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- SEM imaging modes
- Comparison of ordinary SEM and FESEM
- Electron behavior
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- Backscattered electrons and imaging
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Basic structure of SEM

Various subsystem of SEM and their function is explained

- Two major component – Electron column and Control console

Electron Column:
- Electron gun and 2 or more electron lenses to control the path of travelling electron in the vacuum column

Control Console:
- Computers, Monitors and knobs to control various imaging parameters
Basic structure of SEM

Electron gun and lenses

- Electron gun generate electron and accelerated them to an energy level (0.1-30keV)
- Electron lenses focuses the beam to smaller spot size to produce sharp images
Basic structure of SEM

Deflection system

- Deflection system consists of electromagnetic coils.
- Causes the beam to move in a series of discrete points in a rectangular region to scan complete specimen.
- Excitation of coils also control the magnification.
- In modern SEM, magnification is automatically compensated against working distance from sample.
Basic structure of SEM

Electron Detectors

• Detectors collect the signal generated from interaction of beam with specimen.
• Electronic of detectors convert the signal into digital images.
• Most often collected signal are SE (Secondary electrons) and BSE (Backscattered electrons) signal.
Basic structure of SEM

Operator controls

• The very first control for generation of electron beam is *Acceleration voltage* and *Emission current*.
• Then condenser lens control – amount of beam current available and minimum beam size
• Next is objective lens control – to focus the beam at a smaller diameter spot.
• Finally viewing screen controls like brightness, contrast etc.
SEM imaging modes

4 parameters controls different imaging modes in SEM

- Electron probe size dia. ($d_p$) - Dia. of electron beam focused at the specimen
- Electron probe current ($i_p$) - Current impinging upon the specimen and generating various signals
- Electron probe convergence angle ($\alpha_p$) - Half cone angle of electrons converging onto the specimen
- Electron beam accelerating voltage ($V_o$) kV
SEM imaging modes

Mode I - Resolution Mode

• This mode is governed by the Electron probe size dia. \((d_p)\)
• Resolution refers to the size of finest detail that can be observed
• To image the finest details \(d_p\) must be comparable with or smaller than the feature itself.
• Resolution mode is only meaningful at high image magnifications (>10,000 X)
• Beam should contain sufficient current to exceed visibility threshold
SEM imaging modes

Mode II – High Current Mode

• This mode is governed by the Electron probe current \( (i_p) \)
• For the best image visibility and quality – Large \( i_p \)
• Unless a sufficient amount of current (required to overcome random noise) is there details cannot be seen even if the spot size is small enough.
SEM imaging modes

Mode III – Depth-of-Focus Mode

• This mode is governed by the probe convergence angle ($\alpha_p$)
• For the best image quality – $\alpha_p$ as small as possible
• With low beam convergence angle, beam dia. changes only a little over a long vertical distance, so surface features at different heights will all appear to be in focus at the same time.

$\alpha_p = 15 \text{ mrad}$

$\alpha_p = 1 \text{ mrad}$
SEM imaging modes

Mode III – Low-Voltage Mode

• This mode is governed by the beam acceleration voltage
• At low accelerating voltage ($\leq 5$ kV), the beam interaction with the specimen is confined to the regions very close to the surface
• This provides an image rich in surface details compared to images at higher accelerating voltages.

Sharp surface feature

$V_0 = 5$ keV

$\checkmark$

Poor surface feature

$V_0 = 15$ keV

$\times$

Poor surface feature

$V_0 = 30$ keV

$\times$
Most of the older SEM uses Tungsten hairpin or thermionic Lanthanum Hexaboride (LaB$_6$) Electron sources.

These thermionic sources are resistively heated to very high temperature for the emission and release of electrons.

**Advantage:** Less expansive source, no special vacuum requirement

**Disadvantage:** Low brightness, limited lifetime and large energy spread
FE (Field emission) SEM

- Field emission is alternate method where potential barrier for electrons is lowered and narrowed by applying an negative potential at a very sharp wire tip (radius ≤ 100 nm) cathode.
- When the tip concentrated field reaches about 10 V/nm electrons emit
- FE sources provide enhanced performance, reliability and lifetime.
- Two class of field emitter (I) Cold field emitter (CFE) and (II) Schottky field emitters (SFE) and Thermal field emitters (TFE)
- CFE relies purely on the high applied field for electron emission independent of the tip temperature.
- TFE has the same property as CFE, but is operated at elevated temperature, helps to keep the tip clean, reducing noise and instability even in degraded vacuum condition.
- SFE guns are similar to other FE sources, but include a suppresser grid to eliminate unwanted thermionic emission from region outside of the tip.
Comparison of ordinary SEM and FESEM

Comparison of various parameters for different electron sources at 20 kV

<table>
<thead>
<tr>
<th>Source</th>
<th>Brightness (A/cm² sr)</th>
<th>Lifetime (h)</th>
<th>Source size</th>
<th>Energy spread ΔE (eV)</th>
<th>Beam current stability (%/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten hairpin</td>
<td>10⁵</td>
<td>40–100</td>
<td>30–100 µm</td>
<td>1–3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>10⁶</td>
<td>200–1000</td>
<td>5–50 µm</td>
<td>1–2</td>
<td>1</td>
</tr>
<tr>
<td>LaB₆</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field emission</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold</td>
<td>10⁸</td>
<td>&gt;1000</td>
<td>&lt;5 nm</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>Thermal</td>
<td>10⁸</td>
<td>&gt;1000</td>
<td>&lt;5 nm</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Schottky</td>
<td>10⁸</td>
<td>&gt;1000</td>
<td>15–30 nm</td>
<td>0.3–1.0</td>
<td>~1</td>
</tr>
</tbody>
</table>

Better performance of FE sources are evident from the comparison
Electrons

• Elementary particle carrying a negative charge
• Accelerated electron not only acts as a particle but acts as wave too.
• Rest mass of electron = \( m_o = 9.109 \times 10^{-31} \) kg
• Charge of electron = \( e = -1.602 \times 10^{-19} \) C
• For an accelerating electron, wave length of moving electron (considering the relativistic effects) is given as,

\[
\lambda = \frac{h}{\sqrt{2m_o eV \left(1 + \frac{eV}{2m_o c^2}\right)}}
\]

Where,
- \( h \) = Planck Constant,
- \( V \) = Applied Voltage
- \( c \) = Velocity of light in vacuum = \( 2.998 \times 10^8 \) m/s

• Above equation in useful in calculating the acceleration potential for a particular wave length of electron waves.
Electron wave

- Waves in electron beam can be coherent or incoherent.

  - Coherent: Waves of same wave lengths
  - Incoherent: Waves of different wave lengths

- Electron beam from a SEM electron source is a bundle of coherent electron waves, before hitting a specimen.
- After interacting with specimen, electron waves can form either coherent or incoherent beams
Electron matter Interaction

- Electron entering a material interacts as a negatively charged particle with electric fields of specimen atoms.
- The positive charge of the atom is strongly concentrated at the nucleus, whereas negatively charged electron atoms are much more dispersed in the a shell structure.

These interactions are classified into two different types:
- *Elastic interactions*: In this case, no energy is transferred from electron to sample. As a result, electron leaving the sample still has the original energy.
- *Inelastic interactions*: The energy of the incident electron is transferred to the sample atoms. Hence, after the interaction, electron energy is reduced.
Elastic Interaction

- Elastic interactions deflects the electron beam along new trajectory, causing them to spread laterally.
- A strong elastic scatter very near to the nucleus may result in beam electron leaving the specimen via back scattering, called Backscattered electrons (BSE). These electrons provide an important class of information for SEM imaging.
- Probability of elastic scattering
  - Increases strongly with atomic number ($\text{as } Z^2$), as heavier atoms have much stronger positive charge at nucleus
  - Decreases as electron energy increases ($\text{as } 1/E^2$)
Inelastic Interaction

- With the elastic scattering, beam electrons loose energy to specimen atoms in various ways.
- Such inelastic interactions gives rise to useful imaging signals such as Secondary Electrons (SE) and analytical signals such a X-rays.
- This energy loss happens gradually with distance traveled inside the atom.
Interaction Volume

- Elastic and Inelastic scattering together distribute a single incident electron beam over a 3-Dimensional region inside the material.
- Region generated because of these phenomenon is called interaction volume.
- Size and shape of the interaction volume depends on the relative amount of elastic and inelastic scattering on electron beams.
- Direct measurement of interaction volume for materials with intermediate and high atomic number materials is not possible.
Interaction Volume - Simulation

• Monte Carlo simulation is highly useful tool to simulate the scattering of electron beam in a material.
• To construct a Monte Carlo electron trajectory simulation, the effects of elastic and inelastic scattering are calculated from appropriate models to determine scattering angles, distances between scattering sites ("step length"), and the rate of energy loss with distance traveled.
• Effect of different parameters like atomic number (Z), beam tilt angle, beam energy etc. can be studied using these simulations.
• An online version of this simulation can be found at following link

www.matter.org.uk/tem/electron_scattering.htm#
Electron Range
A simple measure of interaction volume

- Interaction volume is a complex 3-dimensional region which depends on beam energy, material parameters, and tilt angle (complement of angle between the beam and surface plane).
- Despite this complexity, the interaction volume can be simply described with a single parameter called "electron range."
- The electron range is thus a simple value that is useful for rough comparisons and scaling various signal distributions.
- Within the electron range, the density of scattering events changes sharply with distance from the beam impact area.
- Analytical equations of the electron range are available in literatures.
Electron Range
A simple measure of interaction volume

- Using the Monte Carlo depiction of the interaction volume, consider a hemisphere constructed with a radius whose origin is the entry point of the beam into the specimen and which contains a specified fraction of the electron trajectories, for example, 90%. Radius of this hemisphere is called *electron range*.

\[
R_{KO} (\mu m) = \frac{0.0276A E_0^{1.67}}{Z^{0.89} \rho}
\]

Where, \( A \) is the atomic weight (g/mole), \( Z \) is the atomic number, \( \rho \) is the density (g/cm\(^3\)) and \( E_0 \) is the beam energy (keV).

For using this formula, the specimen is assumed to be flat, thick enough to be electron-opaque and of sufficiently large lateral extent that there are no edges or boundary within electron range. Tilt angle is 0 degree.
Backscattered Electrons - Imaging

• Backscattered electrons (BSE) are beam electrons whose trajectories have intercepted a surface usually, but not necessarily, the entrance surface and which thus escape the specimen.

• Backscattered electrons remove a significant amount of the total energy of the primary beam.

• Backscattering is quantified by the backscatter coefficient $\eta$ which is defined as

$$\eta = \frac{\eta_{BSE}}{\eta_B} = \frac{i_{BSE}}{i_B}$$

where $\eta_B$ is the number of beam electrons incident on the specimen and $\eta_{BSE}$ is the number of backscattered electrons (BSE). The backscatter coefficient can also be expressed in terms of currents, where $i_B$ refers to the beam current injected into the specimen and $i_{BSE}$ to the backscattered electron current passing out of the specimen.
Backscattered Electrons - Imaging

Atomic number dependence of BSE

• Backscattering increases monotonically as Atomic number \((Z)\) increases. Hence it forms the basis for atomic number contrast.

• The slope of \(\eta\) vs \(Z\) is initially steep but decreases with increase in \(Z\). Hence atomic number contrast between adjacent pair of elements is strong at low atomic number and weak at high atomic number.

\[
\eta = -0.0254 + 0.016Z - 1.86 \times 10^{-4} Z^2 + 8.3 \times 10^{-7} Z^3
\]
Backscattered Electrons - Imaging

Beam energy dependence of BSE

- For beam energy 5-50 keV there is only a small change (<10%) in the backscatter coefficient ($\eta$) w.r.t. beam energy.
- At beam energies below 5 keV, $\eta$ of light elements increases and those for heavy element decreases.

$$\eta(Z, E) = E^m C$$

where, $m = 0.1382 - (0.9211 / \sqrt{Z})$ and

$$C = 0.1904 - 0.2235 \ln Z + 0.1292 (\ln Z)^2 - 0.01491 (\ln Z)^3$$
Backscattered Electrons - Imaging

Title angle dependence of BSE

- Backscattering increases monotonically with tilt angle.
- This increase is the basis for topographic contrast in SEM, by which shape of object is recognized.
- At very high tilt angle, which correspond to grazing incidence, values of $\eta$ tend towards unity.
- For different elements at high values of $\theta$, $\eta$ tend to converge for all elements.
Backscattered Electrons - Imaging

Angular distribution of BSE – Normal beam incidence (0° tilt)

- Angular distribution of BSE is defined relative to normal of incident surface
- $\eta$ at an angle $\phi$ is given by,
  $$\eta(\phi) = \eta_n \cos\phi$$
  where, $\eta_n$ is the value measurement along normal vector $\mathbf{n}$.

- Thus maximum number of BSE is emitted along the normal to surface
- As the detector is placed at an angle $\phi$ n away from surface normal, number of BSE decreases.
- At shallow angle just above the surface, there are virtually no BSE trajectories.
- Thus Angular distribution of BSE detector relative to surface specimen will have a strong influence on its collection efficiency.
Backscattered Electrons - Imaging

Angular distribution of BSE – Non-normal beam incidence

- For titled surface angular distribution becomes asymmetric.
- At higher tile angles (>45°) distribution resembles a highly elongated ellipse, with the long axis at approx. same angle above the surface as the incident beam.

- Titling of specimen also results in asymmetry of interaction volume, this asymmetry also affects backscattering.

- For highly tilted surfaces, many of beam electrons skip off the first few atom layers and exit the specimen only after a few scattering events, so that the most are contained in a plane defined by the beam vector and the surface normal.
Backscattered Electrons - Imaging

Energy distribution of BSE

- The energy distribution is a continuum extending from the incident beam energy to essentially no energy.
- Region I represents the high energy dump of BSEs that have lost less than 50% of $E_0$.
- For most target of intermediate and high atomic number, the majority of BSEs will be found in region I.

- Region II is the gradually decreasing tail of energy distribution represents the electron that travel progressively greater distances, loosing progressively more energy within the specimen prior to backscattering.
Backscattered Electrons - Imaging

Energy distribution of BSE

- The energy distribution peak becomes more distinct for higher atomic number targets.
- Cumulative integrals calculated from the BSEs energy distributions show that BSEs retain at least 50% of the incident beam energy, with the fraction rising sharply for intermediate and high-atomic-number targets.
- Low-atomic number scatterers produce far fewer high-energy BSEs.

<table>
<thead>
<tr>
<th>Element</th>
<th>Cumulative fraction of BSE from 0 energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Carbon</td>
<td>$0.55E/E_0$</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.63</td>
</tr>
<tr>
<td>Copper</td>
<td>0.74</td>
</tr>
<tr>
<td>Silver</td>
<td>0.79</td>
</tr>
<tr>
<td>Gold</td>
<td>0.84</td>
</tr>
</tbody>
</table>
Secondary Electrons - Imaging

• Secondary electrons (SE) are loosely bound outer shell electrons from the specimen atoms which receive sufficient kinetic energy during inelastic scattering of the beam electrons to be ejected from the atom and set into motion.

• Thus SE will propagate through the solid, and some will intersect the surface and escape.

• SE are defined purely on the basis of their KE, i.e. all emitted electron less than a particular energy (say 50eV) are considered as SE.

• The total SE coefficient $\delta$ is given by

$$\delta = \frac{\eta_{SE}}{\eta_B} = \frac{i_{SE}}{i_B}$$

where $\eta_{SE}$ is the number of secondary electrons emitted from a sample bombarded by $\eta_B$ beam electrons and $I$ designates the corresponding currents.
Secondary Electrons - Imaging

- $\delta$ generally rises as the beam energy is lowered, as shown in table below, from increase in energy from 5keV to 50keV, $\delta$ gradually decreases

<table>
<thead>
<tr>
<th>Element</th>
<th>5 keV</th>
<th>20 keV</th>
<th>50 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>0.4</td>
<td>0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>Au</td>
<td>0.7</td>
<td>0.2</td>
<td>0.10</td>
</tr>
</tbody>
</table>

- SE generated while the incident beam passes through specimen surface are designated as $SE_1$. The $SE_1$ signal is inherently is high-resolution signal that preserves both the lateral spatial resolution of the focused beam and the shallow sampling depth of the SE.
Secondary Electrons - Imaging

• SE are also generated by the BSE approaching the surface. These are designated as $SE_2$. $SE_2$ signal is a low-resolution signal.

• Compared to $\eta$, $\delta$ is relatively insensitive to atomic number.
• The emission on SE is very sensitive to the condition of the surface because the low KE severely limits the range of SEs.
• As the angle of tilt ($\theta$) increases, $\delta$ increases.
Secondary Electrons - Imaging

- $\eta + \delta$ – Total electron emission from sample (BSE + SE$_2$)
- Variation of $\eta + \delta$ with beam energy is shown.
- As energy decreases there comes a crossover point $E_2$, where $\eta + \delta$ reaches unity. With further decrease in energy, $\eta + \delta$ increases above unity, i.e. more electron are emitted from the surface then supplied by the beam.
- $\eta + \delta$ reaches a peak and then reduces on further decrease in energy, until the second crossover point $E_1$ is reached, and then continues to decreases.
- Values of $E_1$ are less than 1keV and is difficult to measure
- Values of $E_2$ can be as high as 5-20, as listed
- Knowledge $E_2$ point and $\eta + \delta$ behavior at low beam energy forms the basis for controlling charging in SEM imaging of insulators through careful choice of beam energy and specimen tilt.

<table>
<thead>
<tr>
<th>Material</th>
<th>$E_2$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton</td>
<td>0.4</td>
</tr>
<tr>
<td>Electron resist</td>
<td>0.55–0.70</td>
</tr>
<tr>
<td>Nylon</td>
<td>1.18</td>
</tr>
<tr>
<td>5% PB7/nylon</td>
<td>1.40</td>
</tr>
<tr>
<td>Acetal</td>
<td>1.65</td>
</tr>
<tr>
<td>Polyvinyl chloride</td>
<td>1.65</td>
</tr>
<tr>
<td>Teflon</td>
<td>1.82</td>
</tr>
<tr>
<td>Glass passivation</td>
<td>2.0</td>
</tr>
<tr>
<td>GaAs</td>
<td>2.6</td>
</tr>
<tr>
<td>Quartz</td>
<td>3.0</td>
</tr>
<tr>
<td>Alumina</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Upper crossover energy for various materials (Normal beam incidence)
Summary

• Basis structure of a SEM, construction and functioning of its important components are discussed.
• Different modes of imaging in the SEM is explained with the effect of different parameters on the quality of imaging in all modes.
• Difference between ordinary SEM and FESEM is discussed is brief
• With a short review of electron behavior and properties, interaction of electron beam with material inside the SEM is explained.
• Various imaging signals resulting from the interaction of beam and specimen are discussed. Effects of different signal parameters and their importance for best quality of imaging is explained in details