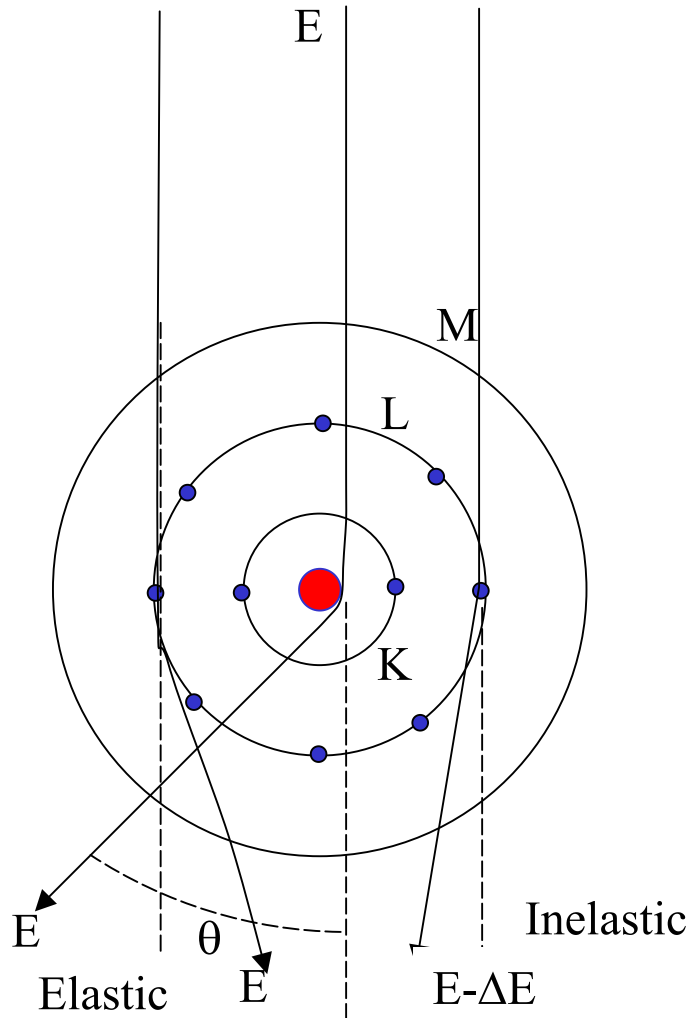
Characterization Techniques

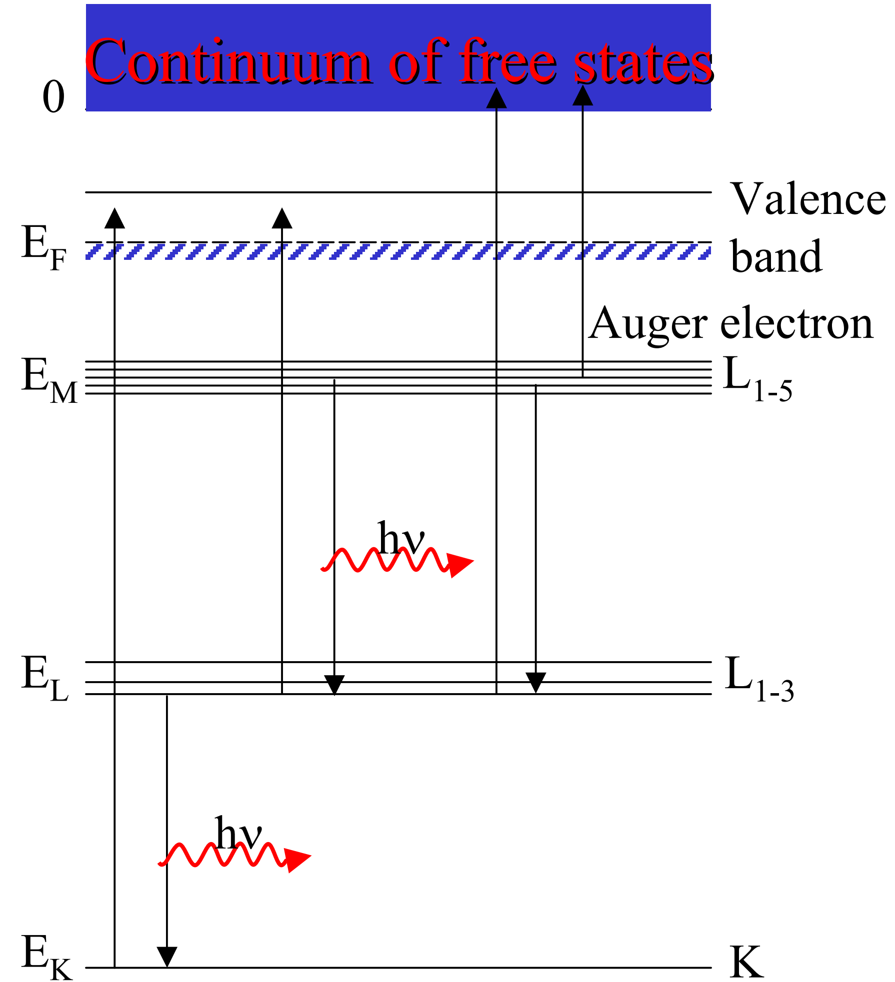
- SEM
  - Electron specimen interactions
  - Probe formation
  - Available signals
  - Limitations
  - Artefacts
    - Charging
    - Contamination
    - Damage
  - Contrast and metrology
- AFM
  - Basics
  - Limitations
  - Metrology

"Image Formation in Low-Voltage Scanning Electron Microscopy", Ludwig Reimer, SPIE, Bellingham (1993)

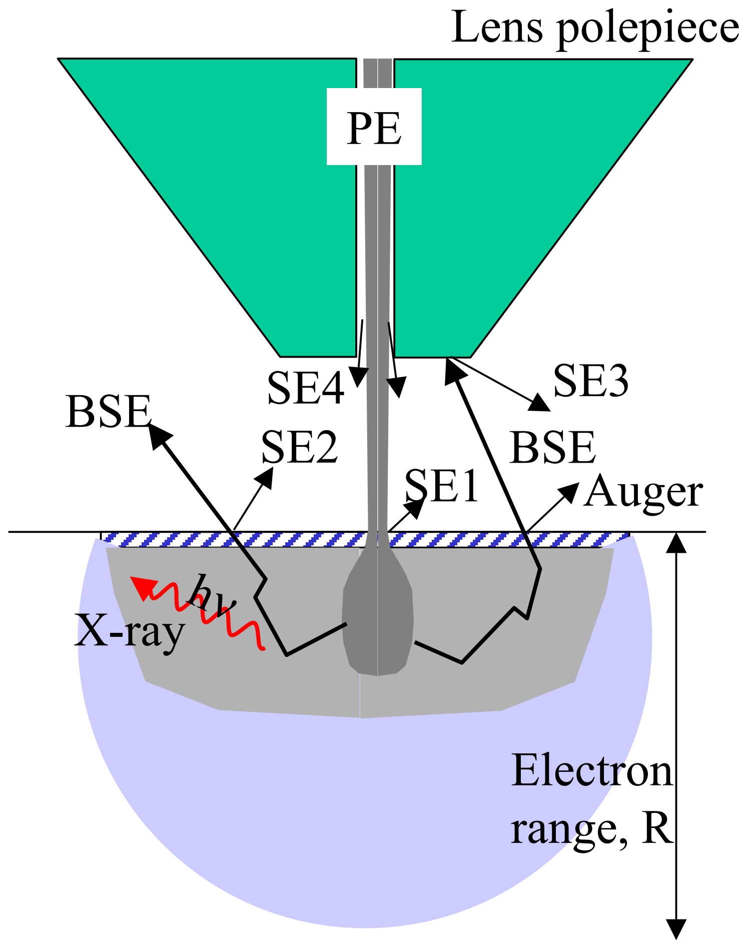
"Image Sharpness Measurement in the Scanning Electron Microscope - Part III", N.F. Zhang et al., *Scanning*, **21** p246 (1999)

Electron-Specimen Interactions

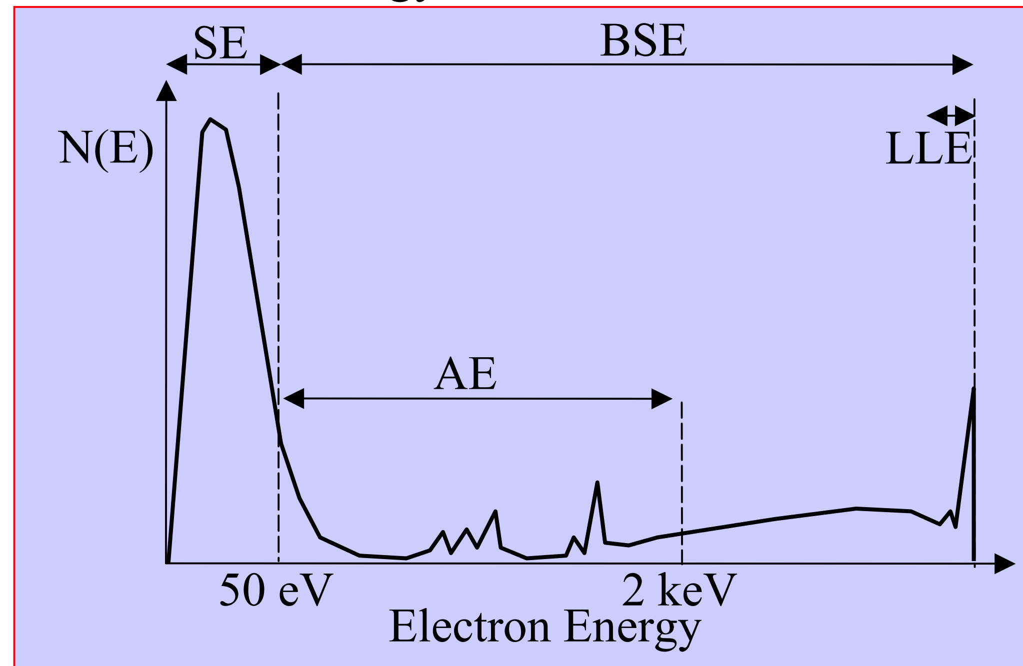




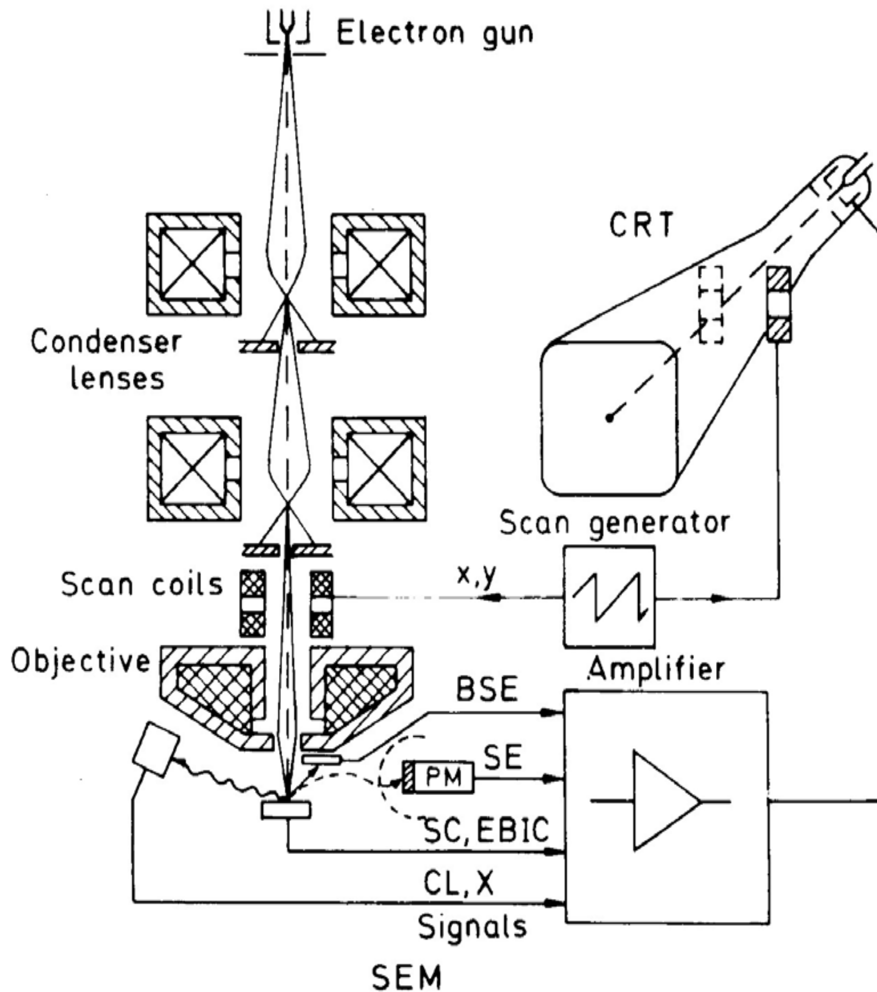
Excitation Volumes & Energy Distribution



- Primary electrons (PE) produce secondaries
  - SE escape depth is 1 - 10 nm
  - BSE generation volume ranges from 5 nm - 1µm depending on material and energy



SEM



Schematic of SEM showing different signals that can be detected:

SE - secondary electrons
BSE - backscattered electrons
SC - specimen current
CL - cathodo-luminescence
X - X-ray

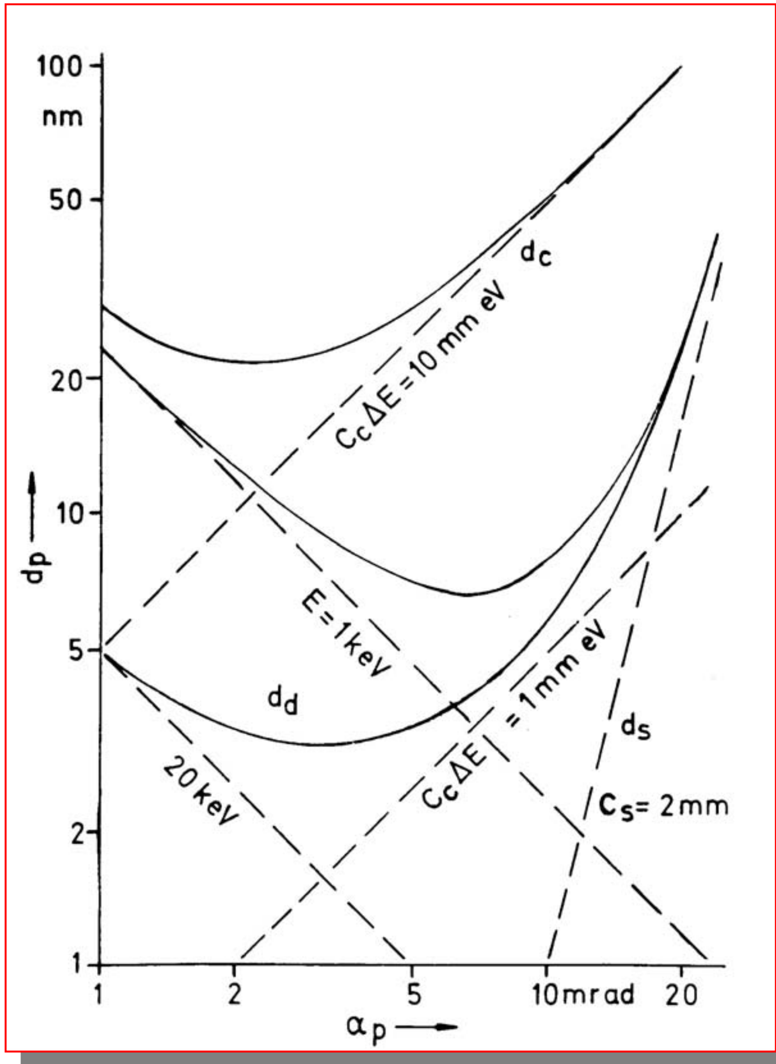
Magnification is ratio of CRT pixel size to pixel size on specimen

"Image Formation in Low-Voltage Scanning Electron Microscopy", Ludwig Reimer, SPIE, Bellingham (1993)

Probe Formation in SEM I

- Axial gun brightness, β, the current density, j_c, per solid angle, $\pi\alpha^2$, is conserved
  - Probe current cannot be changed without corresponding change in α
  - Minimum probe diameter for a given current, I_p, is $d_g^2 = 4I_p / \pi^2\beta\alpha^2 = C_0/\alpha^2$
- Minimum probe current is determined by signal to noise considerations
  - Mean number of electrons/pixel dwell time, τ, is $n = I_p / \tau e$
  - Secondary electron yield is δ and noise factor is b
  - RMS shot noise is $I_{RMS} = e\sqrt{n} / \tau = \sqrt{eI_p \tau}, \quad I_{SE} = \delta I_p, \quad Noise\ in\ I_{SE}, I_n = \frac{e\delta}{\tau}\sqrt{n(1+b)}$
  - $S/N = \frac{\Delta I_{SE}}{I_n} = \sqrt{\frac{I_p \tau}{e(1+b)}} \frac{\Delta I_{SE}}{I_{SE}} \geq k$
  - k ≥ 3 for detectablity of a signal ΔI_{SE}
  - Smaller pixels and/or lower noise requires higher beam currents ⇒ brighter sources

Probe Formation in SEM II



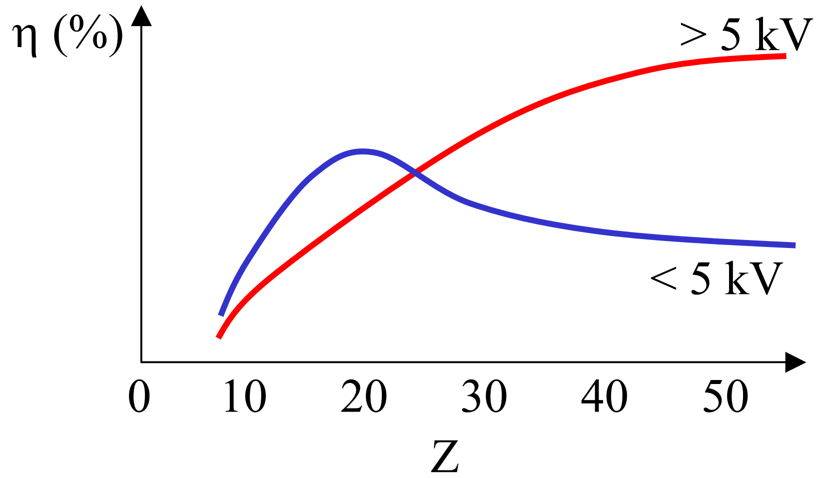
- Principal aberrations are spherical and chromatic:
  - $d_s = 0.5\ C_s\alpha^3$
  - $d_c = C_c(\Delta E/E)\ \alpha$
- Diffraction is also important:
  - $d_d = 0.6\lambda/\alpha$
- Minimum probe size:
  - $d_p^{\ 2} = d_d^{\ 2} + d_s^{\ 2} + d_c^{\ 2} + d_g^{\ 2}$
- Probe sizes as small as 1 - 2 nm can be produced in systems with field emission sources

"Image Formation in Low-Voltage Scanning Electron Microscopy", Ludwig Reimer, SPIE, Bellingham (1993)

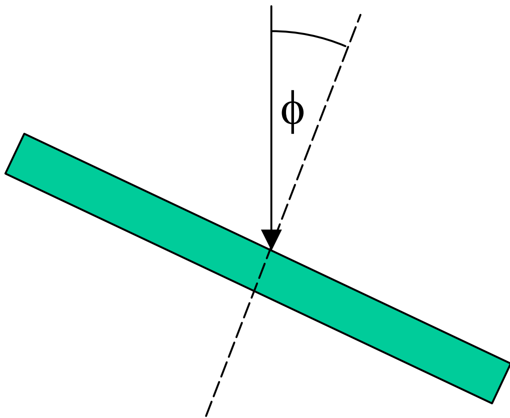
Electron Detectors

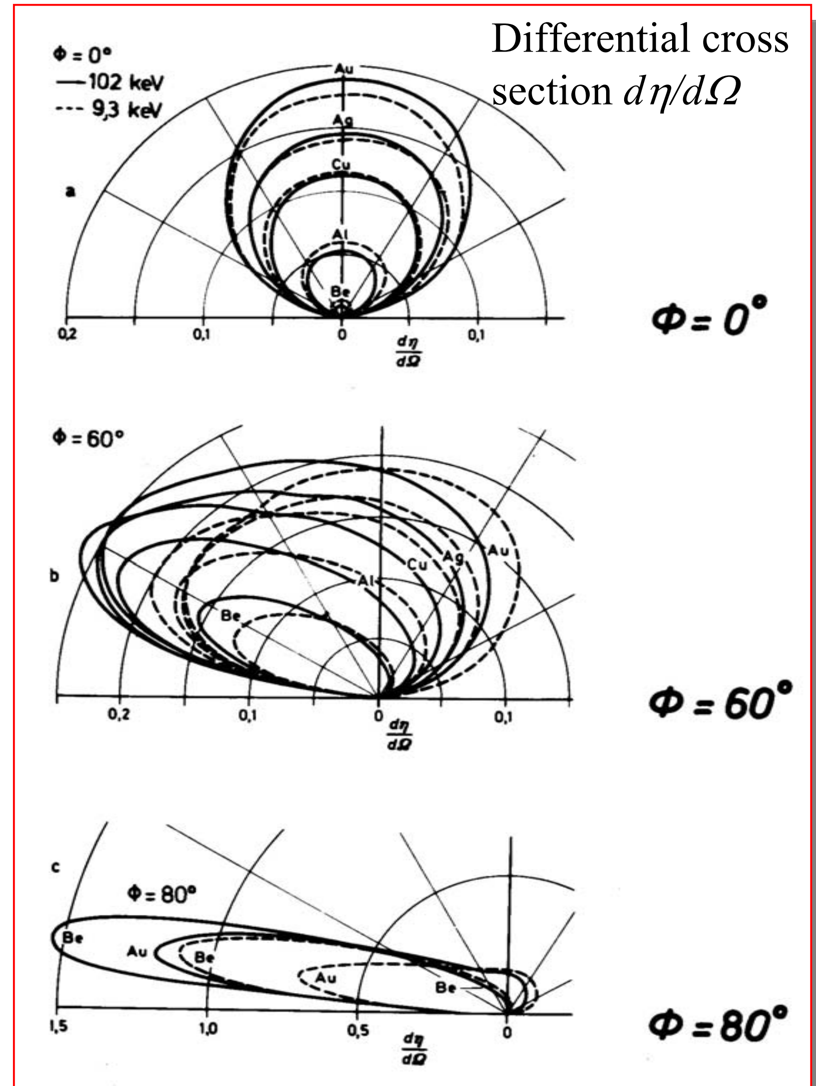
- Everhart-Thornley
  - Positively biased grid in front of scintillator collects electrons
    - Small solid angle collection
    - Efficient only for SE’s
    - Highly directional - detection shadowing
- Semiconductor Detectors
  - Au on n-Si Schottky diode or p-n junction
    - Existence of threshold voltage due to surface layer of detector restricts use to BSE (or transmitted)
    - RC time constants typically large, limiting acquisition rate (see Nanofab SEM)
- MicroChannel Plate
  - Arrays of 10 - 20 μm diameter glass capillaries with continuous voltage drop (1 kV) along length act as miniature photomultipliers
    - Very efficient
    - Biasing of front surface allows selection of SE+BSE or BSE only
- In-Lens
  - At short working distances, lens magnetic field extends to specimen and SE can follow spiral trajectories up in lens. Electrostatic field inside lens deflects SE to an E-T detector
    - Efficient collection of electrons by magnetic field
    - Relatively small detector shadowing

Backscattered Electron Distribution



$$\eta(Z,\phi) = (1+\cos\phi)^{-9/\sqrt{Z}}$$





"Image Formation in Low-Voltage Scanning Electron Microscopy", Ludwig Reimer, SPIE, Bellingham (1993)

Secondary Electron Distribution

- SE Emission
  - Penetration and diffusion of primary electrons
  - Excitation of electrons up to a few hundred eV
  - Transport to surface through a sequence of elastic and inelastic scattering events
  - Exit across surface potential barrier

$$n(s) = \left| dE_m / ds \right| \frac{s}{\varepsilon}$$

Number/path length (s)

s = path length

ε = mean energy loss to produce SE

$\left| dE_m / ds \right|$ = Bethe stopping power

$$dN_{SE} / dE_{SE} \propto \frac{1}{E} \frac{E_{SE}}{(E_{SE} + \phi)^4}$$

Energy distribution

ϕ = work function

$\phi / 3$ = most probable SE energy

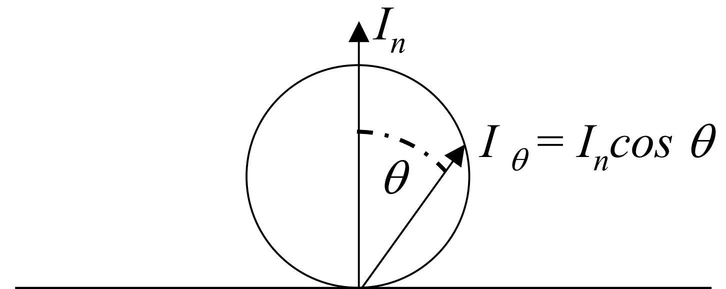
$$p(z) = 0.5 \exp(-z / \Lambda_{SE})$$

Probability of escape as fn. of depth (z)

z = depth

Λ_{SE} = mean free path or escape depth

$\varepsilon = 125\, eV$, $\Lambda_{SE} = 2.5\, nm$ for Al



Secondary Electron Yield

- SE1 are excited by the primary electrons (PE) and SE2 by BSE (yield η) as they exit the sample with yields δ_{PE} and δ_{BSE}
  - For E ≥ 5 keV the total yield is $\delta = \delta_{PE} + \delta_{BSE} = \delta_0(1+\beta\eta)$
  - $3 \geq \beta \geq 2$ and represents how many more SE are produced by BSE than PE as a result of the increased efficiency of the lower energy BSE in losing energy
  - For high energies (E ≥ 10 keV) $\delta_{PE} \propto |dE/ds| \Lambda_{SE}$
  - For a tilted sample δ_{PE} is proportional to the path length within the layer of depth Λ_{SE}, which is proportional to sec ϕ, i.e. tilted surfaces look brighter
  - Maximum in yield, δ_m, occurs at an energy, E_m, when primary electron range = Λ_{SE}

$$\delta = \delta_{PE} + \delta_{BSE} = \int_0^R \frac{\Phi(z)}{2\varepsilon} \exp(-z/\Lambda_{SE})dz$$

$\Phi(z) = depth\ distribution\ of\ ionization\ events$

$R = electron\ range$

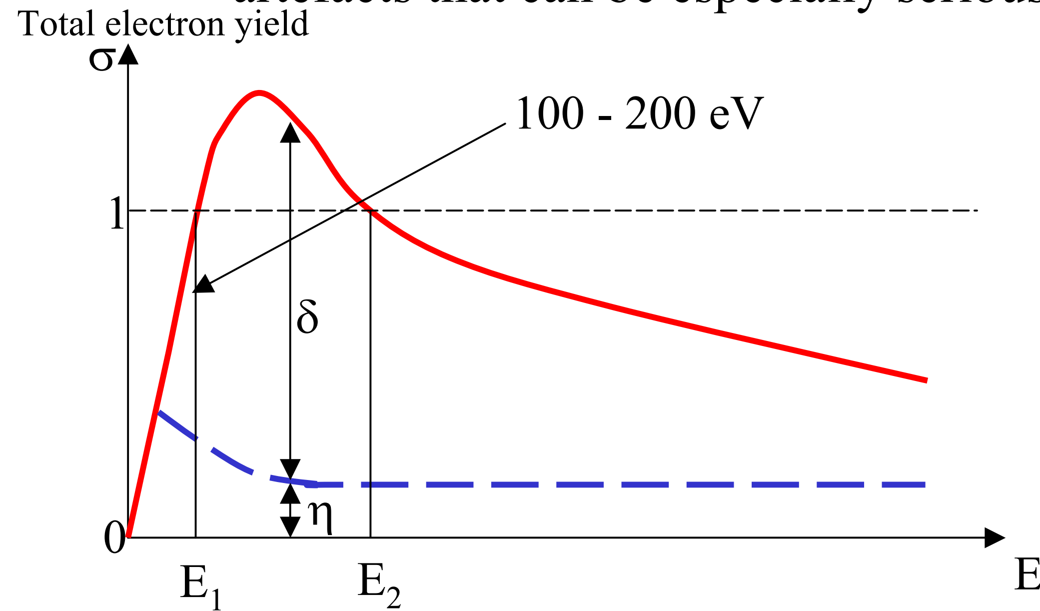
$$R << \Lambda_{SE} \Rightarrow \delta = \frac{E}{2\varepsilon}(1-\eta')$$

$\eta' =$ *fraction of incident energy carried away by SE and BSE*

$$R >> \Lambda_{SE} \Rightarrow \delta = \frac{\Phi(0)}{2\varepsilon} \Lambda_{SE} \sec\phi$$

Charging

- Insulators can charge dramatically in the SEM resulting in image artefacts that can be especially serious for accurate metrology



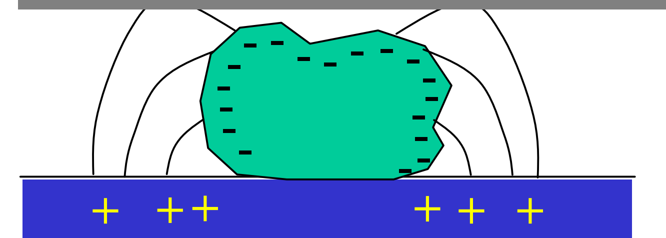
Note:
- Charging effects are typically time dependent. Most insulators leak charge so the time constant is an RC-type. Scan speed can have a very large impact on image quality

- Charging effects are also angle dependent through angular dependence of SE and BSE yields

Surface Potential U_S :

$$E_1 \le E \le E_2 : \quad \sigma = \eta + \delta_{eff} = 1; \quad \delta_{eff} = \int_{eU_S}^{50eV} \frac{d\delta}{dE} dE$$

$$E \ge E_2 : \quad U_S = -(E - E_2)/e$$



Bright particle and dark surround

Image Contrast I

- Contrast types
  - Topographic
    - Surface tilt: SE yield depends on surface normal
    - Shadow contrast: SE signal depends on surface normal and surface structure between SE point of origin and detector
    - BSE diffusion: signal of SE2 and SE3 increases when scattered electrons pass through increased surface area at edges etc. Signal also generated when BSE strike other parts of sample
    - SE diffusion: controlled by escape depth and surface topography
  - Material
  - Channeling
  - Voltage/surface potential
  - Capacitative coupling
  - Magnetic

Damage & Contamination

- Organic materials are damaged by e-beam
  - Amino acids 36 eV/nm3
  - Paraffin 75
  - PMMA 180
  - DNA/Aromatics 3600
  - Phthalocyanine 36000
- Organic materials are damaged/polymerized by the e-beam on the sample surface
  - Organic materials are always present in the atmosphere
  - Molecules diffuse over the sample surface and are pinned in place by irradiation leading to contamination
    - Scanning of large area before high mag can help
    - Free resist!
  - Contamination can lead to changes in contrast, errors in CD measurement and defects in subsequent processing

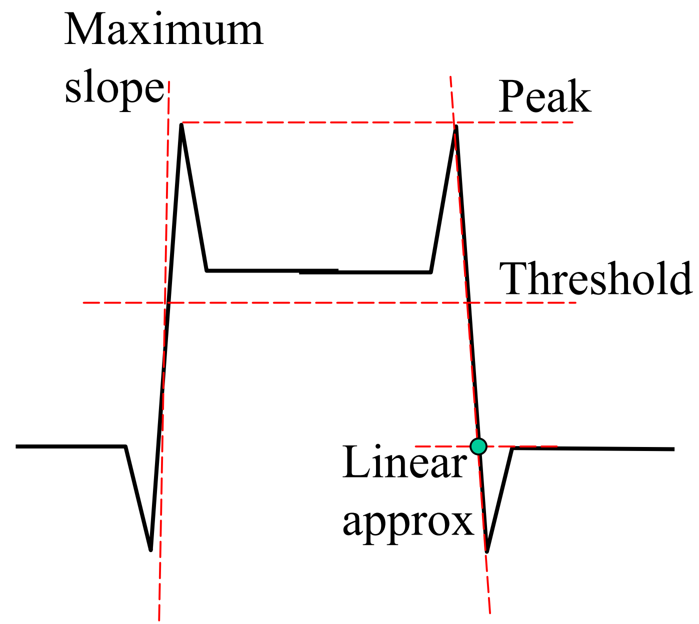
Image Contrast & CD Measurement

BSE
SE1
SE2
Detector
BSE
SE2
R = 50-10,000 nm

Surface tilt

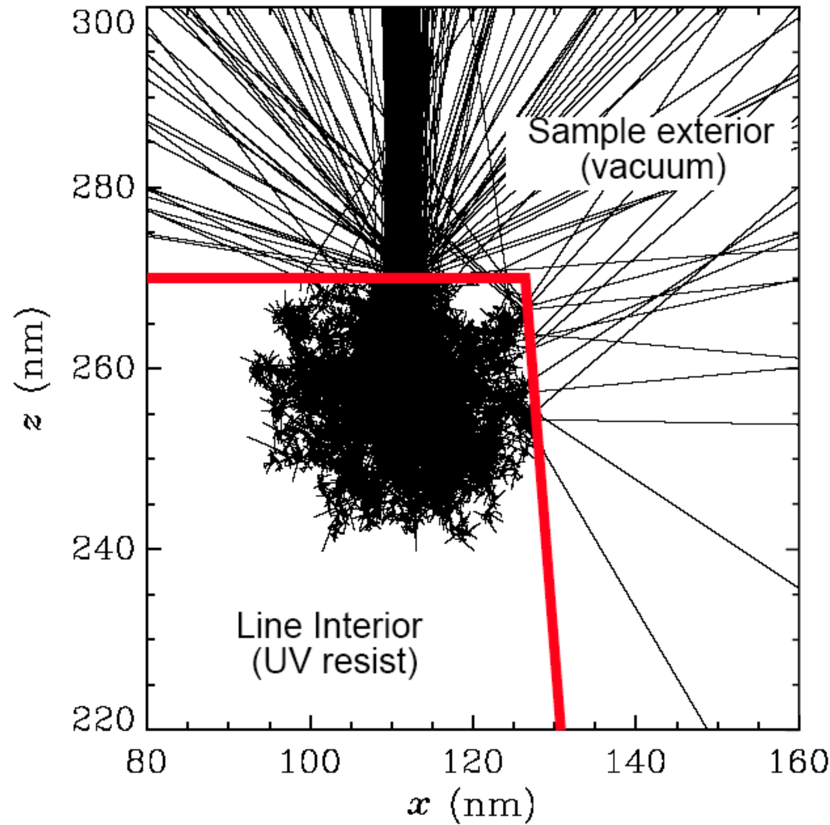
Surface tilt + shadowing

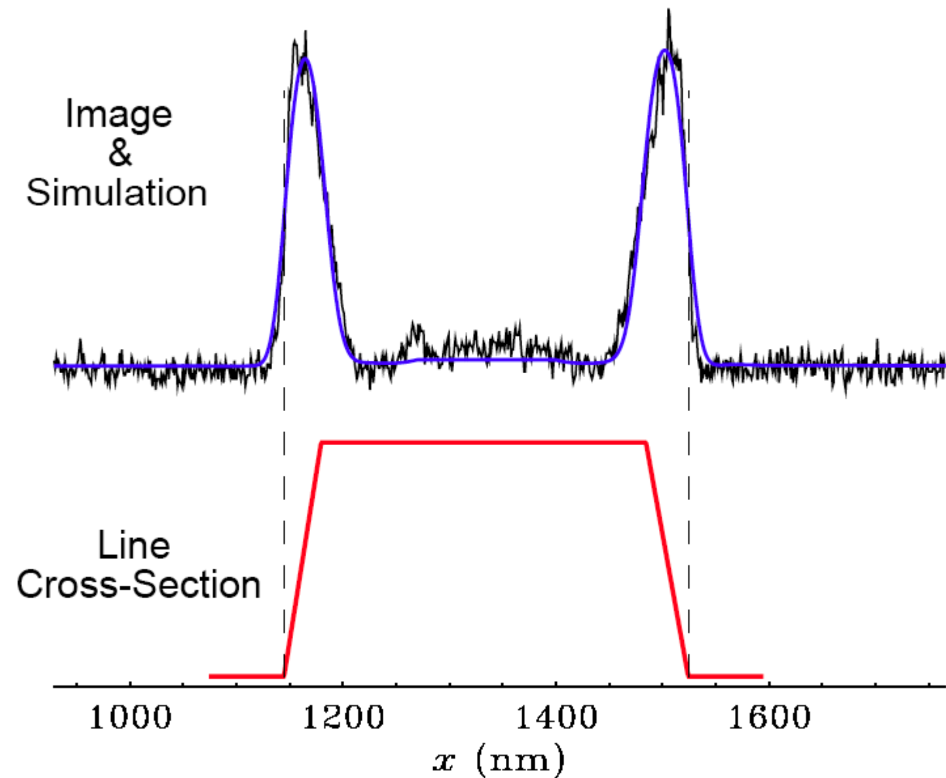
Surface tilt + BSE diffusion



Other linewidth measurement algorithms include fitting with a Fermi-Dirac function

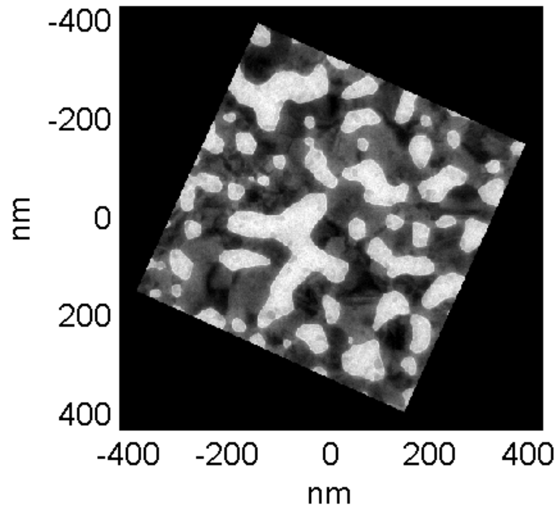
Signal Generation in CD-SEM



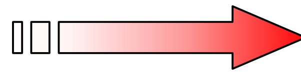


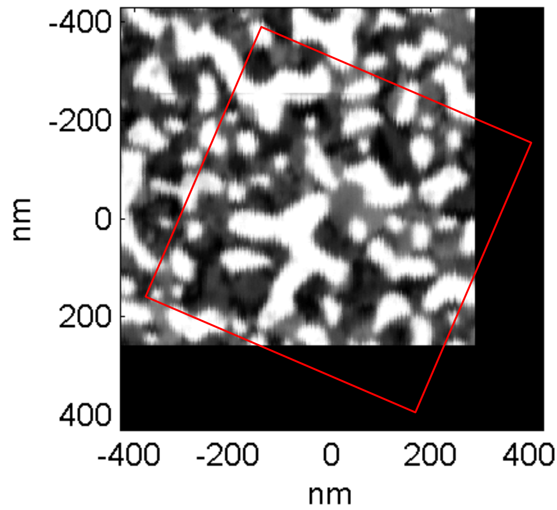
A Simulation Study of Repeatability and Bias in the CD-SEM, J. S. Villarrubia, A. E. Vladár, and M. T. Postek, Proc. SPIE 5038

Resolution

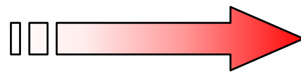


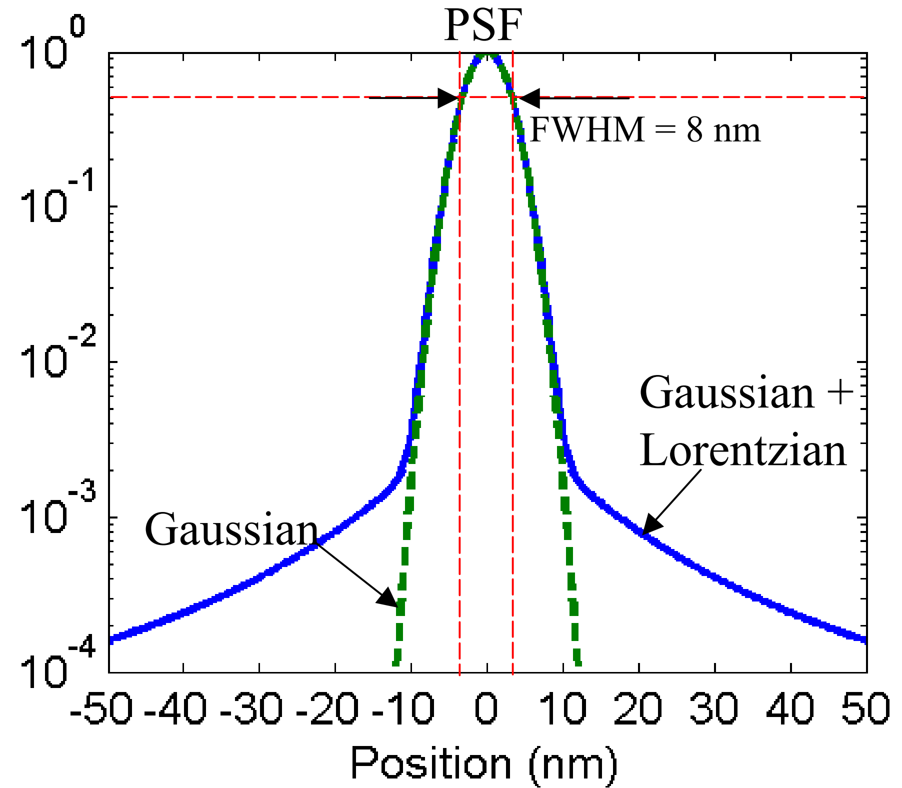
TEM





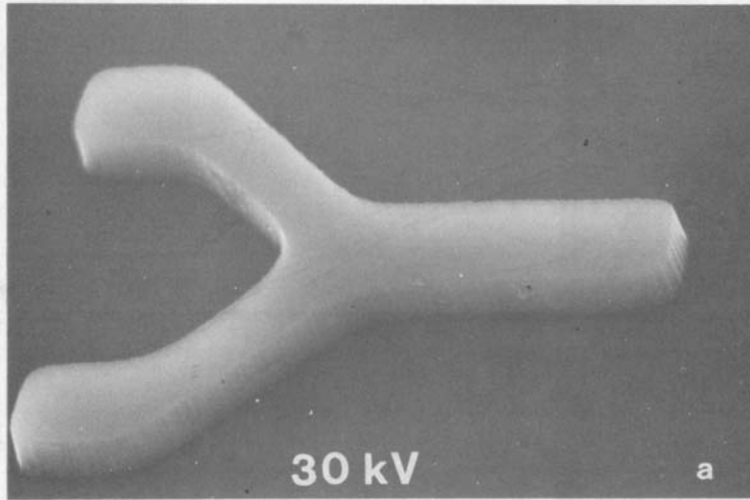
Nanowriter

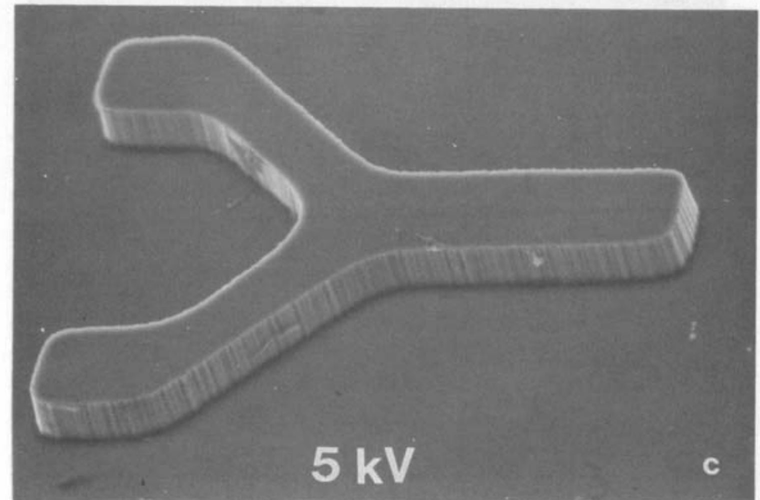


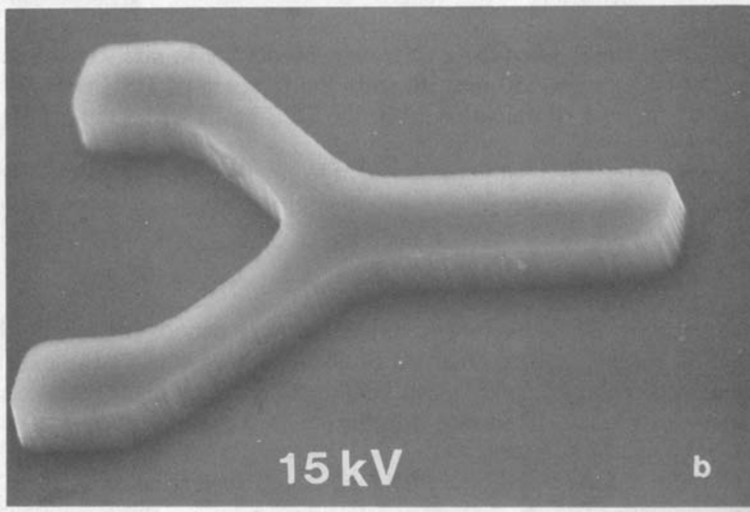


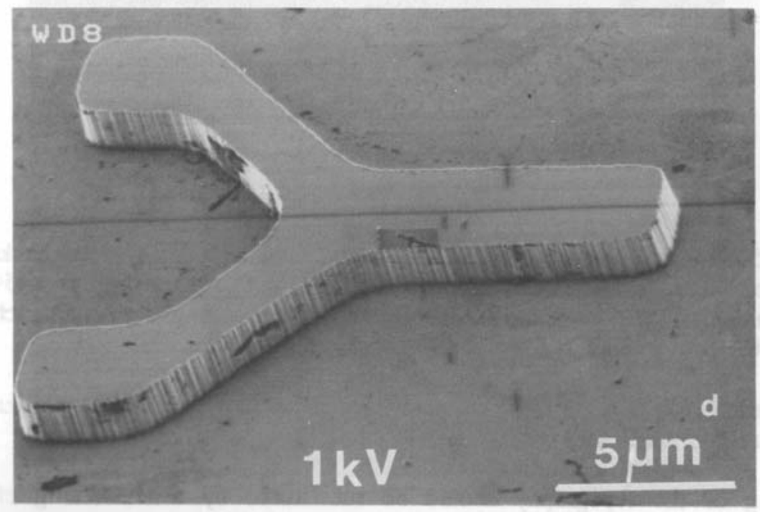
Trial PSF is convolved with TEM image – difference with actual beamwriter image is used for NL-LS fit

Effect of Voltage on BSE Diffusion



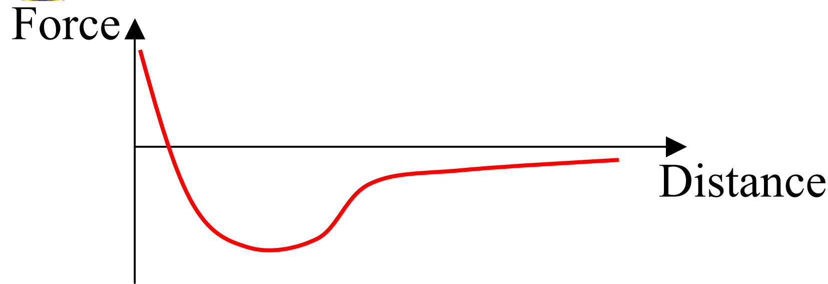


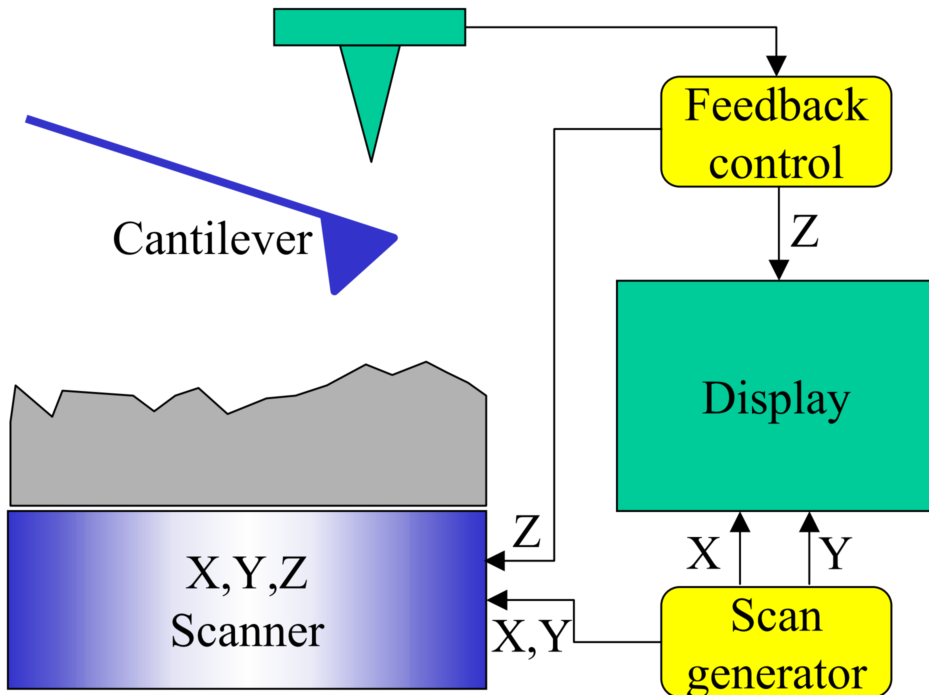




"Image Formation in Low-Voltage Scanning Electron Microscopy", Ludwig Reimer, SPIE, Bellingham (1993)

AFM



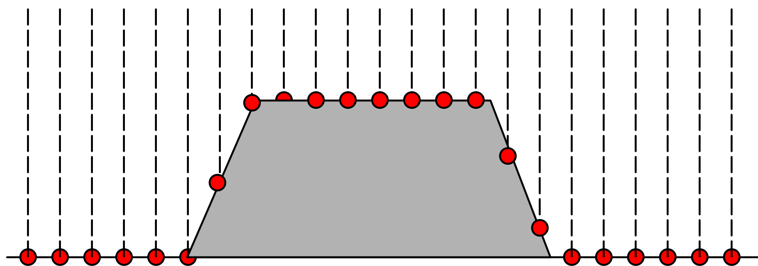


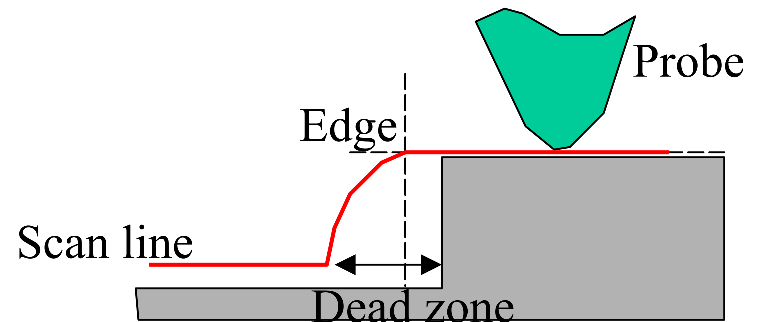
Contact Mode AFM

- Contact mode AFM operates by maintaining constant repulsive force between tip and sample
  - Rapid damage of tip
  - Crashes into steep sidewalls
- Non-contact mode maintains constant attractive force between tip and sample
  - Can sense lateral forces
  - Tip preserved
  - Measurements repeatable
  - Accuracy dependent on environmental conditions
- Resonating cantilever enables precise measurement of proximity through changes in frequency or Q

AFM Measurement Issues

- Probe motion typically generated by piezoelectric actuator
  - Hysteresis and creep occur in ferroelectric materials leading to non-linear motion
    - Hysteresis addressed through polynomial scan function
    - Creep difficult to deal with
- Abbe errors in the probe position occur because there is always an offset between where the probe position is measured and the probe tip
- Errors occur due to measurement algorithm and tip shape

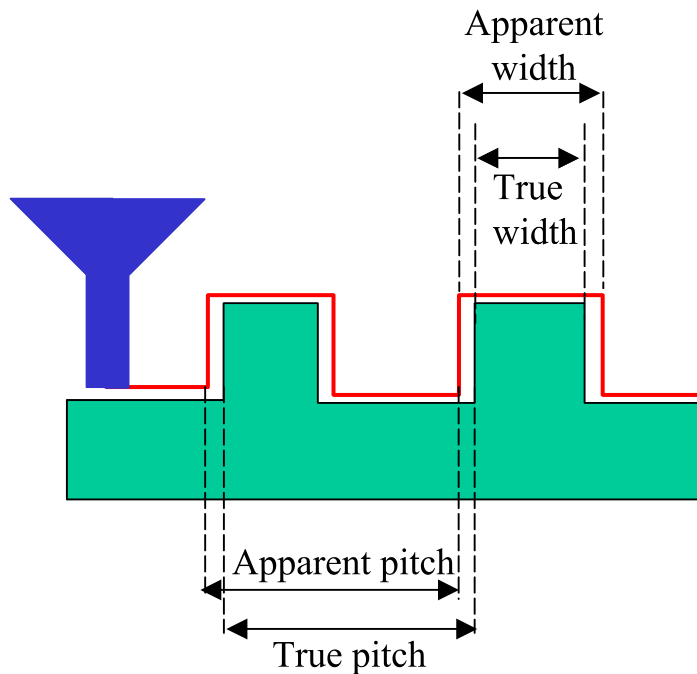


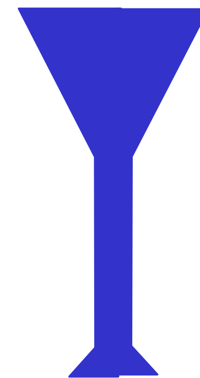


"Dimensional Metrology with Scanning Probe Microscopes", J.E. Griffith and D.A. Grigg, *J. Appl. Phys.*, **74** R83 (1993)

AFM CD Metrology

- Probe length controls height of features that can be measured
- Probe shape controls ability to measure sidewalls
- Probe diameter/angle controls resolution
  - Aspect ratios > 10 can result in flexing of probe due to sidewall forces





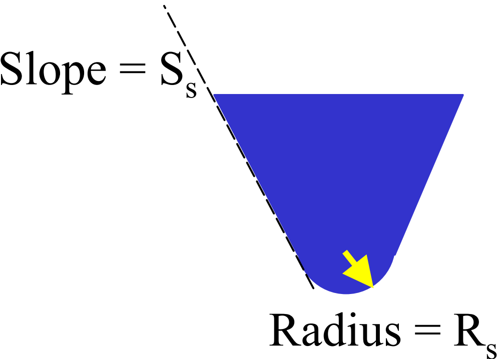
Tip shape for accurate sidewall measurements

"Dimensional Metrology with Scanning Probe Microscopes", J.E. Griffith and D.A. Grigg, *J. Appl. Phys.*, **74** R83 (1993)

Surface Roughness Measurements

- Surface roughness measurements are affected by tip geometry

R_h and R_v are horizontal and vertical bounds
r_h and r_v are determined by instrument sensitivity
S_d is the minimum slope that can be measured



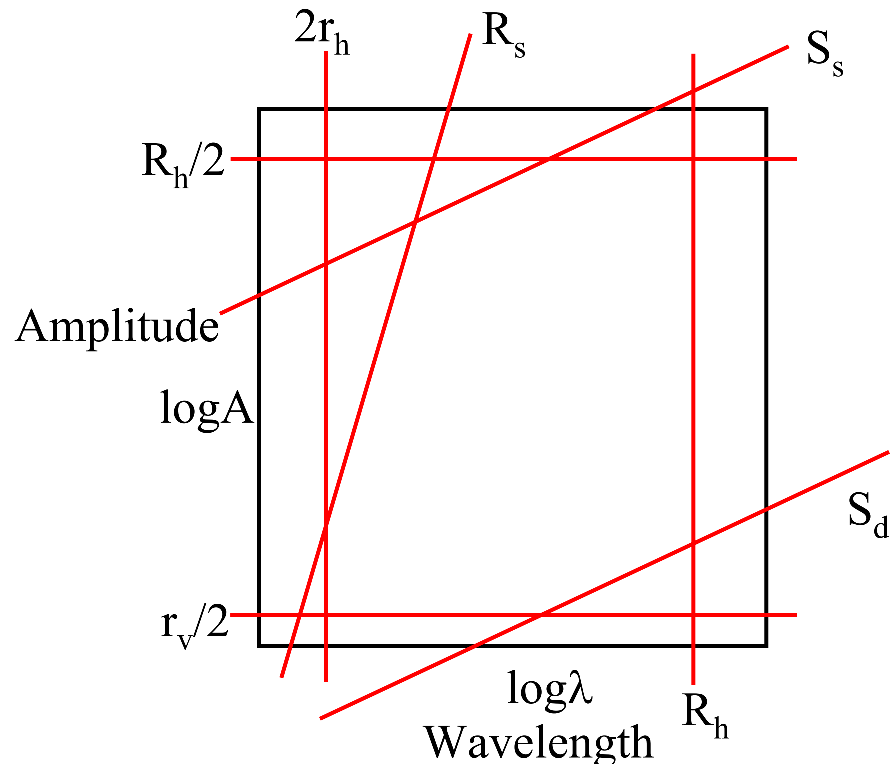
Surface Profile: $y = A\sin(2\pi x/\lambda)$

$$S_{\max} = 2\pi A/\lambda$$

$$R_{\min} = \lambda^2/4\pi^2 A$$

$$\log A = \log(S_{\max}/2\pi) + \log\lambda$$

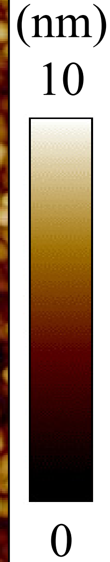
$$\log A = \log(1/4\pi^2 R_{\min}) + 2\log\lambda$$



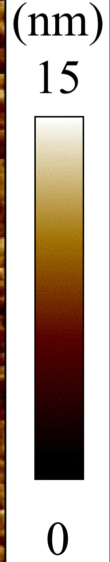
"Dimensional Metrology with Scanning Probe Microscopes", J.E. Griffith and D.A. Grigg, *J. Appl. Phys.*, **74** R83 (1993)

Probe Size vs Roughness

Conventional tip
RMS = 1.8 nm



Nanotube tip
RMS = 2.5 nm



- Surface height/roughness measurements depend strongly on AFM probe type
- Measured topography *increases* after multilayer coating

Probe Size vs Roughness