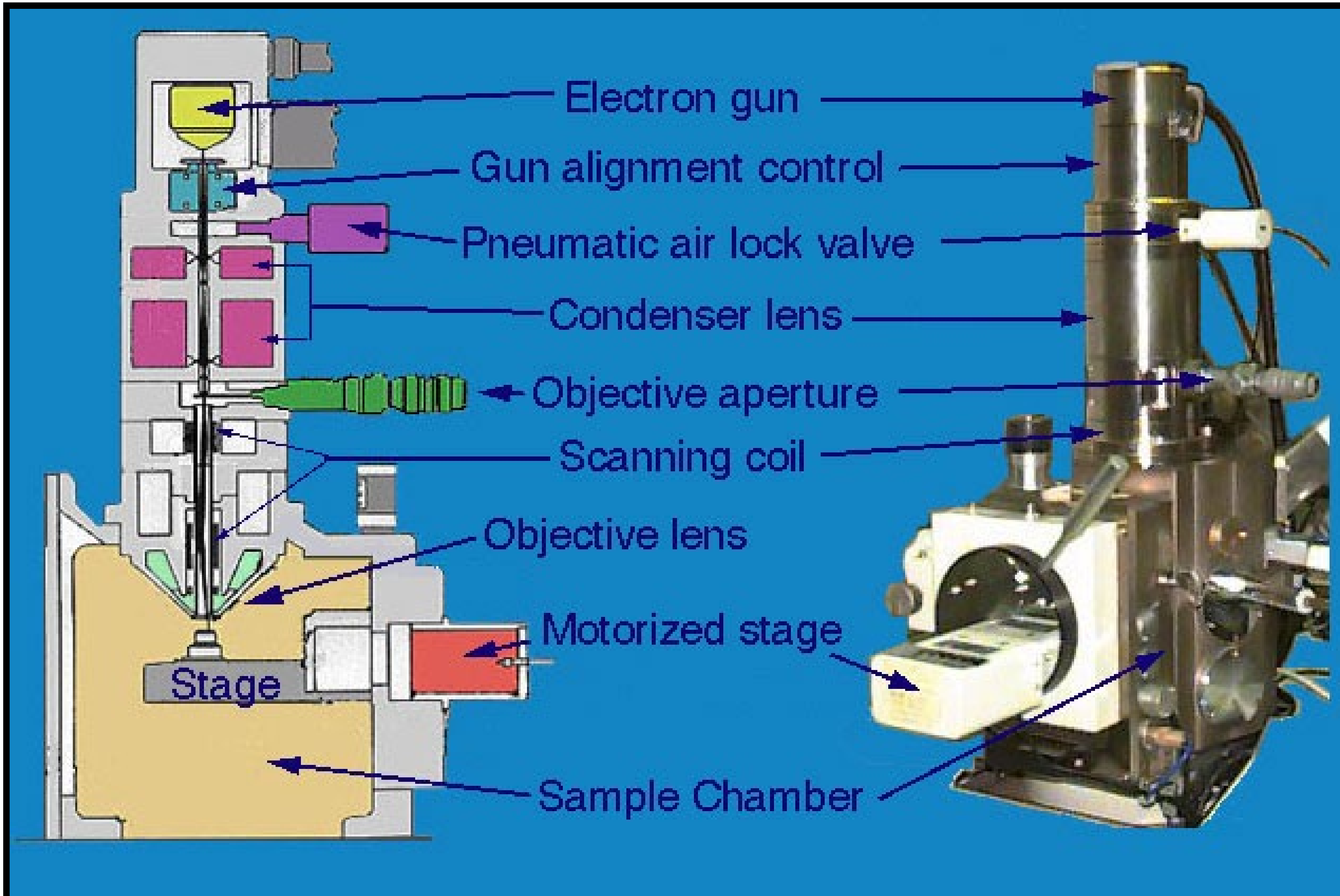
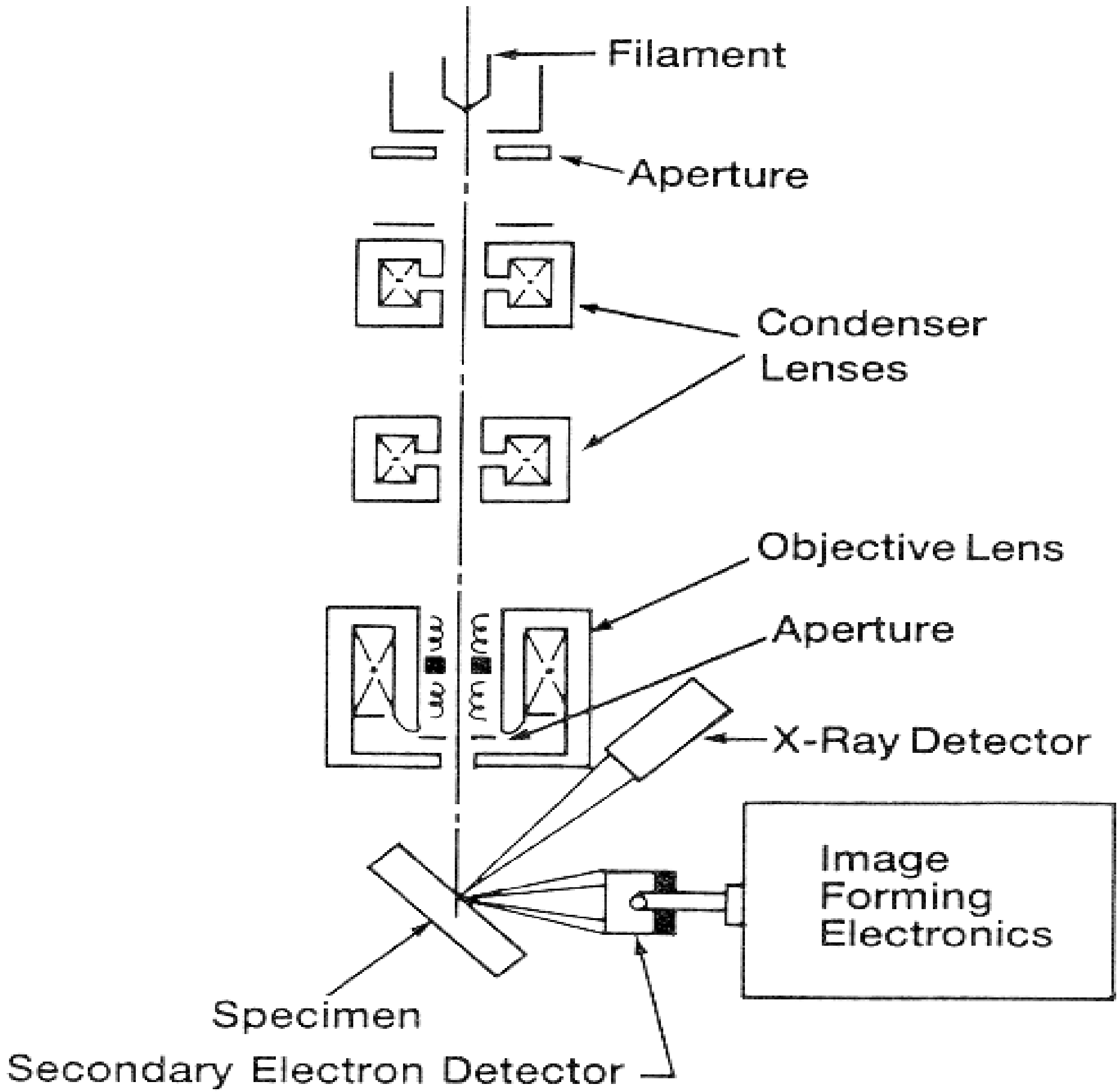
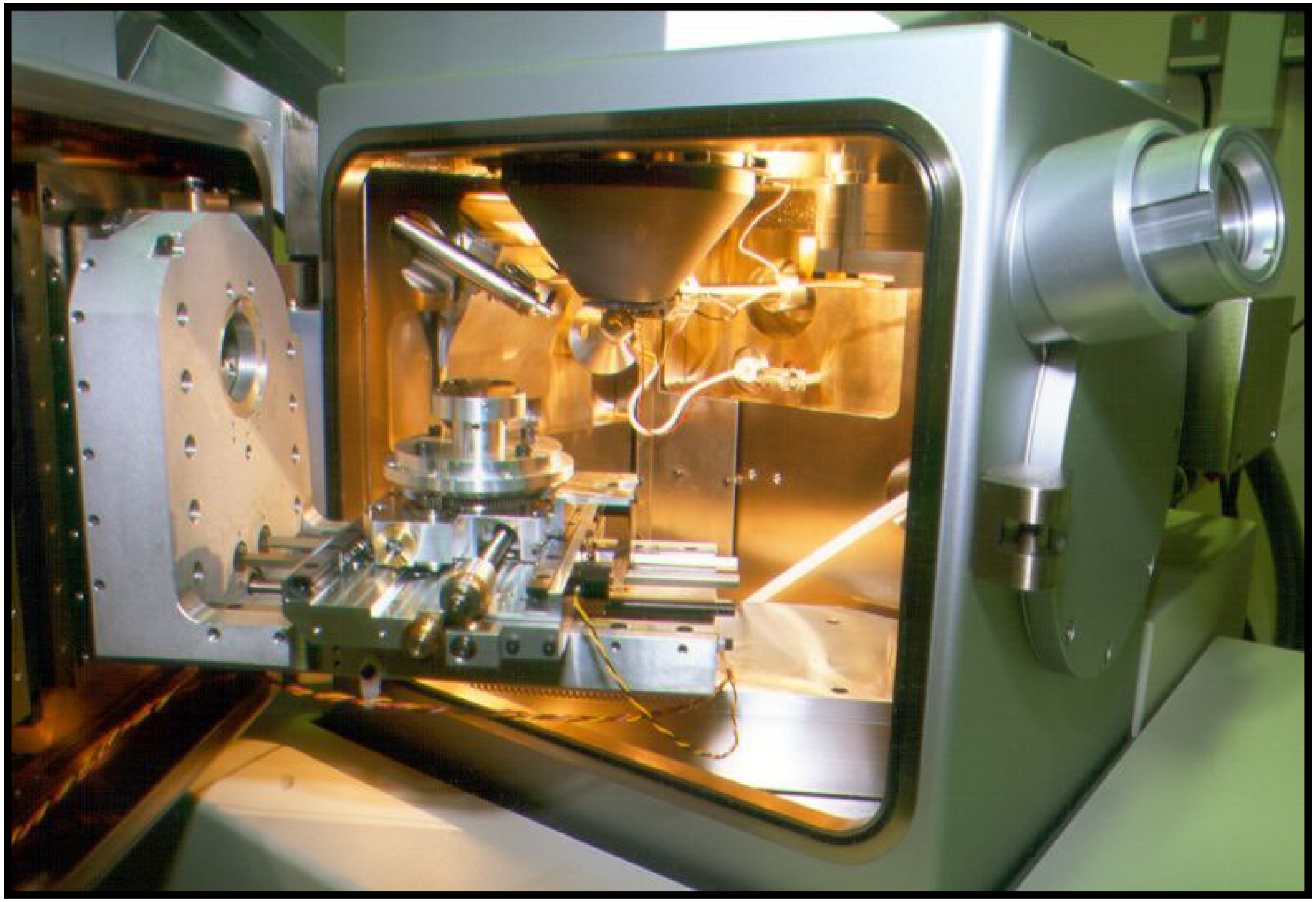
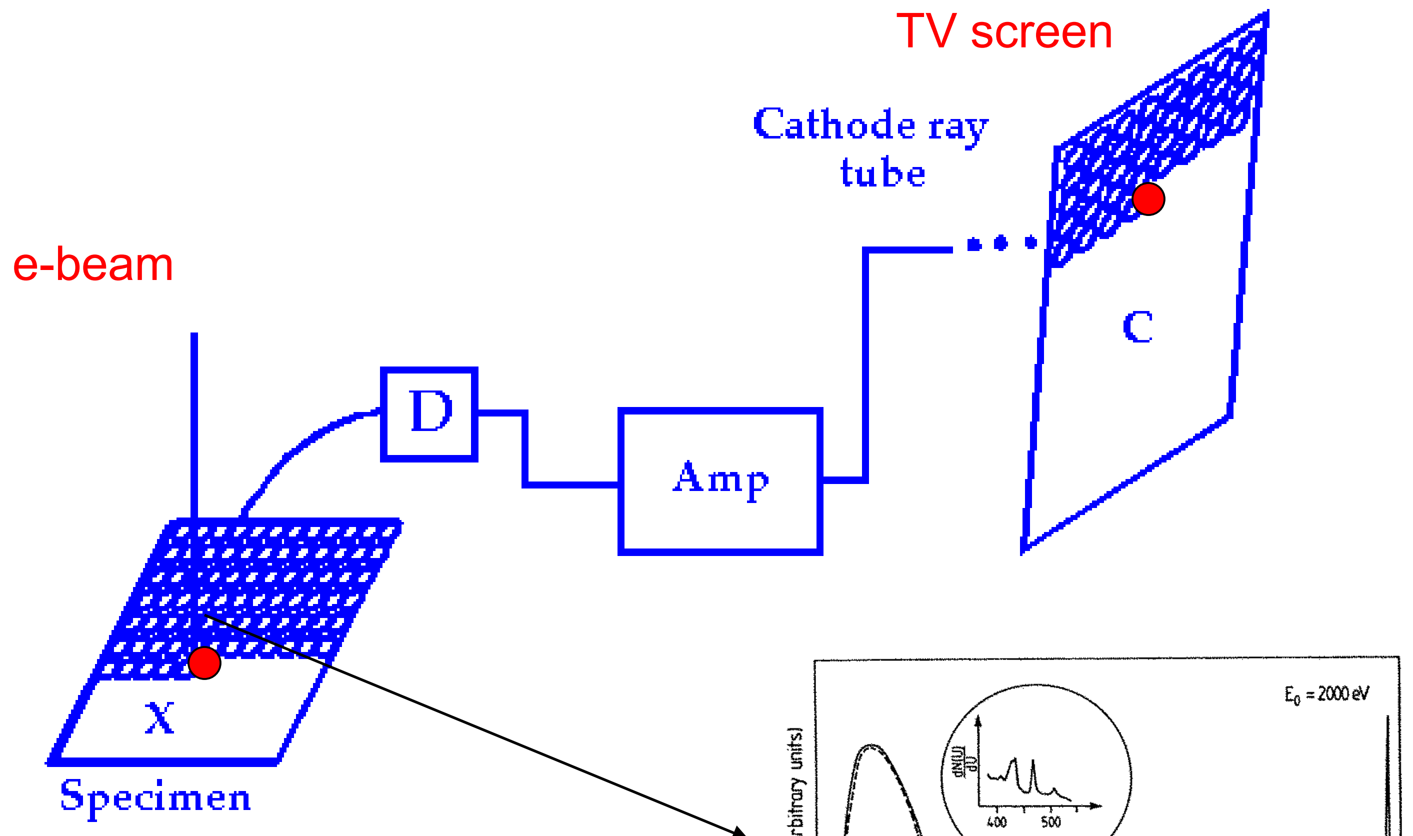

Electron gun
Gun alignment control
Pneumatic air lock valve
Condenser lens
Objective aperture
Scanning coil
Objective lens
Motorized stage
Stage
Sample Chamber


Filament
Aperture
Condenser
Lenses
Objective Lens
Aperture
X-Ray Detector
Image
Forming
Electronics
Specimen
Secondary Electron Detector

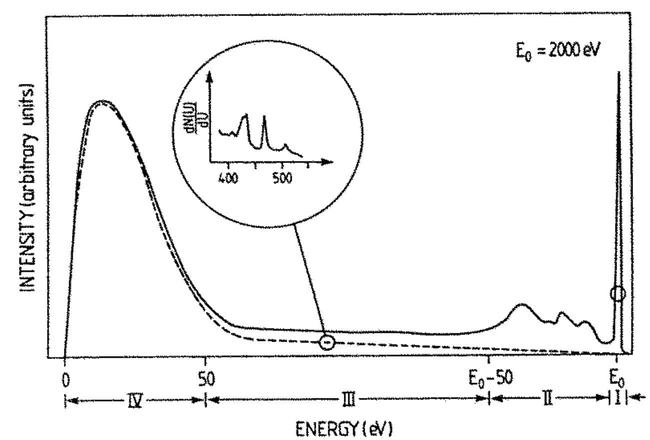


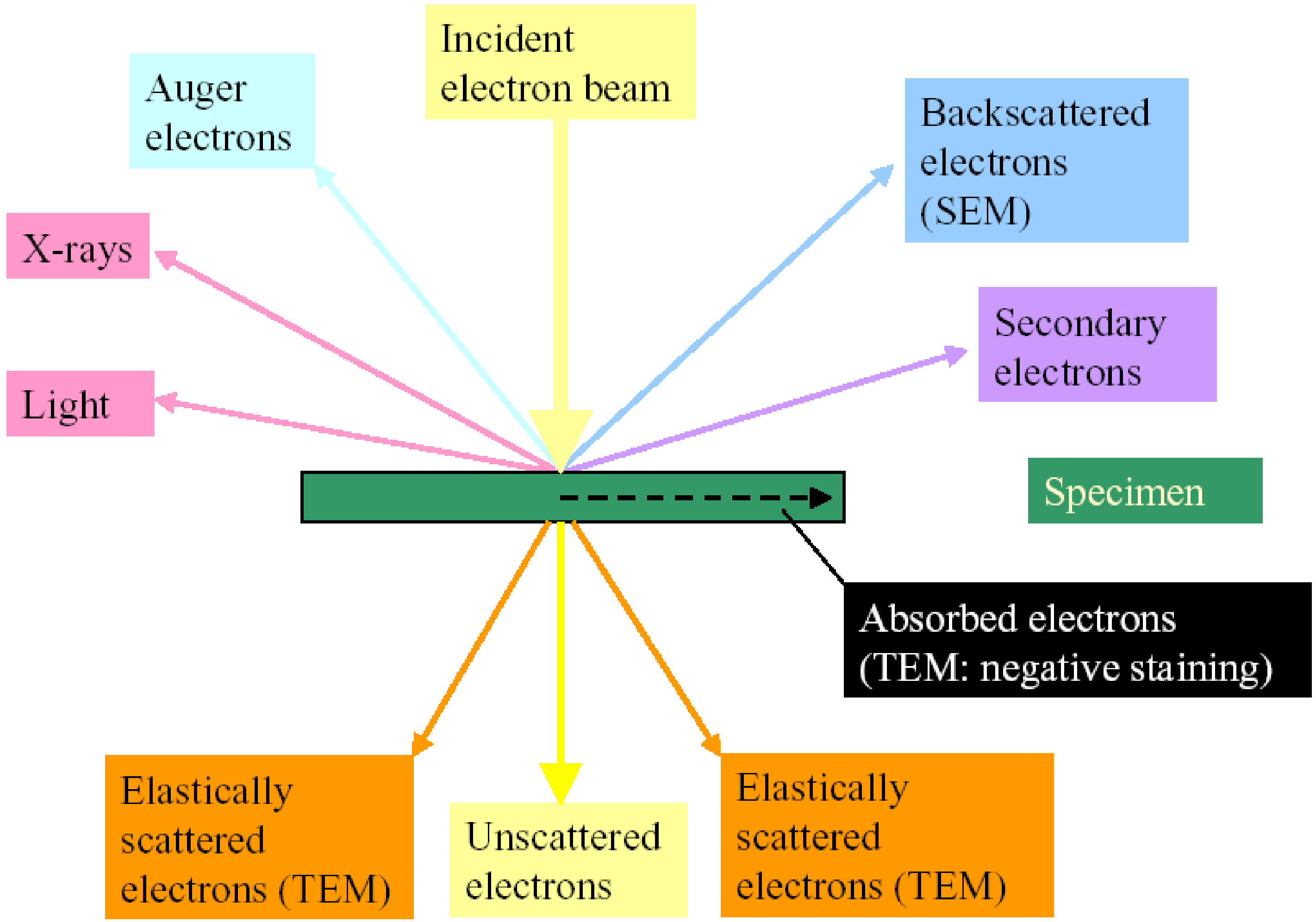
A number of different detectors can be incorporated into the chamber surrounding the specimen.

Image Formation



The selection of signal

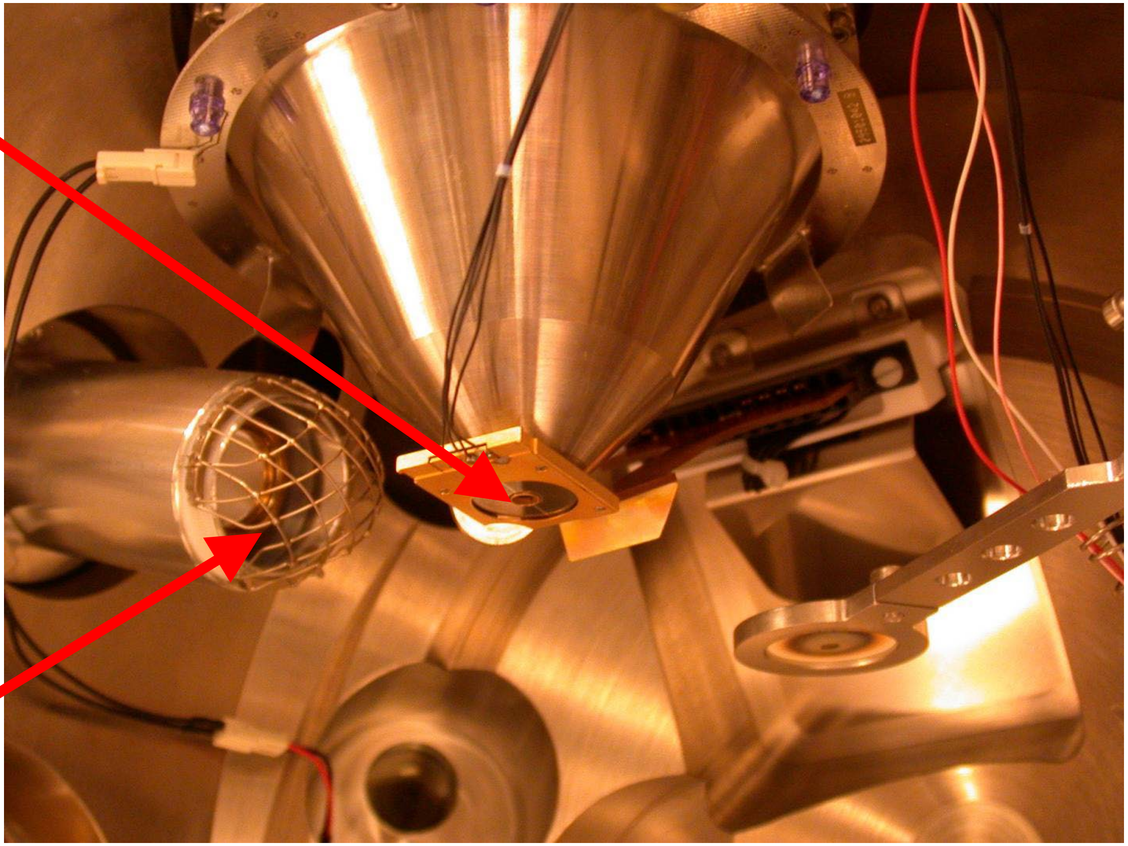




Interaction of electron with specimen

Detectors

Backscattered electron detector:
(Solid-State Detector)

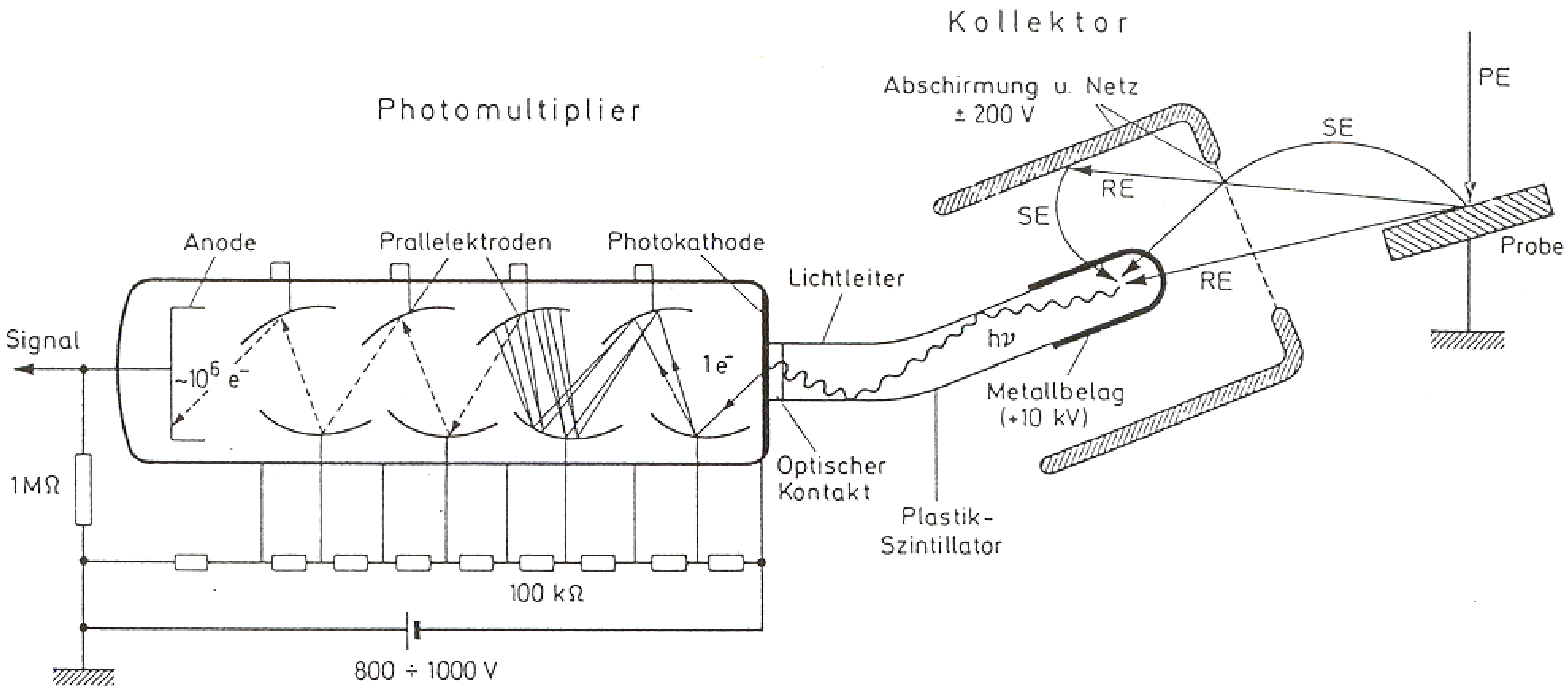


Secondary electron detector:
(Everhart-Thornley)

Image: Anders W. B. Skilbred, UiO

Detector for secondary electrons

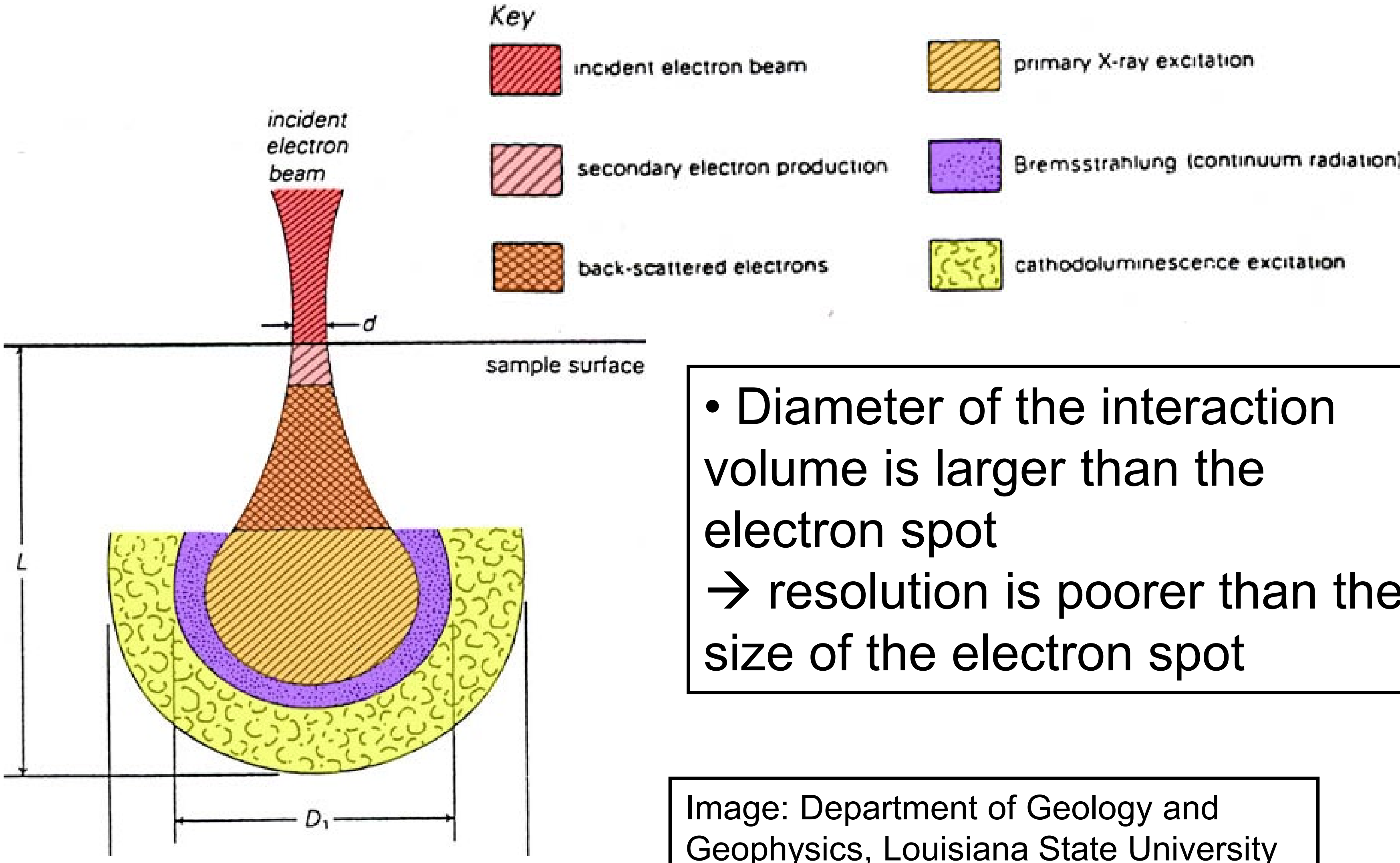
The most common scintillator is consisting of Y2SiO5 doped with cerium – luminescent material which changes electrons into photons – at photocathode change of phonons into electrons – these are multiplied then



The $64,000 Question

- Do we need to consider coherence?
- Formation of probe in SEM is coherent
- Image/Contrast Mechanisms
  - At low resolution many are incoherent, depend only upon $|\psi(r)|^2=\rho(r)$
  - These images are "simple", interpretation similar to light images
  - At high resolution (~1nm) coherence *cannot* be neglected
  - Hence in most cases (lower resolution) SEM is simple.

Where does the signals come from?

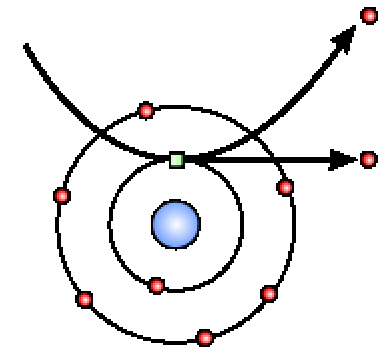


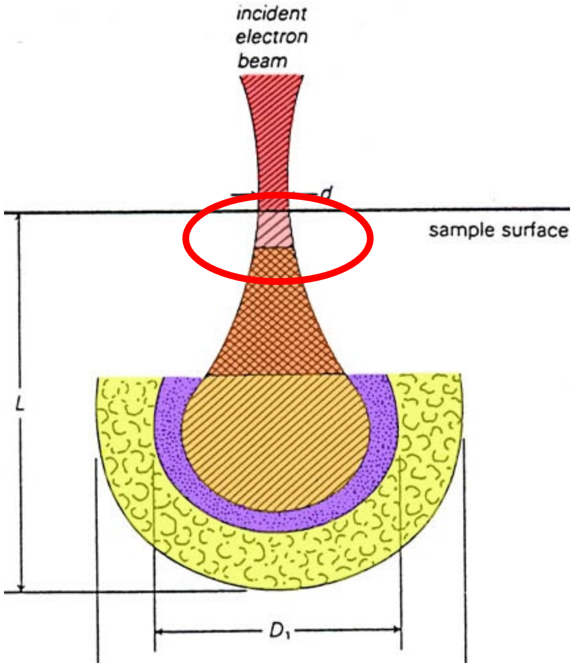
- Diameter of the interaction volume is larger than the electron spot
→ resolution is poorer than the size of the electron spot

Image: Department of Geology and Geophysics, Louisiana State University

Secondary electrons (SE)

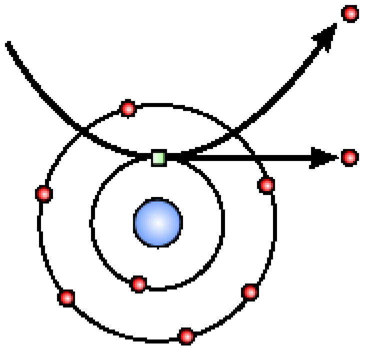
- Generated from the collision between the incoming electrons and the loosely bonded outer electrons
- Low energy electrons (~10-50 eV)
- Only SE generated close to surface escape (topographic information is obtained)
- Number of SE is greater than the number of incoming electrons
- We differentiate between SE1 and SE2





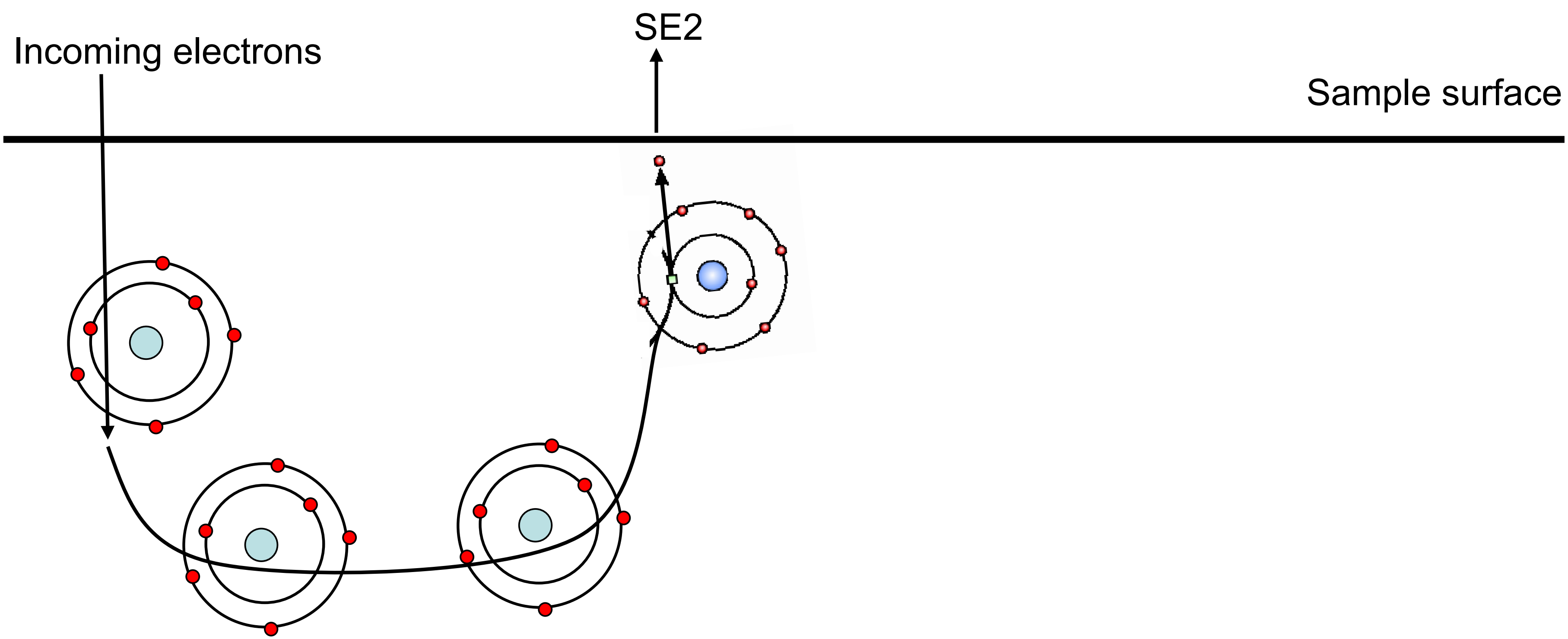
SE1

- The secondary electrons that are generated by the incoming electron beam as they enter the surface
- High resolution signal with a resolution which is only limited by the electron beam diameter



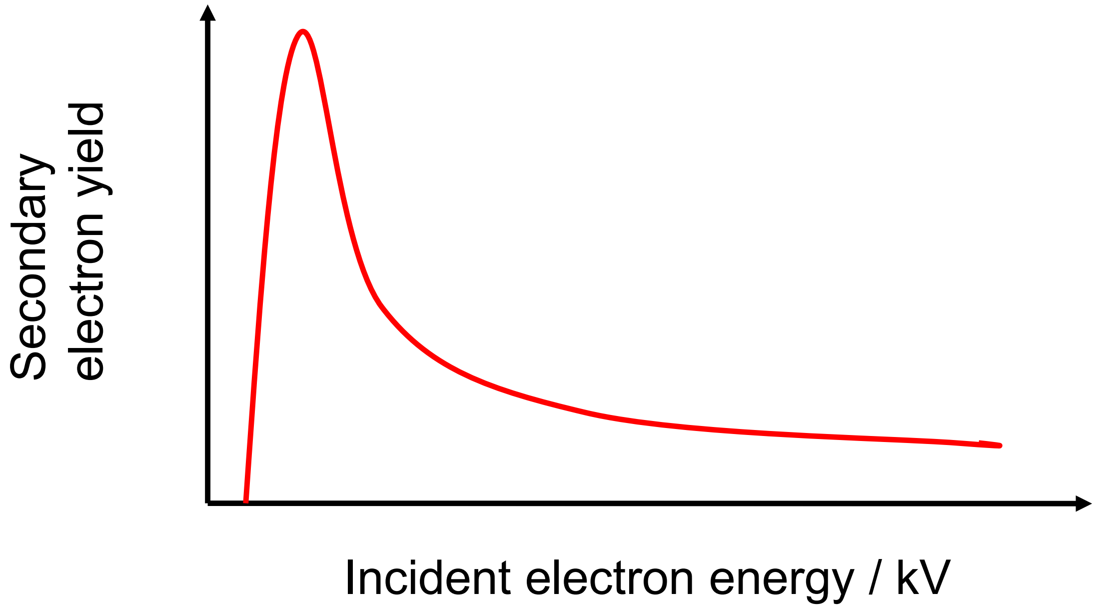
SE2

- The secondary electrons that are generated by the backscattered electrons that have returned to the surface after several inelastic scattering events
- SE2 come from a surface area that is bigger than the spot from the incoming electrons → resolution is poorer than for SE1 exclusively



Factors that affect SE emission

1. Work function of the surface
2. Beam energy and beam current
   - Electron yield goes through a maximum at low acc. voltage, then decreases with increasing acc. voltage



Factors that affect SE2 emission

3. Atomic number (Z)
   - More SE2 are created with increasing Z
   - The Z-dependence is more pronounced at lower beam energies
4. The local curvature of the surface (the most important factor)

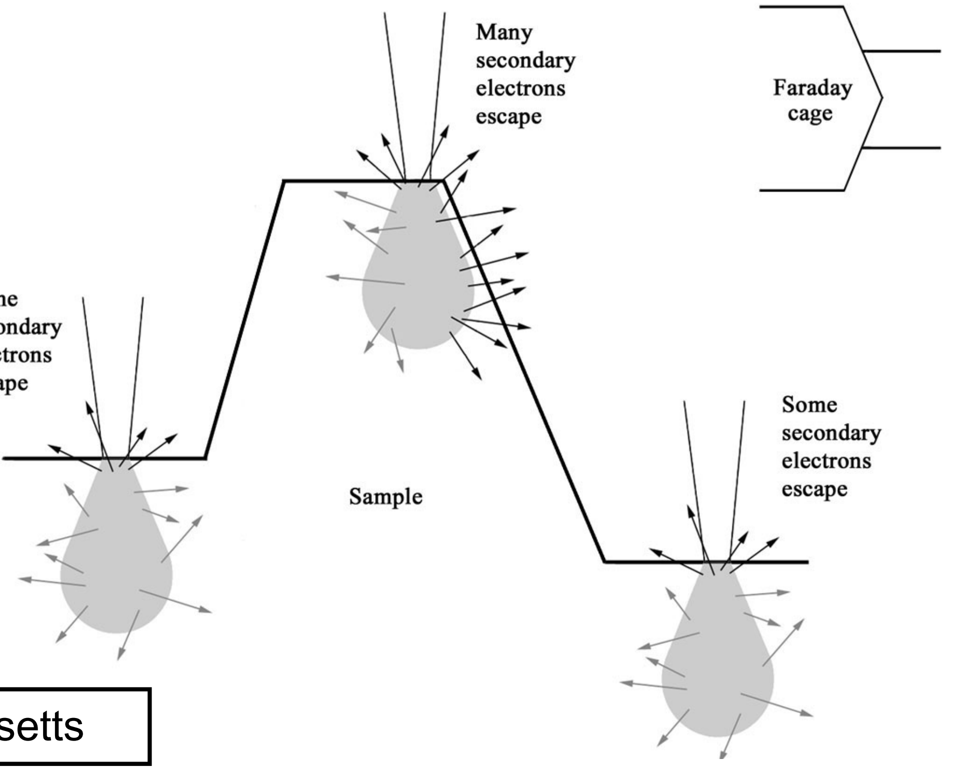
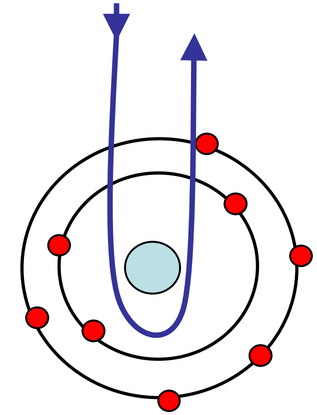
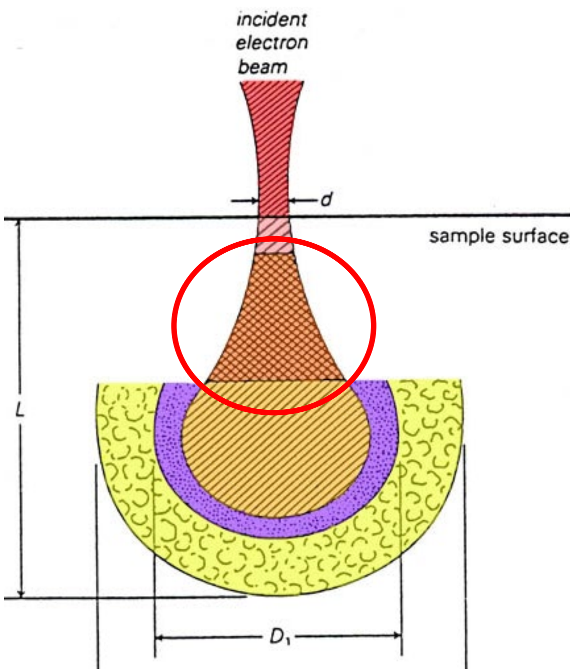


Image: Smith College Northampton, Massachusetts

Backscattered electrons (BSE)

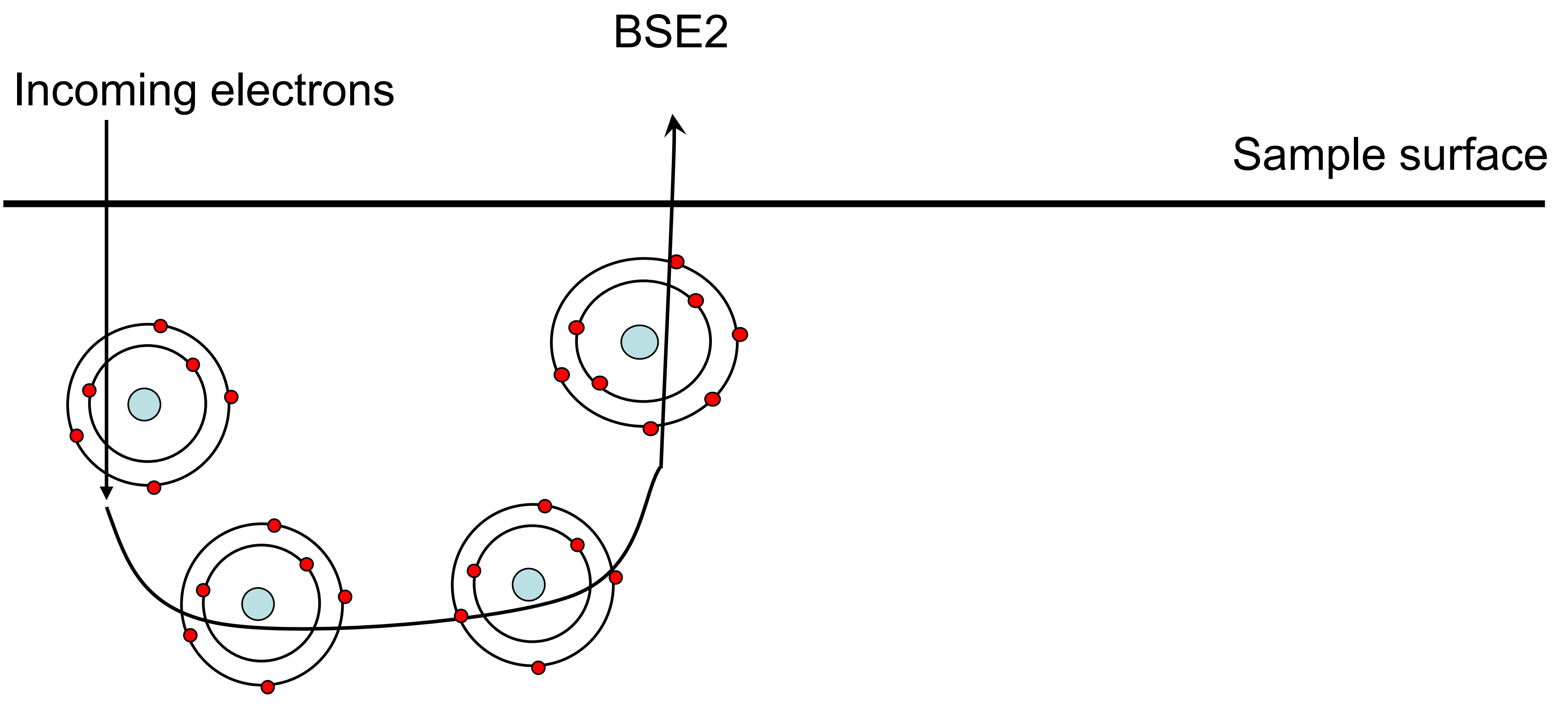


- A fraction of the incident electrons is retarded by the electro-magnetic field of the nucleus and if the scattering angle is greater than 180 ° the electron can escape from the surface



BSE2

- Most BSE are of BSE2 type



BSE as a function of atomic number

- For phases containing more than one element, it is the average atomic number that determines the backscatter coefficient η

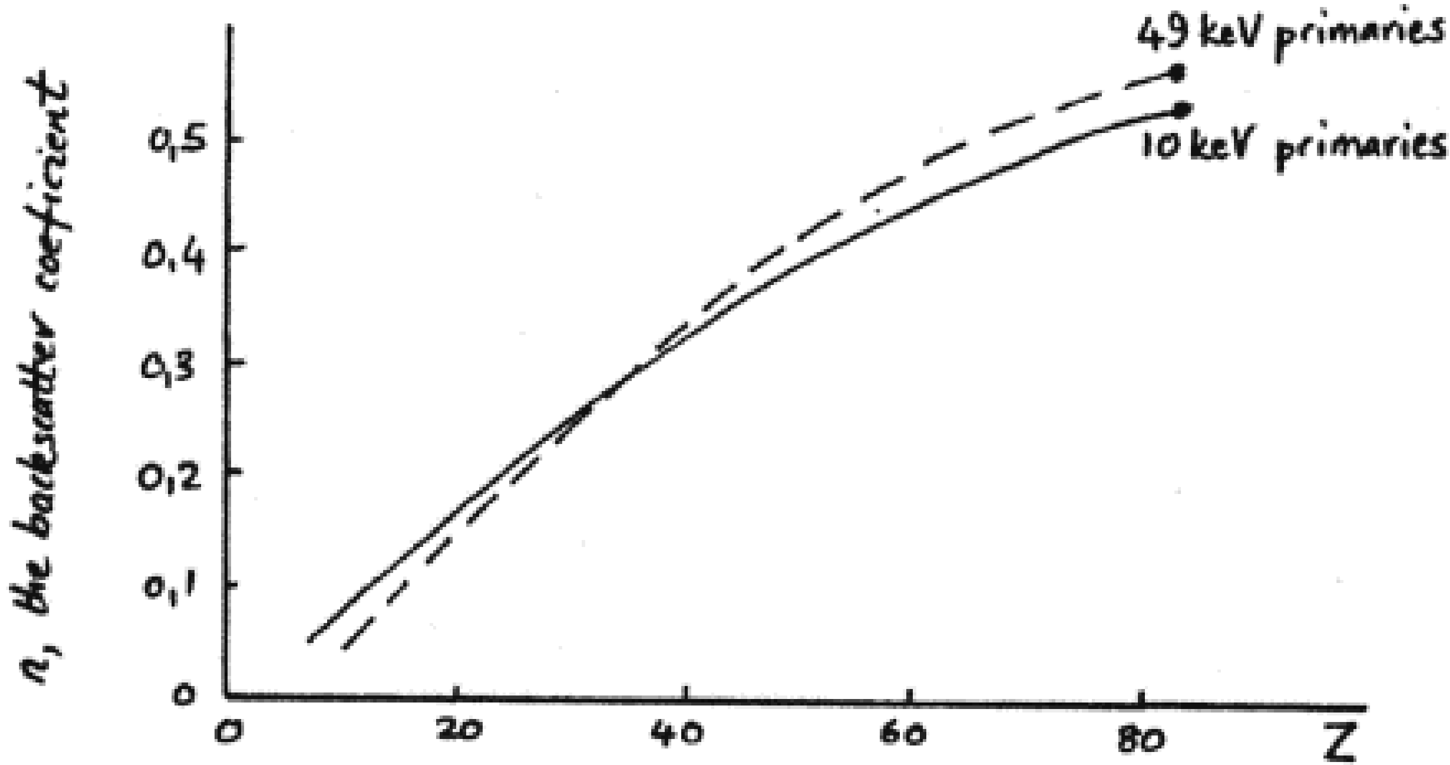


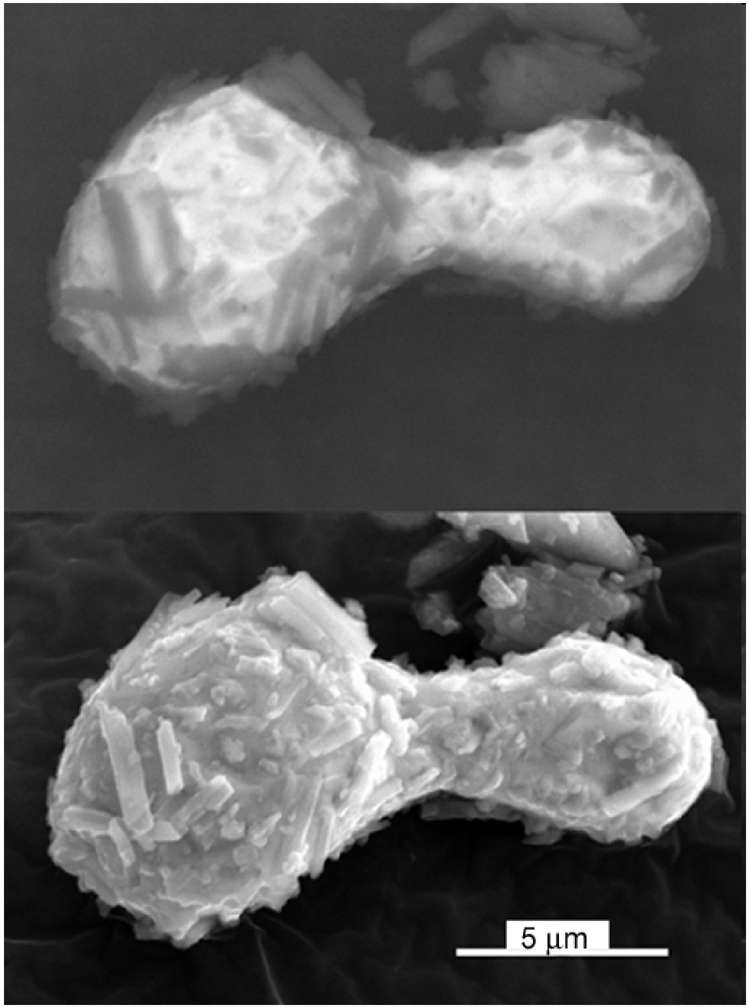
Image: University of Cape Town

Factors that affect BSE emission

- Direction of the irritated surface
  - more electrons will hit the BSE detector when the surface is aligned towards the BSE detector
- Average atomic number

- When you want to study differences in atomic numbers the sample should be as levelled as possible (sample preparation is an issue!)

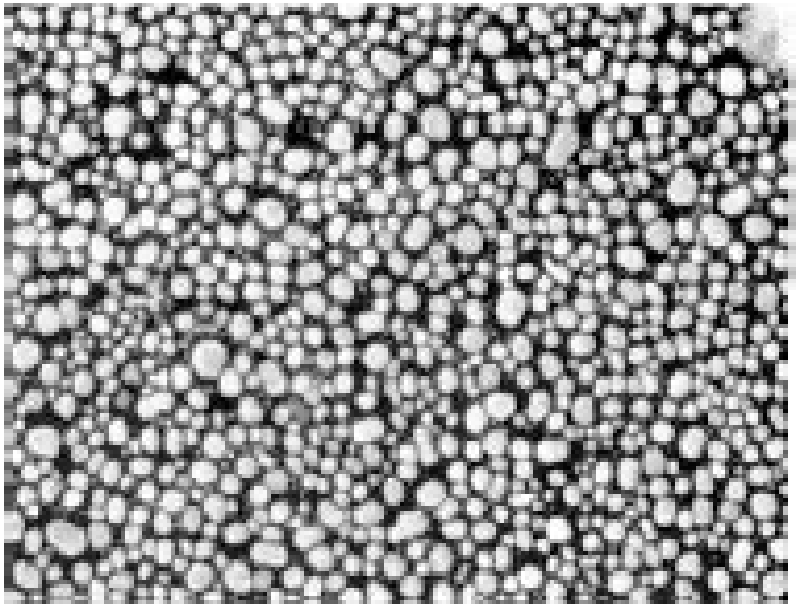
BSE vs SE2



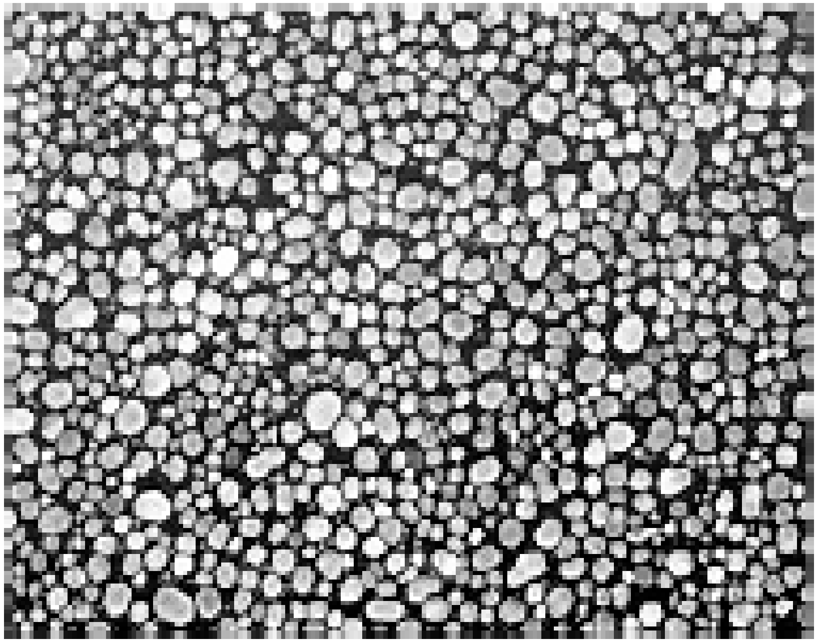
Images: Greg Meeker, USGS

Tungsten SEM images

In Older SEMs High Resolution Meant High kV

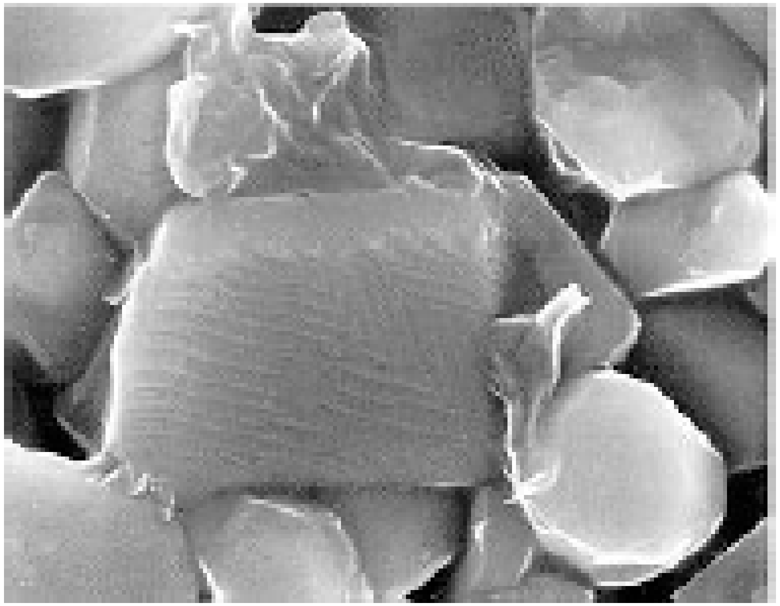


(a) 5 kV x 36,000

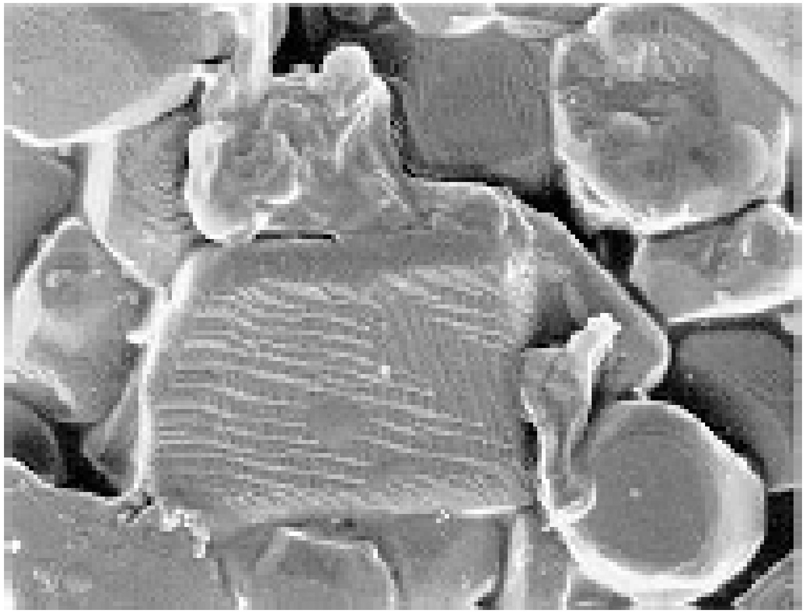


(b) 25 kV x 36,000

Higher kV can mean large beam penetration & loss of surface detail

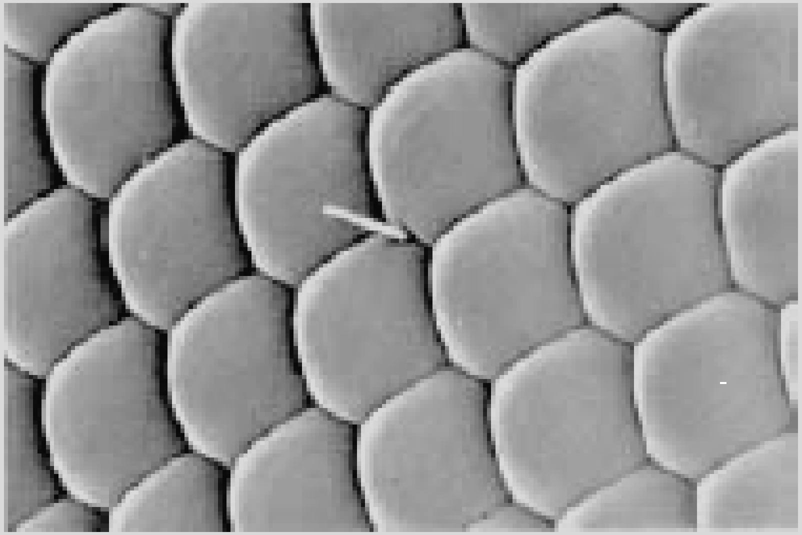


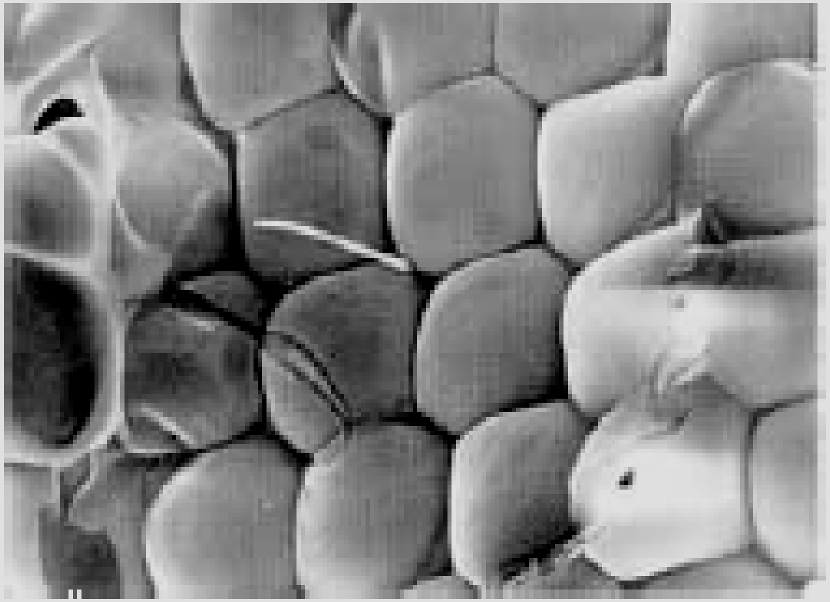
(b) 25 kV x7,200



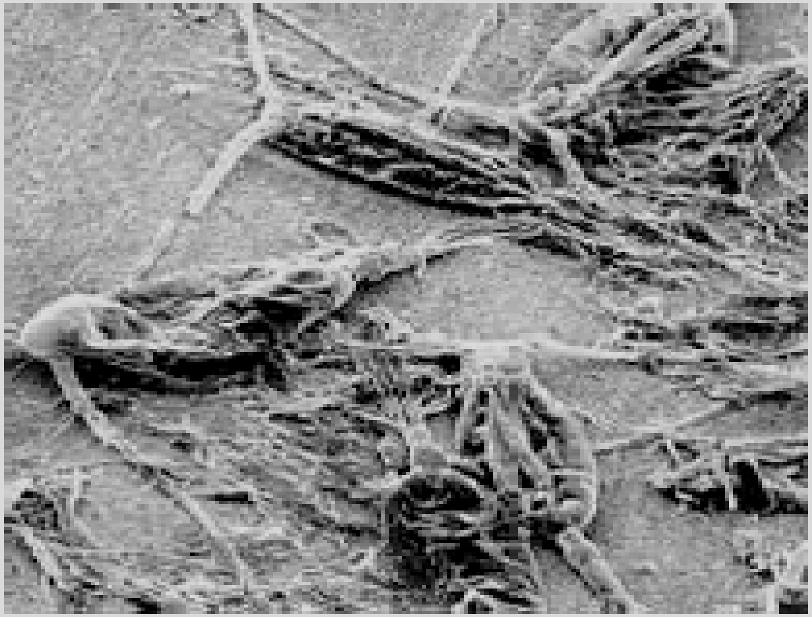
(a) 5 kV x7,200

It can also mean thermal beam damage to sensitive samples

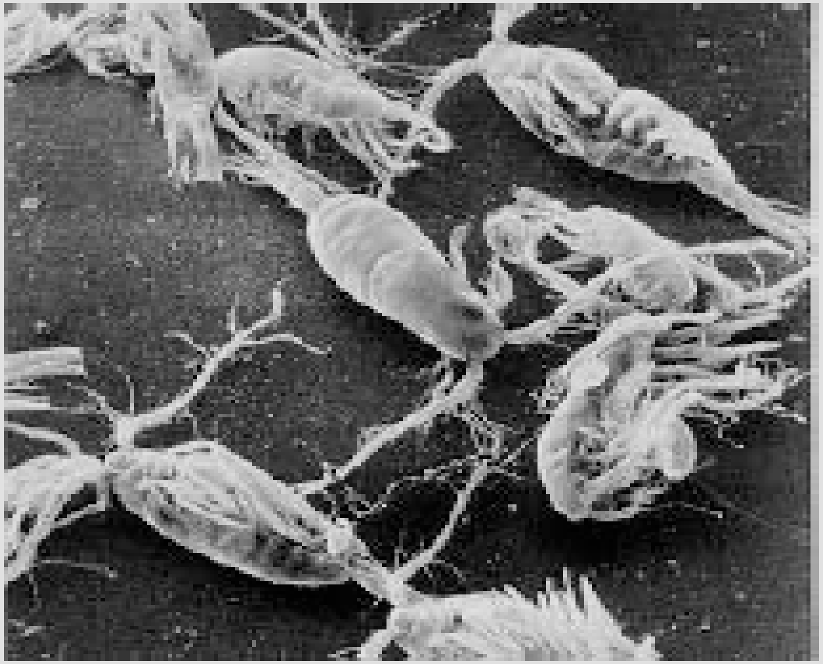

(a) Undamaged specimen


(b) Damaged specimen

And for wet, fragile samples results were often disastrous or sample prep was very difficult

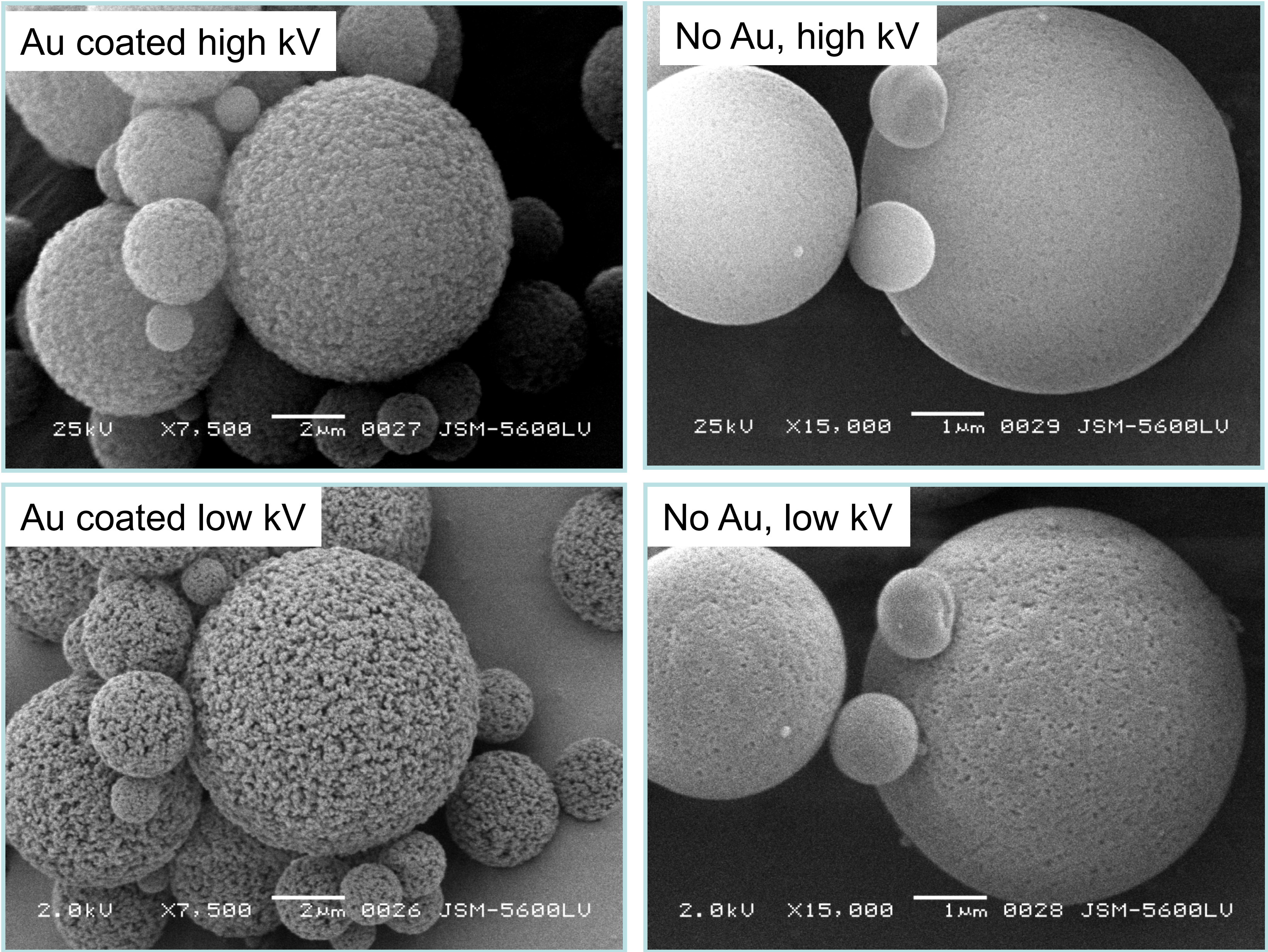


(a) Air drying

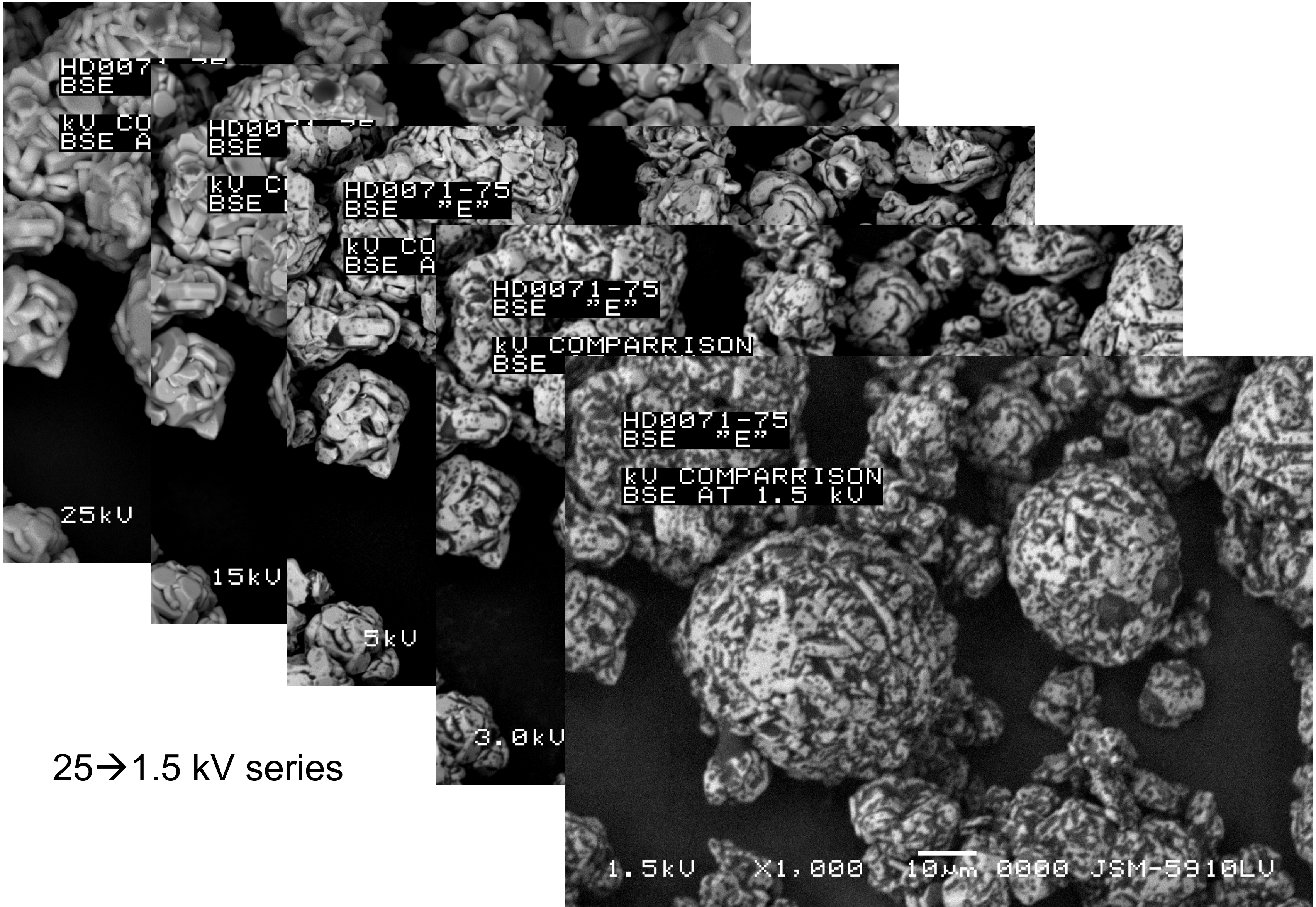


(b) Critical point drying

Coated or Uncoated

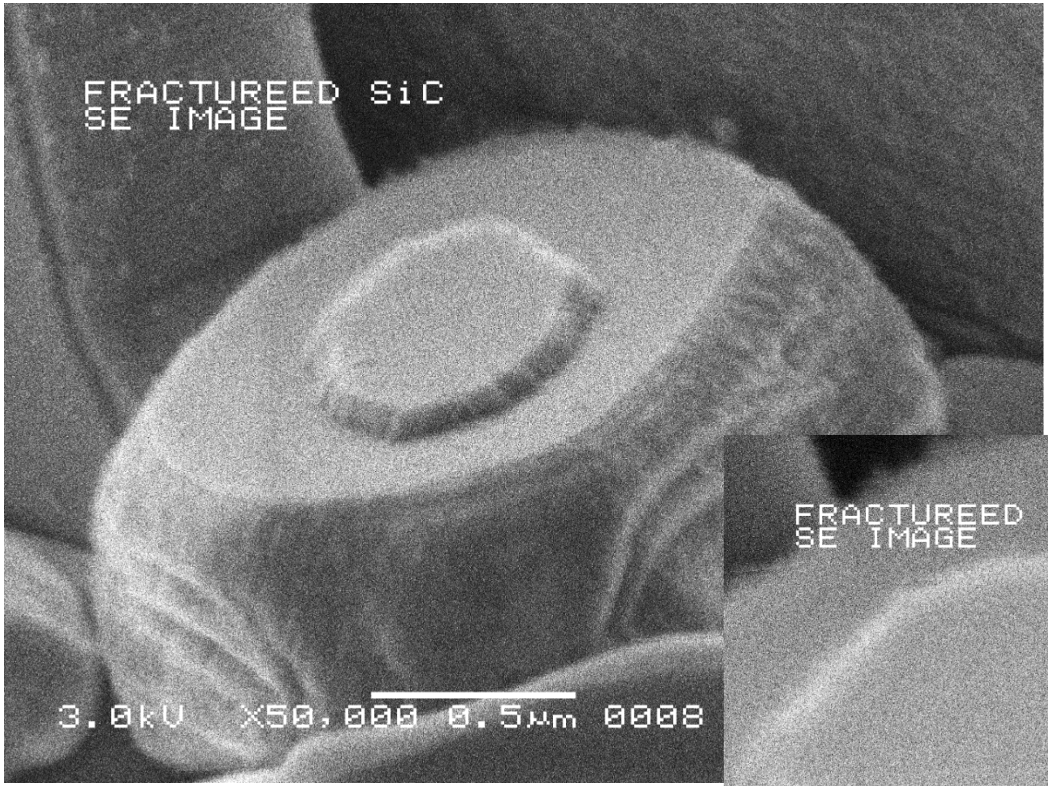


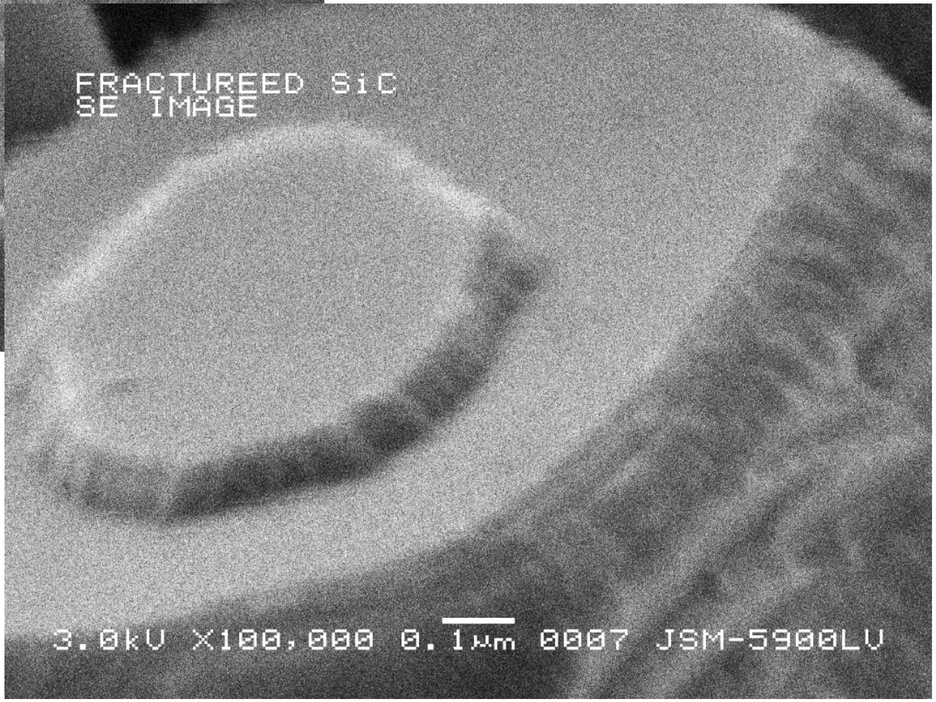
Low kV BSE of Polymer coating



25→1.5 kV series

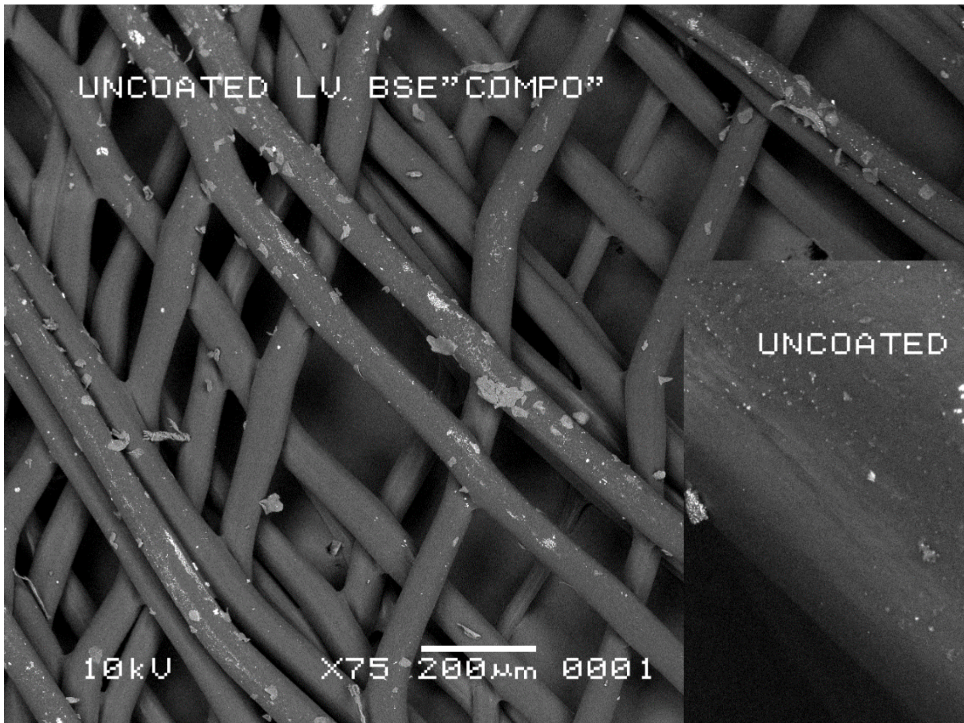
High Resolution Imaging



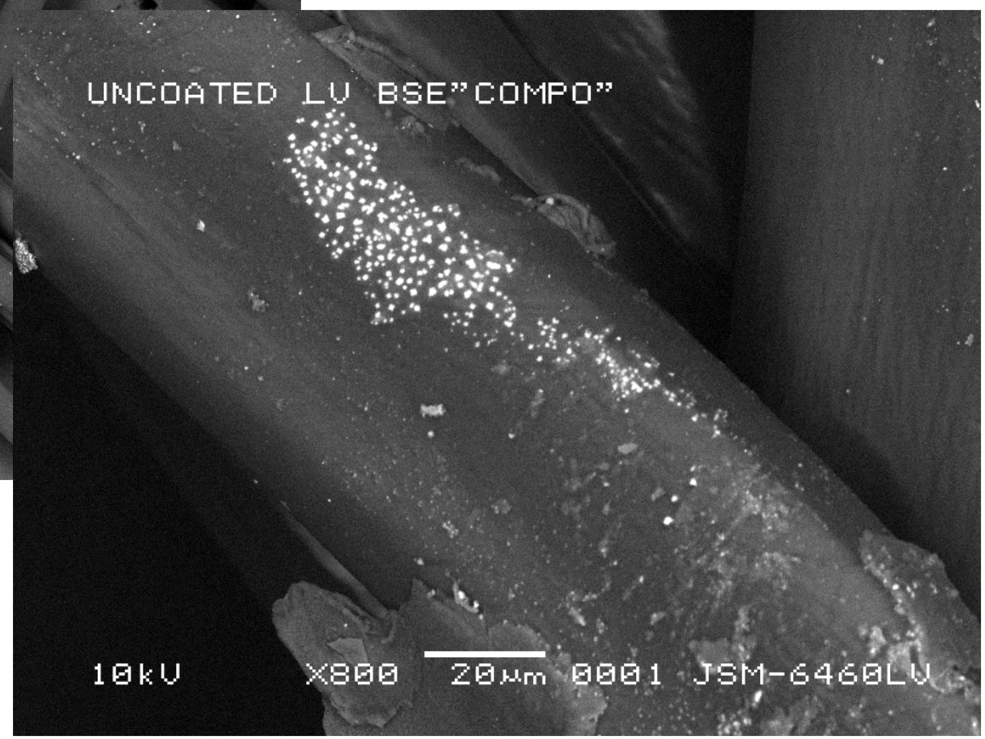


Tungsten LV (low vacuum) SEM images

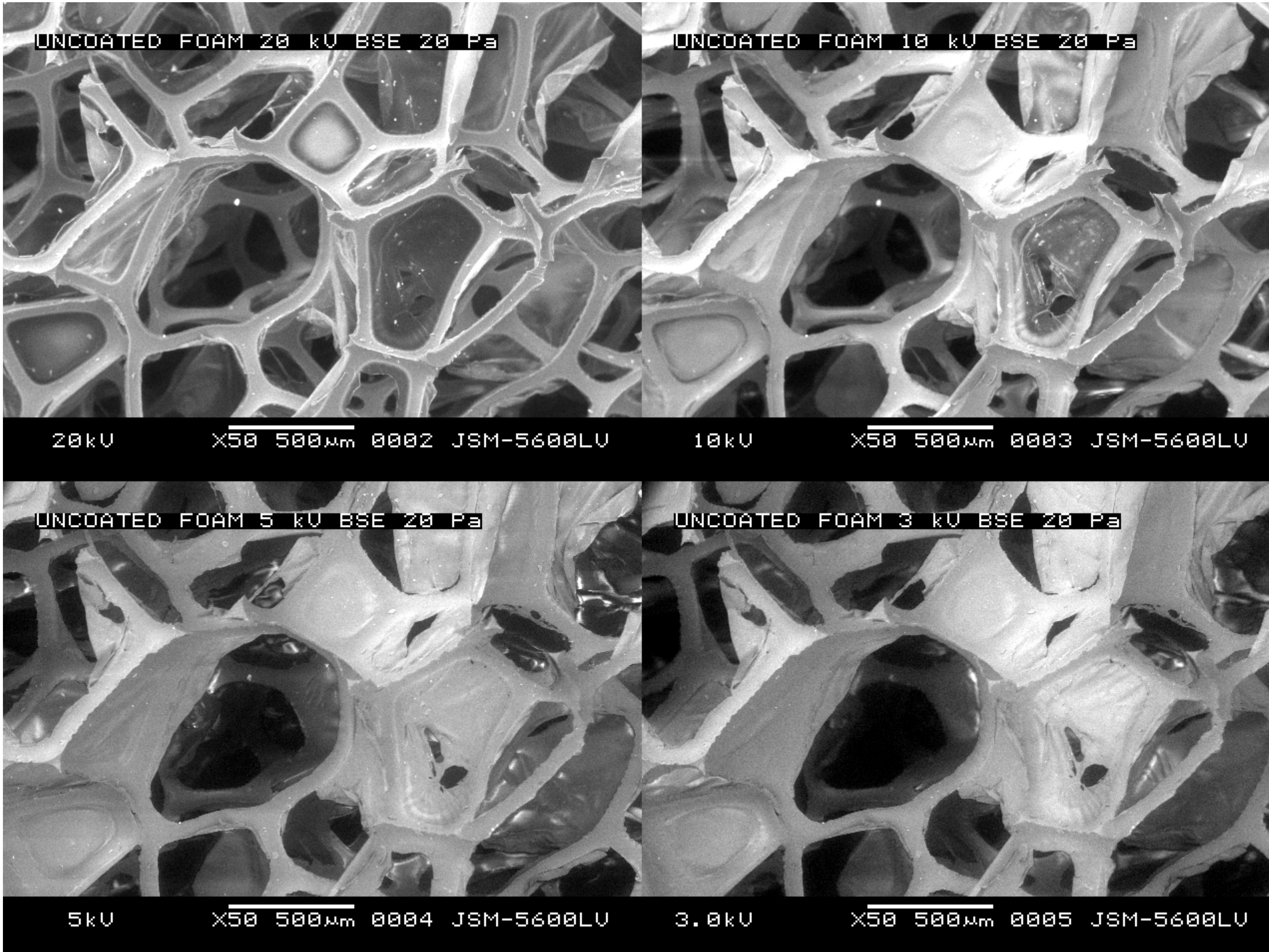
Spun Polymer Uncoated



10 kV

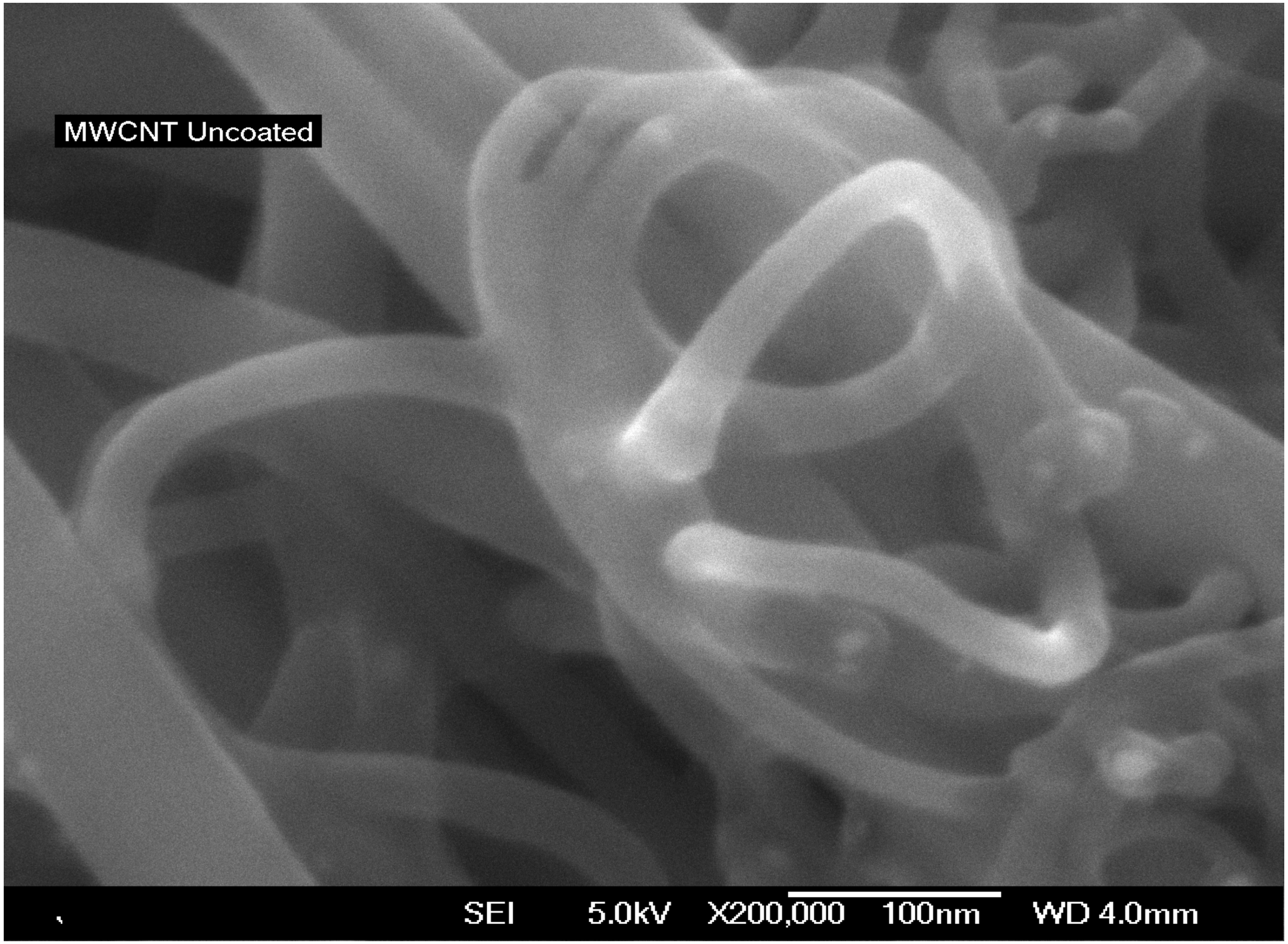


Polyurethane Foam Uncoated (20 kV→3 kV @ 20Pa)

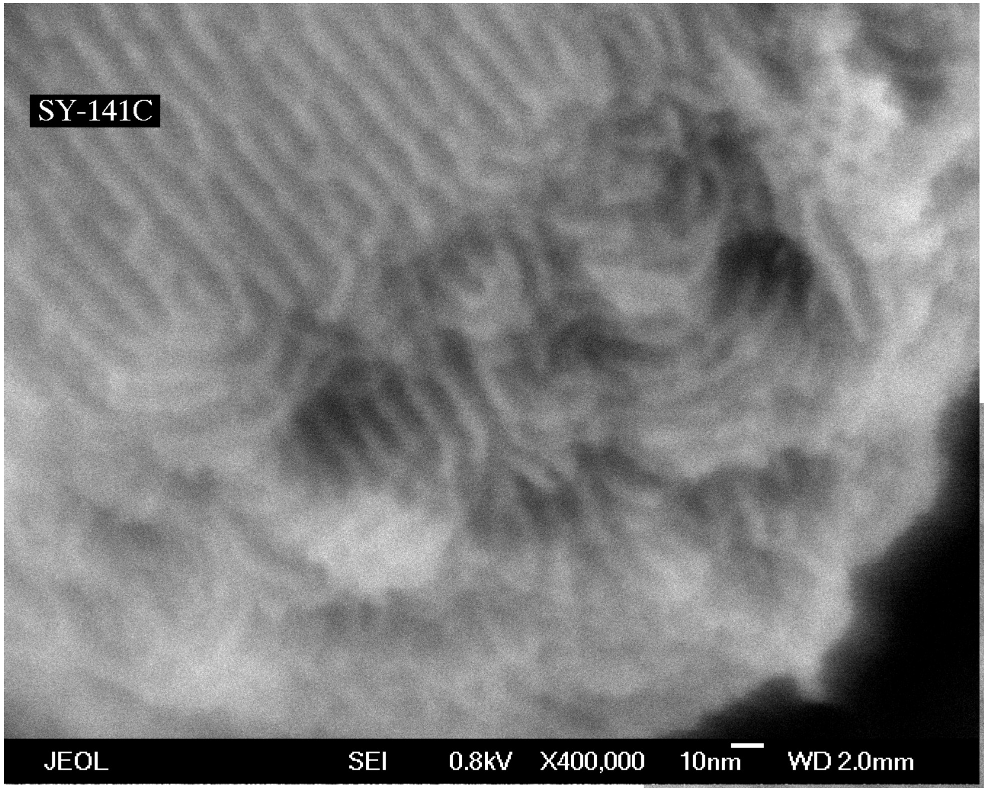


FEG SEM images

Carbon Nanotubes

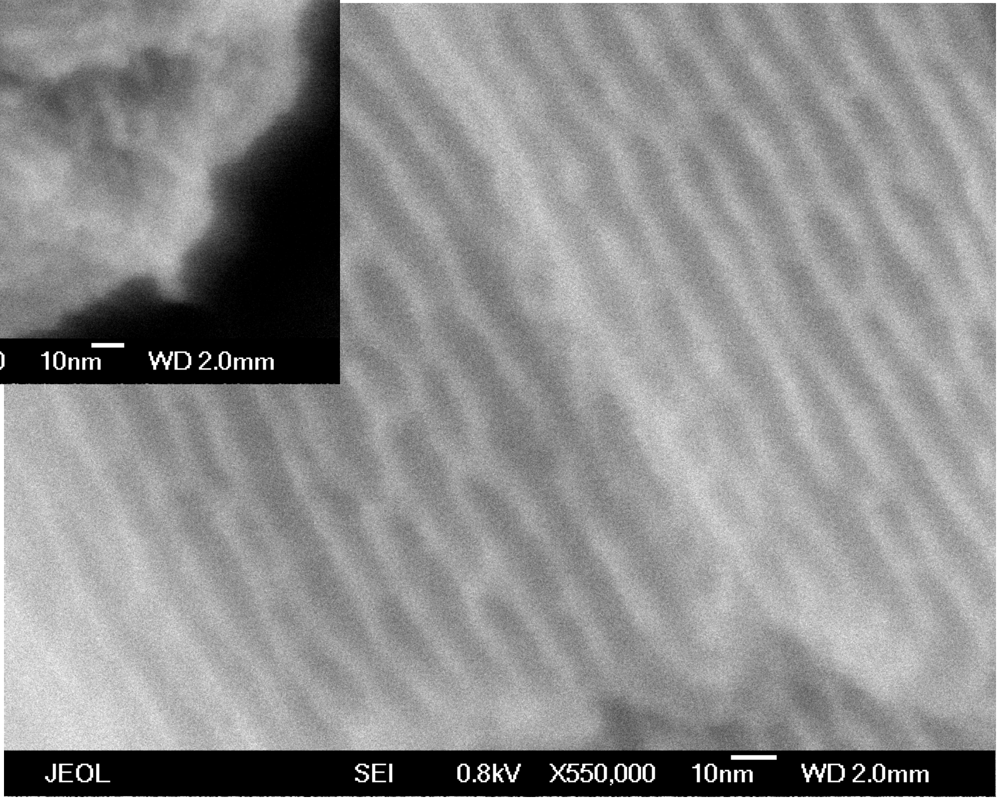


Uncoated

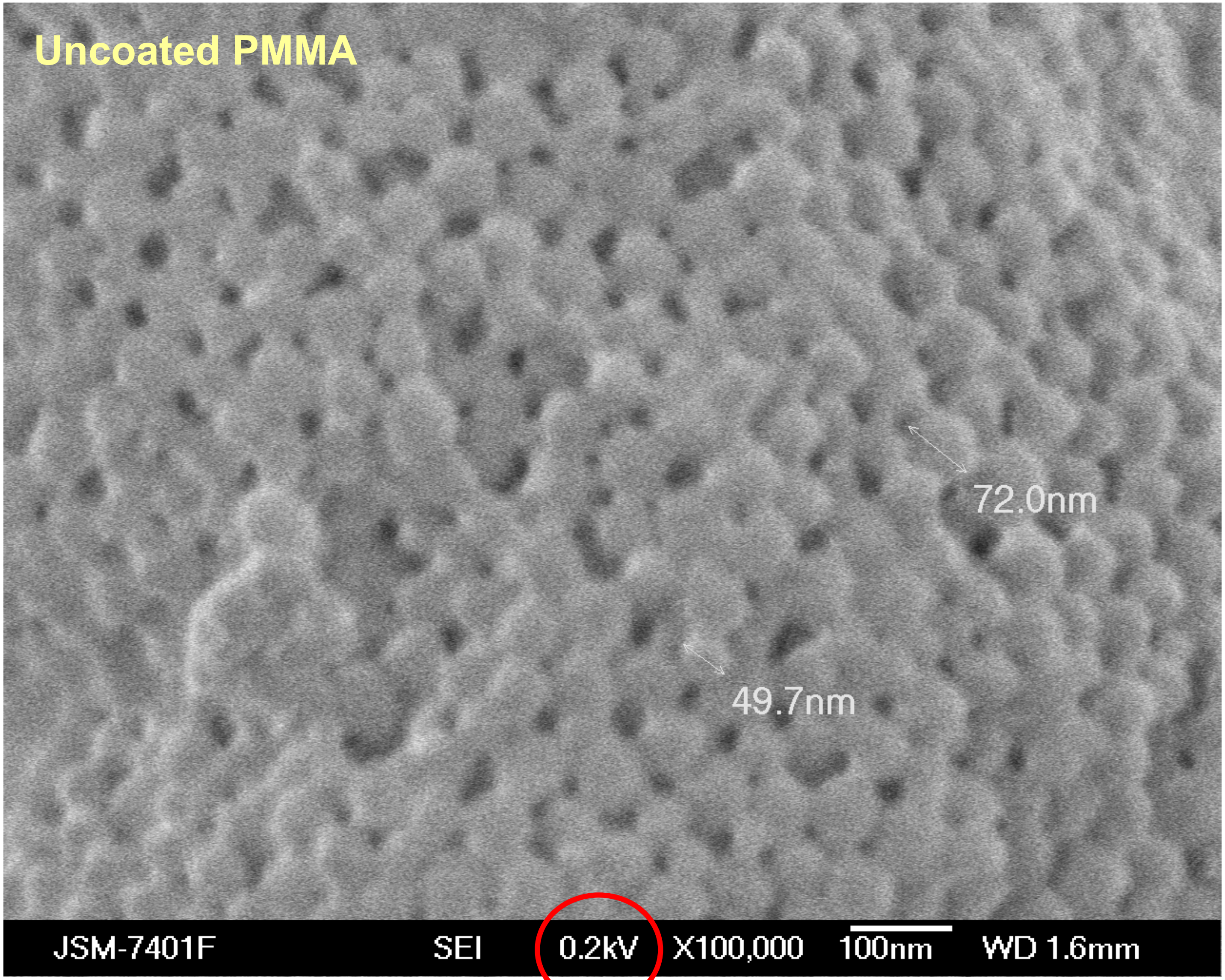


Mesoporous Silica

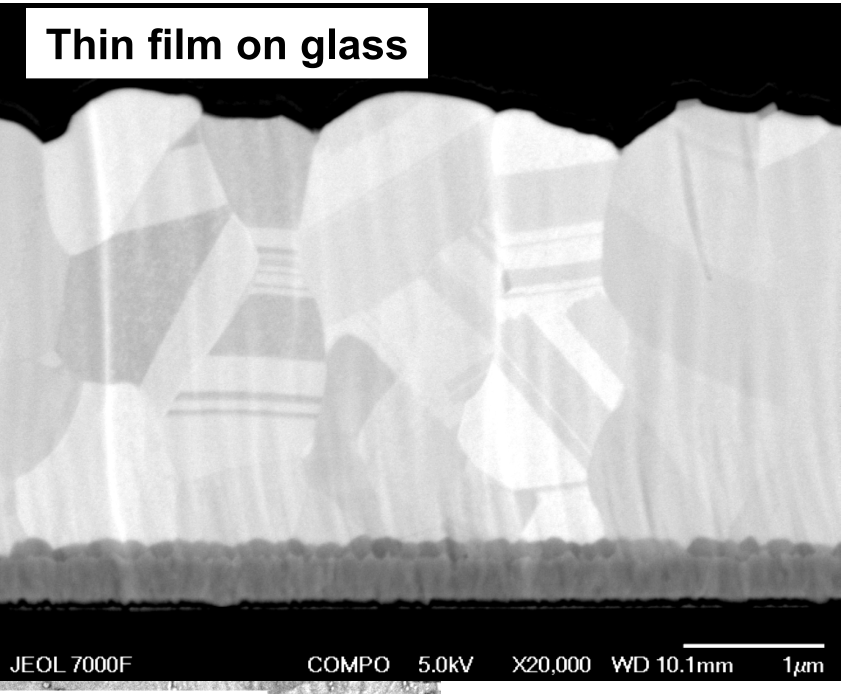
Low voltage imaging



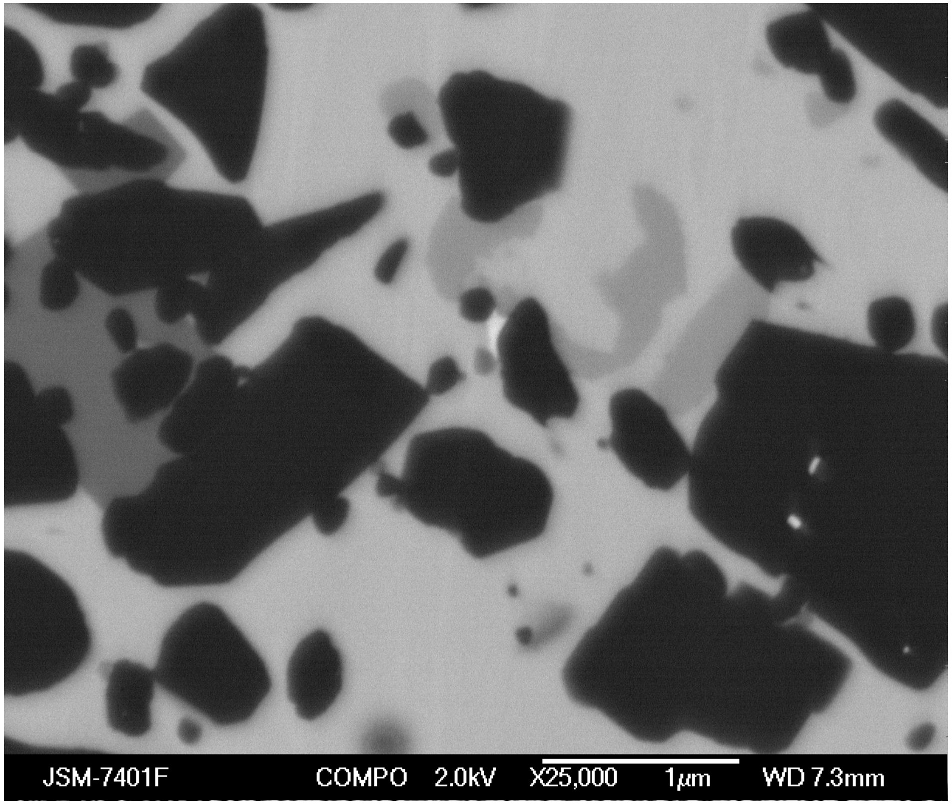
Ultra low kV High Resolution



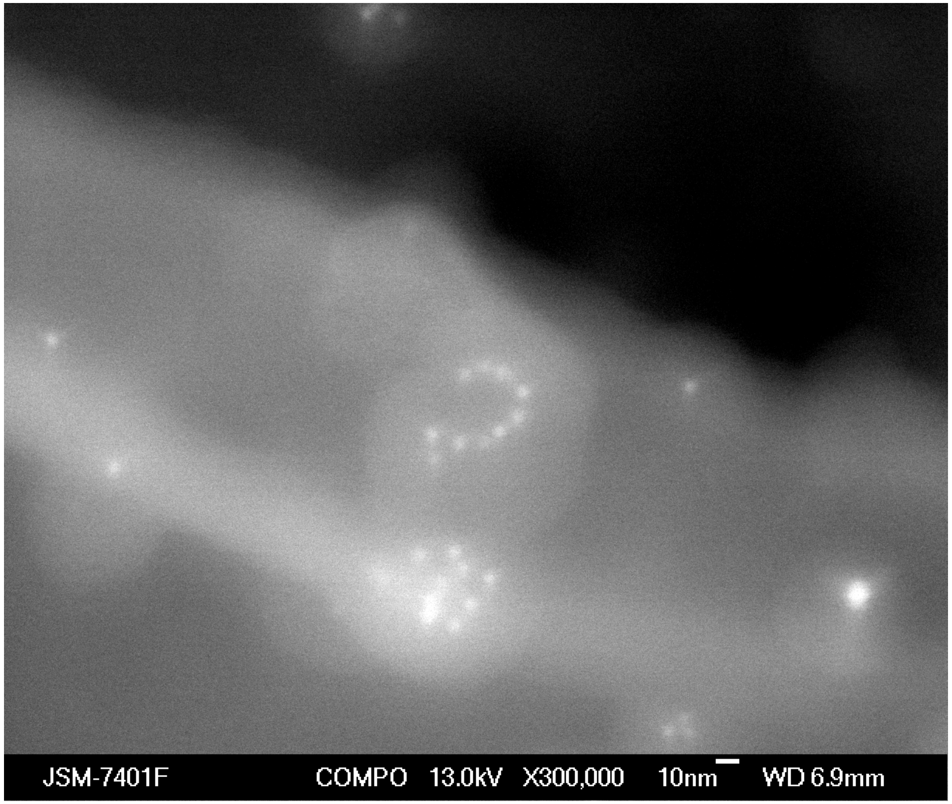
Back-scatter imaging- channeling contrast



Back-scatter imaging – compositional contrast

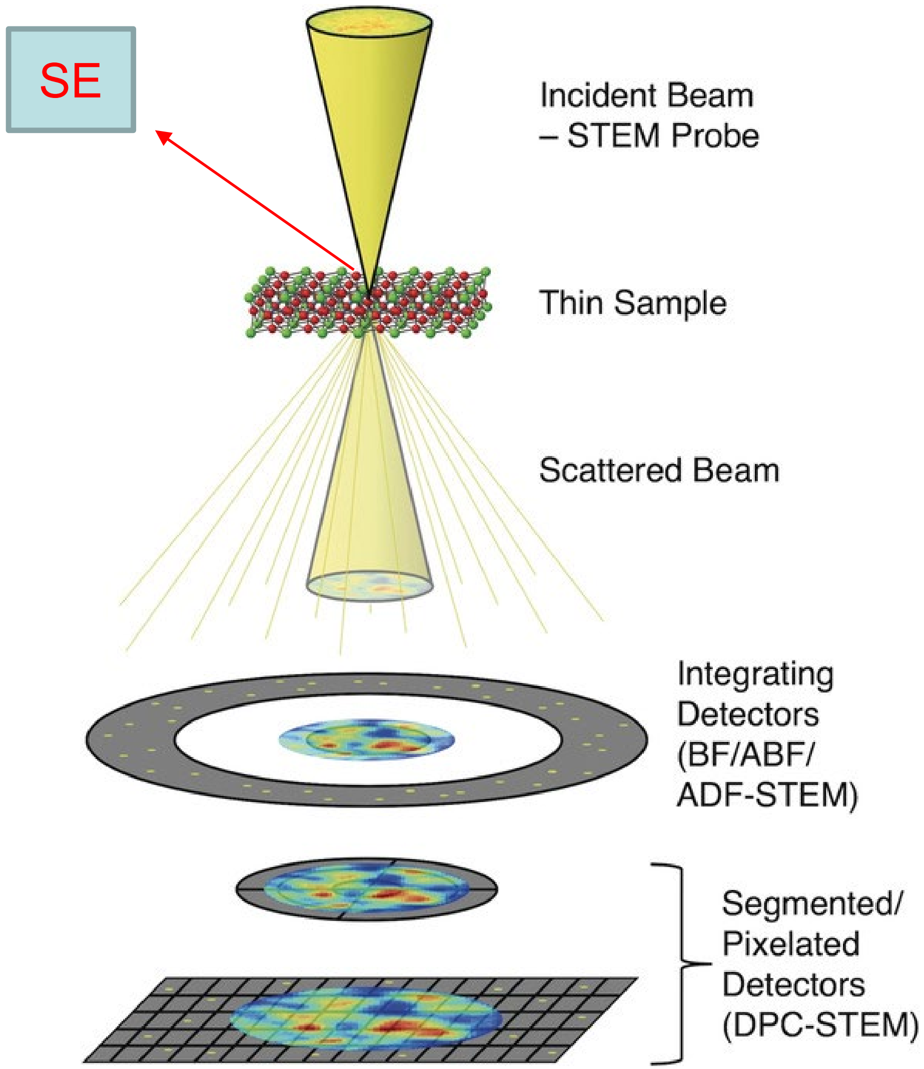


Metal-ceramic composite



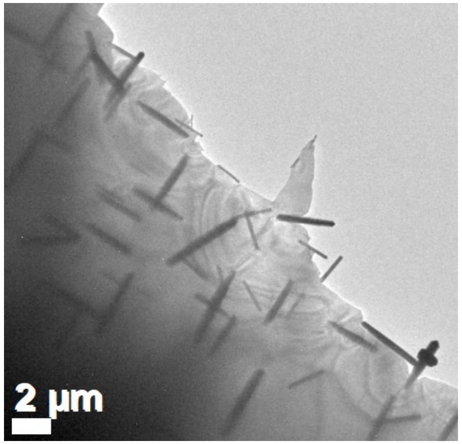
4-6 nm gold immunolabels

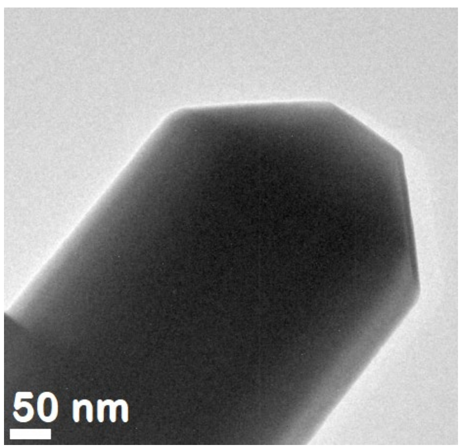
Also, SE detector in TEM (Hitachi, JEOL…)



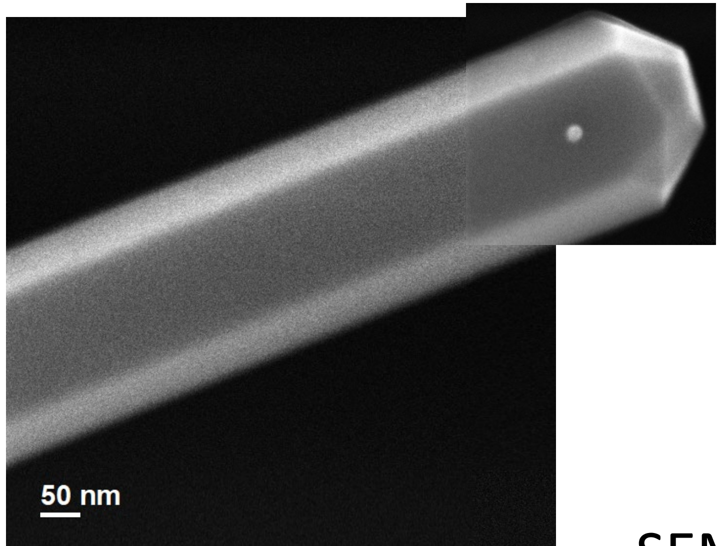
Angew. Chem. Int. Ed., Volume: 59, Issue: 4, Pages: 1384-1396, First published: 13 May 2019, DOI: (10.1002/anie.201902993)

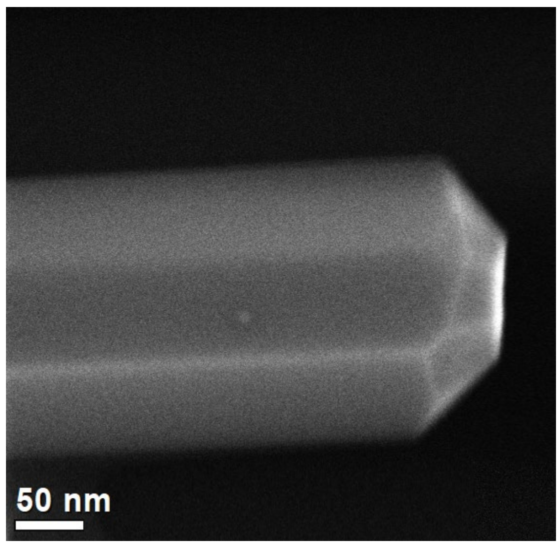
Rods in $KTaO_3$



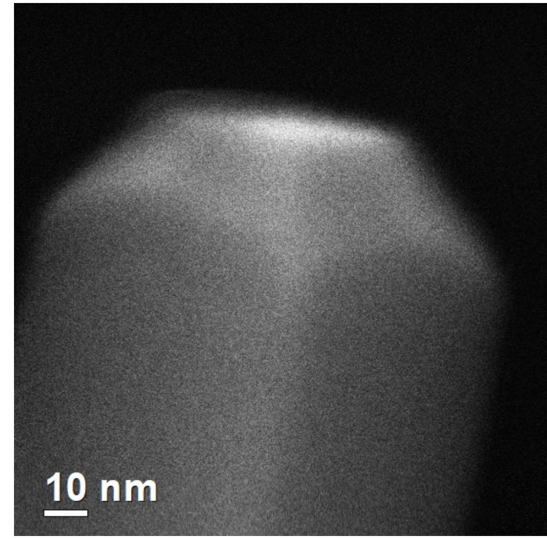


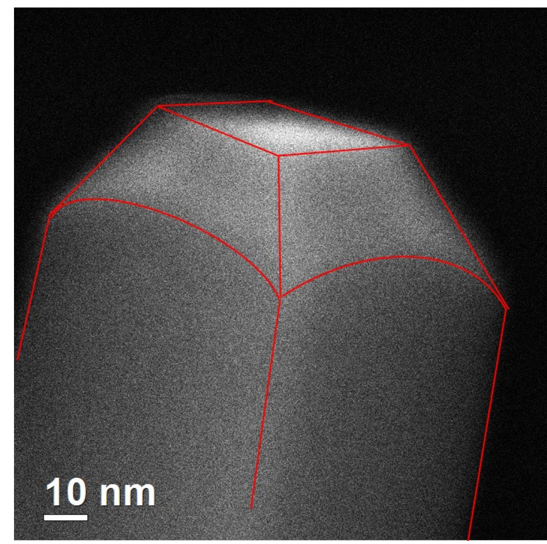
Bright Field TEM

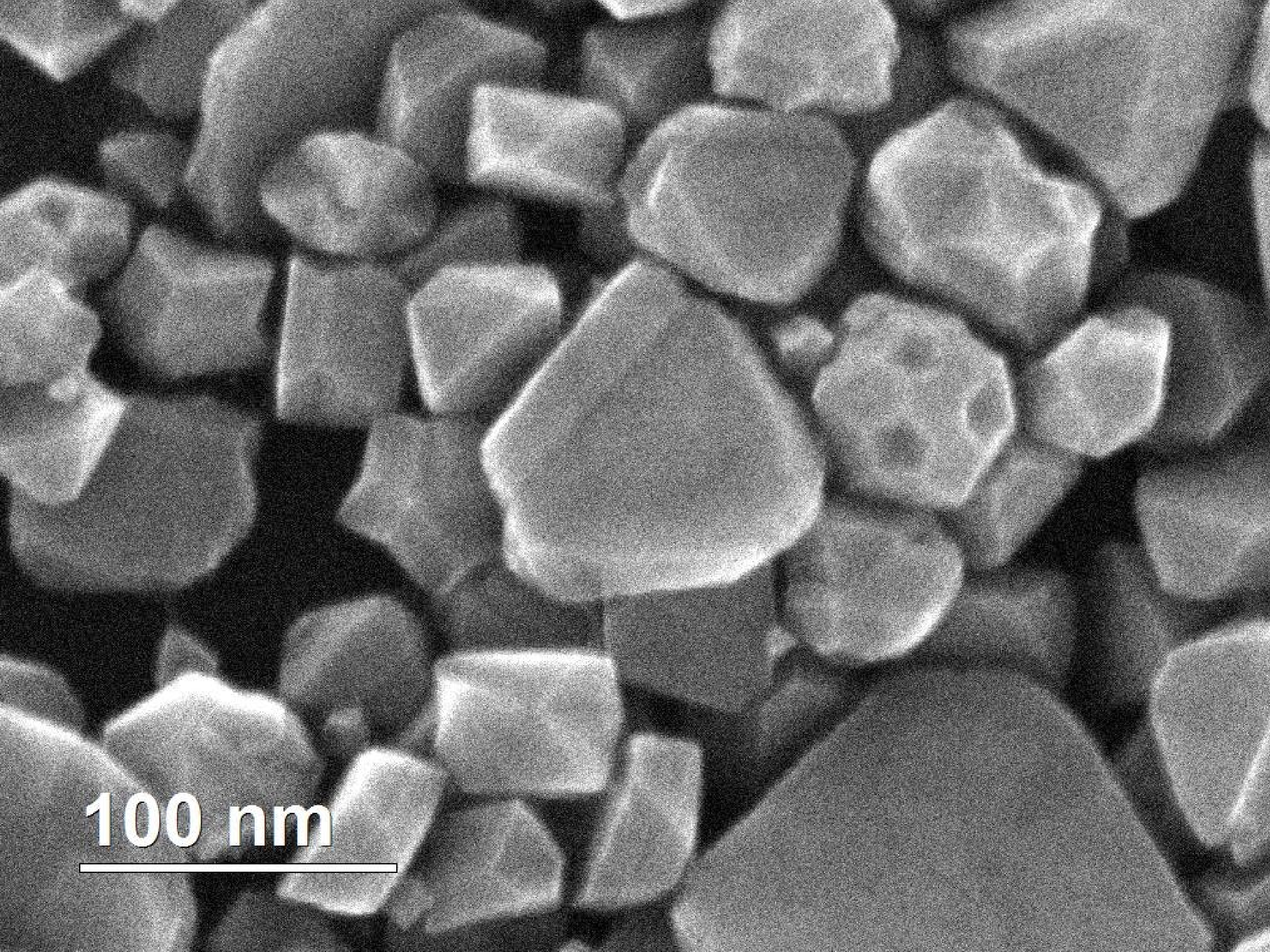




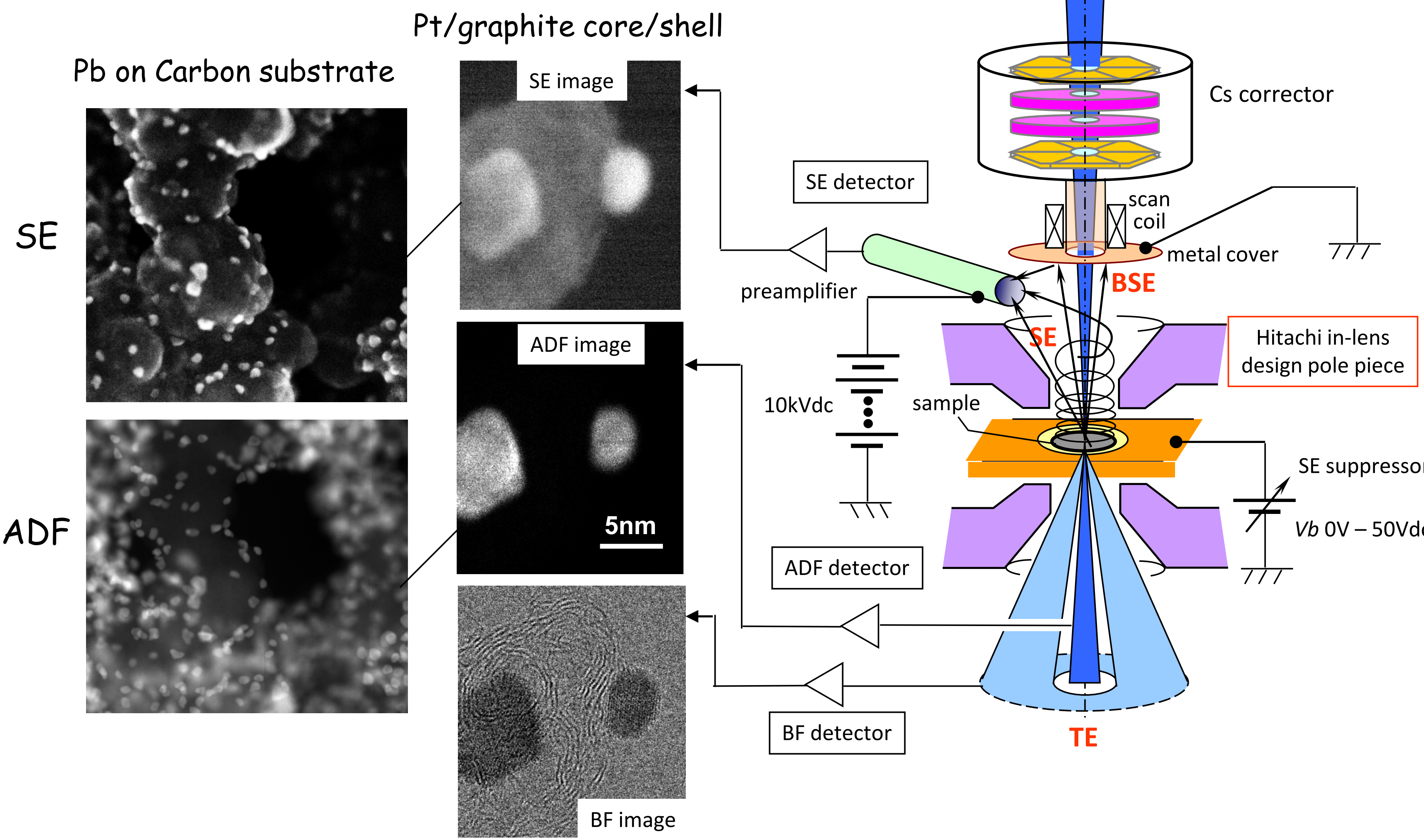
SEM



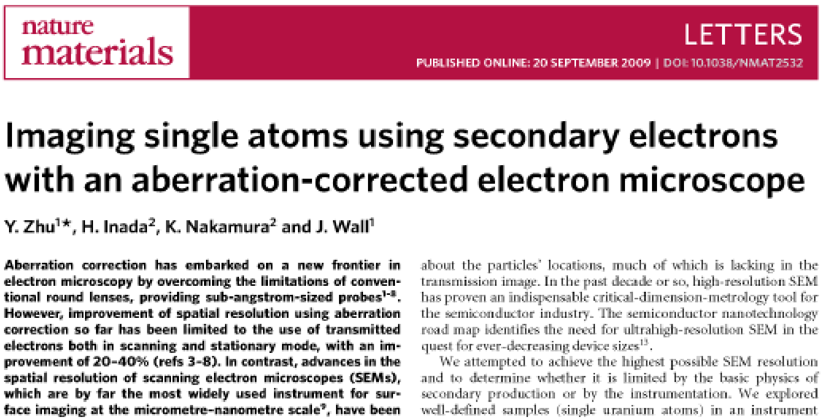



100 nm

Any STEM, just add a SE detector (Hitachi, JEOL…)



Imaging surface U atoms



nature materials | LETTERS

PUBLISHED ONLINE: 20 SEPTEMBER 2009 | DOI: 10.1038/NMAT2532

Imaging single atoms using secondary electrons with an aberration-corrected electron microscope

Y. Zhu[1]*, H. Inada[2], K. Nakamura[2] and J. Wall[1]

Aberration correction has embarked on a new frontier in electron microscopy by overcoming the limitations of conventional round lenses, providing sub-angstrom-sized probes[1-8]. However, improvement of spatial resolution using aberration correction so far has been limited to the use of transmitted electrons both in scanning and stationary mode, with an improvement of 20–40% (refs 3–8). In contrast, advances in the spatial resolution of scanning electron microscopes (SEMs), which are by far the most widely used instrument for surface imaging at the micrometre–nanometre scale[9], have been

about the particles' locations, much of which is lacking in the transmission image. In the past decade or so, high-resolution SEM has proven an indispensable critical-dimension-metrology tool for the semiconductor industry. The semiconductor nanotechnology road map identifies the need for ultrahigh-resolution SEM in the quest for ever-decreasing device sizes[13].

We attempted to achieve the highest possible SEM resolution and to determine whether it is limited by the basic physics of secondary production or by the instrumentation. We explored well-defined samples (single uranium atoms) in an instrument

news & views

SCANNING ELECTRON MICROSCOPY

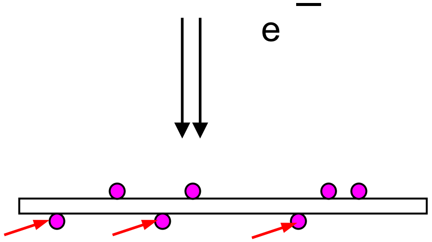
Second best no more

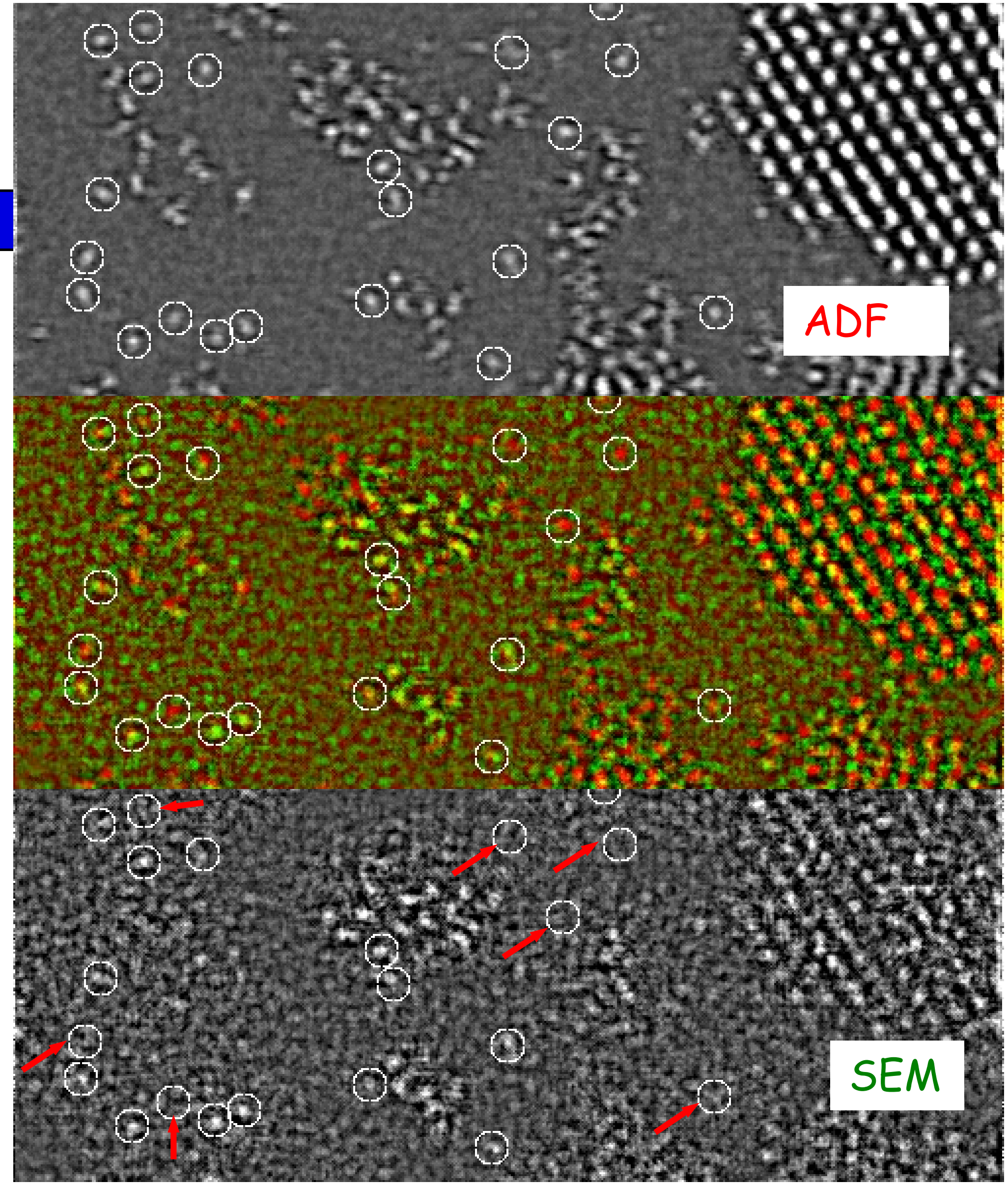
Secondary electron imaging in electron microscopy can achieve resolutions that compete with transmission electron microscopy, and allows imaging of both surface and bulk atoms simultaneously.

David C. Joy

Secondary electron imaging is the most popular mode of operation of the scanning electron microscope (SEM).

Figure 1 shows a secondary electron image of interconnect lines in a semiconductor device. Each is seen to be outlined by





Nature Materials, **8**, 808 - 812 (2009)

Surface Layers Matter (complicated)

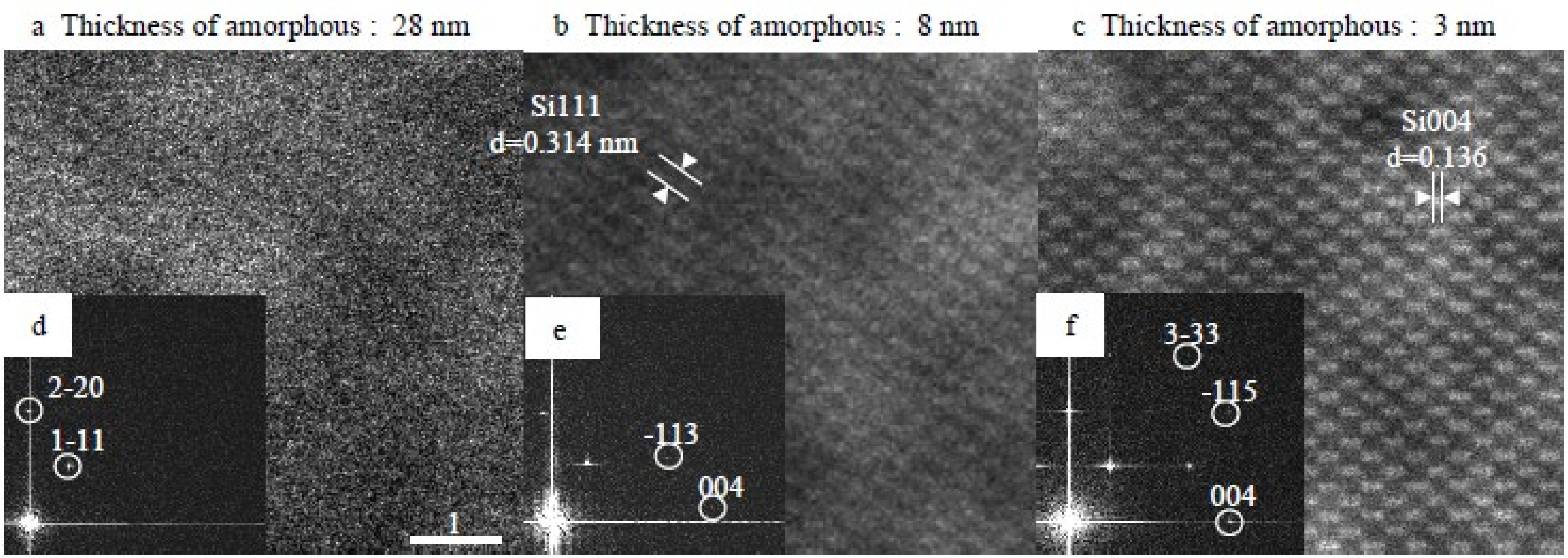
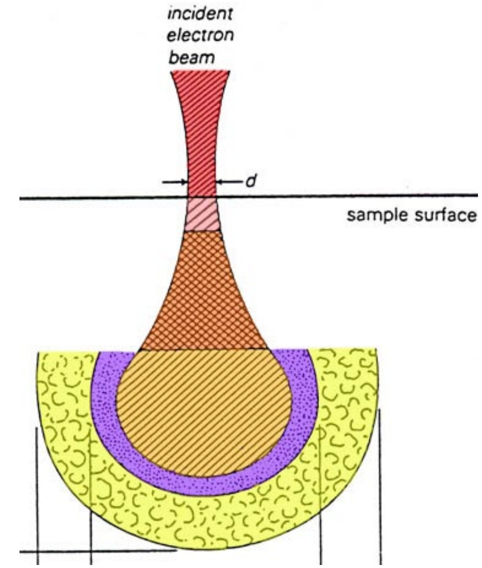


Figure 3. SE images taken with HD-2700 at 200 kV along the Si[011] zone axis with the corresponding FFT of a Si samples prepared by a FIB beam at accelerating voltages of (a) 40 kV , (b) 10 kV and (c) 2 kV.

Summary



- Signals:
  - Secondary electrons (SE): mainly topography
    - Low energy electrons, high resolution
    - Surface signal dependent on curvature
  - Backscattered electrons (BSE): mainly chemistry
    - High energy electrons
    - “Bulk” signal dependent on atomic number
  - Resolution
    - Can be atomic (~0.2nm), a bit complex