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Low Voltage Imaging

Low Voltage SEM

- Low voltage scanning electron microscopy is distinctive because it differs in several significant ways from conventional SEM operation, and has specialized electron optical requirements

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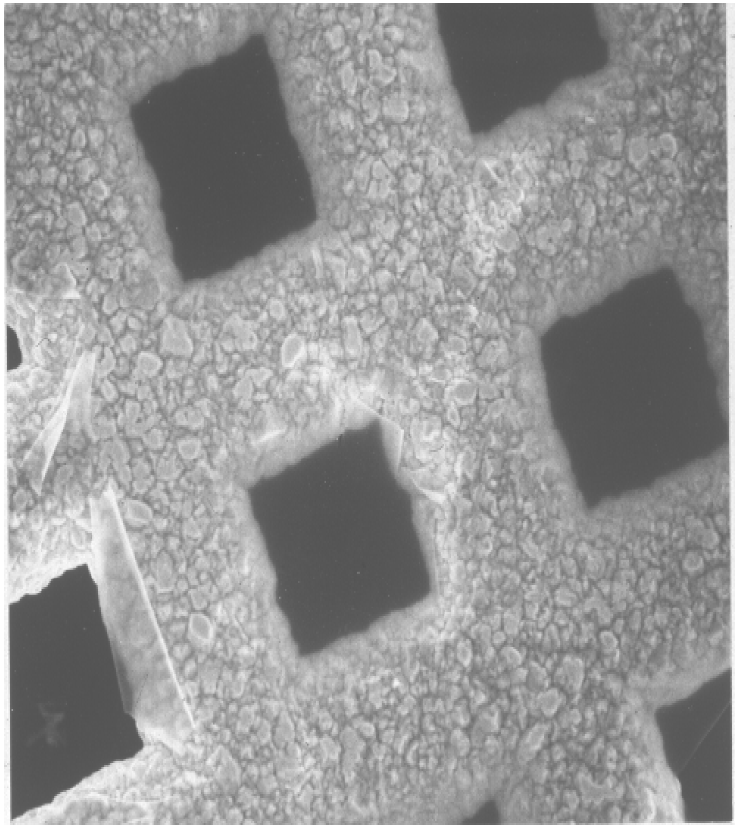
Seeing is believing

- The sample is a 300Å film of carbon on a copper grid
- At 20keV the carbon film is transparent because it is penetrated by the beam.The SE signal comes from the carbon film but is produced by electrons backscattered from the copper



SE image of TEM grid 20keV

Electron range at low energy

- At 1keV - by comparison - the carbon appears solid and opaque because the beam does not penetrate through the film, and the copper grid is not visible at all
- The variation of beam range with energy is dramatic and has significant results on what we see

Same area as before but 1keV beam

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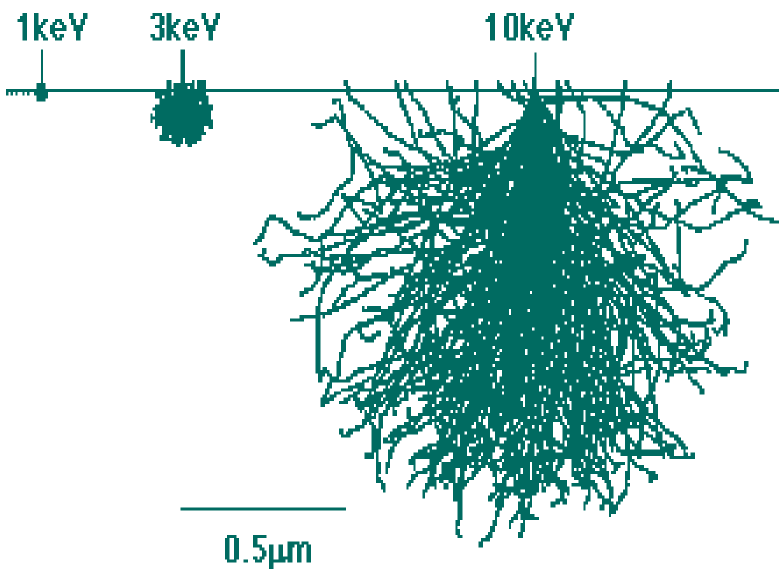
Some consequences of low energy operation

- The interaction volume decreases in size and shrinks towards the surface
- Spatial resolution is improved in all image modes
- The SE yield rises significantly improving images and as a result

  ..less charge is deposited in the sample
- Beam damage is higher but is more localized

Interaction volume

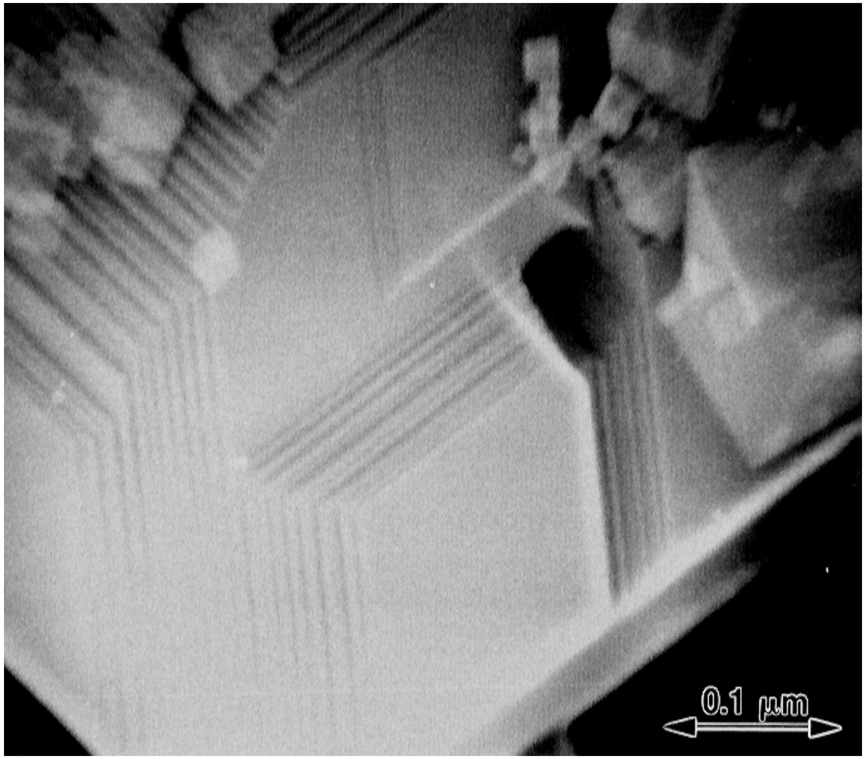
- The interaction volume falls with beam energy E as about $1/E^5$
- The interaction volume no longer samples the bulk of the specimen but is now restricted to the near-surface regions only
- The information in the signals produced is therefore much more surface oriented at low energies than at high



Monte Carlo simulations of interactions in silicon

High Energy Images

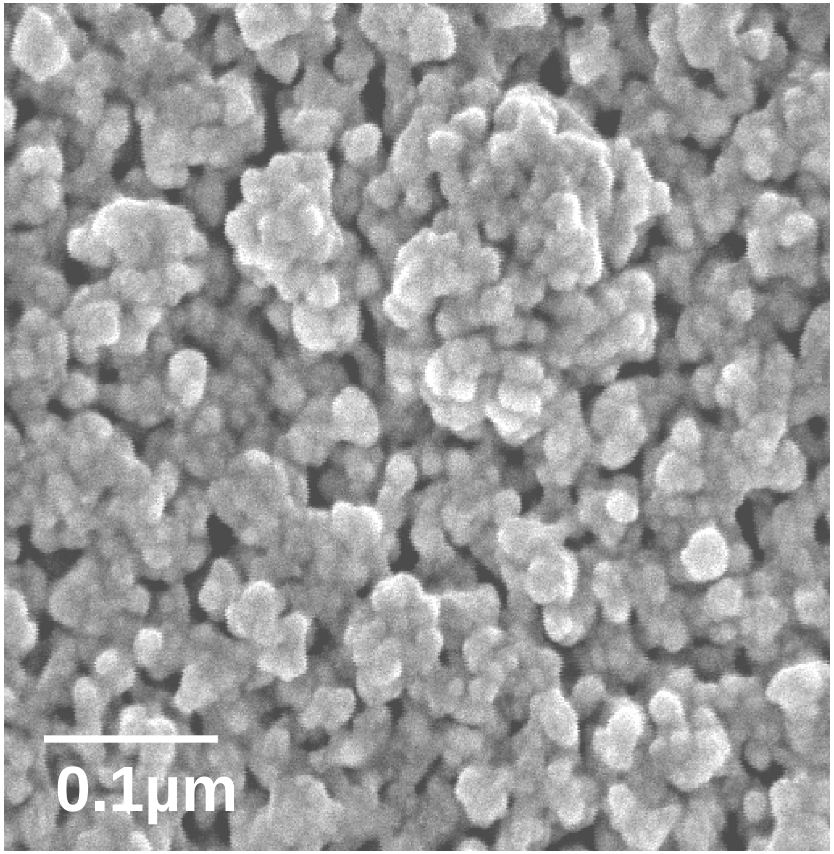
- At high beam energies the beam penetrates the sample for many micrometers giving it a translucent appearance
- The image information mainly comes from the bulk of the sample and only edges and corners on the surface are visible at high contrast



MgO cubes 30keV S900

Low Energy Images

- At low energy the beam only penetrates a few tens of nanometers.
- The image now only contains information about the surface and the near surface regions of the specimen
- The sample appears solid rather than translucent



Nanocrystals of silver
3keV x100k S4500

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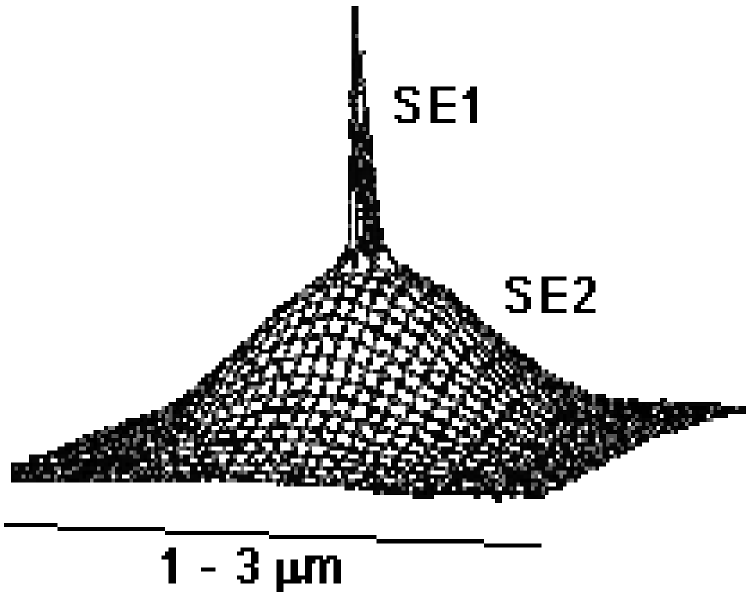
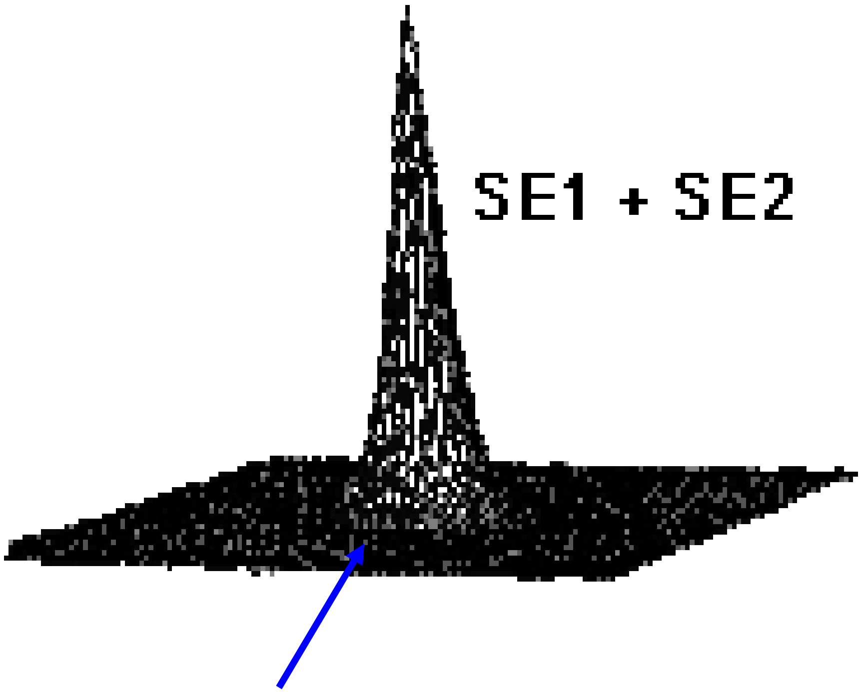
Spatial resolution…..



SE2 come from the full width of interaction volume

- At high energy the SE1 signal typically comes from a volume 3-5nm in diameter, but the SE2 signal from a volume of 1-3µm in diameter
- High resolution contrast information is therefore diluted by the low spatial resolution SE2 background

But at low energies……



the interaction volume shrinks

- ..the SE1 and SE2 electrons emerge from the same volume because of the reduction in the size of the interaction volume
- So SE1, SE2 and BSE images will all exhibit high resolution….

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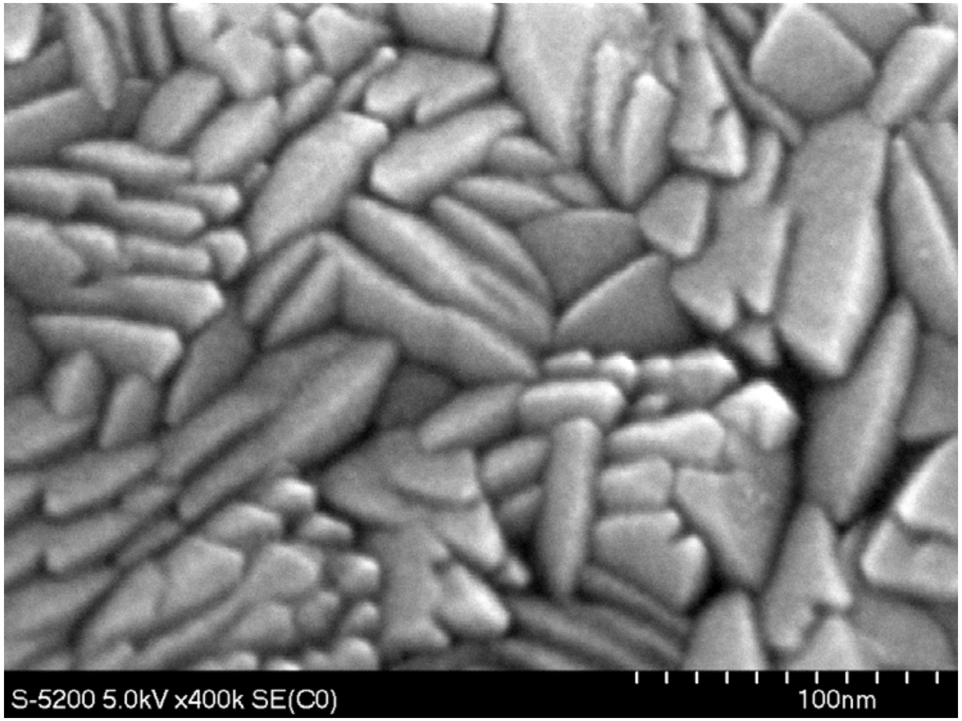
Low Voltage SE imaging

- A point resolution of close to 2nm at 1keV is possible in current SEMs
- Efficient TTL detectors provide good S/N ratios
- The low voltage SE image contains topographic, electronic, and chemical information about the sample

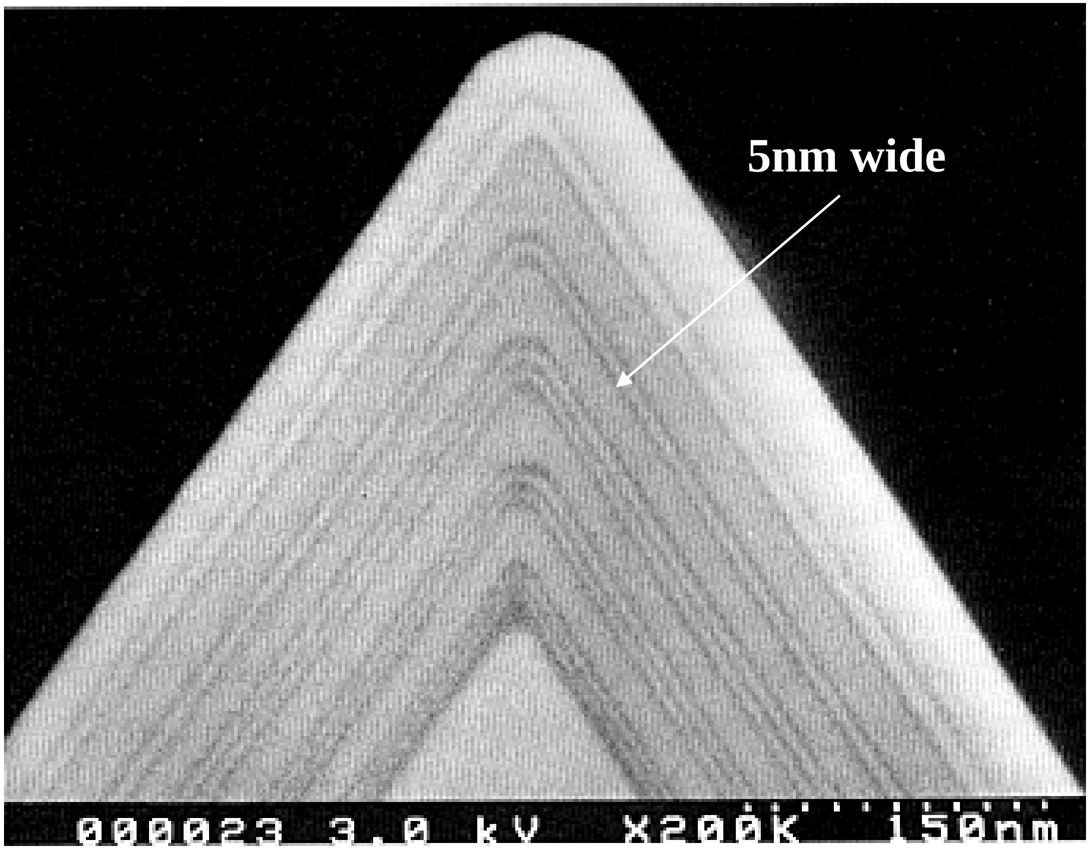


Mode : Pure SE   Vacc. : 5kV

Indium Tin Oxide (ITO)

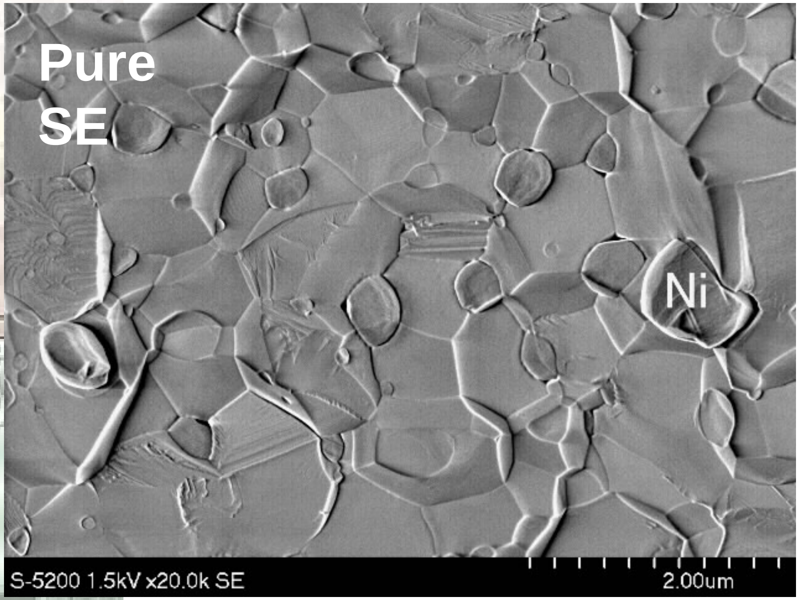
Low voltage BSE imaging

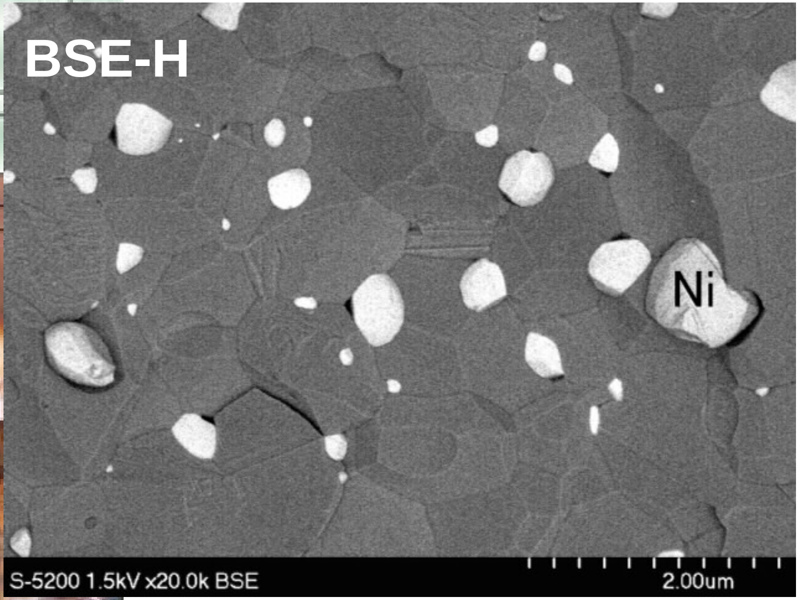
- BSE mode provides high resolution Z contrast, topographic detail, and provides freedom from charging artifacts
- Conventional BSE detectors are not good at low energies, and they require a long WD but the new ExB filter solves this problem

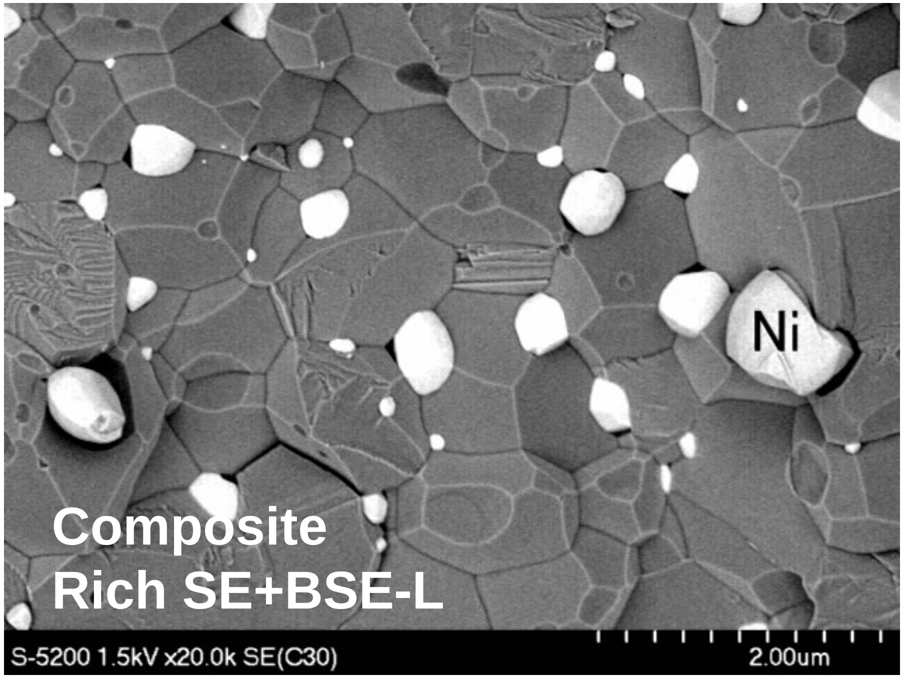


GaAs/GaAlAs quantum wells at 3keV

Mixed Signal Modes using ExB





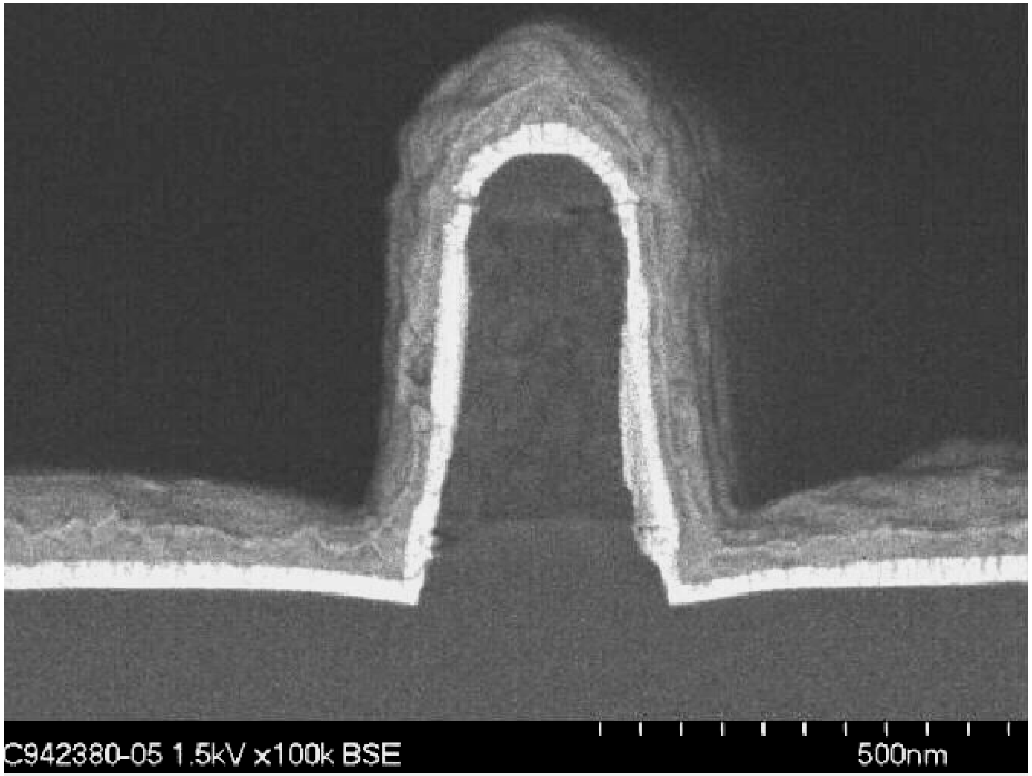


Alumina / Nickel Composite

Courtesy of Associate Prof.. T. Sekino,
ISIR, Osaka Univ.

Low Voltage BSE imaging

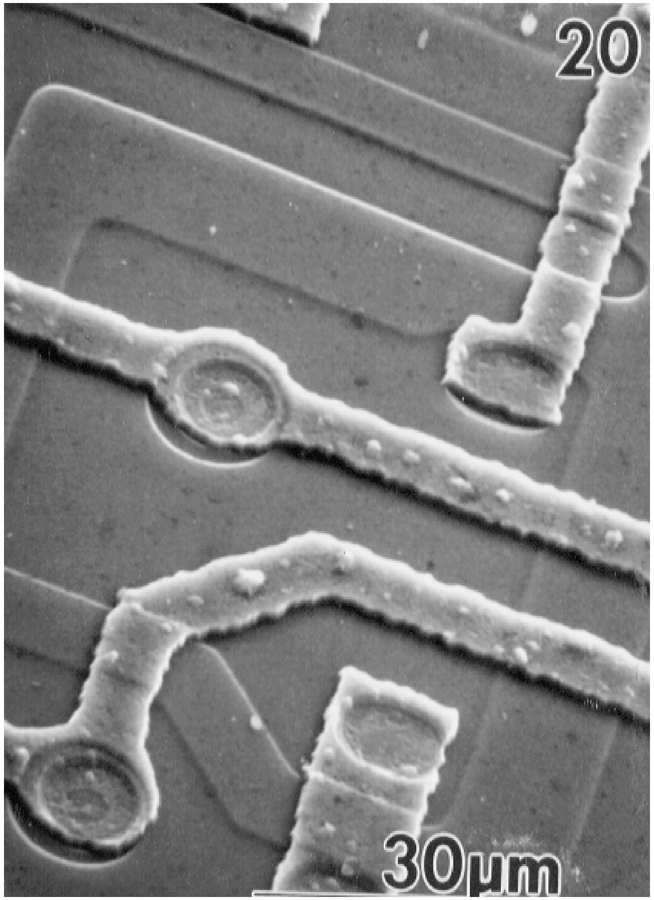
- At a WD of 1.5 or 2mm high resolution BSE imaging is readily possible and is very efficient
- Note that 'Z' contrast may be a little less evident at low energies than at high.
- Turn up emission current to improve signal to noise and contrast



Ta barrier under copper seed

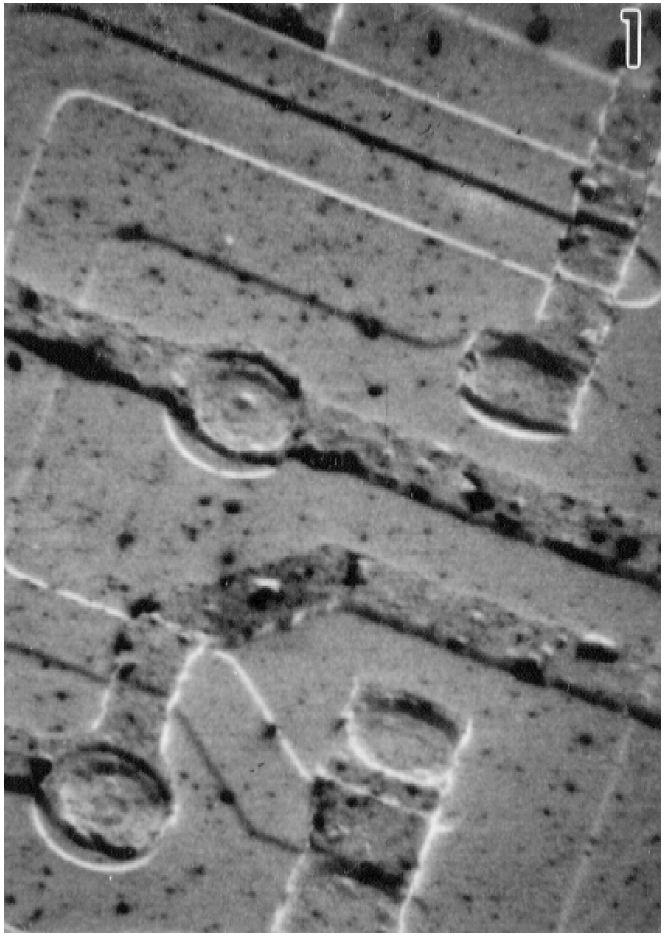
The high energy image

- The changes discussed above affect the form of the image
- At high energies we see the classic SEM ‘three dimensional’ appearance
- Surface detail is revealed by topographic contrast
- Because the interaction volume is large features above the surface are highlighted

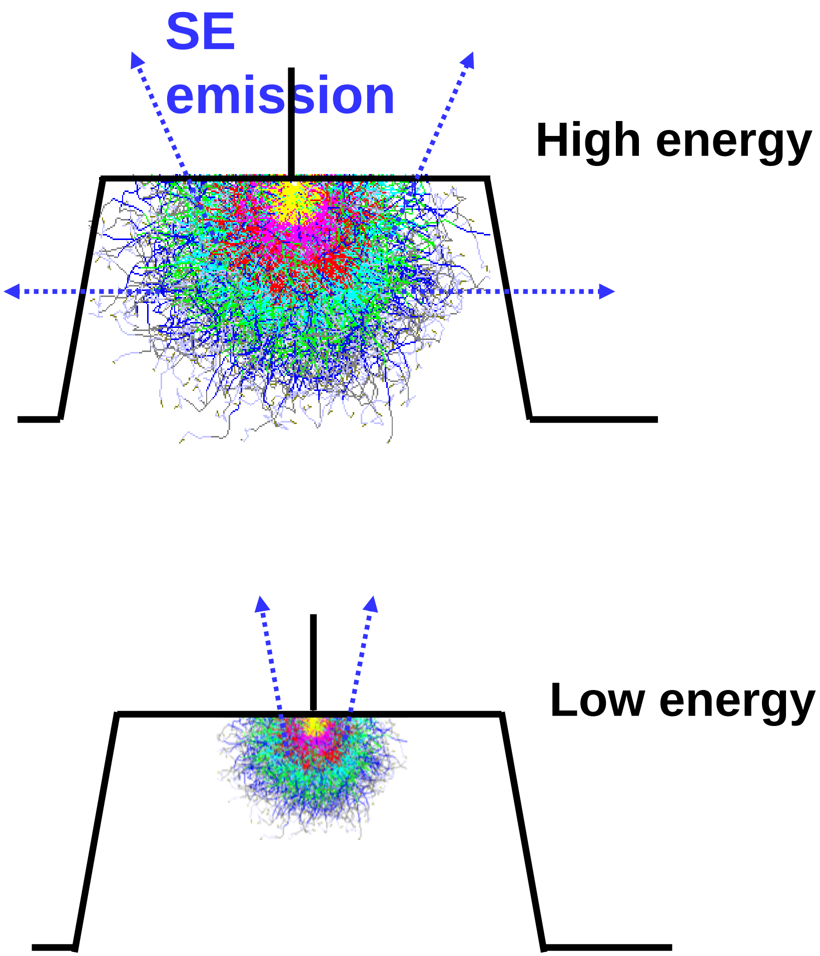


The LVSEM image

- The low voltage images appears much flatter and less three dimensional than the high voltage image
- This is because topographic contrast is reduced
- There is also no highlighting of features on the surface
- Greater visibility of surface marks and contamination



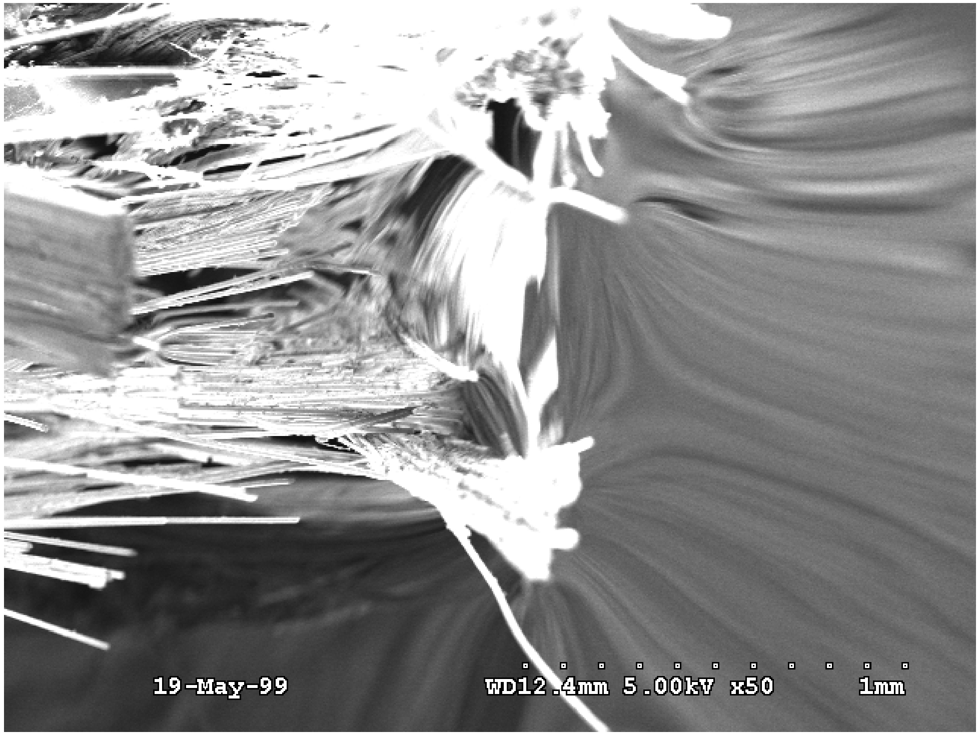
Beam penetration effects



- At high energy the interaction volume fills features on the surface - SE2 emission leads to enhanced SE emission making objects look almost 3-dimensional
- But at low energies the reduced interaction volume means that only the edges of features are enhanced

The LVSEM and charging

- When electron beams impinge on non-conducting samples a charge can build up which can make SEM imaging unstable, difficult or even impossible
- By operating at low beam energies this problem can often be minimized or eliminated



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Damage at low energies

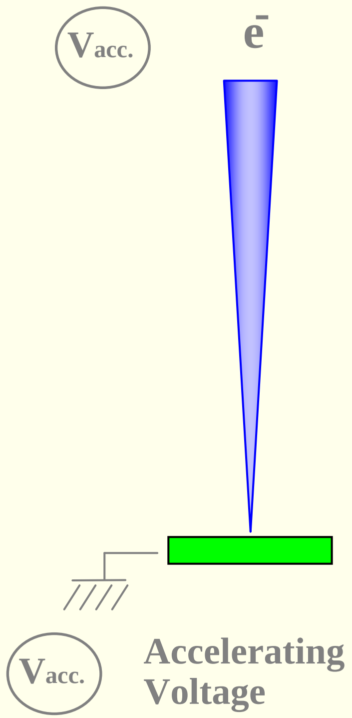
- It is often stated that operation at low beam energies minimizes or eliminates beam induced damage
- From casual observation this may appear to be true, but physics and measurements show that the truth is just the opposite

Damage and Beam Energy

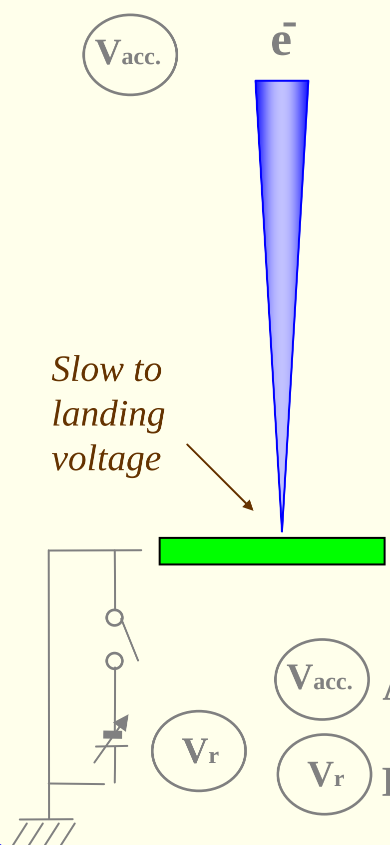
- The usual misconception is that low energy electrons damage less than higher energies.
- At higher accelerating voltages the great majority of the energy will be deposited far below the surface regions that are of interest
- So in some cases it is better to use high kV to “bury” the charge.

Beam Deceleration

No Beam Deceleration (Normal Condition)



Beam Deceleration



By applying a voltage (Vr) to the stage the primary beam is "decelerated". Benefits of this technique include improved resolution at lower kVs and real surface imaging.

Vacc. − Vr = Landing Voltage

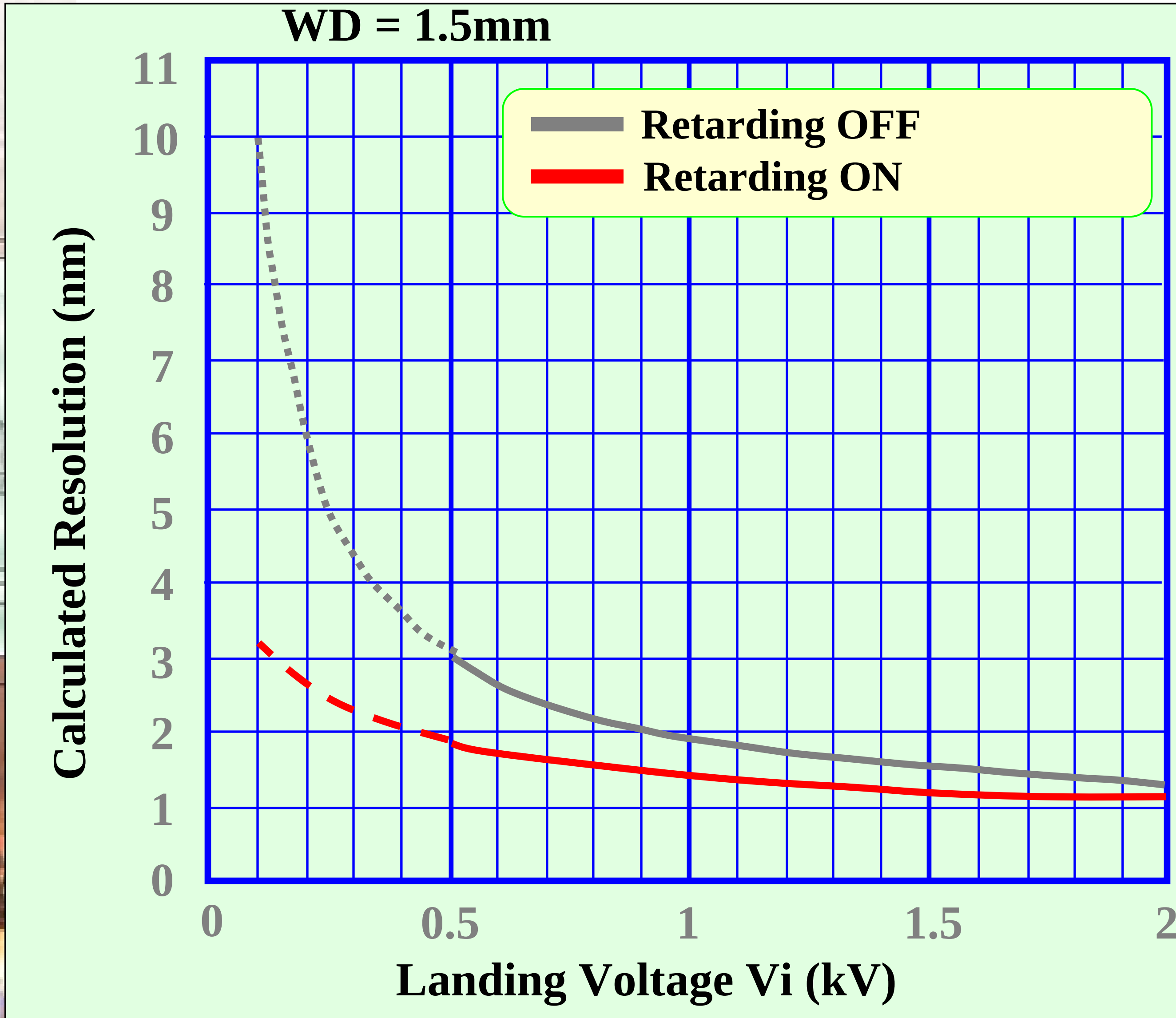
2.0kV – 1.5kV = 500V

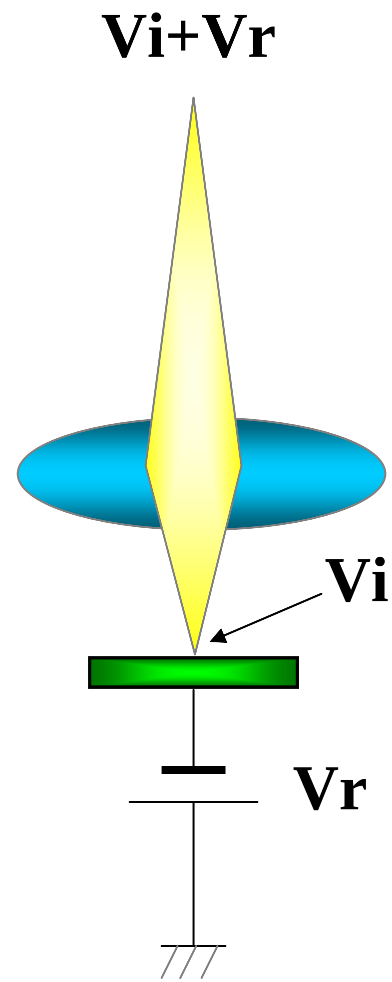
For Example: an accelerating voltage of 2kV in combination with a deceleration voltage of 1.5kV results in a landing (imaging) voltage of 500 volts with a clarity similar to a 2kV image.

Vacc. Acceleration Voltage

Vr Deceleration Voltage

Resolution Under Beam Deceleration Mode





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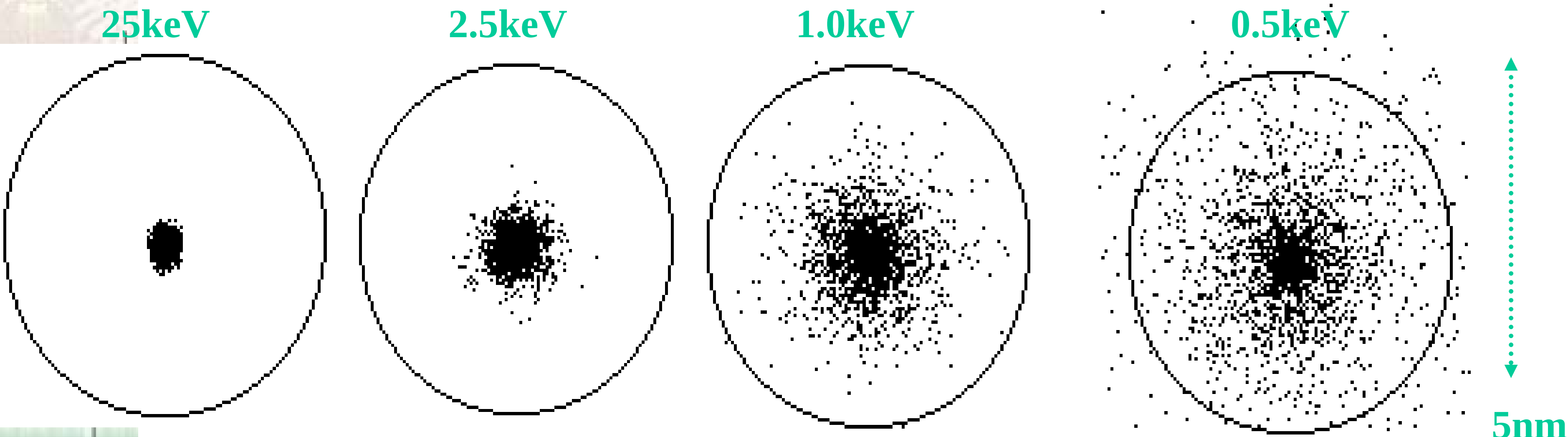
Chromatic aberration effects



Kenway-Cliff numerical ray-tracing simulations of electron arrivals with a lens Cs=3mm,Cc=3mm, α =7 m.rads

The energy spread of the beam causes a chromatic error in the focus. Even with a cold FEG source (~ 0.3eV wide) this greatly degrades the probe at 0.5 keV and below. Both the source and the objective lens are important factors

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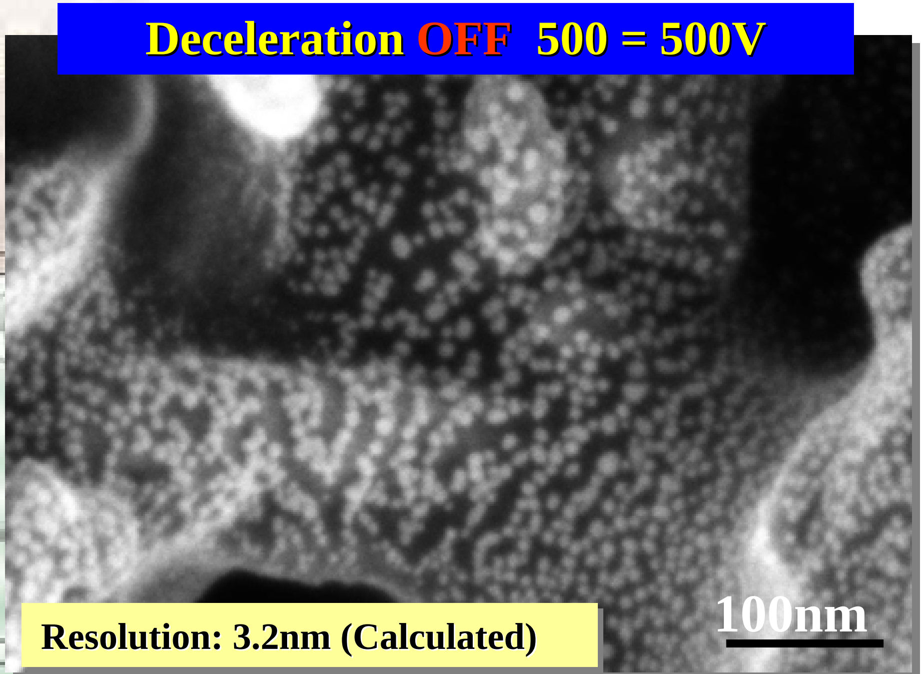
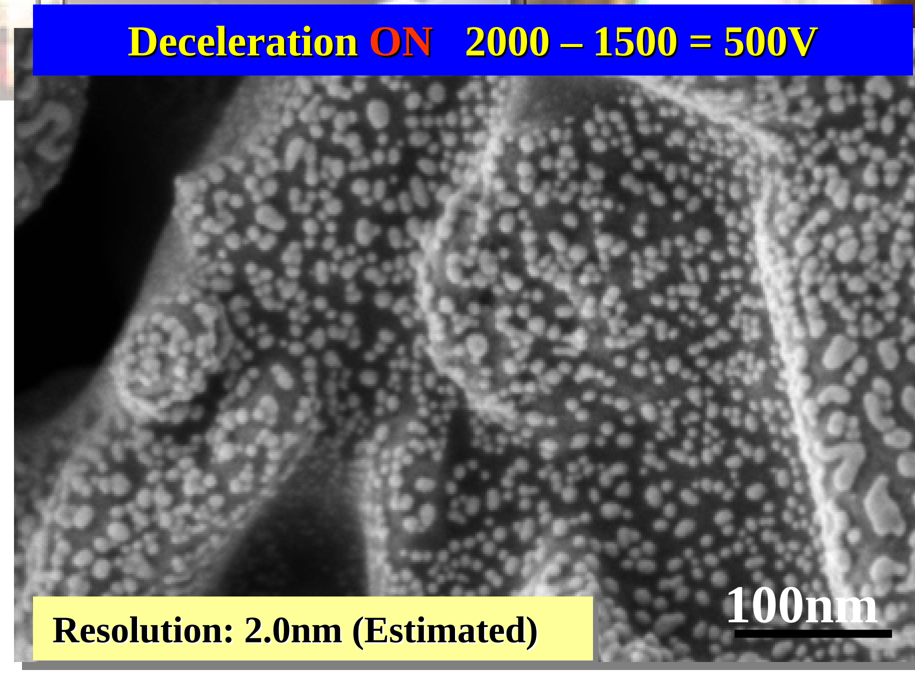
Resolution





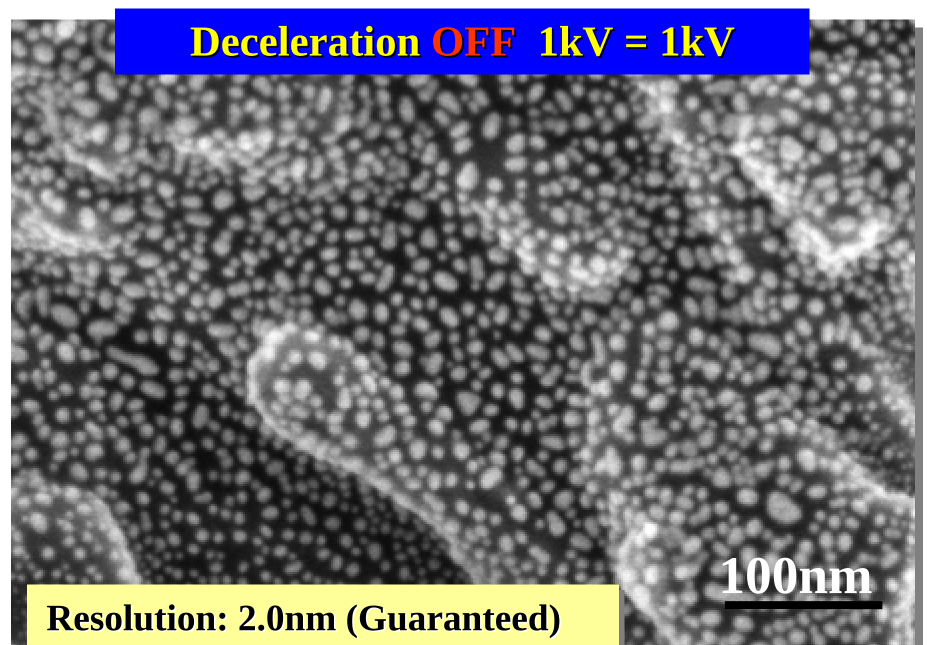
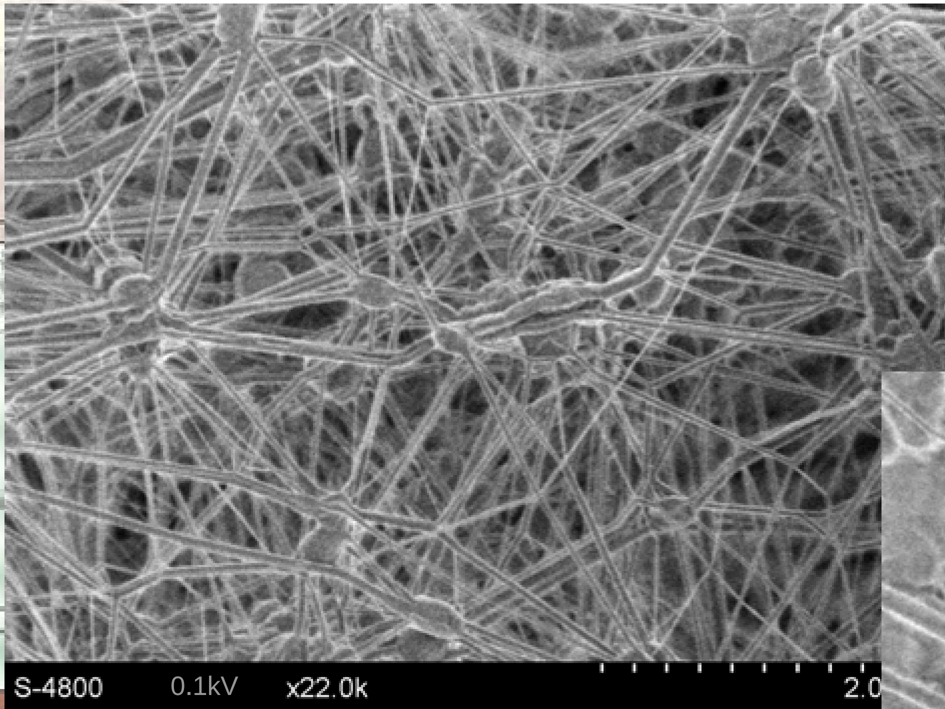


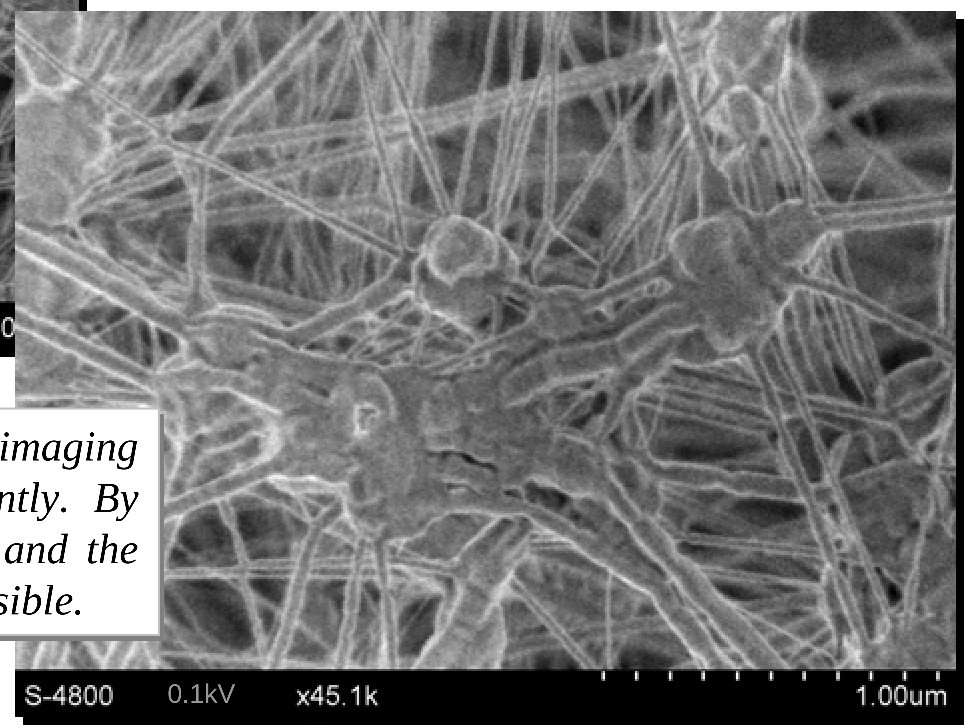
Image clarity at 500 volts with a decelerated beam is much better than the image from an initial 500-volt beam. The estimated resolution at 500 volts with beam deceleration is equivalent to the guaranteed resolution of a 1kV beam.

Membrane Filter



Observation at 100V

Deceleration ON 1600 – 1500 = 100V



This membrane filter is uncoated. Under normal imaging conditions the sample would charge significantly. By imaging at 100 volts charging does not occur and the ribbed surface structure of the fiber clusters is visible.

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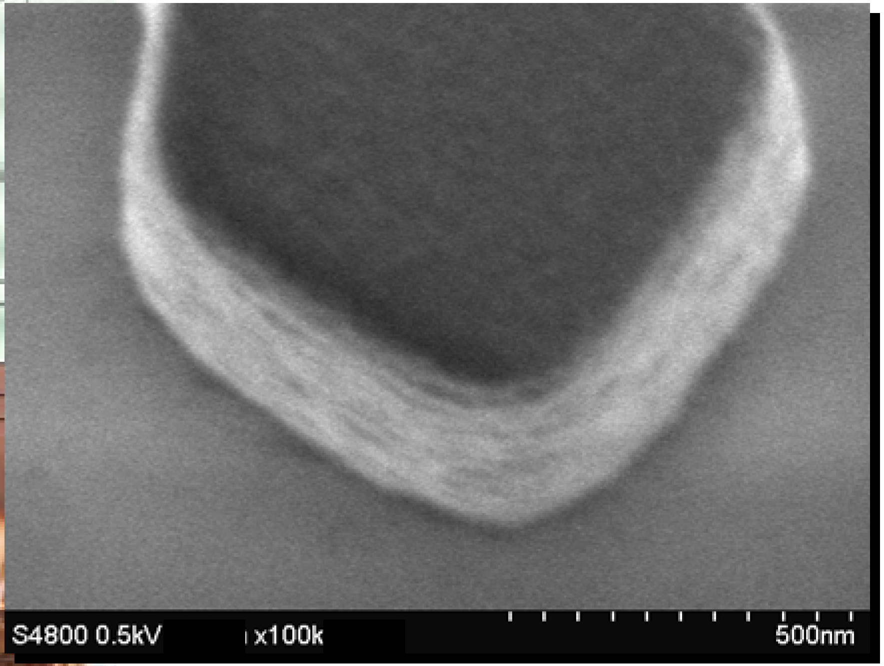
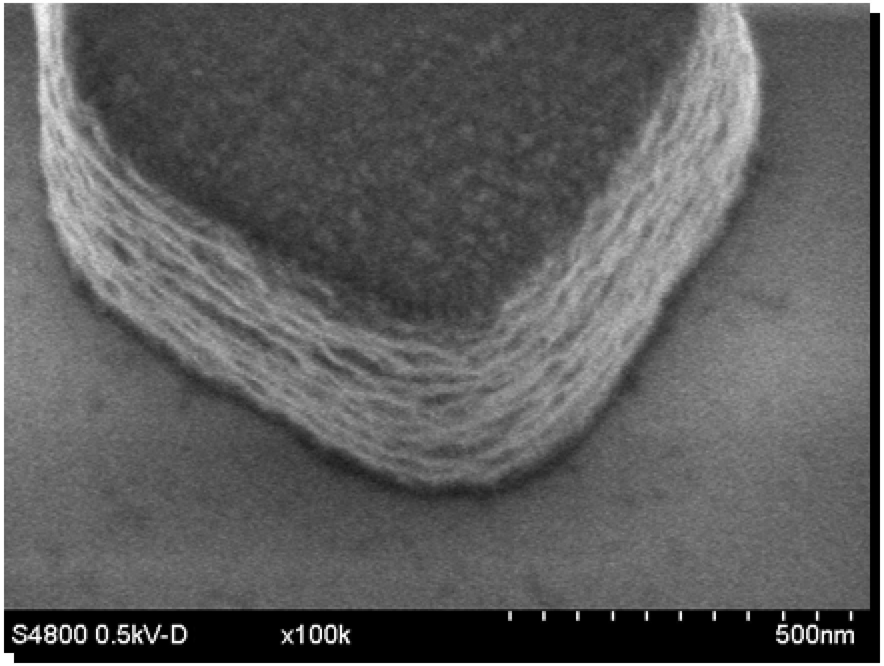
Photo Resist

At higher magnifications the resolution improvement is more dramatic. The characteristic ripple in the side walls of the resist pattern are clearly seen with the improved resolution gained from the higher initial voltage of the beam deceleration technology.

Observation at 500V



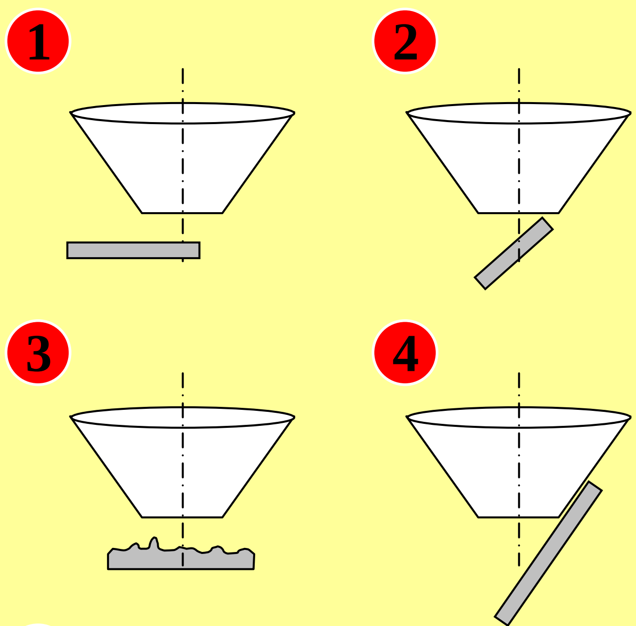
Beam Deceleration ***OFF***

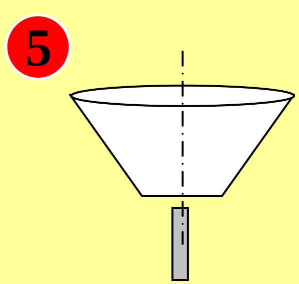


Beam Deceleration ***ON***

Application of the Beam Deceleration System

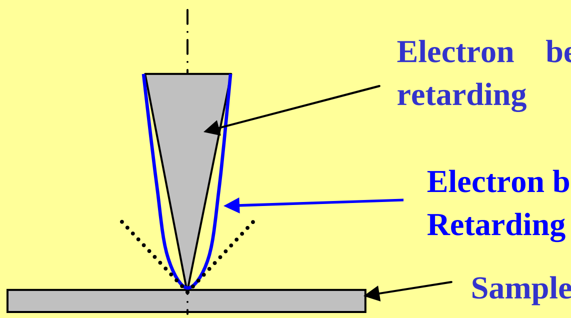
Not usable for general sample observation





1 Sample edge area
2 Pre-Tilted sample
3 Rough surface sample
4 Tilting stage
5 Cross-section

Depth of Focus becomes shallow



(SE/BSE) Signal Control cannot be used

Secondary electrons are accelerated by retarding voltage and have same energy level as backscattered electrons. So, it becomes impossible to detect each signal separately. As a result, always mixed signal of SE and BSE is detected and its mixing ration cannot be controlled.

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Electrical Field Simulation

Unsymmetrical electrical field is generated.

Worse aberrations

Worse resolution.