Scanning He$^+$ Ion Beam Microscopy and Metrology

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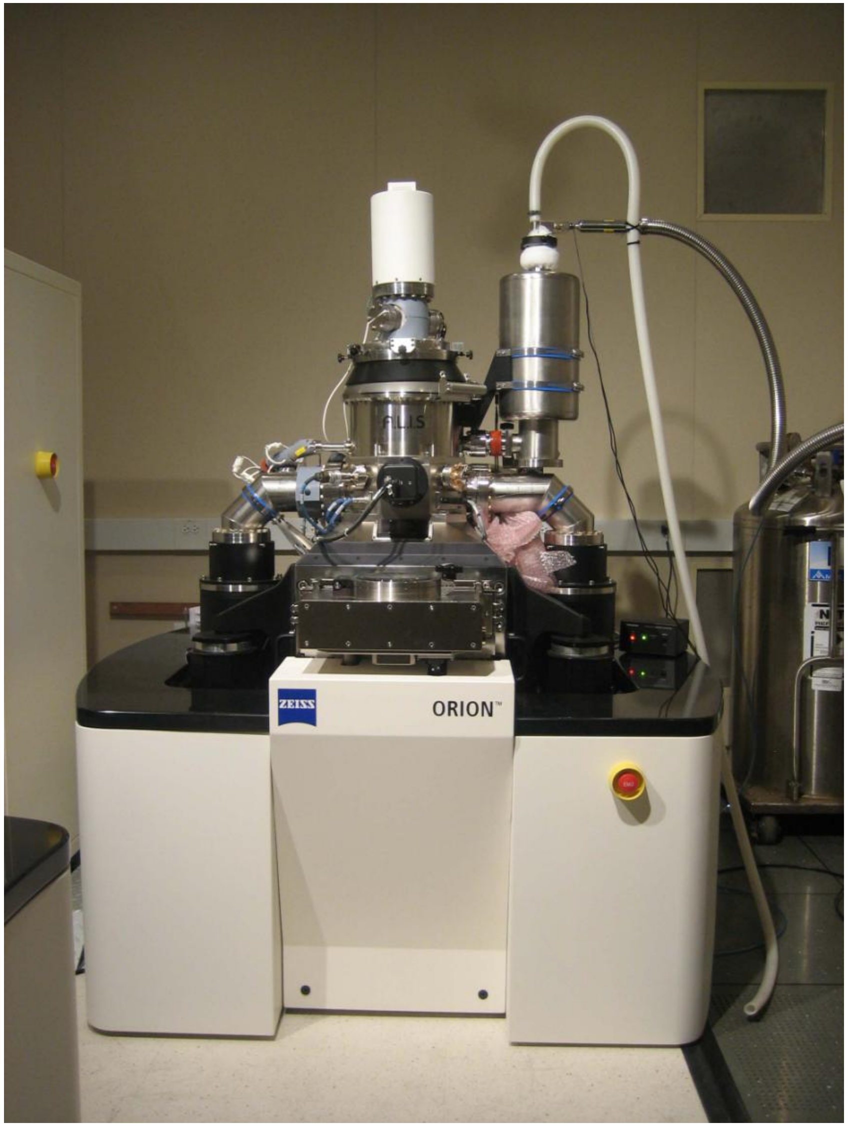
The CD-SEM

For thirty years the CD-SEM has been the tool for metrology

But now, as critical dimensions have shrunk to the low nanometer level, something better is needed..

The Helium Ion Microscope

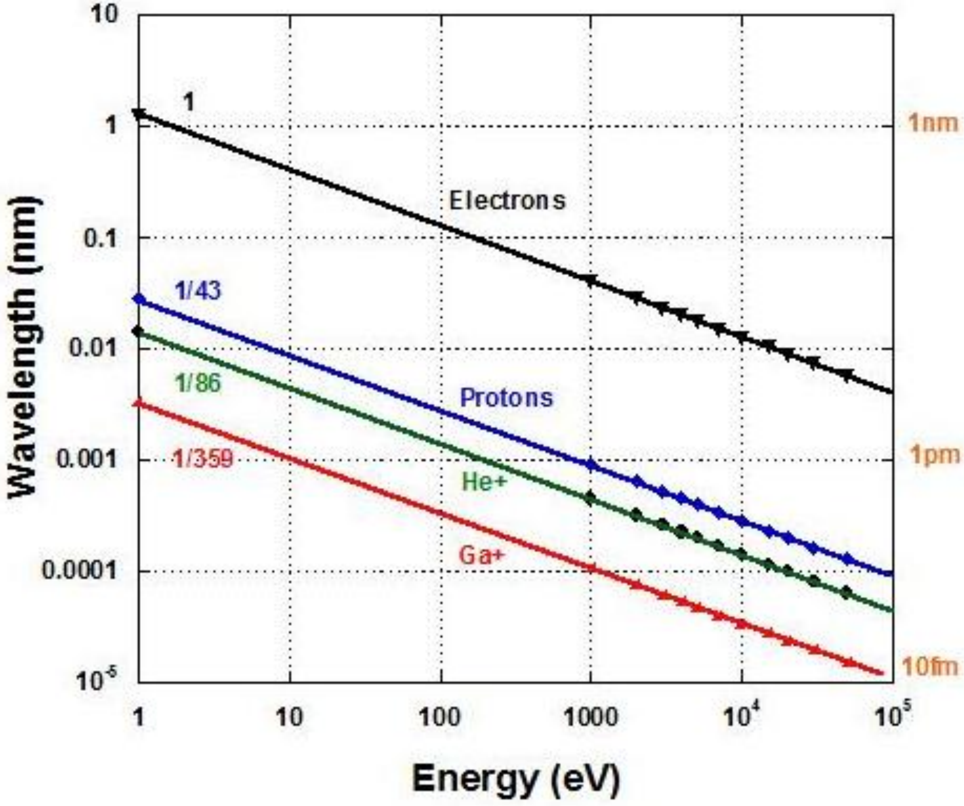
- Similar in concept to the SEM but different in crucial details..
- Uses a He+ (or other) ion instead of electrons



ZEISS ORION
installed at Harvard Courtesy
Dr. David Bell

Why use ions?

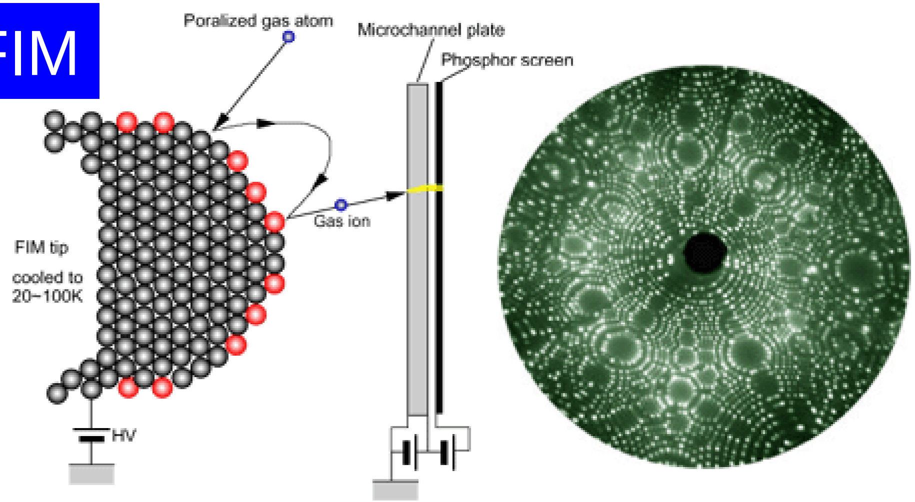
- Ions have wavelengths λ ~1% or less of that for electrons of same energy
- Diffraction limited spot size (=λ/α) is negligible
- Which ion to chose?
- H+ (proton) medium iSE yield, low sputter damage. Used by R.Levi-Setti with success (1970s)
- He+ - higher yields but more sputter. Good source available…



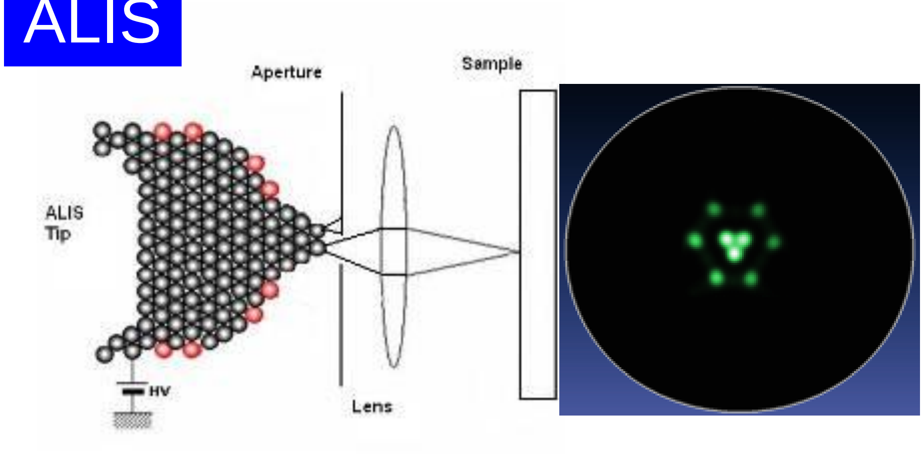
Wavelength (λ nm) of electrons, and protons, helium and gallium ions, as a function of energy

The He+ ion source

FIM

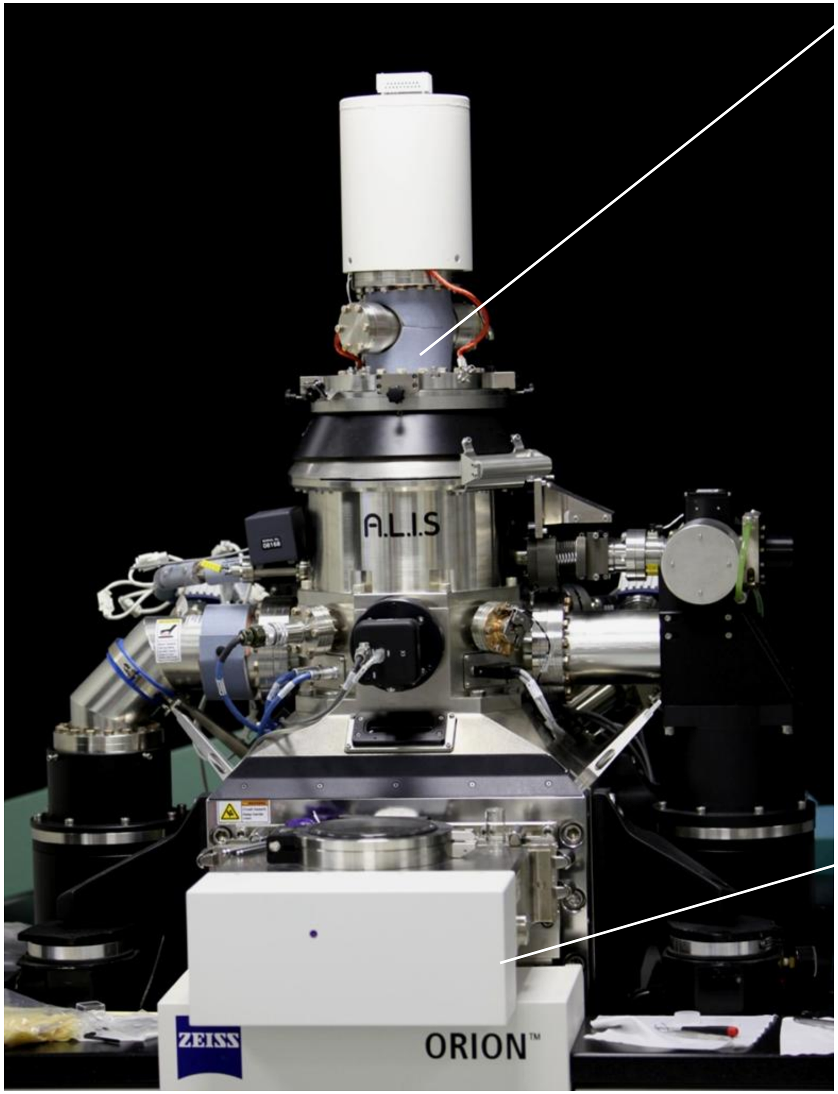


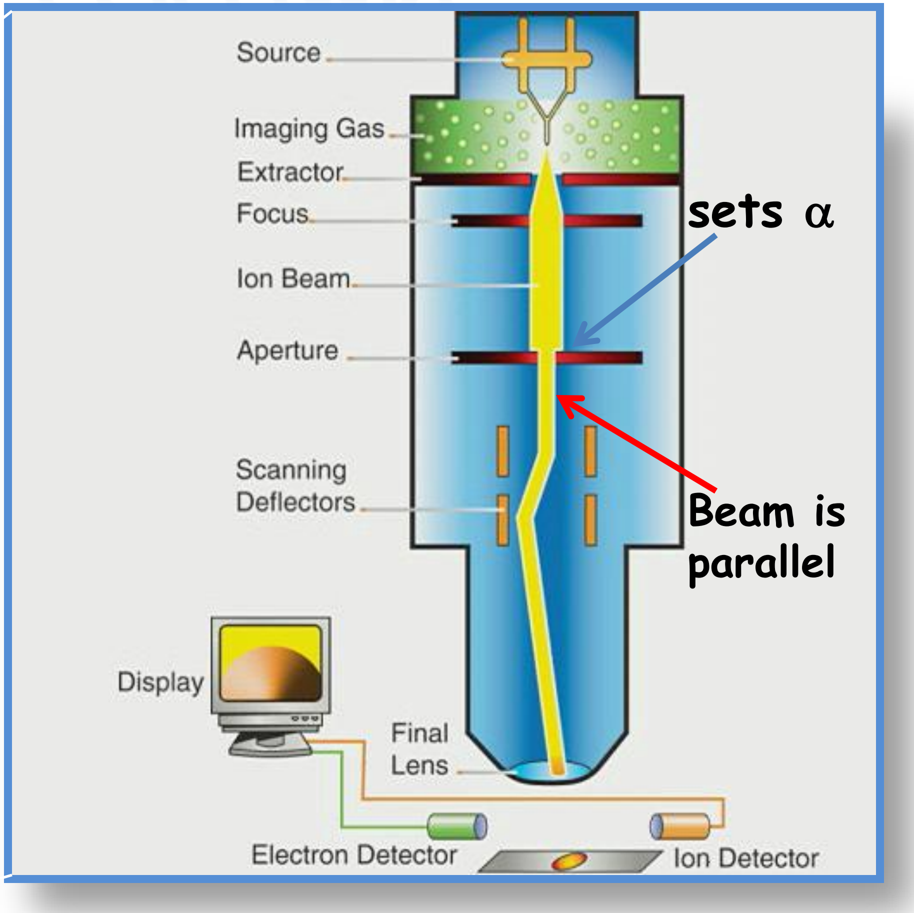
ALIS



- Field Ion microscope: Prof. Erwin Muller (1950)
- Beam current shared among hundreds or thousands of atoms
- ALIS: Atomic Level Ion Source
- 3 atom shelf - “trimer”
- Single atom selected as source for the final probe
- Source size~1 Atom diameter
- Brightness >$5X10^9 A/cm^2.sr$ at 40keV

THE ORION COLUMN





sets α

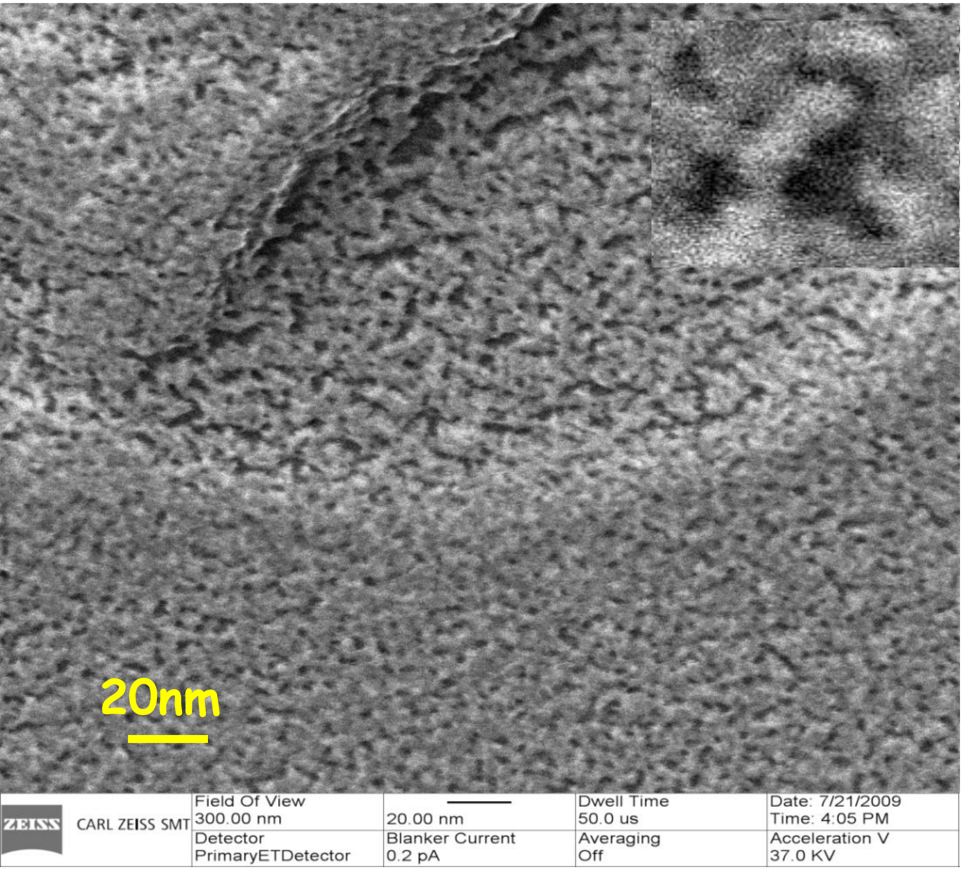
Beam is parallel

Lenses and scan are electrostatic – not affected by magnetic fields

What limits resolution now?

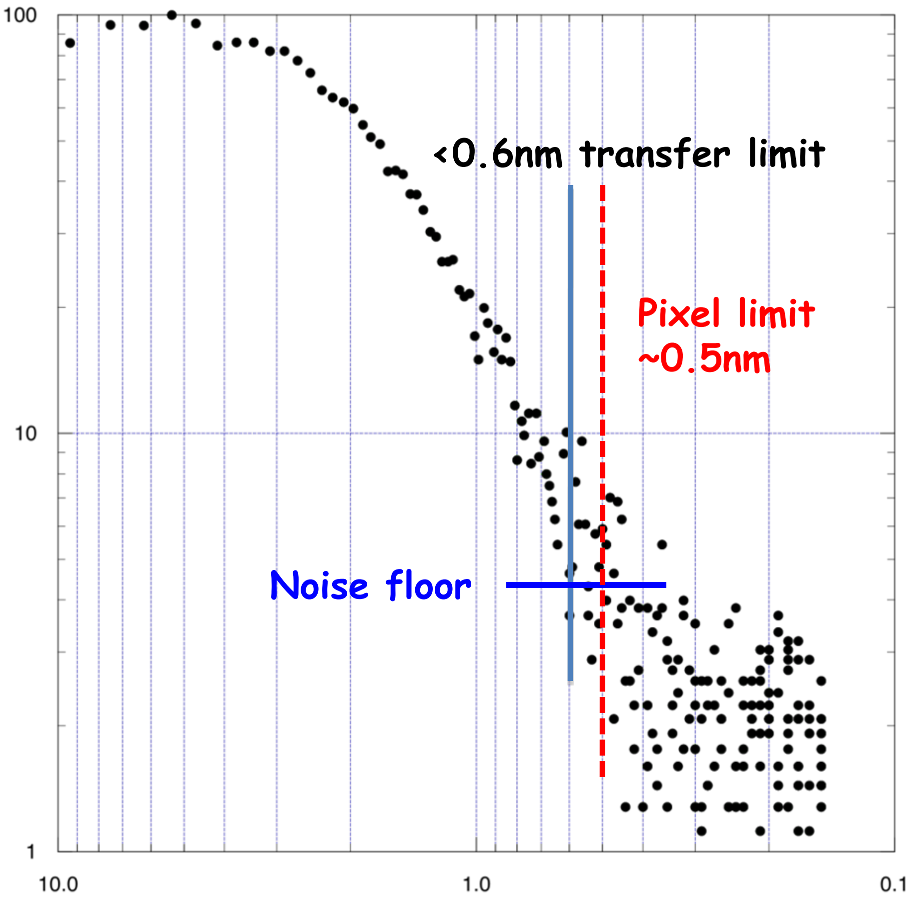
- ✓ Probe size? - NO (demagnified image of single atom)
- ✓ Lens aberrations? -NO (negligible with collimated beam)
- ✓ Depth of field? – NO (larger than field of view)
- ✓ Diffraction limiting? – NO (picometer wavelength)
- ✓ Boersch effect? – NO (at typical beam currents (~10pA) and energies emitted ions are separated by about 10cms and beam is divergent)
- ✓ Stray magnetic fields? - NO (no effect on beam)
- Stability of high voltage and lens power supplies? - YES
- Mechanical stability? - YES
- PREDICTION - sub-Angstrom imaging from bulk samples will ultimately be possible

State of the Art resolution



CARL ZEISS SMT
Field Of View 300.00 nm
Detector PrimaryETDetector
20.00 nm
Blanker Current 0.2 pA
Dwell Time 50.0 us
Averaging Off
Date: 7/21/2009 Time: 4:05 PM
Acceleration V 37.0 KV

iSE image Pt on Si
39keV single scan I_B=0.2pA
Zeiss ORION



Size (nm)
Contrast Transfer Function

+ Extreme Depth of Field

- He+ beam is collimated to <0.5mrad
- depth of field is then more than 1.5 μm for a horizontal field of view of 1μm
- Extended DoF essential for 3-D metrology e.g. nano-structures and particles

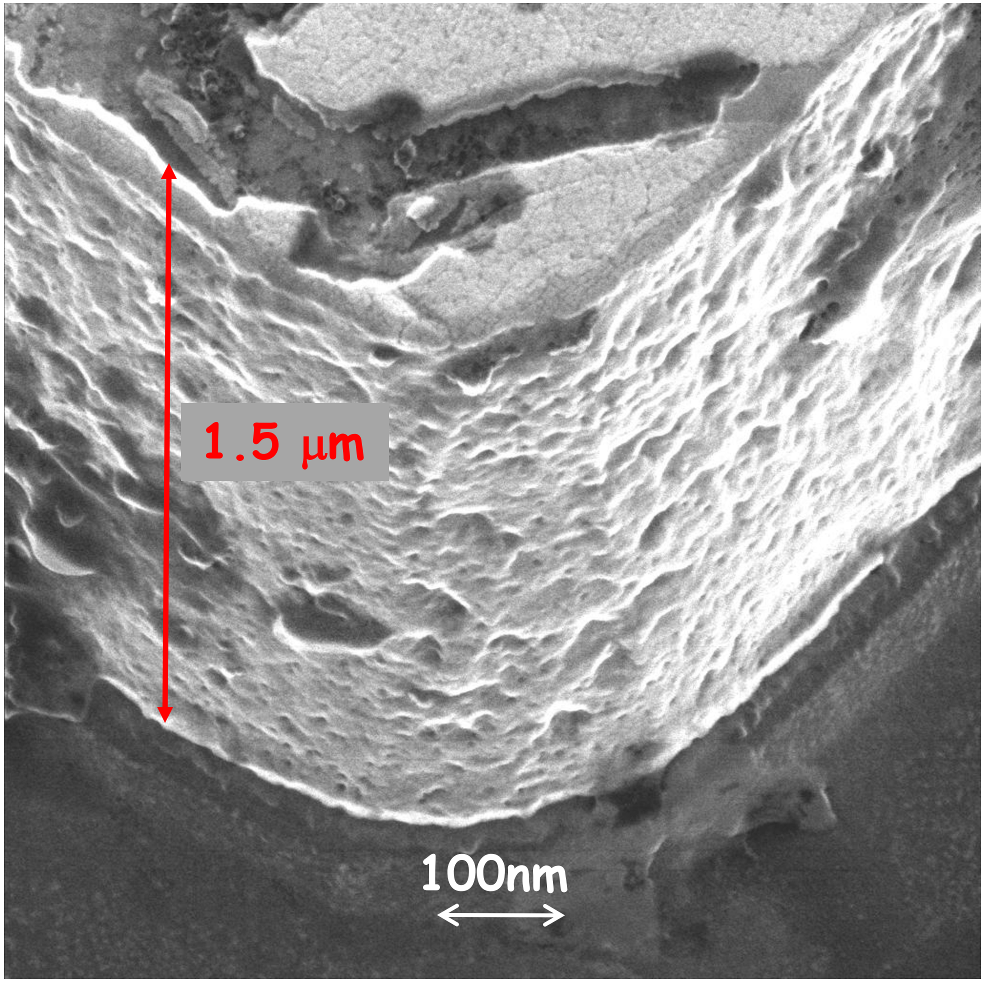
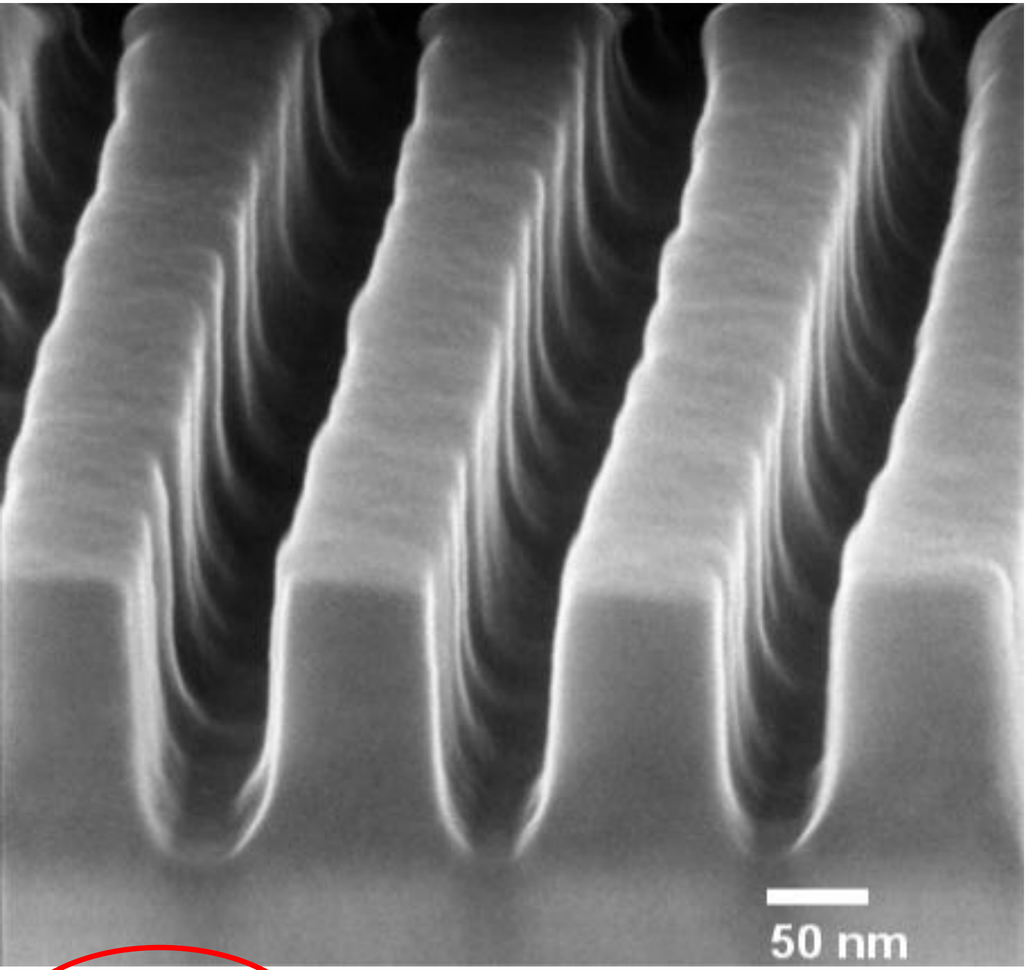


Image courtesy Zeiss SMT

“iBeam” and “eBeam” metrology



39keV He+ iSE image of photo-resist

- He+ ions generate secondary electrons (iSE) an imaging mode familiar and well understood
- Images look similar to e-beam mode although experimental conditions and details may be quite different
- For example…

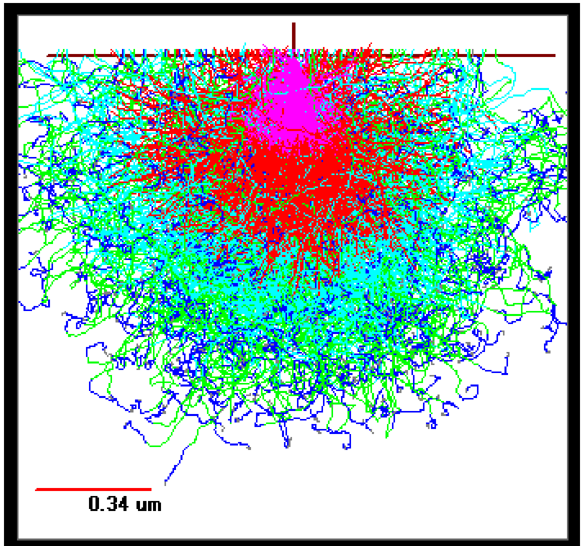
Sample courtesy of SELETE

Why is the beam energy so high?

- He+ beam energy is typically 40keV not <1keV as for an electron beam
- The interactions of electrons and ions are a function of their velocity not their energy
- He+ ion are 7800x heavier than an electron so a 40keV He+ ion has the same velocity as a 5eV electron
- As a result…the new standard of low voltage is now 20-30keV!

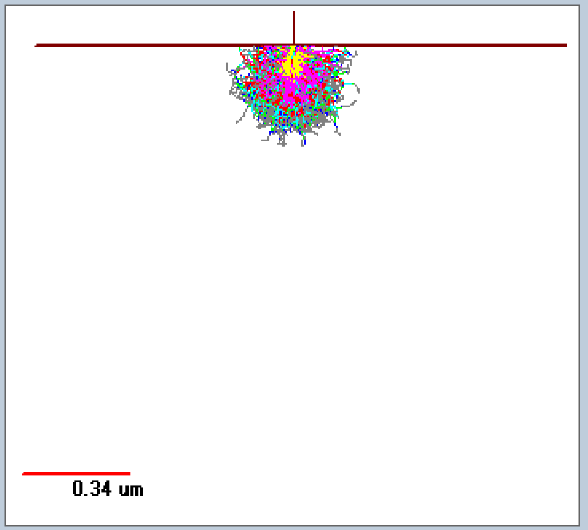
This affects interaction volumes..

IONiSE simulations



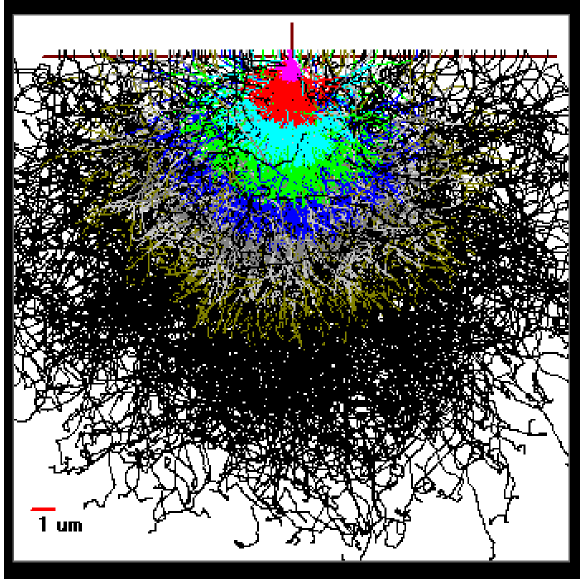
← e^- He^+ →

10keV Si



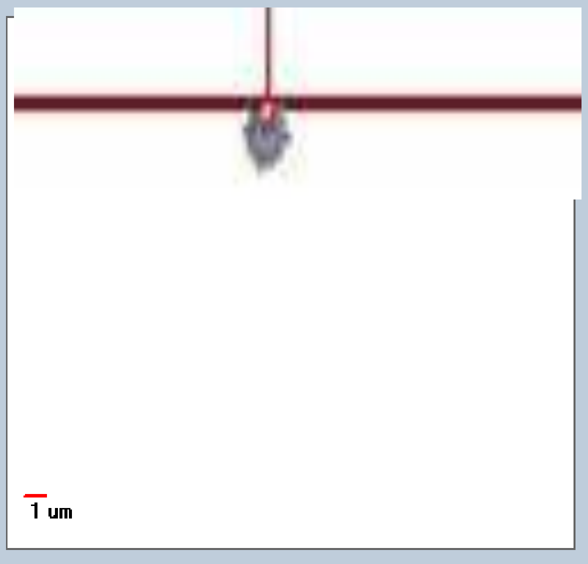
Electron and ion trajectories plotted on the same size scale

Range Ratio @E (Electron/Ion) ~ E



← e^- He^+ →

30keV Si



..Enhancing Soft Materials Imaging

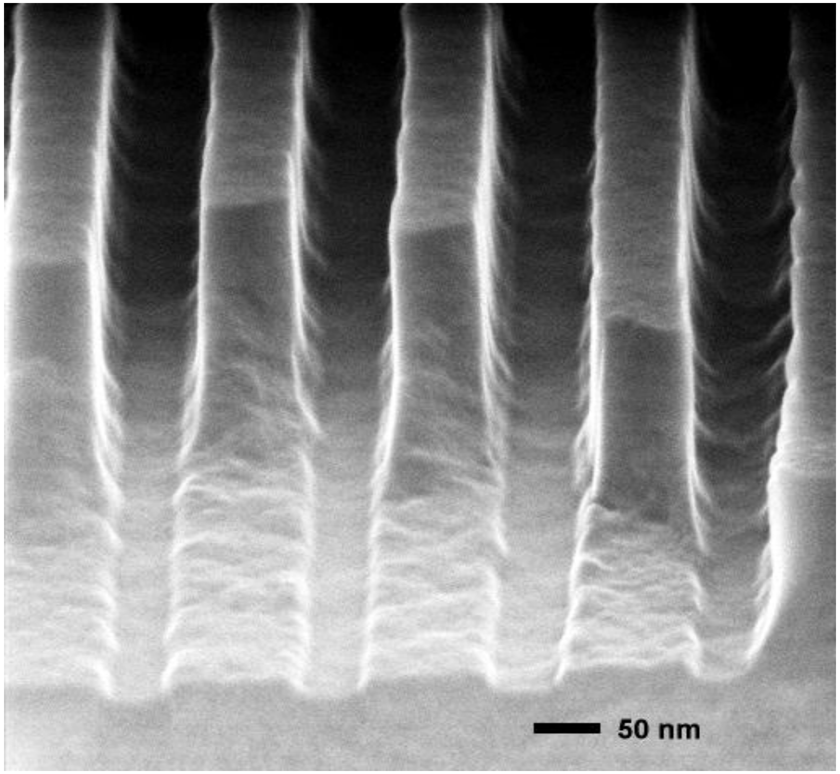
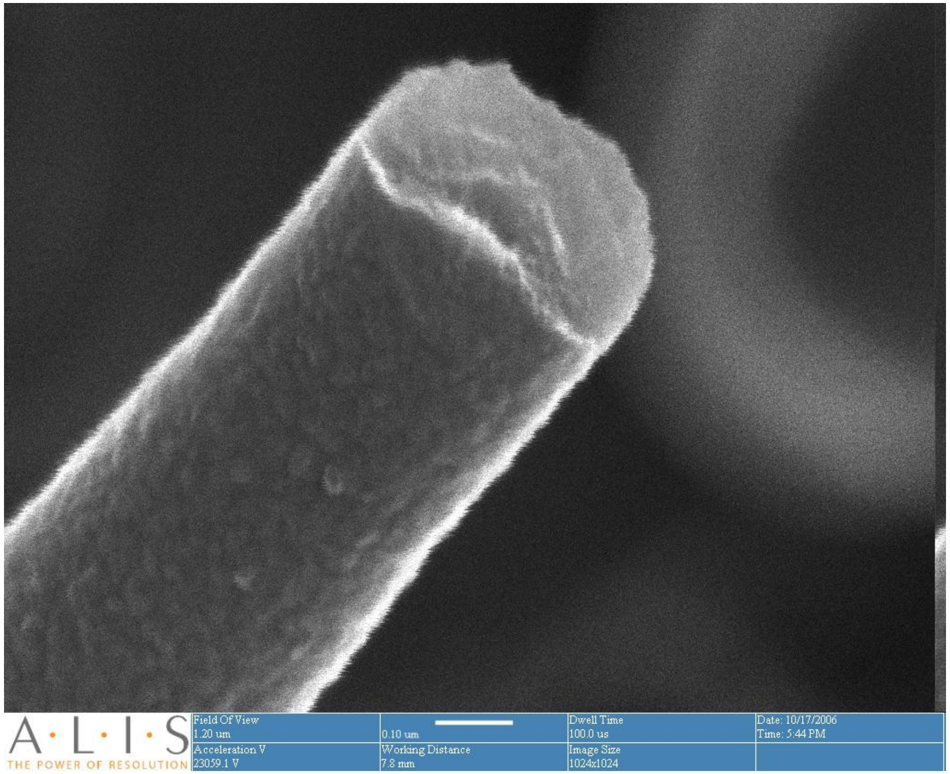


Photo Resist



Field Of View 1.20 um	0.10 um	Dwell Time 100.0 us	Date: 10/17/2006 Time: 5:44 PM
Acceleration V 23059.1 V	Working Distance 7.8 mm	Image Size 1024x1024	

Carbon NanoTube

- Damage to polymers is less severe than for electrons and images are much superior in detail

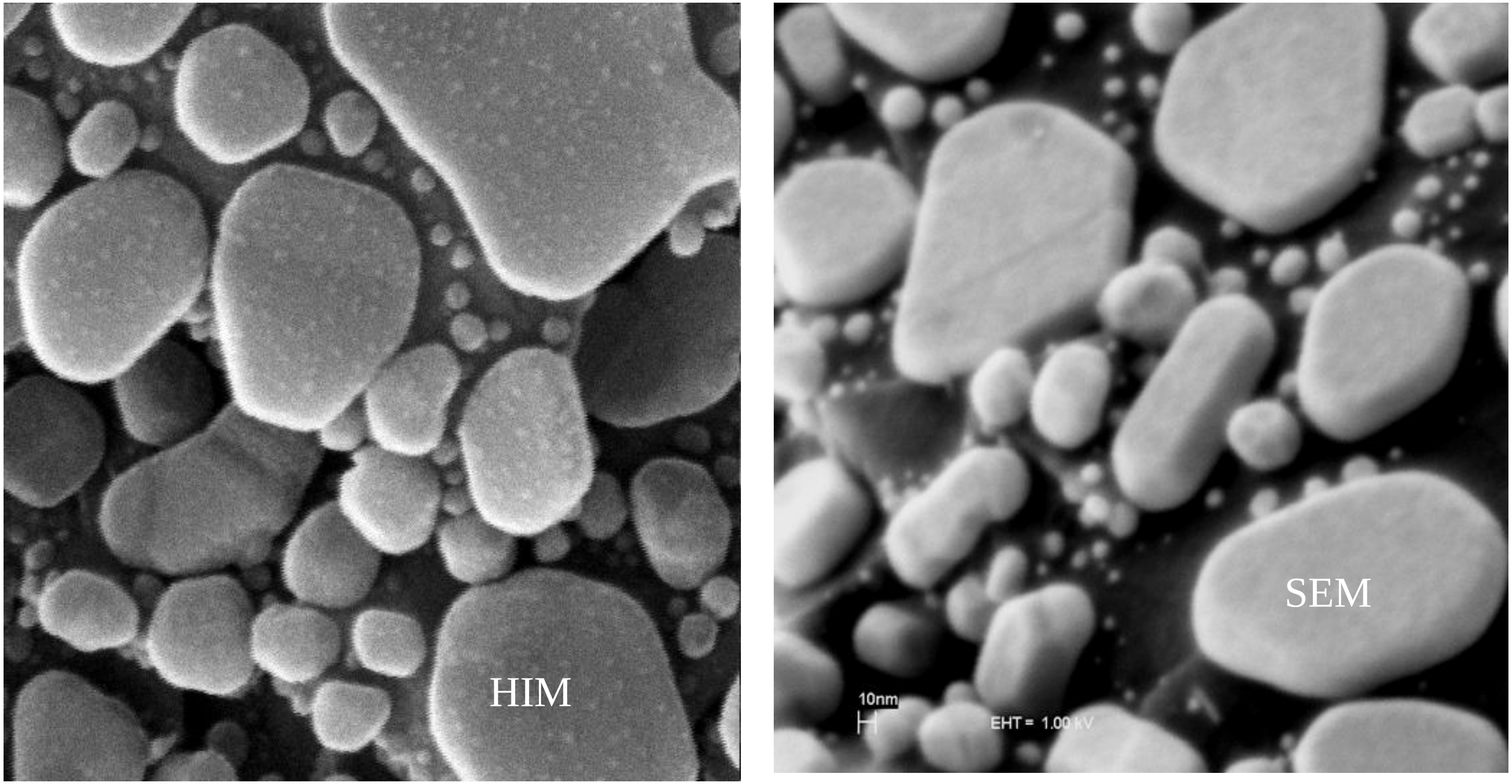
Backscattering is Weak

- In the SEM typically 50% of the SE signal is "SE_2" generated by BSE from deep inside the sample, reducing surface contrast, degrading resolution
- In the HIM image backscatter is weak so...

ELEMENT	iSE_2/iSE_1	eSE_2/eSE_1
Al	0.06	1.0
Ag	0.73	1.2
Au	1.22	1.2

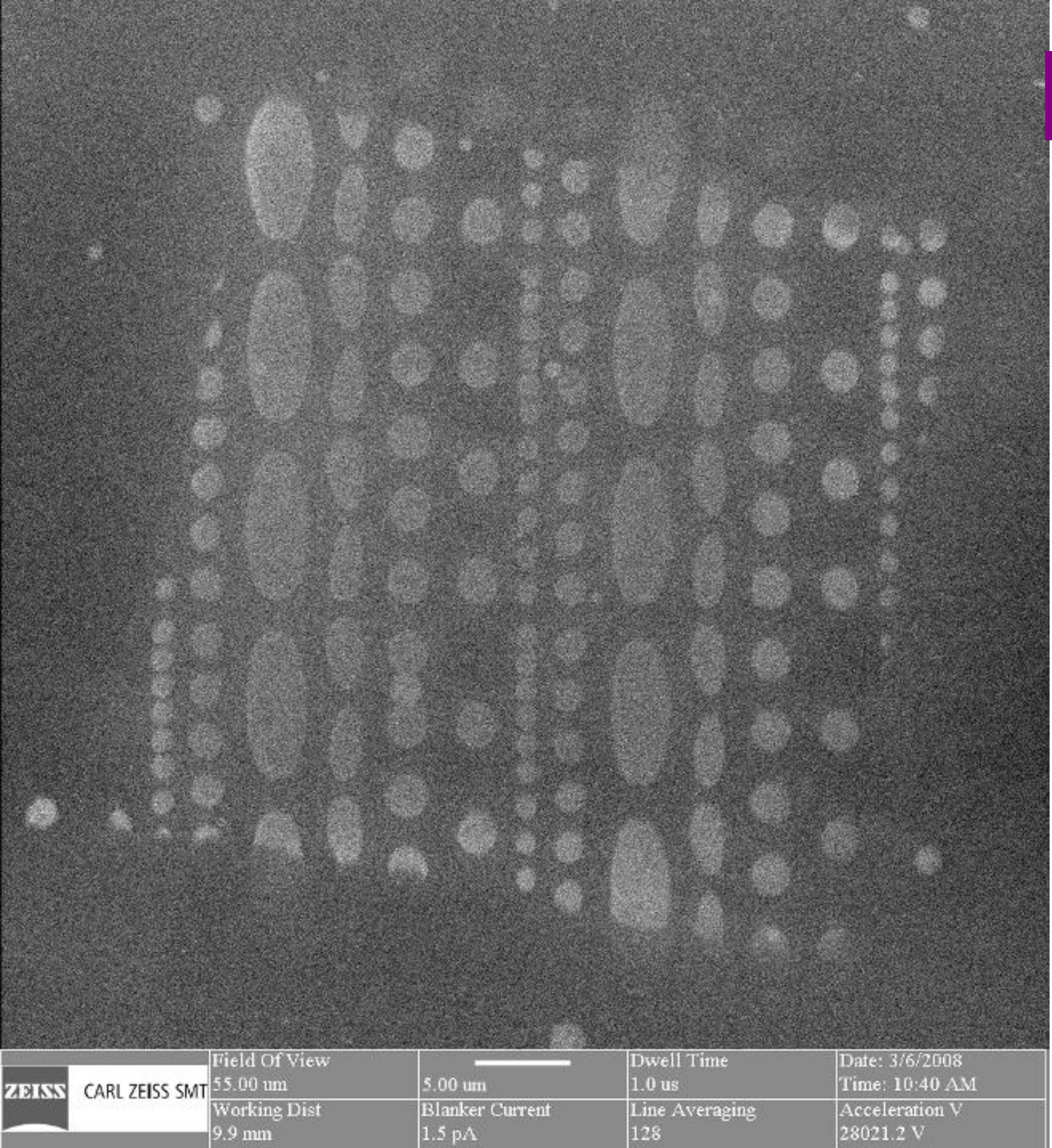
- ..iSE_2/iSE_1 ratio is lower and sensitivity to surface detail and image resolution are enhanced

Enhancing surface detail..



Gold-on-carbon sample. 1 μm field-of-view images, 1 pA beam current,30 keV (HIM) and 20 pA beam current at 1 keV (SEM)

Monolayer Sensitivity !



Field Of View 55.00 um

5.00 um

Dwell Time 1.0 us

Date: 3/6/2008

Time: 10:40 AM

Working Dist 9.9 mm

Blanker Current 1.5 pA

Line Averaging 128

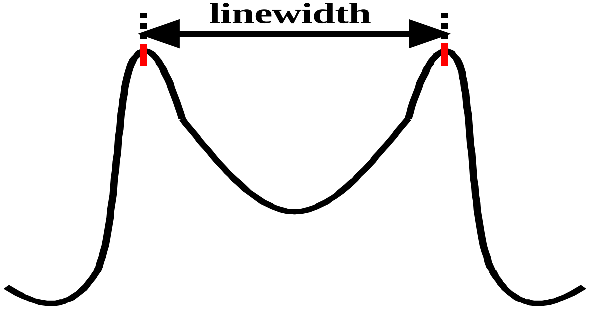
Acceleration V 28021.2 V

28keV Beam
Image of Self
Assembled Monolayer of
4 -nitro-1,1 -biphenyl-4-thiol (NBPT) exposed
with E-beam
Lithography which
modifies the terminal
group from NO_2 to NH_2

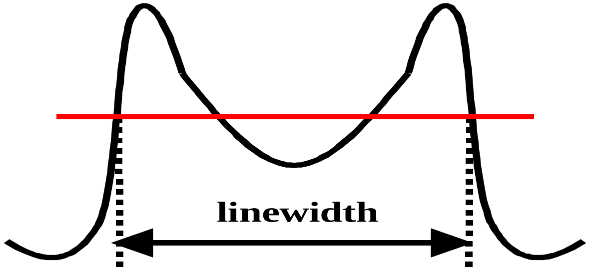
Sample courtesy of University of Bielefeld

CD Measurements

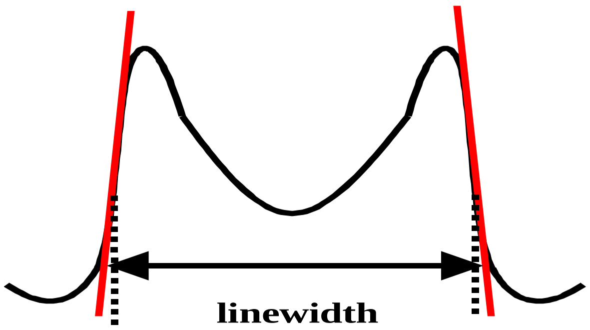
In image-based metrology the three dimensional shape and size of an object is deduced from line traces across the object of interest



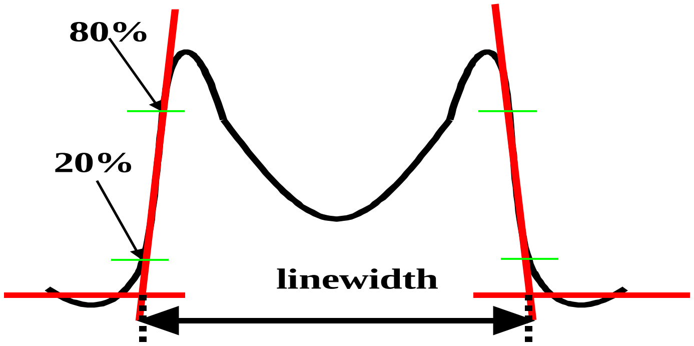
(a) peak to peak method



(b) threshold method



(c) maximum slope method



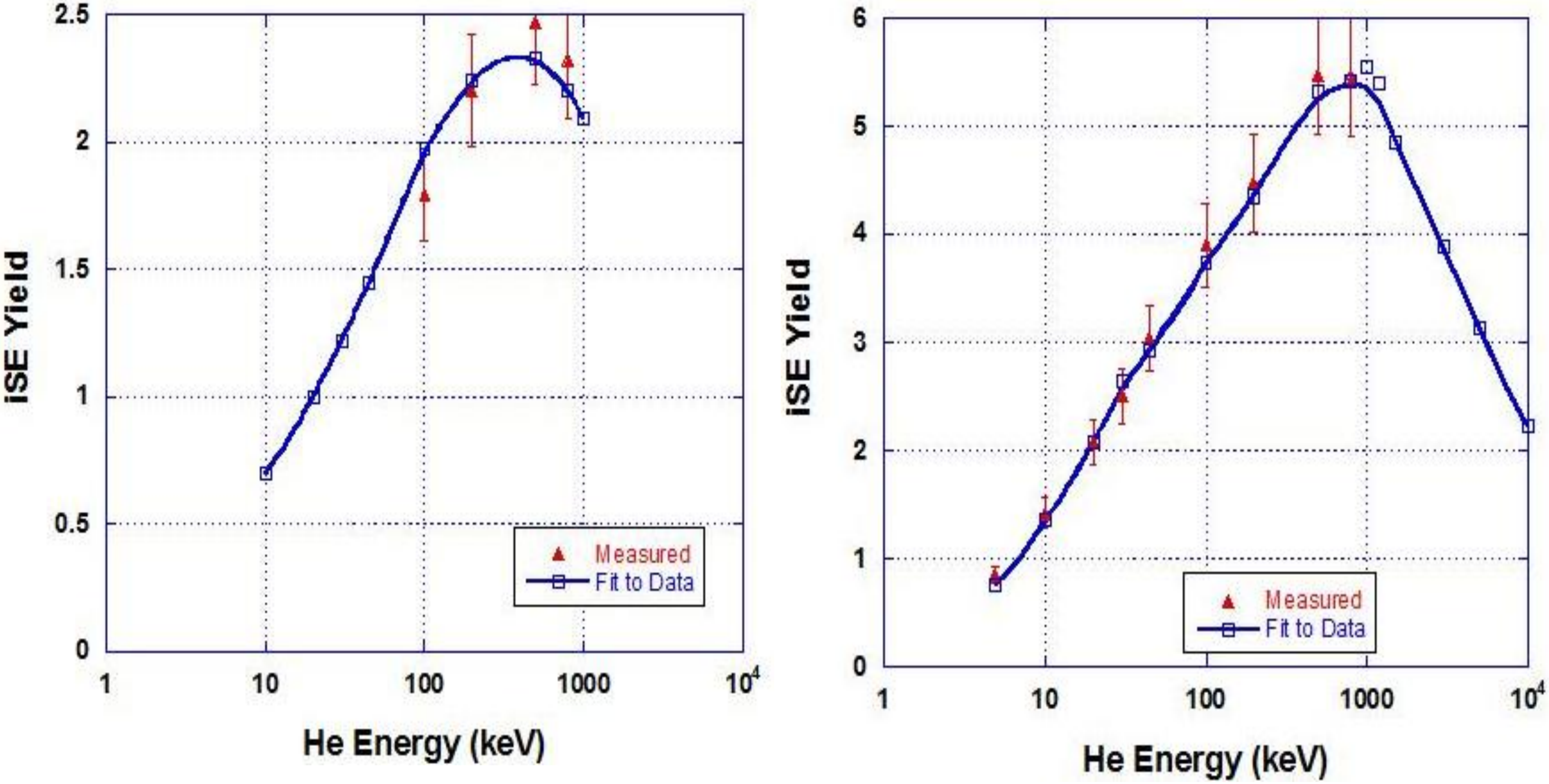
(d) linear regression method

So knowing how signals vary with angle, energy, material is crucial

That requires..

- ..a detailed quantitative model of the ion interactions that occur..and a data base
- IONiSE is a Monte Carlo simulation for iSE production which uses
- ..cross-section and stopping power data from Zeigler et al., ‘*Stopping and Range of Ions in Solids*’, Vol.1,Pergamon Press:1985
- IONiSE calculates iSE yields using the Bethe-Salow model

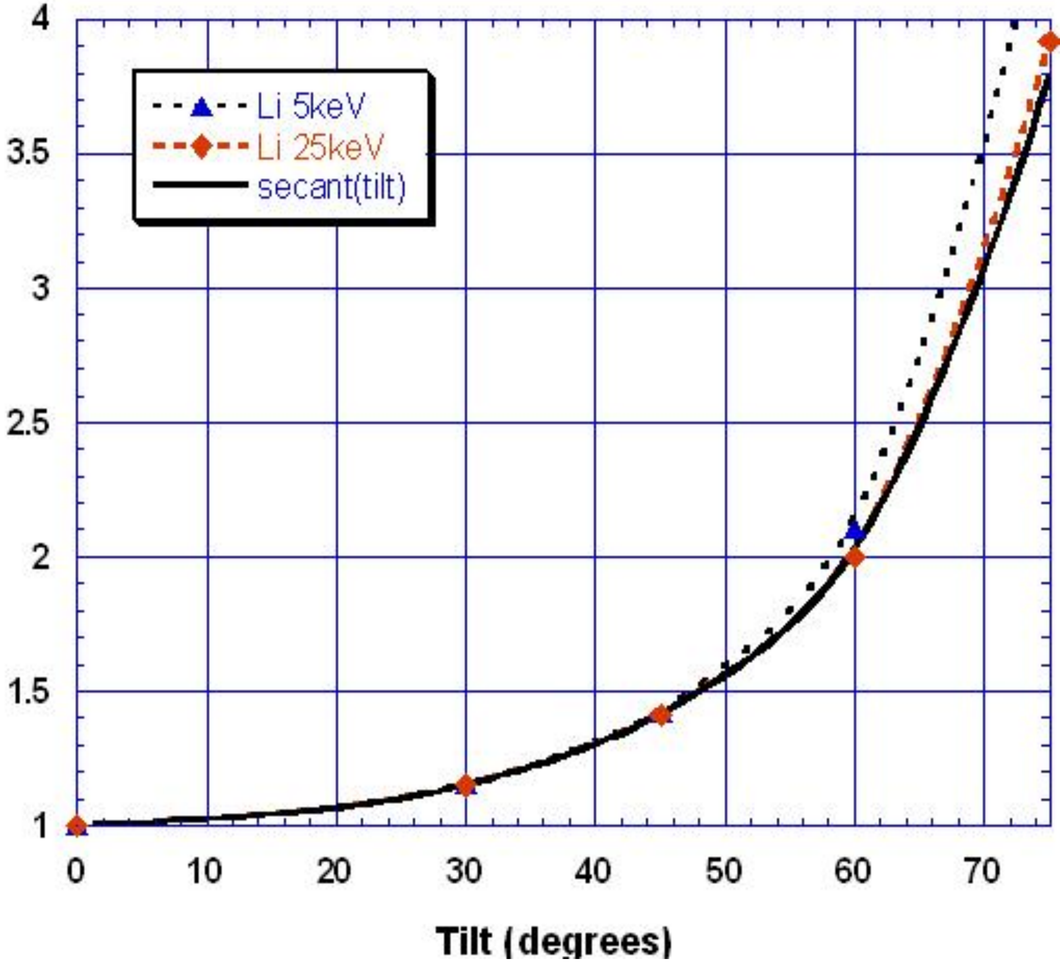
IONiSE models of iSE yield data



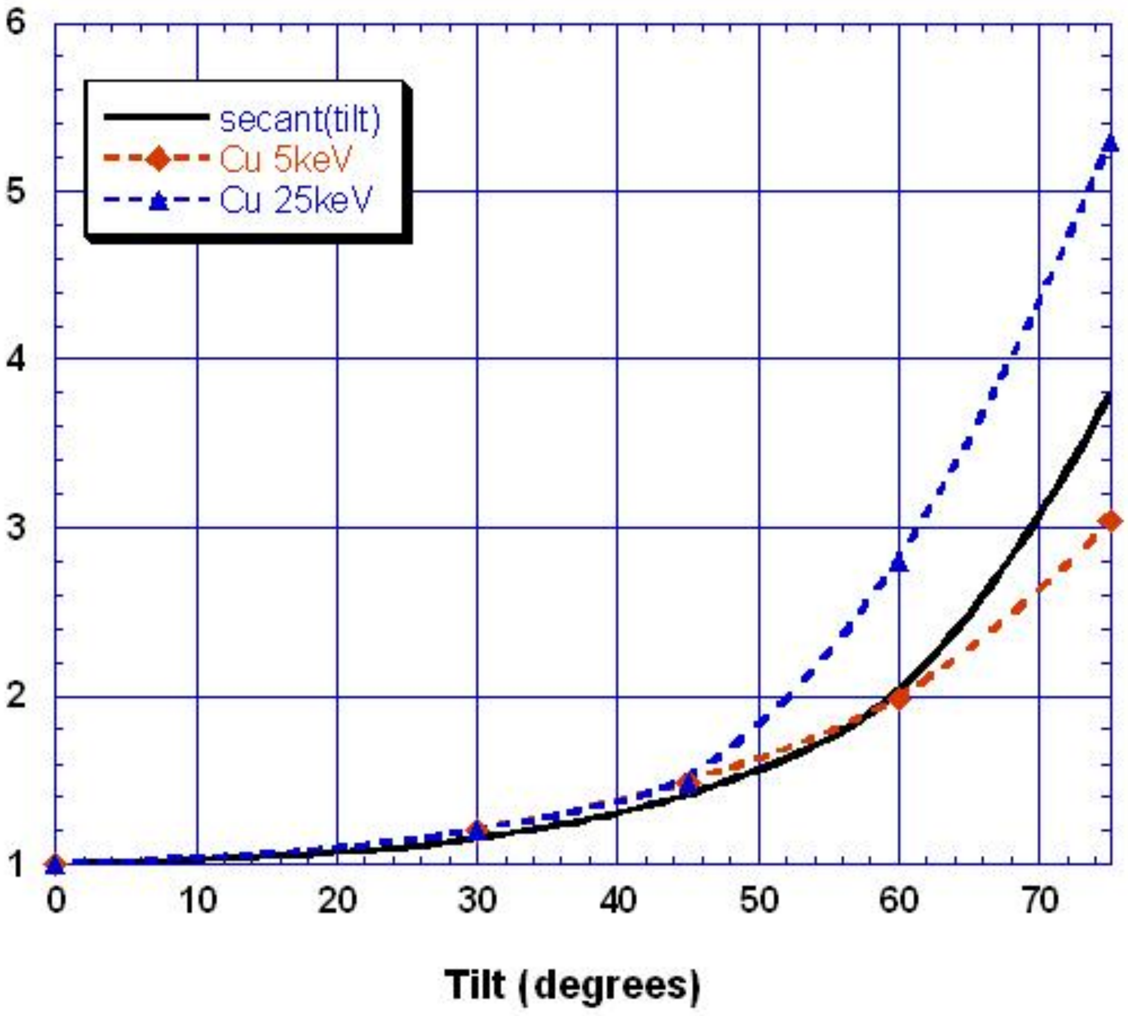
Fits He+ iSE elemental yield data with high accuracy across an energy range of more than 100:1

iSE topo yield for Li /He+

- Topo yield variation is higher at low energy (5keV) than at high energy (25keV) for Li
- But the difference is small and in either case the yield curve is close to the classic "secant θ" curve for electron beams



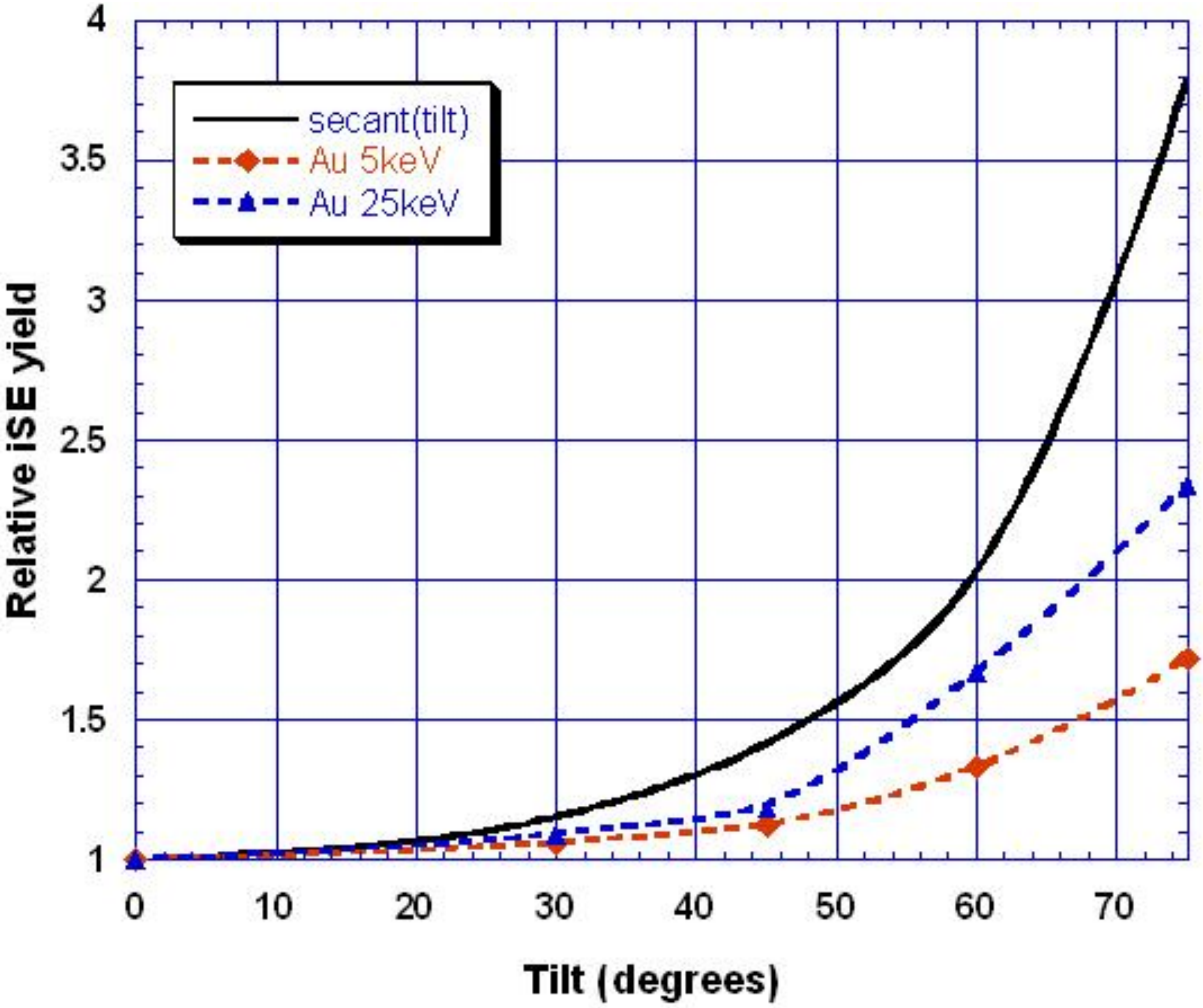
iSE topo-yield for Cu/He+



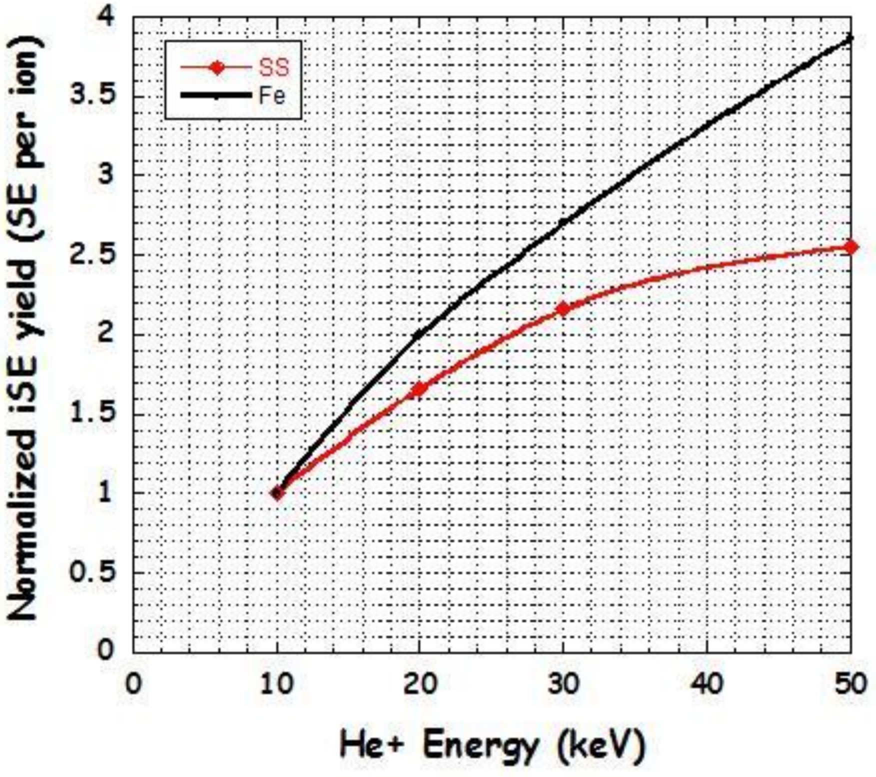
- For a heavier material such as Cu things are more complex
- The iSE topo-yield curve is above the eSE curve at 25keV but below at 5keV

iSE topo-yield for Au/He+

- For Au the iSE topo-yield is below the eSE topo yield curve for 5 and 25keV He+ beams
- *So line profiles will vary with both the atomic number Z of the target material and ion beam energy*



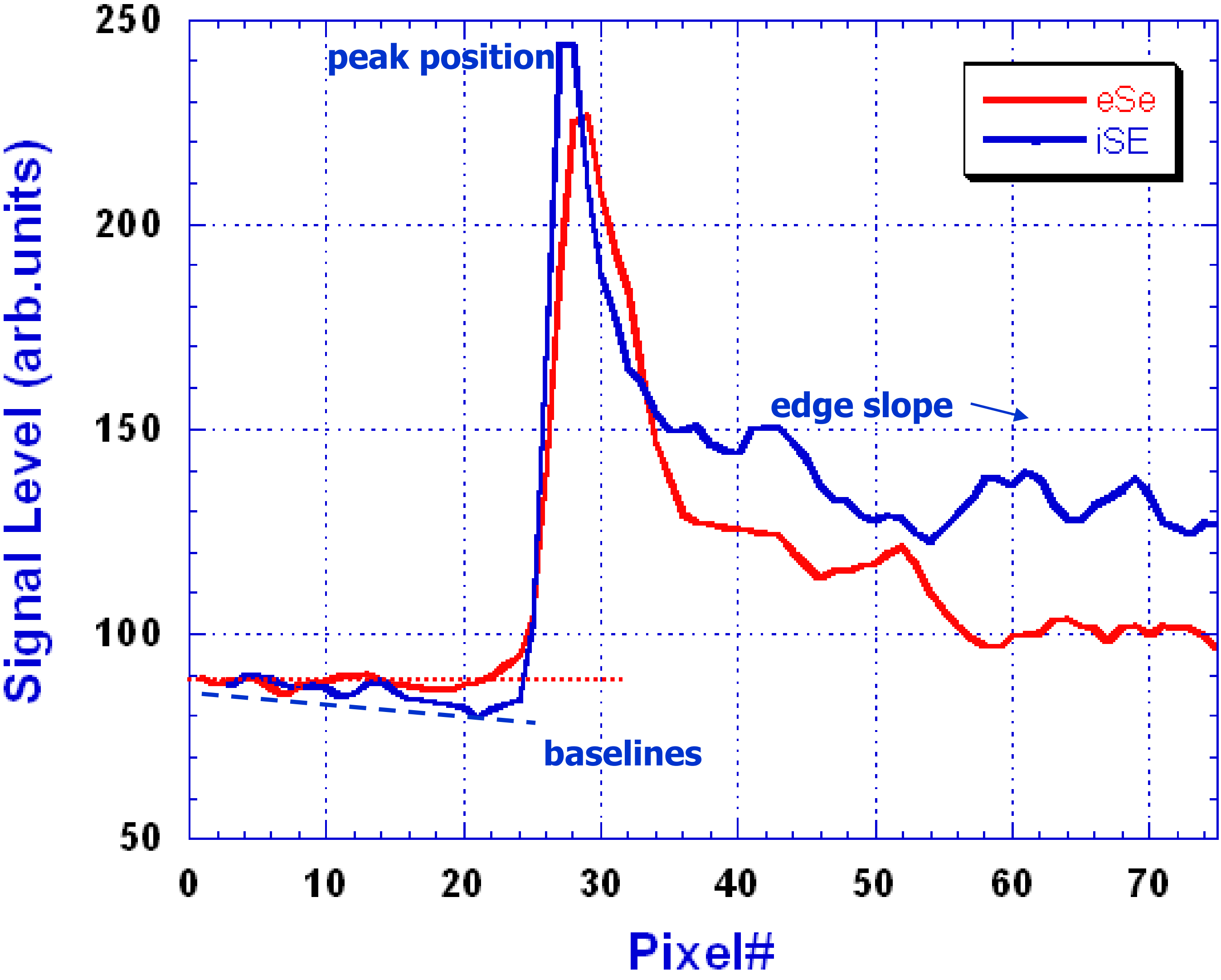
For compounds and alloys..



iSE yields of Fe, Steel normalized at 10keV

- Data is incomplete and not well understood
- It is found for compounds that absolute iSE yields, and yield variations with tilt, may differ significantly from those of a pure element, varying rapidly with composition and beam energy
- Needs more experimental data and lots of work!

Line Edge Profiles iSE vs eSE



✓iSE edge is always sharper (good)

✓iSE and eSE peaks are shifted wrt to each other

✓eSE baseline is flat (good) but iSE baseline is falling near edge (charging)

Comparison of eSE and iSE data

Method	iSE (nm)	SD (nm)	eSE (nm)	SD (nm)
Peak – Peak	145.7	1.50	141.3	1.45
Threshold	151.8	1.5	149.6	1.5
Max. Slope	150.9	1.7	147.9	1.6
Lin.Regress.	155.7	1.6	154.9	1.6

Absolute differences between eSE and iSE measurements are small but they are consistent and larger than the SD

Data analysis using Spectel Research 'Measure' program – courtesy Dr. Mark Davidson

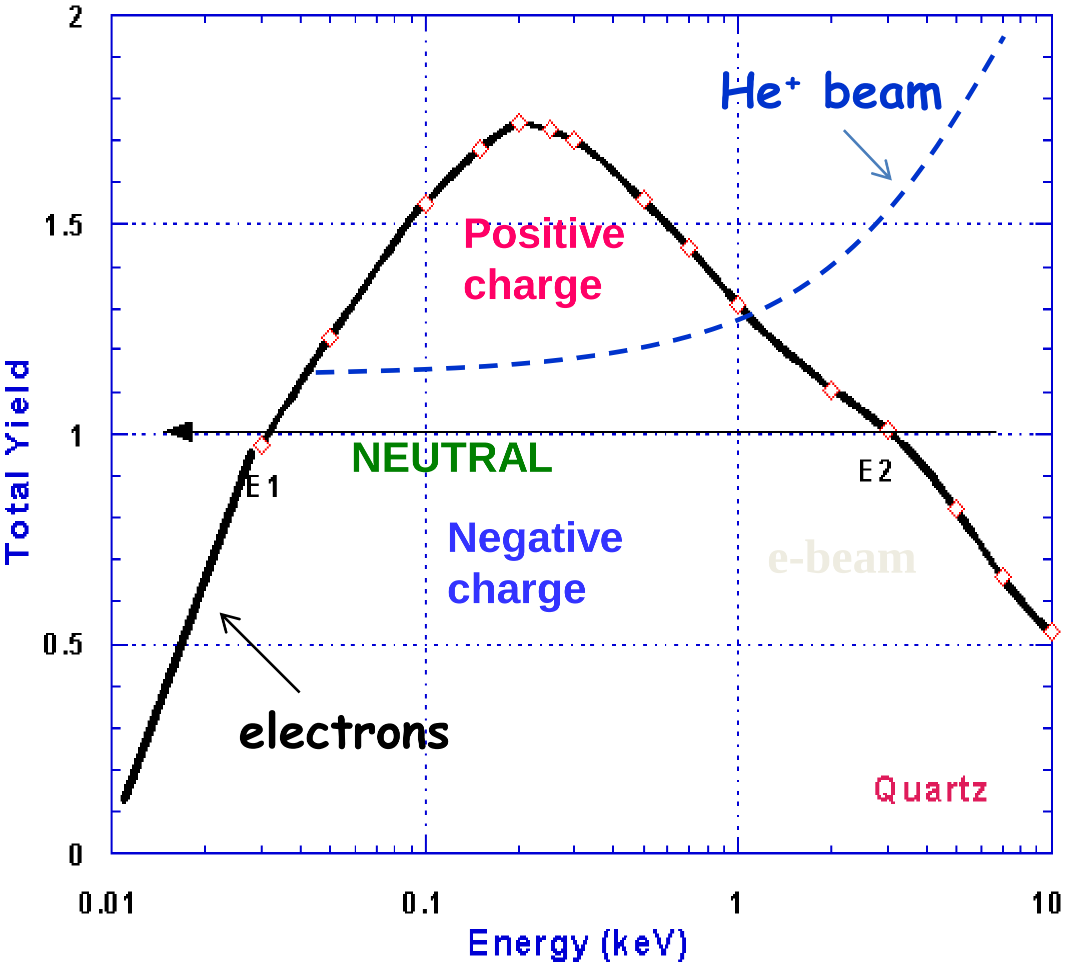
Other Issues

Two other significant issues in HIM-beam metrology will likely be

(1)The effect of Charging, and
(2) Beam Induced Damage

Neither of these is unique to ion beams but both are inevitable

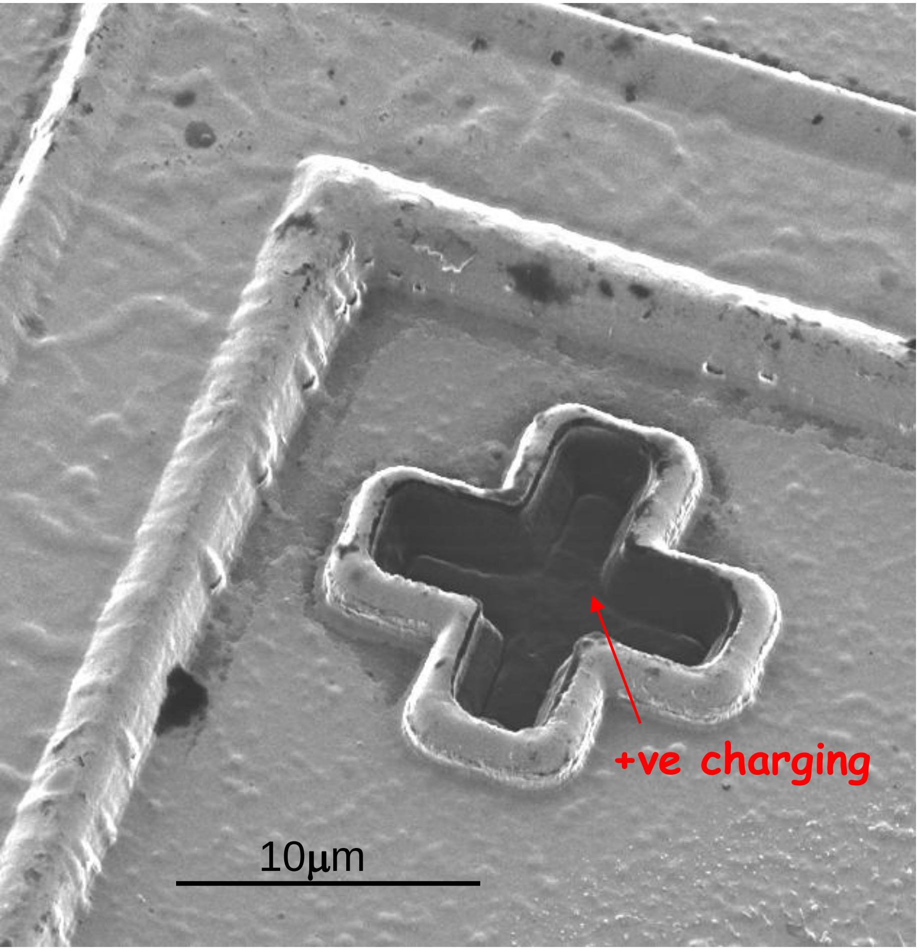
Charging with e$^-$ and i$^+$ beams



Total yield data for quartz (SiO_2) for eSE and He$^+$ induced iSE

- Electron beams have E1,E2 crossovers – regions of both +ve and -ve charging
- Ion beams charge positive at all energies because of the high iSE yield and the injection of +ve ions
- Charge control is therefore essential for HIM metrology

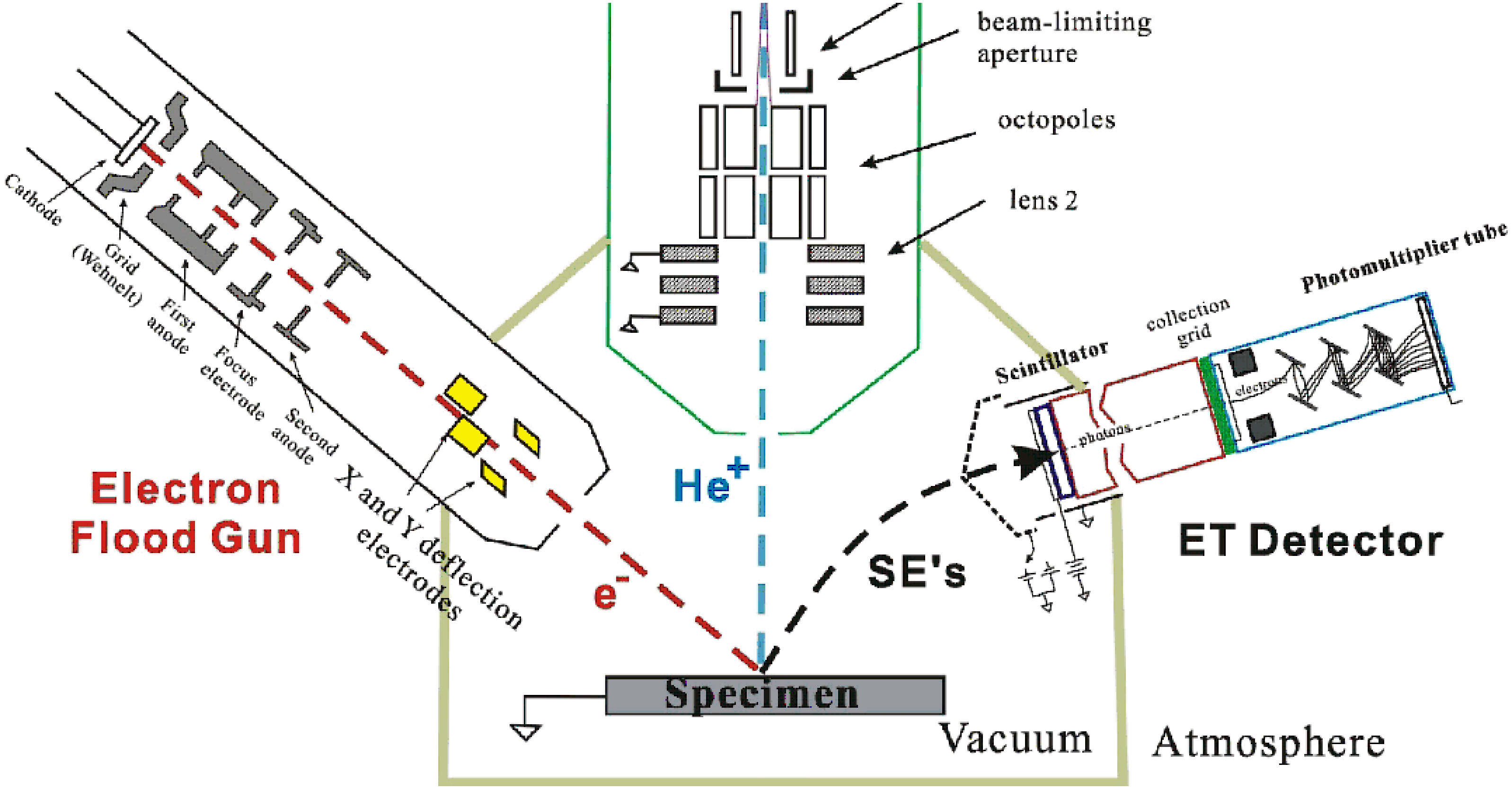
Charging is significant in iSE images



HIM Image @ 35keV Si device

- Ion beam currents are low (few pA) but charging is always significant
- Positive charging locally reduces the iSE yield, distorts line profiles and
- ..decelerates the incoming ion beam - changing the size of each scan raster step so randomly varying image magnification point to point

Eliminating Charging



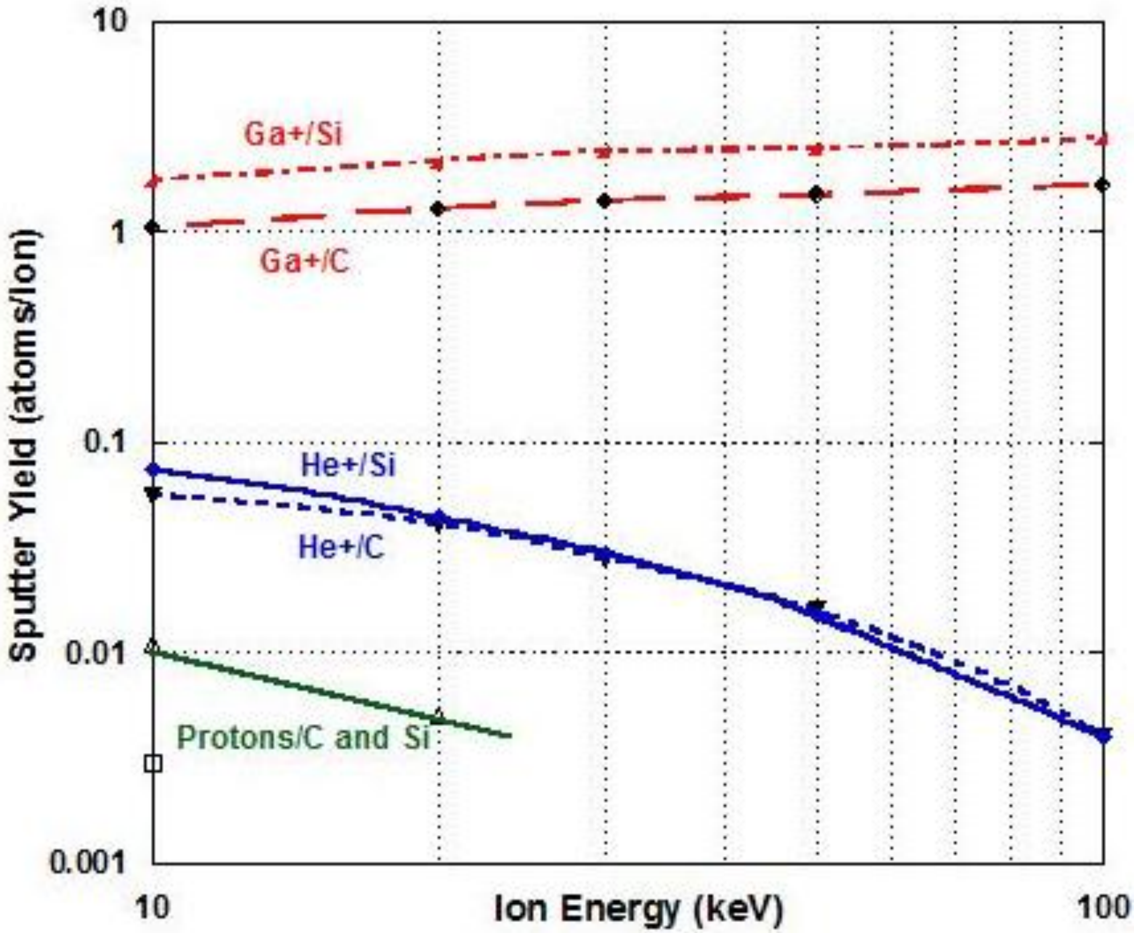
Charging is controlled by an electron flood gun aimed at the specimen – switched on for some fraction of each scan raster period. Effective!

Ion Beam Damage

- The HIM is not an FIB – but He+ ions can, and do, cause damage to samples
- The severity of the damage depends on beam energy and beam current as well as on the sample that is being irradiated

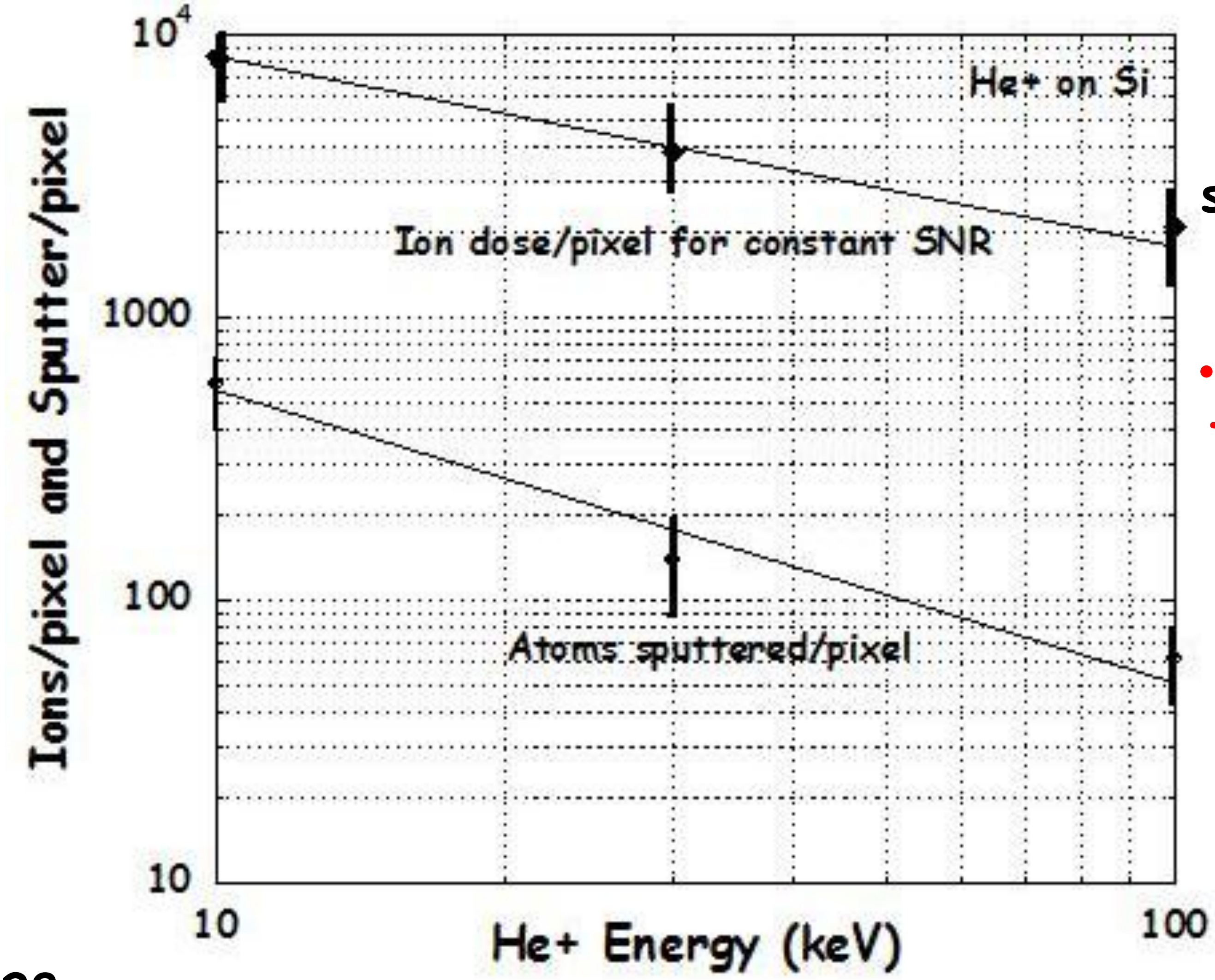
He+ sputter damage

- SRIM simulations show that the sputter yield of He+ is low compared to Ga+, but higher than for protons (H+)
- He+ sputter damage falls with increasing energy
- This is great news..



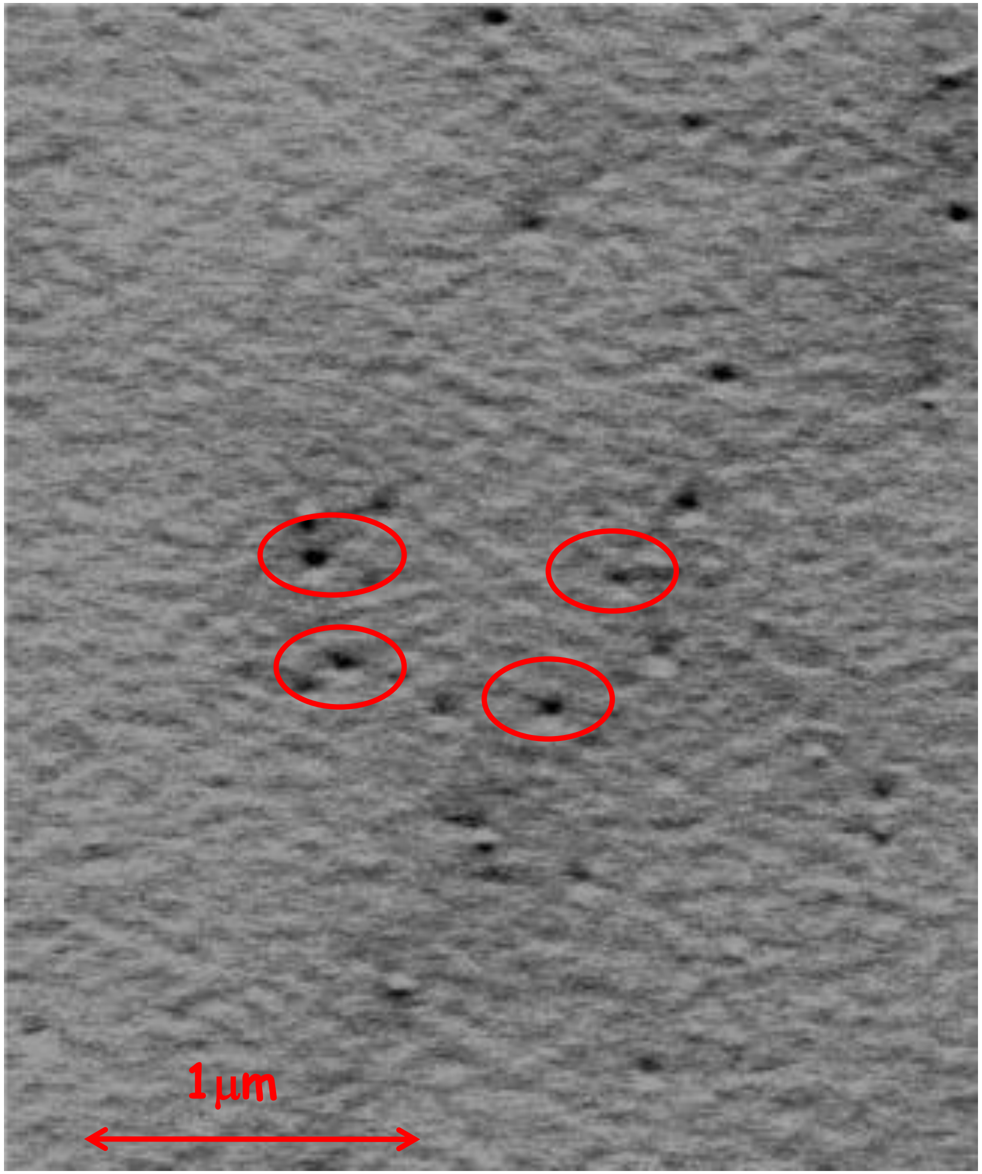
Data from SRIM Ziegler et al.

Minimizing sputter damage



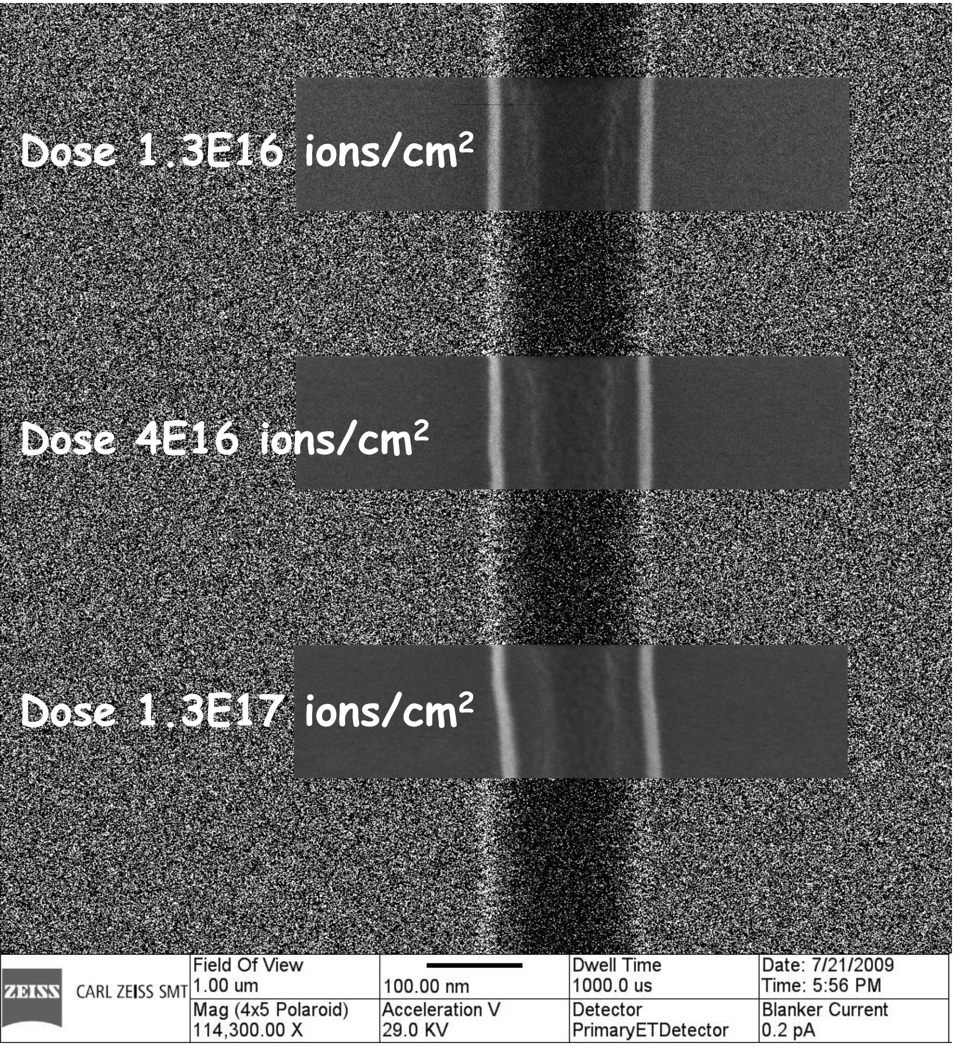
- Increasing the ion energy reduces sputter damage and..
- Increasing energy raises the iSE yield
- So for constant SNR the damage rate can be reduced x10 by moving to 100keV
- But this is not the only damage mechanism…

High Energy He+ ion damage



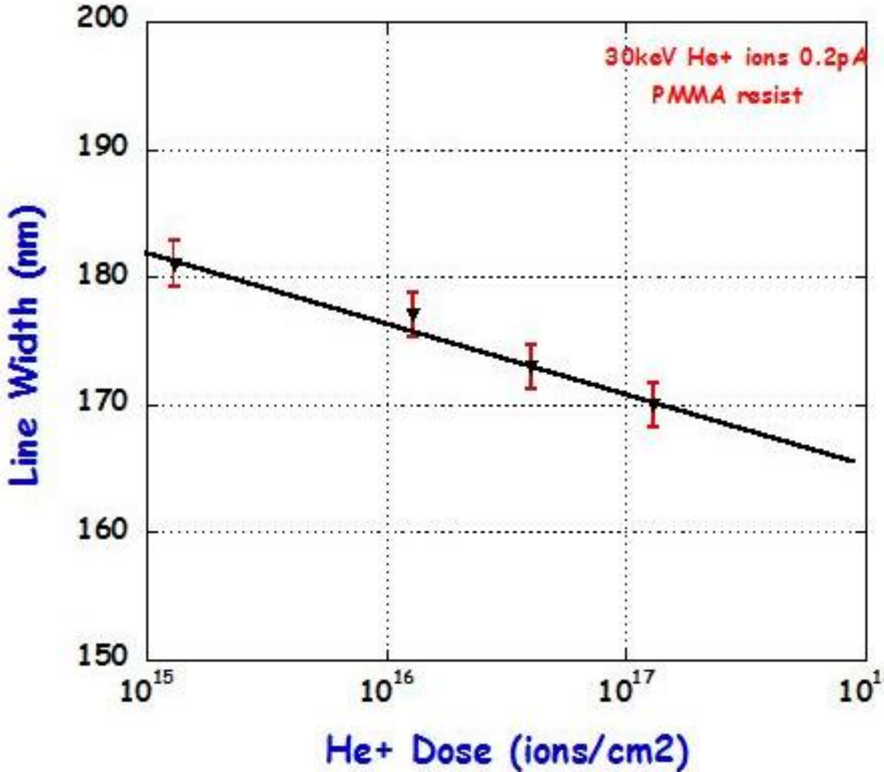
- At beam energies close to the stopping power maximum (~800keV) each incident He+ ion can form impact holes in a polymer film even at low doses
- This appears to be a knock-on collision (*Rosenberg et al. (1962), JAP 33, 1842)*

He+ radiolysis in PMMA



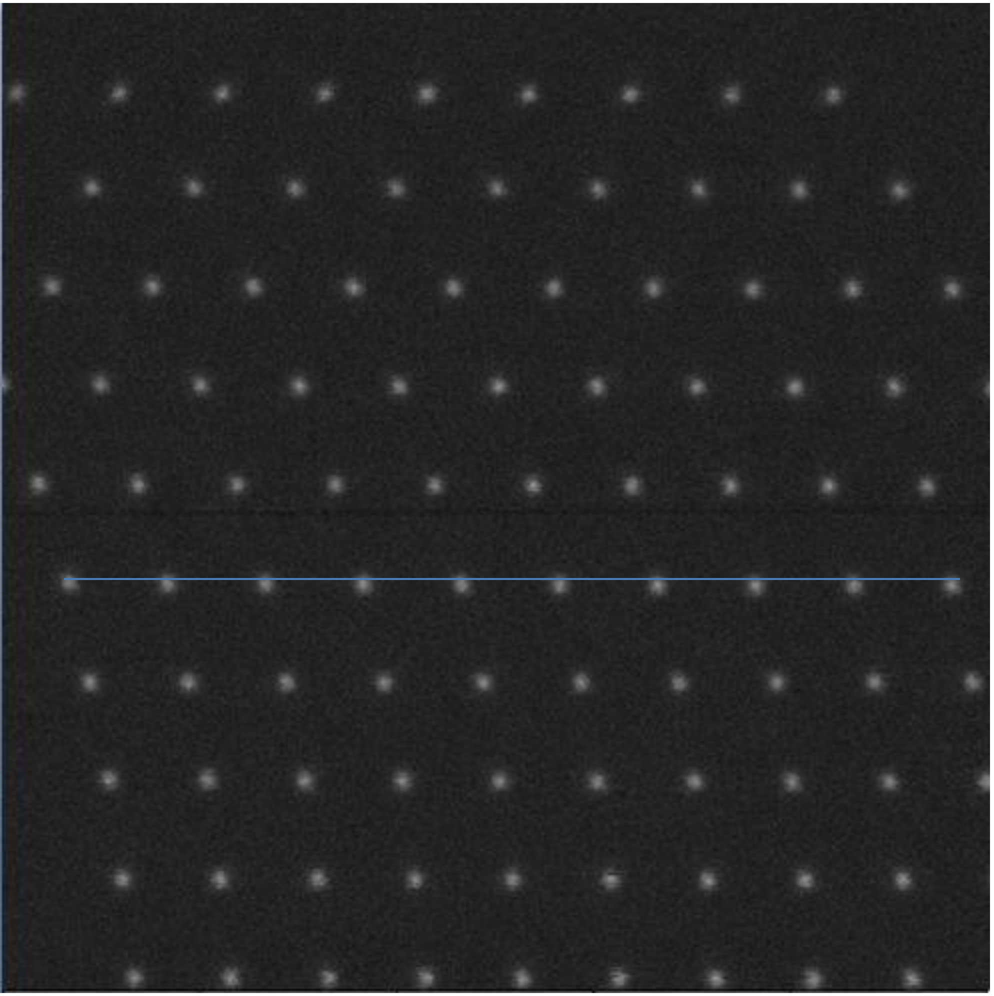
Field Of View 1.00 um
100.00 nm
Dwell Time 1000.0 us
Date: 7/21/2009
Time: 5:56 PM
Mag (4x5 Polaroid) 114,300.00 X
Acceleration V 29.0 KV
Detector PrimaryETDetector
Blanker Current 0.2 pA

- Resist shrinkage 30keV He+ ions
- I_B 0.23pA, dwell time 30µs
- Maximum Dose 1.3E17 ions/cm²
- Shrinkage 5% @ 10 ions/A²
- Manageable and predictable

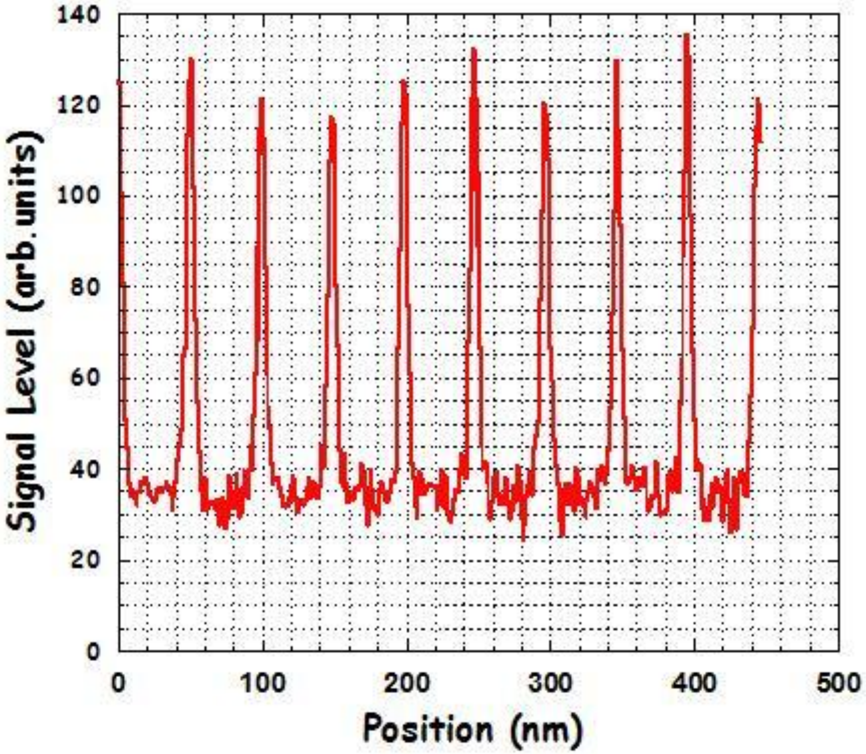


Radiolysis limit for electrons ~10 el/A²

So is HIM metrology an improvement?

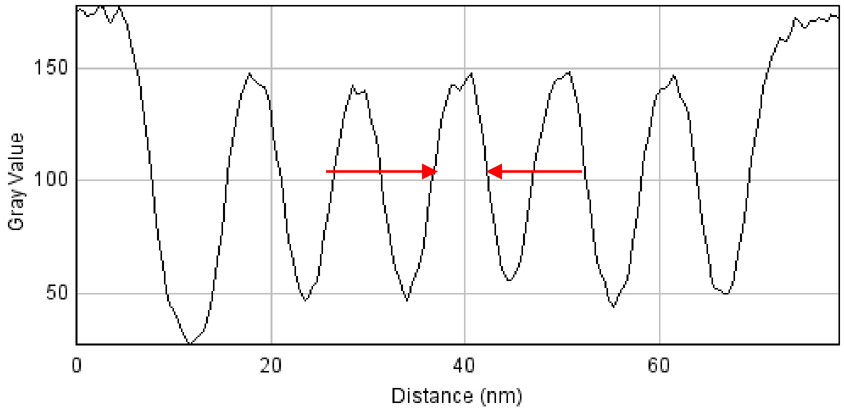


HIM image array of pillars 50nm spacing

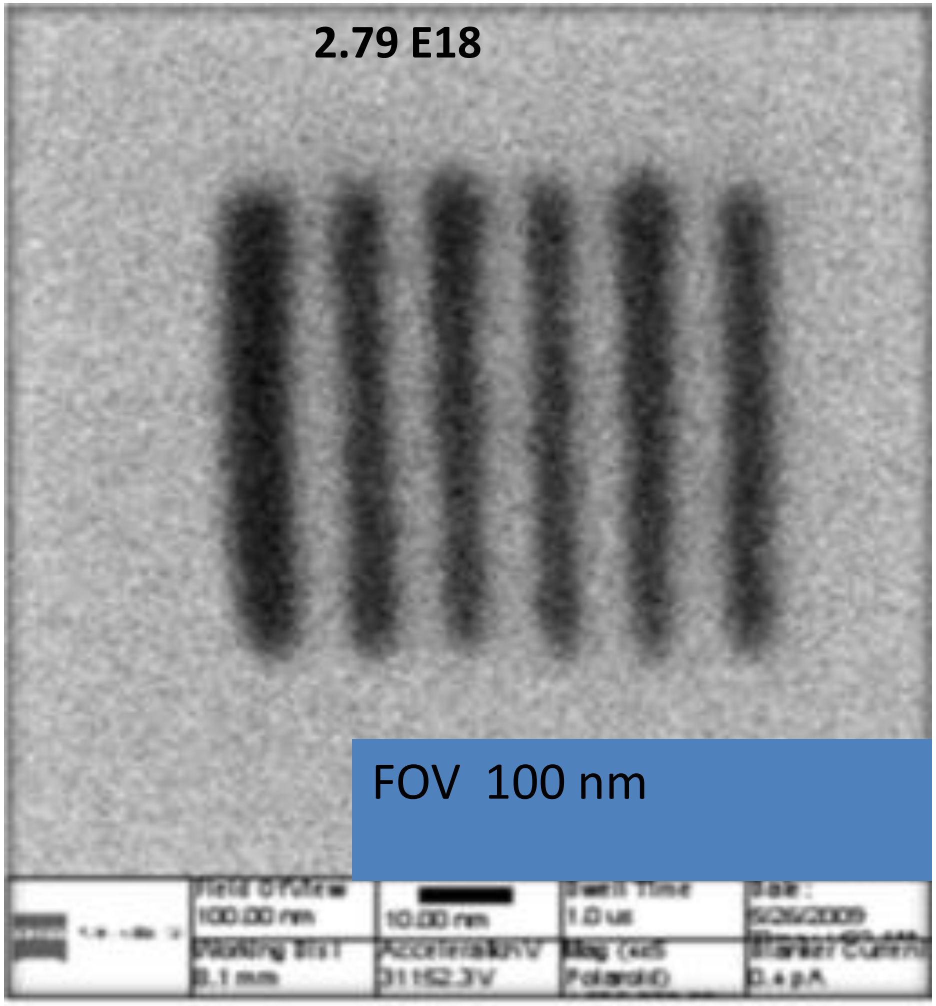


HIM line trace shows <1nm resolution at top, FWHM <3nm at base 100nm lower, no tails or defocus and minimal charging

Is this the future of Metrology?



5-6 nm width



FOV 100 nm

- 31keV beam, Ib=0.4pA
- Single layer graphene sheet – note high contrast, good SNR
- 10nm repeat features, 5nm FWHM – cleanly resolved with detail down to <1nm

Dr. Dan Pickard, Nat'l University of Singapore)

Plus and Minus

- ✓ The high resolution and great depth of field of the HIM is ideal for device metrology
- ✓ Ion dose required for acceptable SNR achieved is consistent with need for speed
- ✓ Damage is comparable with e-beam case
- ✓ Topographic line profiles are similar to e-beam – but care in analysis is needed
- ❖ Ability to model signal profiles is limited by incomplete data base of iSE yields for elements and especially for compounds

Thank You

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- And ..

http://cnms.ornl.gov

Center for NanoPhase Materials Science, Oak Ridge National Laboratory