Scanning Electron Microscopy (SEM):

An Application of Particle Wave dual nature

Telescope

Binocular

All these instruments have circular apertures. Thus the Resolving Powers of all these optical instruments is given by

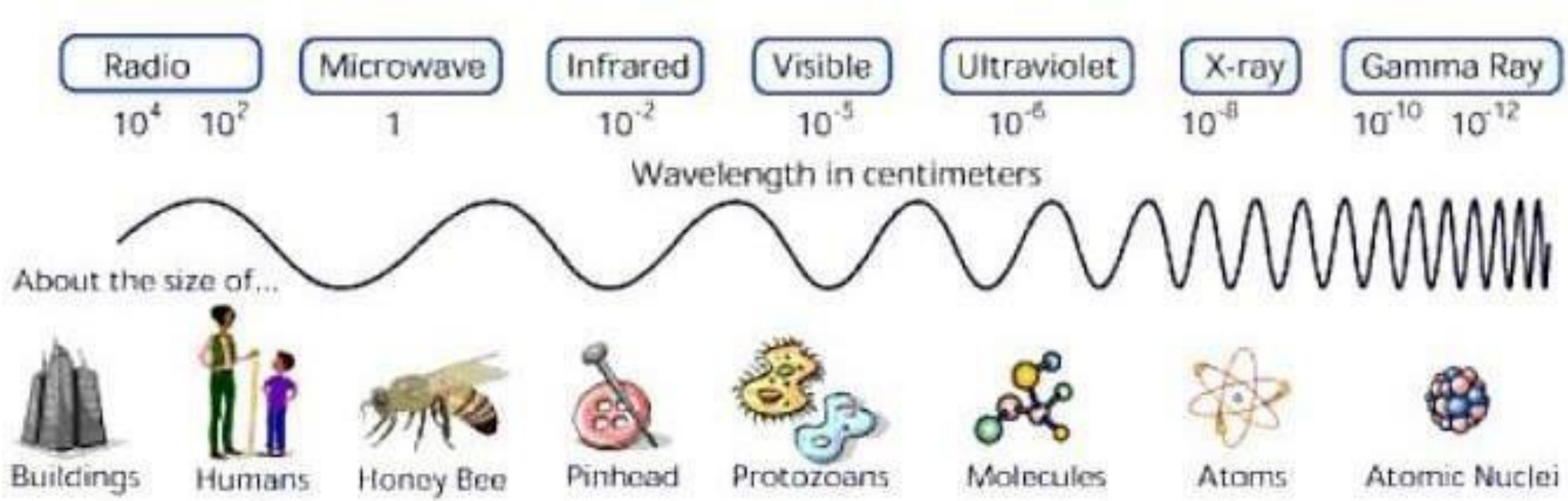
$$\boldsymbol{R.P.} = \frac{\mathbf{1}}{\boldsymbol{\theta_R}} = \frac{\boldsymbol{d}}{\mathbf{1.22}\boldsymbol{\lambda}}$$

Microscope

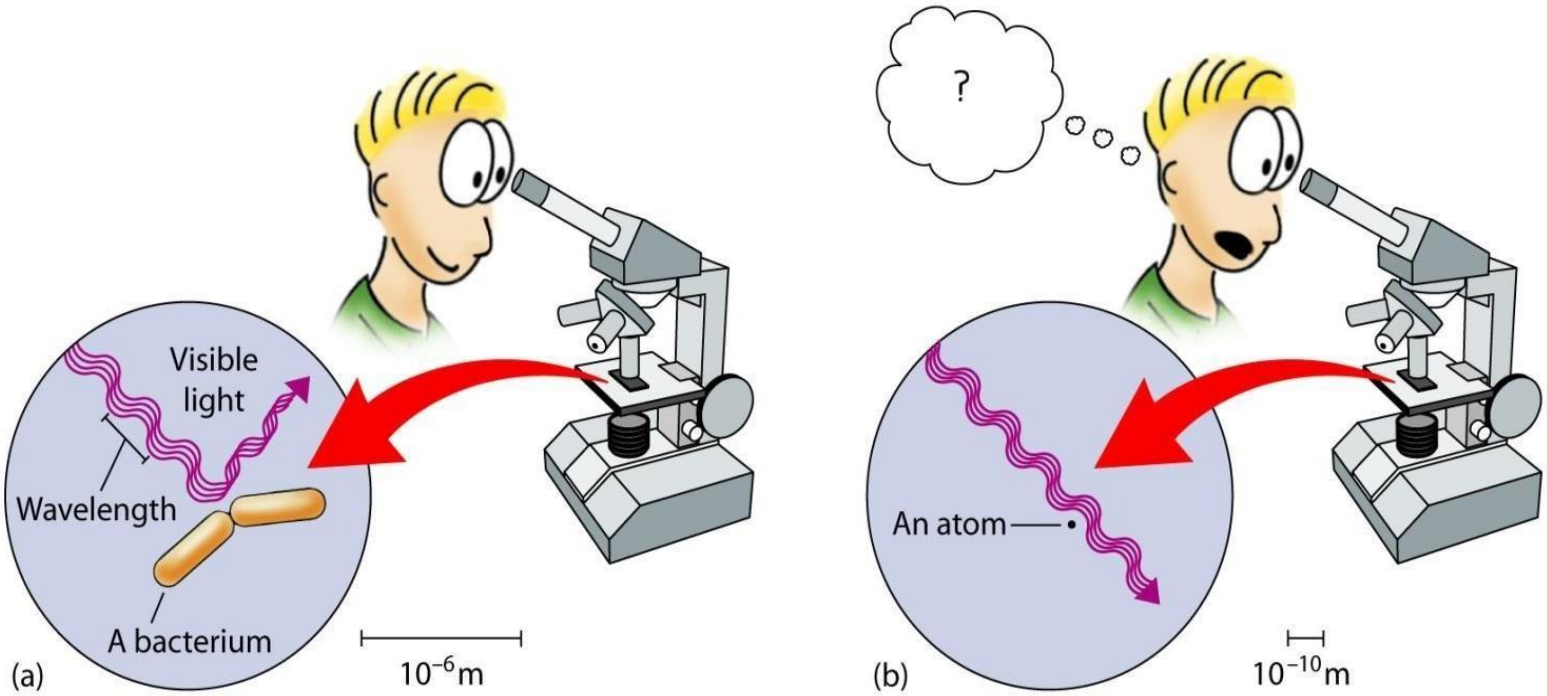
Camera

Eye

Limits of Vision



Limits of Vision



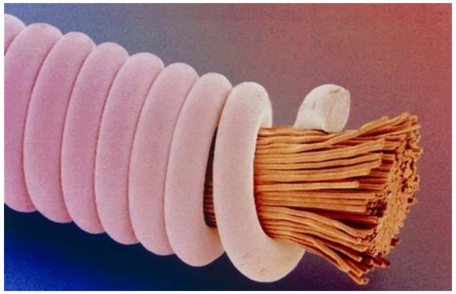
Electron Waves

$\lambda = 2.4 \times 10^{-11} m$

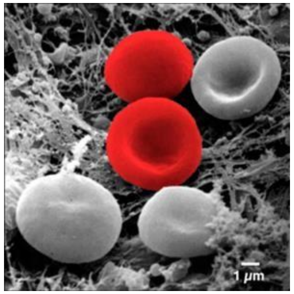
Why electron microscope is incredibly superior to Optical microscope?

In electron microscope, electrons are used for imaging instead of light. The wavelength of electrons is extremely small (100000 $times$) as compared to light. Therefore electron microscope is incredibly superior to optical microscope

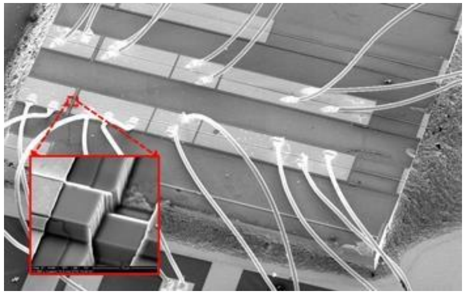
$$R.P. = \frac{1}{\theta_R} = \frac{d}{1.22\lambda}$$



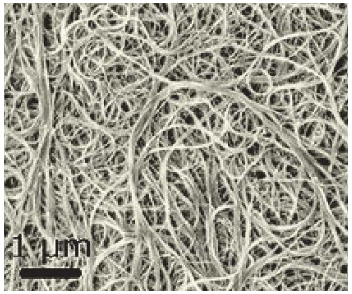
String of a guitar



Blood cells



Integrated circuit



Carbon Nanotubes

Brief Overview of Traditional Microscopes

- Optical Microscope;
- Scanning Electron Microscope (SEM);
- Transmission Electron Microscope (TEM);

- Comparison with scanning probe microscope (SPM)

General philosophy

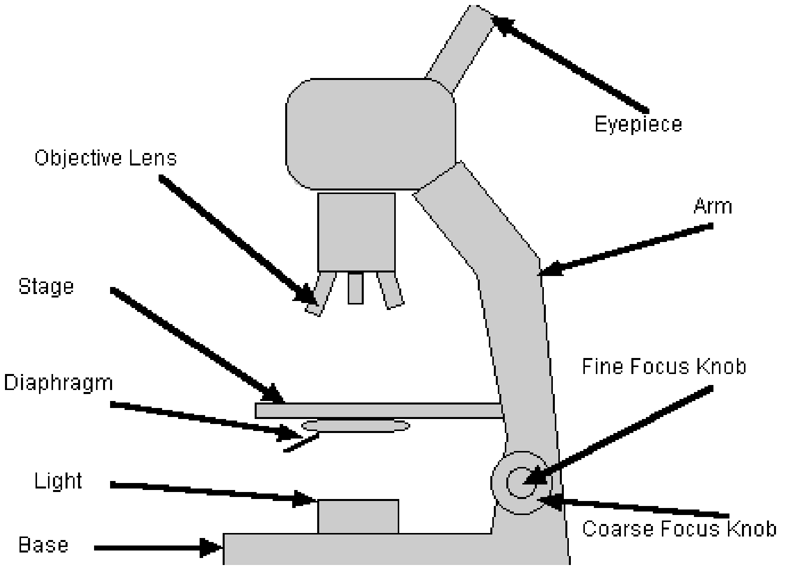
Human beings use two kinds of means to gauge objectives:

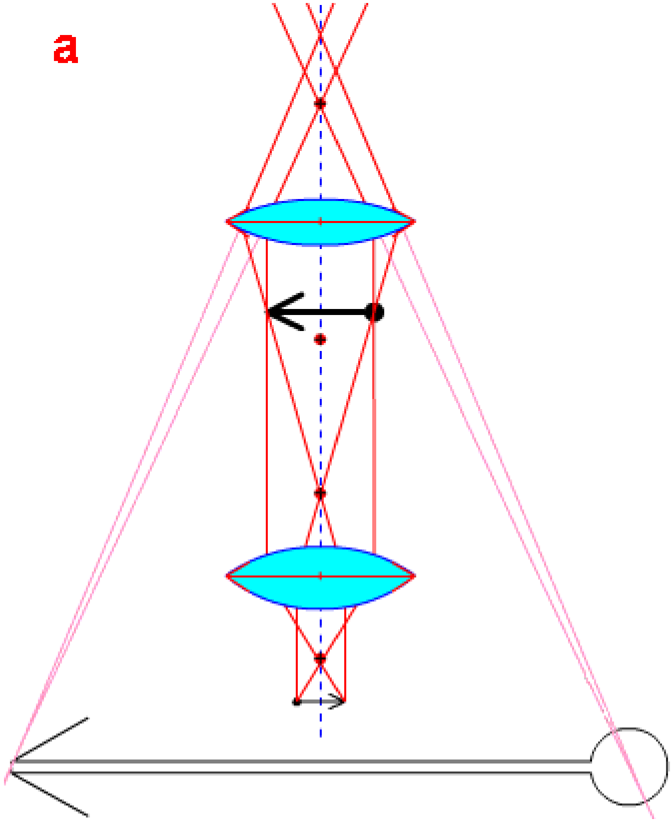
Seeing --- through eyes (light) ↔ optical microscope ↔ electronic microscope *(higher resolution due to short wavelength);*

Touching --- through hands (probe) ↔ SPM.

Converting wavelength (nm) to electron energy (eV): 1240.7/λ(nm), for example, a 500 nm light corresponds to 1240.7/500 = 2.48 eV

Principles of an optical microscope

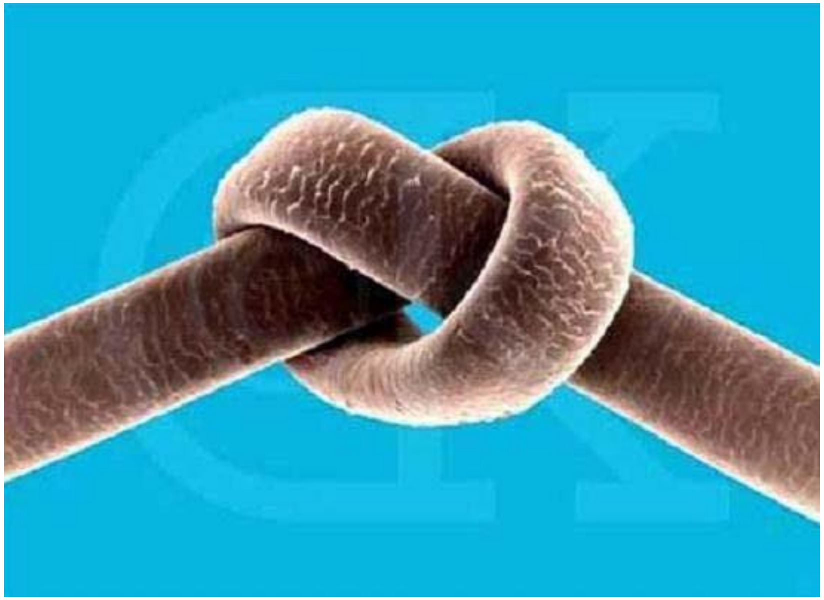




Development of microscope takes us back to 400 years ago

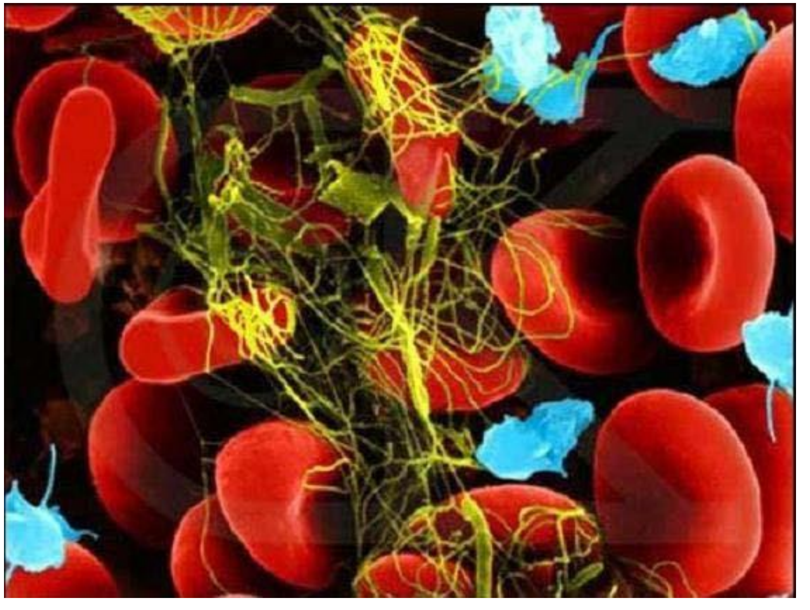
Robert Hooke’s "Micrographia" (1665)

A hair knot

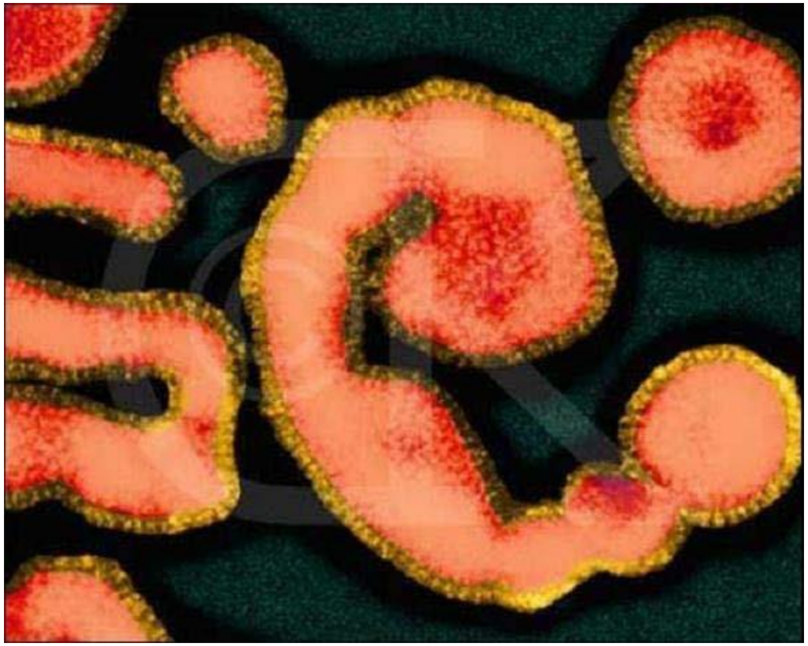


Room dusts

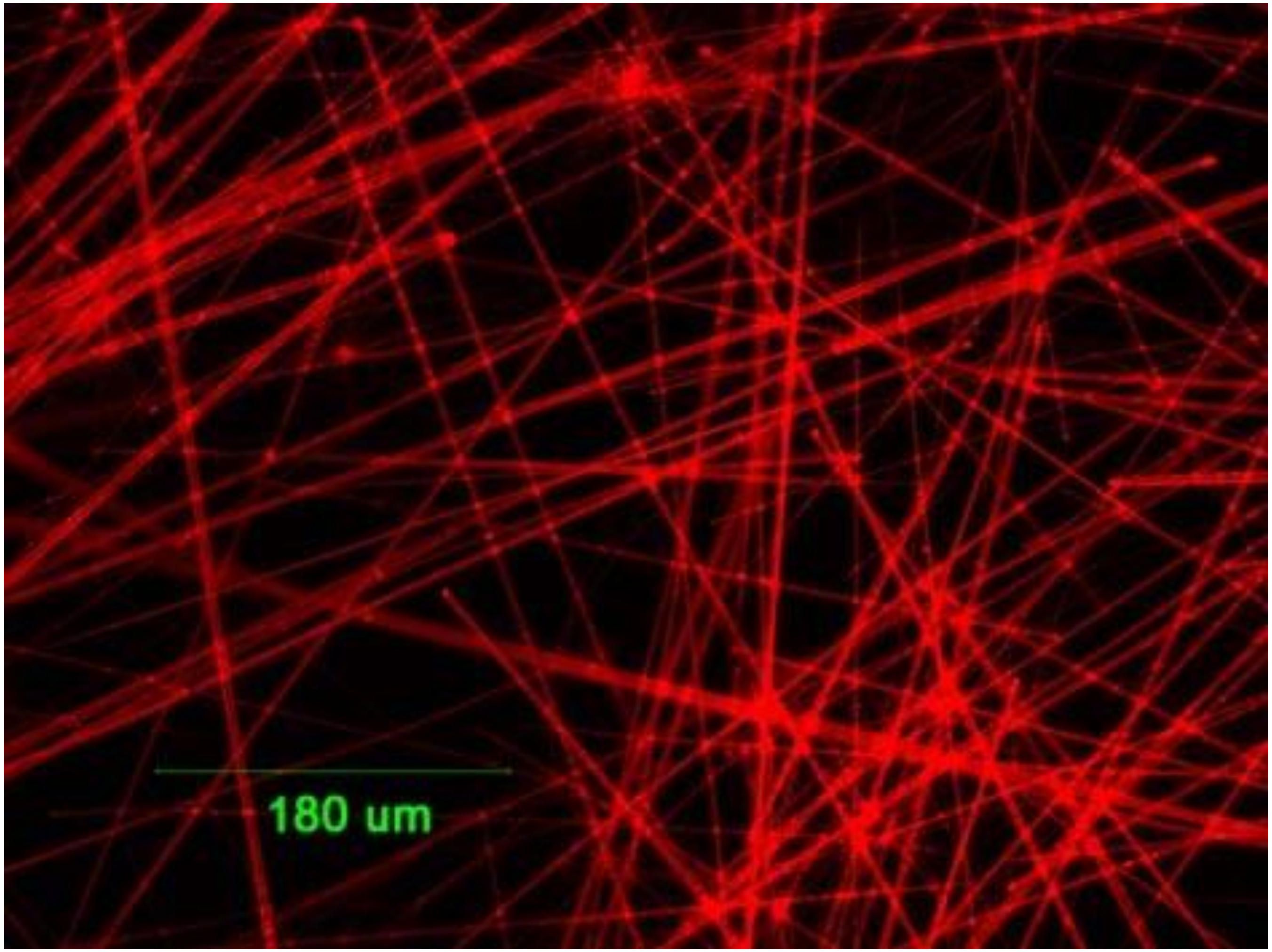
Red blood cell



Flu virus



Organic nanobelts with strong emission



Advantages and Disadvantages of Optical Microscope

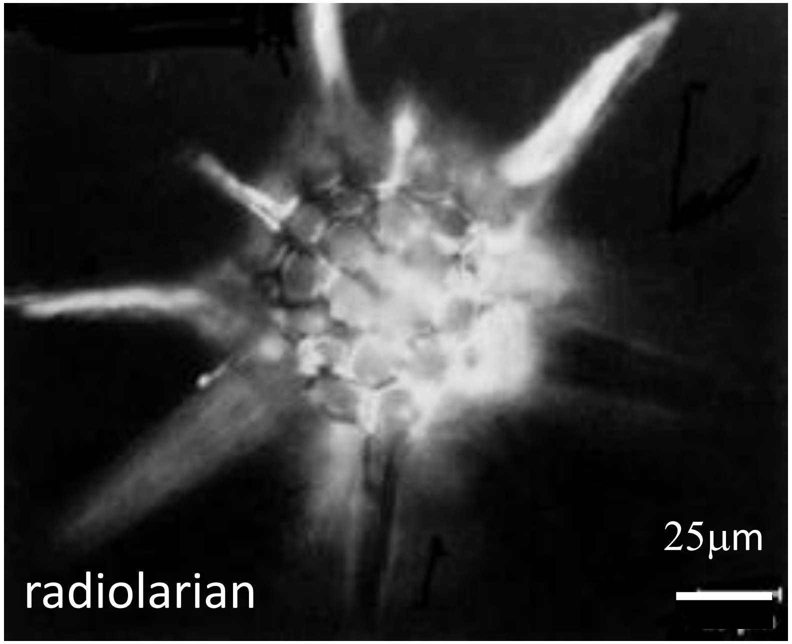
Advantages:

- Direct imaging with no need of sample pre-treatment, the only microscopy for real color imaging.
- Fast, and adaptable to all kinds of sample systems, from gas, to liquid, and to solid sample systems, in any shapes or geometries.
- Easy to be integrated with digital camera systems for data storage and analysis.

Disadvantages:

- Low resolution, usually down to only sub-micron or a few hundreds of nanometers, mainly due to the light diffraction limit.

Optical Microscopy (OM) vs Scanning Electron Microscopy (SEM)



OM

SEM

Small depth of field
Low resolution

Large depth of field
High resolution

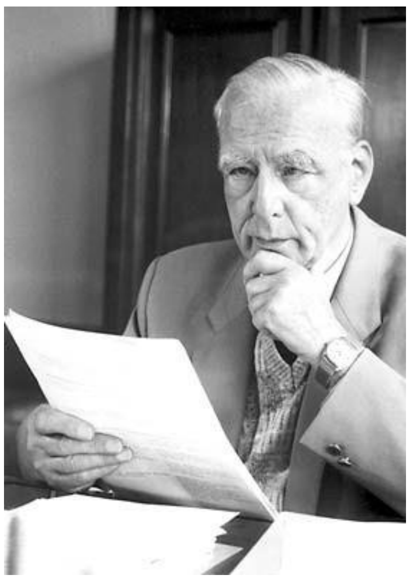
Electronic Microscope for higher resolution

- Resolution limit of optical microscopes is due to the light diffraction; roughly optical resolution can be estimated as wavelength λ/2NA (NA is the numerical aperture of lens, usually ~ 1.0): for white light, average wavelength is around 500 nm, the best resolution is thus a few hundreds nm.
- Decreasing the wavelength is the way to improve the resolution, though nobody would deal with UV light.
- **Electron wave is a unique medium that can be used in imaging. By accelerating the electrons into high energy beam (via high voltage), the wavelength thus created is far shorter than white light**. For example, for an electron beam produced from a 20 kV gun, the wavelength is only 1240.7/20,000 (eV) = 0.06 nm = 0.6 Å, corresponding to a resolution limit of λ/2 = 0.3 Å --- *theoretically, it can be used to image a species as small as 0.3 Å.*

Most atoms are in size of 2-3 Å.

History of Electronic Microscope

The Nobel Prize in Physics 1986



"for his fundamental work in electron optics, and for the design of the first electron microscope"

Ernst Ruska
Born: 25 December 1906, Heidelberg, Germany
Died: 27 May 1988, West Berlin, Germany
Affiliation at the time of the award: Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Federal Republic of Germany

What is SEM?

- In scanning electron microscopy (SEM) an electron beam is focused into a small probe and is rastered across the surface of a specimen.
- Several interactions with the sample that result in the emission of electrons or photons occur as the electrons penetrate the surface.
- These emitted particles can be collected with the appropriate detector to yield valuable information about the material.
- The most immediate result of observation in the scanning electron microscope is that it displays the shape of the sample.
- The resolution is determined by beam diameter.

Basic components of SEM

- Electron optics:

1. condenser lens --- focusing the electron beam to the objective lens.
2. objective lens --- responsible for the size of electron beam impinging on sample surface 3. electromagnetic coils --- responsible for driving the raster scanning by deflecting the electron beam.

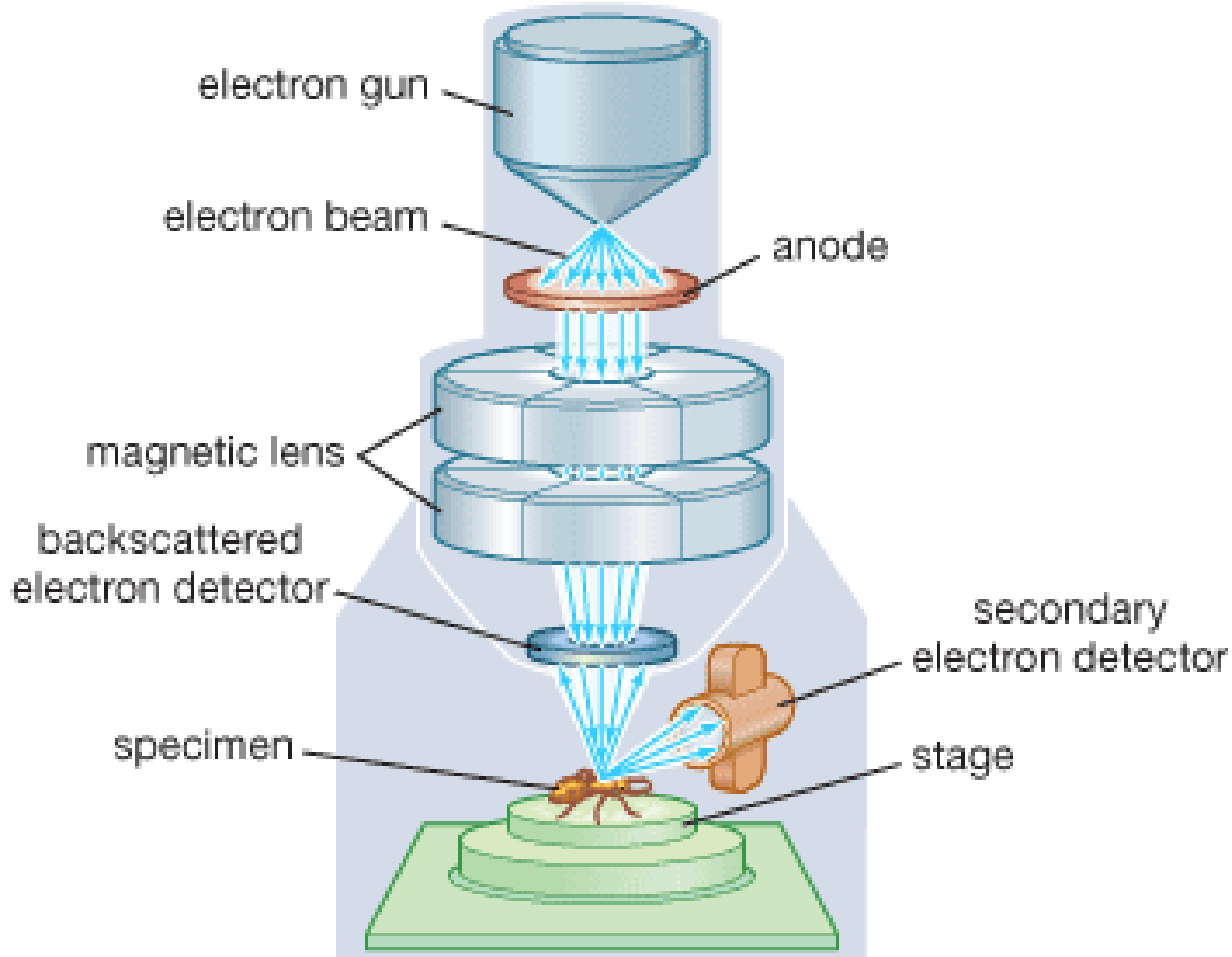
- Sample and sample holder:

1. size --- centimeters.
2. rotation --- sample can be rotated freely at three dimensions, x, y, z, to achieve imaging at all directions.
3. conductivity --- required for sample to be measured. For non-conducting samples, like biological specimens, metallic coating is required.

- Transducers (detectors):

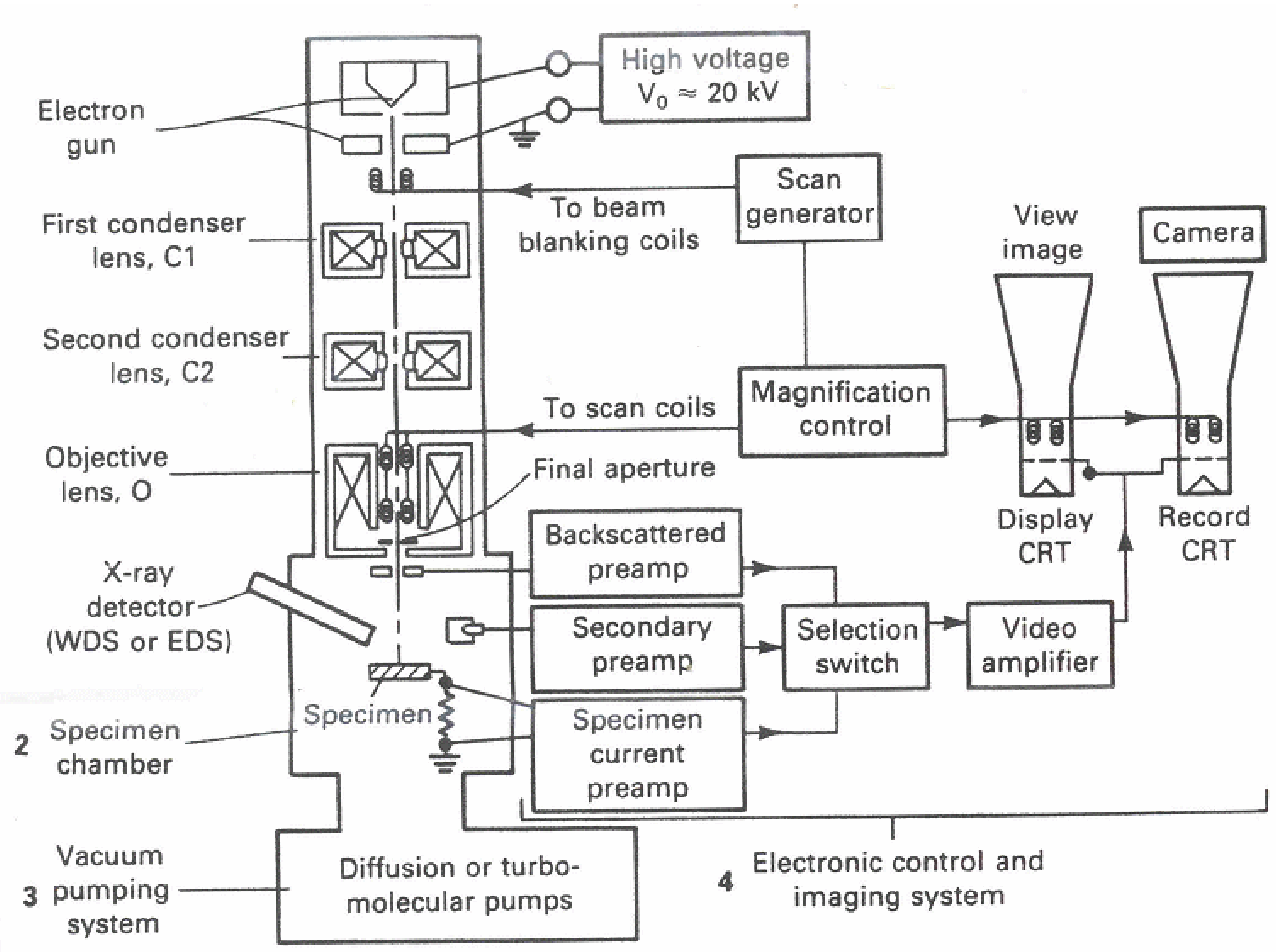
1. scintillation device --- doped glass or plastic target that emits a cascade of visible photons when struck by electrons.
2. semiconductor transducers --- when struck by electrons, electron-hole pairs are generated, thus increasing the conductivity.

Scanning Electron Microscope (SEM)

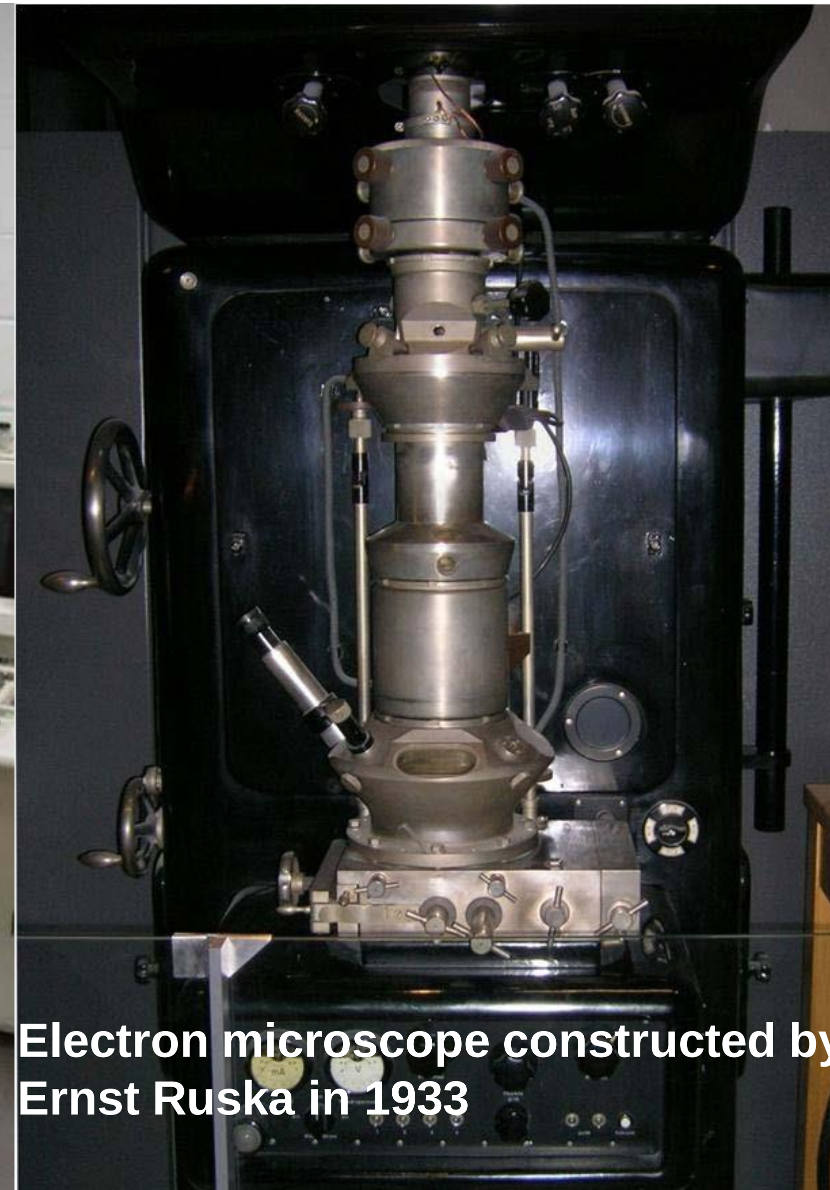


- Electron microscope follows the same ideas of optical microscope, but uses electrons instead of light;
- “Lens” here are not the optical materials (like glass), but electrical field.

Detailed working diagram of SEM



Scanning Electron Microscope (SEM)



Electron microscope constructed by Ernst Ruska in 1933

Advantages and Disadvantages of SEM

Advantages:

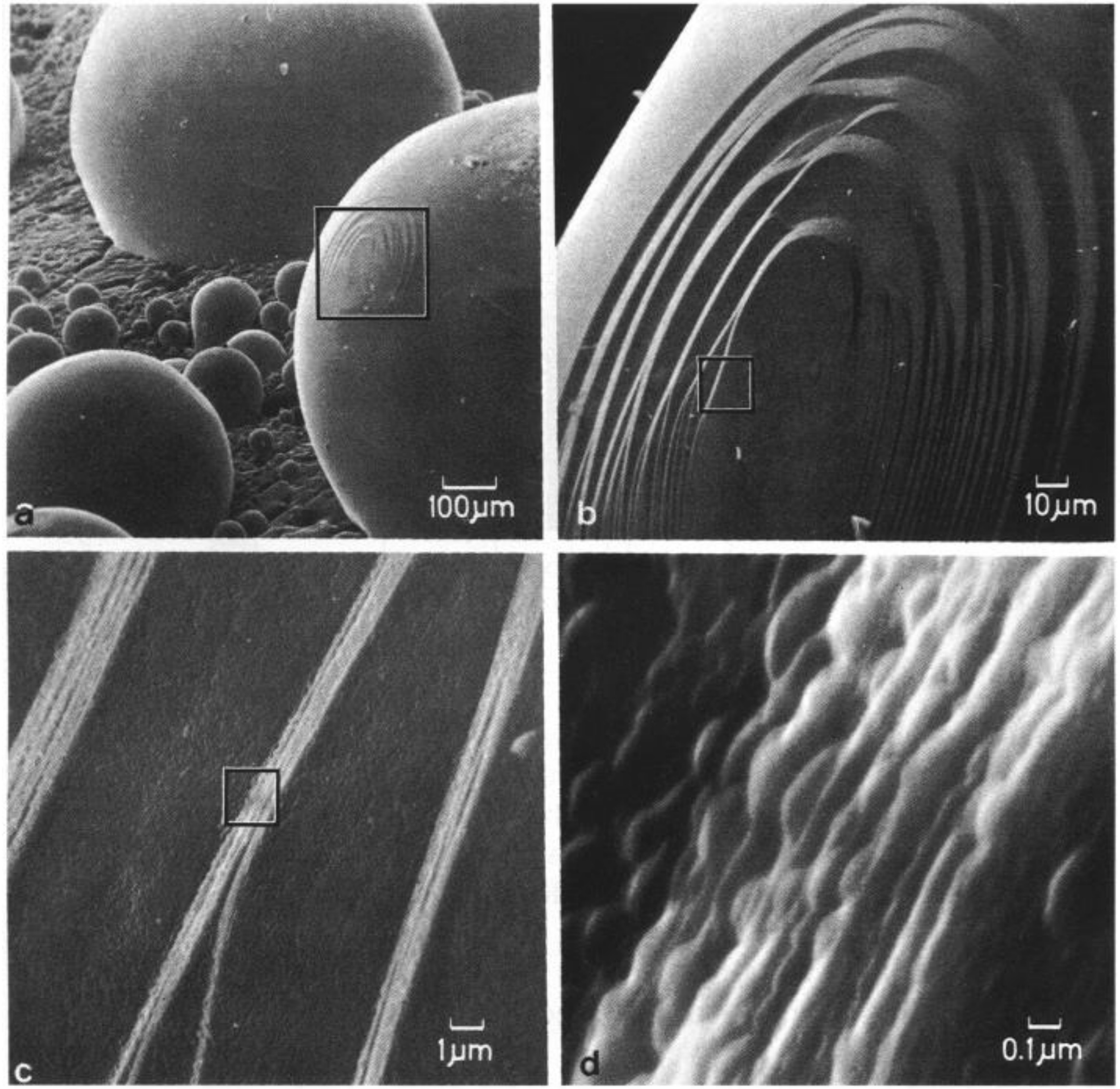
- Almost all kinds of samples, conducting and non-conducting (stain coating needed);
- Based on surface interaction --- no requirement of electron-transparent sample.

•Imaging at all directions through **x-y-z (3D)** rotation of sample.

Disadvantages:

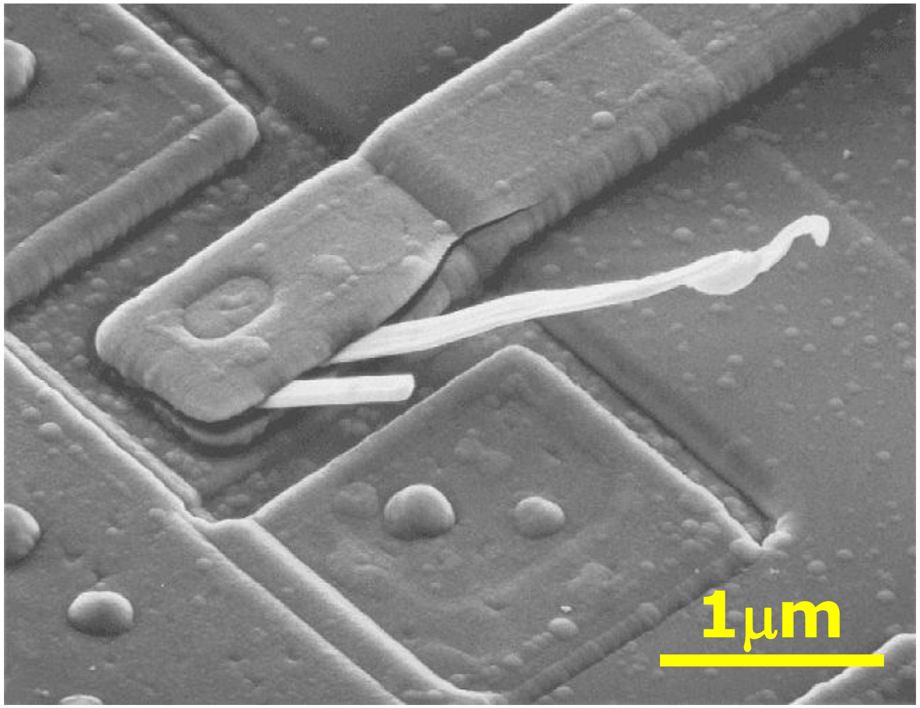
- Low resolution, usually above a few tens of nanometers.
- Usually required surface stain-coating with metals for electron conducting.

Image Magnification



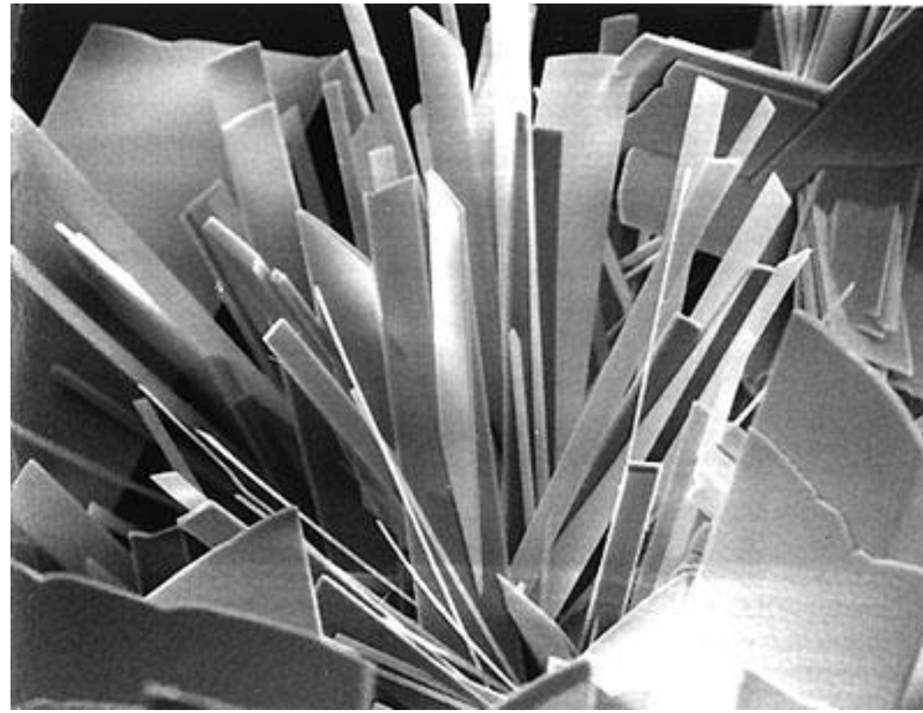
Example of a series of increasing magnification (spherical lead particles imaged in SE mode)

SE Images - Topographic Contrast

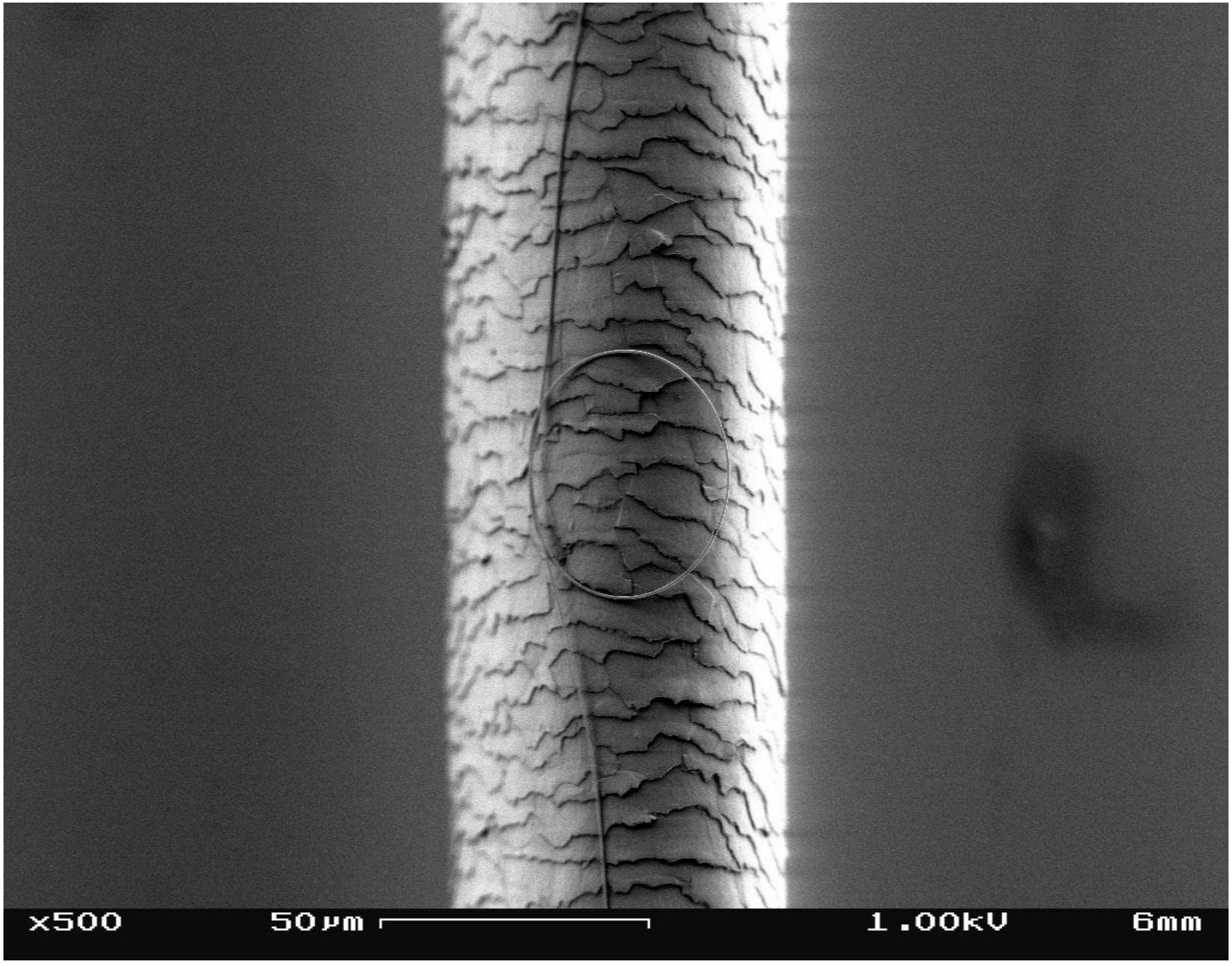


Defect in a semiconductor device

The debris shown here is an oxide fiber got stuck at a semiconductor device detected by SEM

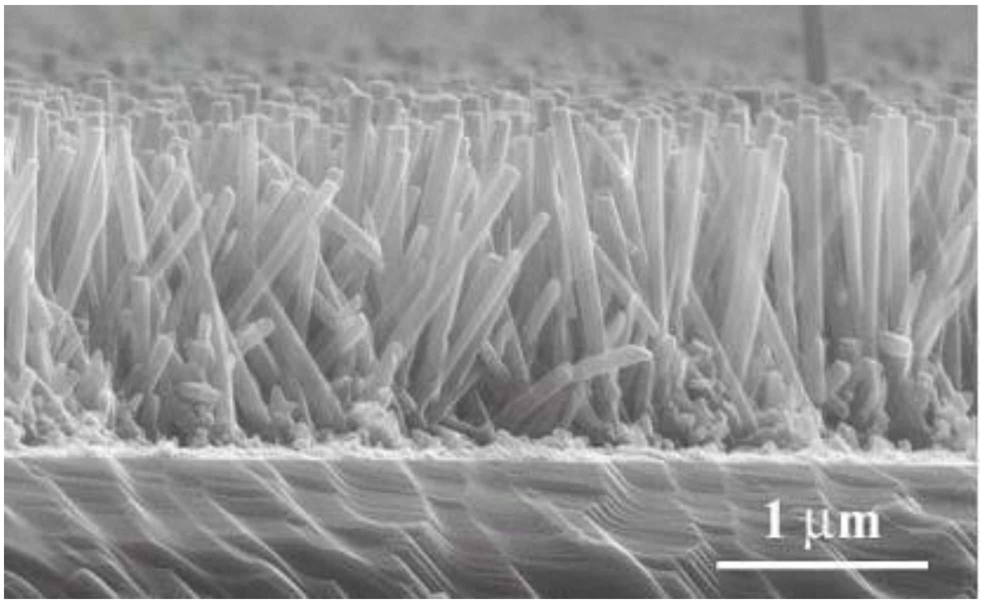


Molybdenum trioxide crystals

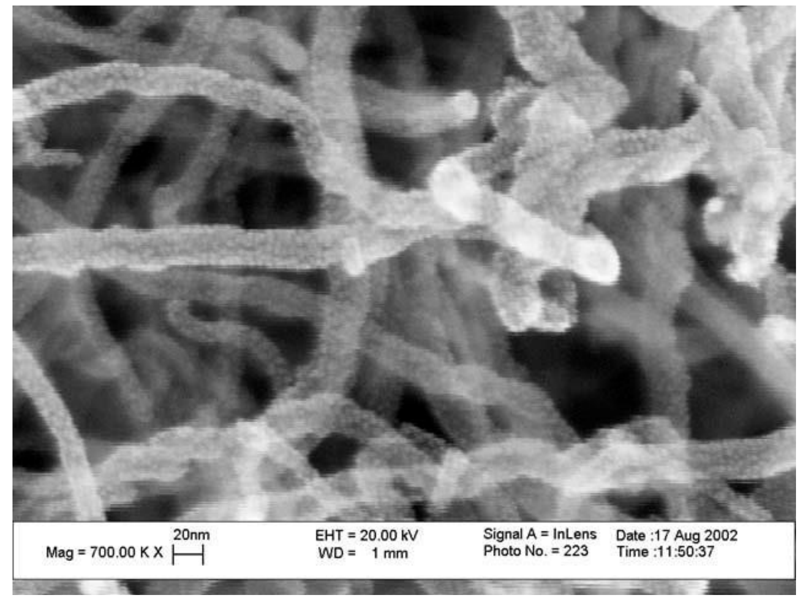


a nanowire curled into a loop in front of a strand of human hair

SEM images conducting and semiconducting materials

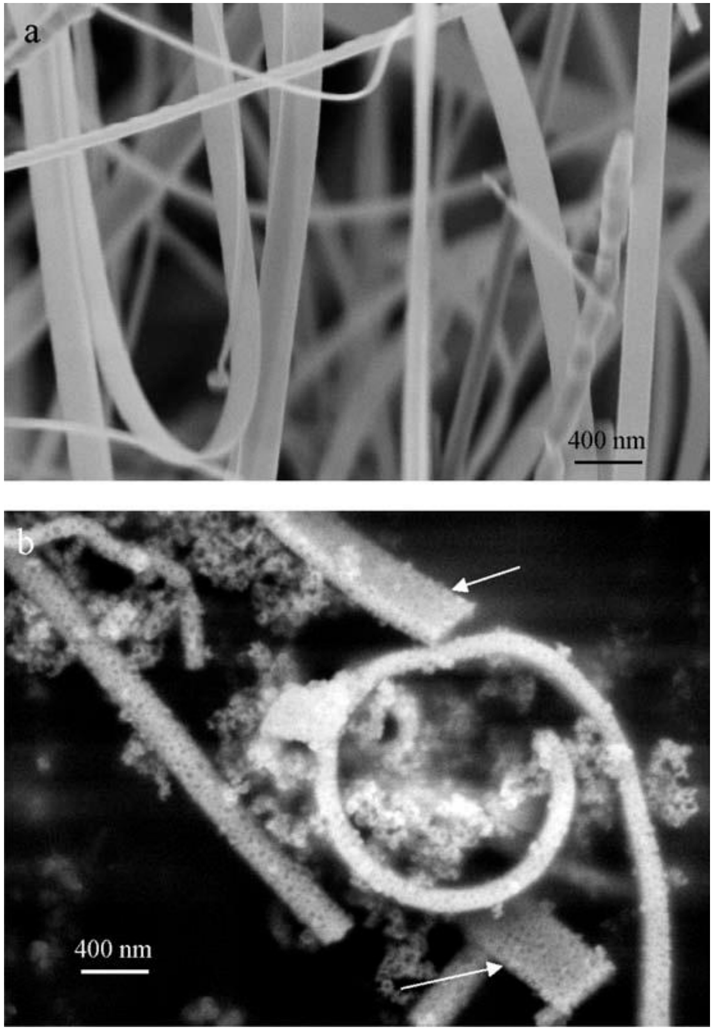


ZnO nano-wires



Carbon nano-tubes

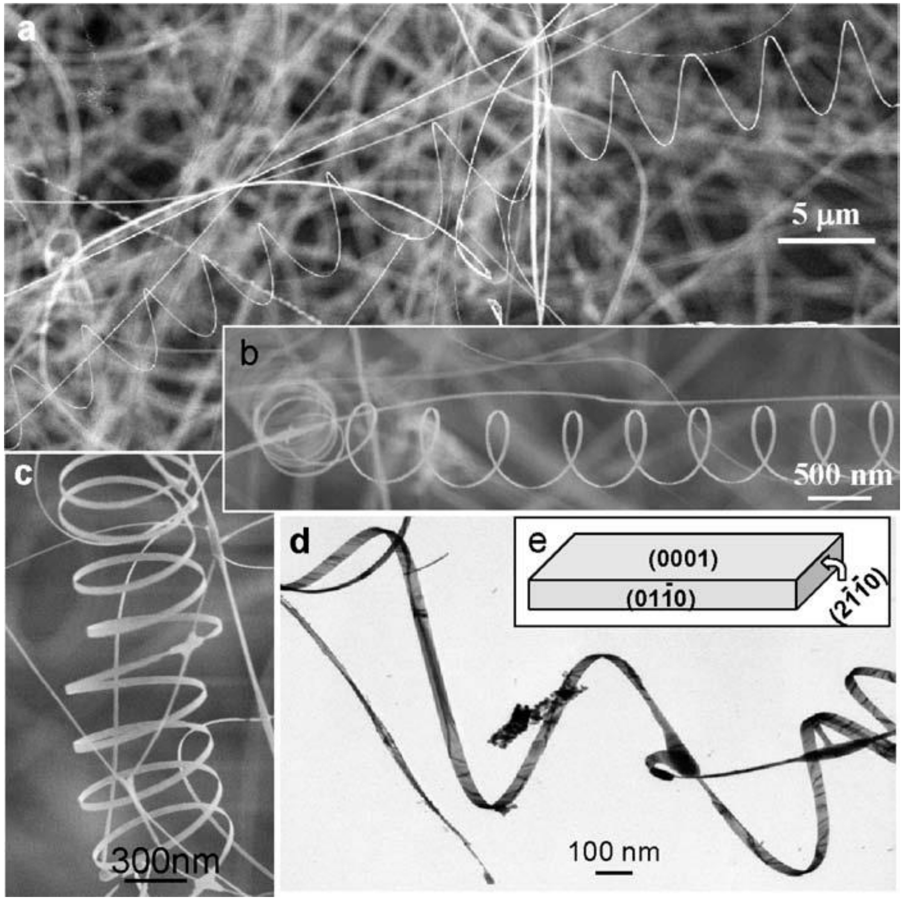
Nanobelts



SEM images of (*a*) **ZnO** nanobelts and (*b*) the **ZnS** nanobelts converted through chemical reaction with H_2S.

Z. L. Wang, Annual Review of Physical Chemistry, 2004, Vol. 55: 159-196

Nanosprings



Nanosprings and nanorings of piezoelectric nanobelts. (*a c*) SEM images of the as-synthesized single-crystal **ZnO** nanobelts, showing helical nanosprings. The typical width of the nanobelt is 30 nm, and pitch distance is rather uniform. (*d*) TEM image of a helical nanospring made of a single-crystal ZnO nanobelt. (*e*) The structure model of the ZnO nanobelt.

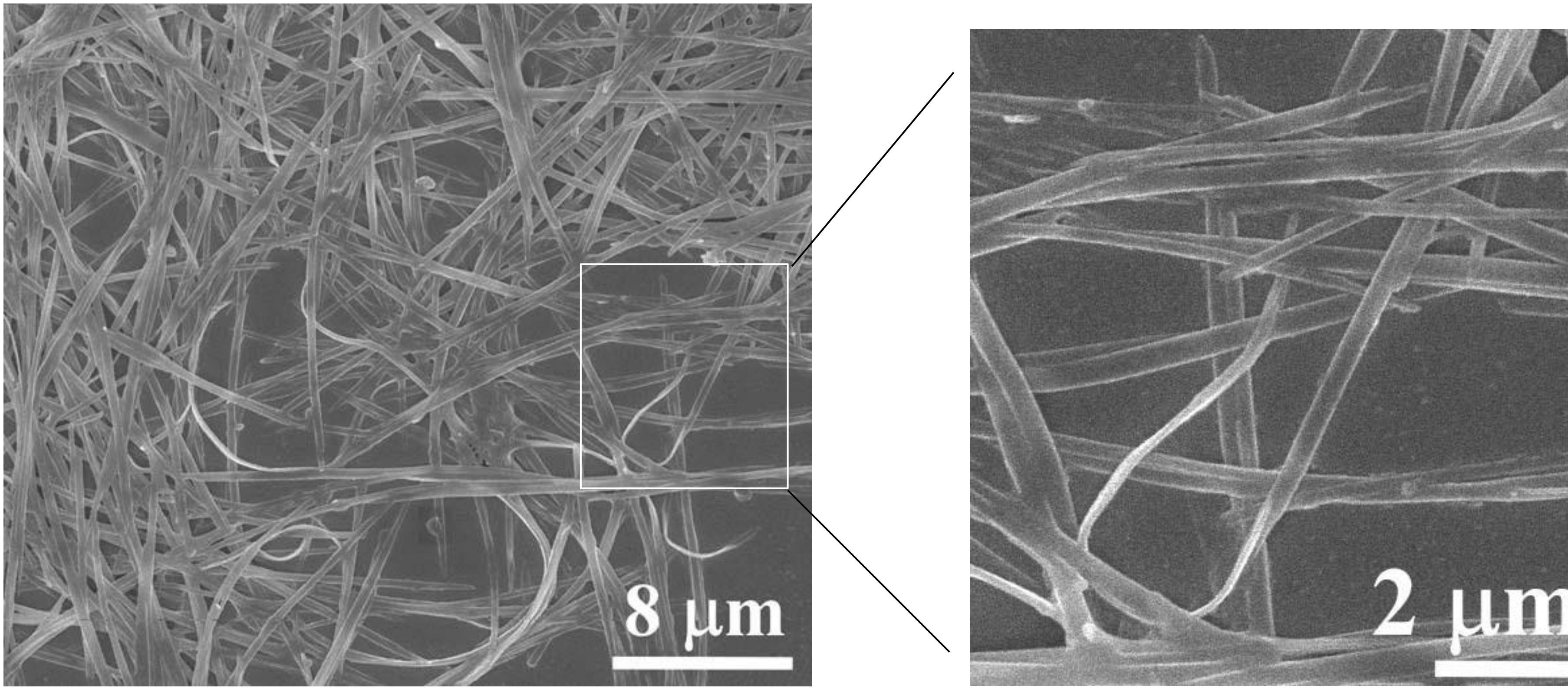
Z. L. Wang, Annual Review of Physical Chemistry, 2004, Vol. 55: 159-196

Nanosaw

SEM image of comb-like nanostructure of **ZnO**, which is the result of surface polarization induced growth.

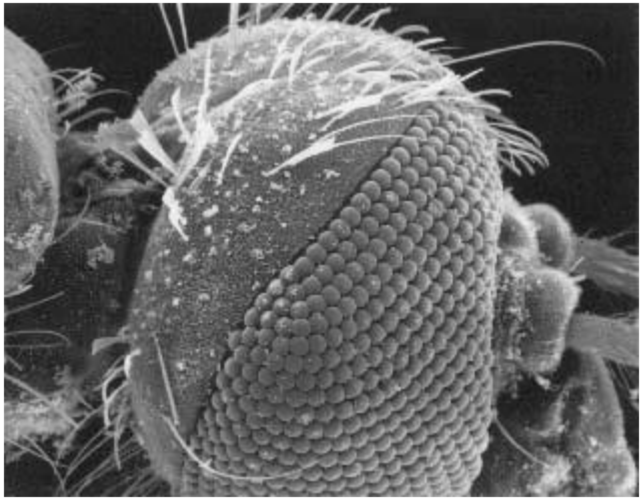
Z. L. Wang, Annual Review of Physical Chemistry, 2004, Vol. 55: 159-196

Twisted Nanobelts

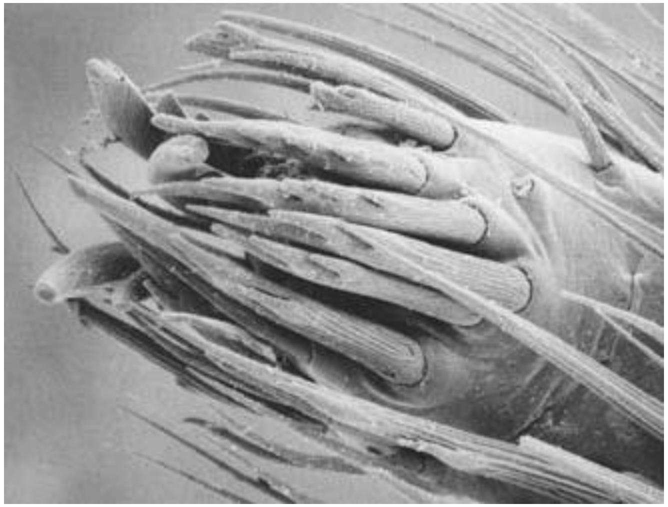


Kaushik Balakrishnan, et al. *J. Am. Chem. Soc.* **127**(2005) 10496-10497

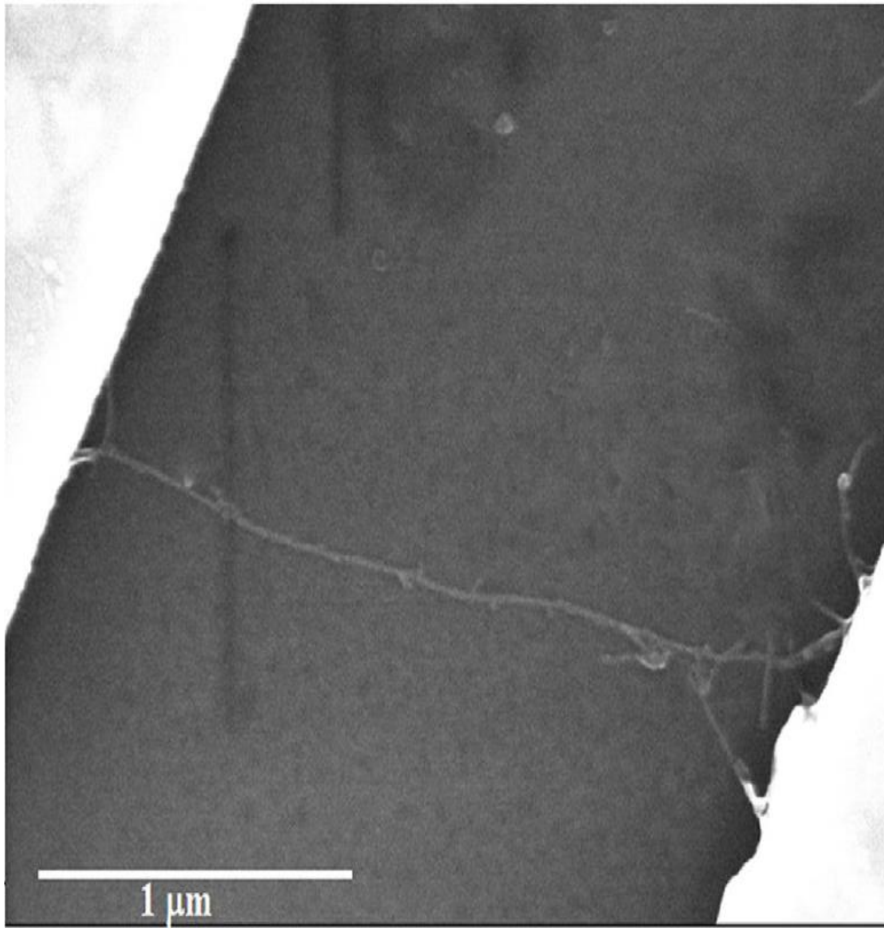
SEM images of bio-species

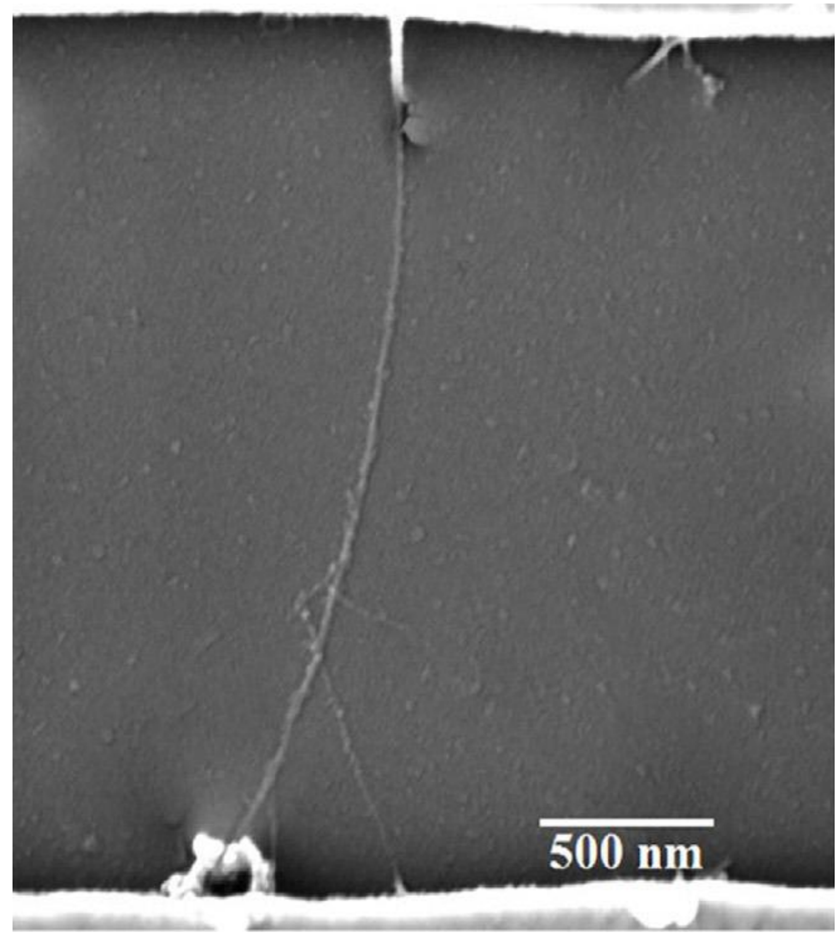


The head of a mosquito is mostly eye. The eyes are compound eyes, made up of many tiny lenses.



Claw of a Black Widow spider. The claw has three hooks, the middle one used to work the silk.

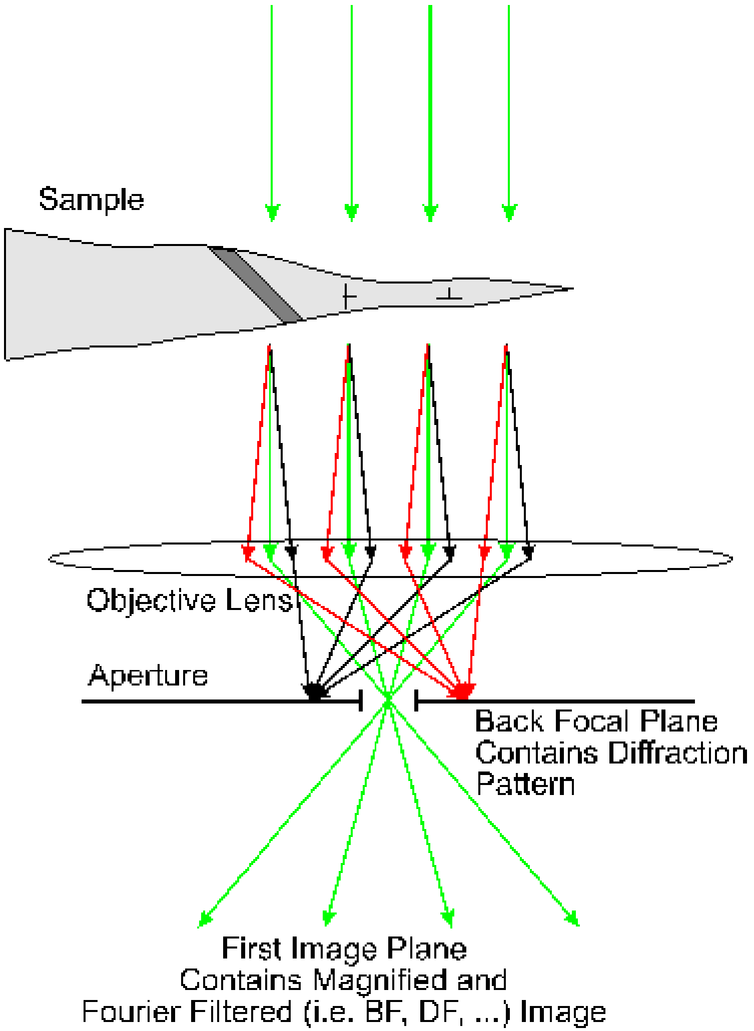




FESEM images of SWNTs FET

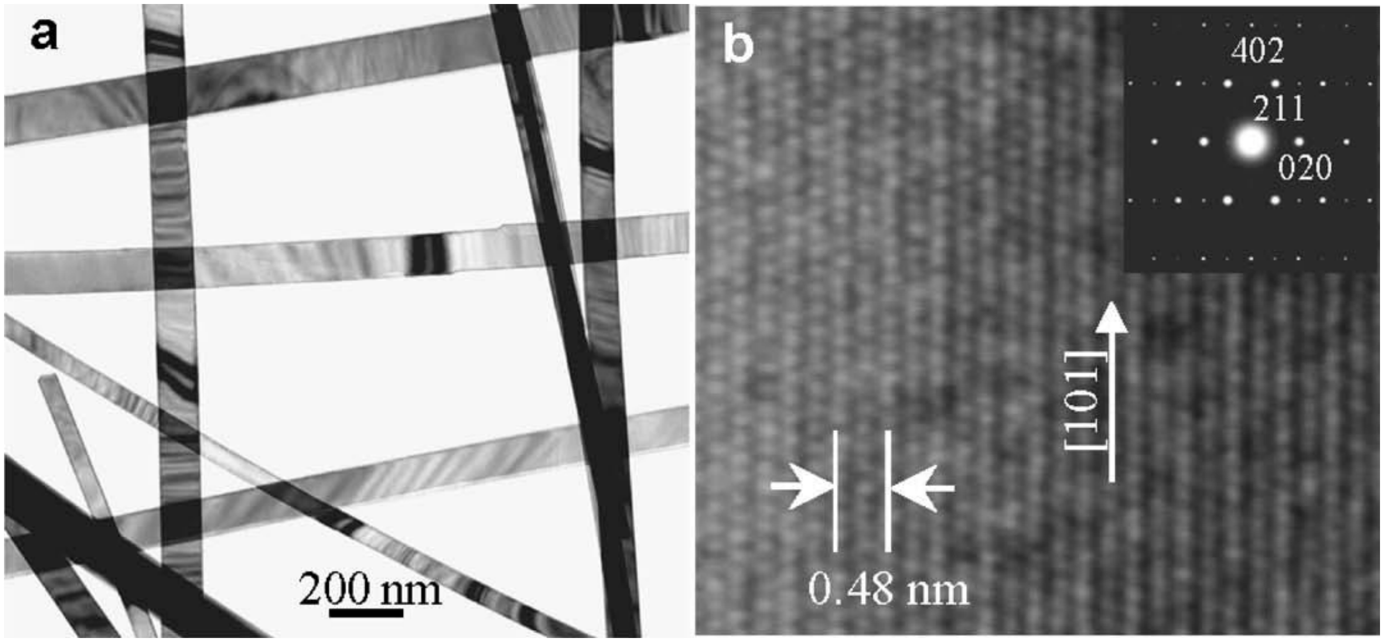
Transmission electron microscopy (TEM)

Hitachi H9000 UHR TEM:
a dedicated HREM TEM,
capable of 0.18nm point
resolution operating at 300kV



Detector: CCD (2D imaging)

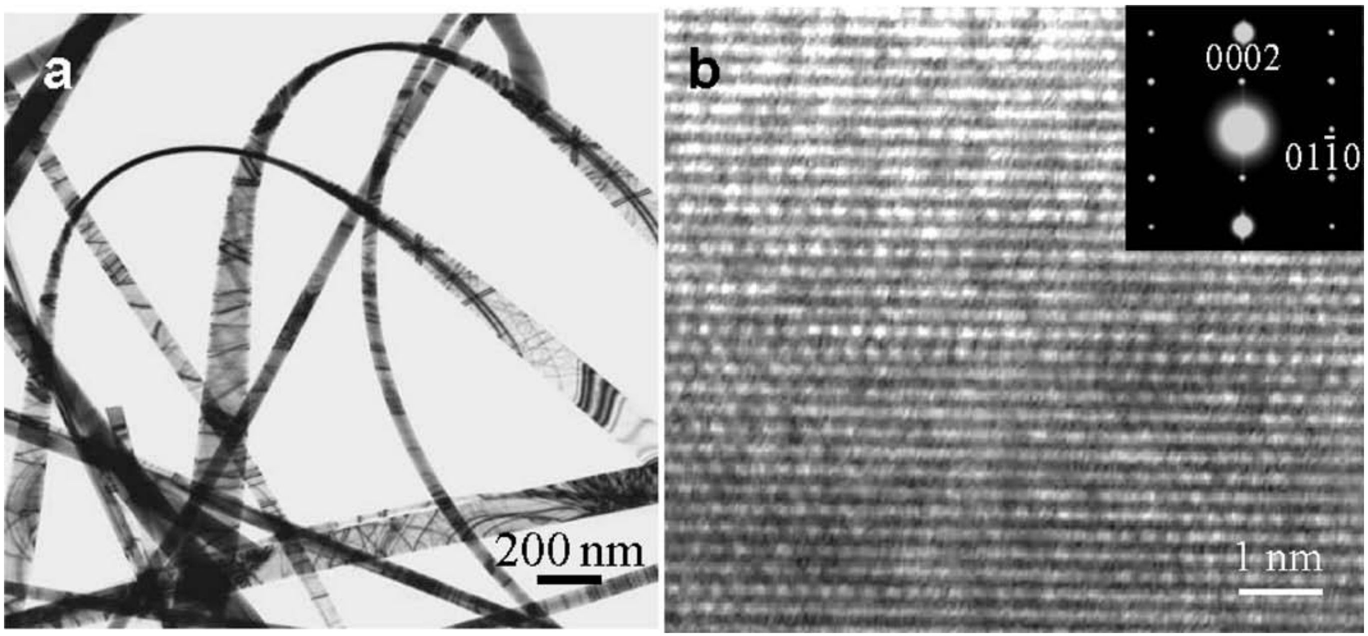
TEM images: nanobelt



(*a*) Transmission electron microscopy (TEM) image of the as-synthesized **SnO2** nanobelts. (*b*) High-resolution TEM image recorded with the incident electron perpendicular to the top surface of the nanobelt.

Z. L. Wang, Annual Review of Physical Chemistry, Vol. 55: 159-196

TEM images: nanobelt



(*a*) Transmission electron microscopy (TEM) image of the as-synthesized **ZnO** nanobelts. (*b*) High-resolution TEM image recorded with the incident electron perpendicular to the top surface of the nanobelt.

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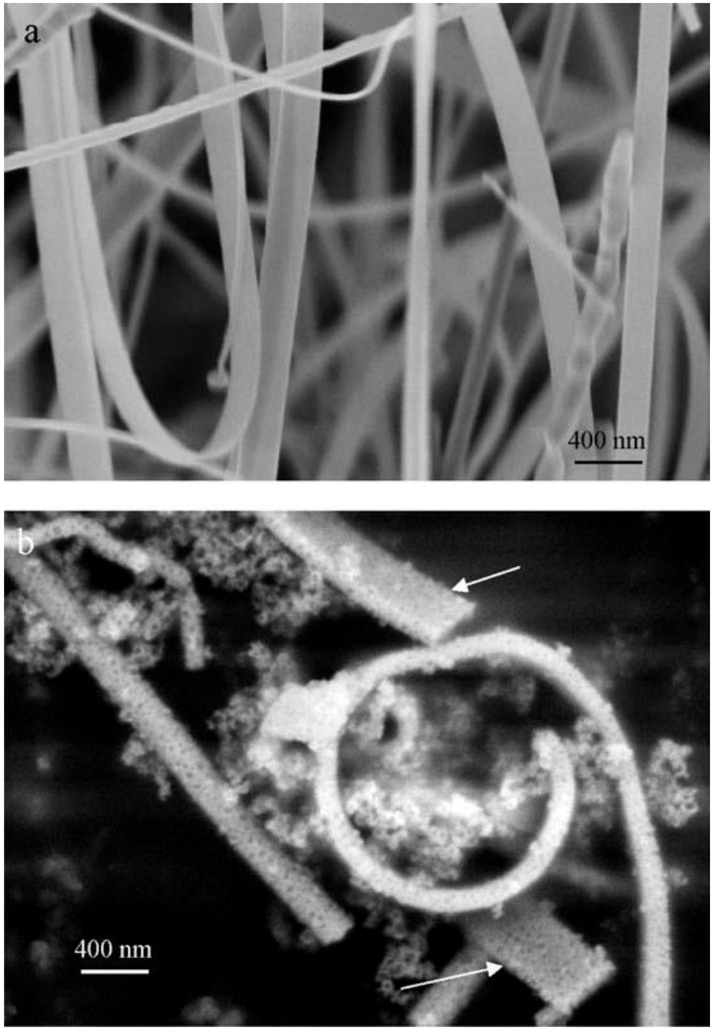
Nanobelts



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