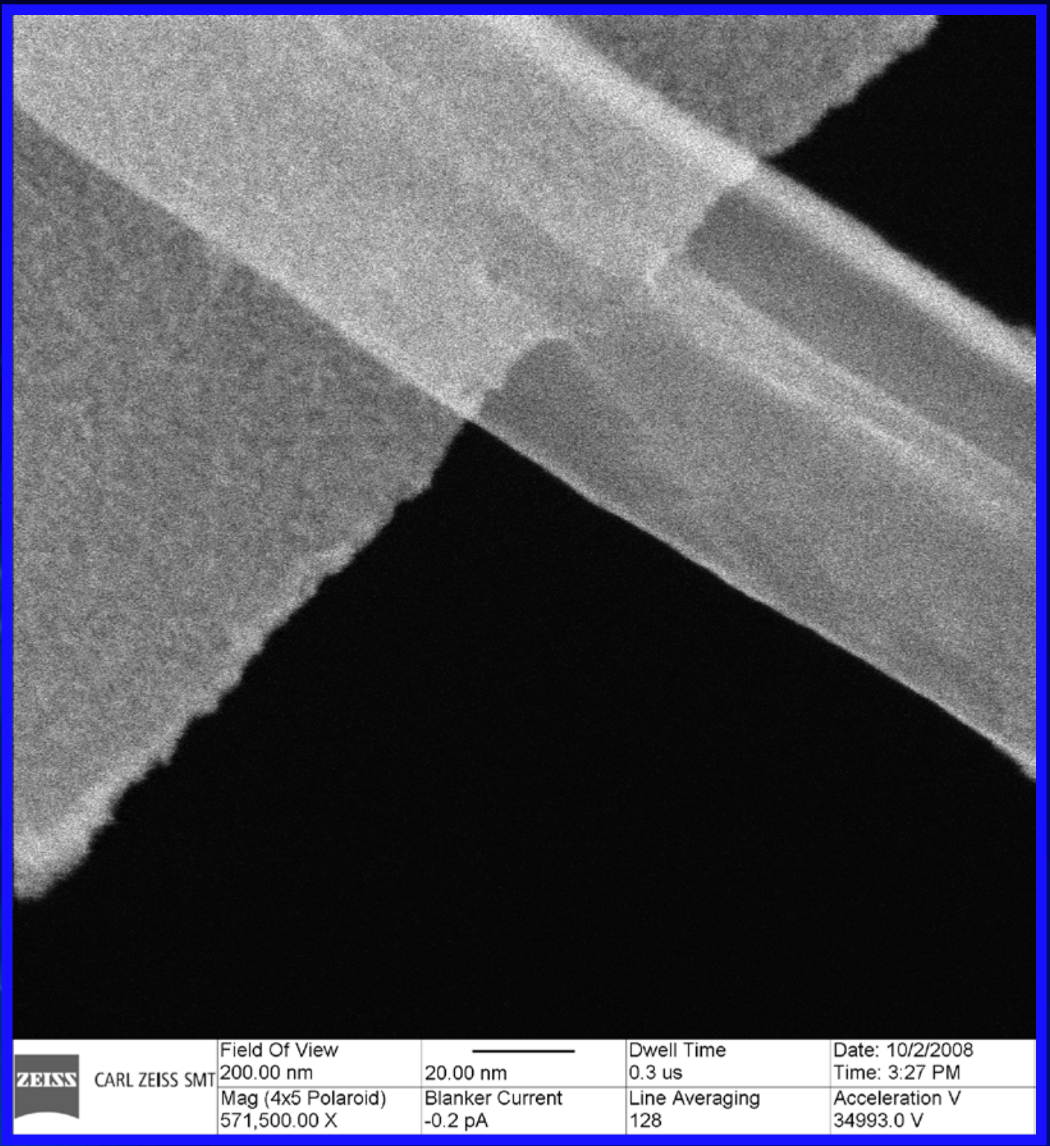


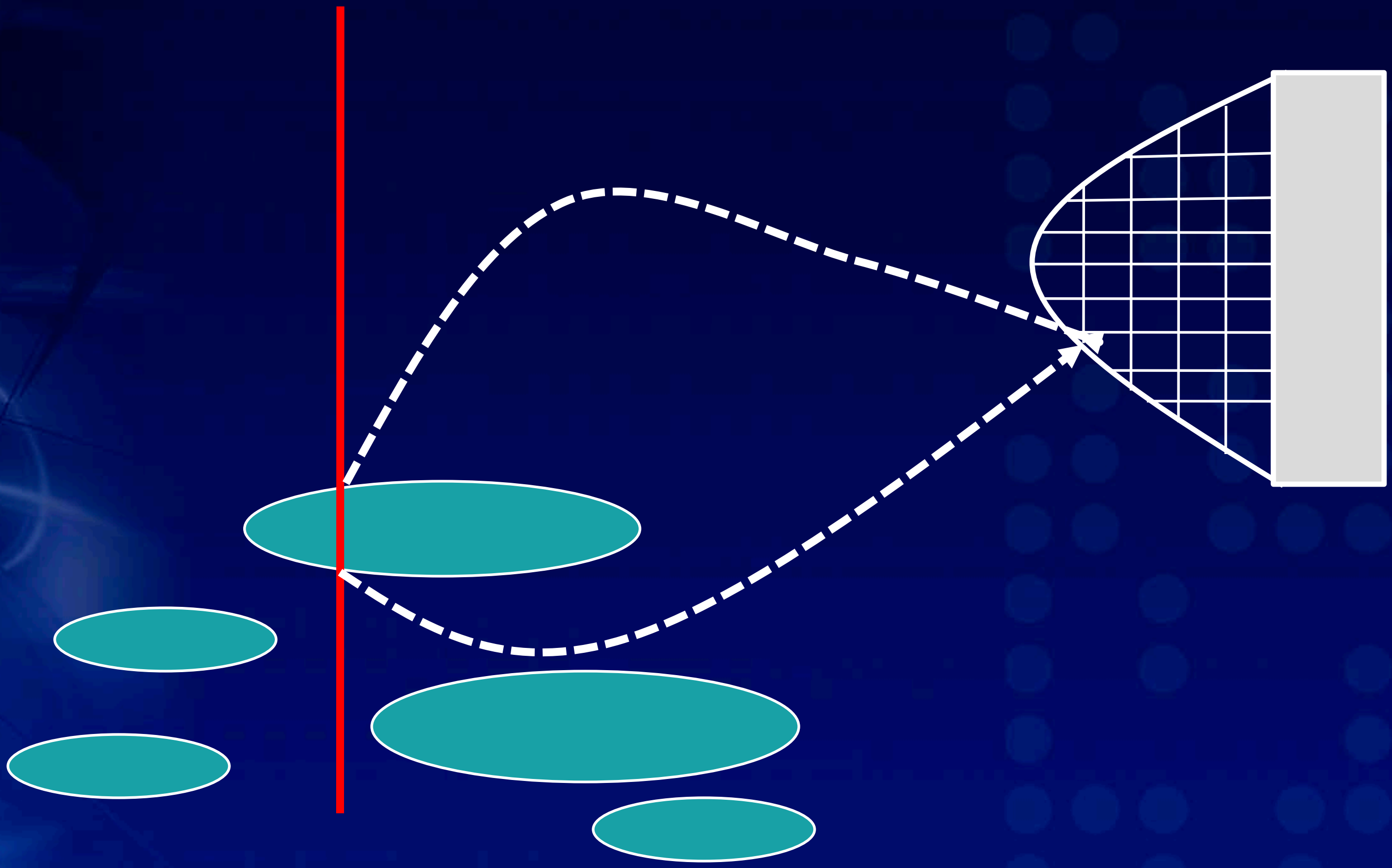

n a n o t e c h n o l o g y

MEL
innovation & productivity

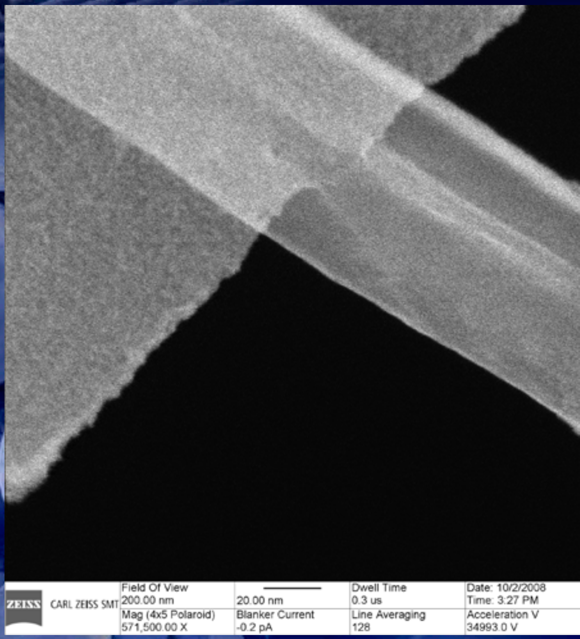
# Primary Beam Interactions

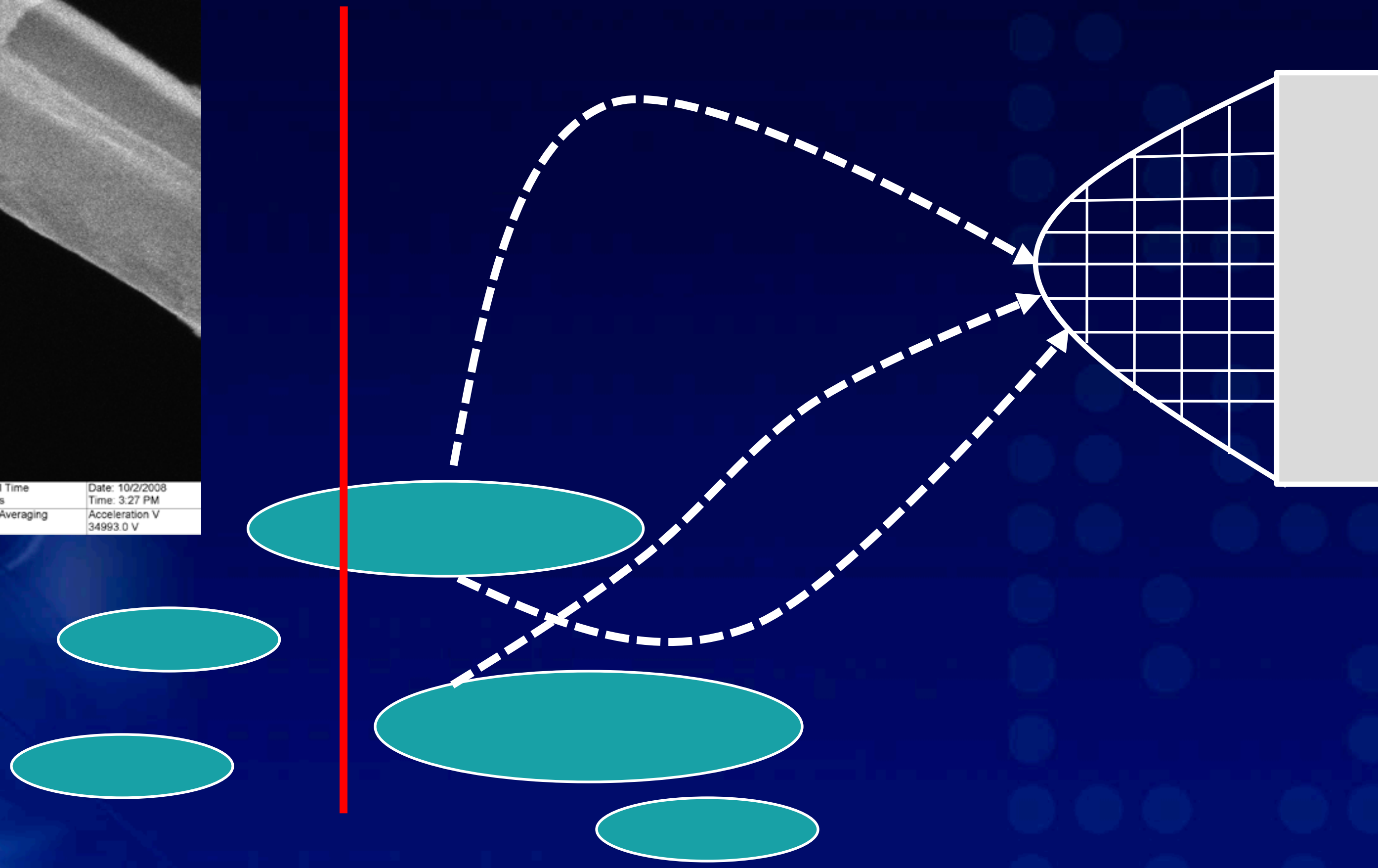


# Signal Generation and Collection

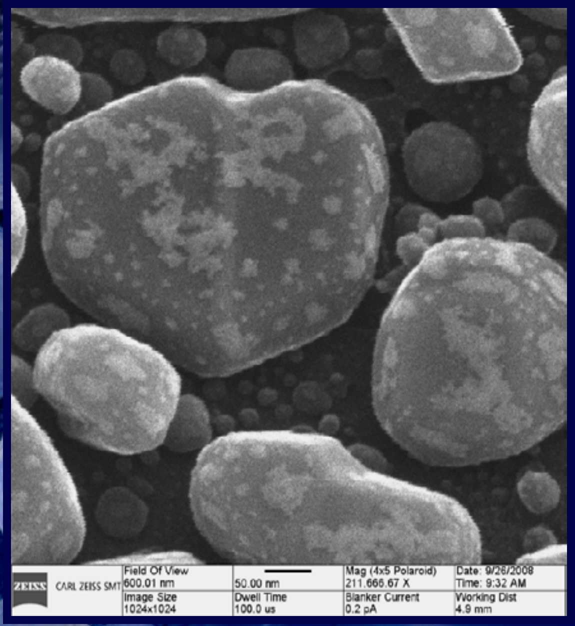


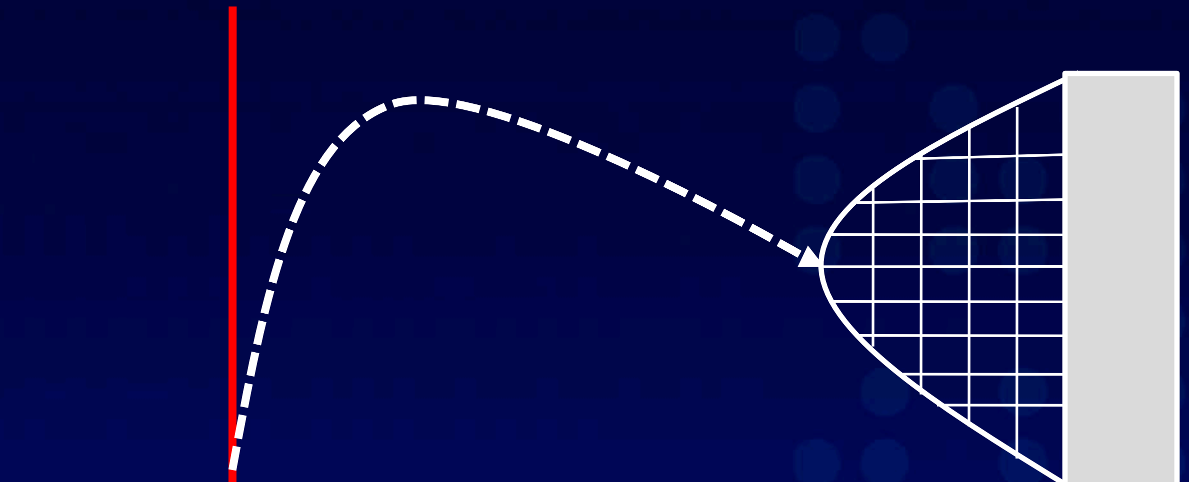
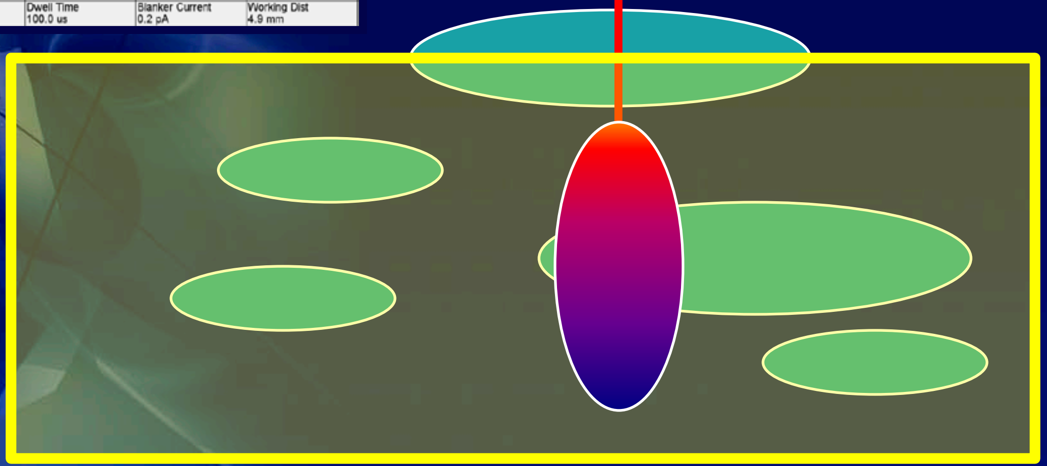
# Signal Generation and Collection



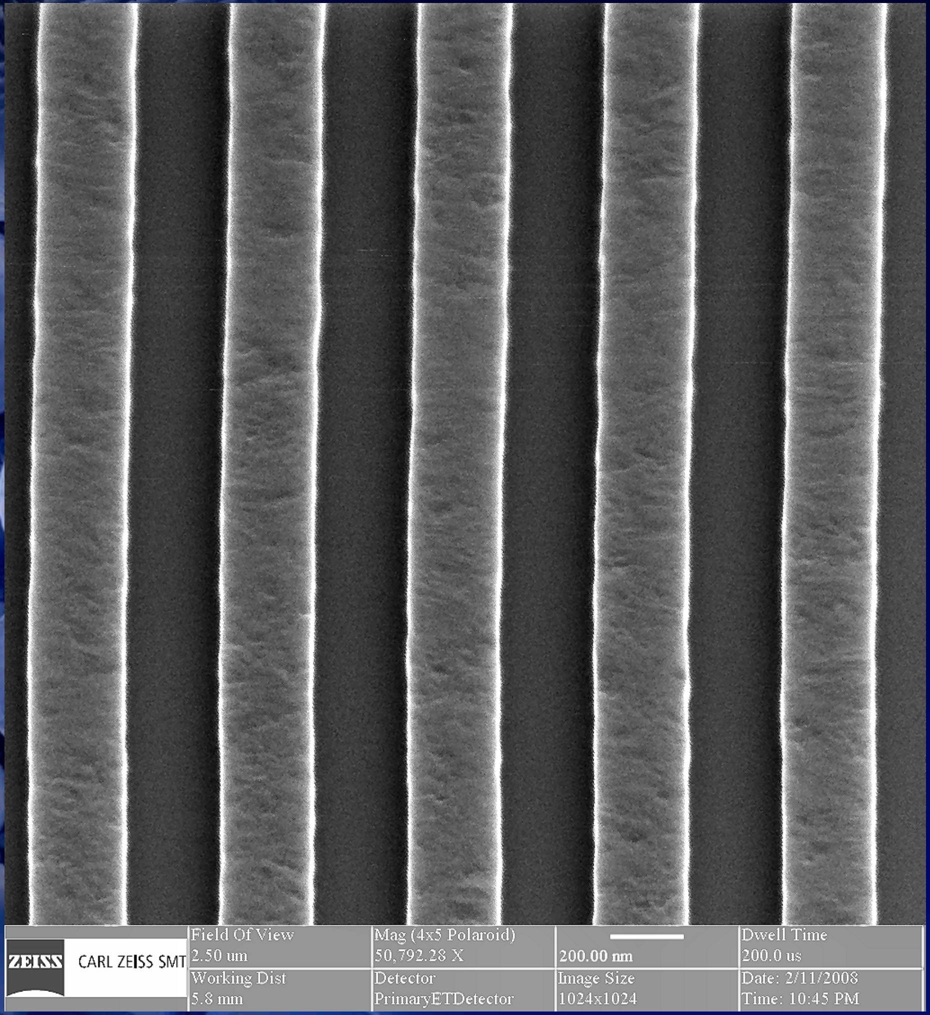



# Signal Generation and Collection

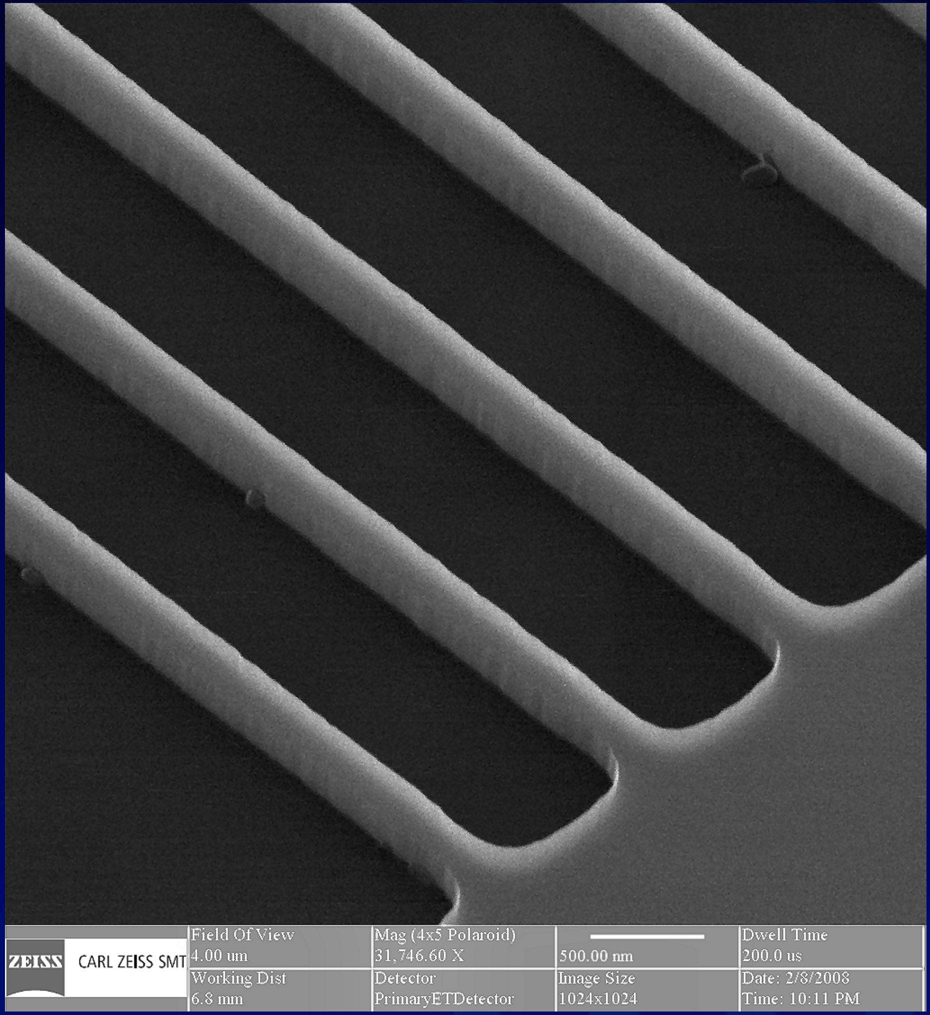


# Semiconductor structure imaging




Polysilicon Lines
field of view = 2.5 micrometers

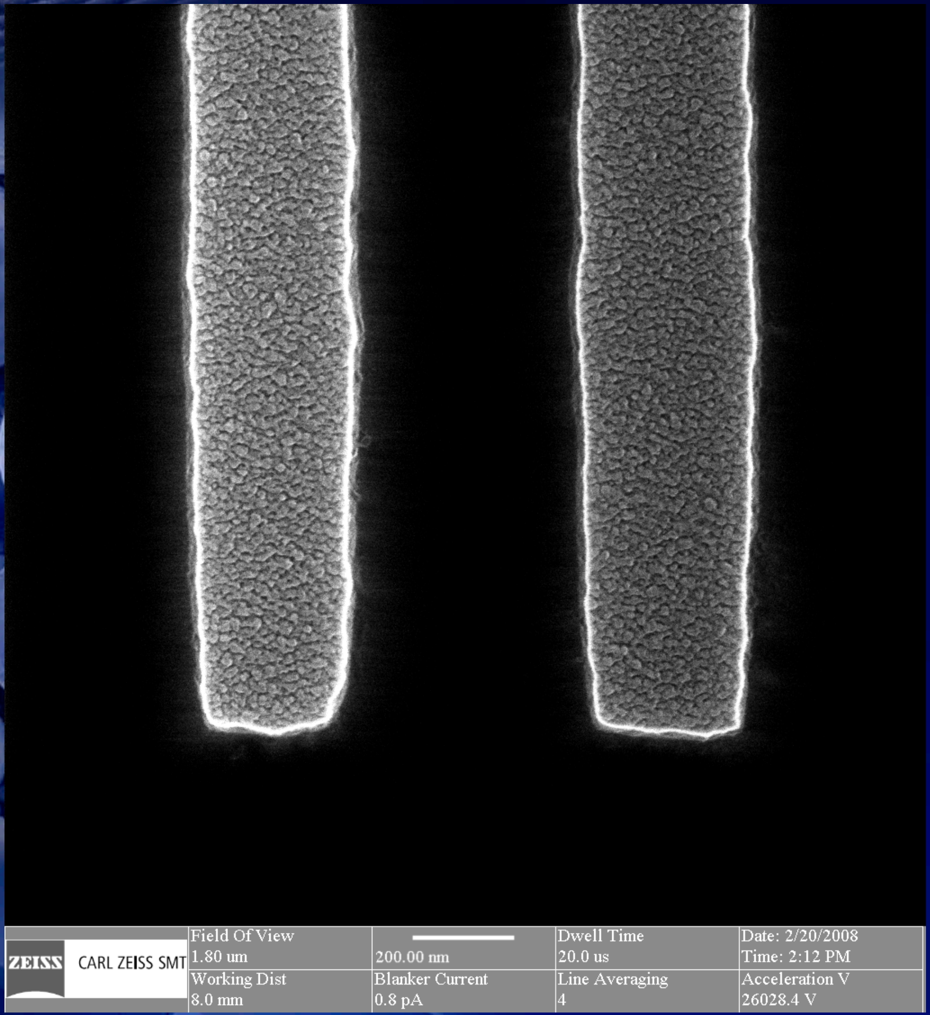


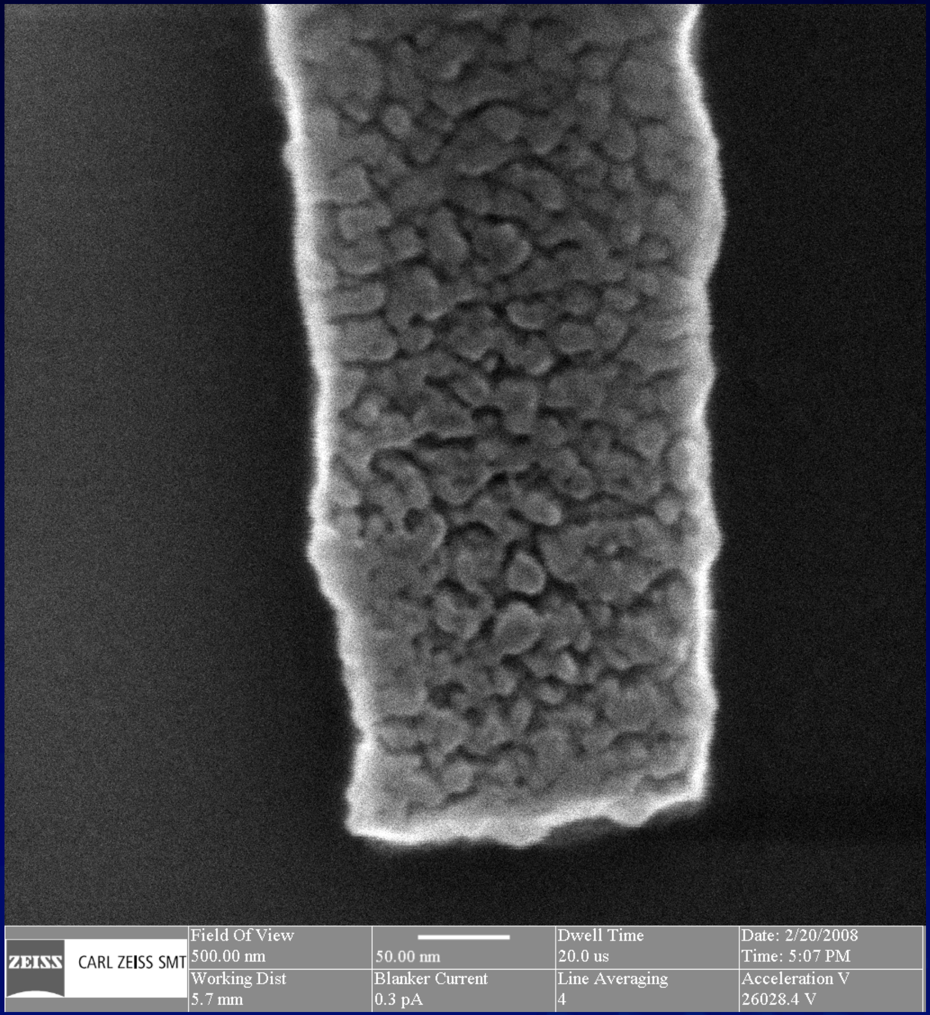

Photoresist Structures
field of view = 4.0 micrometers

n a n o t e c h n o l o g y

MEL
innovation & productivity

# Chromium on Quartz Photomask




**field of view = 1.8 micrometers**

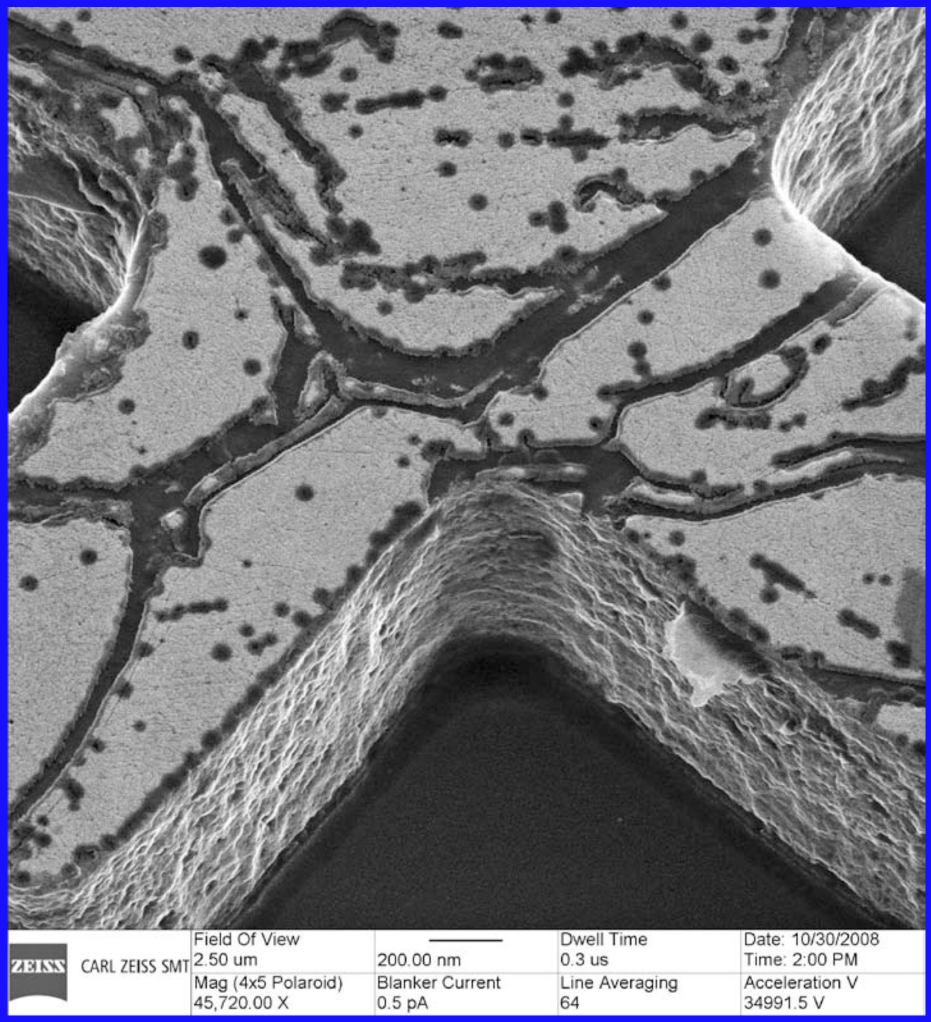
**field of view = 500 nm**

**Imaged using the electron flood gun**

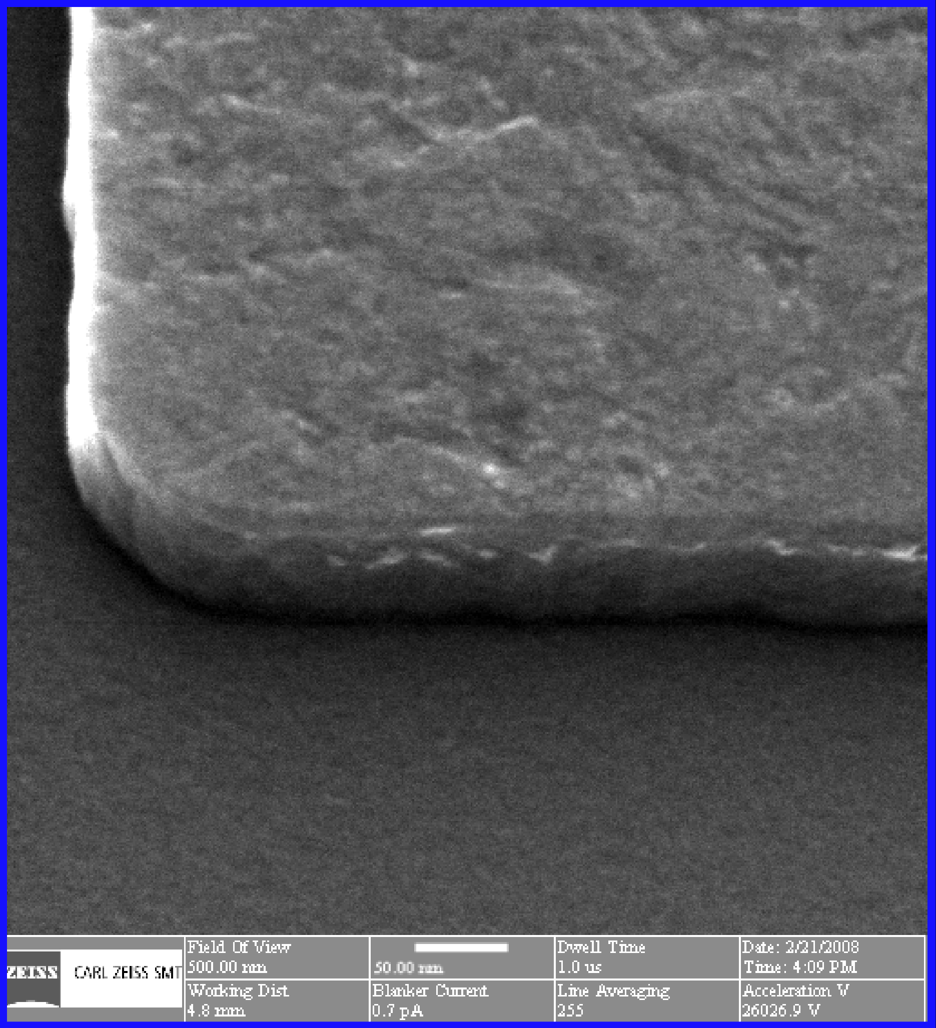
n a n o t e c h n o l o g y

MEL
Innovation & productivity

# Semiconductor Materials Imaging




field of view = 2.5 micrometers



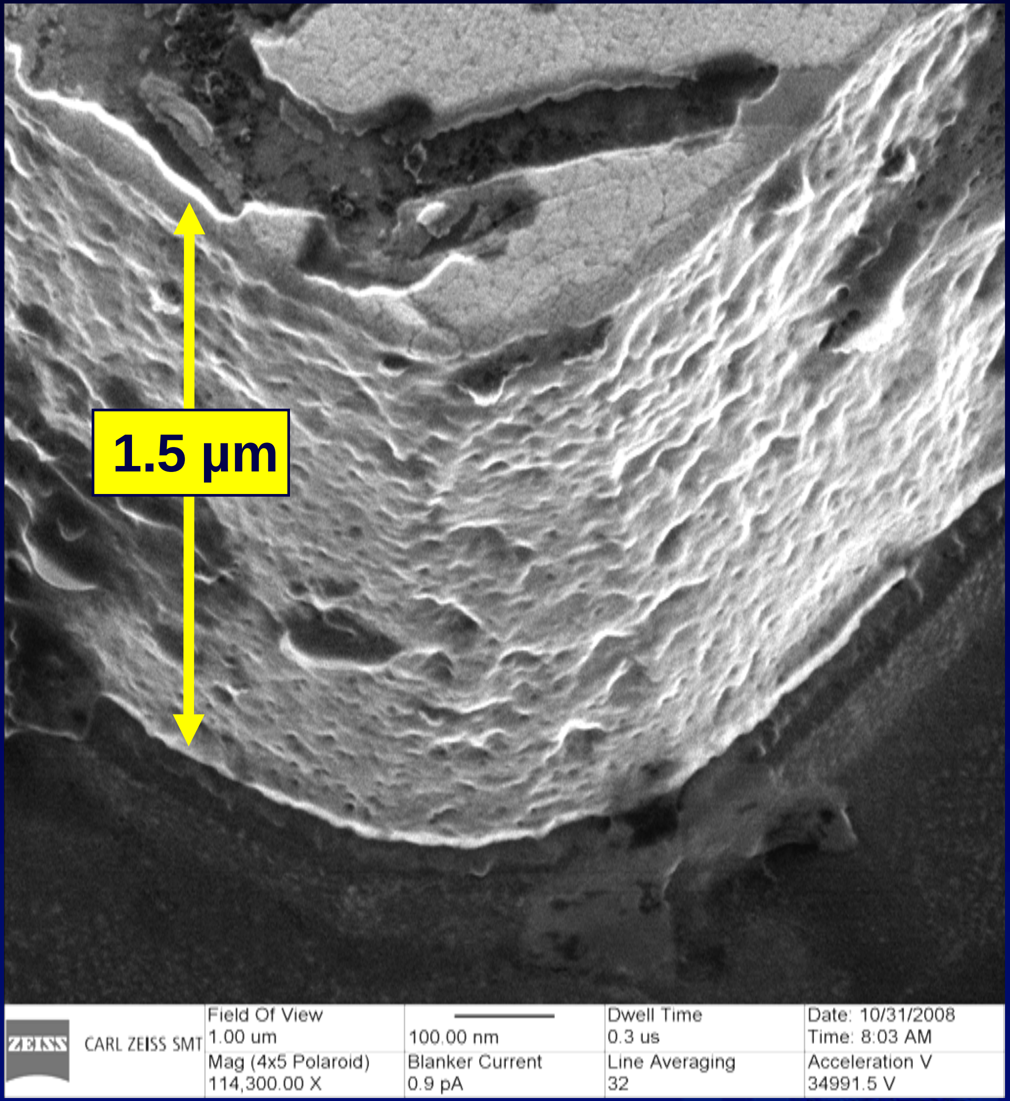

field of view = 500 nm

n a n o t e c h n o l o g y

MEL innovation & productivity

# Depth of Field

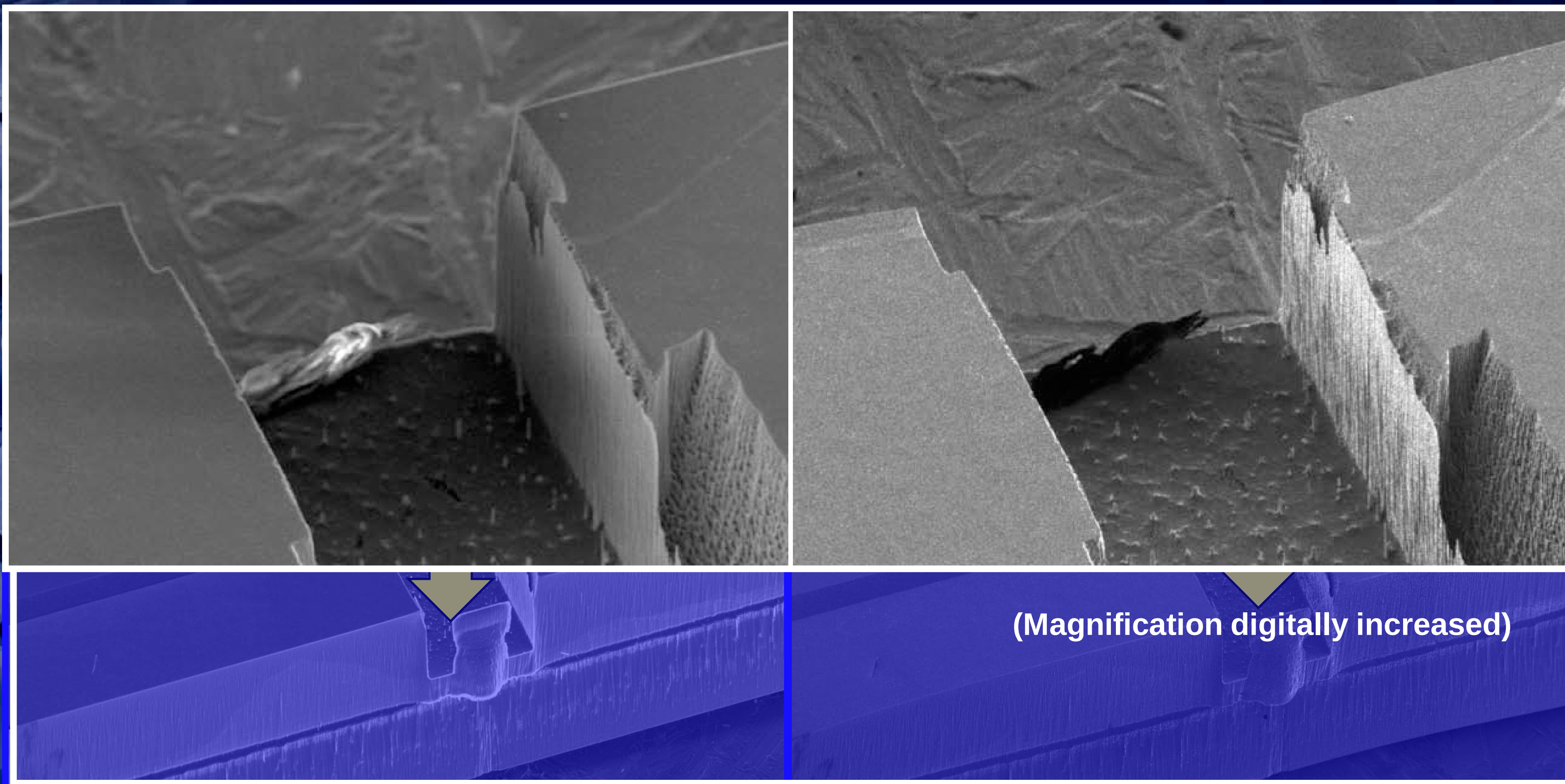
- Extremely small convergence angle
- Depth-of-field in the HIM is about 5x larger than the SEM
- Depth of Field can be as much as 2.5 µm at 1 µm field of view.
- Advantage for imaging, metrology and……



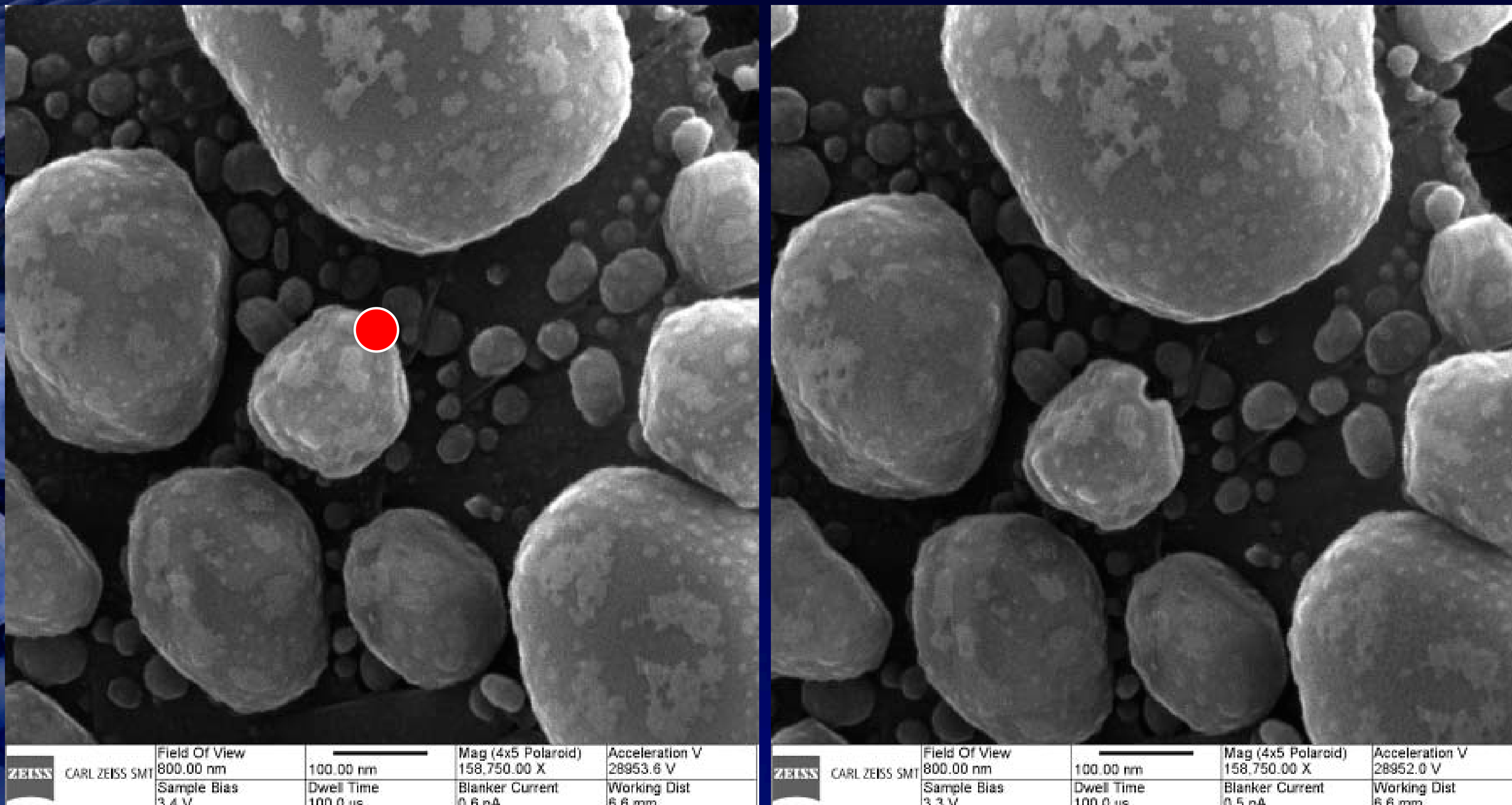

n a n o t e c h n o l o g y

MEL
innovation & productivity

# Depth of Field



# Helium Ion Beam Milling

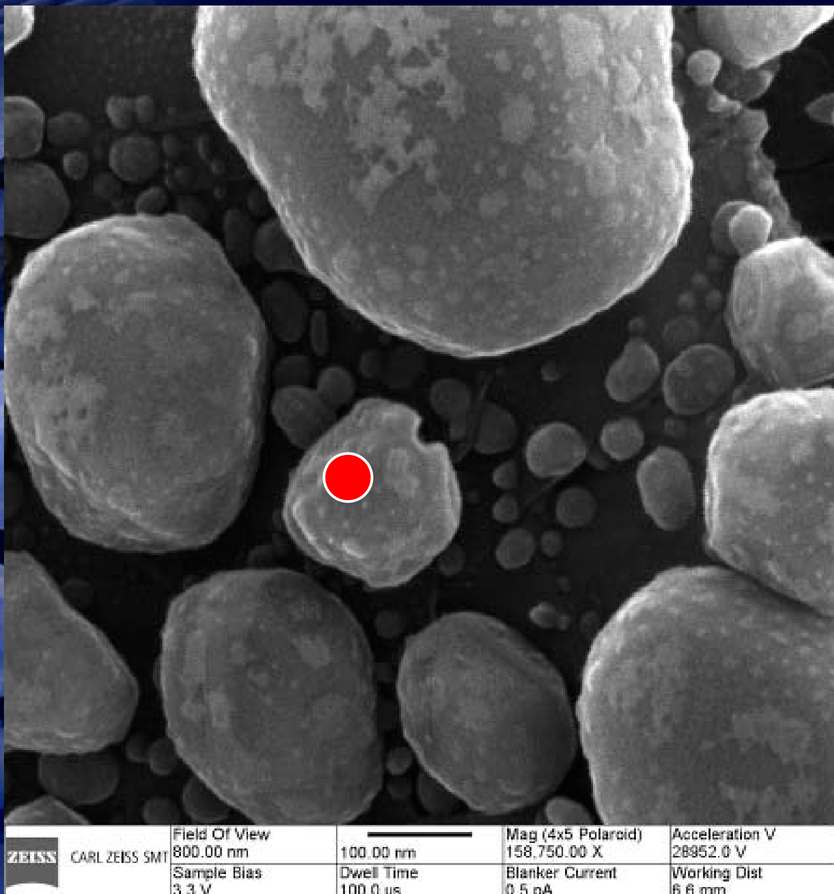


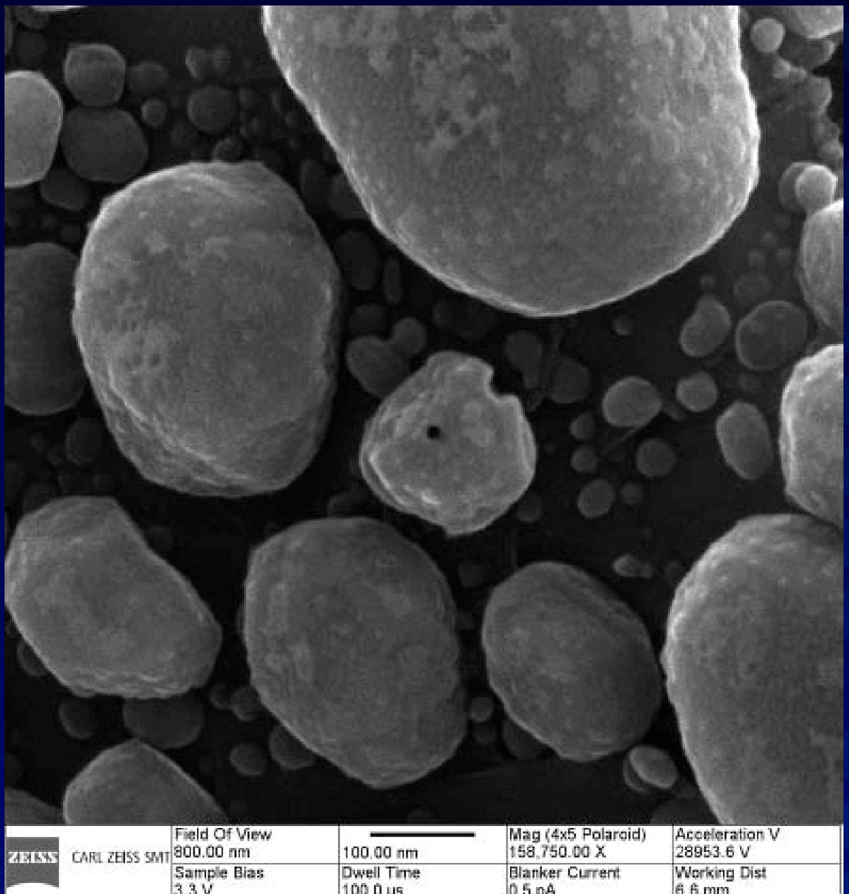

- **Highly precise material removal (and deposition) can be accomplished**
- **Other specimen damage is minimal**

n a n o t e c h n o l o g y

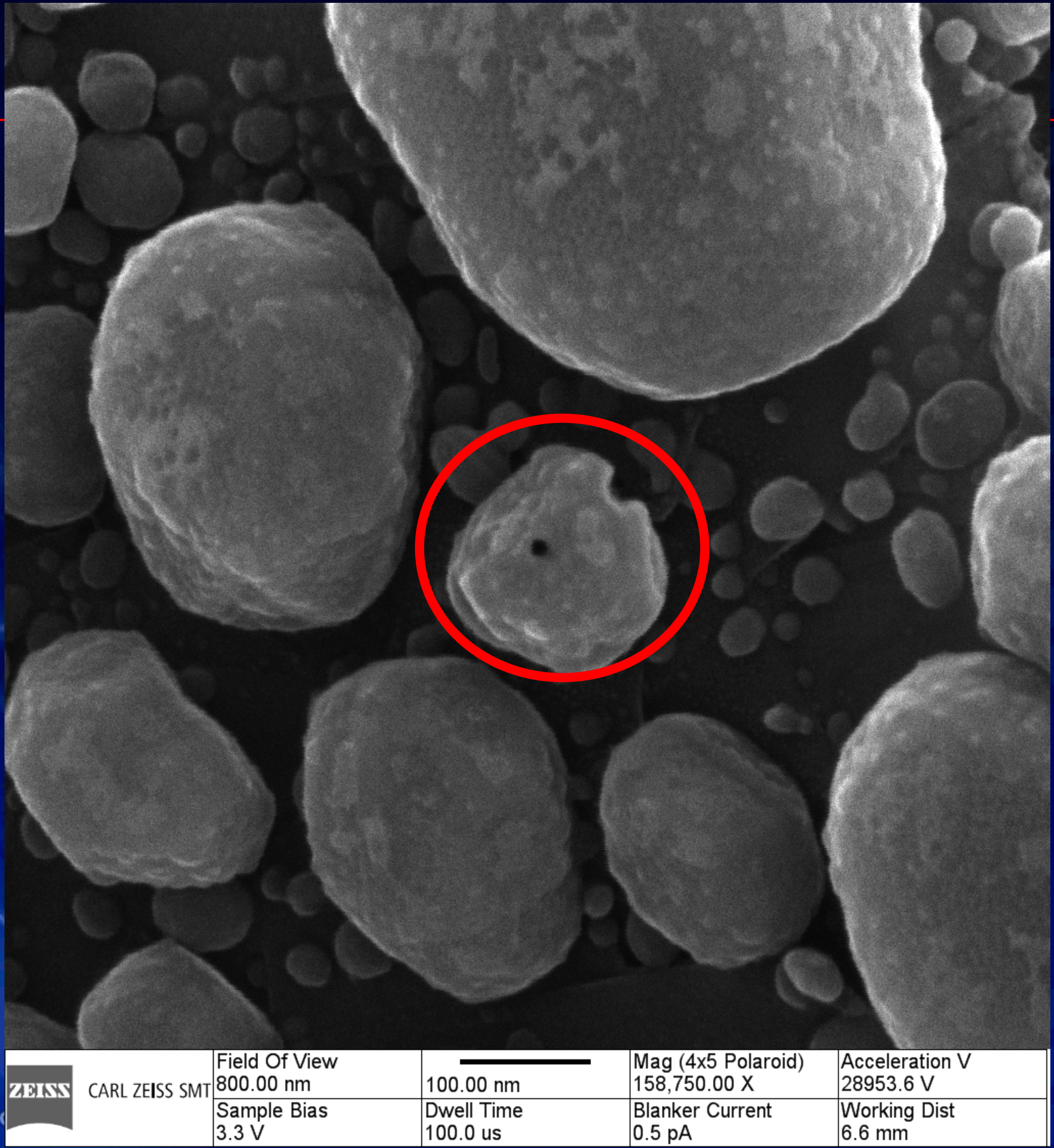
MEL innovation & productivity

# Helium Ion Beam “Drilling”

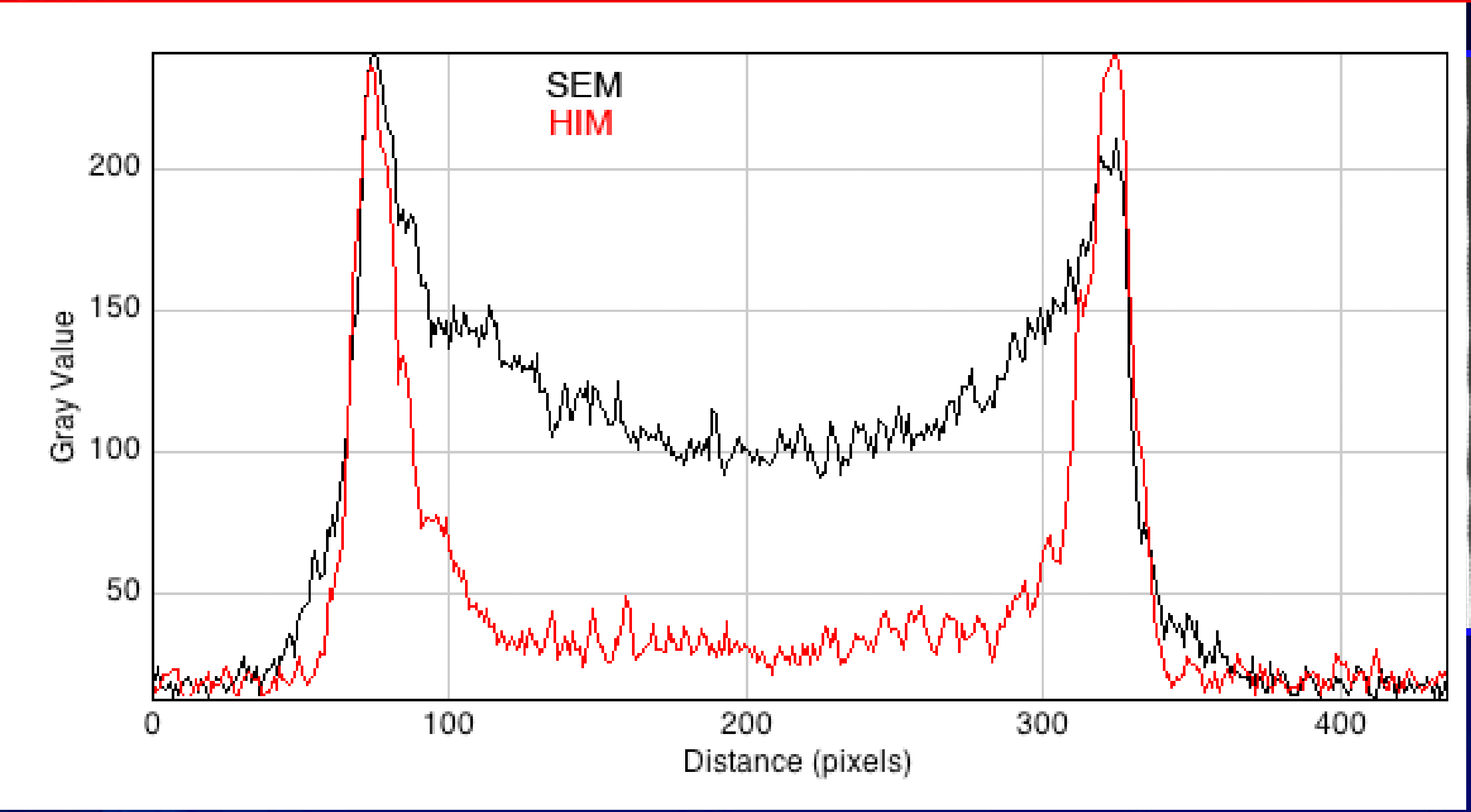



- **Contamination deposition is well controlled**
- **No other method can achieve similar results**


ZEISS
CARL ZEISS SMT
Field Of View
800.00 nm
100.00 nm
Mag (4x5 Polaroid)
158,750.00 X
Acceleration V
28953.6 V
Sample Bias
3.3 V
Dwell Time
100.0 us
Blanker Current
0.5 pA
Working Dist
6.6 mm

# Dimensional Metrology




- Appears better edge definition is possible
- Insufficient amount of measurements have thus far been made to draw any quantitative conclusions
- Difficulty in comparing similar operating conditions
- More accurate modeling needs to be done

# Progress in Modeling

**Papers**

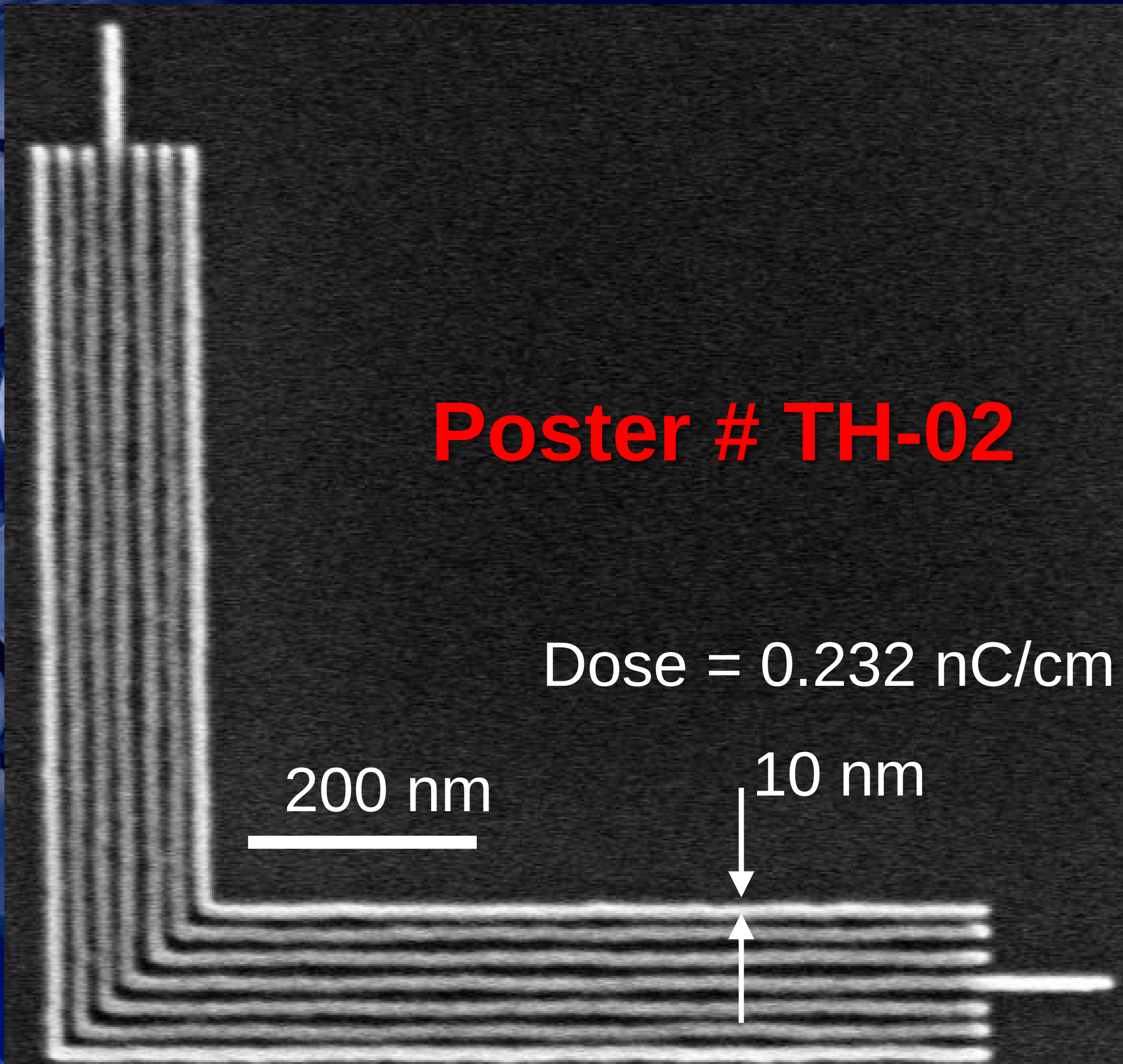
- T. Yamanaka,., K. Inai, K. Ohya, and T. Ishitani. “Simulation of secondary electron emission in helium ion microscope for overcut and undercut line-edge patterns”. Proceedings SPIE (in press) (2009)
- Ramachandra, R., B. Griffen, and D. C. Joy. “Modeling for metrology with a helium beam”. Proc. SPIE 6922: DOI:1017/12.772300. (2008)
- Ramachandra, R. , B. Griffen, and D. C. Joy. “A Model of Secondary Electron Imaging in the Helium Ion Scanning Microscope”. Ultramicroscopy (in press)
- Cohen-Tanugi, D. and N. Yao, J. Appl Phys Superior imaging resolution in scanning helium-ion microscopy: A look at beam-sample interactions104:063504-1 - 063504-7 (2008)

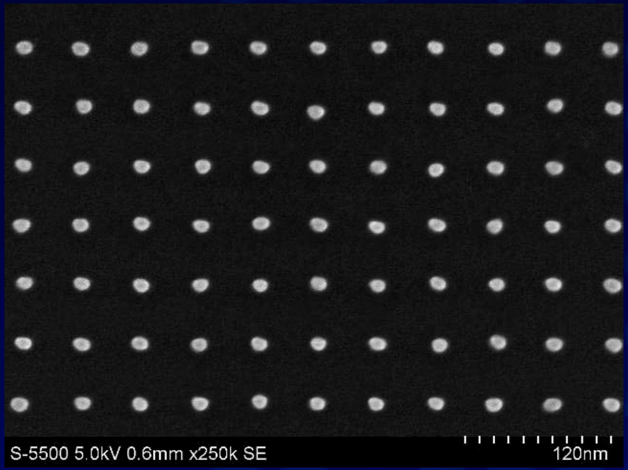
**Model**

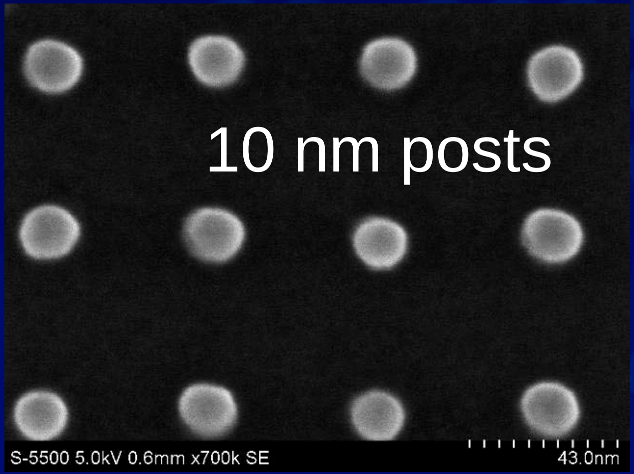
- IONiSE 1.6 Beta and beyond, now available for helium ion induced secondary electron yield estimations now available from David Joy.

# Helium Ion Beam Lithography

D. Winston, B. M. Cord, M. K. Mondol, J. K. W. Yang, K. K. Berggren, *Massachusetts Institute of Technology*
B. Ming, A. E. Vladar, M. T. Postek, *National Institute of Standards and Technology*
D. C. Bell, *Harvard University and* W. F. DiNatale, L. A. Stern, *Carl Zeiss SMT Inc.*



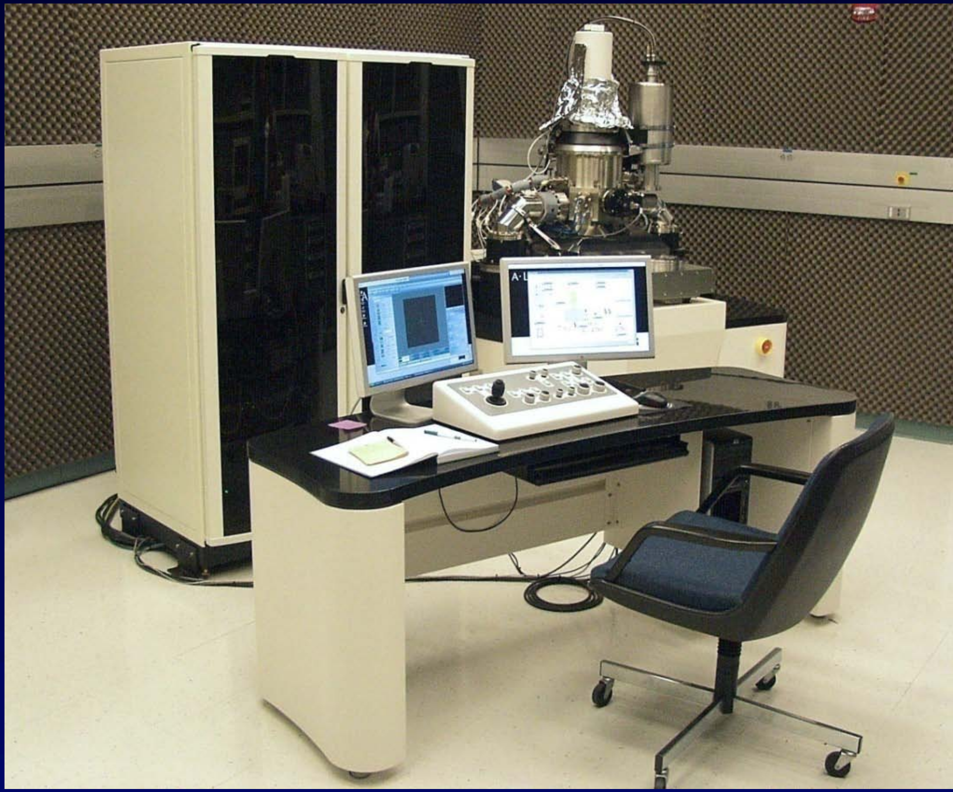
| Scanning Electron Microscope | Scanning Helium Ion Microscope |
|---|---|
| Penetration effects,<br>Ratio of SE 1 to SE 2 and SE 3 limit surface detail | Excellent surface detail<br>High percentage of SE 1 |
| Positive and negative electron charging possible | Positive charging possible but can be 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 microanalysis possible | Other analytical methods are pursued, show promise |
| Surface contamination possible but masked by high kV operation | Surface contamination can be a bigger problem – eliminated with Evactron |
| 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 |

# Conclusion

- HIM has not yet been fully optimized but, rapid progress is being made
- Many potentially useful applications have yet to be explored and exploited
- Today, with several commercial instruments now available, research is being done on:
  - Fundamental science of helium ion beam generation
  - Helium ion beam - specimen interactions
  - Signal generation and contrast mechanisms
  - Modeling to correctly interpret the signal mechanisms
  - Development of accurate metrology
  - Lithography potentials
  - Ion beam milling and deposition

# Conclusion

- SEM and HIM
  - Have some overlapping territory
  - Remain complimentary
- HIM is forging new scientific territory for nanotechnology and nanomanufacturing
- HIM performance is pushing electron columns to higher performance levels



- HIM is a technology, which once optimized will develop new science and contribute to the progress in nanotechnology and nanomanufacturing.

# Acknowledgements


- Collaborations with Alis/Zeiss SMT on the acquisition and optimization of the HIM
- Partial funding through the NIST Office of Microelectronics Programs
- Long standing collaboration with SEMATECH

# Thank you!

nanotechnology

MEL innovation & productivity