Outline

Electron Sources (Electron Guns)
- Thermionic: LaB$_6$ or W
- Field emission gun: cold or Schottky

Lenses
- **Focusing**
- Aberration
- Probe size

Detectors
- electron detectors
- X-ray detectors
- energy loss spectrometers

Imaging
- Diffraction
- Bright field imaging (BF)
- Dark field imaging (DF)
- Phase contrast imaging (HRTEM) mode
- Scanning transmission electron microscopy (STEM) mode
- Holography mode (not covered)
- etc.
Electron / Sample Interaction

- Characteristic X-rays for EDX
- Electron diffraction
- Absorbed electrons
- Electron-hole pairs
- Bremsstrahlung X-rays
- Inelastically scattered electrons
- Backscattered electrons
- Secondary electrons
- Electrons scattered by sample
- Imaging + electron energy loss spectroscopy (EELS)
- Electron beam
- Auger electrons
- E ≤ 10 eV
- Visible light, cathodoluminescence
  0 < hν < 10 eV
- Ray radiation
  0 < hν < Eₐ
- HRTEM image
- ~100KV
- Thin sample

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Illumination system: SEM and TEM are similar

Objective lens and stage

Observation /imaging system
TEM usually have two condenser lenses
E-gun

Schematic lens configuration of a TEM system
Electron Illumination Sources

Major electron beam parameters

• Electron probe diameter, $d_p$
• Electron probe current, $i_p$
• Electron probe convergence, $\alpha_p$
• Accelerating voltage, $V_0$

For AEM we require:
• A stable source of electron
• A large current in a small spot

There are three source types:
• A tungsten thermionic source
• A LaB6 thermionic source
• A field emission source
Final Probe size

A general expression for the beam size, $d_p$:

$$d_p^2 = d_g^2 + d_s^2 + d_c^2 + d_d^2$$

For best resolution in many applications we need to use the smallest beam diameter. For STEM mode, the smallest probe size determines the best resolution. Since $d_p$ includes all the disks of least confusion from all lens aberrations, image resolution can be obtained from above equation.
Final Probe Size (cont’)

\[ d_{p}^{2} = d_{g}^{2} + d_{s}^{2} + d_{c}^{2} + d_{d}^{2} \]

\[ C_{0} = \left( \frac{4i_{p}}{\beta \pi^{2}} \right)^{1/2} \]

For a thermionic gun, \( C_{0} \gg \lambda \), the contribution of \( d_{d} \) and \( d_{c} \) can be neglected.

\[ \alpha_{optimum} = \left( \frac{4}{3} \right)^{1/8} \left( \frac{C_{0}}{C_{s}} \right)^{1/4} \]

\[ d_{min} = \left( \frac{3}{4} \right)^{1/8} C_{0}^{3/4} C_{s}^{1/4} \approx 0.96 C_{0}^{3/4} C_{s}^{1/4} \ldots \ (a) \]
Final Probe Size (cont’)

\[ d_p^2 = d_g^2 + d_s^2 + d_c^2 + d_d^2 \]

\[ C_0 = \left( \frac{4i_p}{\beta \pi^2} \right)^{1/2} \]

For a FEG gun, \( C_0 \ll \lambda \), the contribution of \( d_g \) and \( d_c \) can be neglected.

\[ \alpha_{optimum} = 0.9 \left( \frac{\lambda}{C_s} \right)^{1/4} \]

\[ d_{min} = 0.8 \lambda^4 C_s^{-1/4} \] ..... (b)

These expressions can be used to estimate the optimum aperture angle and the resolution limit of a high resolution TEM/STEM. Equation (b) is especially important for evaluating the capabilities of different TEM instruments.

Note that for resolution depends more strongly \( \lambda \) than \( C_s \). This encourages the use of high accelerating voltage (small \( \lambda \)). \( C_s \) can be corrected by current technology.
Probe size @ V0=200 KV and $\lambda=2.5$ pm
Focusing of Electrons: Magnetic Lenses

- All modern analytical electron microscopes use magnetic lenses.
- Magnetic lenses are poor compared to glass lenses suffer many aberrations (distortions) that reduce image quality.
- In analytical electron microscope, magnetic lenses are used to produce a demagnified image of the electron source cross over at the specimen (condenser lens).

- A thermionic spot size lies between 10-50 µm and the normal desired spot size is 1-10 nm. This requires a demagnification of 10,000x. Tip vibration is also reduced by 10,000x, so some vibration may be tolerated.
- The spot size of a field emission is ~5nm, so for the same 1nm spot size a demagnification of only 5x is required. Vibration of the tip is also demagnified but by 5x so a very stable platform is needed!!
**Lens**
A lens is an optical component which is used to focus beams of radiation. Lenses for light are usually made of a glassy material, whereas non-uniform electromagnetic fields are used as lens for electrons.

(a) schematic representation of the magnetic field lines around a circular current carrying coil; (b) a magnetic yoke concentrates the field lines near the center of the coil and provides a particular geometry to the field.
Magnetic Lenses

• A magnetic lens consists of a wire winding around a soft iron core.
• The magnetic field in the lens deflects the electron path, resulting in a focusing of the beam.
• Right hand rule of vector product to determine the force on the electron.

\[ \vec{F} = m \frac{d^2 \vec{r}}{dt^2} = q\left(\vec{E} + \vec{v} \times \vec{B}\right) = e\left(\vec{v} \times \vec{B}\right) \]

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- $B_r$ vanishes @ $z=0$
- $B_r=0$, @ $r=0$
- $B_z \to \text{max.} @ z=0$
- for large $|z|$ and moderate $r$, $B_r > B_z$
- $B_\varnothing = 0$ by cylindrical symmetry

Magnetic field in and around a short solenoid, as shown the $B_z$ and $B_r$ component
• Br vanishes @ z=0
• Br=0, @ r=0
• Bz->max.@ z=0
• for large IzI and moderate r, Br> Bz
• Be = 0 by cylindrical symmetry

The Lorentz force produces the focusing action to the moving electron

\[ \mathbf{F} = e \mathbf{v} \times \mathbf{B} \]
\[ \mathbf{v} = v_r \hat{r} + v_\theta \hat{\theta} + v_z \hat{z} \]
\[ \mathbf{B} = B_r \hat{r} + B_\theta \hat{\theta} + B_z \hat{z} \]

So
\[ F_z = ev_\theta B_r \]
\[ F_\theta = e \left( v_z B_r - B_r v_r \right) \]
\[ F_r = ev_\theta B_z \]
The electron travels in nearly helical path in a homogeneous field $B$. Force towards optic axis.

$F = e \nu \times B$

$F_z = ev_\theta B_r$

$F_\theta = e(v_z B_r - B_r v_r)$

$F_r = ev_\theta B_z$

Trajectory rotates out of plane by $\Theta$ (image rotation).

Or Paraxial trajectory.

Spiral out

Spiral in

$\text{Fr}$

$\text{Br}$

$\text{Vz}$

$\text{Vz}$

$\text{Fr}$

$\text{Br}$

$\text{Bz}$

$\text{Fe}$

$\text{Vz}$

Br<Bz

Br>Bz

$\theta$
Paraxial trajectory governing equation

\[ \Phi \]

\( \Phi \): potential

\[
\frac{d^2 r}{dz^2} + \frac{\eta^2 B^2}{4\Phi} r = 0
\]

\[
\frac{d \theta}{dz} = \frac{\eta B}{2\sqrt{\Phi}}
\]

\[ \eta = \sqrt{\frac{e}{2m_0}} \]

Focusing action of magnetic lens

Upper pole-piece

Lower pole-piece

Optical Axis

Vz

Br

Bz

BFP

f
Focusing action of magnetic lens

• Off-axis electrons interact with these fringe fields and begin to spiral through the lens and move toward the optic axis.

• The distance from the point where an electron starts to bend toward the axis to the point where it crosses the axis is known as the focal length, \( f \).

• The focal length of the lens can be continuously variedly altering the strength of the magnetic field which is controlled by the excitation current passing through the lens coil.
Convex lens
A convex lens (for light) is thicker in the centre than at its periphery. All electromagnetic lenses used in electron microscopy act as if they were convex lenses.

Summary:
• The magnetic lens produces a strong magnetic field $B$ by passing a current through a set of windings (copper coil). In TEM, this field act as a convex lens, bringing off axis rays back to focus.
• For magnetic lens, the image is rotated to a degree depending on the strength of the lens.
• Focal length also can be changed by changing the strength of the current, and thereby of $B$. 
Cross section of the first condensor lens of a JEOL 120CX microscope. The coil winding has an areal density of nearly 300 copper wires per cm$^2$. The pole pieces, visible through the slot on the left, are made of a high permeability Fe-Co alloy.
Definition of Some Important Angles

- $\alpha$, beam-convergence semi-angle
- $\beta$, collection semi-angle
- $\theta$, general scattering angle
Summary 2:

- All electromagnetic lenses act like thin convex lenses. So their thickness can be ignored.
- Equations for convex lens are applicable, like lens formula
  
  \[
  \frac{1}{f} = \frac{1}{v} + \frac{1}{u}
  \]

  Magnification: \( M = \frac{v}{u} \)
Schematic lens configuration of a TEM system
In electron microscope, the condenser lenses are used to demagnify the diameter of the beam.
In electron microscope, **double condenser (C1 and C2)** system is used to adjust the illumination condition.

- The double condenser system or illumination system consists of two or more lenses and an aperture. It is used in both SEM and TEM. Its function is to control spot size (C1) and beam **convergence and intensity (C2)**.

- Two or more lenses can act together and their ray diagrams can be constructed using the thin lens approximation for each of them. The diagram opposite shows the ray diagram for the double condenser system. The black dots represent the focal point of each lens.
First condenser lens, C1

C1 the first condenser lens is shown highlighted in the diagram. Its function is to
- create a demagnified image of the gun crossover, which acts as the object for the illumination system
- control the minimum spot size obtainable in the rest of the condenser system.
First condenser lens

C1 the first condenser lens is shown highlighted in the diagram. Its function is to:
- create a demagnified image of the gun crossover, which acts as the object for the illumination system
- control the minimum spot size obtainable in the rest of the condenser system.
Second condenser lens C2

- C2 is adjusted to produce an image of gun crossover at the front focal plane of the upper objective polepiece, and then generate a broad parallel beam of electron incident on the specimen.

- C2 can affect the convergence of the beam at the specimen, and the diameter of the illuminated area of the specimen.

Question: Sitting at the microscope you can only see the image of the specimen on the fluorescent screen. How would you know when the condenser lens (C2) is focused on the specimen? If you now go away from this condition how could you tell whether the beam was overfocused or underfocused?
C2 is focused

• The illuminated area is at a minimum. The beam is probe (micro or nano probe).
• The beam is at its least coherent and most convergent.
• The intensity of illumination on the viewing screen is the greatest.
• Image contrast will be reduced.
• For routine TEM work, never operate in such beam condition.
• For thick poor-transmission sample, focusing C2 will compensate for poor-transmission.
• The convergent-beam mode, focusing C2, is used for CBED (convergent beam electron diffraction) and STEM (scanning TEM).
• Since convergence destroys the coherency and image contrast, the beam has to be scanned to form an image, i.e. STEM image.
C2 is underfocused

- The illuminated area increases
- The beam is parallel and coherent
- The parallel illumination is essential to get the sharpest diffraction patterns and the best image contrast.
- The small aperture reduce the electron current falling on sample, and decreases the angle of beam convergence, and therefore increase the coherence of the beam.
- The parallel-beam mode, underfocusing C2, is used for SAD (selection area and conventional TEM mode).
- A higher magnification means strengthening C2, so the beam illuminates less of the specimen (it is not really parallel, just not very convergent)
- To underfocus C2, just simply increase the illumination area on the specimen.
C2 is overfocused

• The beam convergence decreases, and the electron come from the crossover only.
• The crossover image is above the image plane.
• Overfocusing C2 can check the beam astigmatism.
The condenser aperture controls the fraction of the beam which is allowed to hit the specimen. It therefore helps to control the intensity of illumination, and in the SEM, the depth of field.
Parallel beam with large aperture, i.e. large convergence.

Parallel beam with small aperture, i.e. small convergence.
Next lecture
• Objective lens
• Imaging mode
• Sample preparation

Demo time: 4:00-4:30 PM, Tuesday, 09/16/08.
I will meet you at 170H, HRC