Outline

This chapter describes the principles of a scanning electron microscope (SEM), the signals generated and associated contrast mechanisms. It starts with a description of the SEM and detectors used, the formation of an electron probe and how SEM parameter’s influence on the spatial resolution.

In order to understand the image formation and the contrast mechanisms involved, an explanation of the electron-matter interaction volume is given followed by a discussion on the origin of the secondary and back-scattered electrons (SE and BSE) will be given. This forms the theoretical basis for how we interpret the different possible contrasts mechanisms that form a SEM images, which will be discussed within this presentation, including artifacts. The presented material concludes with application examples and charging effects that can be reduced with lower accelerating voltages and charge compensation devices.
Outline

1) SEM operation
2) Electron probe and resolution
3) Depth of field
4) Electron-matter interaction volume
5) Secondary and back-scattered electrons
6) Contrast mechanisms
7) Examples
8) Charging effects

1) SEM operation

Energy spectrum of electrons leaving the sample
1) SEM operation

Incident electrons interaction with the sample produces:

- Secondary electrons SE: topography, low energy ≈ 0-50 eV
- Backscattered electrons BSE: atomic number Z, energy ≈ E₀
- Auger Electrons: not detected in conventional SEM, surface analysis
- Cathodoluminescence: photons UV, IR, vis
- Absorbed current, electron-holes pairs creation, EBIC
- plasmons
- Sample heating (phonons)
- Radiation damages: chemical bounding break, atomic displacement (knock-on) damage

1) SEM operation

- Electrons are accelerated to high energies (high spatial resolution!)
- Condenser lens system defines probe size and control probe current
- In some SEMs, there is a variable objective aperture between condenser lens 1 and 2 that used to control convergence angle (depth of field)
- Scanning coils above Objective lens raster beam on sample
- Objective lens focus probe on sample
- Various detectors surrounding sample collected radiated signals
1) SEM operation

Digital sync between the scan generators and image display. Pixel intensity is a function of detector signal, pre- and post processing (e.g., frame averaging, interlacing, etc.) and beam dwell time. Magnification is defined by raster area.

1) SEM operation

- Image formed step by step by the sequential scanning of the sample with the electron probe
- Image acquisition as numerical data
- Bulk sample
- Imaging the sample “surface” (from 1 nm to ≈1 µm depth depending on the analyzed signal
- Contrast is due to secondary electrons (SE) emission or back scattered electrons (or sometimes to photons, X-rays, absorbed current)
- Resolution: 1 nm to 10 nm
2) Electron probe and resolution

- Spatial resolution depends on the size of the interaction volume
- Interaction volume differs material, accelerating voltage, spot size
- Different particles have different interaction volumes sizes and thus different resolution for the same microscope settings

"true" secondary electrons \textbf{SE1} and "converted BSE" secondaries \textbf{SE2+SE3}

The SE signal always contain a high resolution part (SE1 from the probe) and a combined average (low resolution) part from SE2+SE3!
2) Electron probe and resolution

SEM: Limiting parameters on resolving power with SE

1. **High magnification**
   - The probe size (generation of SE1)
     \[ r \sim d_{\text{probe}} \]

2. **The size of the interaction volume** (generation of SE2+SE3 from BSE):
   - Energy and atomic number influence

3. **Low magnification**
   - The screen (or recording media) pixel size \( d_{\text{screen}} \)
     \[ r \sim d_{\text{screen}}/\text{magnification} \]

---

Green light: \( \lambda \approx 532 \text{ nm}, \)  
\( \beta \) (objective collection angle) \( \sim 1 \text{ rad} \)  
n= 1.7 for oil immersion lens  
**d=190nm**  
Electrons 10 keV: \( \lambda \approx 0.0122 \text{nm} \)  
n=1 for vacuum  
\( \beta=0.1 \text{ rad given SEM geometry} \)  
**d=0.075 nm**

**Lens aberrations limit spatial resolution to \( \sim 1 \text{ nm} \)**

\[ d = 0.61 \frac{\lambda}{n \sin \theta} = 0.61 \frac{\lambda}{\beta} \]
2) Electron probe and resolution

Resolution in probe mode

- **Spherical aberration**
  \[ d_{\text{ sph}} = C_s \alpha^3 \]

- **Chromatic aberration**
  \[ d_{\text{ ch}} = \frac{C_{\text{ ch}} \left( \frac{\Delta E}{E} + 2 \frac{\Delta I}{I} \right)}{n \sin \alpha} \]

- **Diffraction (Airy, Rayleigh)**
  \[ d_{\text{ d}} = 0.61 \frac{\lambda}{n \sin \alpha} \]

- **Brightness \( \beta \)** conservation
  \[ d_{\text{ g}} = \sqrt{\frac{4I}{\pi^2 \beta} \frac{1}{\alpha}} \]

- **Combined**
  \[ d_{\text{ ch}} = \sqrt{d_{\text{sph}}^2 + d_{\text{ch}}^2 + d_{\text{d}}^2} \]

Probes with coherent source: see Mory C, Cowley J M, Ultramicroscopy 21 1987 171

2) Electron probe and resolution

How to increase resolving power?

- **Reduce the probe current at constant dose**
  - Reduce probe size
  - Reduce interaction volume
  - Reduce \( C_{\text{ sph}} \)
  - Increase gun brightness
  - Reduce \( C_{\text{ sph}} \) and increase transmitted brightness

- **Increase exposure time \( t \)**
  - Decrease spot size
  - Increase accelerating voltage
  - Reduce accelerating voltage
  - Short focus lenses:
  - In-lens detectors, semi in-lens, Snorkel lens mode
  - Field emission gun:
  - Cold emission, thermal assisted, Schottky effect
  - Dedicated columns: Gemini (Merlin), XL30, …
2) Electron probe and resolution

SEM: Effect of current, probe size and image acquisition time

- **10 pA/10 s**: Good resolution, but small loss of statistical noise.
- **10 pA/160 s**: Good resolution, less statistical noise.
- **100 pA/160 s**: Small loss of resolution, still less statistical noise.
- **1 nA/160 s**: Very few statistical noise, but high resolution loss!

**Optimal Aperture size (30µm)**
- Slow Scan Speed

**Large Aperture size (120µm)**
- Fast Scan Speed

Though large apertures produce larger convergence angles, spherical aberration increases probe size and reduces resolution.
2) Electron probe and resolution

Optimal Aperture size (30µm)
Fast Scan Speed
Optimal Aperture size (30µm)
Slow Scan Speed

You must find balance between resolution, current, and scan speed!
Sample Drift, Beam Damage, and Charging influence your choice of scan speed and current and thus are practical conditions that determine resolution.

How to increase resolving power?

- Reduce the probe current at constant dose
- Increase exposure time $t$
- Reduce probe size
- Decrease spot size
- Increase accelerating voltage
- Reduce interaction volume
- Reduce accelerating voltage
- Reduce $C_{sph}$
- Short focus lenses:
  - in-lens detectors, semi in-lens, Snorkel lens mode
- Increase gun brightness
- Field emission gun:
  - Cold emission, thermal assisted, Schottky effect
- Reduce $C_{sph}$ and increase transmitted brightness
- Dedicated columns: Gemini, XL30, …
2) Electron probe and resolution

Thermionic SEM: low voltage?

![Graphs showing electron probe diameter versus convergence angle and accelerating voltage]

Modern SEM short focus length: $C_{\text{sph}} = 17 \text{ mm}$, $C_{\text{ch}} = 9 \text{ mm}$, $\Delta E = 1.5 \text{ eV}$, $\beta = 1.10^{5} \text{ A/cm}^2\text{sr}$

2) Electron probe and resolution

How to increase resolving power?

- Reduce the probe current at constant dose
- Increase exposure time $t$
- Reduce probe size
- Decrease spot size
- Increase accelerating voltage
- Reduce interaction volume size
- Reduce $C_{\text{sph}}$
- Increase gun brightness
- Reduce $C_{\text{sph}}$ and increase transmitted brightness
- Reduce accelerating voltage
- Short focus lenses:
  - in-lens detectors, semi in-lens, Snorkel lens mode
- Field emission gun:
  - Cold emission, thermal assisted, Schottky effect
- Dedicated columns: Gemini, XL30, …

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2) Electron probe and resolution

Interaction volume versus $E_0$

Penetration depth in Cu as a function of incident energy $E_0$ and proportion of BSE (Monte-Carlo simulation)

$Z = cte$

How to increase resolving power?

- Reduce the probe current at constant dose
- Increase exposure time $t$
- Reduce probe size
- Decrease spot size
- Increase accelerating voltage
- Reduce accelerating voltage
- Reduce $C_{sph}$
- Short focus lenses:
  - in-lens detectors, semi in-lens, Snorkel lens mode
- Increase gun brightness
- Field emission gun:
  - Cold emission, thermal assisted, Schottky effect
- Reduce $C_{sph}$ and increase transmitted brightness
- Dedicated columns: Gemini, Merlin, Teneo, …
2) Electron probe and resolution

Short focus length… or… FEG?

Resolution loss at low voltage

Low voltage, high resolution
Observation of the real surface
Uncoated samples
Very little beam damage

High voltage, high resolution
Edge effects, fine details not resolved
More beam damage

Thomson iconic: 

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2) Electron probe and resolution

Influence of working distance and objective aperture on resolution

Increasing working distance will:
- increase depth of focus
- increase probe size and thus decrease resolution.
- increase the effects of stray magnetic fields and thus decrease resolution.
- increase aberrations due to the need for a weaker lens to focus

Increasing aperture size will:
- increase current and produced signals – better signal to noise
- increase aberration and thus decrease resolution.
- decrease depth of field

3) Depth of field

Light bulb filament

Increasing working distance will:
- increase depth of focus
- increase probe size and thus decrease resolution.
- increase the effects of stray magnetic fields and thus decrease resolution.
- increase aberrations due to the need for a weaker lens to focus

Increasing aperture size will:
- increase current and produced signals – better signal to noise
- increase aberration and thus decrease resolution.
- decrease depth of field
3) Depth of field

Depth of field as a function of $d_{\text{probe}}$

- The depth of field is the depth for which the image can be focused.
- The depth of field increases when the convergence angle of the probe (a) decreases.

- Increase the working distance
- Reduce objective aperture size

$$h_{\text{depth of field}} = \max \left\{ \frac{2d_{\Delta}}{\alpha}, \frac{1}{\text{pixel size}}, \frac{1}{\text{Mag} \alpha} \right\}$$

3) Depth of field

Effect of working distance (WD) and aperture on the depth of field
3) Depth of field

Examples

30 µm

Another example of the effect of the objective aperture diameter

100 µm

30 µm

50 µm
3) Depth of field

Measuring depth of field: stereoscopy

\[ Z_L = \frac{(XL \cos \alpha - XR)}{\sin \alpha} = \frac{3.32 \mu m \cos 6^\circ - 0.33 \mu m \sin 6^\circ}{\sin 6^\circ} = 28.4 \mu m \]

\[ Z_R = \frac{(XL - XR \cos \alpha)}{\sin \alpha} = \frac{3.32 \mu m - 0.33 \mu m \cos 6^\circ}{\sin 6^\circ} = 28.6 \mu m \]

\[ p = (XL - XR), \ h = p/2 \sin \left(\frac{\alpha}{2}\right) = \frac{3 \mu m}{2 \sin(3^\circ)} = 28.7 \mu m \]

Distance between points = \( \sqrt{Z_L^2 + XL^2} = 28.6 \mu m \)

\[ EDS(\text{angle}) = \tan^{-1} \left(\frac{Z_L}{XL}\right) = 83.3^\circ \]

4) Electron-matter interaction volume

Monte-Carlo simulations

1. Electron Flight Simulator ($$$ Small World / D. Joy)
   - old... DOS !!!!
   - http://www.small-world.net

2. Single Scattering Monte Carlo Simulation (Freeware)
   - "Monte Carlo Simulation" Mc_w95.zip
   - by Kimio KANDA
   - http://www.nsknet.or.jp/~kana/soft/sfmenu.html

3. CASINO (Freeware)
   - " monteCArlo SImulation of electroN trajectory in sOlids 
     - by P. Hovington and D. Drouin

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4) Electron-matter interaction volume

Number/Energy of backscattered electrons by Monte-Carlo simulations

Penetration and back-scattering vs elements (Z)

\[ V_{\text{acc}} = 20\text{kV} = \text{cte} \]

Depth of electron penetration vs Z and yield of backscatter electrons BSE (Monte-Carlo simulation):
5) Electron-matter interaction volume

Penetration and back-scattering vs elements (Z)

\[ V_{\text{acc}} = 5 \text{ kV} = \text{cte} \]

Depth of electron penetration vs Z and yield of backscattered electrons BSE (Monte-Carlo simulation):

4) Electron-matter interaction volume

Penetration and back-scattering vs elements (Z)

\[ V_{\text{acc}} = 1 \text{ kV} = \text{cte} \]

Depth of electron penetration vs Z and yield of backscattered electrons BSE (Monte-Carlo simulation):
4) Electron-matter interaction volume

Penetration and backscattering vs energy ($E$)

$Z = \text{cte}$

Depth of electron penetration in Cu vs energy $E_0$ and yield of backscattered electrons BSE (Monte-Carlo simulation):

Cu 20 keV

Cu 5 keV

Cu 1 keV

4) Electron-matter interaction volume

1 kV – surface features are resolved with high spatial resolution

30 kV – buried interfaces are visible though surface features are less resolved

30 keV imaging has higher spatial resolution. However, the larger interaction volume and increased edge effects masks the fine features of the surfaces. Thus, 1 kV imaging, having a smaller interaction volume, is better for observing surface features in this multi-layer sample. Sample Geometry is an important factor in choosing the accelerating voltage.
5) Secondary Electrons and Backscattered

"true" secondary electrons \( SE_1 \) and "converted BSE" secondaries \( SE_2 + SE_3 \)

The SE signal always contain a high resolution part (\( SE_1 \) from the probe) and a combined average (low resolution) part from \( SE_2 + SE_3 \)!

Various SE types from
• \( SE_1 \): incident probe
• \( SE_2 \): BSE leaving the sample
• \( SE_3 \): BSE hitting the surroundings

although this signal is gathered around the probe, its intensity is only attributed to the pixel corresponding to the actual probe position.
5) Secondary Electrons and Backscattered Electrons

Relative contribution of SE1 and SE2 (+SE3) vs primary energy

The total intensity (green and brown) is attributed to the \((x,y)\) pixel, here at 0 nm on this 1-D model (adapted from D.C. Joy Hitachi News 16 1989).

5) Secondary Electrons and Backscattered Electrons

In-lens SE detector  
Everhart Thornley detector
5) Secondary Electrons and Backscattered Electrons

Yield for SE and BSE emission per incident electron vs atomic number Z

- **Secondary Electrons (SE):**
  - Low or no chemical contrast.
  - But for light elements, the topographical contrast will dominate on rough surfaces (SE1).

- **Backscattered Electrons (BSE):**
  - Chemical contrast for all the elements (sensitivity ≈ DZ = 0.5).
  - A fast way to phase mapping.

Sample *surface polished* (no topography) and perpendicular to the incident beam direction (intermediate energy $E_0 \approx 15$ keV).

A toner particle (penetration in light material) is shown at different voltages.

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5) Secondary Electrons and Backscattered Electrons replace Dust on WC (different Z materials)

- flat material
- rough material
- low Z material
- low Z material

**SE** 25 kV **BSE**

5) Secondary Electrons and Backscattered Electrons

- In-lens Backscattered Electron Detector EsB
- In-lens Secondary Electron Detector

Everhart Thornley Secondary Electron Detector

Solid State Backscattered Electron Detector

Variable Pressure Secondary Electron Detector

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5) Secondary Electrons and Backscattered Electrons

Shorter work distance improves spatial resolution of fine topographical features (But at lower depth of field!)
5) Secondary Electrons and Backscattered Electrons

BSD

ET-SE

No contrast — too low voltage

Voltage has 2 important effects on image contrast
1) Size of interaction volume
2) Detector sensitivity/energy selectivity
6) Contrast mechanisms

Size and edge effects

Topographical contrast in SE mode: Effect of sloped surfaces

penetration depth ("range") $\gg$ SE escape length

Relative yield of SE vs angle of incidence on the sample surface

(adapted from D.C. Joy Hitachi News 16 1989)
6) Contrast mechanisms

Topographical contrast at low energy
Effect of the incidence angle

But at low energy...

Range

yield will be nearly independent of tilt


6) Contrast mechanisms

SE and BSE topography contrast

- For one position \((x,y)\) of the electron probe:
- BSE escape from a "pear" volume around the probe position
- SE1 escape from a thin layer under the entrance surface of the probe
- SE2 escape from a thin layer under the escape surface of BSE

\[
\text{contrast} = \frac{2(I_1-I_2)}{I_1+I_2}
\]

\[
I_{SE}(0^\circ) = I_{PE} \cdot d = I_{PE} \cdot 10\%
\]

\[
I_{BSE}(0^\circ) = I_{PE} \cdot \frac{1}{\cos 40^\circ} = I_{PE} \cdot 13\%
\]

\[
I_{SE1}(0^\circ) = I_{SE} \cdot \eta = I_{PE} \cdot 31\%
\]

\[
I_{BSE}(40^\circ) = I_{PE} \cdot 37\%
\]

\[
I_{SE2}(0^\circ) = I_{PE} \cdot 10\%
\]

\[
I_{SE2}(40^\circ) = I_{PE} \cdot 3.1\%
\]

BSE contrast = 18%

BSE topographical contrast is not negligible! Chemical contrast is better observed only on flat, polished surfaces
6) Contrast Mechanisms

Higher voltage gives more edge effects and increased topographical contrast in BSE images. However, it gives lower resolution of fine surface features (larger interaction volume).

Size and edge effects

(By L. Reimer, Image Formation in Low-Voltage Scanning Electron Microscopy, 1993)
6) Contrast mechanisms

Size and edge effects

Do not forget, in SEM:
The signal is displayed at the probe position, not at the actual SE production position!!!
6) Contrast mechanisms

Comparison of SE and BSE contrast modes

If you look down to the column, the "light" seems to come from the Everhardt-Thornley detector.

The trajectories of BSE are not strongly affected by the electrical field, most BSE miss the detector.

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6) Contrast Mechanisms

Everhart Thornley detector

In-lens SE detector

SE2 Detector located on the lower right

In-lens SE Detector located directly above and centered
6) Contrast Mechanisms

The bias on the Faraday cage can be adjusted from +400 V to -250 V

Effect of collector bias voltage on the SE image contrast

-250V  -100V  0V  400V

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6) Contrast mechanisms

Contrast in image suggest the object in the center has a “stepped” pyramid morphology.

Rotated by 180 degrees, and now it looks like an etched pit on the surface.
6) Contrast mechanisms

Influence of voltages on the resolution and contrast mechanisms

Fig. 1  Diffusion of incident electrons (after Ducomb and Shields).

Fig. 2  Effect of accelerating voltage.
6) Contrast mechanisms

- Low voltage better resolution and imaging of fine surface features low Z materials (smaller interaction volume and less SE2 signal)
- High voltage better spatial resolution for isolated particles

Effect of the accelerating voltage on penetration and SE signal

20 kV:
- Strong penetration, SE3 is a much larger signal than SE1/SE2.
- It reveals the copper grid under the C film via the electron backscattering, but the structure of the film itself is hidden

2 kV:
- Low penetration, only a few electrons reach the copper grid and most of the SE3 are produced in the C film together with SE1/SE2.
- The C film and its defects become visible

(from D.C. Joy
Hitachi News 16 1989)
6) Contrast mechanisms

Change in SE topological contrast with the voltage

(from L.Reimer, Image formation in the low-voltage SEM)
6) Contrast mechanisms

Enhancement topographical contrast at low voltage: less delocalization by SE2.

SE, 5 kV

SE, 30 kV

7) Examples: STEM imaging

Physical limit to the imaging in secondary electron mode

- Tin grains on a thin carbon film (TEM supporting grid)
  HRSEM 25 kV 1 nm nominal resolution
- left: SE
- right: scanning transmitted electrons (STEM bright-field)

Micrograph of tin particles on carbon foil at 25 kV: SE (left) and TE (right) signals. Bar = 66.7 nm.

SE: e⁻/e⁺ coulombic

STEM: Rutherford (e⁻/electric field in atom)

(from B. Ocker, Scanning Microscopy 9 (1995) 63...)
7) Examples: STEM resolution

Physical limit of the imaging with secondary electrons

- The average grain size looks larger in SE (12.3 nm) than in STEM (9.1 nm)
- "Delocalization": the elastic scattering in STEM (Rutherford) occurs at a much closer distance from the atom nucleus than the inelastic coulombic e-/e+ interactions required to eject a SE

7) Examples: STEM imaging in modern SEMs

TESCAN MIRA SEM detector configuration
7) Examples: STEM imaging in modern SEMs

Low kV atomic imaging of graphene and other low Z materials in SEM without aberration correction!

Sample: Multi-wall carbon nano tube (lattice fringes)
Vacc.: 30 kV
Mag.: 2.000x
Bright Field (BF)-STEM image

Sample: Graphene (lattice fringes)
Vacc.: 30 kV
Mag.: 3.000x
Bright Field (BF)-STEM image

7) Examples

Al$_x$Ga$_{1-x}$As/GaAs "quantum wire" (2-D quantum well)

GaAs

SE mode image on a cleaved surface. The SE$_2$ (BSE chemical) contrast dominates this image in absence of topographical contrast (SE$_1$=cte)

(by courtesy of Dr. K. Leifer, IPEQ/EPFL)

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7) Examples:

Contrast reversal in BSE mode at low accelerating voltage

![Graph showing dependence of backscattering coefficient on atomic number Z for different electron energies.]

Fig. 4.1. Dependence of the backscattering coefficient $\eta$ at normal incidence ($\phi=0$) on atomic number $Z$ for different electron energies.

from L. Reimer, *Image formation in low-voltage SEM*

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7) Examples: low kV imaging

<table>
<thead>
<tr>
<th>SE image</th>
<th>EsB image</th>
<th>SE image</th>
<th>EsB image</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="SE image at 10 kV" /></td>
<td><img src="image2.png" alt="EsB image at 10 kV" /></td>
<td><img src="image3.png" alt="SE image at 0.5 kV" /></td>
<td><img src="image4.png" alt="EsB image at 0.5 kV" /></td>
</tr>
</tbody>
</table>

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8) Charging effects

Fiberglass on epoxy

(by courtesy of B. Senior CIME/EPFL)

9) Charging effects

Charging-up of an insulating particle of dust

Negative charges left on the particle create an electric field that repels the SE toward the substrate around the dust

(adapted from L. Reimer Scanning Electron Microscopy)
9) Charging effects

Extreme charging-up: electrons are reflected by the sample and hit the microscope sample chamber!!!

8) Charging Effects

In-lens SE detector  Everhart Thornley detector

In-lens detectors collect SE1 electrons, those that emanate from the near surface, which are more sensitive to surface charging
8) Charging effects

Total yield for electron emission (SE + BSE) on insulators

$E_1$ and $E_2$ are critical energies for which 1 electron leaves the surface for each incident electron: neutrality
$eV_{\text{acc}} = E_1$ is unstable
$eV_{\text{acc}} = E_2$ is stable

when $eV_{\text{acc}} < E_2$ positively charged
when $eV_{\text{acc}} > E_2$ negatively charged
when $eV_{\text{acc}} = E_2$ charging disappears

Caution: this extremely simple model is not quantitative for insulators because charge implantation and removal depends on the scanning speed and precise sample geometry

9) Charging effects

Total yield for electron emission (SE + BSE) on insulators

$E_1$ and $E_2$ are specific to the material, but also change with the incidence angle $\theta$ (edge effects change SE emission)!

Caution: $E_1$ and $E_2$ are specific to the material, but also change with the incidence angle $\theta$ (edge effects change SE emission)!
8) Charging effects

Some values of the neutrality $E_2$ energy

$E_2$: upper neutrality energy
$E_m$: maximum emission energy
$\delta_m$: maximum yield at $E_m$

adapted from:
E. Plies, Advances in Optical and Electron Microscopy, 13 (1994) p 226

<table>
<thead>
<tr>
<th>Material</th>
<th>$\delta_m$</th>
<th>$E_m$ (keV)</th>
<th>$E_2$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.94–1.0</td>
<td>0.3–0.55</td>
<td>0.65</td>
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<tr>
<td>Aluminium</td>
<td>0.97–1.17</td>
<td>0.30–0.40</td>
<td>1.05</td>
</tr>
<tr>
<td>Silicon</td>
<td>0.9–1.10</td>
<td>0.25–0.40</td>
<td>1.15</td>
</tr>
<tr>
<td>Chromium</td>
<td>1.0–1.16</td>
<td>0.48–0.60</td>
<td>1.8–2.0</td>
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<tr>
<td>Iron</td>
<td>1.1–1.3</td>
<td>0.40</td>
<td>1.27</td>
</tr>
<tr>
<td>Copper</td>
<td>1.1–1.13</td>
<td>0.50–0.75</td>
<td>2.7–2.8</td>
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<tr>
<td>Be–Cu bronze</td>
<td>2.20–5.0</td>
<td>0.3–0.4</td>
<td>2.2–3.0</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.0–1.24</td>
<td>0.40–0.65</td>
<td>2.2–3.0</td>
</tr>
<tr>
<td>Silver</td>
<td>1.0–1.4</td>
<td>0.70–0.80</td>
<td>3.2–5.8</td>
</tr>
<tr>
<td>Gold</td>
<td>1.31–1.45</td>
<td>0.7–0.8</td>
<td>7.8–8.2</td>
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<td>Al$_2$O$_3$</td>
<td>2.60–3.0</td>
<td>0.30–0.4</td>
<td>3.0</td>
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<td>SiO$_2$</td>
<td>2.5</td>
<td>0.42–0.5</td>
<td>3.0</td>
</tr>
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<td>Glass passivation</td>
<td>2–3</td>
<td>0.3–0.42</td>
<td>2.0</td>
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<tr>
<td>Ni silicide</td>
<td>1.97</td>
<td>0.8</td>
<td>6.5</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.20</td>
<td>0.6</td>
<td>2.6</td>
</tr>
<tr>
<td>PVC</td>
<td>1.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Teflon–FEP</td>
<td>2.21–3.0</td>
<td>0.3–0.4</td>
<td>1.82–1.9</td>
</tr>
<tr>
<td>Kapton (polyimide)</td>
<td>2.10</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>HPR resist</td>
<td>1.09</td>
<td>0.37</td>
<td>0.55</td>
</tr>
<tr>
<td>PBS resist</td>
<td>0.70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ1470 resist</td>
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</tr>
</tbody>
</table>

Charging-up on a mask for microelectronic

(SiO$_2$ substrate, photoresist, SE mode)

$V_{acc} \gg E_2$

$V_{acc} \approx E_2$

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8) Charging effects

Charging-up on spherical silica particles

Charging of particle surface lead to anomalous contrast given a "flying saucer" like morphology at 1.5 kV, close to the neutrality point, particles recover their spherical type contrast.

Contrast reversal in SE mode close to the neutrality point

SiO$_2$-Cr mask for TEG-FET transistors production

$\text{SiO}_2$ (E$_2$=3.0keV) $\text{Cr}$ (E$_2$=1.8keV)
8) Charging effects

Surface potential (voltage) contrast

Charging effects

SE contrast is improved and distortions are minimized at low voltages

fiberglass on epoxy

Which polarity ??????

by courtesy B. Senior/CIME

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8) Charging effects

Charging-up is reduced or even cancelled when working at $E_2$, though finding this can be difficult especially in complex inhomogeneous samples!

Charging can be cancelled under partial atmosphere in a "low vacuum" or "low pressure" Environmental SEM

- Problem: incident electrons from the probe are scattered by the atmosphere ("skirting effect")
- reduced resolution and contrast
- delocalized microanalysis (resolution may decrease to mm!)

Using a charge compensator device may reduce skirting effect by localizing gas near sample surface
8) Charging effects

The variable pressure (VP) mode of the Zeiss Gemini 300 SEM allows the observation of non-conductive samples though resolution is reduced due to “skirting” effects and noise.

8) Charging effects

Charge compensator device on the Zeiss Merlin

- Gas introduced near the sample
- Gas is ionized by electron beam
- Surface charge is reduced due to ion bombardment
- SEM is operated at high voltages instead low voltages, i.e., ionization of the gas and thus surface charge compensation is better at higher voltages
Other effects

1) Leakage:
   - Magnet field from distribution board
   - Stray fields from power lines in the surrounding walls
   - High-tension line located too close to the instrument
2) Low floor strength (acoustic vibrations)
3) Improper grounding
4) Detector discharging and/or contaminated

QUESTIONS?