Chapter 2: TEM components and operation

Reza Zamani, PhD
Senior Staff Scientist
reza.zamani@epfl.ch

Components of TEM and vacuum

1. Electron propagation is only possible through vacuum!
2. Need a good vacuum system to reduce contamination!

High vacuum everywhere in the column! (with exception of ETEM)

Gun>Column>Detector
Outline

1) Electron optics  
   A. Basics  
   B. Magnetic lens  
2) Resolution in a TEM  
   A. Aberrations and spatial resolution limits in a TEM  
   B. Astigmatism correction  
3) Components of TEM  
   A. Electron sources  
   B. Condenser system  
   C. Apertures  
   D. Objective lens  
   E. Intermediate and projector lenses  
   F. Detectors

Basics of electron optics

Classic ray diagram
Basics of electron optics

Classic ray diagram, concept of focus and defocus

1. Over-focus
2. Focus
3. Under-focus

“crossover” point
• used for the alignment of the TEM column and apertures

Figure 6.5. (a) Ray diagram illustrating the concepts of overfocus, in which a strong lens focuses the rays before the image plane, and (c) underfocus, where a weaker lens focuses after the image plane. It is clear from (c) that at a given underfocus the convergent rays are more parallel than the equivalent divergent rays at overfocus ($\theta_c < \theta_o$).

Basics of electron optics

Classic ray diagram, focal plane

Figure 6.1. Image formation by a convex lens. A point object is imaged on a plane and the collective wavelength of the rays is defined relative to the object (f or the image).
Basics of electron optics

Classic ray diagram

Electron optics: lenses

Two types of lenses
- Electrostatic lenses
  - Applied potential and electric field lines define deflection force and focusing
- Electromagnetic lenses: Lorentz Force!
  - Variable focus (no moving parts)
  - Tunable correctors (astigmatism)
  - "Pole piece" metal cone that confines the magnetic field
  - No (simple) divergent lens!
  - Image rotation!
Electromagnetic lenses

Interaction of an electromagnetic field on a moving electron:
Lorenz force
\[
\vec{F} = -e(\vec{v} \times \vec{B})
\]

- Component of \( v \perp B \): \( v \ll |v| \)

Magnitude of Force
\[
F = eVB\sin\theta
\]

- Focal length depends on \( B \)
  - Increasing \( B \) lowers \( f \)
- To obtain the same focal length at higher electron voltages, \( B \) must increase
- Spiral with radius \( r = \frac{mv}{eB} \)

Electromagnetic lens focal length

Focal Length (f): Point on Z axis where initially parallel rays cross the axis after passing through the lens

**HIGHER LENS STRENGTH = SHORTER FOCAL LENGTH**

- \( B \) = vector parallel to field
- \( B_r \) = radial component of field (vector perpendicular to axis)
- \( B_z \) = axial component of field (vector parallel to axis)
- \( B \) varies depending on position in lens
- Force strongest at center of the gap

Low lens strength = long focal length

High lens strength = short focal length
Electromagnetic lens aberrations

- Field with rotational symmetry
- Lorenz Force: \( F = -eVB\sin\theta \)
- Electrons on optic axis: \( F = 0 \)
- Electrons not on optic axis: deviated

**Optic axis is the symmetry axis**

### Scherzer 1936:

Magnetic lens with rotational symmetry:
- Aberration coefficients:
  - \( C_s \): spherical
  - \( C_c \): chromatic
- Always positive!!

\[
C_s = \frac{1}{16} \left( \frac{h'k'' + 2(h'b' + k'b')h'}{h''} \right) \frac{d}{d'}
\]

\[
C_c = \frac{1}{2} \left( \frac{b'k''}{h''} \right) d
\]

Resolution limit: \( D_{\text{res}} = 0.66\lambda 3^{1/4} C_s^{1/4} \)

---

Resolution

Limits for a modern TEM

- Spherical aberration
  \( d_{\text{sa}} = C_s \alpha^3 \)

- Chromatic aberration
  \( d_{\text{ch}} = C_{\text{ch}} \left( \frac{AE}{E} + 2 \frac{NI}{I} \right) \alpha \)

- Diffraction (Airy, Rayleigh)
  \( d_d = 0.61 \frac{\lambda}{n \sin \alpha} \)

- Brightness \( \beta \) conservation
  \( d_{\beta} = \left( \frac{4T}{2} \right)^{1/2} \frac{1}{\sqrt{\beta}} \frac{1}{\alpha} \)

- Combined
  \( d_{\text{tot}} = \sqrt{d_{\text{sa}}^2 + d_{\text{ch}}^2 + d_{\beta}^2 + d_d^2} \)

Using an optimal convergence angle, resolution is:

- \( 2.5 \times 10^{-10} \) m @ 200 kV
- \( \alpha = (4\lambda/C_s)^{1/4} < 10 \) mrad
- \( d \) is 0.2-0.3 nm
Aberrations

Lens aberrations
- Focus
- Astigmatism
- Spherical and chromatic aberrations

- Can be corrected or minimized

Physical limits
- Diffraction limited resolution

Condenser astigmatism affecting beam shape

Astigmatism: focal length varies in different planes.

This causes the image to be blurred along different directions depending on the focus.
**Aberrations: astigmatism**

**How to correct astigmatism:**
- Correction with quadrupole lenses. 2 quadrupole lenses under 45 degree allow to control strength and direction of correction.

**Aberrations: chromatic**

Focal length varies with energy critical for non-monochromatic beams (advantage for FE guns).
Aberrations: spherical

- Focal length varies with distance from optical axis, i.e., rays from the center to edge of the lens have different focal points
- Image of the object is dispersed (or blurred) along the optical axis
- Circle of least confusion \( d_s = \frac{1}{2} C_s \alpha^3 \)

*Spherical aberration and delocalization*

“Ghost” white contrast that is delocalized from specimen results from the diffracted beam being distorted by the spherical aberration of the Objective lens
Cs aberration correction - HRTEM

Combination of standard radially-symmetric convergent lenses with multipole divergent lenses (e.g. tetrapoles, hexapoles) to tune Cs

=> Resolution jumps to sub-Å!

Example: Σ3 grain boundaries in Al

Uncorrected

Cs-corrected

Oikawa, JEOL

Components of TEM

A. Electron source
B. Illumination system (Condenser lenses)
C. (Apertures)
D. Imaging lens (Objective)
E. Magnification and projection (intermediate and projector lenses)
F. Detectors
Components of TEM

A. Electron Sources

Electron gun: generates and accelerates the electrons to the desired energy (velocity)

Filament: emits the electrons

Accelerator stage: accelerates them to high energies >60keV

BRIGHTNESS, COHERENCE, STABILITY

<table>
<thead>
<tr>
<th>Unit</th>
<th>Brightness</th>
<th>Cross over size</th>
<th>E-spread</th>
<th>Vacuum</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aim²/s</td>
<td>10⁻⁶</td>
<td>10⁻⁴</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>LaB₆</td>
<td>5.10⁻⁶</td>
<td>5.10⁻⁶</td>
<td>5.10⁻⁶</td>
<td>5.10⁻⁶</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>FEG</td>
<td>6.10⁻⁶</td>
<td>6.10⁻⁶</td>
<td>6.10⁻⁶</td>
<td>6.10⁻⁶</td>
<td>&gt;1000</td>
</tr>
<tr>
<td>Cold FEG</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
<td>10⁻⁶</td>
<td>&gt;1000</td>
</tr>
</tbody>
</table>

A typical TEM: Jeol 200cx

LaB₆ Cathode

Electron Sources: thermionic vs. field-emission

http://www.feibeamtech.com

Tungsten Field Emission Tip

from Williams & Center (2nd ed)
Components of TEM

A. Electron Sources: Thermionic gun

- Electron boil from surface
- Tungsten wire heated to ~2800K
- LaB$_6$ crystal heated to 1900K
- Main advantages: simple, cheap, no high vacuum required and maintenance friendly
- Disadvantages: low brightness, high energy spread and large source size (10-100 µm)
Components of TEM

A. Electron Sources: FEG

- **Cold field emission** (E=10^9 V/m)
  - W single crystal with a sharp tip (radius ~25nm)
  - Advantages
    - Small energy dispersion (<0.1eV)
    - High coherence, high brightness
    - Higher resolution at lower energies
  - Disadvantages:
    - Expensive, high vacuum necessary
    - Cold emission needs flushing (cleaning) after 8 hrs

- **Thermally assisted emission:** Schottky effect
  - W/Co tip at 1700-1800K
  - ZrO complexes lower work function
  - Continuous operation “self-cleaning”

Components of TEM

A. Electron Sources: FEG

First anode (extractor)
- Some kV
- 5.10^9 V/m

Second anode
- Final acceleration
- Grounded

Characteristics
- Tip and anodes form an electrostatic condensor
- Cross-over (source) is virtual Ø~5nm
Components of TEM

A. Electron Sources: Comparison of the different electron sources

<table>
<thead>
<tr>
<th>TABLE 5.1 Characteristics of the Principal Electron Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Work function, $\Phi$</td>
</tr>
<tr>
<td>Richardson's constant</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Current density (at 100 kV)</td>
</tr>
<tr>
<td>Crossover size</td>
</tr>
<tr>
<td>Brightness (at 100 kV)</td>
</tr>
<tr>
<td>Energy spread (at 100 kV)</td>
</tr>
<tr>
<td>Emission current stability</td>
</tr>
<tr>
<td>Vacuum</td>
</tr>
<tr>
<td>Lifetime</td>
</tr>
</tbody>
</table>

B. Condenser lens system

1. Demagnifies gun crossover (electron "point" source) on sample
2. First condenser lens (C1) defines probe size
3. Second Condenser (C2) lens controls the illumination area (intensity) on the sample
4. Third condenser (or condenser mini) lens controls convergence angle
5. Apertures control signal, convergence angle and coherence
Components of TEM

B. Condenser lens system: Condenser lens 1 defines probe size

A typical TEM: Jeol 200cx
Components of TEM

B. Condenser lens system: C2 strength changes illumination area

C. Apertures

Small, 10-200 µm holes (generally 4 to 8 sizes to choose from) limiting the beam diameter in specific imaging planes and lens crossovers to change properties of illuminating electron beam or specimen scattered electrons

1. Condenser: used to change convergence angle and electron beam coherence
2. Objective: used to form diffraction (and phase) contrast images and other type images by omitting scattered beams
3. Selected Area: to select (limit) the area on the sample that contributes to the electron diffraction pattern
Components of TEM

C. Apertures

Condenser apertures
- Angle limiting
- Used to change current, convergence angle, probe coherence and size in combination with condenser lens system

Objective aperture
- Located in back focal plane of the objective lens
- Used to isolate and limit scattered beams and form TEM images with enhance contrast
- Bright-field – centered on unscattered beam
- Dark-field – centered on diffracted beams
- Mass-thickness contrast – centered on optic axis of objective lens and aperture diameter controls Z-contrast

Selected Area Diffraction aperture
- Located in the forward image plane of the objective (object plane of the intermediate lens)
- Limit diffraction area on sample
Components of TEM

D. Objective lens

- Eucentric Focus is the “standard” or optimal objective lens current (focus)
- Eucentric height/plane is the optimal specimen position at the objective lens standard focus
- Image will appear over or under focus if specimen is not at the eucentric plane
Components of TEM

E. Intermediate and projection lenses

1. Intermediate lenses are used to switch between imaging & diffraction mode
2. Intermediate lenses are used to change magnification and camera length, i.e., objective lens current.
3. Three intermediate lenses are necessary to compensate for the spiraling of electrons and resulting image rotation
4. Projector lens used to greatly magnify the last intermediate lens image plane onto the detector
Components of TEM

**F. Detectors**

1. Phosphor screen
2. Film
3. Image plates
4. CCD or CMOS cameras
5. YAG scintillator – multichannel plates
6. Phosphor – photomultiplier tube
7. X-ray detectors
8. BSE, SE, STEM detectors

**CCD cameras**

A. Incoming light
   - Dielectric
   - Potential well

B. CCD Camera
   - (charge coupled device)
   - 1x1k, 2x2k, 4x4k Pixel
   - + high dynamic range, linear, sensitive
   - - Slow (because of readout procedure)
   - - expensive

Readout of pixels through charge transfer to output node and 1 pixel readout at a time (very slow)

From http://www.gatan.com
Components of TEM

F. Detectors: CMOS cameras

New cameras currently sold by vendors are based on CMOS technology which has almost completely replaced CCD cameras in the market.

Summary

1. TEM require a vacuum for electron propagations
   - High vacuum and clean vacuum system reduce sample contamination
2. Electrons are focused and manipulated using electromagnetic lens via Lorentz forces
   - Electrons spiral in lens and thus images rotate with changes in lens strength – need 3 lens to compensate image rotation with changes in magnification
3. Resolution
   - Chromatic and Spherical lens aberrations limit resolution –
   - Condenser and Objective lens astigmatism can be corrected
   - Spherical aberration correctors for condenser lens and objective lens systems are commercially available in high-end TEMs
Summary (components of TEM)

A. Electron Source: Produces high energy, large current, and high coherence electron beams necessary for generating diffraction patterns and high spatial resolution images

B. Condenser lenses: Controls spot size and illumination area on sample (beam intensity)

C. Apertures:
   • Condenser: changes illumination size, convergence angle, and beam coherence
   • Objective: located in back-focal plane and provide image contrast by limiting scattered beams that form the image
   • Selected Area: located in first image plane and used to select area on the sample that contributes to the diffraction patterns

D. Objective lens: Images sample and is strongest lens in the system

E. Intermediate and projector lenses: Change modes from diffraction to imaging, control magnification

F. Detectors: CCD and CMOS cameras

References

Williams & Carter TEM textbook

Special thanks to Thomas LaGrange (slides from last semester)