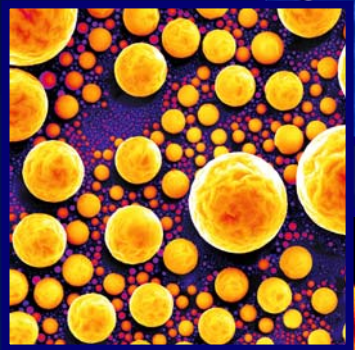
Advanced Metrology Needs for Nanotechnology and Nanomanufacturing

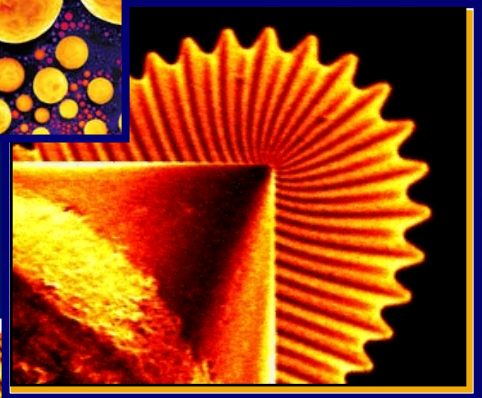
Dr. Michael T. Postek

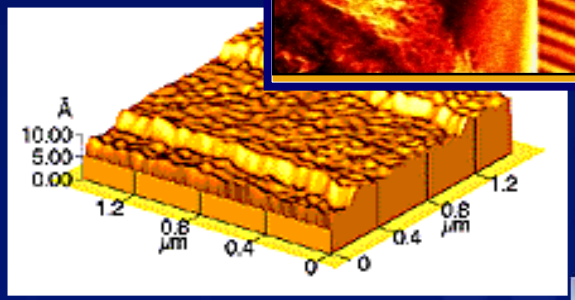
Assistant to the Director for Nanotechnology and

Program Manager, MEL Nanomanufacturing Program

2005 Micro-Nano Breakthrough
Portland State University, Oregon
July 2005







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

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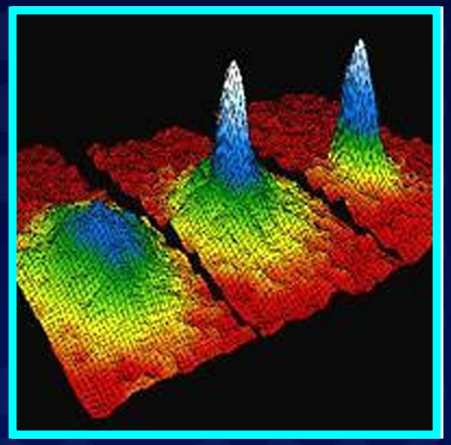
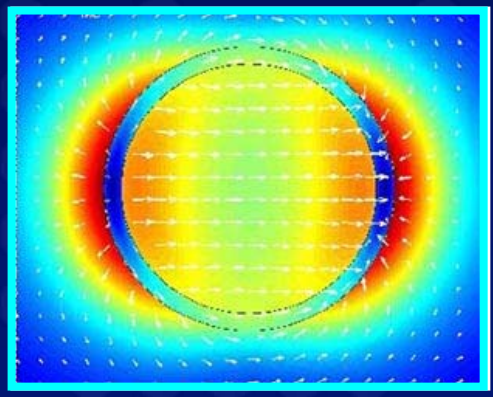
Nanotechnology

- Enabling technology that is the convergence of the state of the art in materials science, chemical science and biological science to make better products for the future.
- Revolutionize and possibly revitalize many industries and yield many new high-tech products
  - Nanomanufacturing is the link between scientific discovery and commercial products
- Both nanotechnology and nanomanufacturing will require:
  - Atomic level measurement accuracy and repeatability
  - Ability to measure desired performance attributes
  - Commercially viable production costs
    - High throughput metrology





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Nanotechnology

- In order to be characterized as nanotechnology by the National Nanotechnology Initiative, work must meet the following criteria:
  - Research and technol[illegible] work at atomic and m[illegible] th scale of approximatel[illegible].
  - Ability to understand, [illegible] devices and systems that have fundamentally new properties and functions because of their nanoscale structure.
  - Ability to control – to see, measure, and manipulate matter on the atomic scale to exploit those properties and functions.

How do you know?

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Nanotechnology

- In order to be characterized as nanotechnology by the National Nanotechnology Initiative, work must meet the following criteria:
  - Research and technology development aimed to work at atomic and molecular scales, in the length scale of approximately 1 - 100 nanometer range.
  - Ability to understand, create, and use structures, ve fundamentally new ause of their nanoscale structure.
  - Ability to control – to see, measure, and manipulate matter on the atomic scale to exploit those properties and functions.

How do you measure?

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Nanotechnology

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How do you image or visualize?

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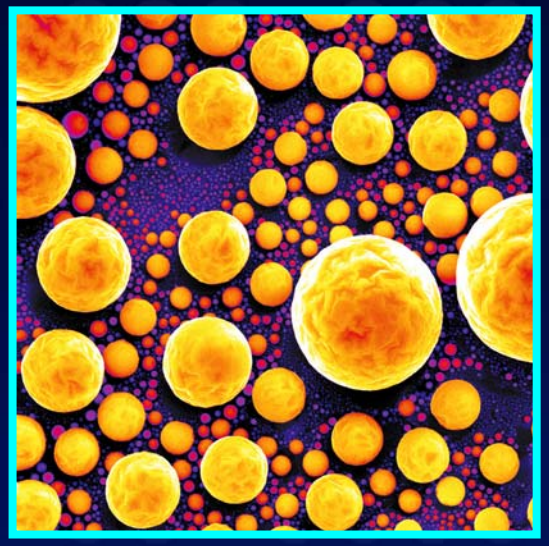
Nanometrology

- Advances in fundamental nanoscience, design of new nano-materials, and ultimately nanomanufacturing will all depend to some degree on the capability to accurately and reproducibly measure dimensions, properties and performance characteristics at the nanoscale.



  - *"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers where unique phenomena enable new and novel applications."*

- Where these new and unique properties manifest themselves is not fully known and new measurement tools and techniques are needed to measure them.

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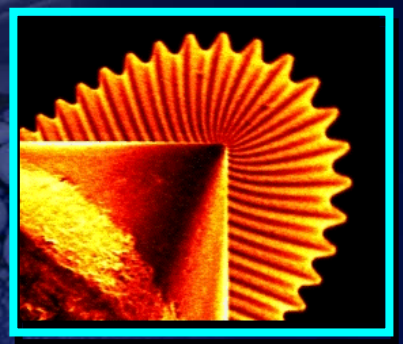
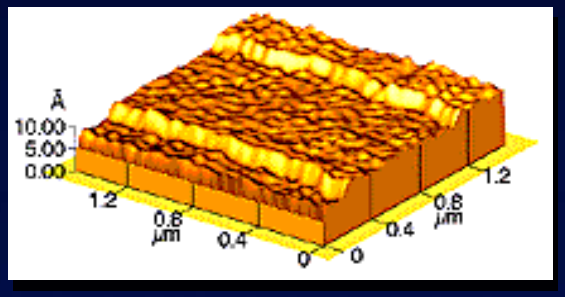
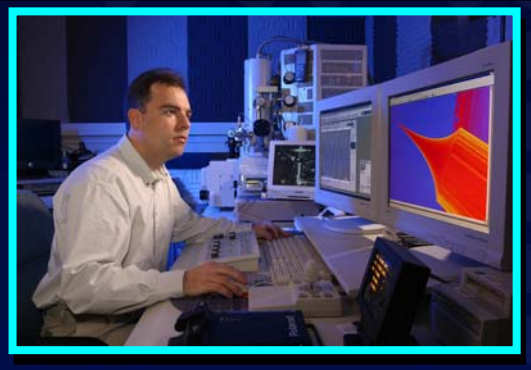
Instrumentation and Metrology







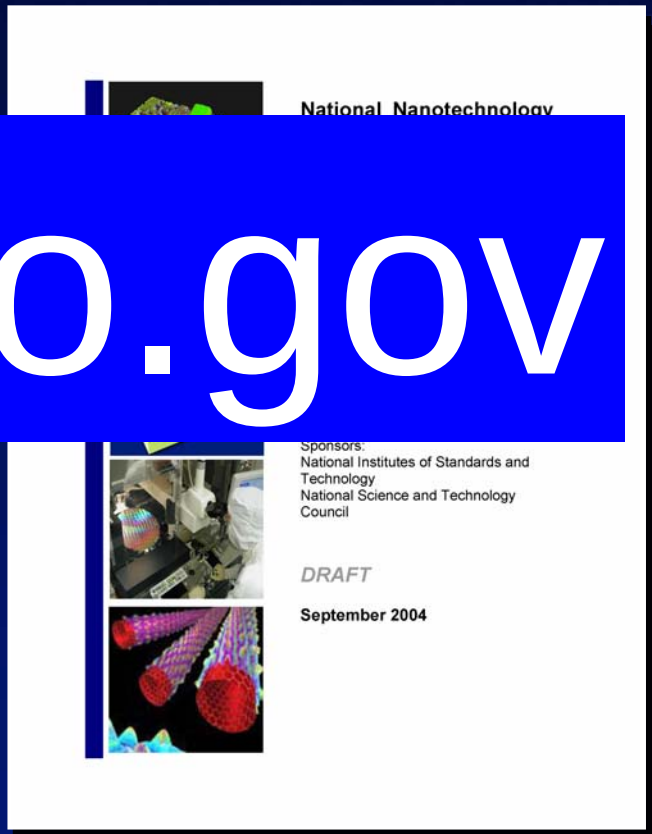
- Instrumentation and Metrology are integral to the entire emerging nanotechnology enterprise
- Crosscut <u>all</u> the current NNI Grand Challenges/Program Component Areas
- Instrumentation and metrology are imperative to the overall success of the NNI and well as nanomanufacturing
- NIST supports these needs

Instrumentation and Metrology for Nanotechnology

- The *NNI Interagency Workshop on Instrumentation and Metrology for Nanotechnology:*

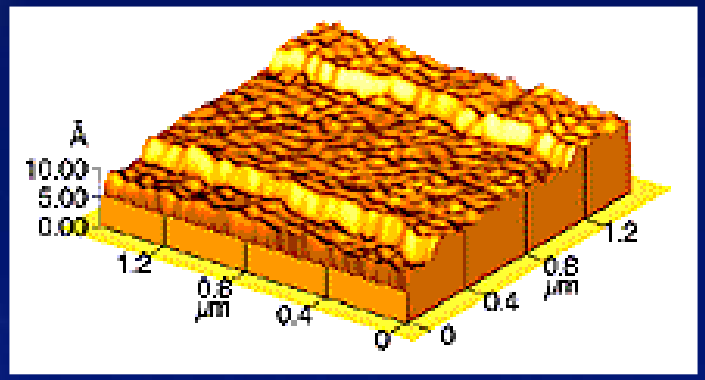
www.nano.gov

  - Academia: 1/3 Government
  - Draft Final Report is being reviewed by the NNCO, NSET, attendees and NIST
- Publication imminent



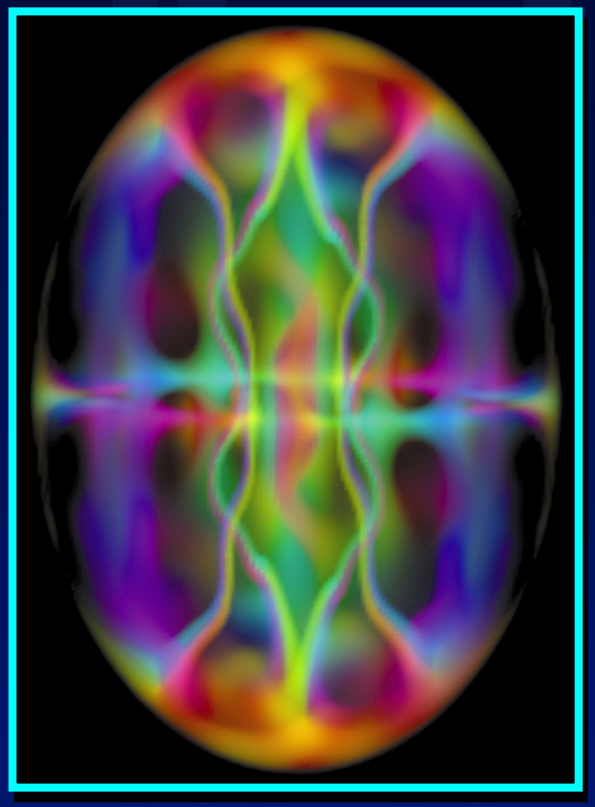
Nanometrology

- There is available a vast array of current tools available for nanometrology
  - Scanning Electron Microscope, Transmission Electron Microscope, Focused Ion Beam, Scanned Probes, Neutron Scattering, many analytical techniques, etc.
- Accuracy of the measurements is more important than ever before.
- Another question is whether or not the tools are providing the right measurement data – or just reams of inconsequential information.



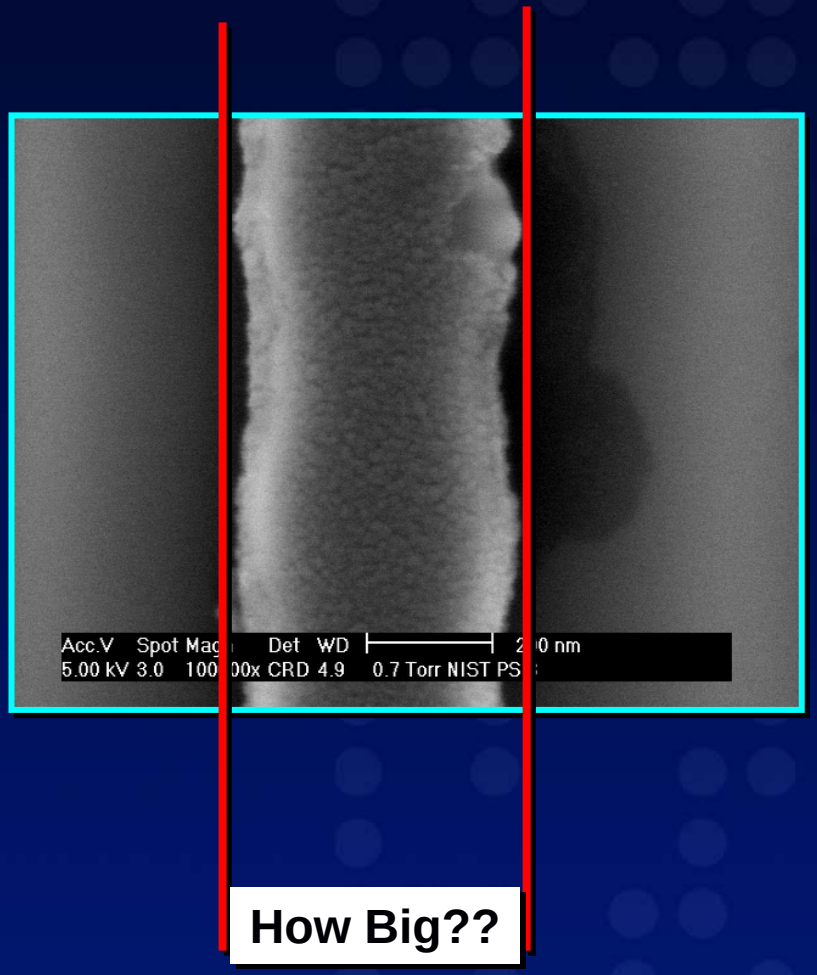
Metrology for Nanomanufacturing

- Good metrology practice is more than just reading numbers from a data sheet.
- In order to measure a quantity accurately, it is necessary to fully study and understand the entire measurement process itself
  - Instrument issues
  - Derivation of the measured signal
- This may require multiple disciplines working closely together to achieve the final goal
- Nanotechnology is causing this to happen more than ever before!

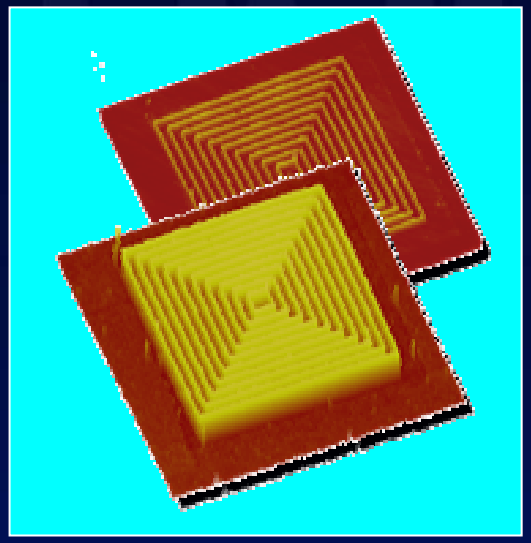


NIST's Technical Role

- Development of the measurement technology
  - What is measured
  - How it is measured
  - Determination of the limitations of the measurement process
- Development of new standards
- Development of uncertainty statement
  - Provides a means of comparison of metrology techniques
- Value of metrology
  - Economics of nanometrology



Nanometrology



- Many of the various measurement techniques currently applied to nanotechnology are adapted from methodology used for larger size structures, devices, and circuits
  - Evolutionary metrology
  - The methodology remains the same or very similar.
- However, there are fundamental differences due to the size and physical, chemical and mechanical properties of the materials at the nanoscale which must be considered.

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Nanometrology

- Currently available metrology tools are beginning to reach the limits of resolution and are not expected to meet future requirements for nanomanufacturing.
  - Revolutionary approaches to the metrology may be required in the near future.
- Current measurement parameters need to be highly optimized and the measurement tools need to work continually at their best specified performance levels or beyond.
  - Built-in performance testing is imperative
- Almost all existing measurement methods and tools have some limitation.
  - Once the limitation is identified it can potentially be overcome.
    - Optics has extended much longer than ever predicted
    - New approaches need to be developed.

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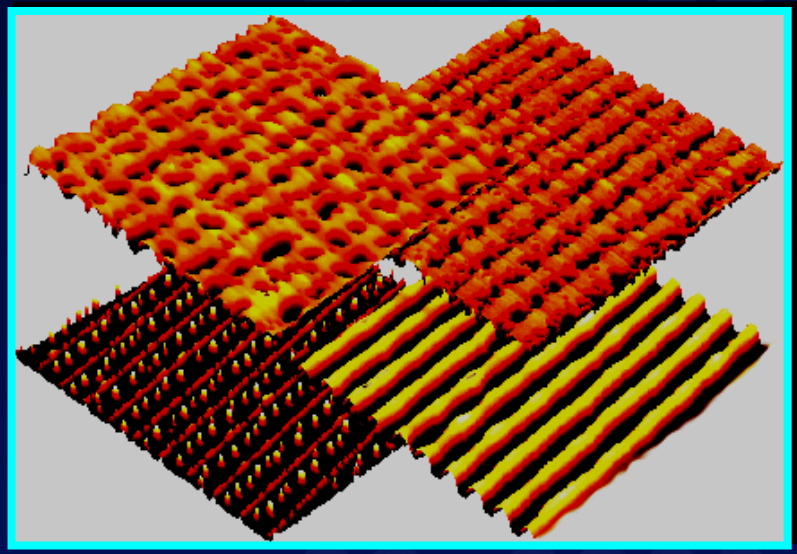
Nanometrology



- The Scanning Electron Microscope (SEM) remains one of the major tools for nanotechnology imaging and nanometrology
- Three approaches undertaken to improve the imaging and metrology of nanomaterials in the *Scanning Electron Microscope Dimensional Metrology Project* of the Nanomanufacturing Program at NIST are discussed below.
  - Nanotip Electron Emitters
  - Modeling for Accuracy
  - Variable Pressure SEM

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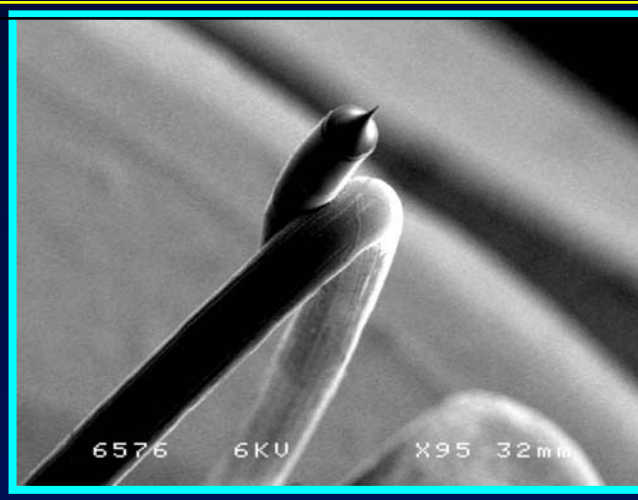
Nano-tips: SEM Performance limitations and possibilities for improvement

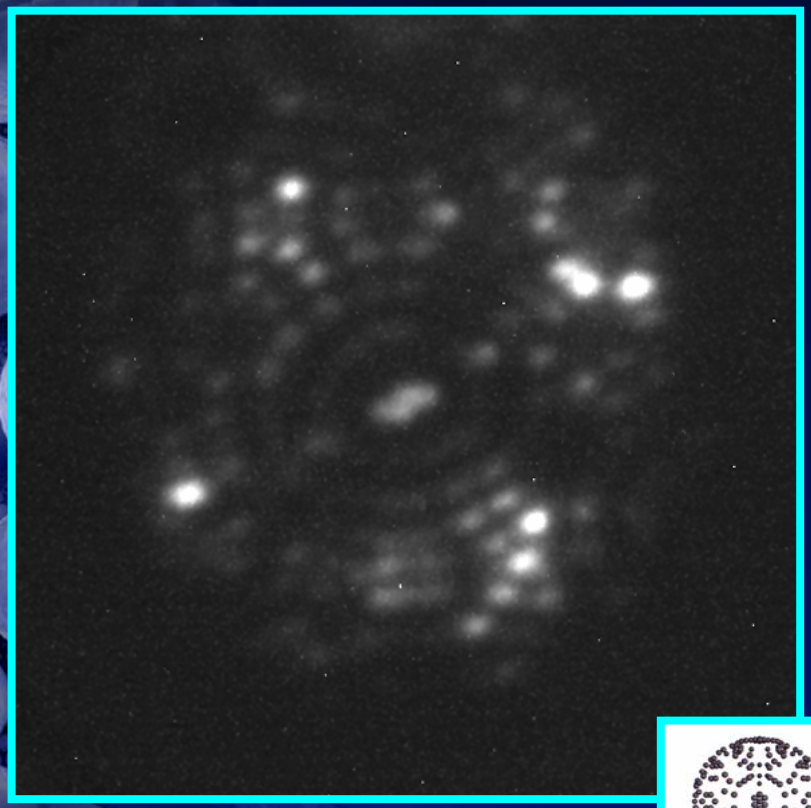


- Resolution and signal-to-noise ratio are two of the major performance limitations in SEM.
  - New electron emitter technology is needed.
- Nano-tips are one possible alternative:
  - Nano-tips are extremely sharp field emitter tips (5 -15 nm)
  - Emission occurs at energies from 60 eV (vs. 3 keV)
  - Emission currents 1 nA to 1 mA
- For a given beam current a smaller probe size results.
- Increase in beam current enhances the SNR and allows for a resolution limit at higher spatial frequencies.
- Nano-tips may combine both characteristics
- Consequently, may extend the useful life of SEM technology.

Nano-tips: SEM Performance limitations and possibilities for improvement

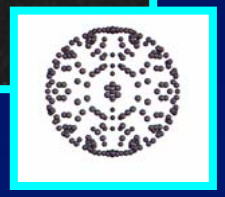
- Theoretical assessment of the nano-tip electron gun for a Hitachi S-6000 – Collaboration with Dr. David Joy (UT)
- Preparation of the Hitachi S-6000 CD-SEM test bench
  - SEM Sentinel: computerized system for measurements of vacuum, electron optics, and wafer handling
  - Development of tip exchange and baking procedures
  - Modification of the gun control circuitry
- Nano-tip preparation procedures
  - Routine fabrication process developed
- Conducted experiments with regular, sharp and nano-tips
  - Sharp tips showed performance improvement
  - Nano-tips work even better

Nano-tips: SEM Performance Limitations and Possibilities for Improvement

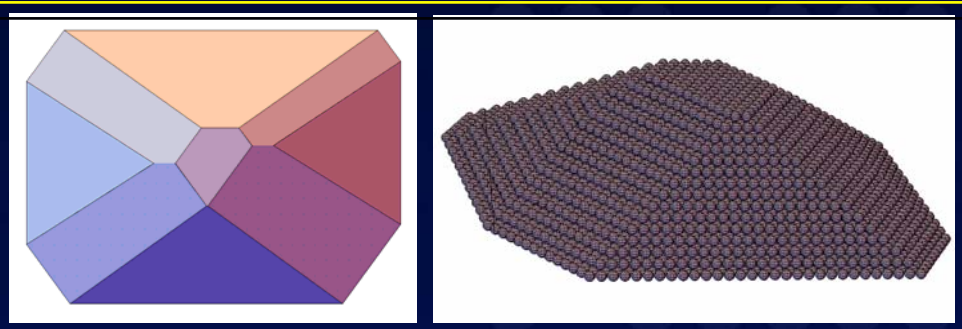


Field ion microscope image of a nano-tip

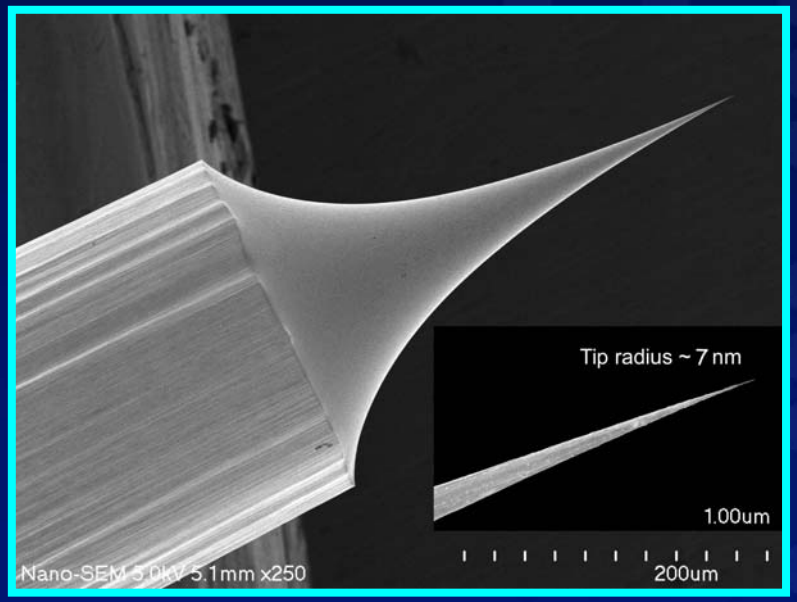
(FIM image taken by Hui Zhou)



Modeled image



3D reconstructions of a nano-tip



SEM Image of a nano-tip

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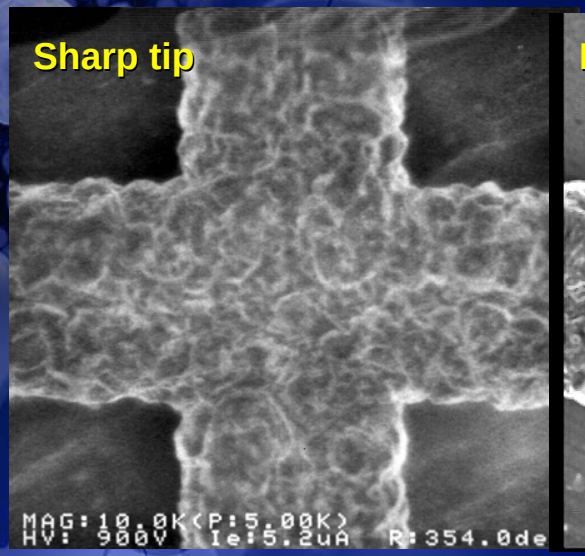
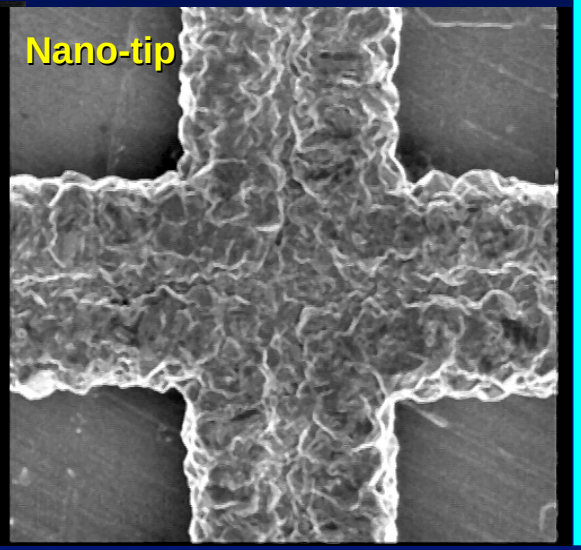
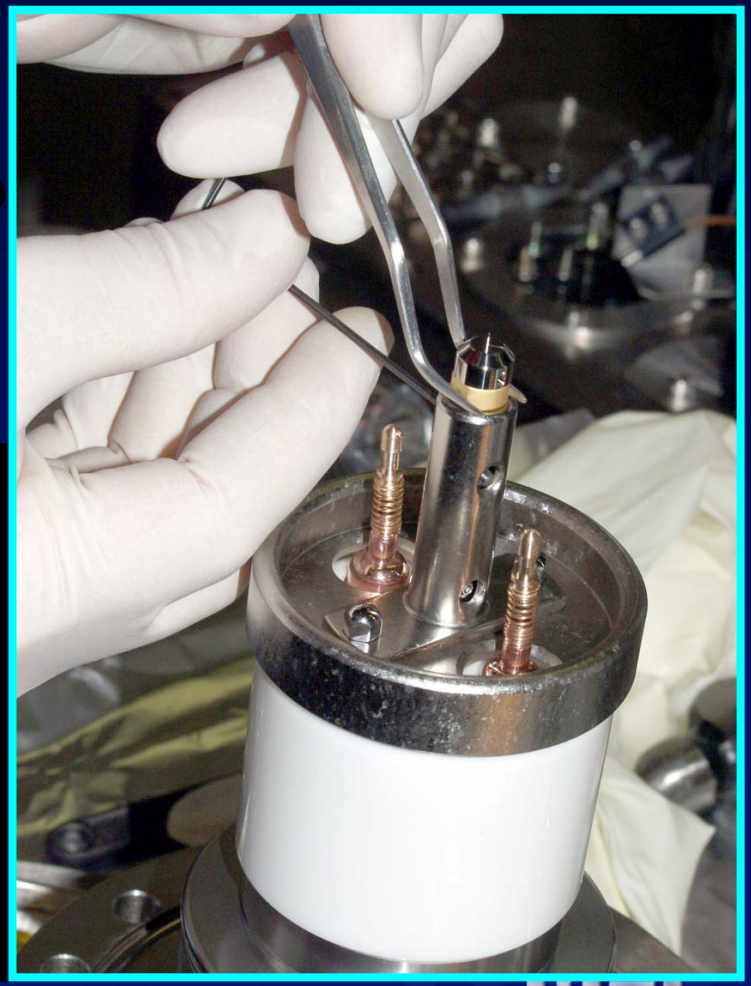
Nano-tips: SEM Performance limitations and possibilities for improvement

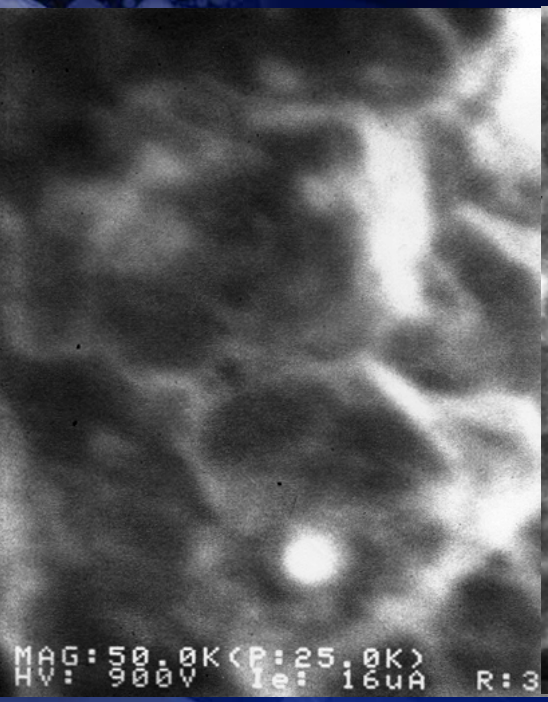
- A new nano-tip was inserted into the electron gun assembly of the SEM
- The tip functioned as nano-tip
  - Resolution is better than with sharp-tip and way better than with regular tip

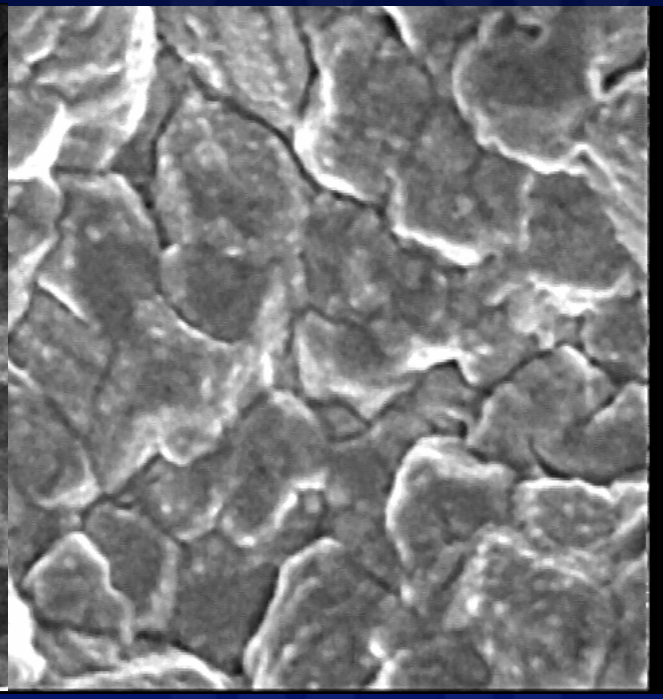






Nano-tips: SEM Performance limitations and possibilities for improvement



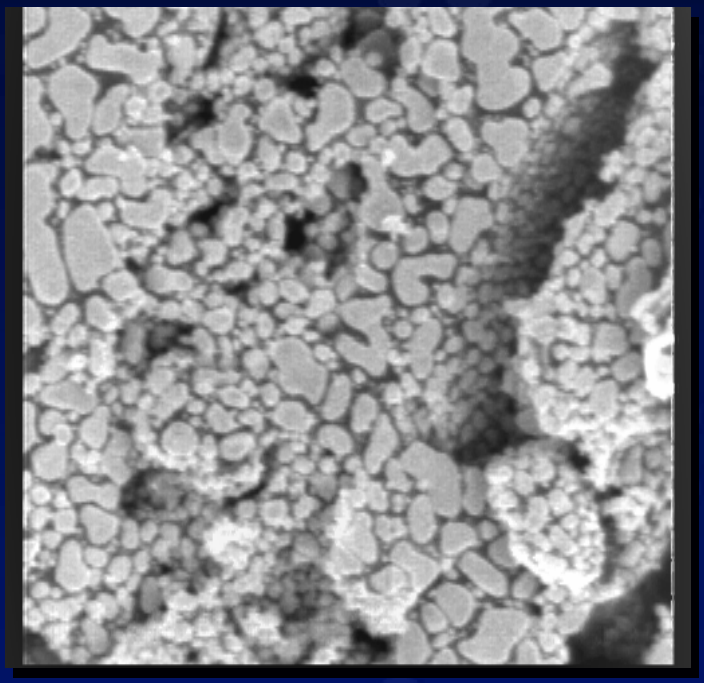


Regular tip **Sharp tip** **NIST Nano-tip**

Copper alignment grid sample, same magnifications

Nano-tips: SEM Performance limitations and possibilities for improvement

- The S-6000 CD-SEM used as test bench is one of the first automated tools in the U.S.
- Specification is 15 nm guaranteed resolution.
- The nano-tip gun delivers at least 3x better resolution than the regular tip (5 nm).
- The nano-tip gun delivers better signal-to-noise ratio images.
- The tip is operational without the standard flashing.



Gold-on-Carbon sample

75 000 x magnification

1.0 kV accelerating voltage

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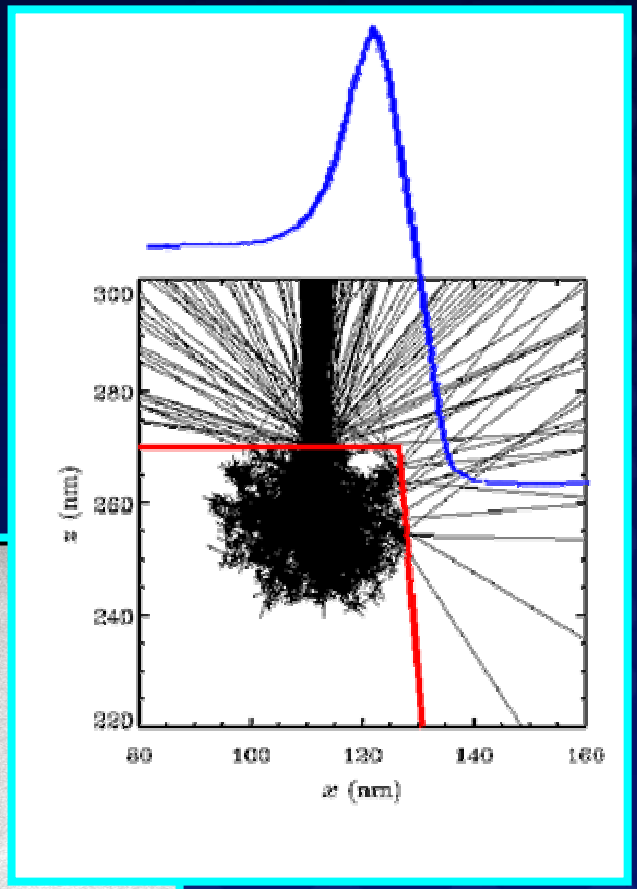
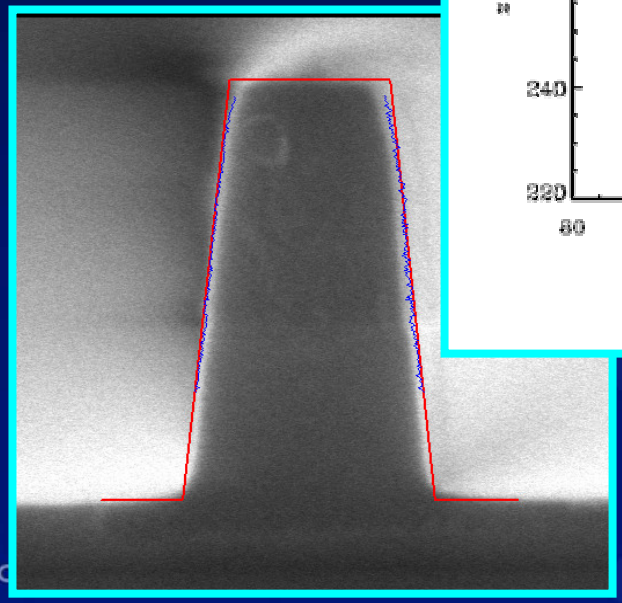
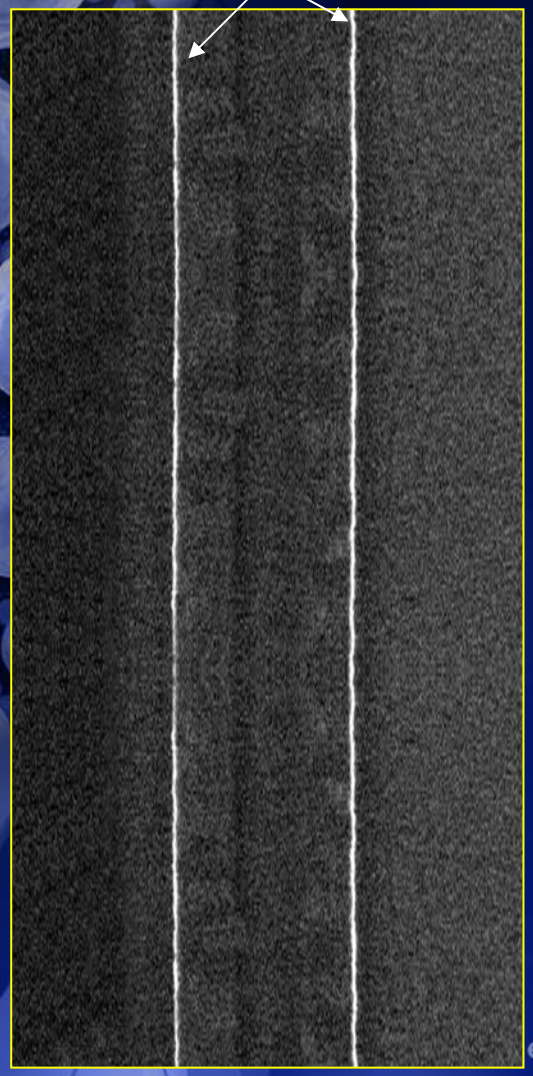
Shape-Sensitive Linewidth Measurement for Accurate Nanometrology

- Even with the best field emission source, accurate SEM metrology requires that the electron beam interactions and the signal comprising the SEM image be understood and modeled.



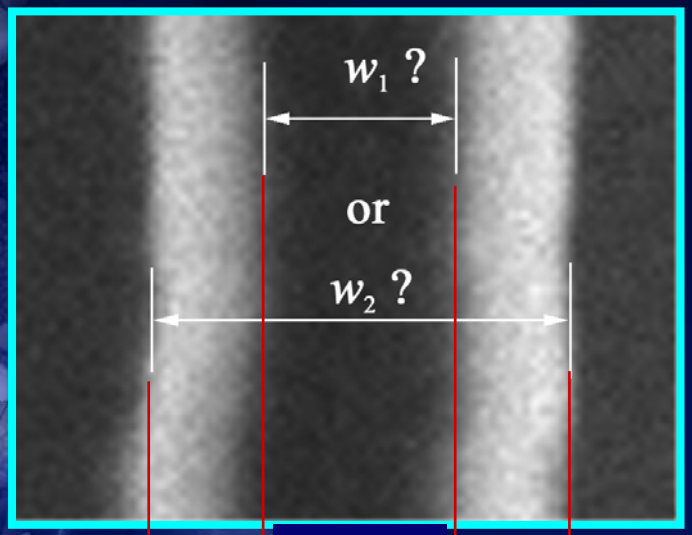


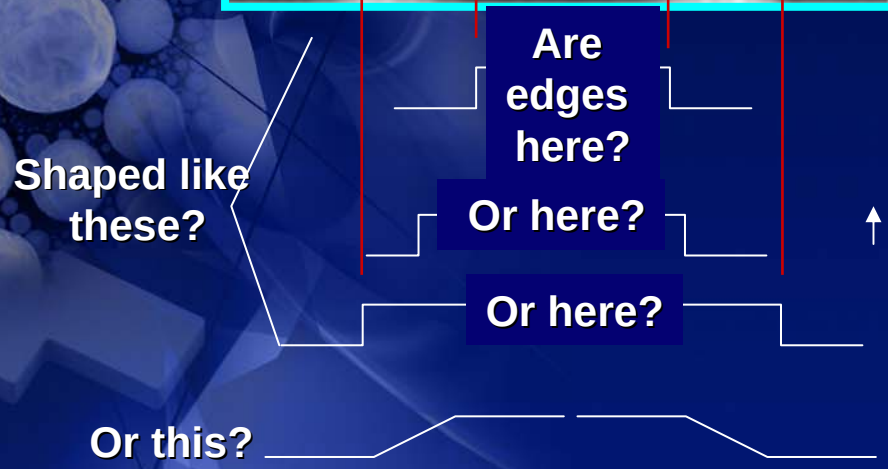
Shape-Sensitive Linewidth Measurement for Accurate Nanometrology



- Accurate nanometrology requires a model to deconvolute the relationship between the sample and its image
- The implicit model currently used by CD-SEM algorithms utilize no physics:
  - Lines, gates, etc. are things with sharp edges
  - The edges are located where the bright edge bloom is visible in the SEM image.
  - The CD is the distance from left bloom to right bloom.
- This model assumes that the bloom width is insignificant.

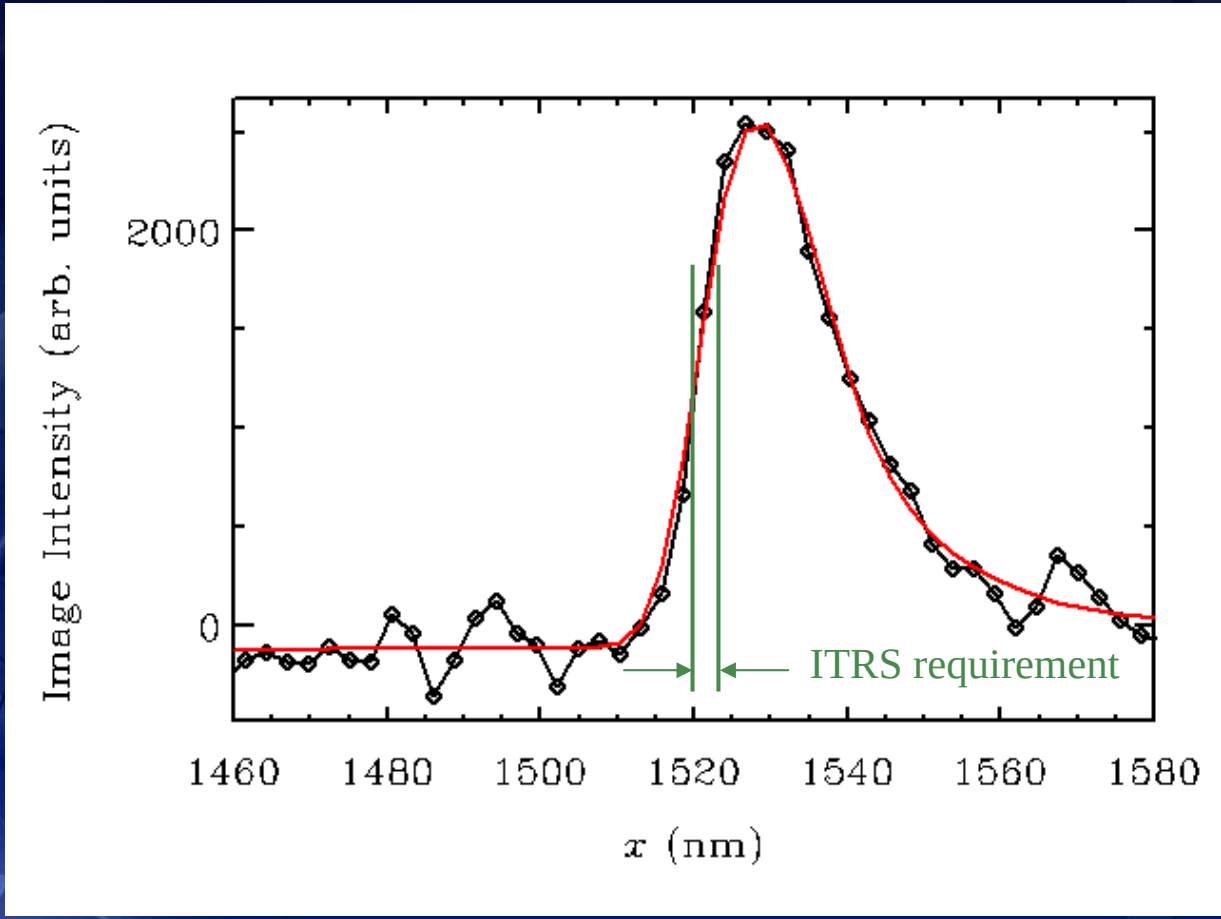
Shape-Sensitive Linewidth Measurement for Accurate Nanometrology





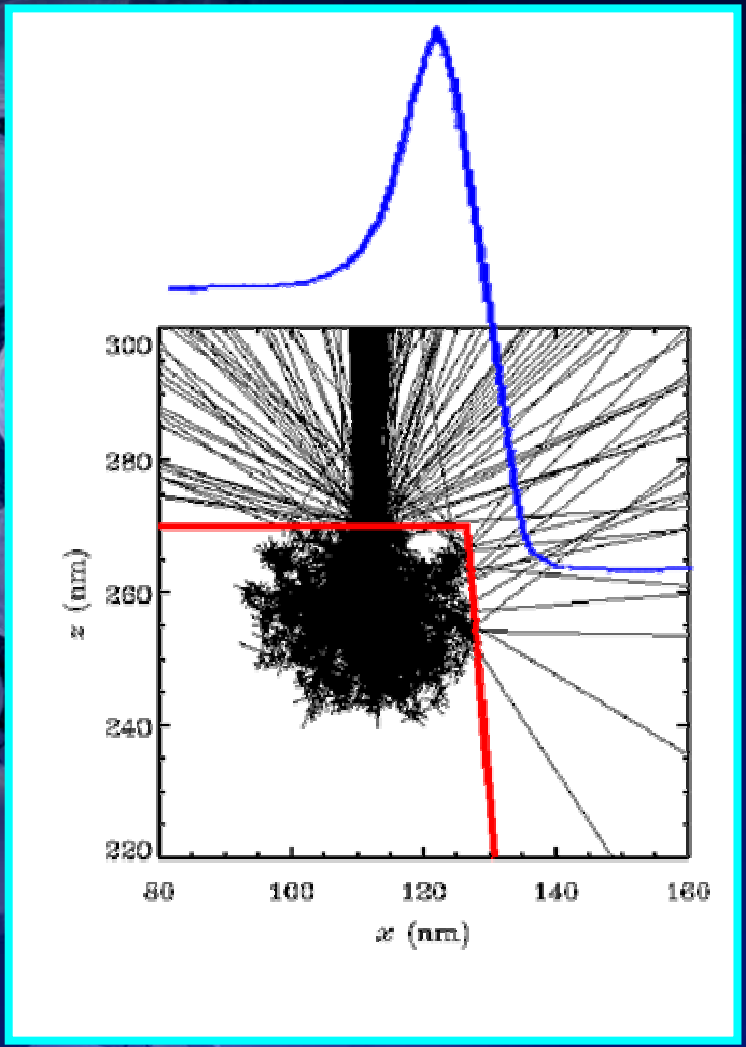
- With narrower lines and tighter tolerances, bloom widths are no longer insignificant.
- The difference between peak max and regression to baseline can be 10's of nanometers—there's lots of room for error.
- Widths are ambiguous at nm scale.
- This contributes to both absolute and relative errors.

Shape-Sensitive Linewidth Measurement for Accurate Nanometrology



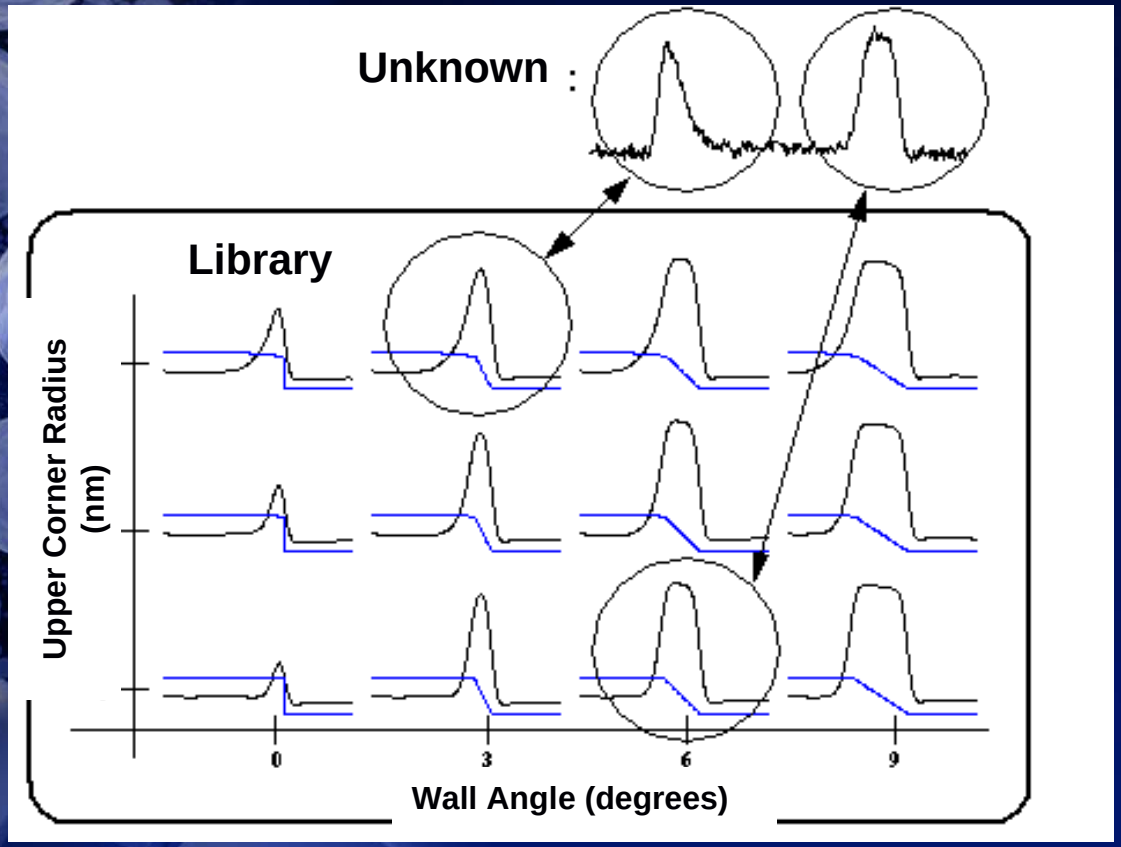
- A more quantitative imaging model is needed
- Adjust unknown instrument and sample parameters for best fit.

Shape-Sensitive Linewidth Measurement for Accurate Nanometrology



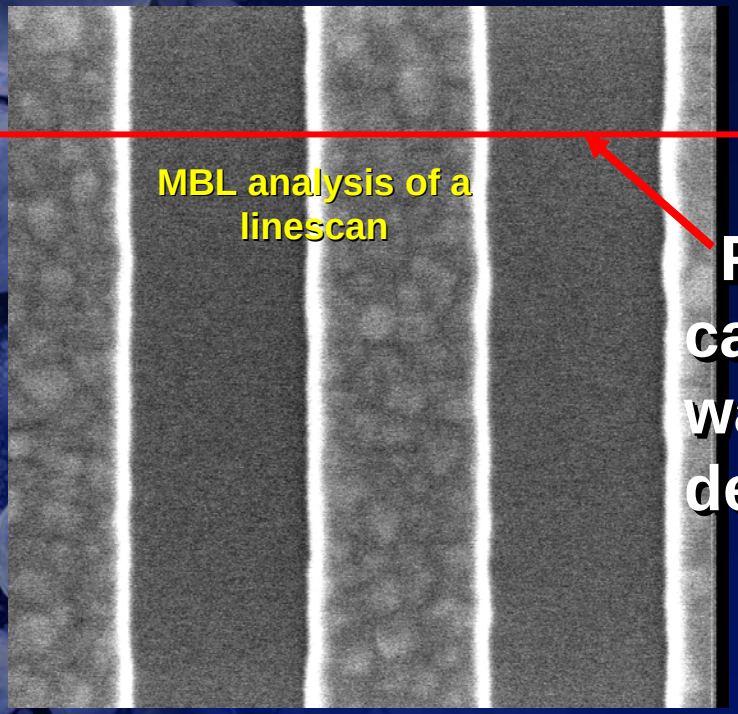
- MONSEL Monte Carlo Model is employed
- Trajectories of thousands of electrons and all of their secondary electrons are followed
- Given a sample geometry, *S*, these codes predict the image, *I*(*S*).
- The result tells us the edge location relative to identifiable features in the image
  - Unfortunately, these calculations are too slow for use in real time.

Shape-Sensitive Linewidth Measurement for Accurate Nanometrology

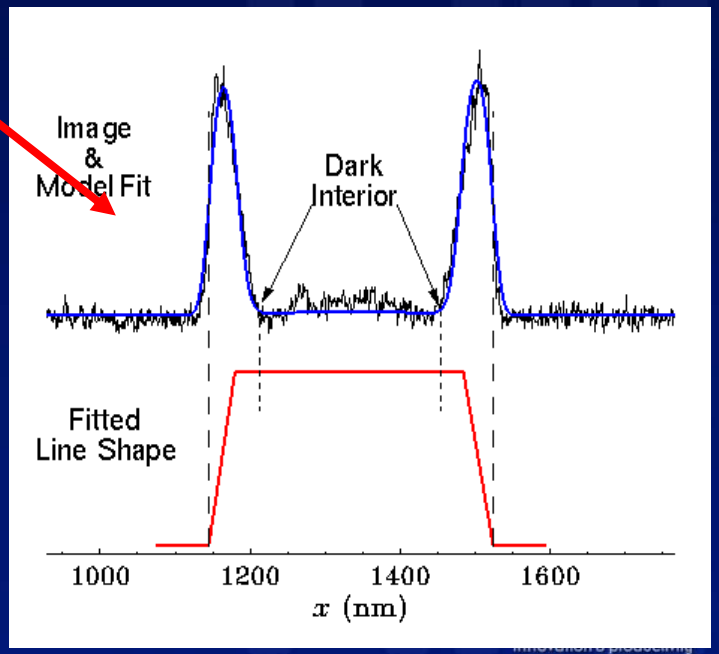


- Solution is to build a library of edges.
- Match unknowns to the library.
- A single function evaluation (interpolating the library) takes a few milliseconds.
- Time to match an isolated line 1s/linescan

Shape-Sensitive Linewidth Measurement for Accurate Nanometrology



From a top-down image we can determine linewidth and wall angles using MBL as just described.



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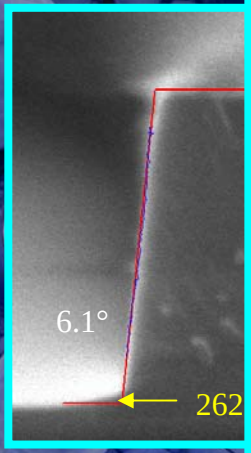
Lab SEM, …



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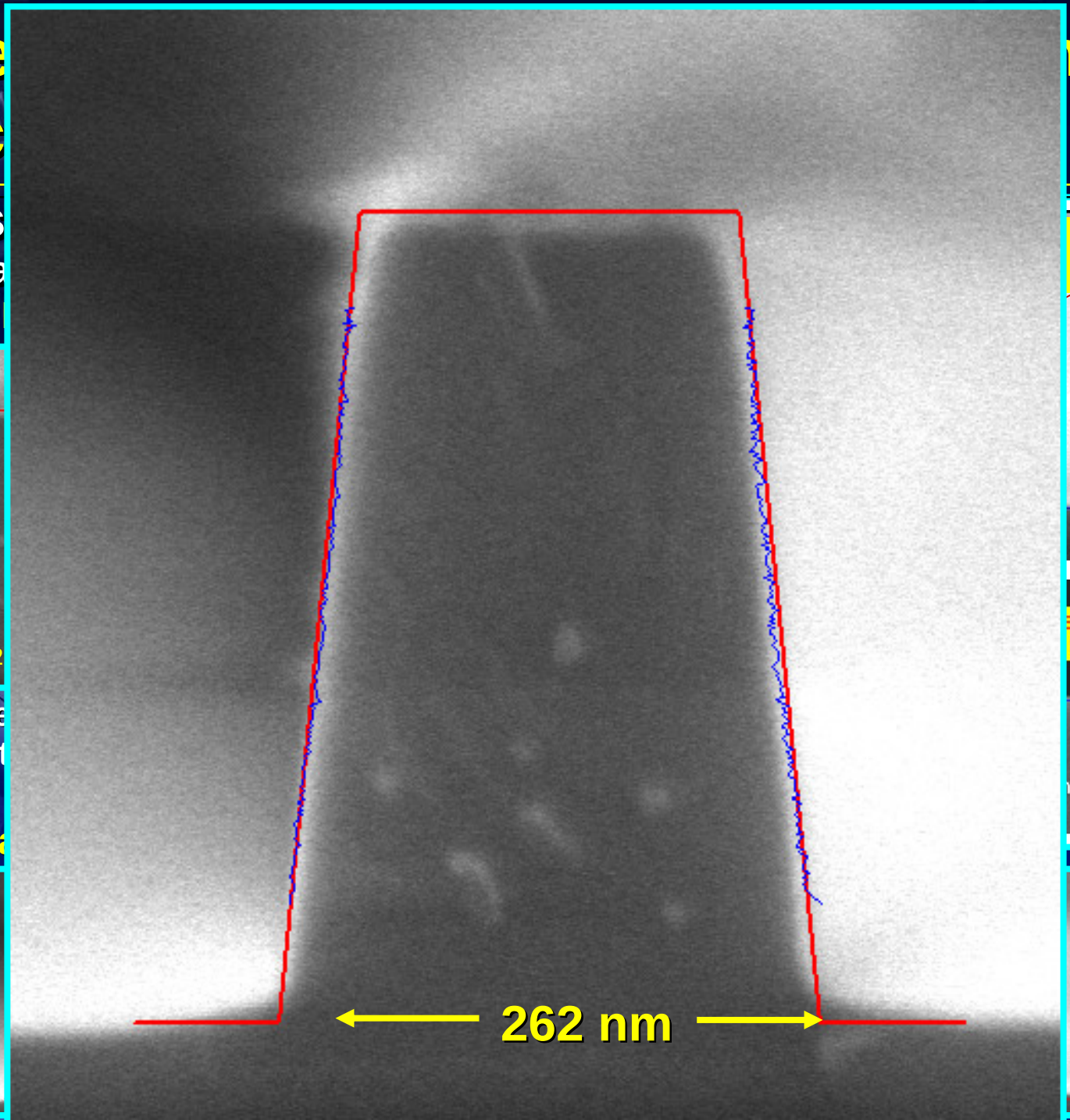

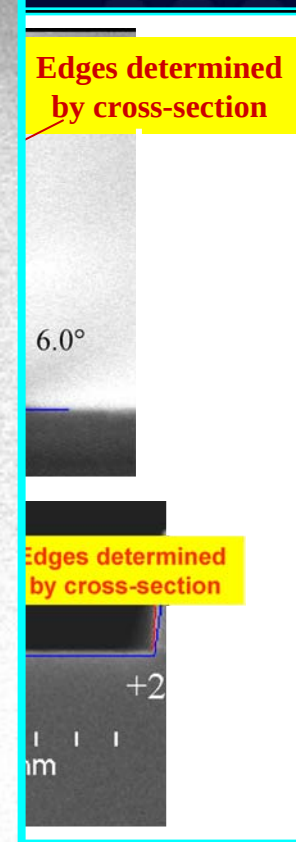

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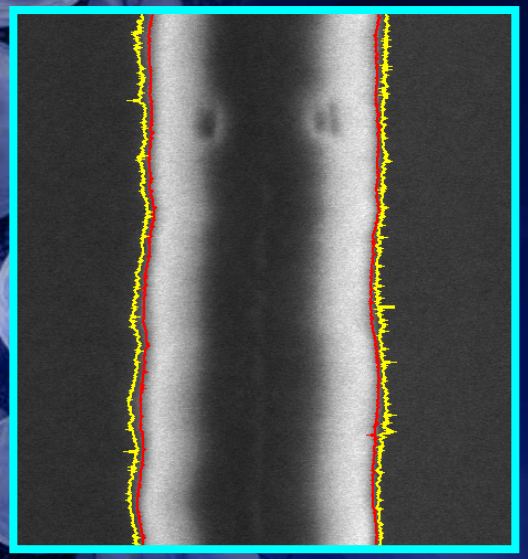
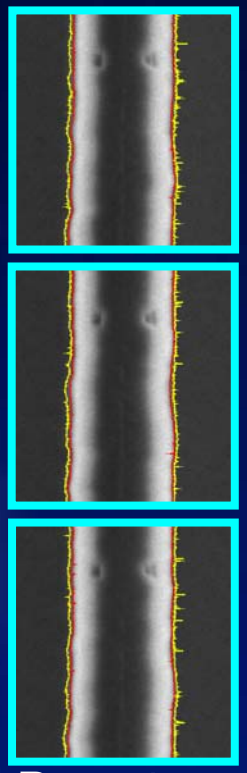
Shape-Sensitive Linewidth Measurement for Accurate Nanometrology

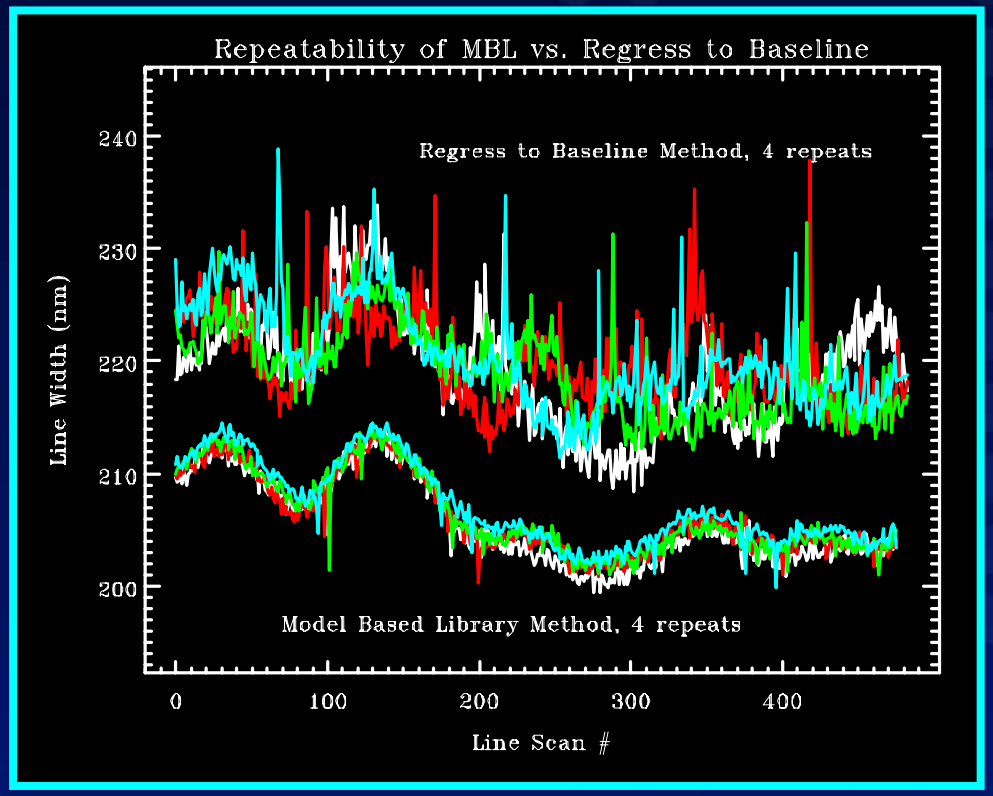
Repeatability of Model-Based vs. Regression to Baseline



1. Take 4 individual images and assign line edge positions by each method (Model-based in RED Regression in Yellow)



2. Repeat analysis using the remaining images



3. MBL edge positions have a factor of 3x better repeatability.

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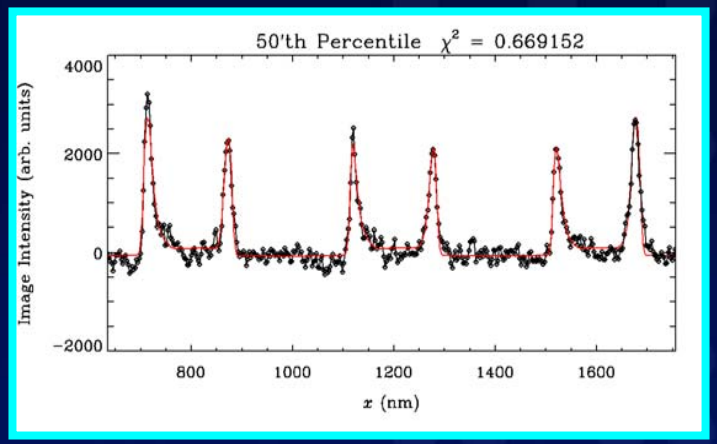
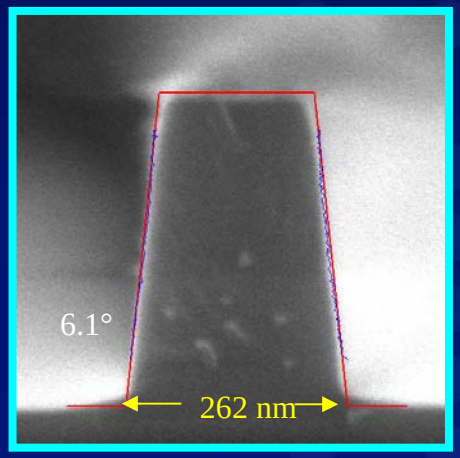
Shape-Sensitive Linewidth Measurement for Accurate Nanometrology

- Model-Based Library (MBL) metrology demonstrated excellent results for both polycrystalline Si lines and photoresist
  - Better accuracy
  - Less sensitivity of CD metric to sidewall angle and other extraneous sample characteristics
  - Better repeatability
- Allows extraction of far more information residing in the SEM signal
- Application to other nano-sized objects



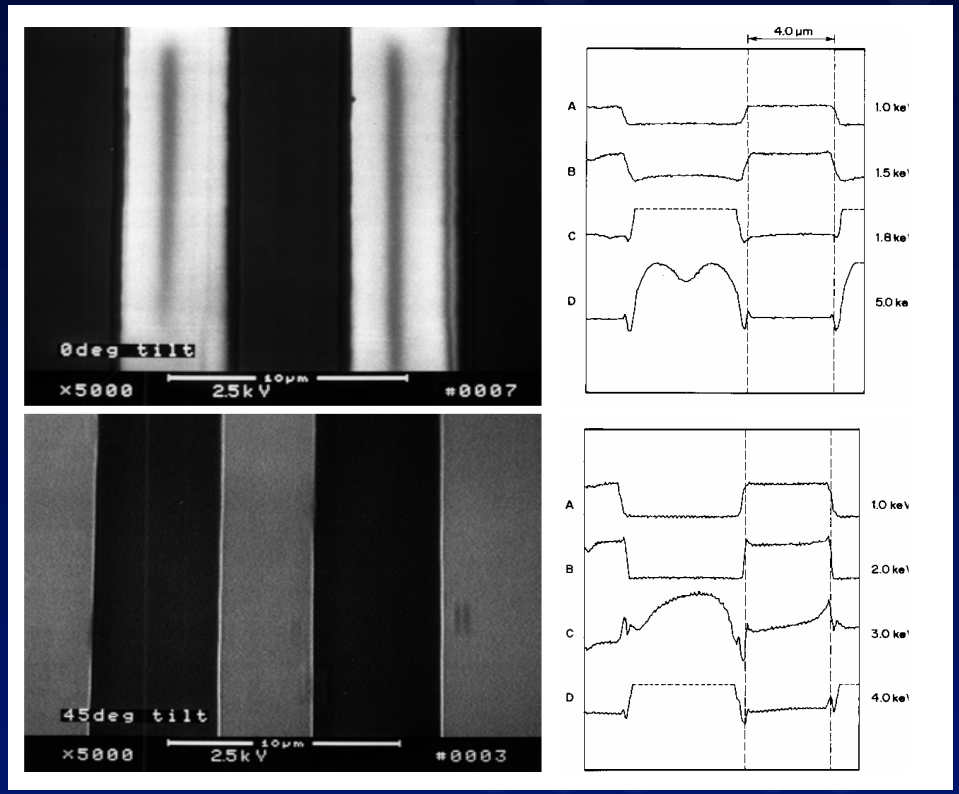


Variable Pressure SEM for Accurate Nanometrology

- All the modeling in the world cannot fully compensate for a charging specimen.
- Nanotechnology places more emphasis on resolution, signal to noise, and the need to view samples uncoated.
  - Obscure the sample with the coating
- Photomasks are an especially difficult insulating specimen for the SEM
- Typically viewed uncoated at low accelerating voltages.
- Many of the issues challenging wafer metrology at 1x are reduced by a factor of 4-5 in photomasks and thus, up until now have been swept aside
- Facing a paradigm change
  - Need for localized information (effects of LER)
  - The introduction of advanced masks with optical proximity correction and phase shifting features
  - Smaller features used in sub-100/65 nm circuit generations
  - Greater emphasis on e-beam measurements

Variable Pressure SEM for Accurate Nanometrology

- Early work on photomask CD-metrology pointed to the problems charging posed.
  - Extensive charging study
- Charging was shown to be a major issue to be overcome.
- Optics has been able to handle the work until now
- Renewed emphasis on SEM photomask metrology has occurred



Postek, M. T. 1984. Critical Dimension Measurement in the Scanning Electron Microscope. SPIE Proceedings Vol. 480:109-118.

Variable Pressure SEM for Accurate Nanometrology

- Today, photomask charging still remains an issue for SEM inspection and metrology
  - Also an issue for other samples for nanotechnology
- Charging is and has been acceptably handled but, must be always considered
  - Low accelerating voltage operation
  - Beam deflection
- Effective charge modeling remains an obstacle to accurate metrology
  - Good progress has been made (Ko, Grella and Joy)
  - Complex issue
    - Highly variable (instrument, sample, detector, geometry etc.)
  - Relatively uncontrollable
- ITRS statement relative to SEM charging:

  "<u>alternative paths should be sought</u>"

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Variable Pressure SEM for Accurate Nanometrology

Controlling Charging:

- Conductive samples/Sample coating
  - Makes entire sample conductive
  - Destructive
  - Contrast reduction
- Low kV/Ultra low kV - Charge balance
  - Most common approach
  - Work between 600V and 1.5 kV (or lower)
  - Is charging really balanced?
  - Can this be modeled?
- Backscattered electron imaging
  - Filter out the secondary electrons
  - Low loss electron imaging
- Variable pressure/Environmental techniques

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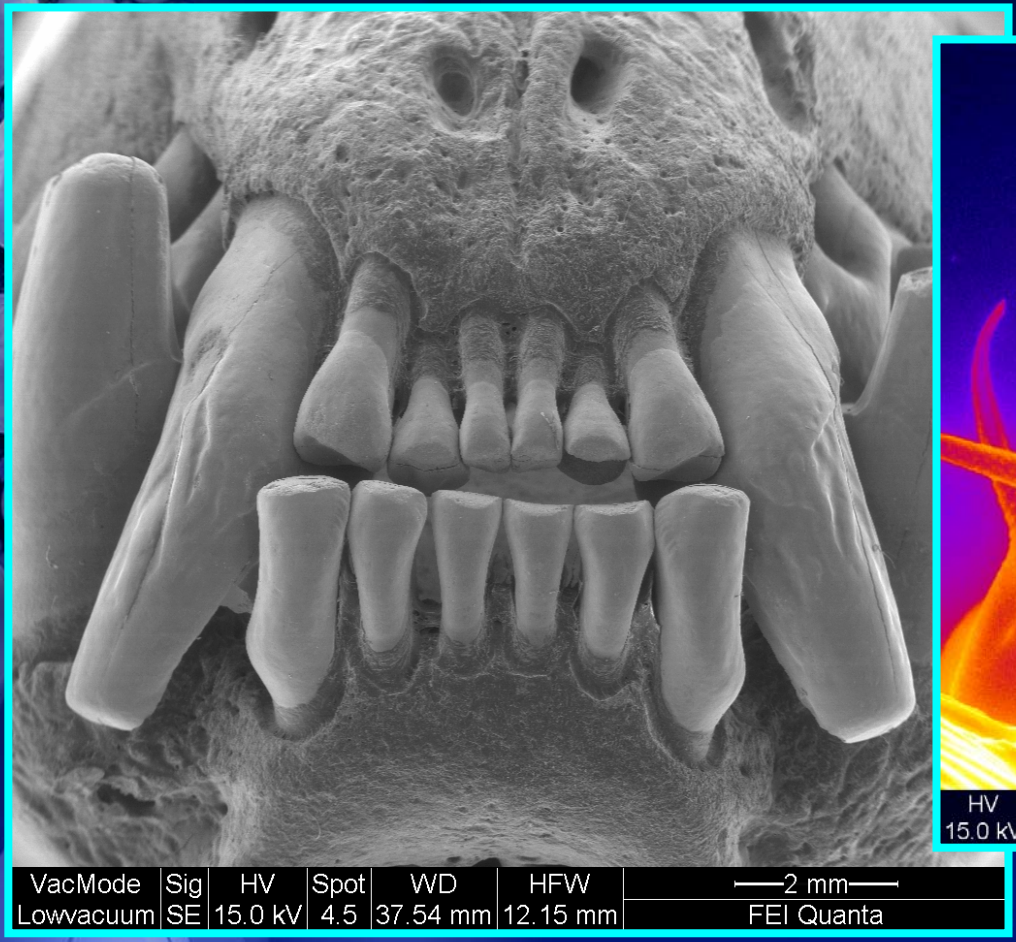
Variable Pressure SEM for Accurate Nanometrology

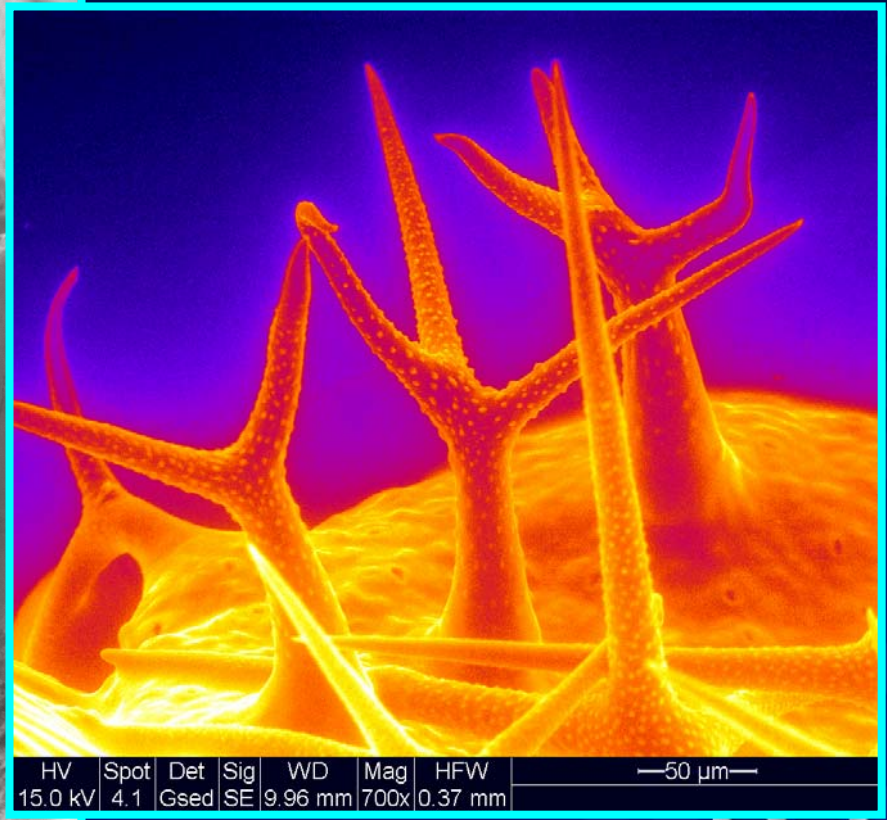
- Much of the early work done with environmental cells
- Robinson 1974 using BSE collection showed reduced charging
- Danilatos et al., mid-1980's proposed environmental SEM
  - 1987 dedicated ESEM Introduced
    - Knew founders of the company
    - Tried to get them to apply the technology to semiconductor metrology
      - Actually provided them with photomask samples
    - Technical reasons existed - not possible at that time
- Several other high-pressure instruments and signal collection methodologies subsequently emerged
  - Ion detection, SE, BSE, Sample current, Light
- Historically, used for "typical" laboratory instrument applications, not "production worthy" - yet

Variable Pressure SEM for Accurate Nanometrology

- Typically used in biological, medical, materials and pharmaceutical applications



Bat skull

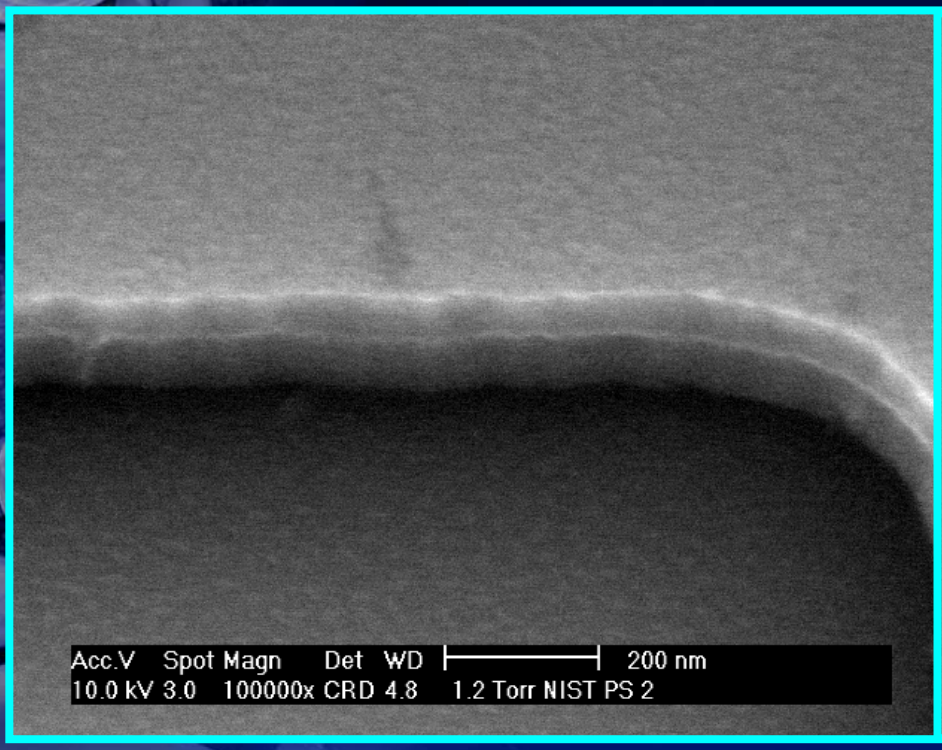


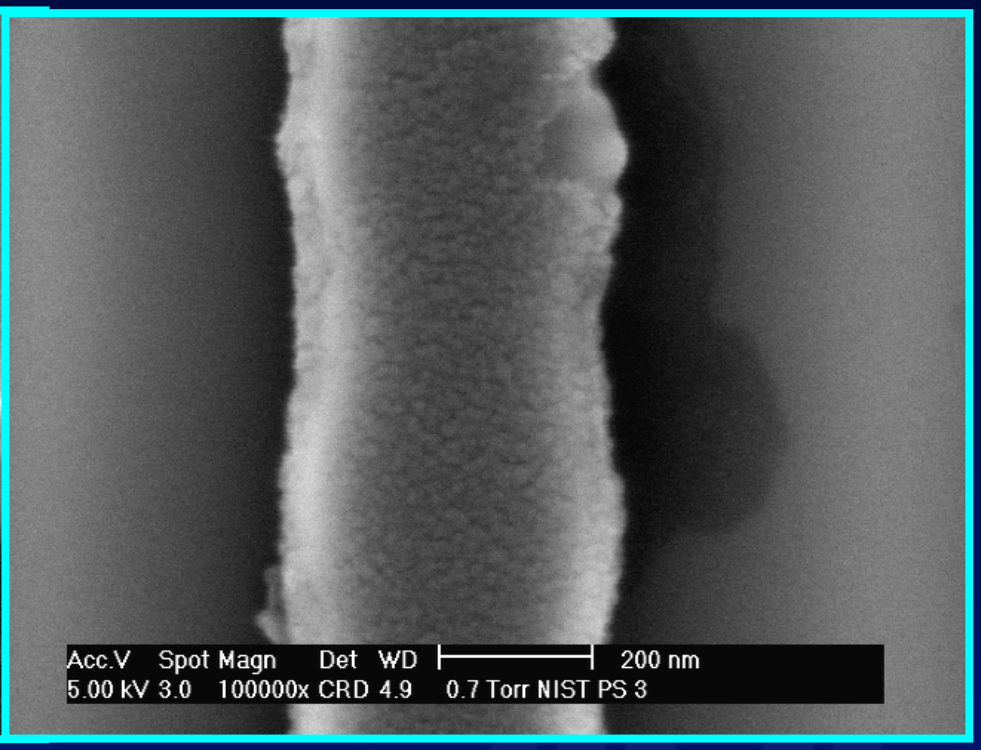
Trichome

Variable Pressure SEM for Accurate Nanometrology

- Evolution of instrumentation to the level needed took time and investments.
- Photomask metrology requires a combination of technological components:
  - High-signal, high-brightness, high-resolution field-emission electron source
    - Good S/N for metrology
  - Automated wafer/mask handling capabilities
  - Totally integrated automated high pressure/environment control system
    - “Secondary electron” detector
- Improved technology has now resulted in the potential for application to photomask inspection and metrology
  - As well as, other potential production applications
- Instruments are becoming available

Variable Pressure SEM for Accurate Nanometrology





Tilt

1.2 Torr
10 kV
100,000 x

Top Down

0.7 Torr
5 kV
100,000 x

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NIST-MAS-AMAS Workshop:

Variable Pressure and Environmental Scanning Electron Microscopy (VPSEM-ESEM) for Imaging and Microanalysis: Roadmap 3

Place:

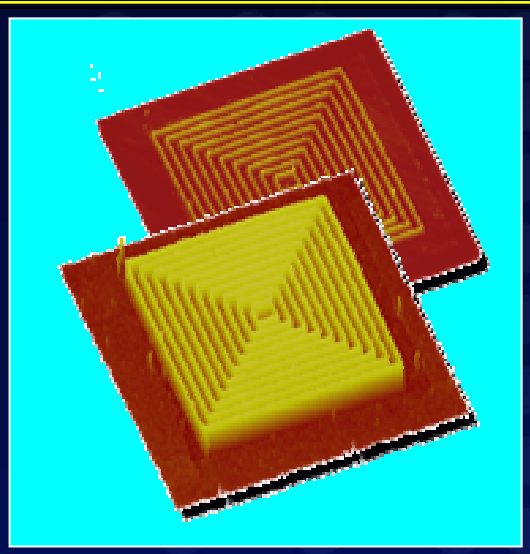
Lecture Room A and Poster Hall, National Institute of Standards and Technology,
100 Bureau Drive, Gaithersburg, Maryland 20899
Dates: November 2- 4, 2005

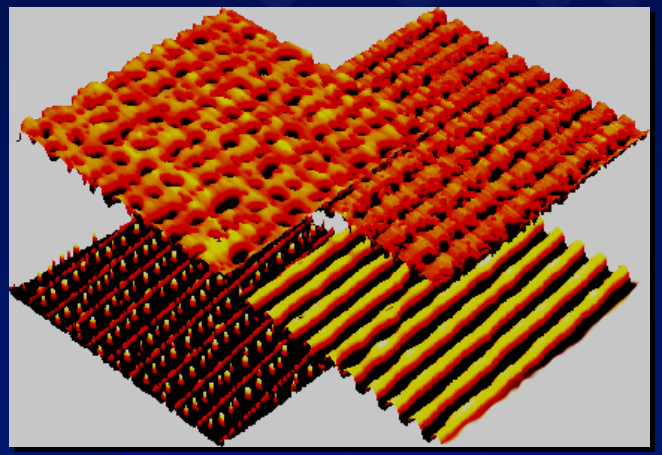
Co-organizers:

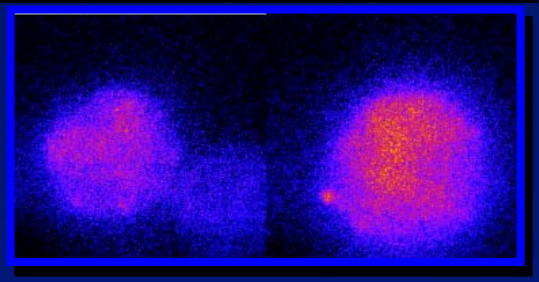
NIST (Surface and Microanalysis Science Division (837) and Precision Engineering Division (821))
Microbeam Analysis Society (MAS) (http://www.microprobe.org/index.html)
Australian Microbeam Analysis Society (AMAS) (http://www.microscopy.org.au/amas/symposium_page.html)

Conclusion

- Nanotechnology if nothing else, has provided:
  - A catalyst for US Industry
  - New common research focal point
  - Generated a new enthusiasm for research
  - Re-energized US industry and developed new business opportunities
  - New paradigm for US industry/government/academia collaboration
- Accurate metrology is imperative
  - Evolutionary and revolutionary tools are necessary.

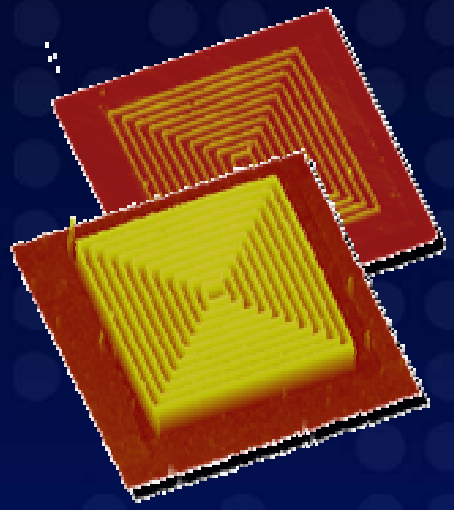


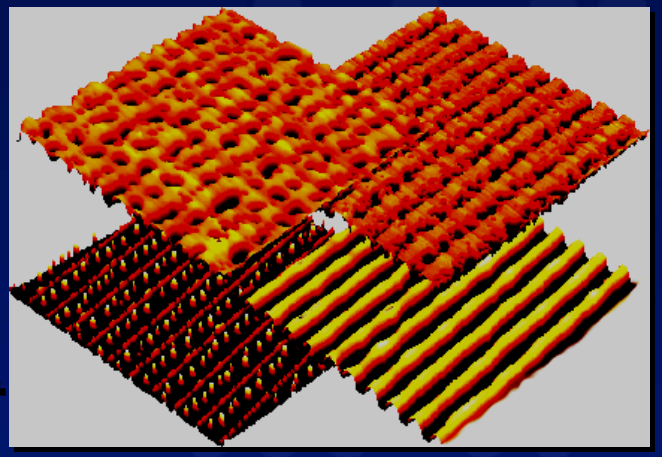


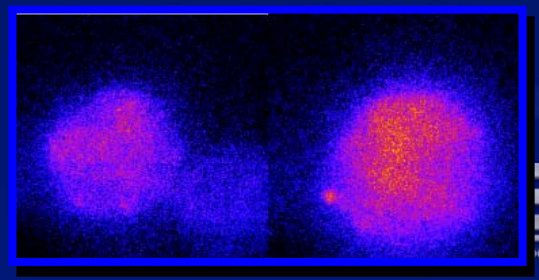


Conclusion

- Nanometrology is not easy and revolutionary techniques may need to be developed.
- For now evolutionary techniques will suffice but not for long…..
- Questions about making the right measurements still abound both for the laboratory and manufacturing.
- Accurate measurements may be as important to nanotechnology as precise measurements were to earlier production measurements.







Thank You

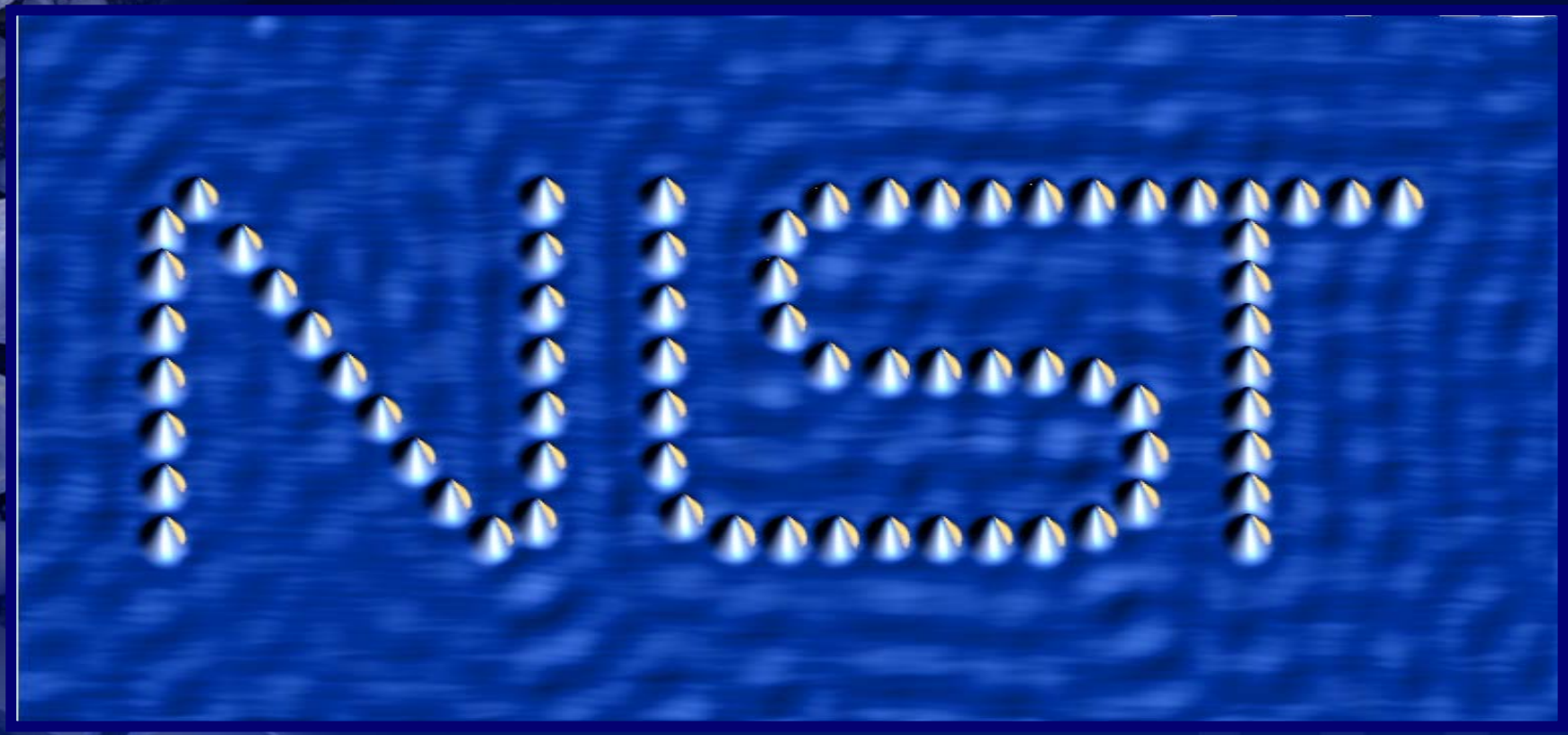


Image:
Cobalt atoms on a copper surface
Courtesy of: Joe Stroscio, NIST

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