Advanced Techniques for Microelectronic Reliability Investigation

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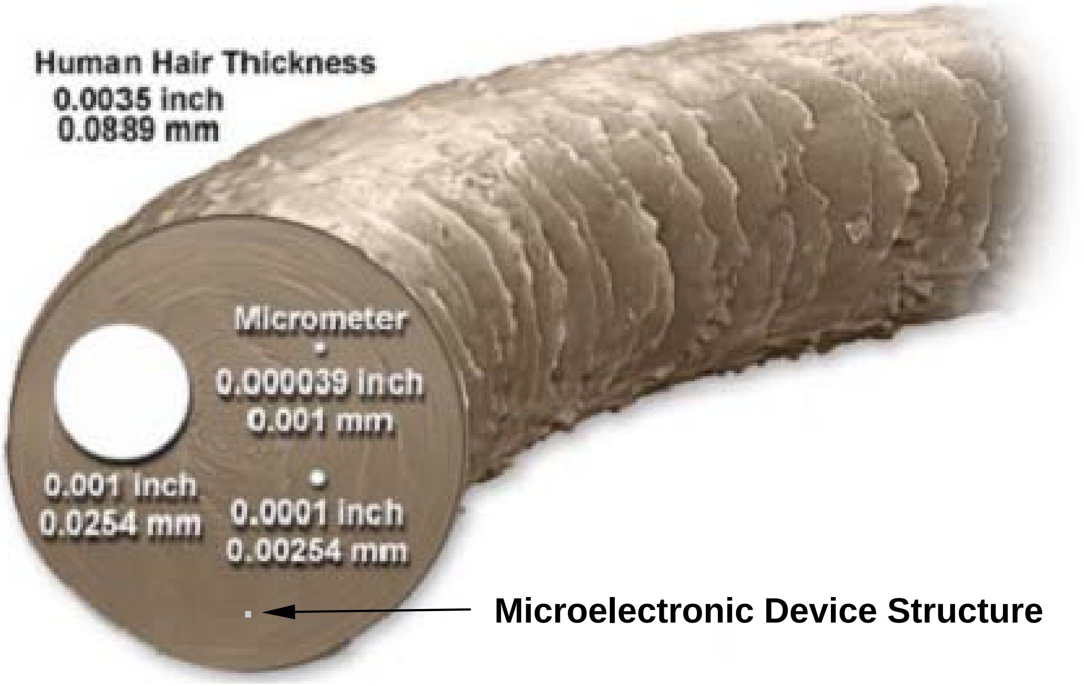
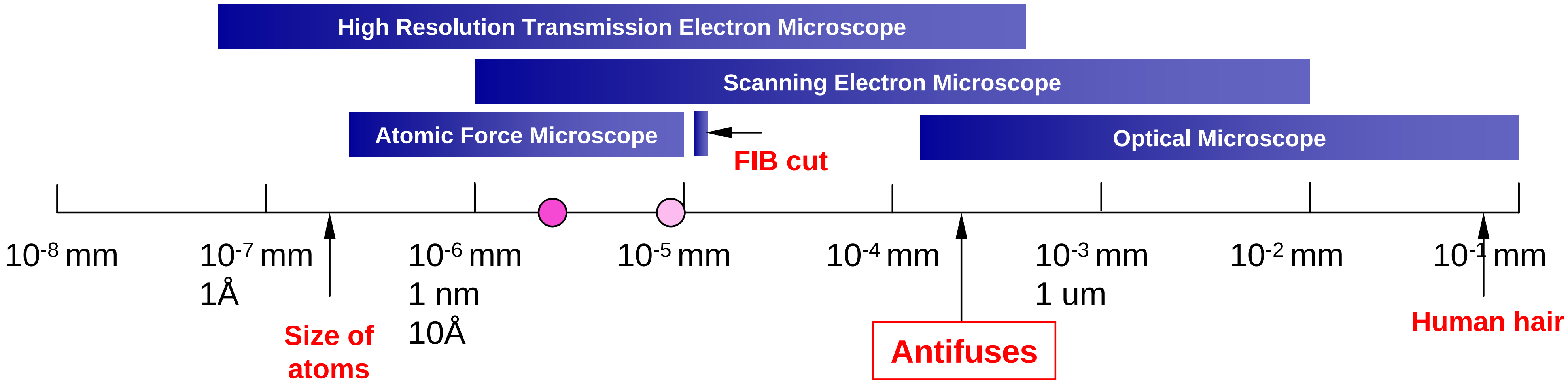
Orders of Scale



Microelectronic Device Structure


High Resolution Transmission Electron Microscope

Scanning Electron Microscope

Atomic Force Microscope

FIB cut

Optical Microscope

10^{-8} mm

10^{-7} mm
1Å

10^{-6} mm
1 nm
10Å

10^{-5} mm

10^{-4} mm

10^{-3} mm
1 um

10^{-2} mm

10^{-1} mm

Size of atoms

Antifuses

Human hair

Diagnostic Tools for Microscopic Investigation

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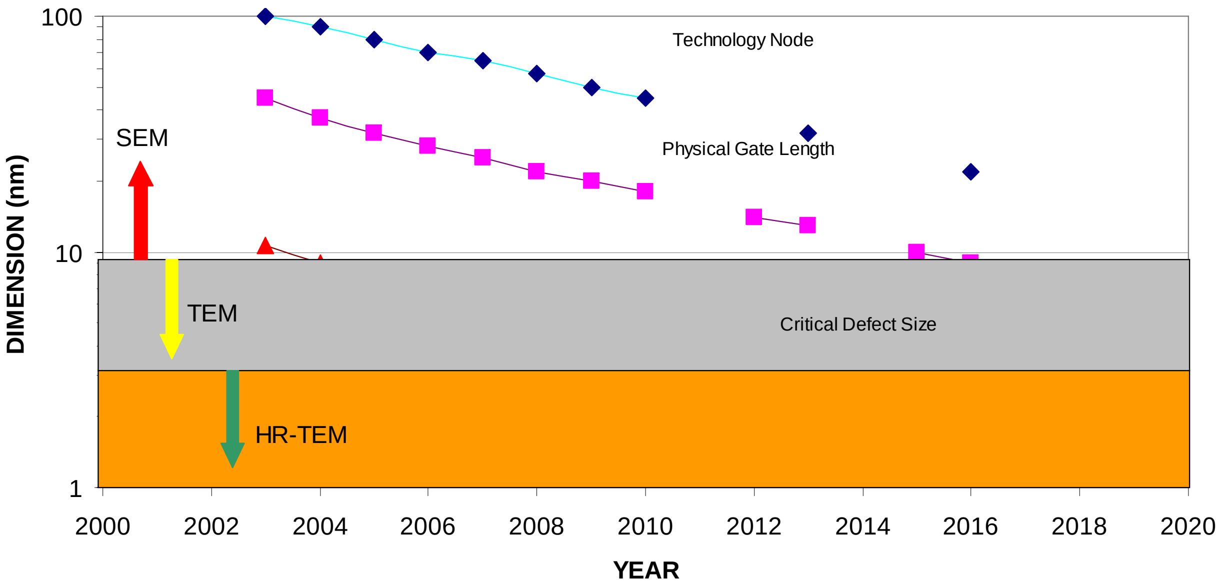
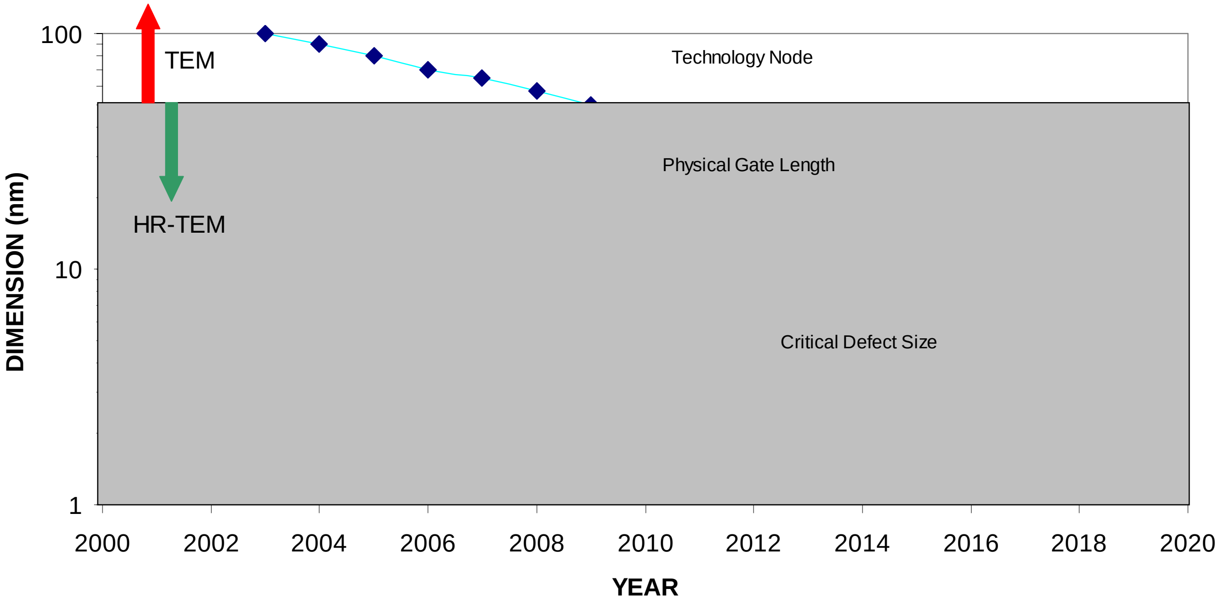
2004 ITRS Roadmap
Imaging - Morphology



Imaging - Chemical Analysis

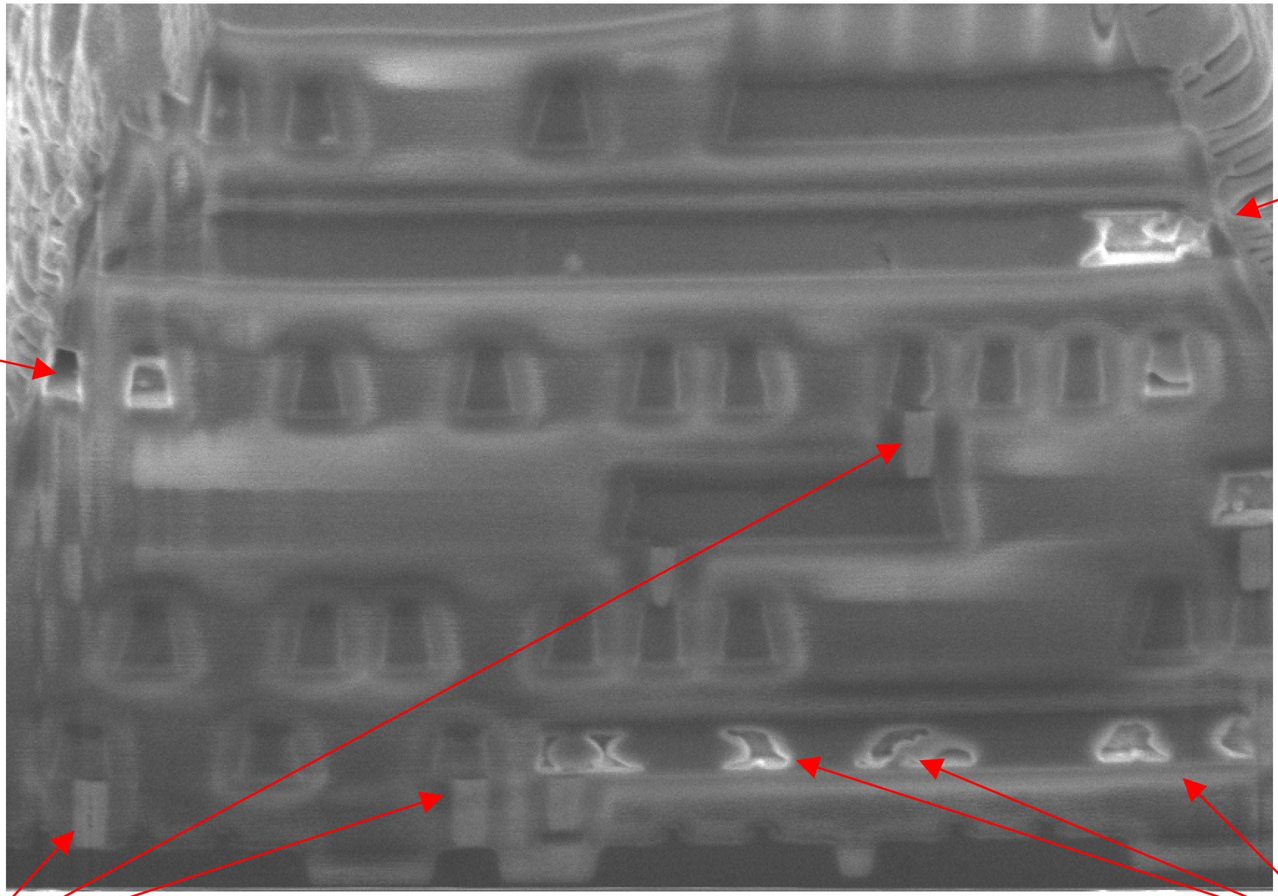


Microanalysis is Critical for Understanding Susceptibility to Radiation Effects and Part Reliability

- Modeling and simulation of device reliability and susceptibility to radiation effects are usually based upon idealizations that do not represent real device structures
- Real device structures often contain voids, misalignments or misregistration of critical elements, features with varying or incorrect dimensions, and hidden highly proprietary elements that vendors do not commonly acknowledge
- Techniques for three-dimensional imaging and chemical analysis are needed to validate vendor device design and fabrication as well as to conduct destructive failure analysis for reliability investigations

FIB/SEM Slices

Consumer Electronic Component



Metallization Void

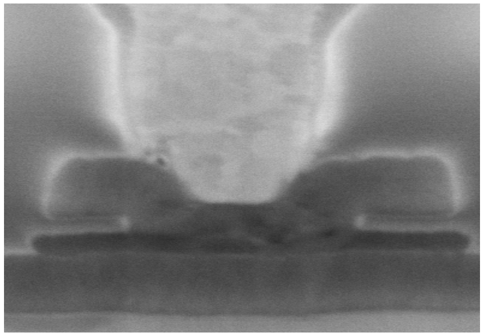
Missing metal in trace

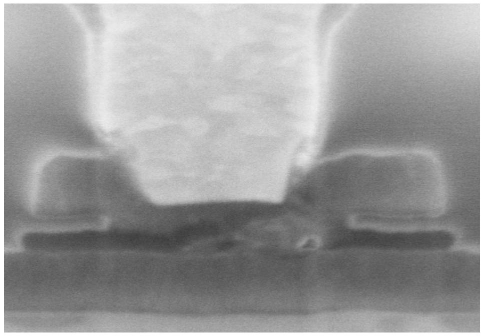
Via alignment

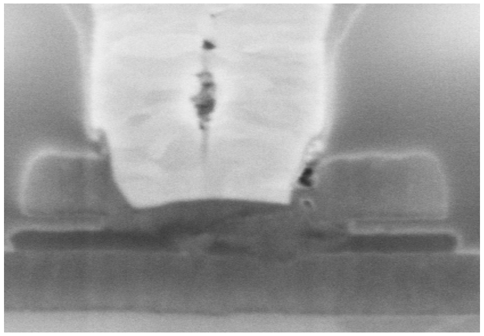
Metallization Voids

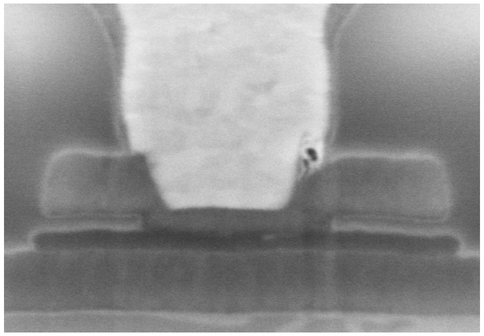
3D vs. 2D Rationale

Physical features are different within the device’s structure


Slice at 70 nm


Slice at 83 nm


Slice at 101 nm


Slice at 133 nm

The slices show different spatial regions of an antifuse structure including the tungsten plug at the top, titanium nitride metallization, the dielectric and base metallization. The middle two slices show a nominal antifuse link. Any single slice would not provide the correct information about true morphology and location of important features

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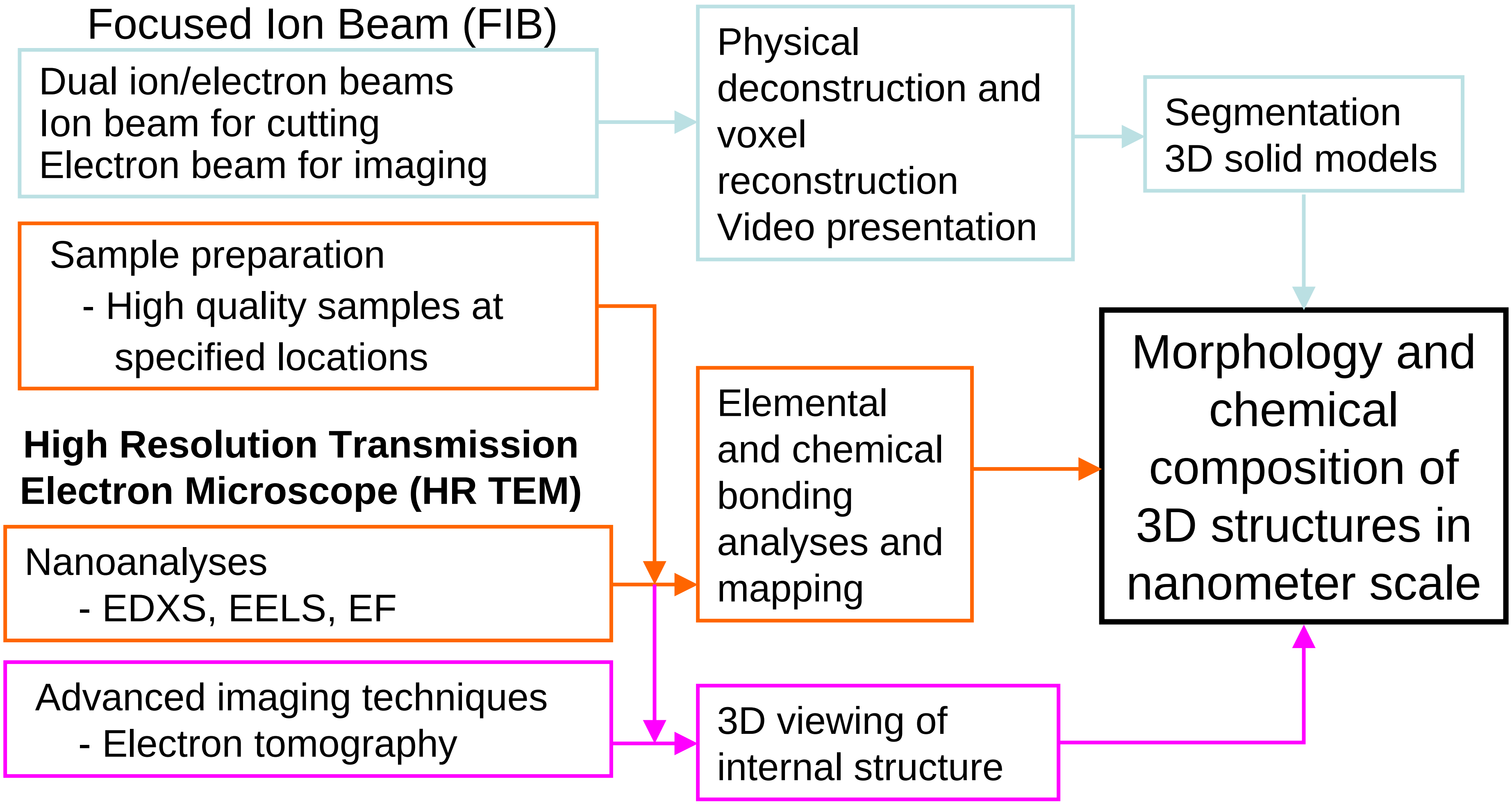
Some of the Analytic Techniques Available at Aerospace Laboratories

- Morphology (what does it look like?)
  - Optical microscopy
  - X-ray microscopy
  - Scanning electron microscopy (SEM)
  - Transmission electron microscopy (TEM)
- Composition (what is it made of?)
  - Auger electron spectroscopy
  - Secondary ion mass spectroscopy
  - Time-of-flight secondary mass spectroscopy
  - SEM/energy dispersive X-ray spectroscopy (EDXS)
  - TEM/EDS, electron energy loss spectroscopy (EELS)
  - Electron tomography with three-dimensional chemical specificity
- Focused ion beam (FIB) milling (key to successful resolution of many problems)
  - FIB rewiring
  - Cross sectioning for SEM sample preparation
  - FIB nano-tomography
  - Preparation of TEM samples

The Big Small Picture

Confluence of Hardware, Software and Expertise



Focused Ion Beam (FIB)

Dual ion/electron beams
Ion beam for cutting
Electron beam for imaging

Sample preparation
- High quality samples at specified locations

High Resolution Transmission Electron Microscope (HR TEM)

Nanoanalyses
- EDXS, EELS, EF

Advanced imaging techniques
- Electron tomography

Physical deconstruction and voxel reconstruction
Video presentation

Segmentation
3D solid models

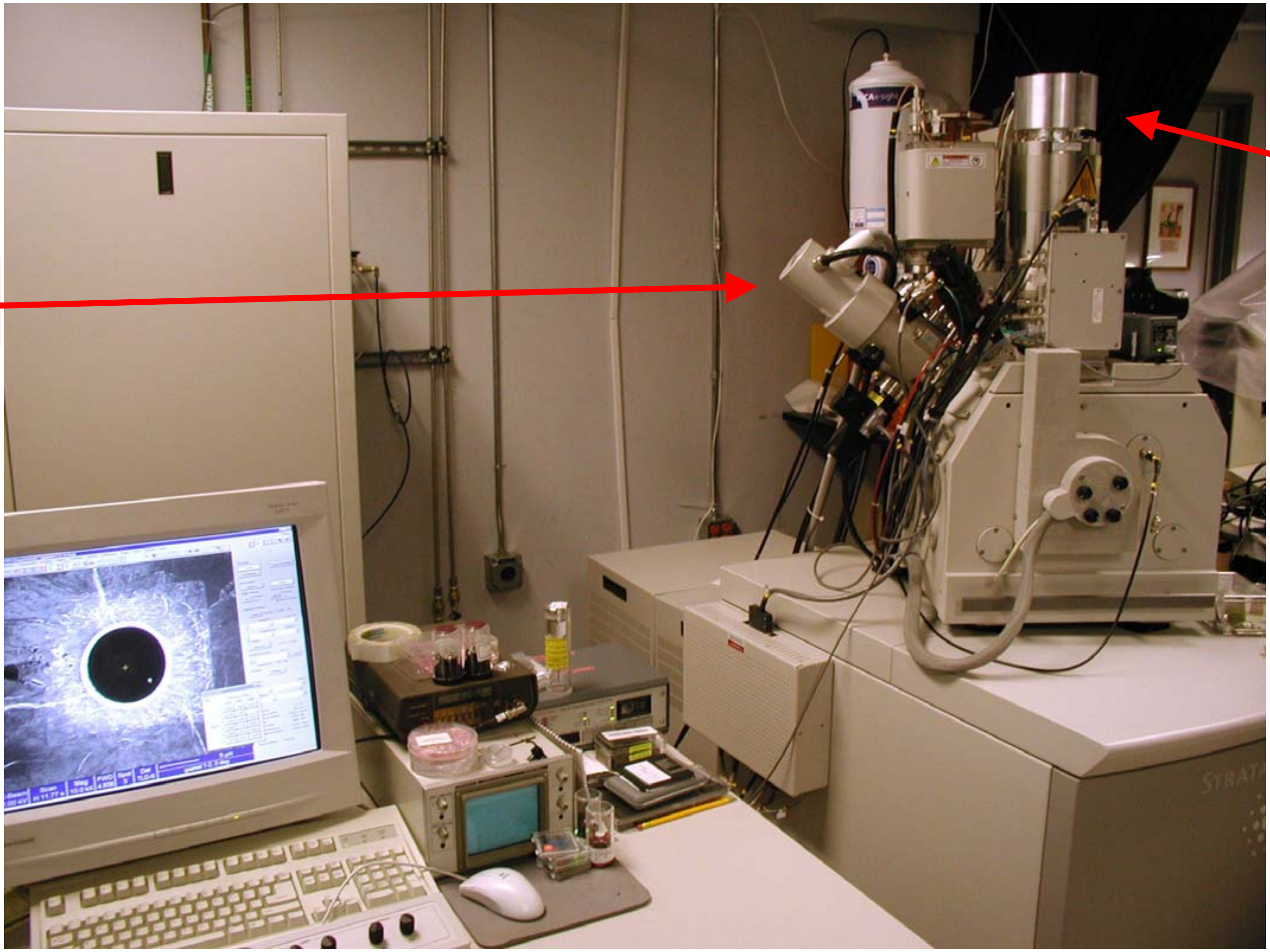
Elemental and chemical bonding analyses and mapping

3D viewing of internal structure

Morphology and chemical composition of 3D structures in nanometer scale

Dual-Beam FIB

FEI DB-235



Scanning electron microscope

Ga ion beam

Ion beam for cutting and electron bean for looking

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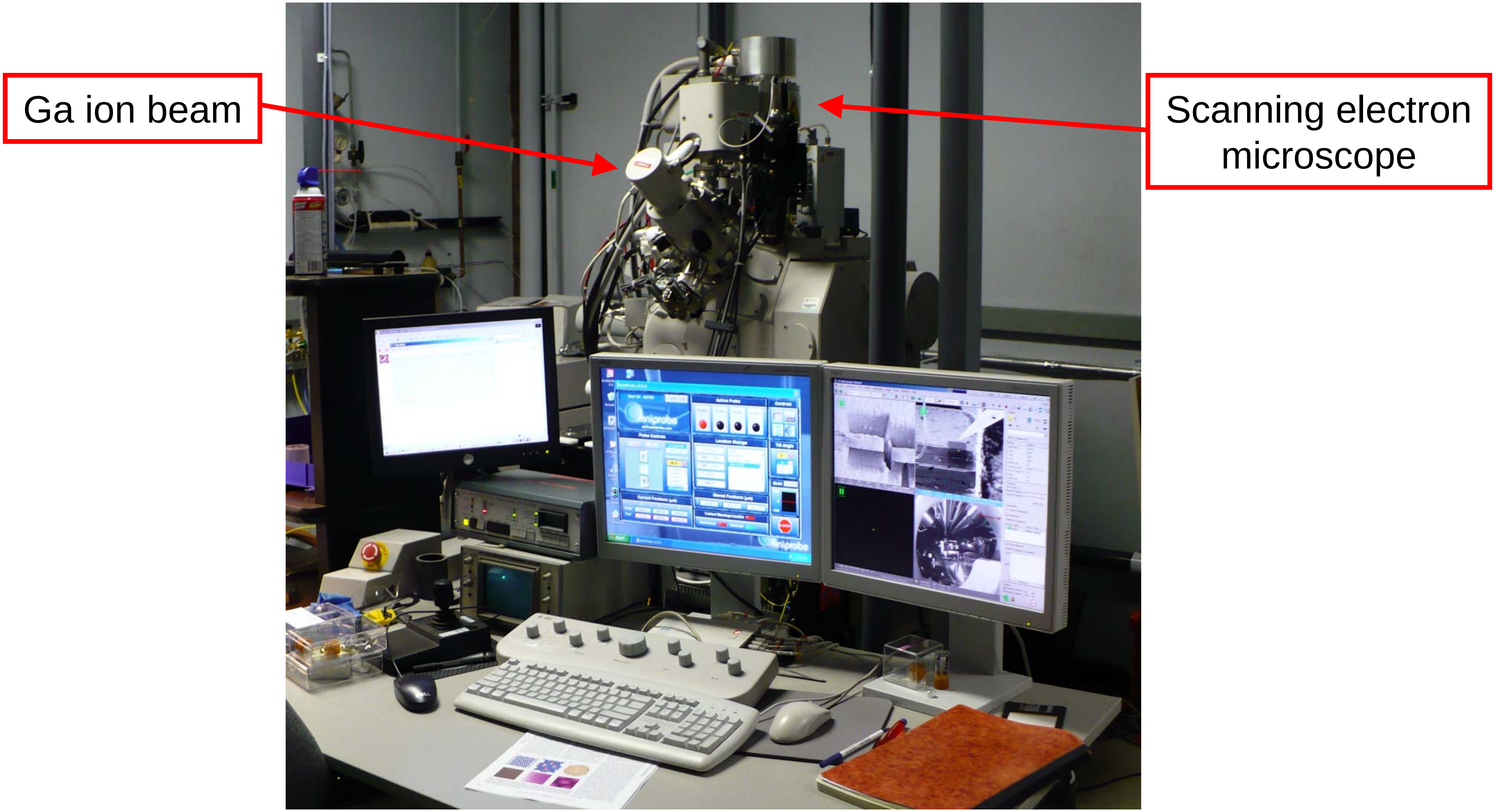
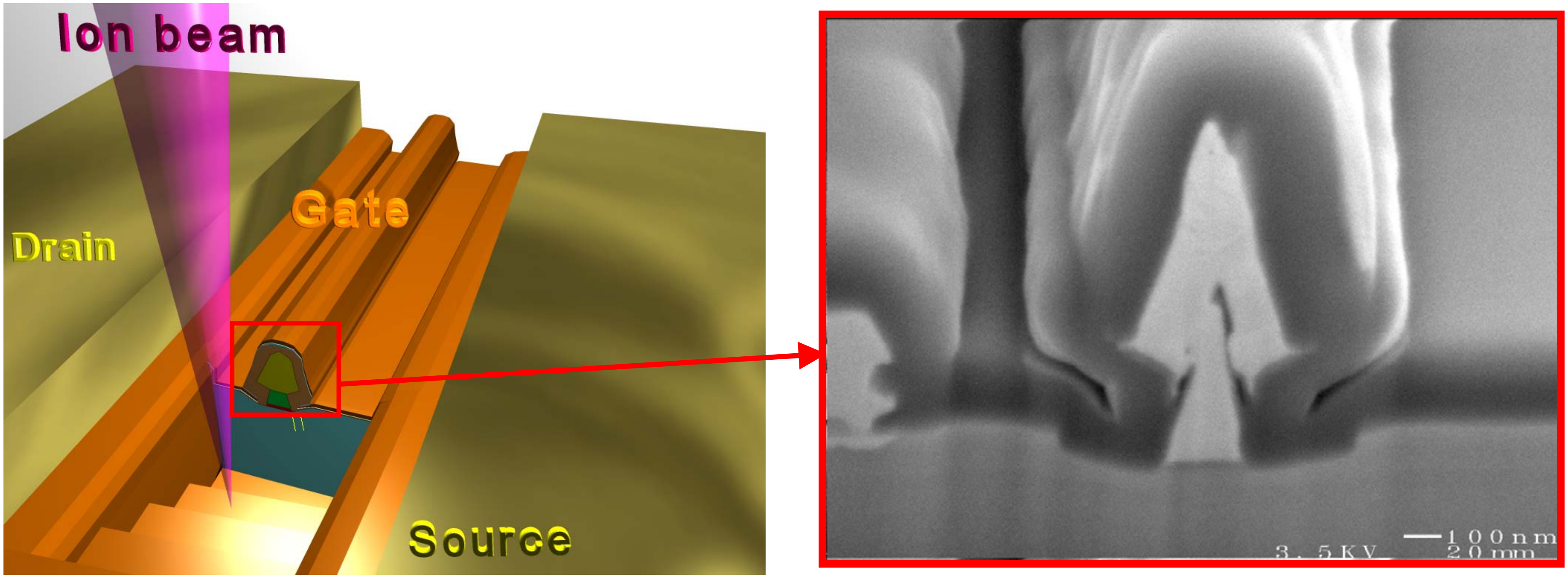
Dual-Beam FIB

FEI Strata 400

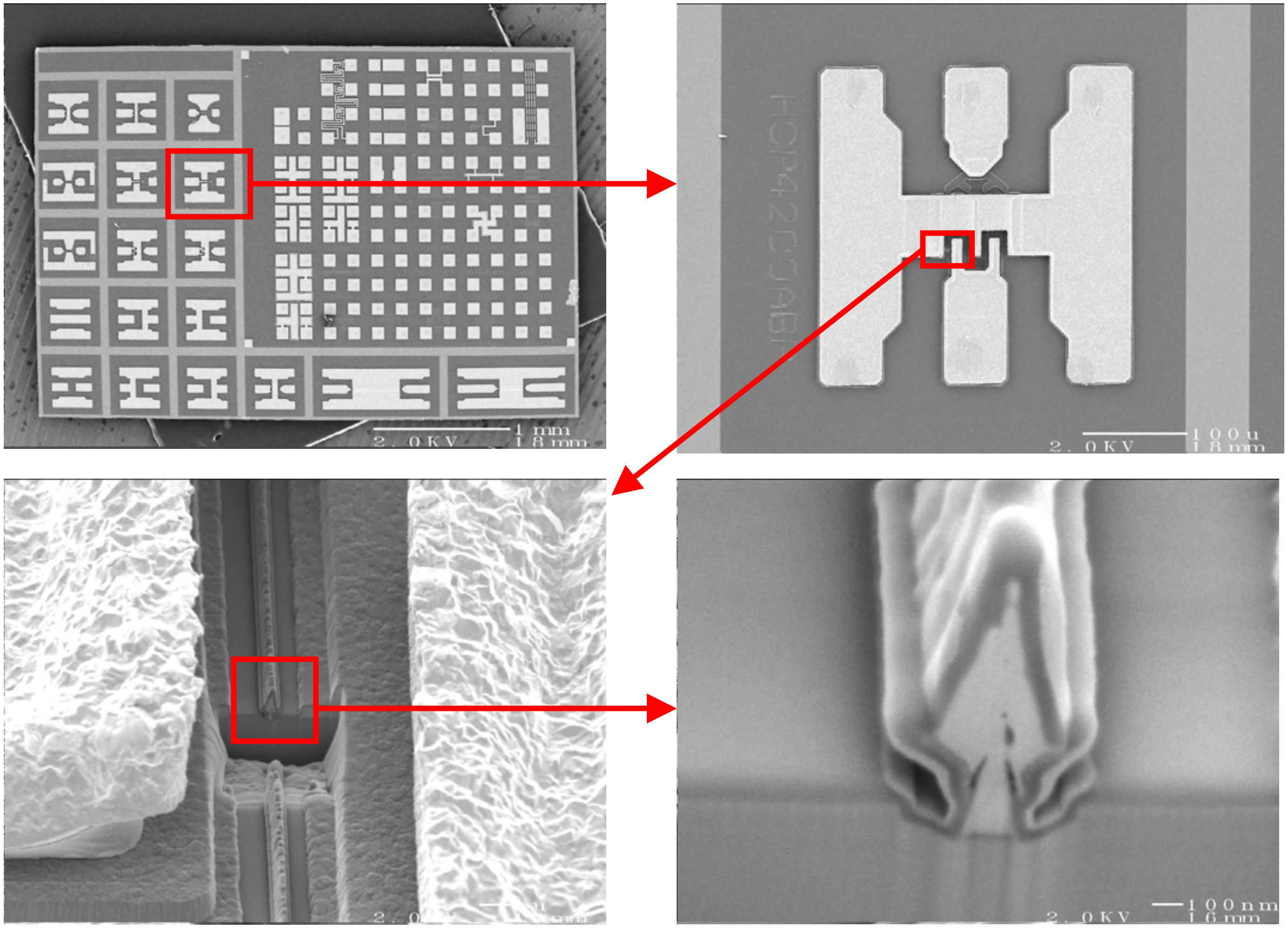


Cross-sectioning



- Most common application for FIB milling
- Offers advantages over conventional methods

FIB Systems in Failure Analysis



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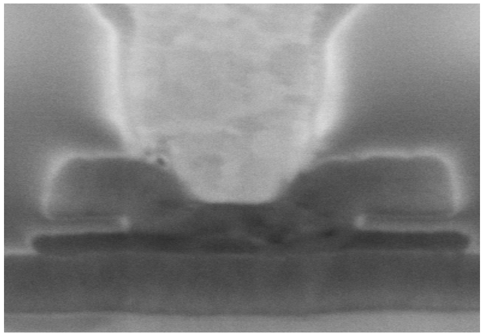
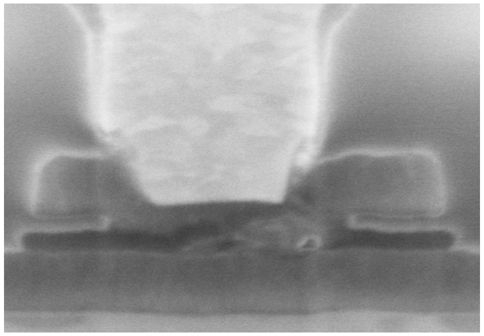
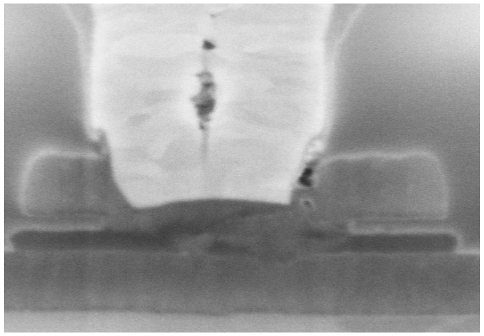
3-Dimensional Visualization on the Nanoscale Range

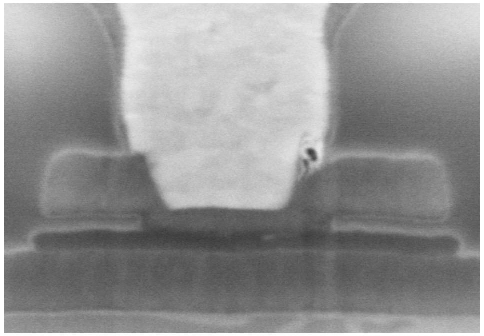
3D vs. 2D Rationale

Physical features are different within the device’s structure


Slice at 70 nm


Slice at 83 nm


Slice at 101 nm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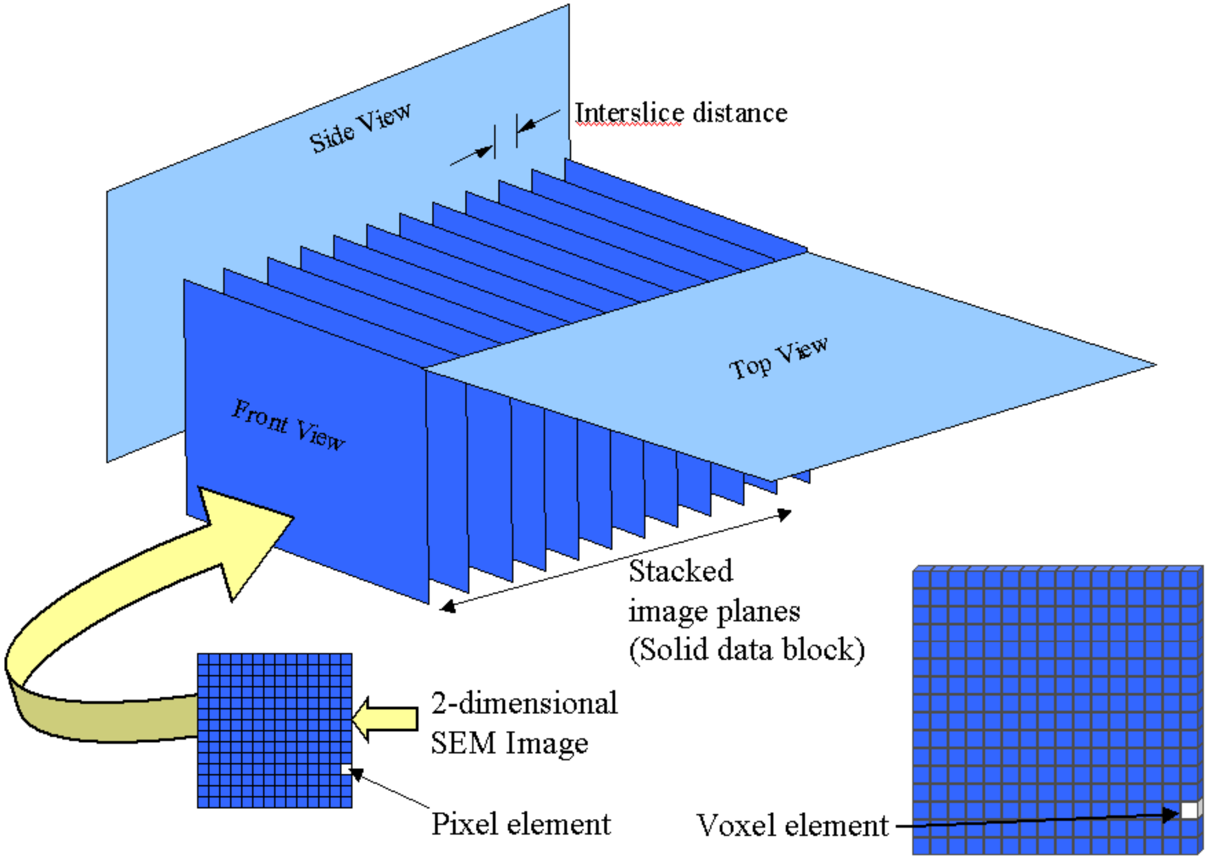
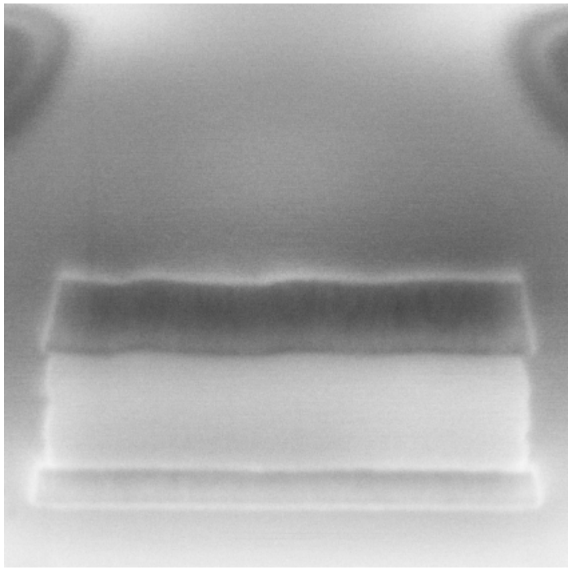
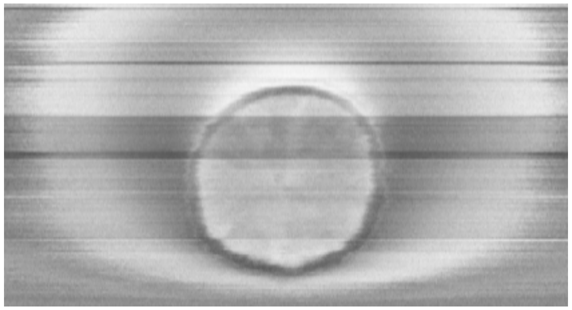
Focused Ion Beam Nanotomography



Voxel Reconstructions



Through sample image stack



Virtual top-down slice

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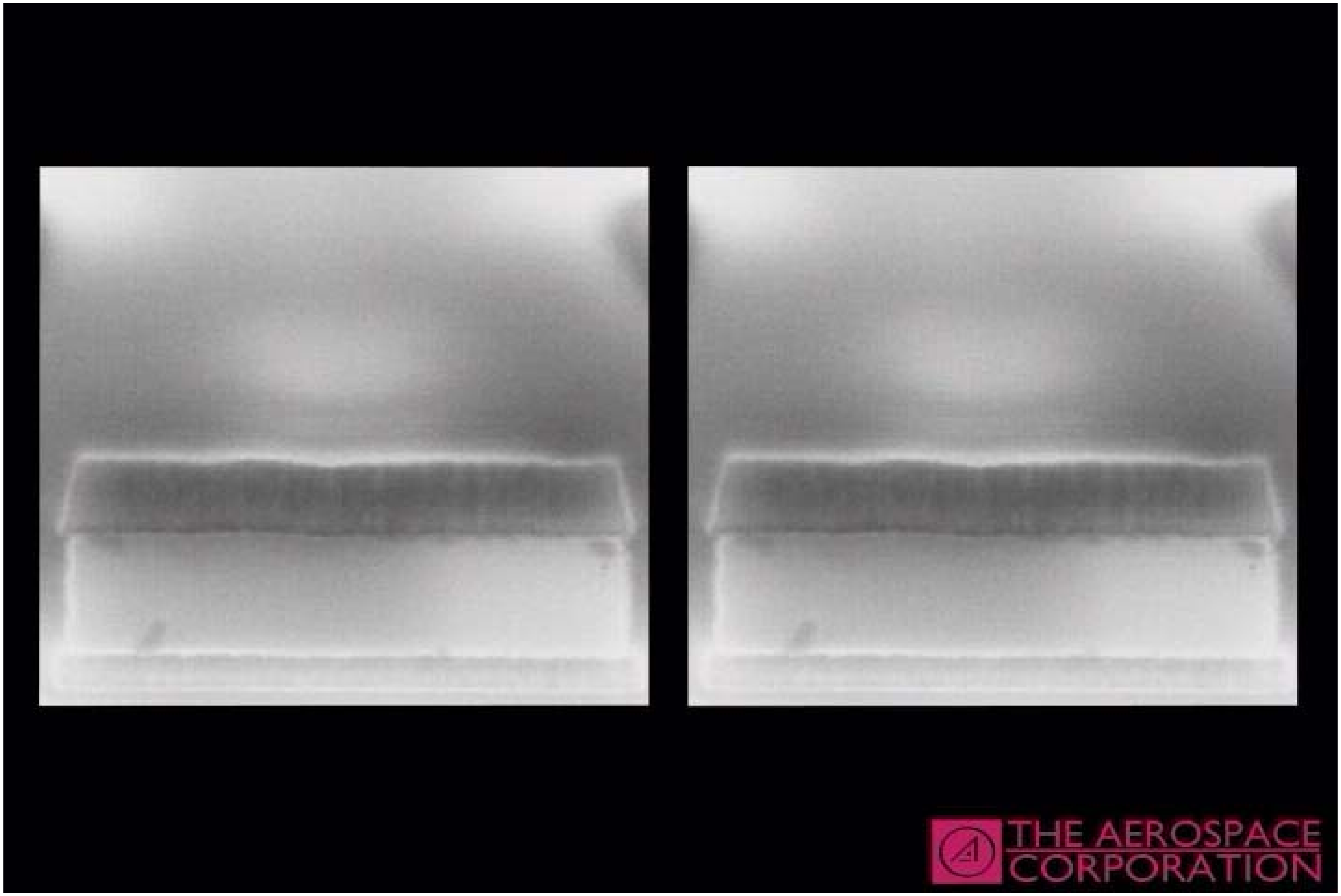
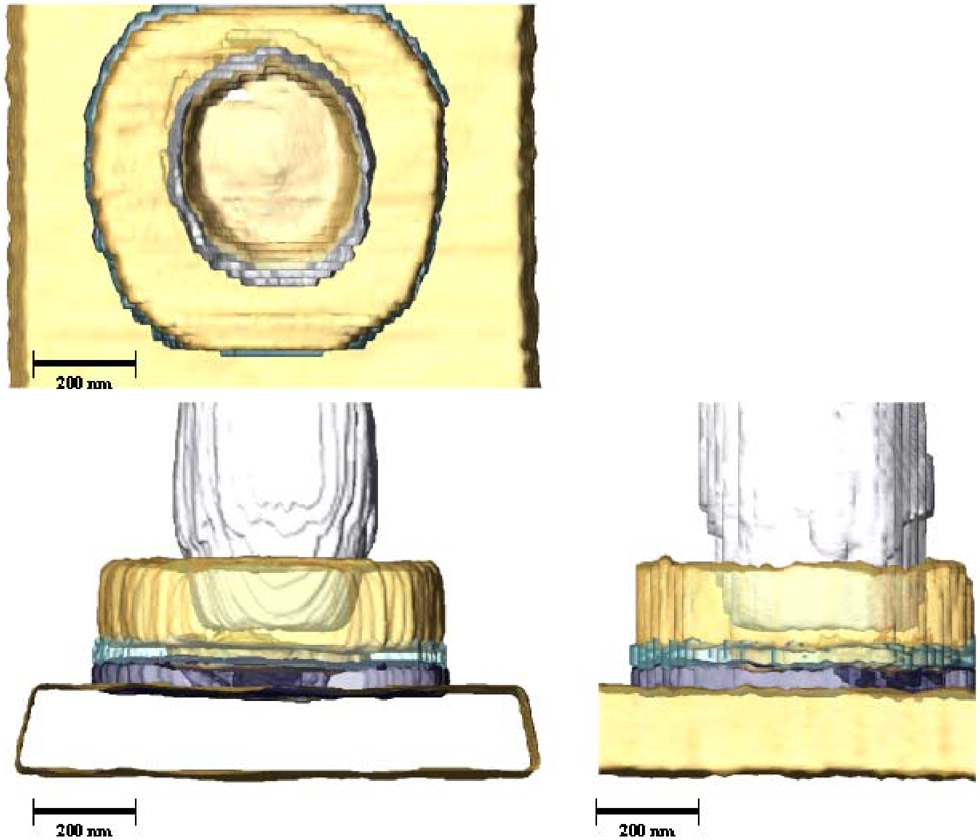
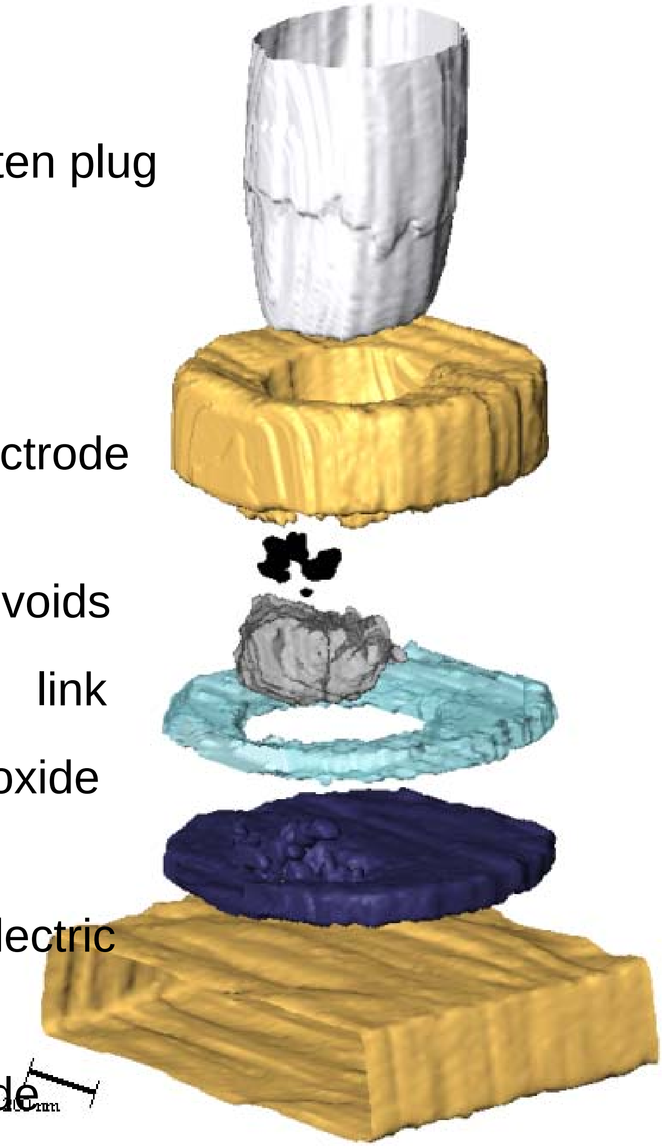
3-Dimensional Model



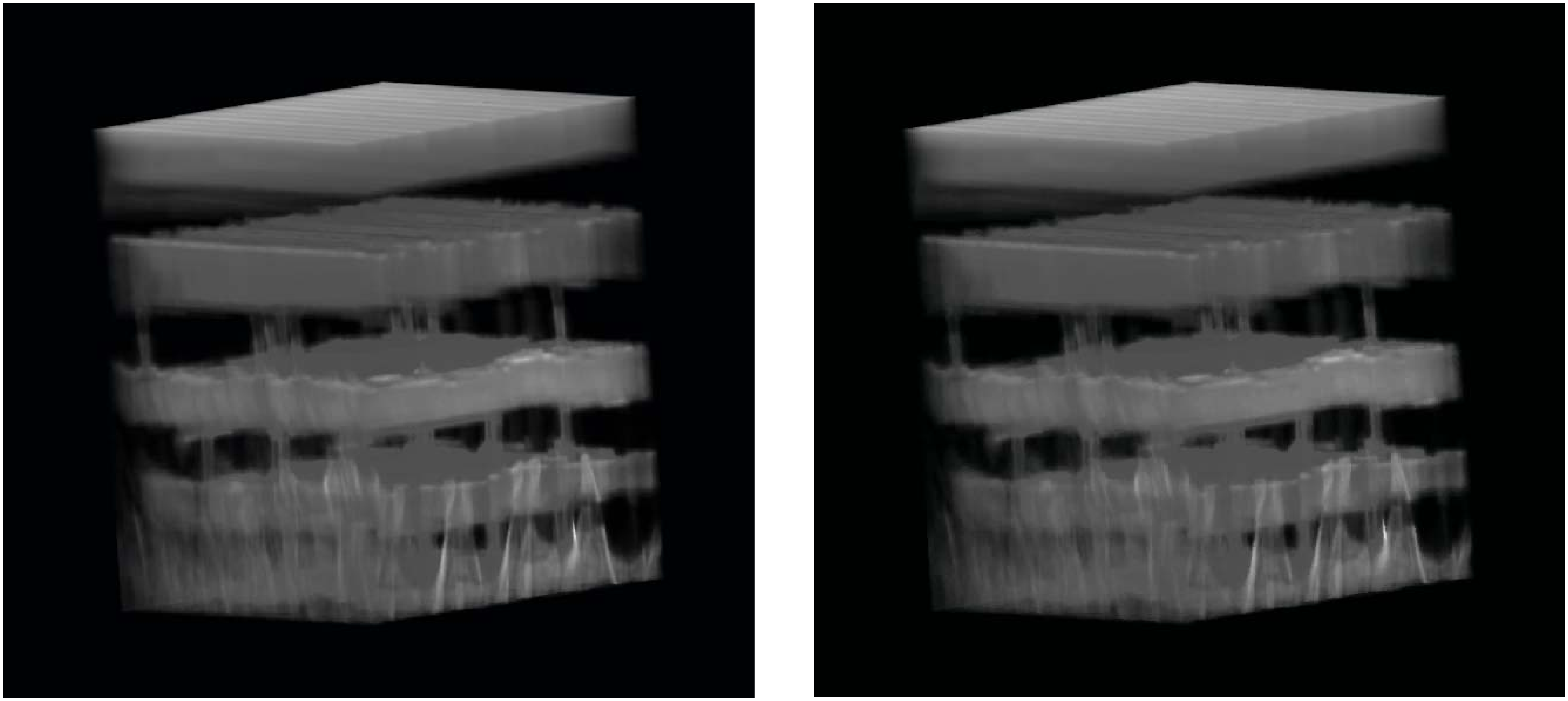
3D Voxel Reconstruction





Top Down FIB Profiling and 3D Reconstruction

Visualization of 5 layers of metallization with via interconnects



4M-SRAM

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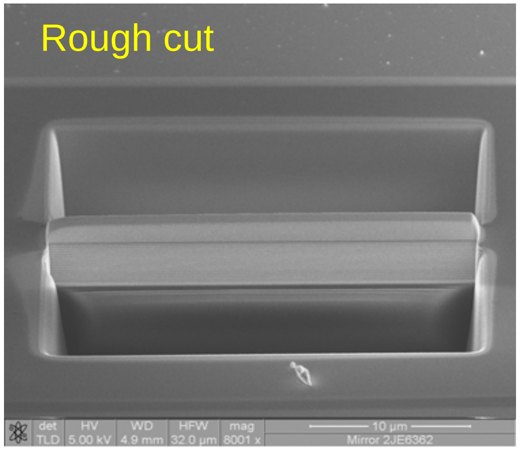
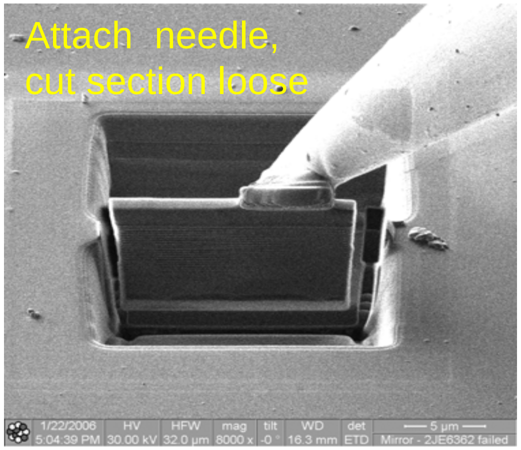
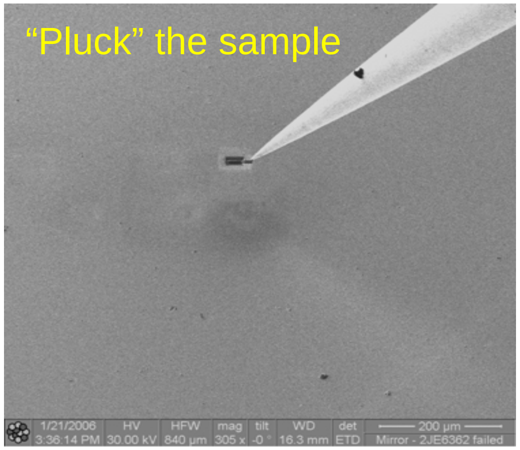
TEM Sample Preparation

- One of the really neat things you can do with a FIB is make specimens for transmission electron microscopy (TEM) and electron tomography
- TEM sample prep with older methods is a painful process
  - Sections must be thin (≤ 80 nm)
  - A section through a very specific location is nearly impossible

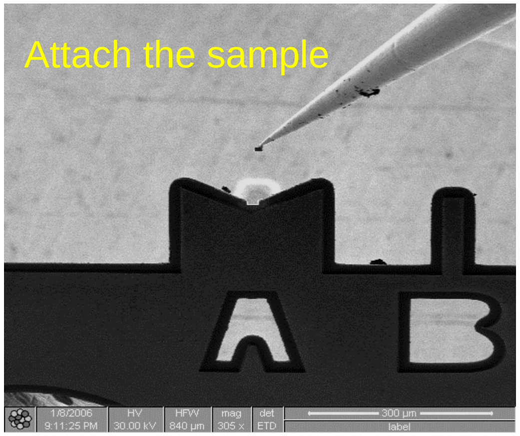
FIB Preparation of TEM Sample

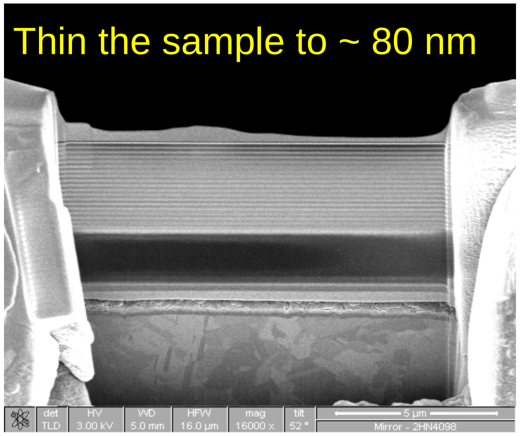

Rough cut


Attach needle,
cut section loose


"Pluck" the sample


Move to the TEM holder


Attach the sample


Thin the sample to ~ 80 nm

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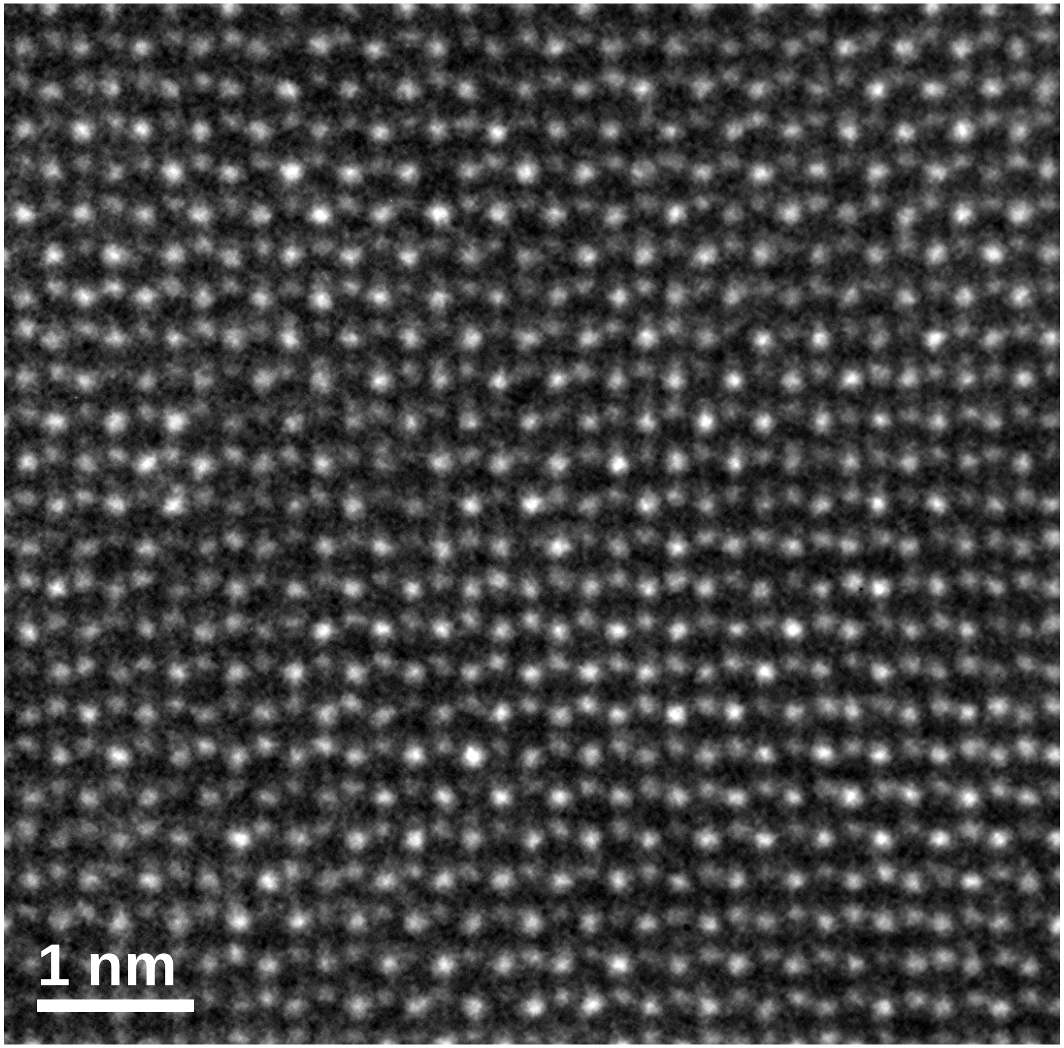
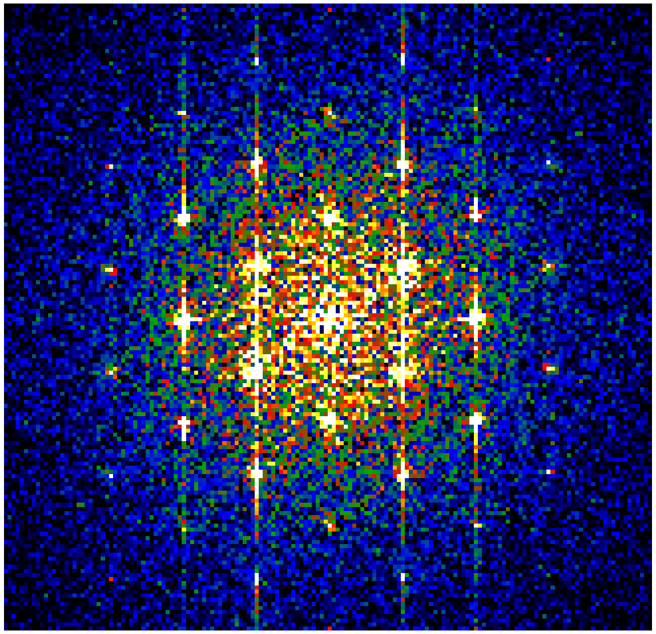
High Resolution Transmission Electron Microscope

- Atomic imaging
- Scanning transmission electron microscopy (STEM)
- Energy dispersive X-ray spectroscopy (EDXS)
- Electron energy loss spectroscopy (EELS)
- Electron tomography

HRTEM Image

Silicon <110> and Fourier Transform





- Atomic resolution, 0.16 nm
- This image is from our new 300 kV TEM

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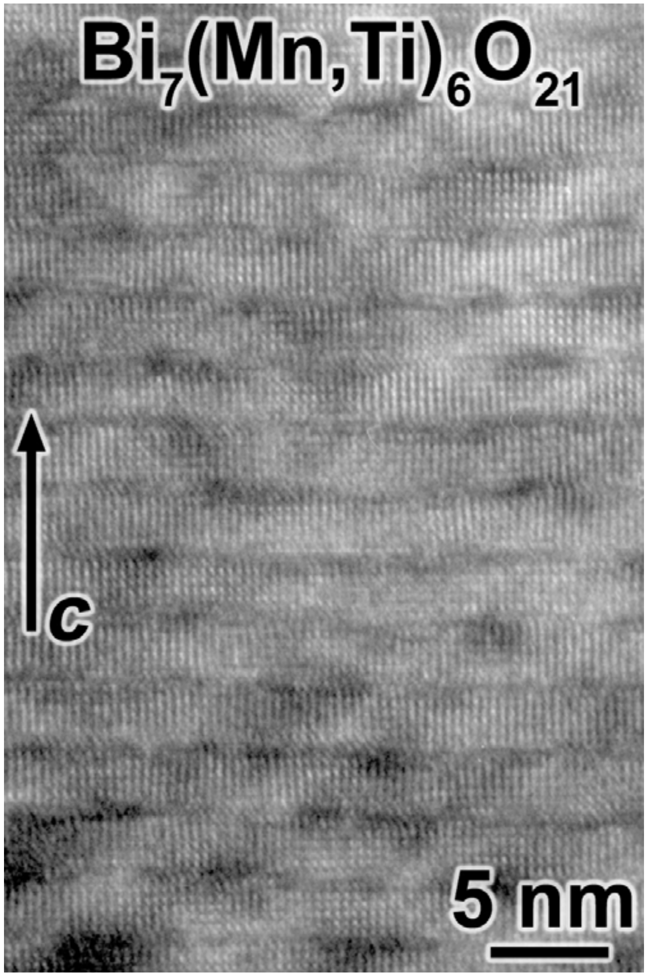
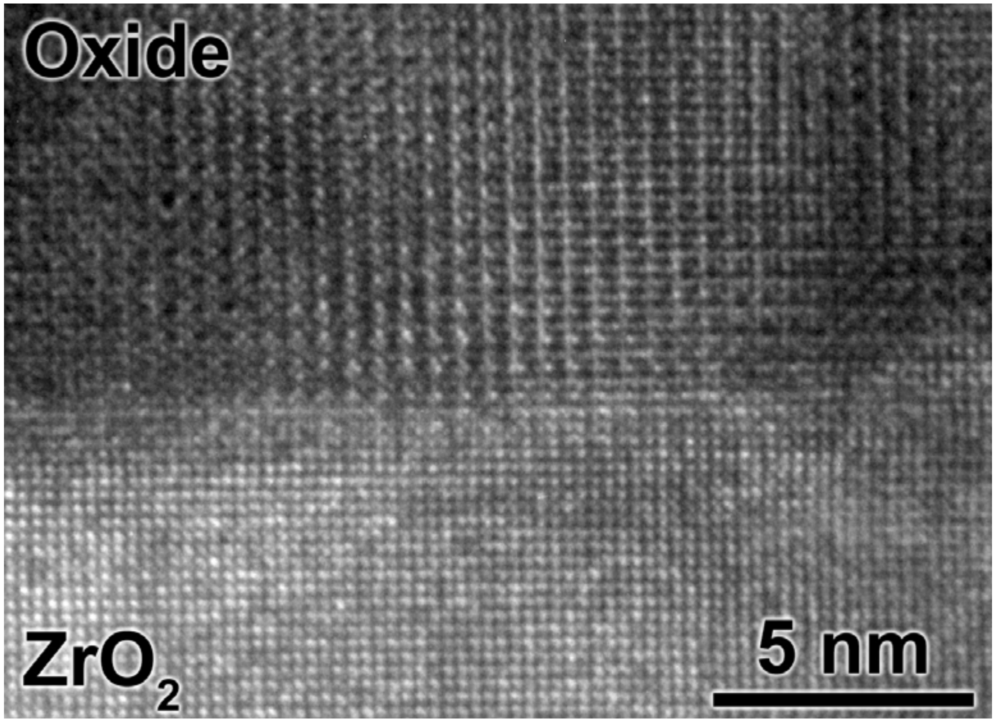
Atomic Scale Resolution via TEM

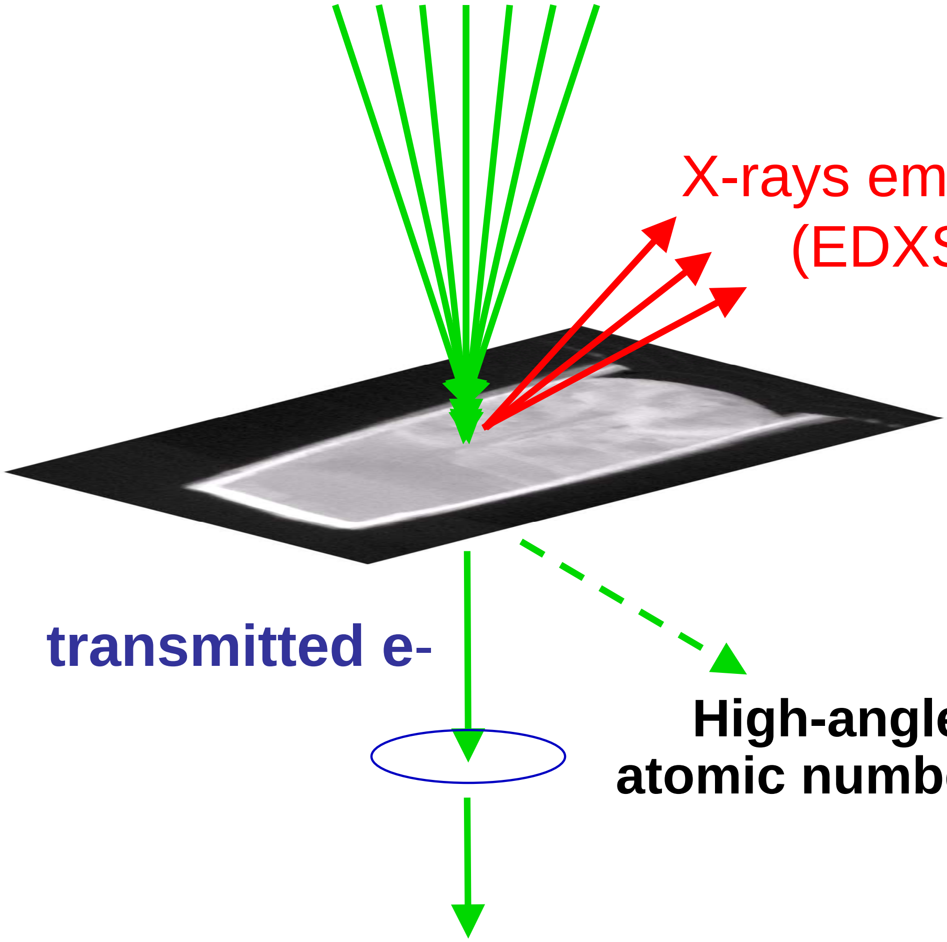


Layered nanocomposite of ferroelectric/ ferromagnetic materials



Atomically sharp epitaxial interface between zirconium dioxide and another oxide layer

2-D STEM chemical analysis



STEM: focused e- probe

X-rays emission
(EDXS)

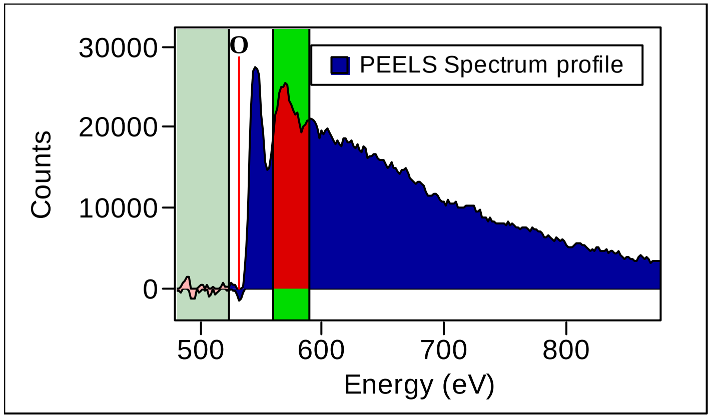
transmitted e-

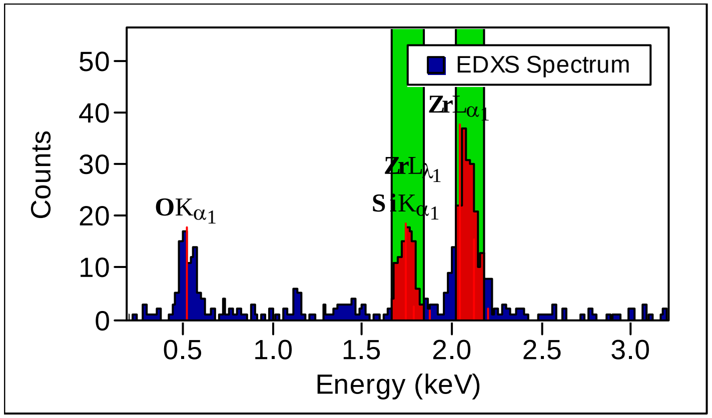
High-angle scattered electrons for atomic number sensitive image contrast

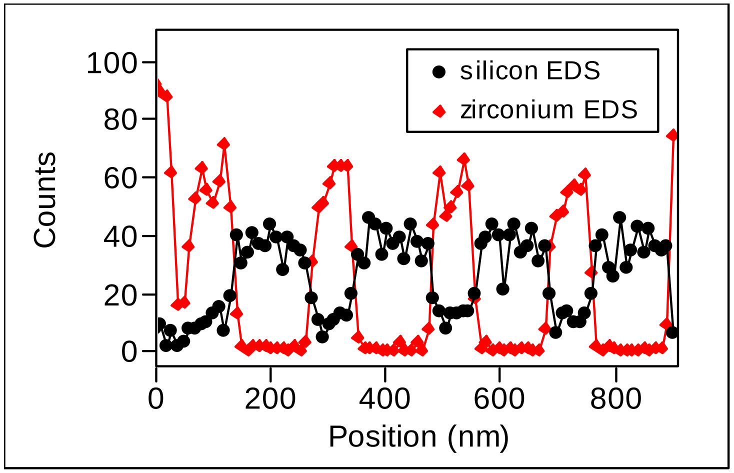
Inelastic scattered electrons:

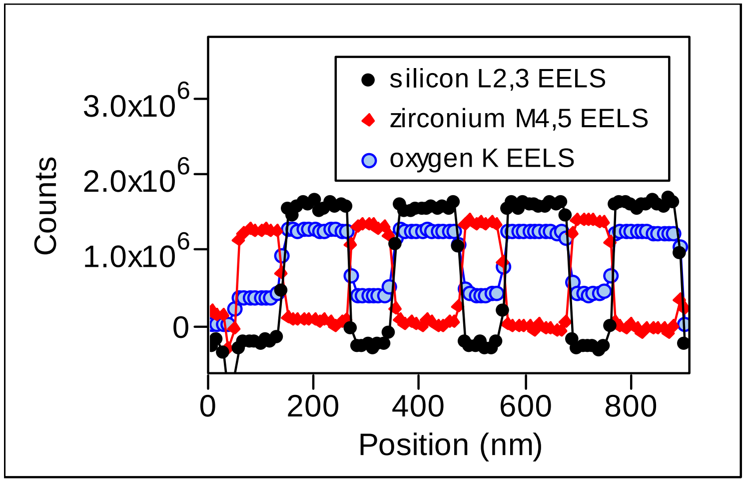
Electron Energy Loss Spectroscopy (EELS)

Composition Profiles with EDXS and EELS









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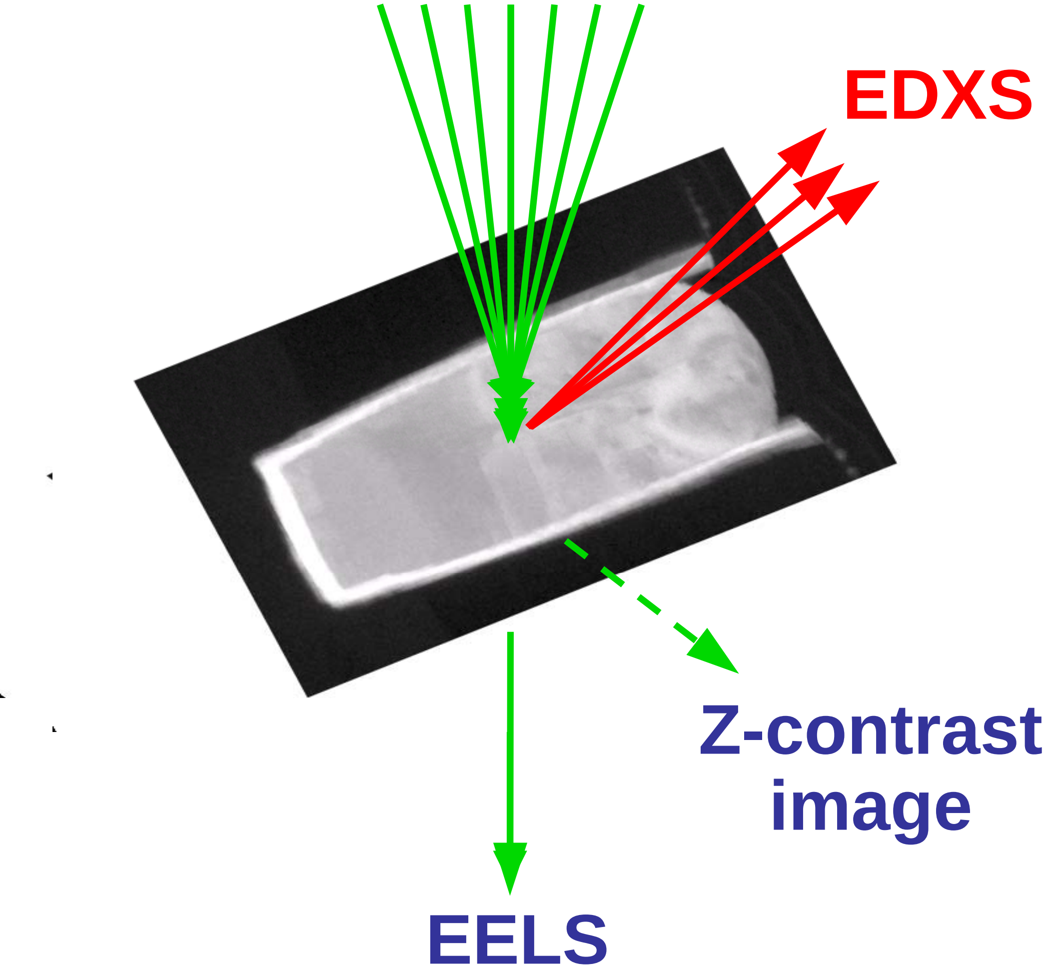
Three Dimensional (3D) Transmission Electron Microscopy

- Scanning Transmission Electron Microscope (STEM) Tomography
  - Tilt series with sub-nanometer spatial resolution
  - Contrast related to atomic number gives chemical sensitivity
  - Weighted back-projection or Simultaneous Iterative Reconstruction Techniques Developed.
- Chemical Tomography
  - Electron energy loss spectroscopy (EELS) in the TEM for chemical delineation with near sub-nanometer spatial resolution
    - Optimal quantitative analysis of lighter elements
    - Compositional analysis with sensitivity to bonding environments
  - Energy dispersive X-ray spectroscopy (EDXS)
    - Quantitative analysis optimal for heavy elements

3-D STEM Chemical Tomography



1. Acquire tilt series of Images, EELS, and EDXS

2. Compute tomographic reconstruction with 3-D chemical segmentation

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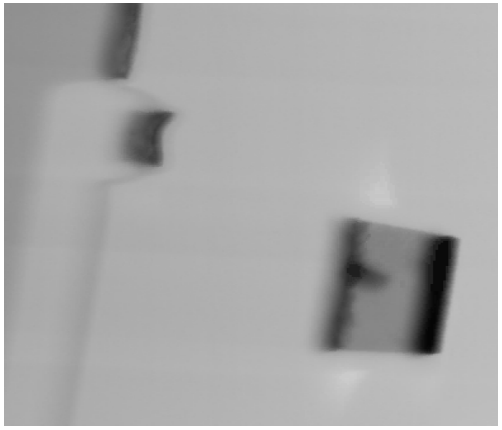
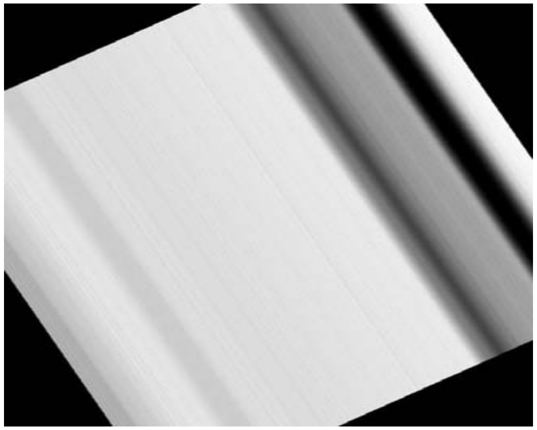
Electron Tomography Steps

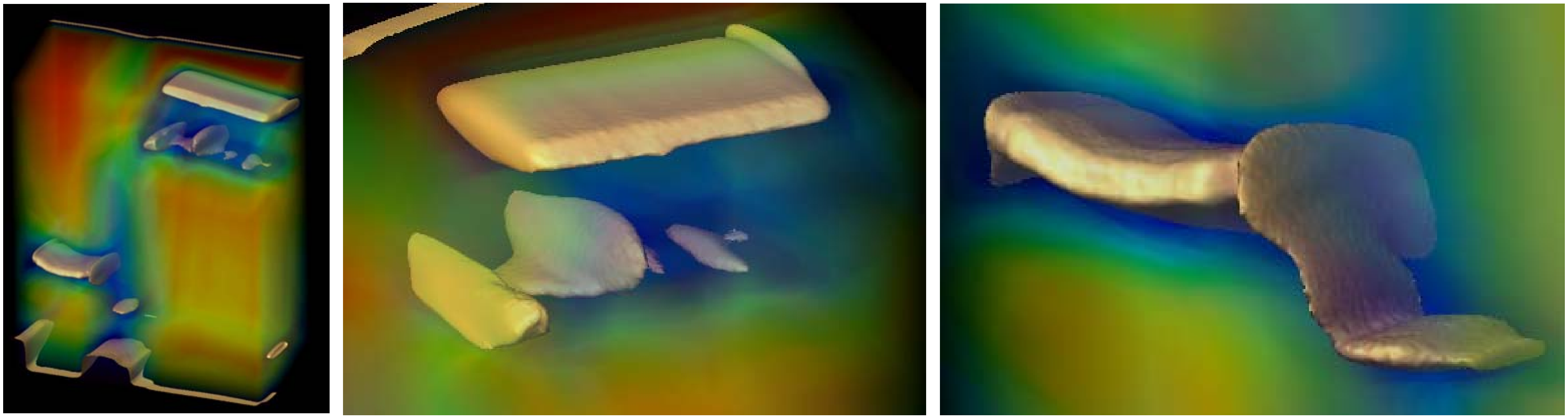


Transmissive imaging



Compute Sinogram

Segmentation



Summary

- Devices are getting smaller and more complex
  - Requires greater attention to nanoscale and atomic scale features
- Techniques for three-dimensional imaging and chemical analysis have been and are being developed to provide needed information on the nanoscale range
  - Three-dimensional ToF SIMS
  - FIB nanotomography
  - Electron tomography with chemical specificity
- Root cause investigations enabled by:
  - unique combination of instrumentation
  - expertise in materials physics and chemistry
  - knowledge of image processing and analysis techniques
  - software modeling tools

Acknowledgement

This work was supported under The Aerospace Corporation's Independent Research and Development Program.

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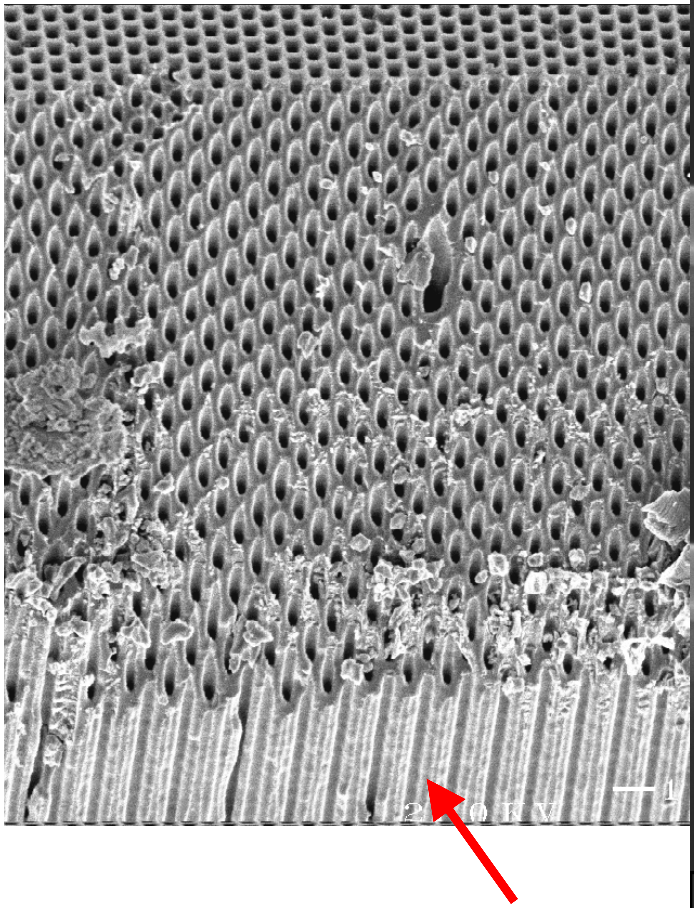
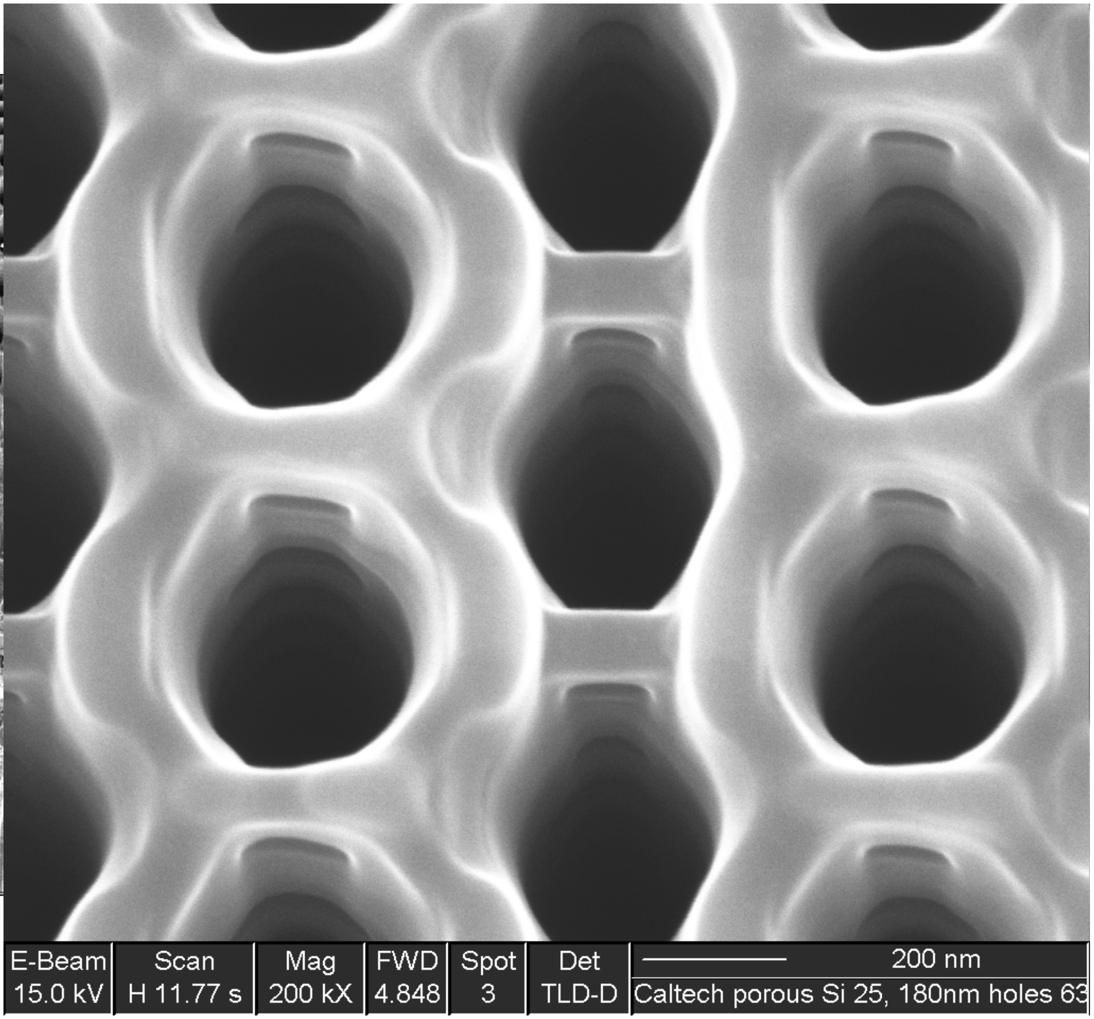
The Aerospace Corporation routinely works with outside organizations

3D Photonic Crystals

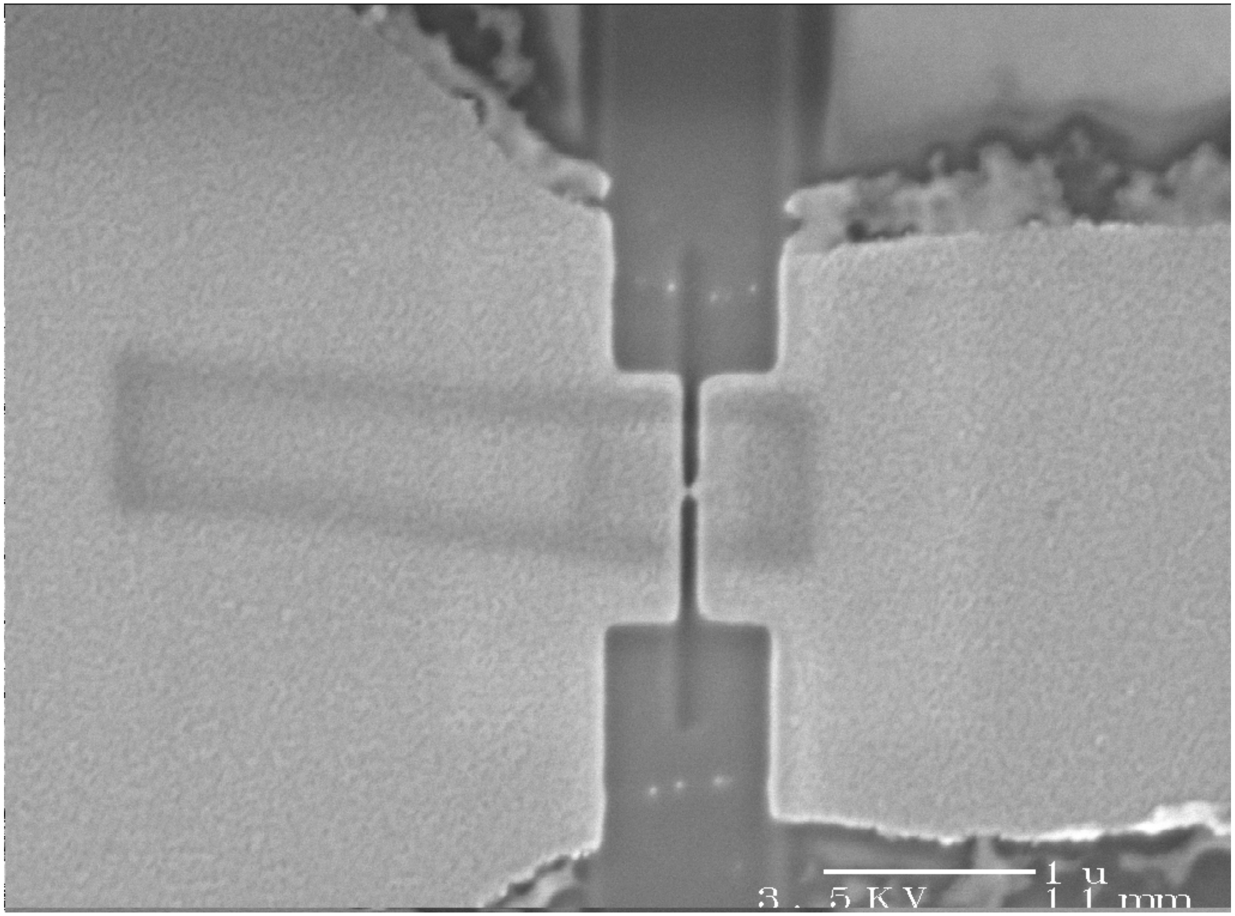
(Work done with Caltech)





Hall Probes

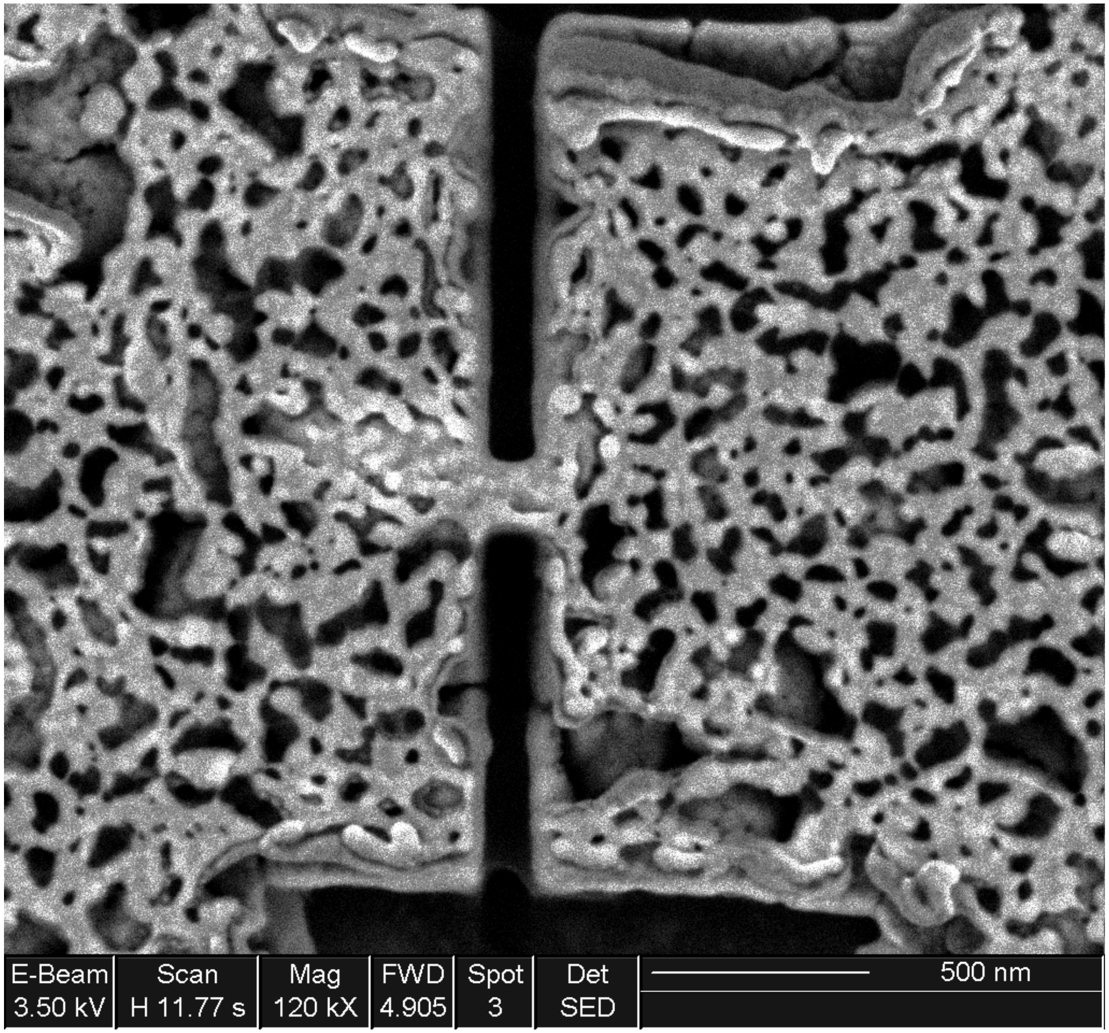
(Work Done with NYU)



- Ref: Guillou, Kent, Stupian, and Leung, ***J. Applied Physics 93***, 2746 (1 March 2003)

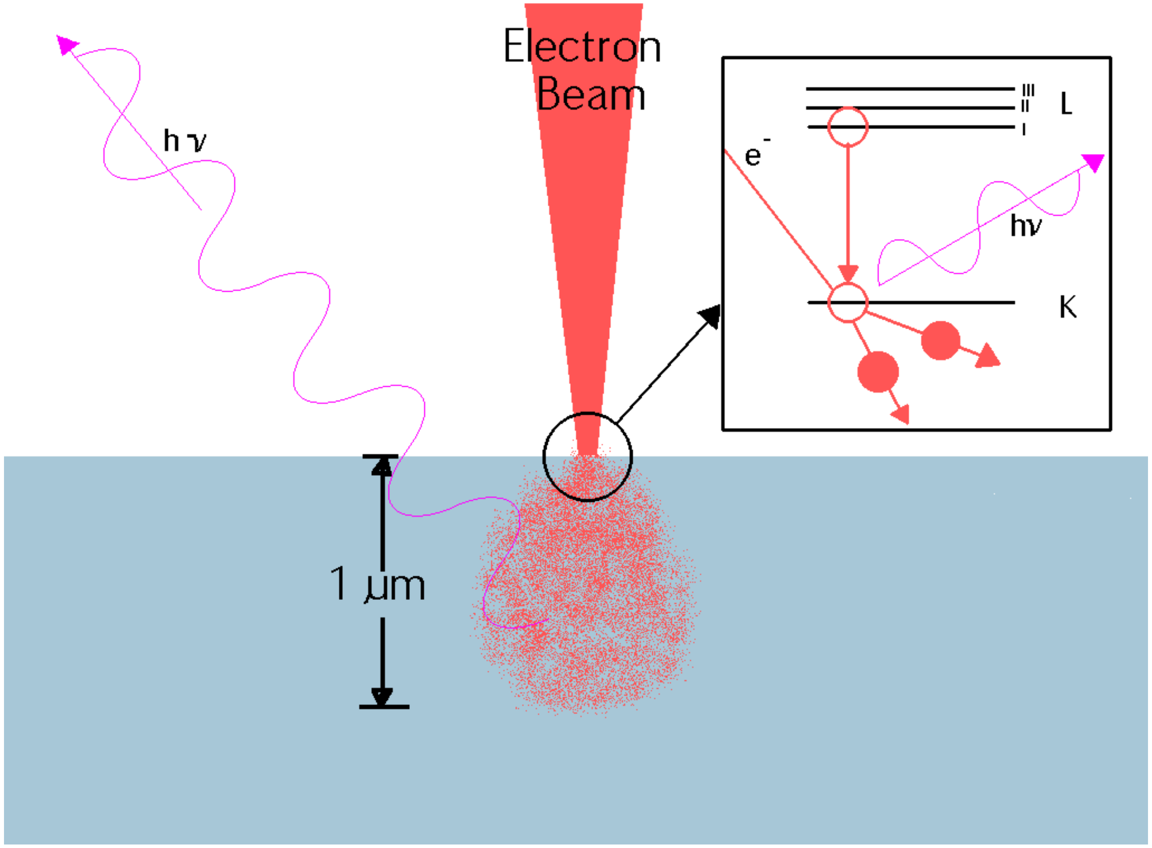
Superconducting MgB_2 Links

(work done with Caltech)



Back-up Charts

Energy Dispersive X-ray Analysis



- EDX spatial resolution is limited to a few μm
- Limitation does not apply to thin sections

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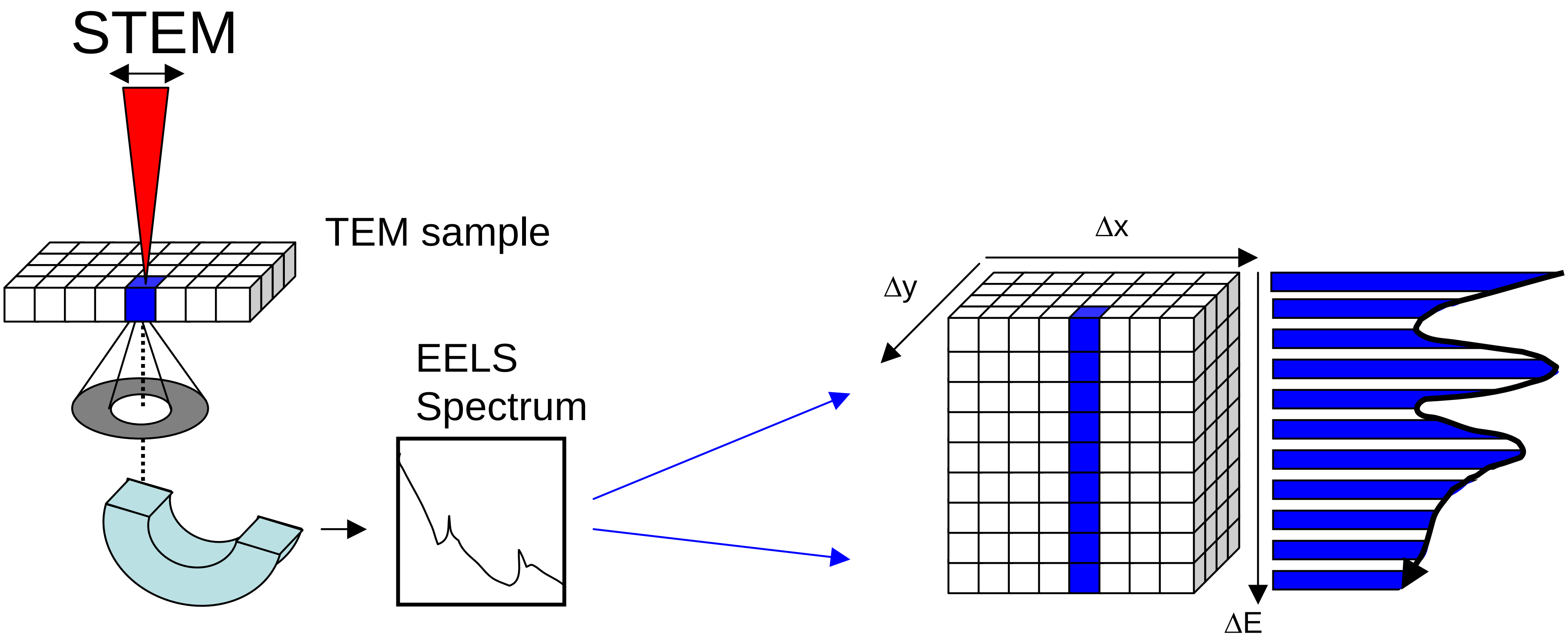
Electron Energy Loss Spectroscopy



Measured electron energy loss spectrum related to chemical bonding

The blue column represents the local chemical spectrum taken from the blue pixel on the TEM sample

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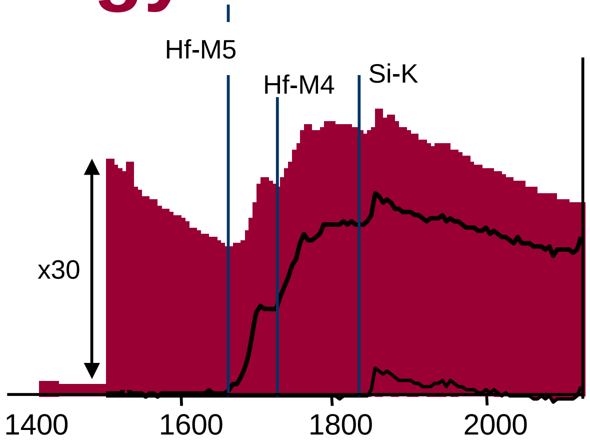
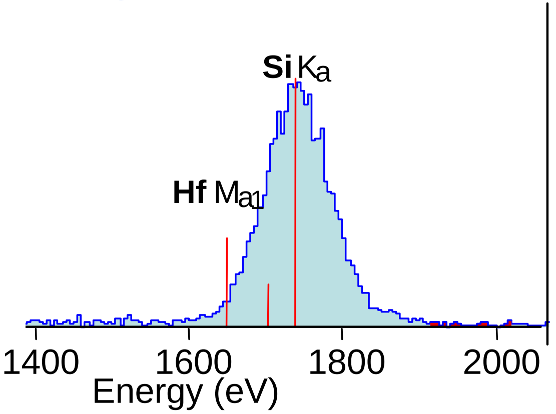
Common Spectroscopic Resolution

- **EELS energy resolution ~1 eV FWHM**



Commercial monochromated TEM instruments routinely attain ~0.3 eV FWHM energy resolution

- **EDXS energy resolution ~130 eV FWHM**



Next generation X-ray detectors currently being developed have attained energy resolutions of ~2.0 eV FWHM

Energy resolution must be ~1 eV to measure chemical shifts relating changes in atomic bonding.

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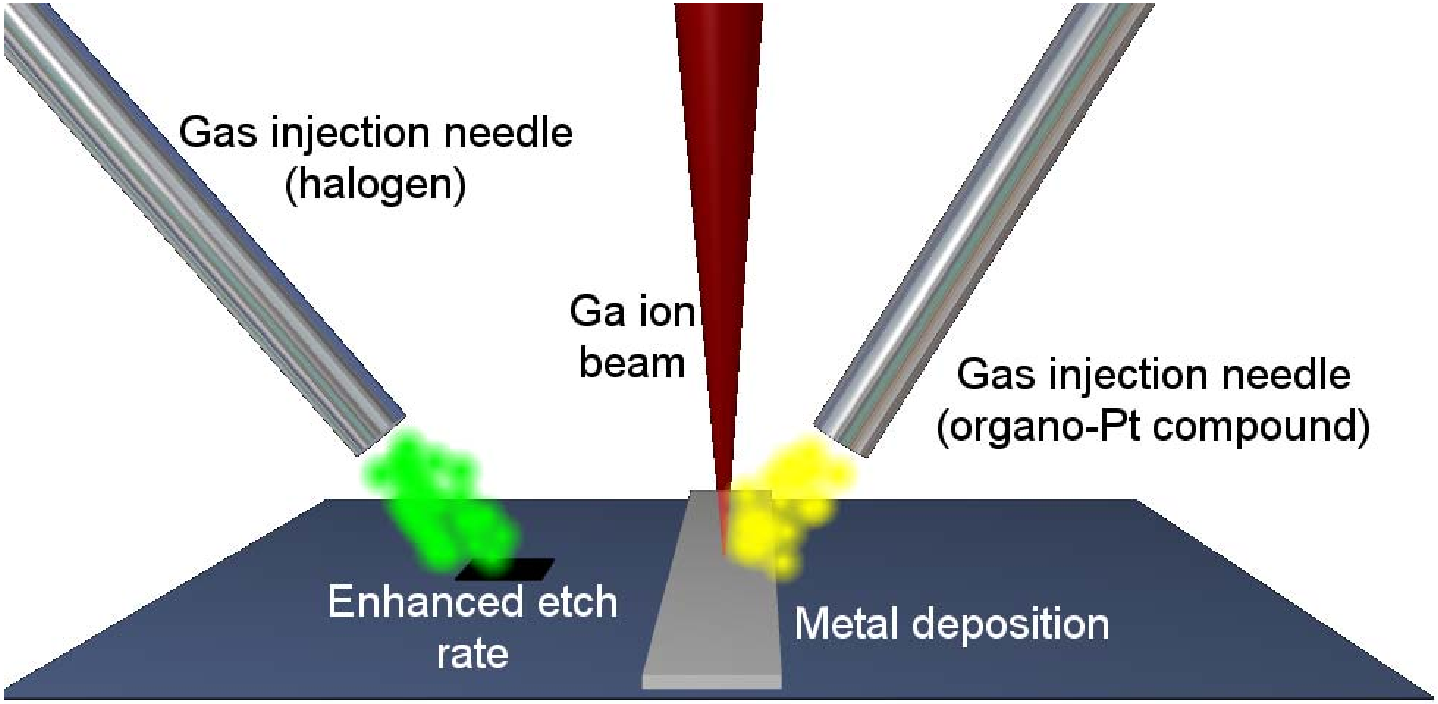
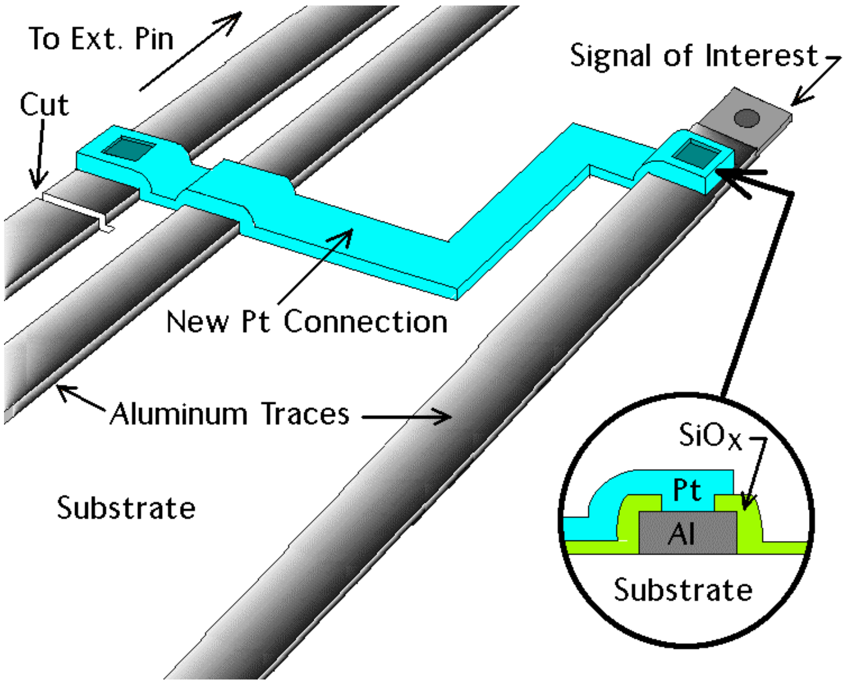
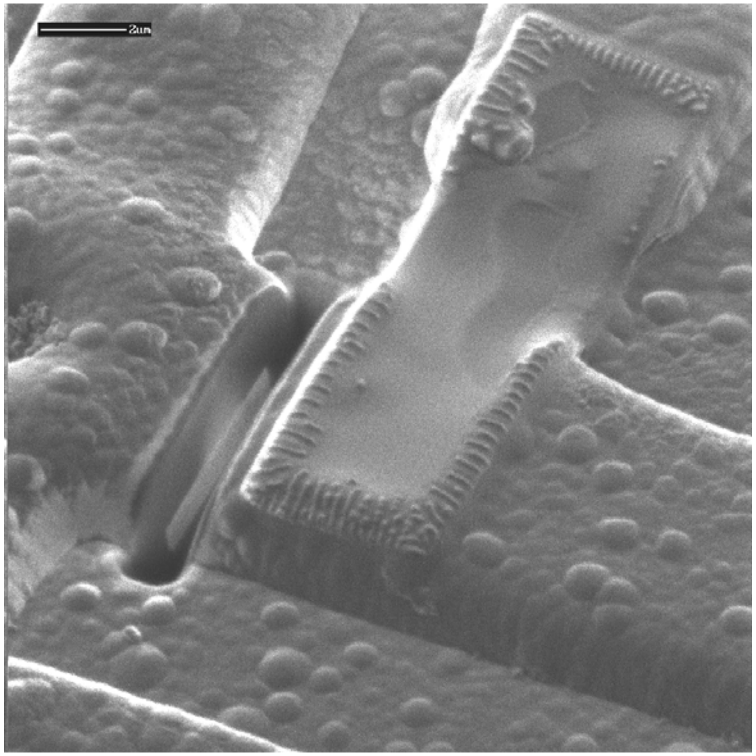
Ion Beam Chemistry



- Etch rates are greatly enhanced through introduction of a halogen
- Decomposition of a Pt-compound results in metal deposition

Rewiring





- FIB systems can cut and splice: they can “rewire” circuits
- Rewiring a circuit is often a very useful thing to do

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3-Dimensional Depth Profiling with Time of Flight Secondary Ion Mass Spectrometry (ToF SIMS)

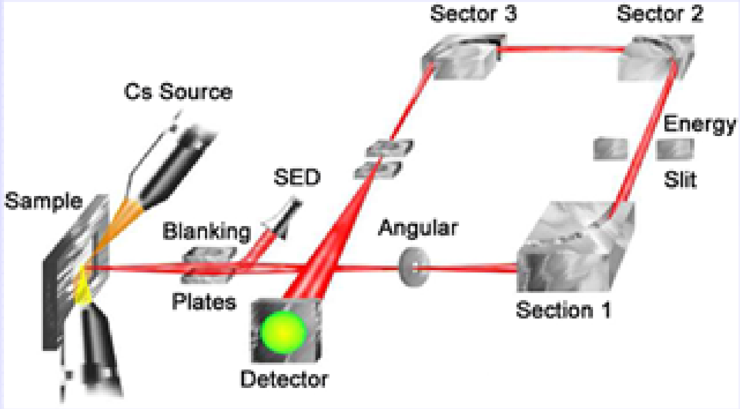
Rationale

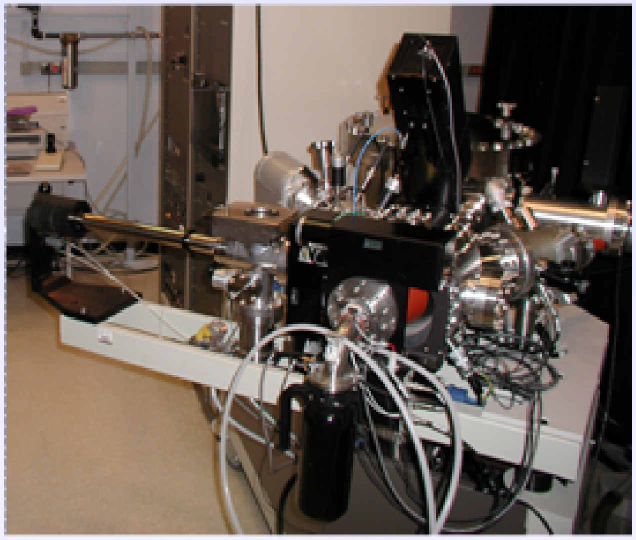
- Most modern analytical techniques provide information in two dimensions (2D)
  - Visual images
  - Spectroscopic analyses
  - Chemical maps
- 2D representation does not give sufficient information about entire object of interest
- 3-Dimensional representation of object desired

Method of Two Dimensional SIMS

Phi Trift II System

- Triple focusing ion detector either (+) or (-) ion extraction
  - 0.5 µm imaging resolution
  - 0.001 AMU resolution or better
- Pulsed primary liquid metal ion gun pure Isotopic ^{69}Ga+
  - 25 keV
  - 15 ns pulse
  - <600 pA sample current
- Cs+ source for dynamic SIMS
  - 1 – 2 keV
  - >20 µa sample current





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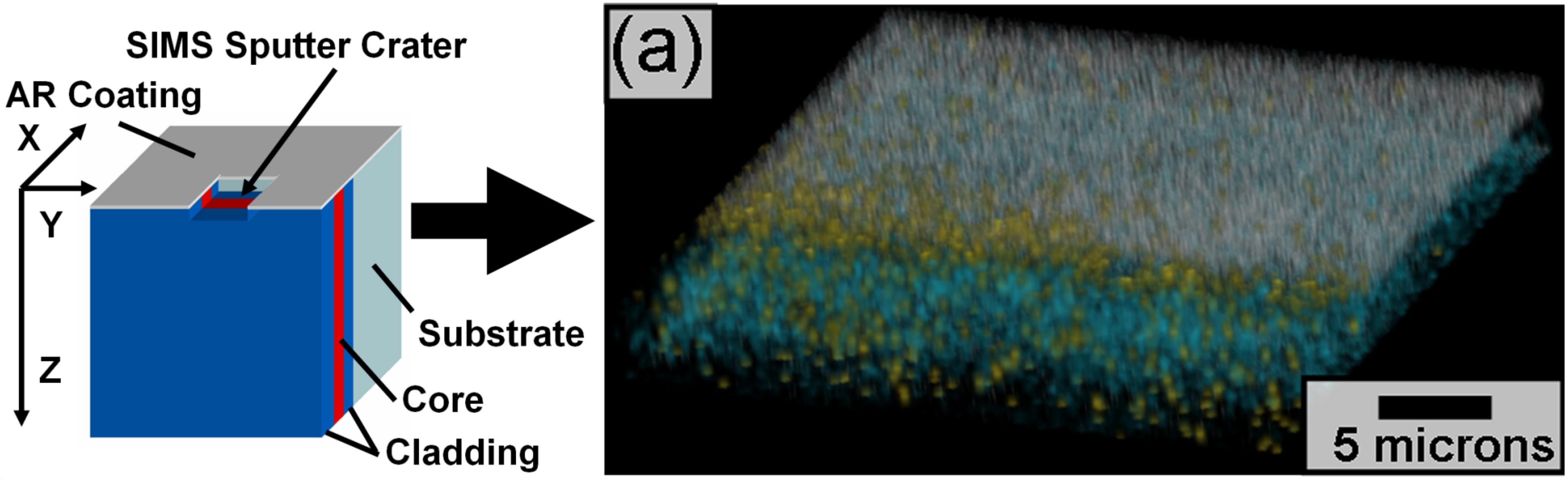
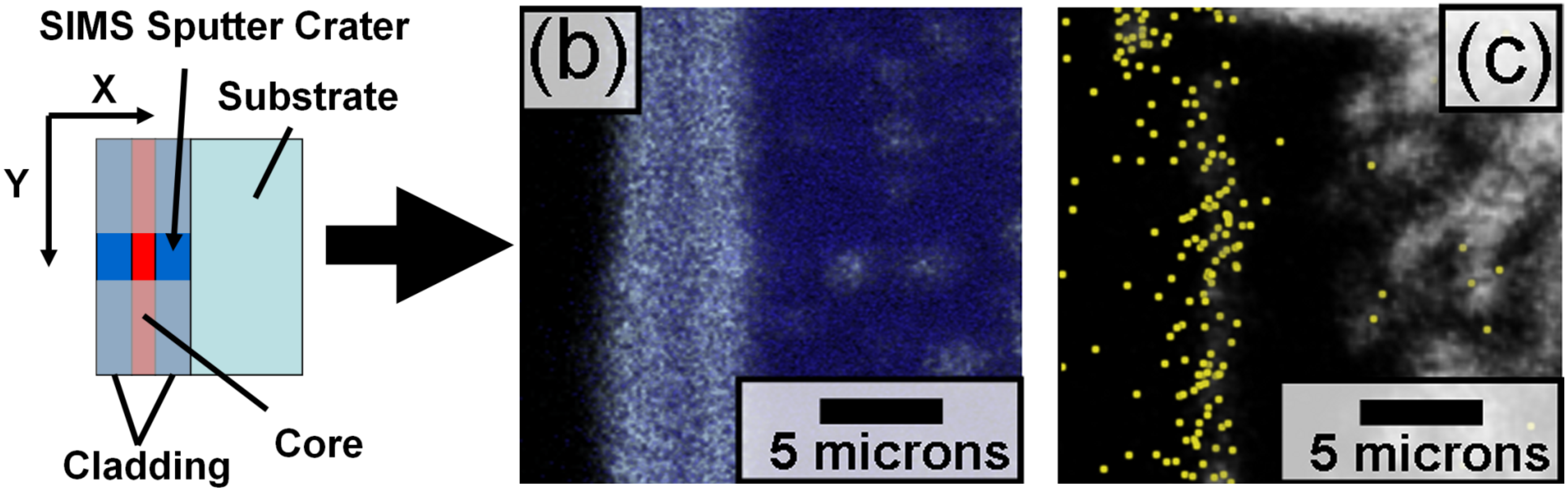
Three-Dimensional ToF SIMS





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3D ToF SIMS Depth Profile of HPLD Damage Region