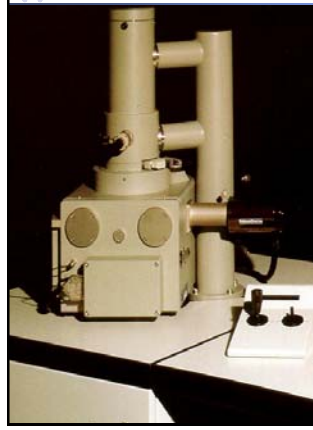
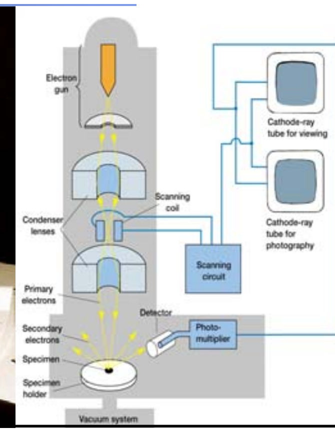
Scanning Electron Microscopy Technique issues

Prof. Jin Zou

Centre for Microscopy and Microanalysis
The University of Queensland
St Lucia, QLD 4072
Australia

Scanning Electron Microscopes



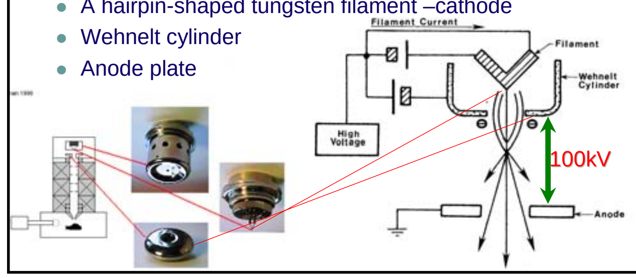


Essential Components

- **Electron gun:** In order to extract a lot of electrons from a material, the material we used should have a low work-function, e.g. tungsten. [Work-function: energy (or work) required to withdraw an electron completely from a metal surface. This energy is a measure of how tightly a particular metal holds its electrons.]
- **Lenses for electrons:** As negatively charged particles, electrons can be bent in the magnetic field. For this reason, electron microscopes use magnetic lenses to bend electrons.
- **Vacuum system:** Electrons, very light in mass, will be strongly scattered by gas molecules when they travel in air. In order to avoid it, a vacuum system needs to be built.

Electron Gun

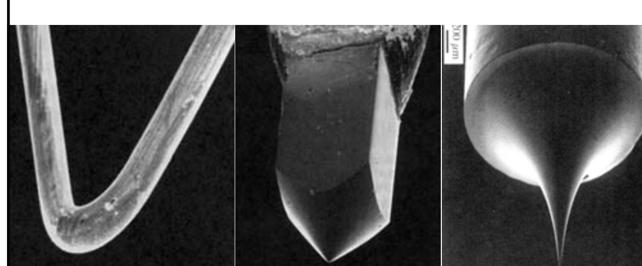
- Providing electron source
  - A focussed beam of electrons to strike the specimen
- The simplest way (and cheapest) electron gun (Thermionic emission)
  - A hairpin-shaped tungsten filament –cathode
  - Wehnelt cylinder
  - Anode plate



Electron Optics - Cathode

- Cathode or electron emitter
  - which is a thermionic electron emission source.
- Electron emitters are:-
  - Thermionic emission
    - white-hot tungsten (W) filament – 1mm
    - lanthanum hexaboride (LaB_6) filament, single crystal with 4 polished faces
  - Field-emission
    - Single crystal W, <310>, chemically thinned to about 50nm tip

Commonly Used Cathodes (filaments)



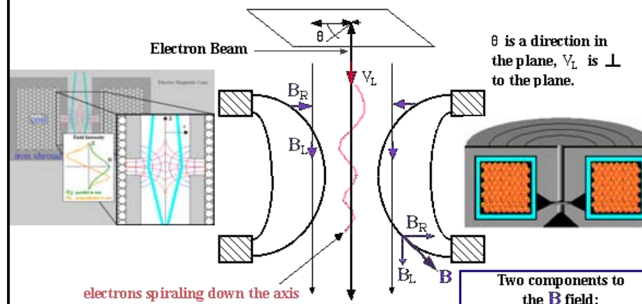
Tungsten hairpin | LaB_6 single crystal | Field emission tip

Comparison of Different Cathodes

Type of source	Tungsten thermionic	LaB_6 thermionic	Schottky emission	Cold field emission
Material	W	LaB_6	ZrO/W	W
φ (eV)	4.5	2.7	2.8	4.5
T (K)	2700	1800	1800	300
E (V/m)	low	low	$\approx 10^8$	$> 10^9$
J_c (A/m^2)	$\approx 10^4$	$\approx 10^6$	$\approx 10^7$	$\approx 10^9$
β (Am^{-2}/sr^{-1})	$\approx 10^9$	$\approx 10^{10}$	$\approx 10^{11}$	$\approx 10^{12}$
d_s (μm)	≈ 40	≈ 10	≈ 0.02	≈ 0.01
Vacuum (Pa)	$< 10^{-2}$	$< 10^{-4}$	$< 10^{-7}$	$\approx 10^{-8}$
Lifetime (hours)	≈ 100	≈ 1000	$\approx 10^4$	$\approx 10^4$
ΔE (eV)	1.5	1.0	0.5	0.3

* φ is the work function, T the temperature, E the electric field, J_c the current density, and β the electron-optical brightness at the cathode; d_s is the effective (or virtual) source diameter, and ΔE is the energy spread of the emitted electrons.

Electromagnetic Lens



θ is a direction in the plane, V_L is ⊥ to the plane.

Nonaxial electrons will experience a force both down the axis and one radial to it. Only electrons traveling down the axis feel equal radial forces from all sides of the lens. The unequal force felt by the off-axis electrons causes spiralling about the optic axis.

Two components to the B field:

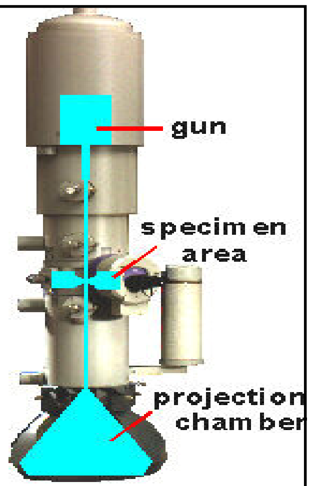
B_L = longitudinal component (down the axis)

B_R = radial component (perpendicular to axis)

Vacuum System

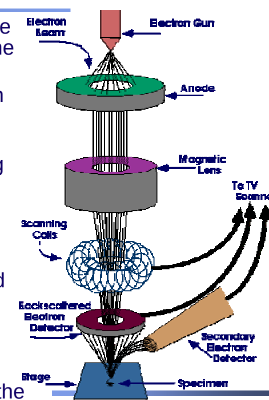
- To prevent scattering of electrons by gas particles
- To reduce contamination of the electron source

Multi-stage pumping of the column using a range of roughing and high/ultra-high vacuum pumps to achieve pressures of between 10-5 Torr (1.3 x 10^{-3} Pa) and 10-9 Torr (1.3 x 10^{-7} Pa)

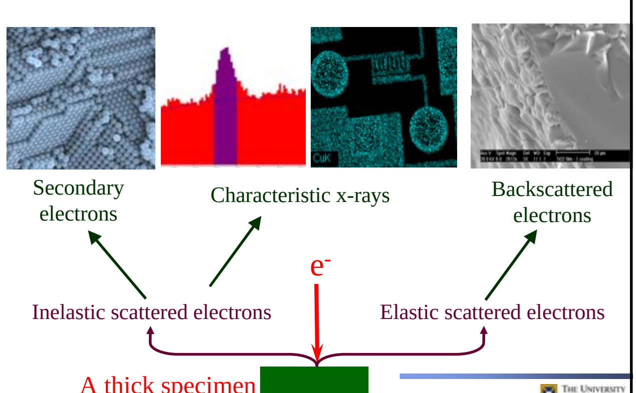


Working Principle of SEM

- A electron beam is produced by the electron gun and accelerated by the anode.
- Magnetic lenses focus the electron beam down the sample.
- Focused electron beam scans across the sample by the scanning coils.
- Once the electron beam hits the sample, other electrons originated from the sample are ejected.
- The detectors collect these ejected electrons and convert them to signals that are sent to a viewing screen (CRT).
- The CRT and the scan are synchronous, so that an image of the entire sample is built up on the CRT.



Main Signals Collected in a SEM

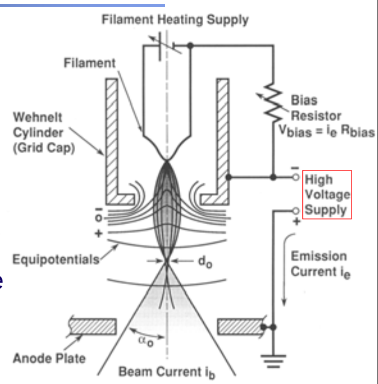


Key Operational Parameters

- Accelerate Voltage
- Spot Size
- Aperture
- Working distance

Accelerate Voltage

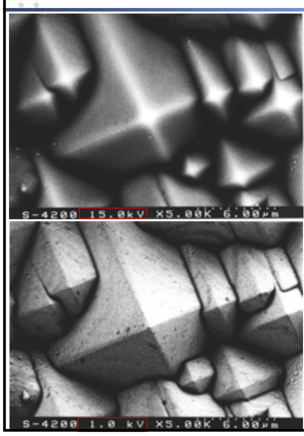
- Accelerating voltage (kV) is the voltage difference between the filament and the anode which accelerates the electron beam towards the anode.
- the greater the kV the greater the power of penetration.



Effects of Accelerate Voltage

Issues	Accelerate Voltage (kV) Low	→ High
Beam penetration	Shallow	Deep
Resolution	Low	High
Details of surface	Clear	Blurry
Image quality	Soft	Hard
SE signal	Strong	Weak
X-ray analysis		
Charging	Little	Heavy
Non-Evaporated Obs.	Easy to see	
Effect by disturbances	Large	Small

Effects of Accelerate Voltage



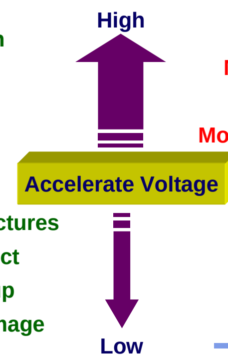
High accelerate voltage leads to smooth images, but cannot provide detailed surface information, although the resolution is high!!!

Low accelerate voltage leads to grainy images, but can provide detailed surface information, although the resolution is poor when compared with high accelerate voltage !!!

Effect of Accelerate Voltage

High resolution
Smooth Image

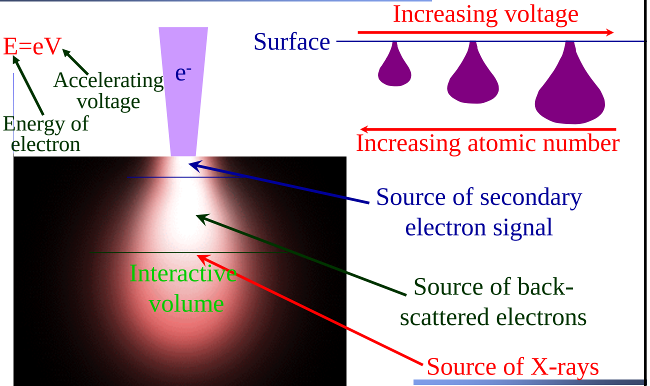
Unclear surface structures
More edge effect
More charge-up
More E beam damage



Clear surface structures
Less edge effect
Less charge-up
Less E beam damage

Low resolution
Grainy image

Interactive Volume and Signals

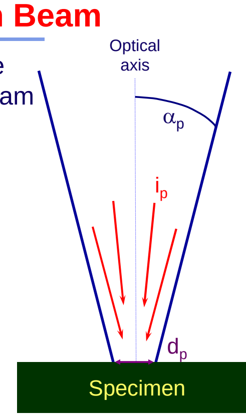


Effects of the Electron Beam

When the electron beam hits the specimen, three key electron beam parameters that can impact significantly on the quality of the SEM image are

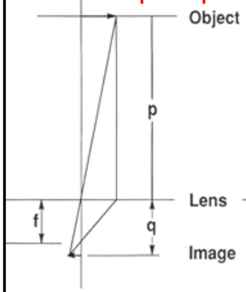
- E beam probe size d_p (resolution)
- E beam probe current i_p (strength)
- E beam convergence angle α_p (depth of field)

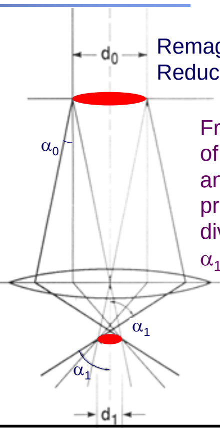
In fact, these three electron beam parameters can be fully controlled in SEM!



Function of the Condenser Lens

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q}$$



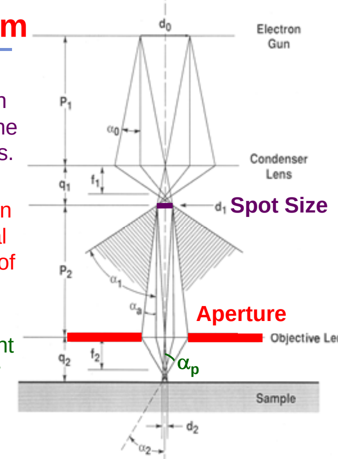


Remagnifying the probe
Reducing the spot size

From a probe size of d_0 and divergent angle of α_0 to a prove size of d_1 and divergent angle of α_1.

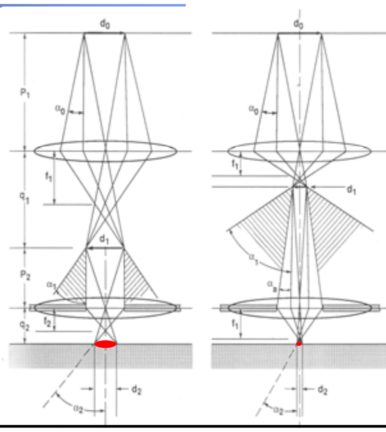
Two Lens System

- **Spot Size**, the cross over of the condenser lens, can be controlled by varying the strength of condenser lens.
- A **aperture**, located in probe-performing lens, can be used to control the final probe size and the depth of field.
- A **convergence angle α_p** can be resulted by different settings. This is critical for the depth of field. The larger the α_p, the smaller the depth of field!



Effect of Condenser Lens Strength

- Increase the strength of condenser lens reduces the spot size, hance increase the resolution.
- Increase the strength of condenser lens reduces the probe current as many electrons scattered to high angles will be lost for performing image.



Effect of Spot Size

Large

Large probe current
(important for BEI, X-ray μ-analysis)
Smooth Image

Larger probe size
Low resolution
Smaller depth of field
More E beam damage

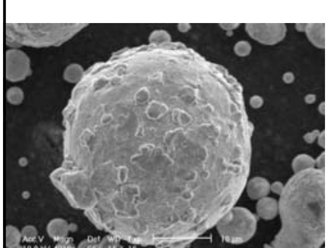
Spot Size

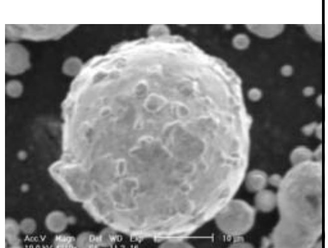
Smaller probe size
High resolution
Greater depth of field
Less E beam damage

Smaller probe current
Grainy image

Small

Comparison of Different Spot Sizes

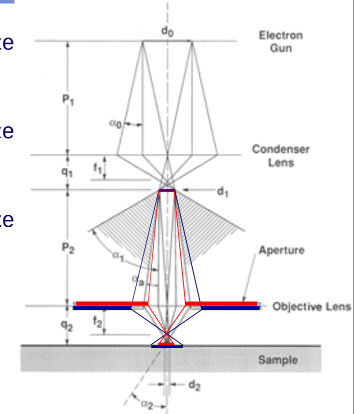




Which uses smaller spot size???

Effect of Aperture Size

- Decreasing the aperture size reduces the final probe, hance increase the resolution.
- Decreasing the aperture size reduces the convergence angle, hance increase the depth of field.
- Decreasing the aperture size limits more electrons to performing images, hance reduce the electron beam current.



Effect of Aperture Size

Large

Large probe current
(important for BEI, X-ray µ-analysis)
Smooth Image

Larger probe size
Low resolution
Smaller depth of field
More E beam damage

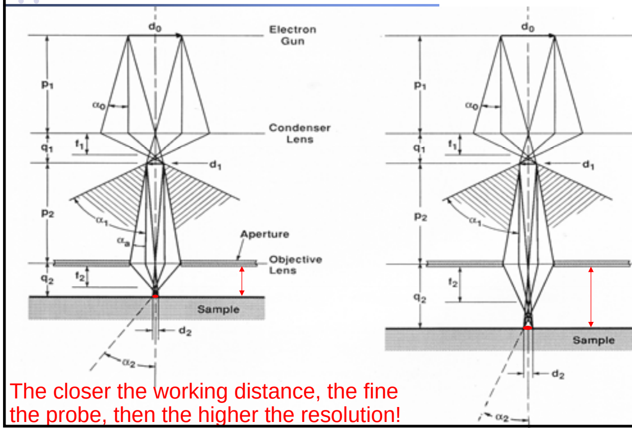
Aperture Size

Smaller probe size
High resolution
Greater depth of field
Less E beam damage

Smaller probe current
Grainy image

Small

Effect of Working Distance



The closer the working distance, the fine the probe, then the higher the resolution!

Effect of Working Distance

Large

Greater depth of field

Larger probe size
Low resolution

Working Distance

Smaller probe size
High resolution

Smaller depth of field

Small

In this case, the beam current is a constant!

Operational Parameters

- 4 key Operational Parameters
  - Accelerate Voltage
  - Spot Size
  - Aperture
  - Working distance
- Typical Operating Parameters of SEM
  - Accelerating voltage: V = 1 ~ 50 kV, usually 5 ~ 40 kV
  - Interaction volume of electron beam: 1 ~ 50 µm
  - Energy of secondary electrons: < 50 eV
  - Signals of backscattered electrons: > 70% incidental electrons
  - Energy range of X-ray: 0.5 ~ 20 keV

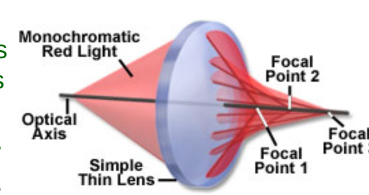
Imperfection of Electromagnetic Lens

Imperfection of electromagnetic lens restricts the performance (resolution) of electron microscopy. Some imperfection cannot be corrected at this technological stage, but some imperfection can be corrected through alignment.

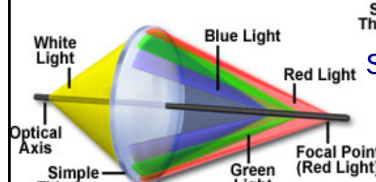
- On-Axis Lens Aberrations
- Astigmatism

On-Axis Lens Aberrations

Technologically, these on-axis lens aberrations in electron microscopes cannot removable, so the resolution is limited.

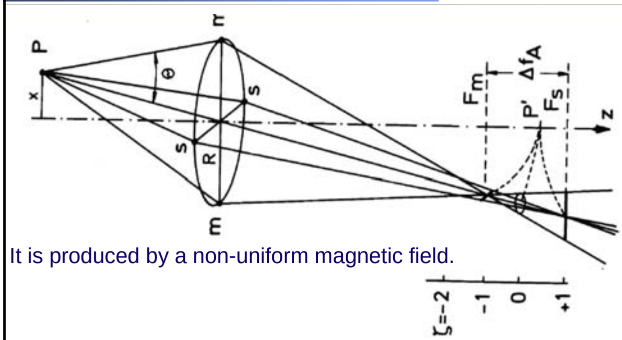


Spherical Aberration



Chromatic aberration

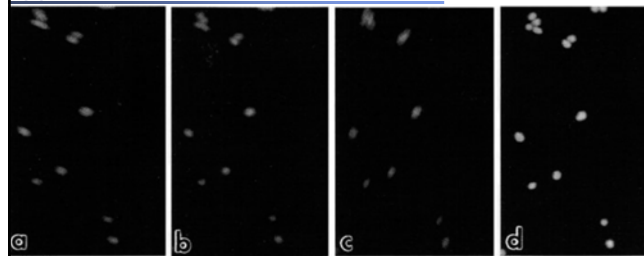
Astigmatism



It is produced by a non-uniform magnetic field.

Astigmatism is a off-axis lens aberration and can be corrected by instrument alignment!

Effect of Astigmatism



Out of focus | **In focus** | Out of focus | **In focus**

Astigmatism uncorrected

Astigmatism corrected

Important to Gain Good SEM Images

- Understanding the principles of SEM and their image formations. Based on that, preparing appropriate SEM specimens
- Alignment of SEM including correcting the stigmatism
- Correctly Set SEM performing conditions
  - Accelerating voltages
  - Spot size
  - Aperture size
  - Working distance

References & Useful Websites

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