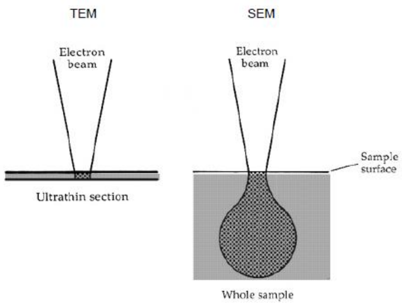
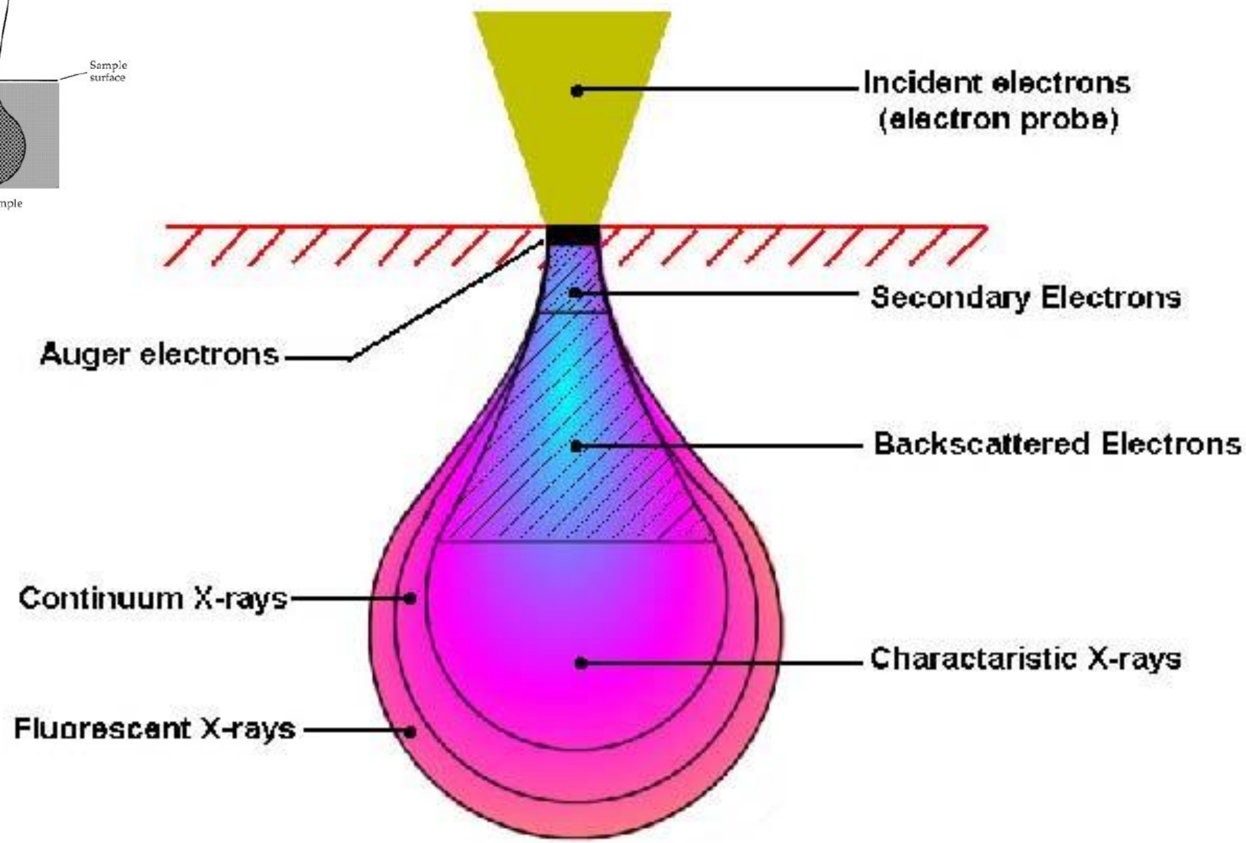
Introduction to Zeiss's GeminiSEM 500

The Basics

Beam Interaction Diagram

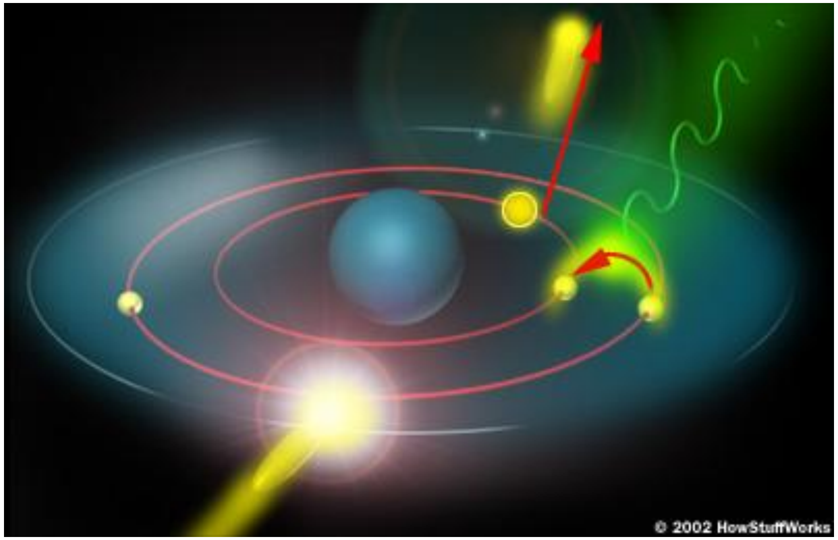




Electron Beam Interaction Diagram

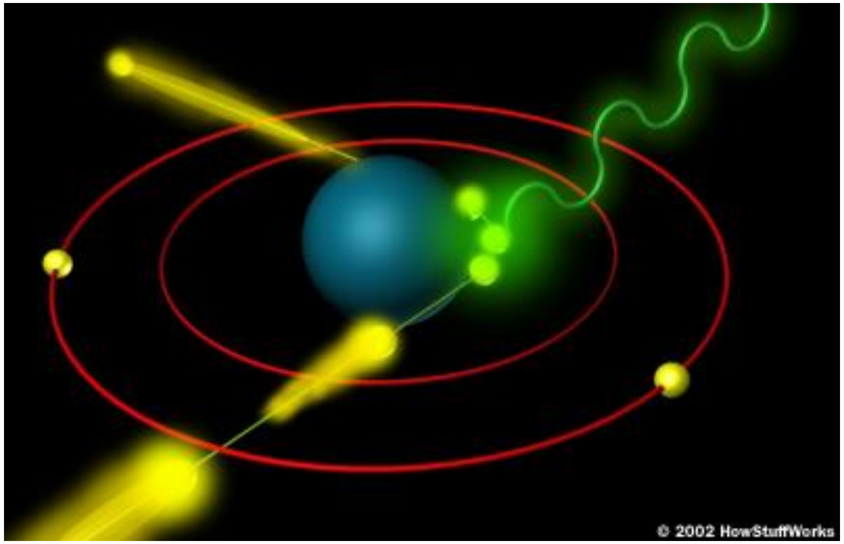
How X-rays (Photons) are Generated

Inelastic Scattering – Secondary Electron



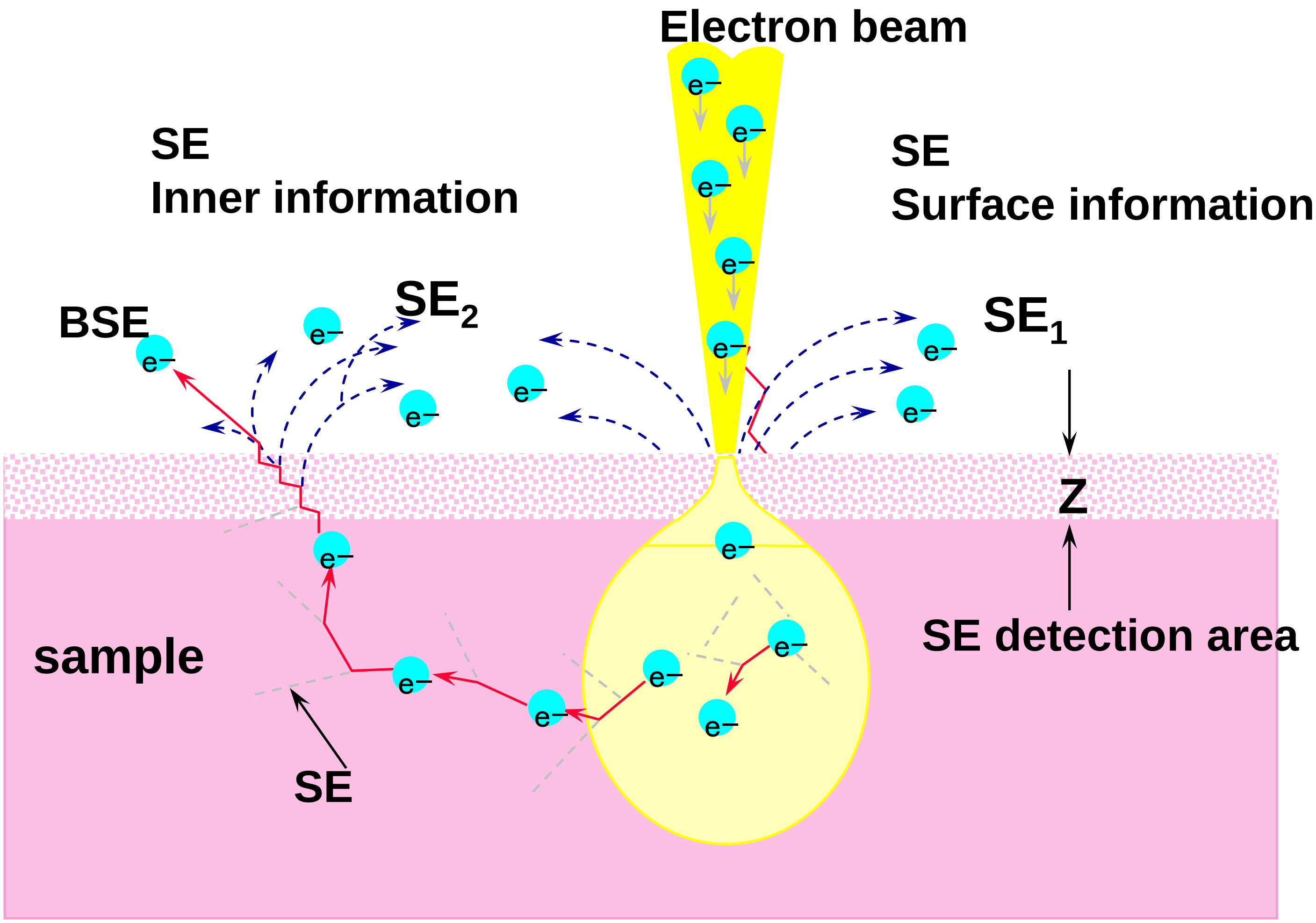
The primary electron interacts with the atom, knocking an electron out of a lower orbital. A higher orbital electron fills the empty position, releasing a (characteristic) photon of a known and measureable energy and wavelength

Elastic Scattering – Backscattered Electron



The primary electron is attracted to the atom nucleus. The electron course is altered as the electron passes the nucleus resulting a release of an X-ray photon (bremsstrahlung).

Electron Beam Interaction of SE and BSE



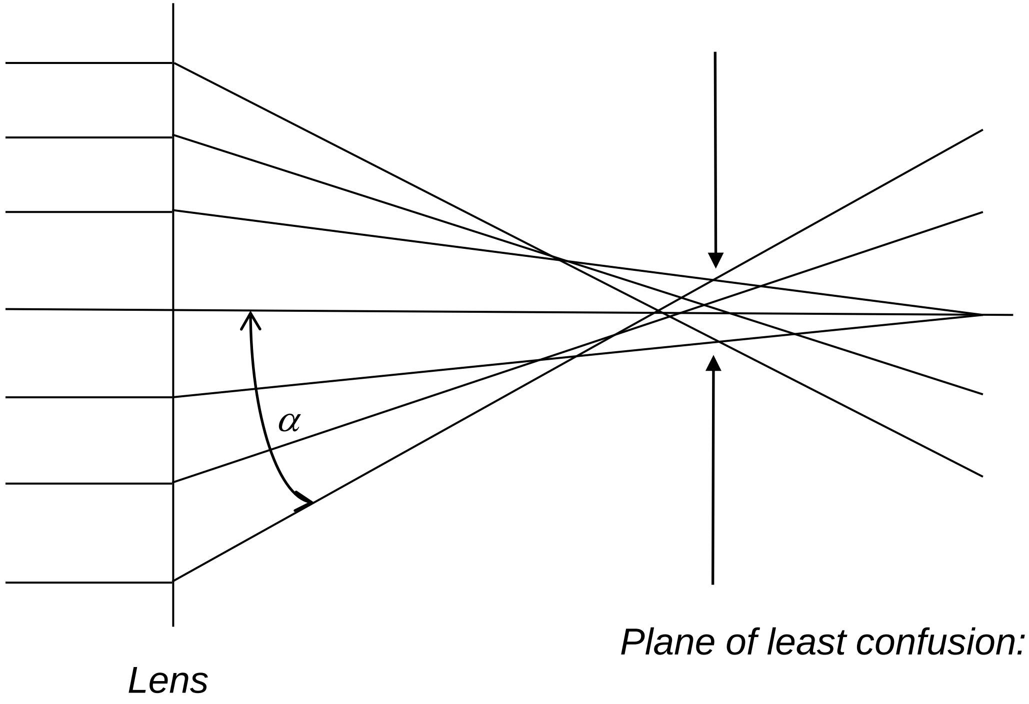
Secondary electrons are emitted from the top 10nm of the sample surface by initial interaction with the sample (SE1) and when a backscatter electron leaves the sample (SE2).

Courtesy Dr. David Joy – ORNL / UTK

Electron Lenses: Aberrations

Spherical aberration:

Rays further from the optical axis are focussed closer to the lens resulting in an aberration disc: $d_S = 0.5 C_S \alpha^3$

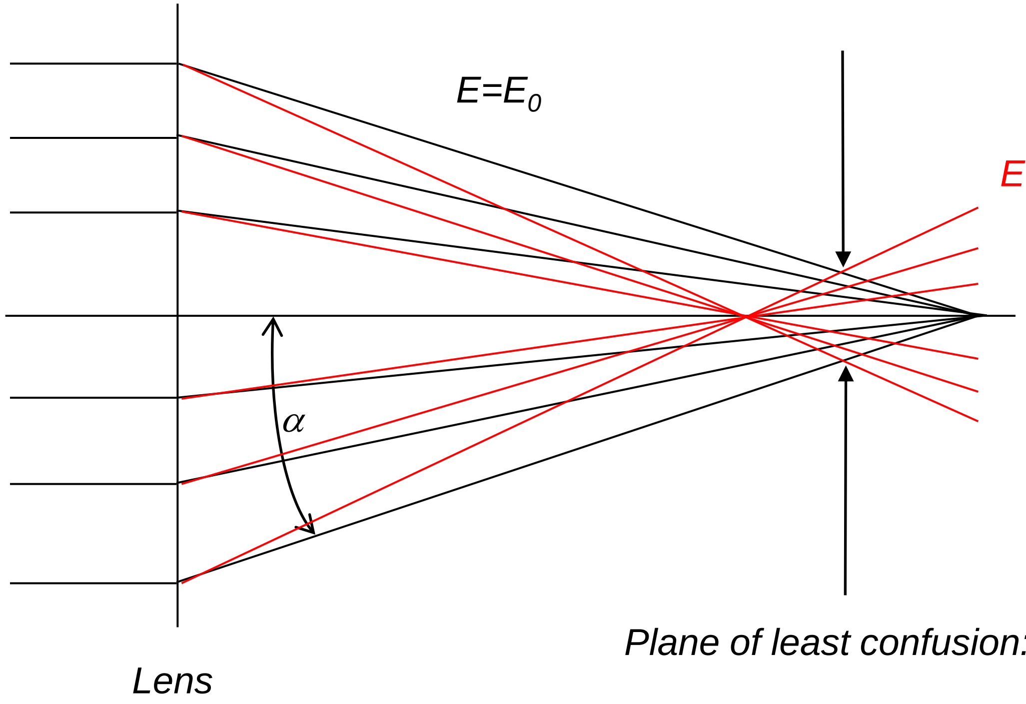


Plane of least confusion: $d_S = 0.5 C_S \alpha^3$

Electron Lenses: Aberrations

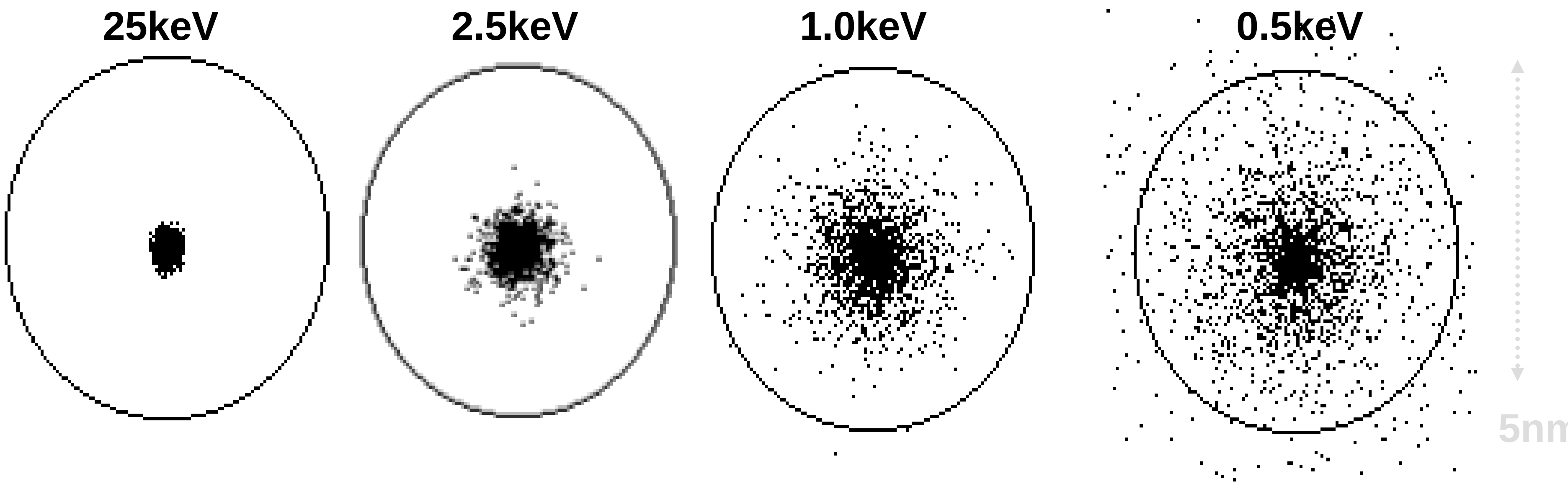
Chromatic aberration:

The focal length depends on the electron energy.
An energy spread of the electrons result in an aberration disc: $d_C = C_C \frac{\Delta U}{U} \alpha$



Plane of least confusion: $d_C = C_C \frac{\Delta U}{U} \alpha$

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. This greatly degrades the probe at 0.5 keV and below. Both the source and the objective lens are important factors

Courtesy Dr. David Joy – ORNL / UTK

Detectors Types

- ✓ **Secondary Electron Detector** (SED)
  - In-chamber Everhart Thornley
    - *Best for surface topography*
  - In-column (in-lens)
    - *Best for surface information (low energy)*
- ✓ **Backscattered Detector** (BSE)
  - AsB solid state (below objective lens)
    - *Best for channeling contrast (3kV and above)*
  - EsB in-column
    - *Best for Z contrast (3kV and below)*
- ✓ **Scanning Transmitted Electron Detector**
- ✓ **Variable Pressure and Extended Pressure Detectors**
  - Ionization Detectors used at 1Pa and below
- ✓ Energy Dispersive Spectrometer (EDS)
- ✓ Wavelength Dispersive Spectrometer (WDS)
- ✓ Cathodoluminescence Detector (CL)
- ✓ Electron Backscattered Diffraction Pattern (EBSD or EBSP)

When to use which detector

Detector	Information	Opt.Working Distance	Best Energy
Everhart-Thornley	Topographic surface information	5-12mm	0.02-30kV
InLens	Surface details, High Resolution Imaging	<5mm	0.02-5kV
AsB or SSBSE	Z-Contrast Channeling contrast (crystallographic information, strain, deformation)	5-10mm 2-5mm (material dependent)	>5kV
EsB	Z-Contrast (sharp due to energy filter) Low Loss BSE: Compositions, Bondings	<5mm	<1.5 kV

The Four Basic Parameters

The Four Basic Parameters

- ✓**Accelerating Voltage** **(EHT)**
- ✓**Aperture Size** **(diameter)**
- ✓**Spot Size** **(High Current mode)**
- ✓**Working Distance** **(sample to lens distance when at focus)**

Accelerating Voltage

High kV

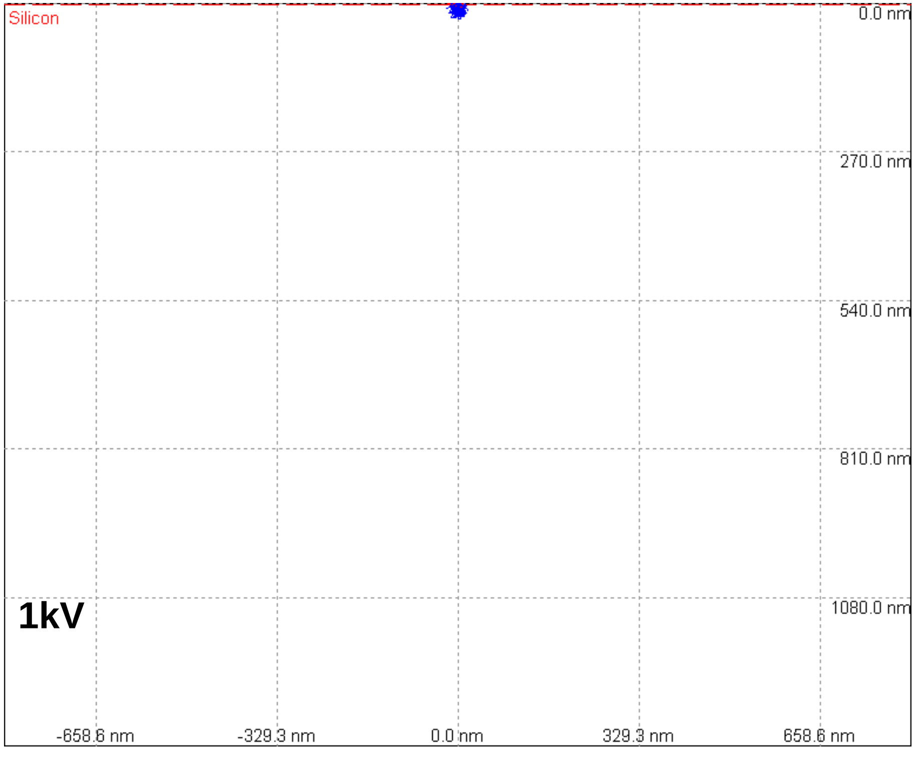
- Higher resolution
- Greater beam penetration
- Higher beam current
- Higher signal to noise
- More x-ray yield
- Good for VP

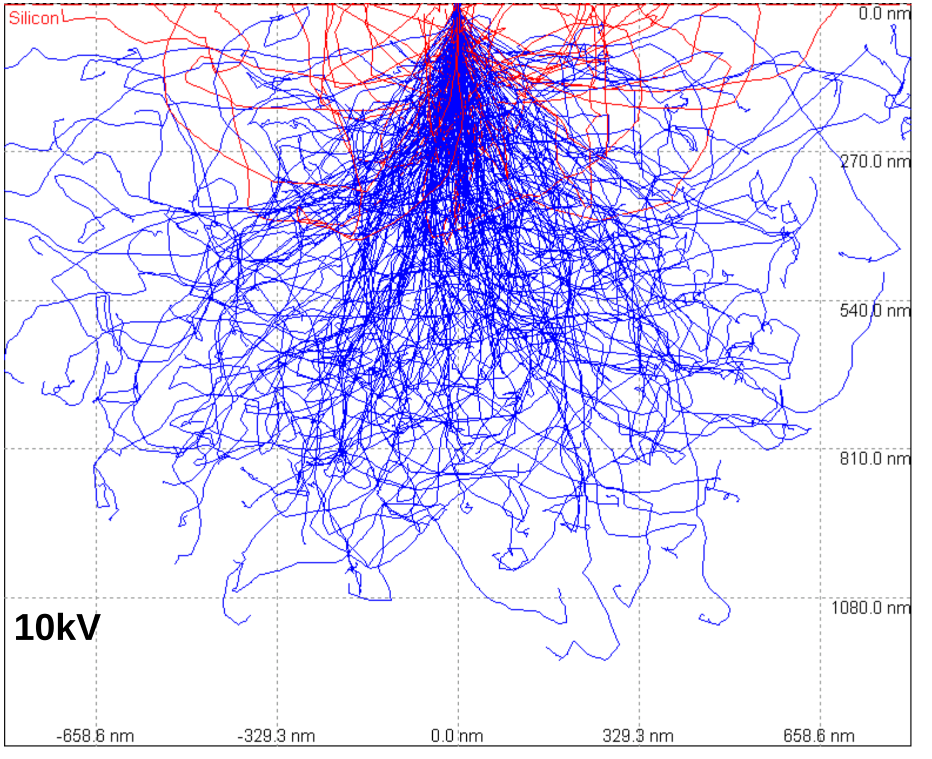
Low kV

- Lower resolution
- Less beam penetration
- Lower beam current
- Lower signal to noise
- Lower x-ray yield
- Not so good for VP

Beam Sample Interaction – Influence of Beam Energy

Monte Carlo Simulations



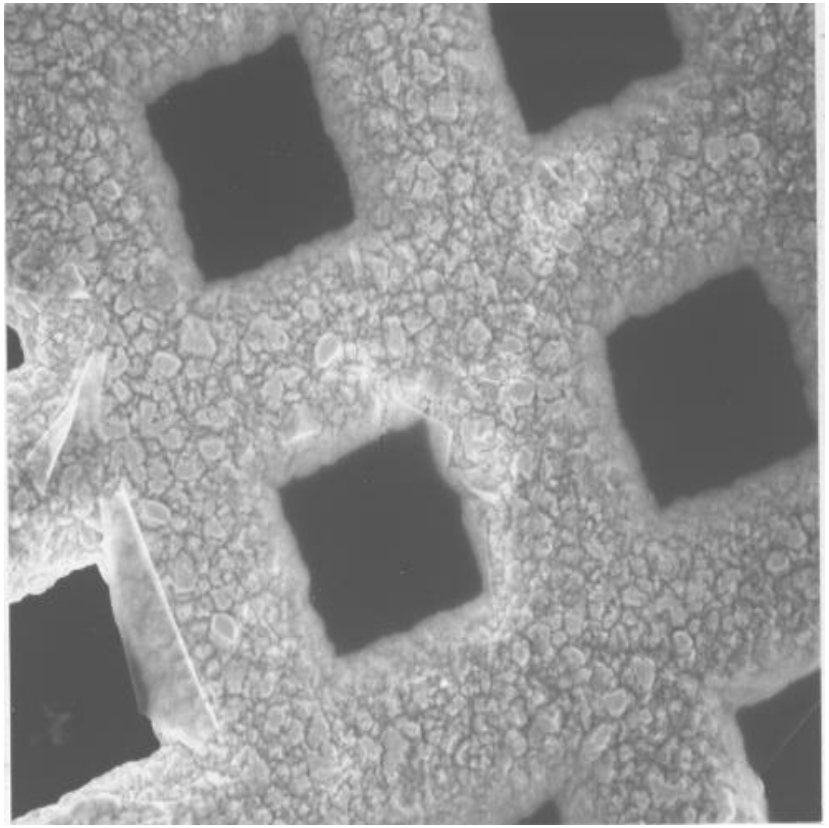


Monte Carlo simulation of the beam – sample interaction for a Si sample at 1kV and 10kV.

Courtesy Dr. David Joy – ORNL / UTK

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

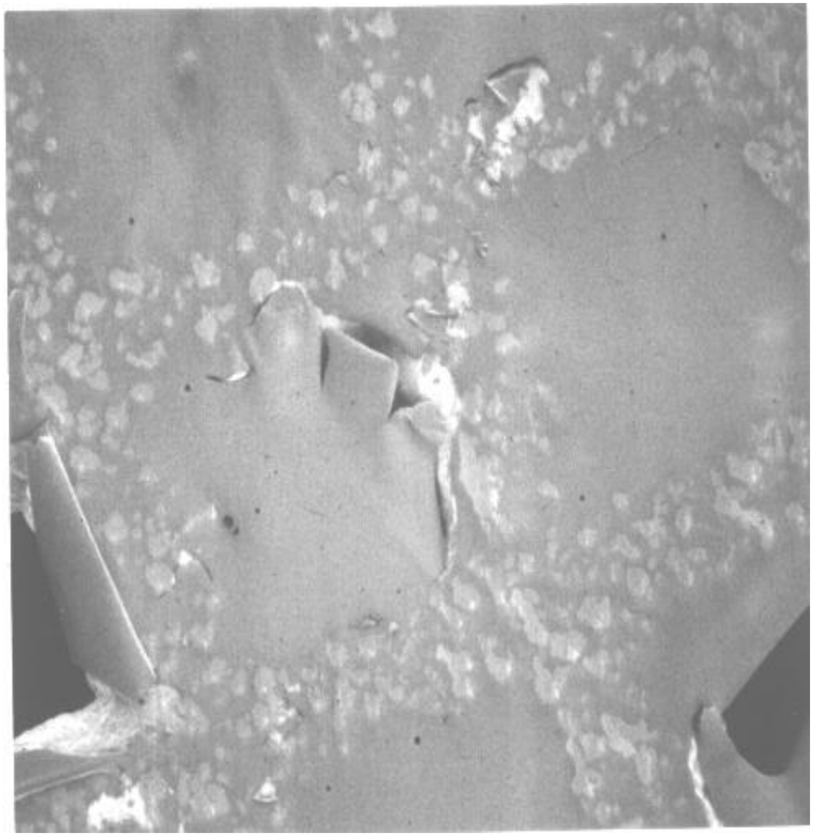


SE image of TEM grid 20keV

Courtesy Dr. David Joy – ORNL / UTK

Electron range at low energy

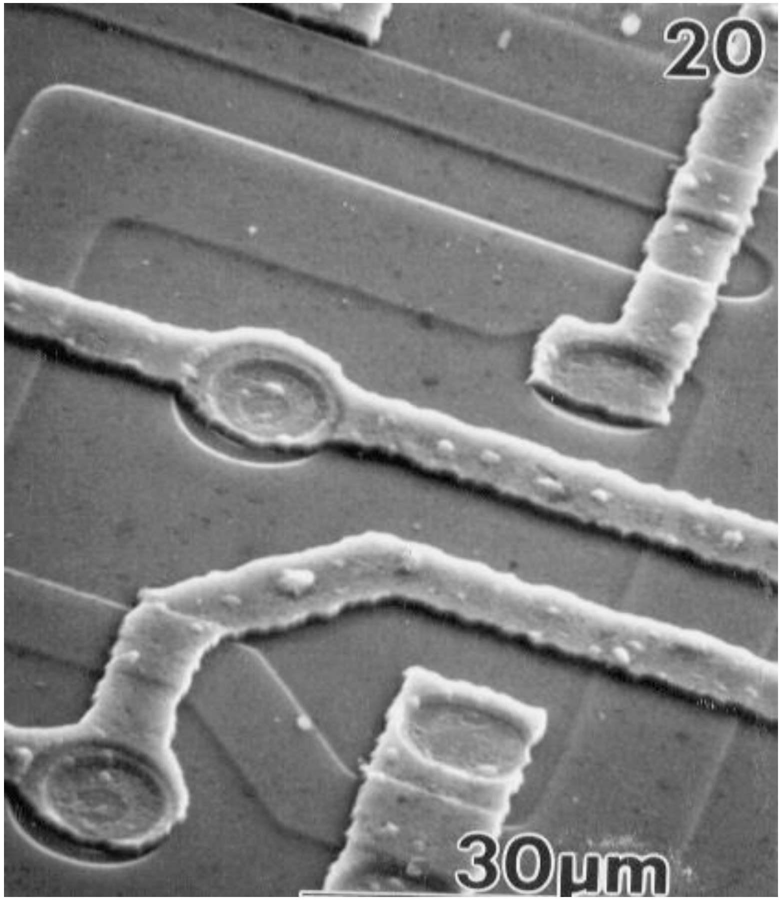
- At 1keV - by comparison - the Carbon appears solid and opaque because the beam does not penetrate through the film, and the Copper grid is not visible at all
- The variation of beam range with energy is dramatic and has significant results on what we see



Same area as before but 1keV beam

The High Energy Image

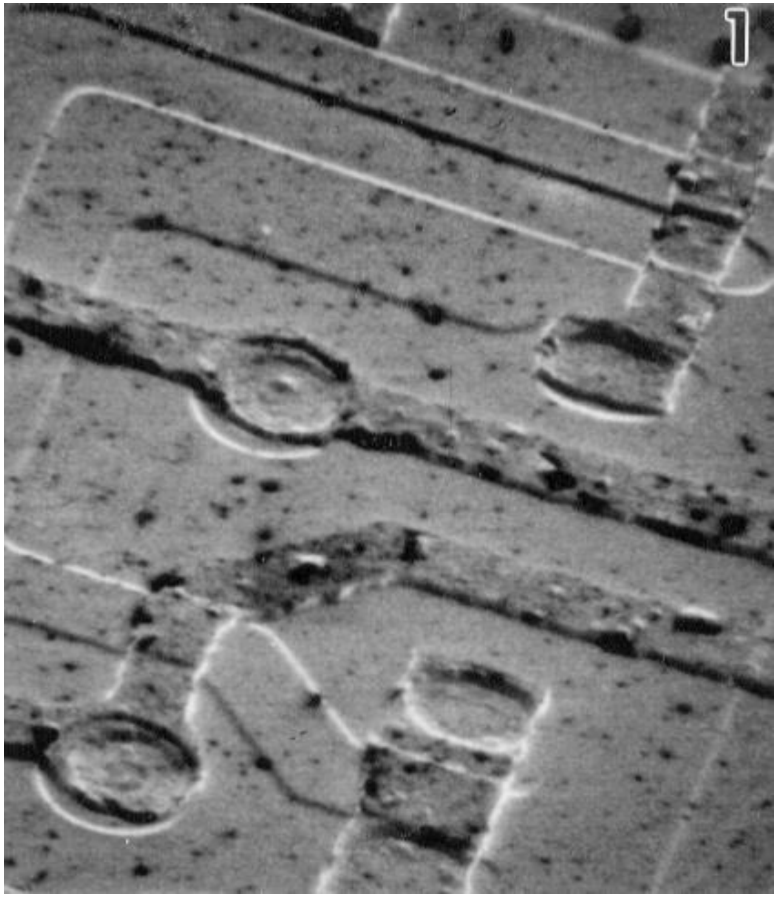
- The changes discussed above affect the form of the image
- At high energies we see the classic SEM ‘three dimensional’ appearance
- Surface detail is revealed by topographic contrast
- Because the interaction volume is large features above the surface are highlighted



Courtesy Dr. David Joy – ORNL / UTK

The Low Voltage SEM 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



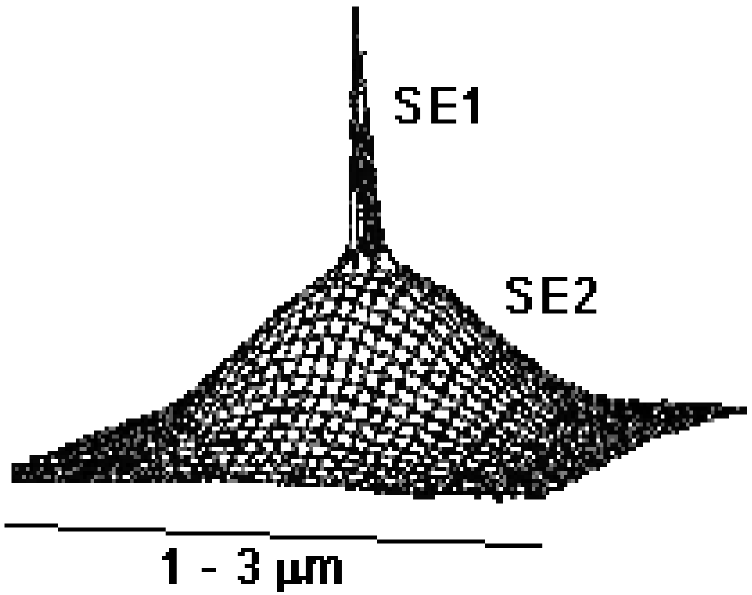
Courtesy Dr. David Joy – ORNL / UTK

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
- Less charge is deposited in the sample
- Beam damage is higher but is more localized
- But chromatic aberration deteriorates resolution

Courtesy Dr. David Joy – ORNL / UTK

Spatial Resolution…..

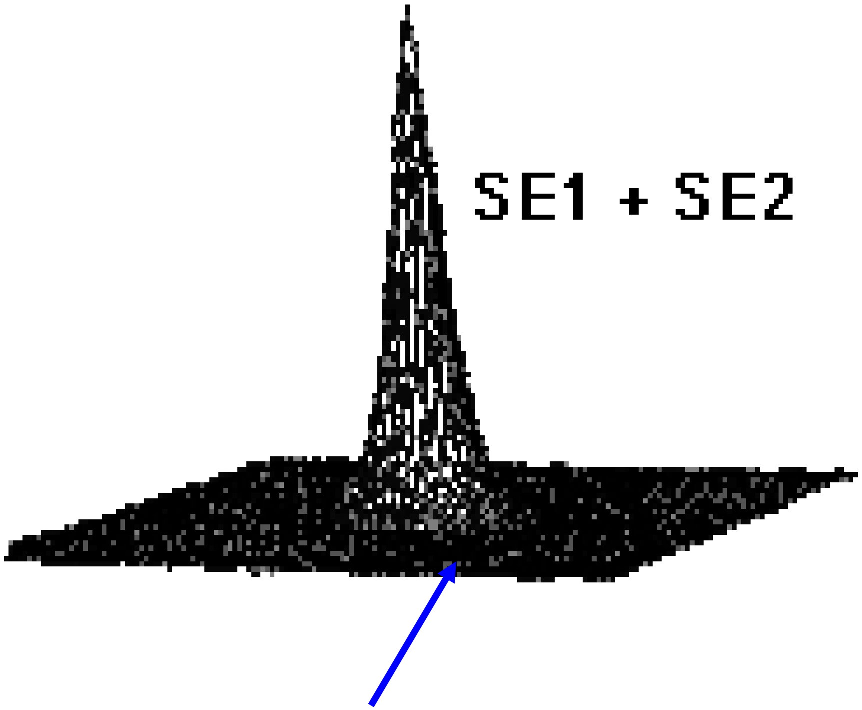


SE2 come from the full width of interaction volume

- 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

Courtesy Dr. David Joy – ORNL / UTK

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….

Aperture Size

Small Aperture

- Higher resolution
- Higher depth of focus
- Lower beam current
- Lower signal to noise
- Less x-ray yield
- May have smaller field of view (aperture cut-off)
- Not so good for VP

Large Aperture

- Lower resolution
- Less depth of focus
- Higher beam current
- Higher signal to noise
- Higher x-ray yield
- Good for VP

High Current Mode (Beam Current Adjustment)

Small Spot Size

- Higher resolution
- Lower beam current
- Lower signal to noise
- Less x-ray yield

Large Spot Size

- Lower resolution
- Higher beam current
- Higher signal to noise
- Higher x-ray yield
- Good for VP

Note: Spot size must be adjusted as a function of final field of view (magnification); i.e. the higher the magnification, the smaller the spot size and visa versa

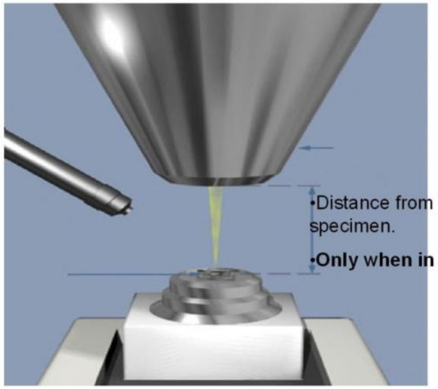
Working Distance

Short Working Distance

- Higher resolution
- Less Depth of Focus
- Better collection efficiency for In-Lens, AsB and EsB detectors
- Good for VP

Long Working Distance

- Lower resolution
- Greater Depth of Focus
- Better collection efficiency for In-Chamber SE
- Not so good for VP



•Distance from lens to specimen.

•**Only when in focus!!**

Variables Involved in Image Formation

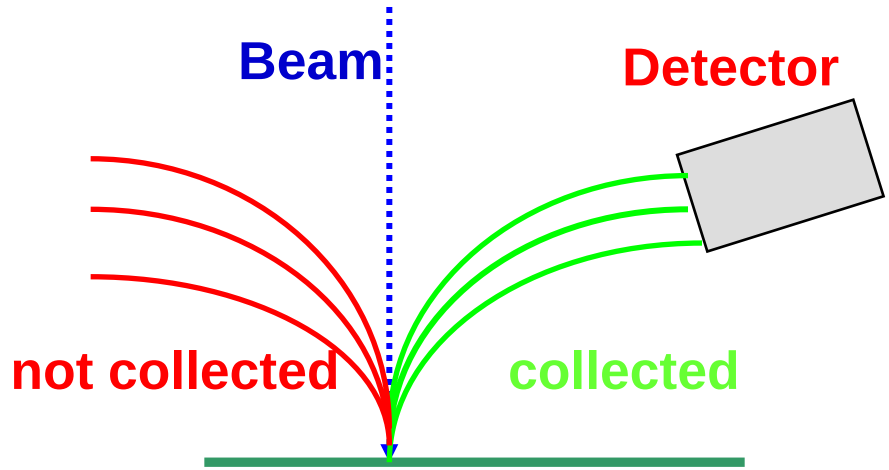
- ✓Acceleration Voltage (kV)
- ✓Final Aperture (size)
- ✓Probe Current (I probe)
- ✓Working Distance (WD)
- ✓Specimen
- ✓Column/Aperture Alignment
- ✓Optibeam

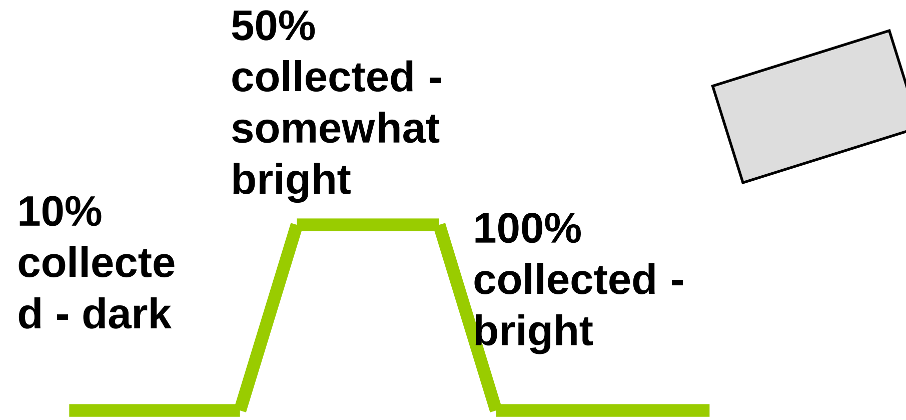
- ✓ Detector
- ✓ Specimen geometry
- ✓ Scanning speed
- ✓ Signal processing
- ✓ Noise reduction
- ✓ Contrast / brightness
- ✓ Chamber pressure
- ✓ System cleanliness

Image Formation

Detector Efficiency Contrast

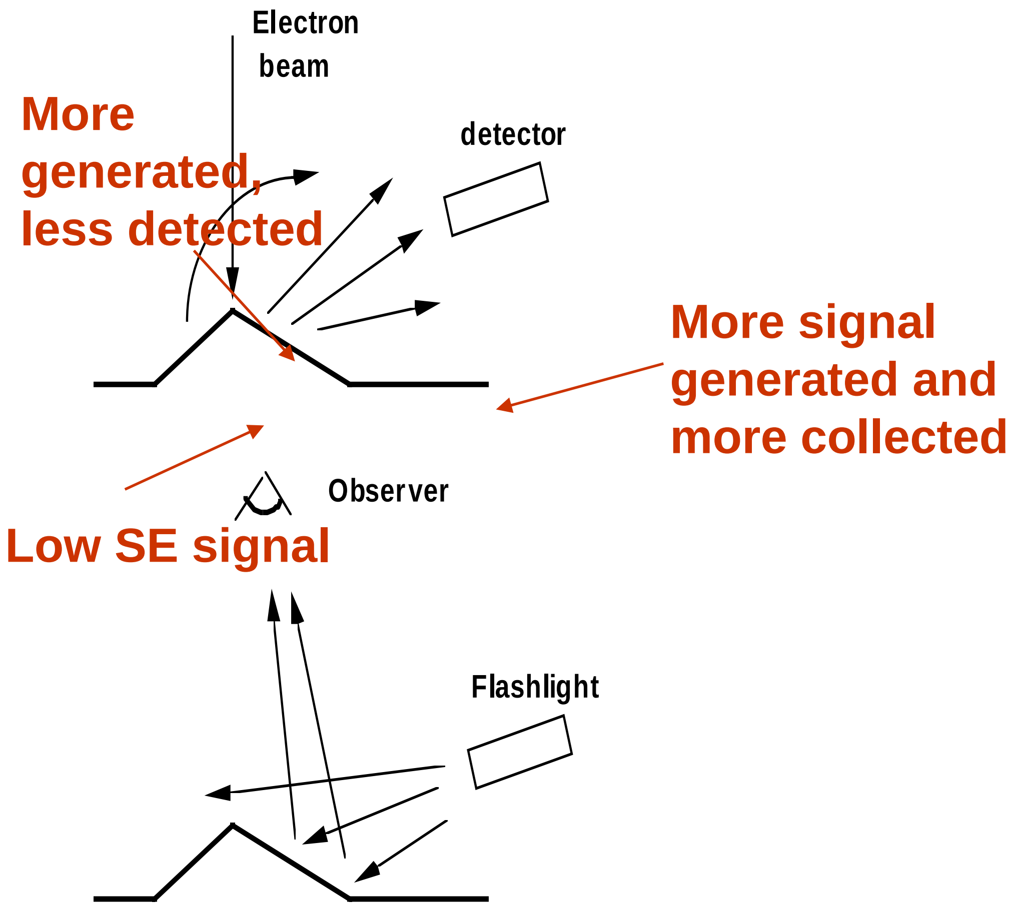
- SE emitted towards the detector are more likely to be collected than those traveling away from the detector since typical SE detectors collect <50%
- The position of a surface relative to the detector will therefore affect how bright it looks in the image.
- This ‘detector efficiency contrast’ is combined with topographic contrast
- In-lens detector will have less topographical contrast





Courtesy Dr. David Joy – ORNL / UTK

Interpreting the SE Image

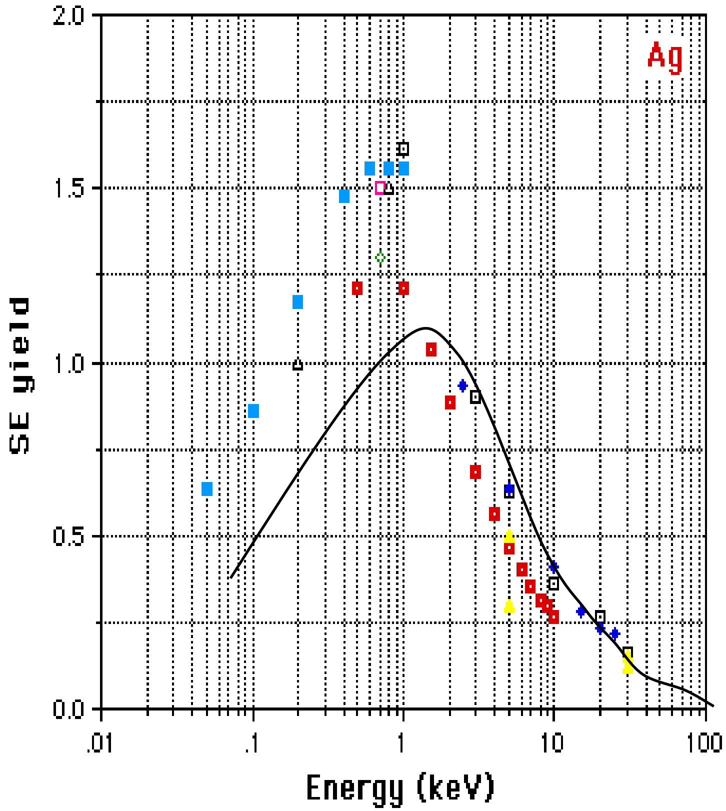


- Replace the detector by a flashlight, and imagine looking at the sample from the gun
- The SE image ‘looks’ like a real world image, light and dark, shadow and highlight
- A detector on the sample horizon will give strong shadows
- A detector above the sample gives no shadow information

Courtesy Dr. David Joy – ORNL / UTK

SE Yield Variation

- The rapid change in the incident electron beam range causes a large, characteristic variation in the SE yield from all samples
- Typically the yield rises from ~0.1 at 30keV to in excess of 1 at around 1keV, and as high as 100 for some materials

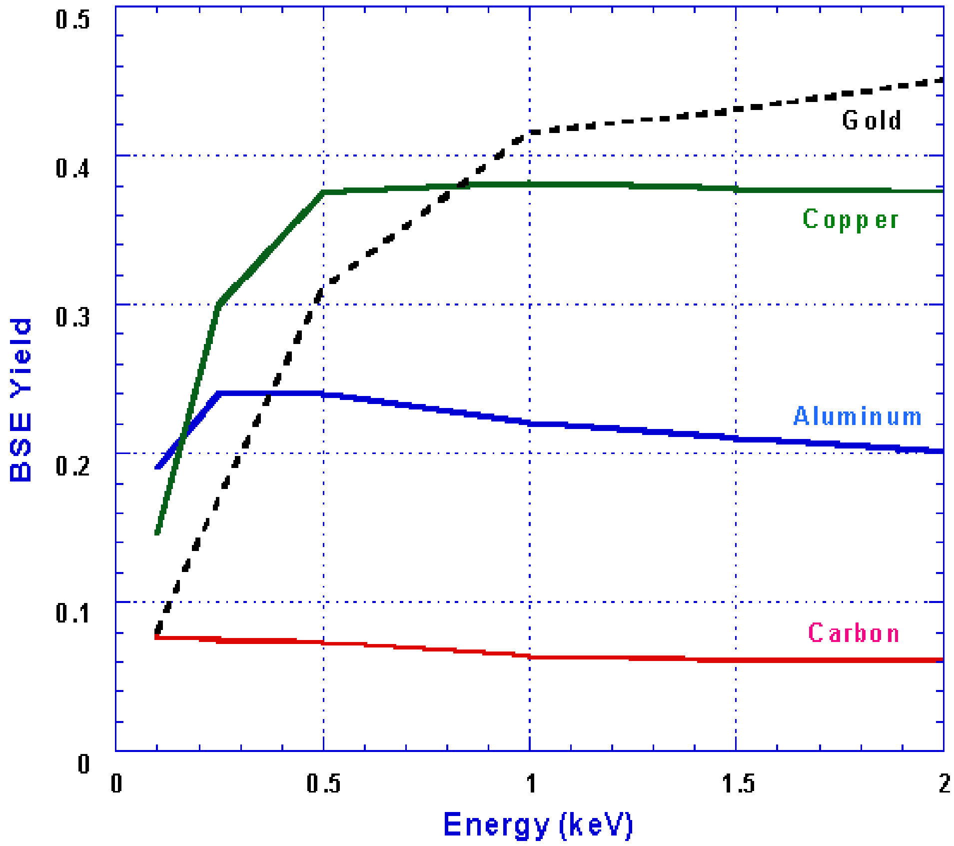


Experimental SE yield data for Ag

Courtesy Dr. David Joy – ORNL / UTK

BSE Yields at Low Voltage

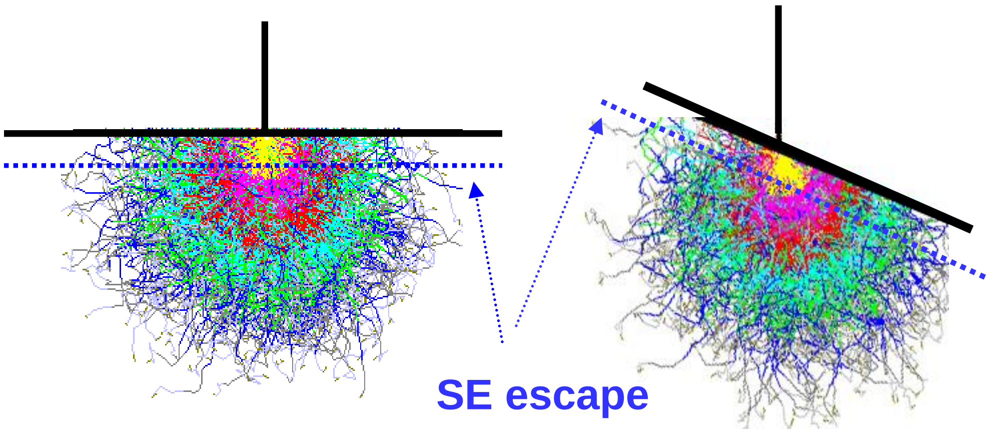
- The BSE yield η varies with energy as well as with atomic number
- Above ~2keV the yield rises steadily with Z
- But at low energies the BSE yield for low Z elements rises, and for high Z elements it falls
- Below 100eV the situation is more complex



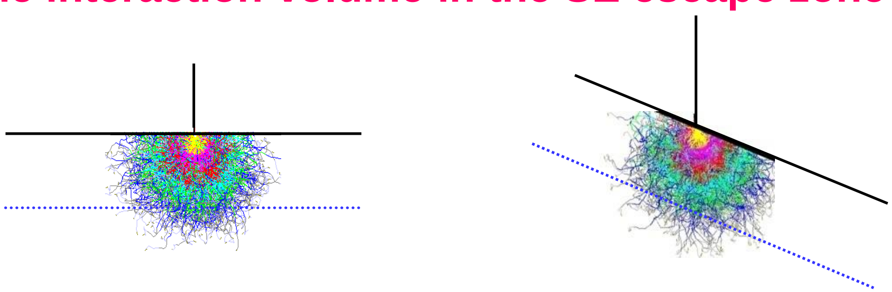
Experimental BSE yield data

Courtesy Dr. David Joy – ORNL / UTK

Origin of Topographic Contrast

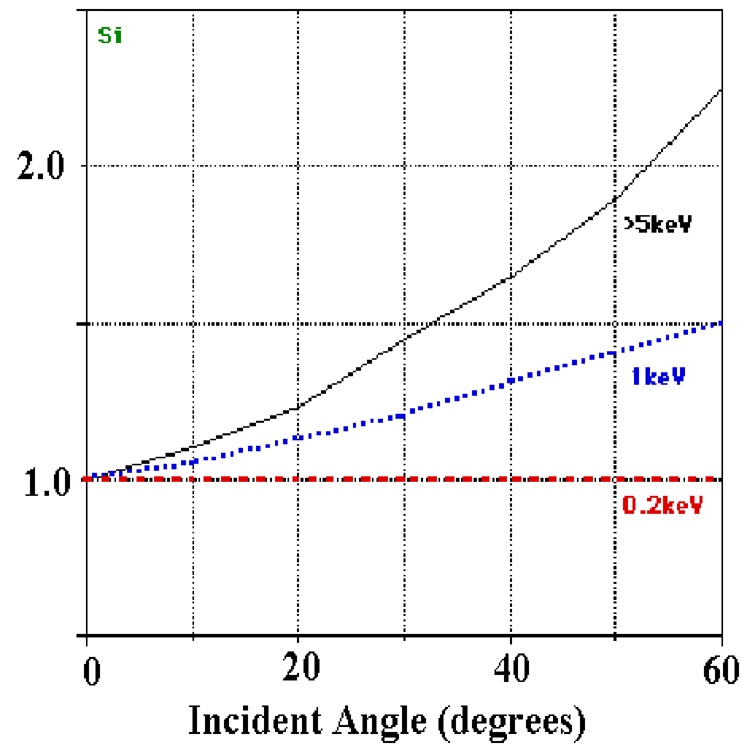


At high energy tilting the sample puts more of the interaction volume in the SE escape zone



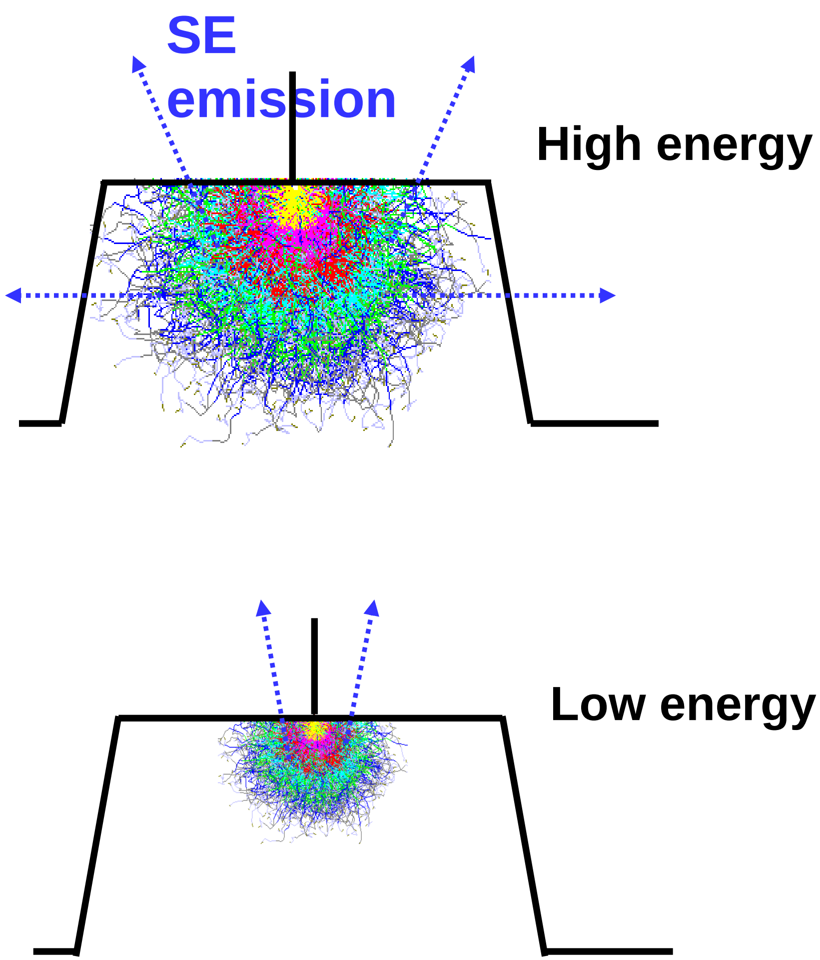
But at low energy all the SE always escape

- Topographic contrast weakens and ultimately disappears as the beam energy is reduced.



Courtesy Dr. David Joy – ORNL / UTK

Beam Penetration Effects

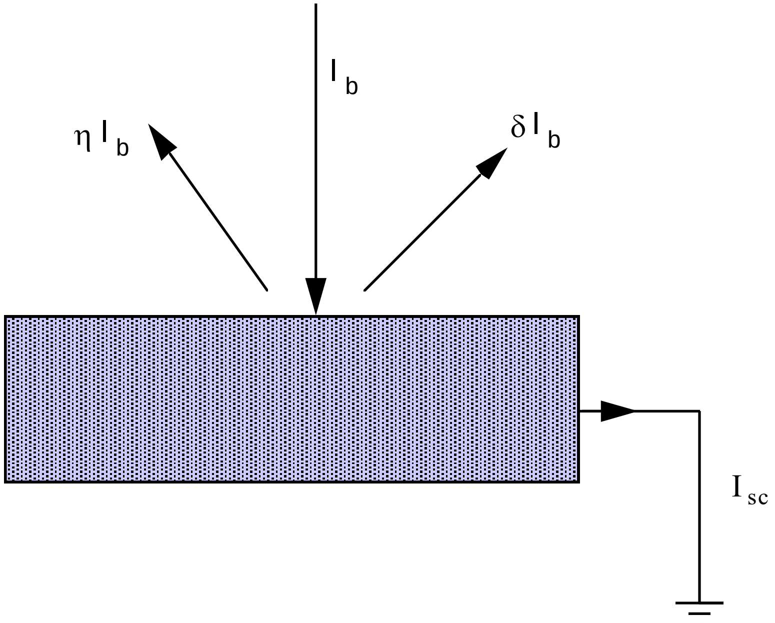


- At high energy the interaction volume fills features on the surface - SE2 emission leads to enhanced SE emission making objects look almost 3-dimensional
- But at low energies the reduced interaction volume means that only the edges of features are enhanced

Courtesy Dr. David Joy – ORNL / UTK

Charge Balance in the Sample

Electrons cannot be created or destroyed so currents at a point must sum to zero. The current flow to earth I_{sc} is the difference between the in and out currents

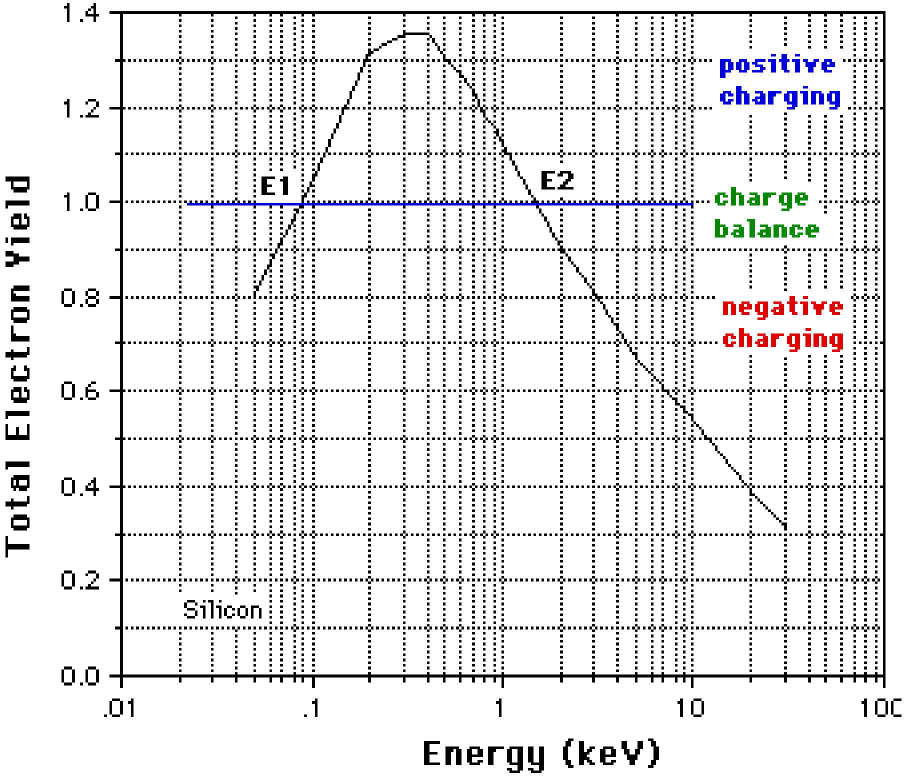


$$I_{sc} = I_b - \eta I_b - \delta I_b = I_b\,(1-(\eta+\delta))$$

If the sample is a conductor I_{sc} can take any value (+ve or -ve) to achieve charge balance

The Charge Balance Condition

- The form of the variation of the (η+δ) yield curve is much the same for all materials
- In almost every case there are energies for which (η+δ) = 1
- These are called the E1 and E2 energies
- E2 is a stable operating conditions, E1 is not

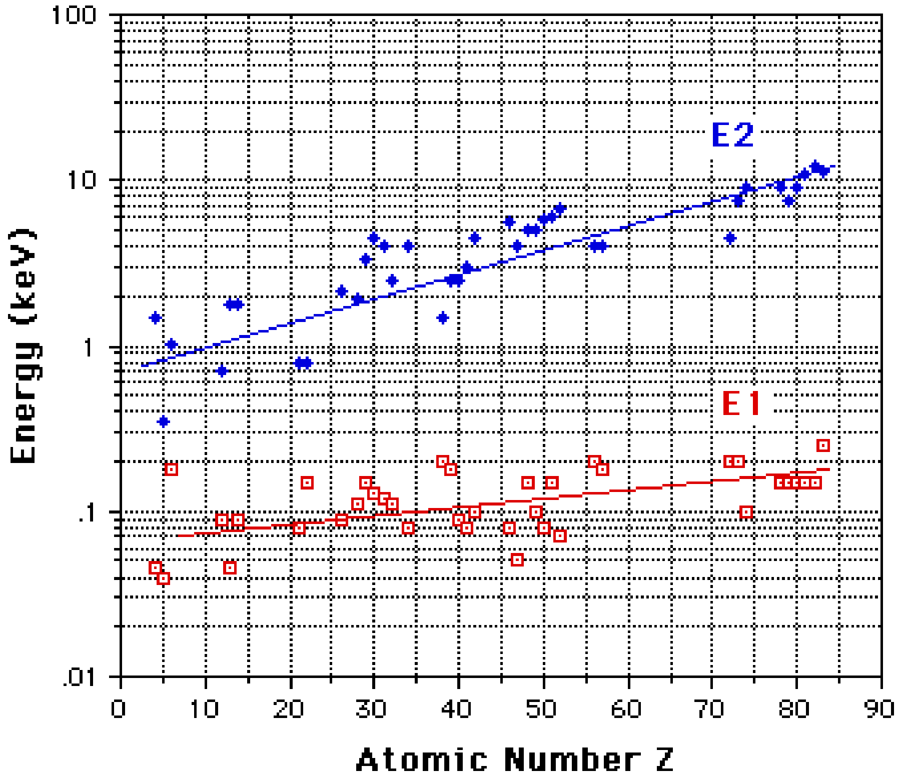


Total yield data for silicon

Courtesy Dr. David Joy – ORNL / UTK

E1 and E2 Values for Pure Elements

- E1 and E2 both increase with atomic number Z
- E2 may also depend on the density (e.g diamond, graphite, and dry biological tissue have very different E2 values)
- A few elements never reach charge balance (e.g Li, Ca)
- Low Z elements need low voltages. Since these elements are the basis of semiconductor technology and biology the goal has been to make SEMs work at these energies (0.5 - 2keV)



Computed E1 and E2 energies

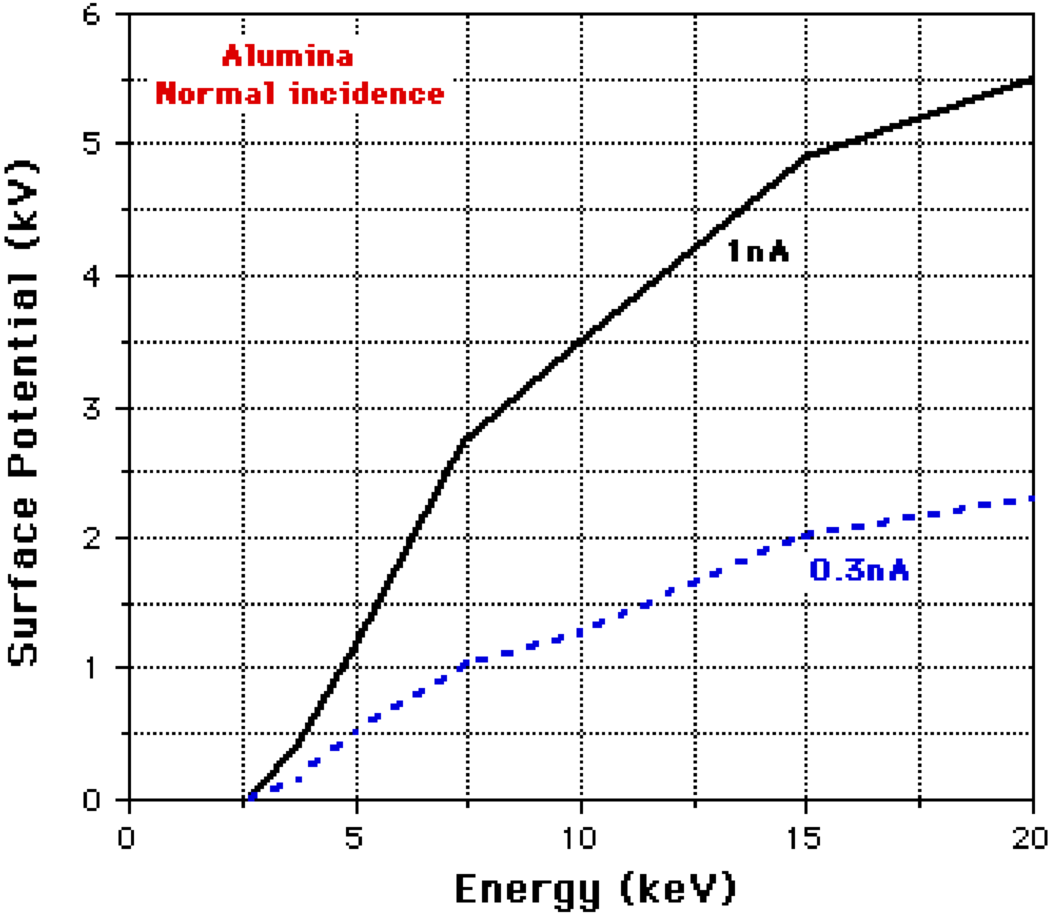
Common E2 Values

Material	E2(keV)	Material	E2 (keV)
Resist	0.55	Kapton	0.4
Resist on Si	1.10	Polysulfone	1.1
PMMA	1.6	Nylon	1.2
Pyrex glass	1.9	Polystyrene	1.3
Cr on glass	2.0	Polyethylene	1.5
GaAs	2.6	PVC	1.65
Sapphire	2.9	PTFE	1.8
Quartz	3.0	Teflon	1.8

Courtesy Dr. David Joy – ORNL / UTK

Living with Charging

- Reduce the beam current since the charging varies directly with I_B
- Use a smaller aperture, or reduce the gun emission current
- Reduces the S/N ratio so longer scan times may be required

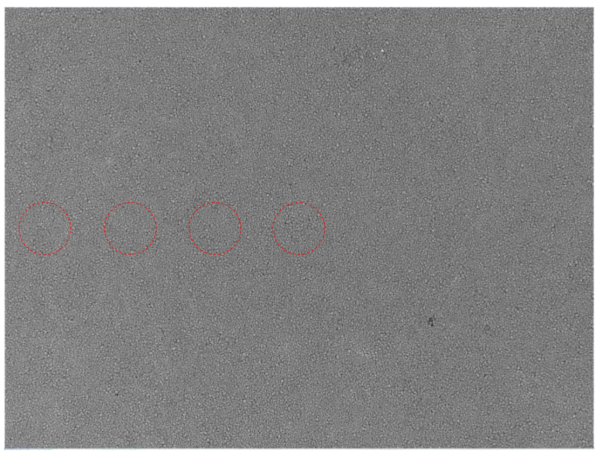


Courtesy Dr. David Joy – ORNL / UTK

	Best Aperture	**Best WD** for in-lens	**Gun Mode**
GeminiSEM 500	20um - Center	~1-1.5mm	2 HR and Analytical

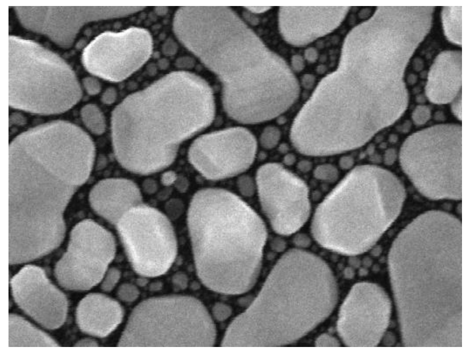
How much can one shift the beam without refocusing?

- The beam shift is simply an offset to the scanning system. As new system has smaller FOV, maximum beam shift is smaller.
- With beam shift the electron goes through the objective with certain angle. The lens abrasion leads to blurring.

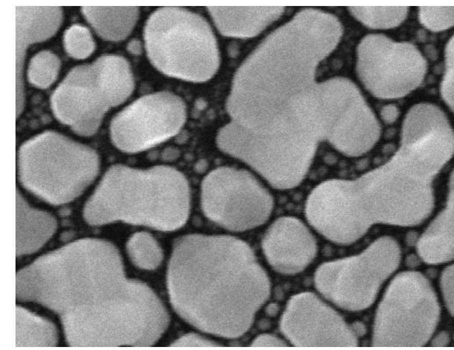


32k image, 64 µm FOV

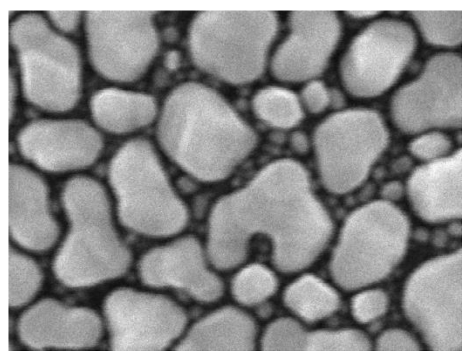
Beam shift below 10 µm without refocusing!



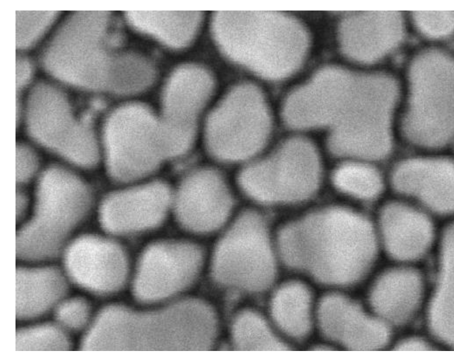
center



10 µm



20 µm



30 µm

Alignment

Ideally the electron beam should pass through center of the objective. Such requirements is much tighter for low-kV lens compared to the old lens. A small misalignment in the aperture apparently leads to reduced resolution.

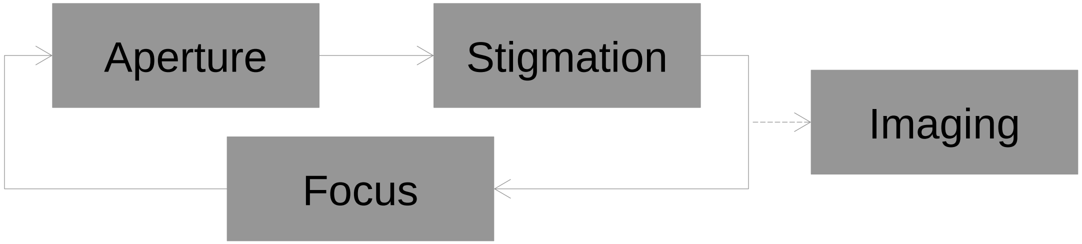
The user might observe:

•Aperture alignment needs to be corrected more often, especially when changing WD.

•The coupling between stigmation and aperture alignment is more pronounced. An iterative alignment might be necessary.

Typical alignment flow on other Gemini Columns

Alignment flow on GeminiSEM 500, worst case



- **The effect of such coupling depends on “stig balance”, a bad “stig balance” will demand more iterative alignment procedure.**

Resolution vs. Aperture Selection

Due to the complicated combination of condenser behavior and aperture sizes, resolution is changing and hard to follow. Example: Probe size / Aperture / Column mode / Current at EHT 1kV WD1

Aperture (µm)	Probe size (nm)	Current (pA)	Probe size (nm) HC	Current (pA) HC
7	1.08	3.5	3.6	6.5
10	1.04	6.6	2.6	12.2
15	1.66	13.5	1.9	24.8
20 (center)	1.10	37.0	1.5	40.7
30	9.3	51.2	1.2	94.2
60	71.9	205	1.9	377
120	574	778	10.1	1440

- **Smaller off-axis aperture in normal mode and larger off-axis aperture in high current mode gives reasonable resolution at low kV.**
- **The situation at high kV is completely different, as the optimum convergence is very different at high kV.**
- **Be careful with off-axis aperture! Try and error.**

Thank You