Scanning Electron Microscopes and Helium-ion Microscopes
SEMs and Secondary electrons

For the investigation of bulk materials

The recorded signals are displayed in synchronism

Signals and information extracted
- SE/BSE: topographic and material, magnetic field
- SE: local potential
- EBIC/CL: p-n junctions, lattice defects, quantitative measurement of semiconductor parameters
- CL: concentration of trace elements
- EDS/WDS: composition
- BSE: crystallographic information (electron channelling patterns/Electron backscattering patterns)

Contrast: the electron energy, the specimen tilt or the collected angular range of emitted electrons, the detector configuration, energy selection
Secondary electrons

- **Primary electrons**
  - Excited by the PE-high resolution
  - SEs diffuse from the column to the chamber

- **Secondary electrons (SEs)**
  - Escape from a small depth 1-10 nm

- **Backscattered electrons (BSEs)**
  - Excited by BSE when striking parts of the specimen chamber (lower polepiece)
  - SEs: escape from a small depth 1-10 nm
  - Excited by BSE: larger diameter:
    - 0.1-1 um (10-20 keV)
    - 5-50 nm (low energies)
  - SEs diffuse from the column to the chamber

- **Auger electrons**
  - Excited by BSE when striking parts of the specimen chamber (lower polepiece)

- **Low-loss electrons**
  - Excited by BSE when striking parts of the specimen chamber (lower polepiece)
  - 5-50 nm (low energies)

- **Elastically Reflected**
  - Excited by BSE when striking parts of the specimen chamber (lower polepiece)

A good detector: SE1 + SE2
Everhart-Thornley (ET) Detector

- Positively biased
- High gain and wide bandwidth up to 10 MHz system
- A bias of ~10 kV
- 4-eV SEs trajectories
- Shadowing effect: only a fraction of SEs can be detected
Topographic Contrast: SE

The dependence of the SE yield on the tilt angle of the local surface normal relative to the incident beam

\[ \delta = \delta_0 \sec \theta \]

Surface normal direct away from the detector: Darker

An Everhart-Thornley detector on the right-hand side does not collect all SE, the signal is lower on the side opposite to the detector.

Electron diffusion with a diameter of the electron range \( \sim 0.05-10\mu m \); Near edge, more SE2 are excited by BSE leaving the side wall.

Much lower scale when the distance from an edge is of the order of the exit depth \( \sim 0.5-20nm \) of the SEs.

Apparent when the probe diameter is the order of the exit depth \( t_{se} \).

Particles < 1nm: increased SE signal.

SE1 is \( \sim \) proportional to the mass-thickness the primary electron have to penetrate.

Non-concentric Isodensities

10keV

30 keV
Material Contrast in SE mode

Local variation of the SE yield that cannot be attributed to differences in surface tilt

The yield increases monotonically with increasing atomic number

The increase of BSE is fast

The main contribution: SE2 excited by BSE

High energy > 5 keV: the SE image shows material contrast similar to that of the BSE

All SEs generated in the gold layer

Magnetite, Fe3O4
Matrix 80% Si, 10% Al
Voltage Contrast

Potentials generated by charging effects or biasing

Variations of electrostatic field between the specimen and the ET detector

Influence the SE trajectories and hence the SE intensity
• Positively bias: darker

Voltage contrast on a MOS-FET by biasing the gate by -6V

Helium-ion Microscope

6th July, 2009
Capability

- **Resolution**<br>  < 0.75 nm at 45kV
- **Field of View**<br>  Variable from 1 mm to 200nm
- **Energy Spread**<br>  0.25-0.5 eV
- **Beam current**<br>  1fA – 100 pA
- **Sample size**<br>  50 mm in diameter x 25 mm thick
- **Detectors**
  - Everhart-Thorley secondary electron detector
  - Energy resolved backscattered ion detector
  - Spectroscopic ally resolved photon detector and manipulator
  - Transmitted ion beam detector

**Imaging**
- Topography
- Material

**Fabrication**
- Lithography
- Ion milling: graphene
- Beam induced chemistry

**Spectroscopy**
- Thin film measurement
- Particle identification

**More?**
- Surface structure
- Work function
## Advantages of the Helium Ion Microscope

### Extended sample base
- **Insulating**, Metal, Semiconductor
- Low-Z/high-Z
- Nanoparticles, thin films, bulk surface

### High spatial resolution
- Small Probe Size
- High secondary electron yield
- Short wavelength of He ions
- Small interaction volume

### More information
- Large depth of focus
- Surface sensitivity
- High Material contrast
- High topographic contrast
- Voltage contrast
- RBI spectra: sub-A film thickness
- RBI imaging: material/channelling contrast: defect analysis

### High precision Nanofabrication
- Low beam damage (beam current: 0.1-10 pA)
- Smaller feature sizes
- Negligible contamination
- Low etching rate for soft/fragile materials

### Semiconductor Applications
- Imaging of defects
- Mask inspection
- Device metrology
- Device failure analysis

### SEMs
- Spatial resolution
- Surface charging
- Surface contamination

### TEMs
- Sample dimension
- Small Sampling

### FIBs
- Spatial resolution: 10 nm (milling)
- Contamination
- Damage
The Ion Source – the Trimer

Source formation: Thermo-field evaporation

Pyramid Tungsten tip
• Three atoms on the top
• Radius ~ 100 nm
• Life span: days/weeks

Diaphragm
• Smallest virtual source size: atomic
• High brightness
• Small energy spread: < 0.5 eV

Gas auto-ionization
• High ionization
• Atomic tip

acceleration

25-35 kV

Cryogenically cooled
• Positively biased
• Gas purification

Preserve the source shape

Destroy the source shape

Absorption/desorption
• W atom migration

W atom migration

High ionization

Gas purification

Positively biased
The ion source: better illumination

<table>
<thead>
<tr>
<th>Beam sources</th>
<th>Electron sources (100 kV)</th>
<th>Ion sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>LaB&lt;sub&gt;6&lt;/sub&gt;</td>
<td>ALIS He&lt;sup&gt;+&lt;/sup&gt;</td>
</tr>
<tr>
<td>Brightness (A cm&lt;sup&gt;-2&lt;/sup&gt; sr&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>~10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>~5×10&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>Energy spread (eV)</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Comparable to the FE electron gun: high-brightness, low energy spread, small probe size
High resolution

The convolution of the probe size and the interaction volume

Secondary particles can also escape from different depths

Confined to the surface

No high energy backscattered electrons
Secondary electron by Ions: iSE

**Potential electron emission (PEE):**
- No lower energy threshold
- Significant: \( v < 10^7 \text{ cm/s} \)
  (He\(^+\), \( \sim 100 \text{ eV} \))
- Free electrons from solid
- Potential energy released from ion neutralization

**Kinetic electron emission (KEE):**
- Free electrons from solid
- Kinetic energy of the ion

**For He\(^+\) (\( > 5 \text{ keV} \)):** PEE a few % of KEE

**1st principal model**
- Stopping Power
- Scattering Cross-section
- Mean free paths

**Semi-empirical**
- Quantitative: not good

**Monte Carlo**
- Fit an accepted model

**Generation of e: Berthe's proposition**
\[
\delta_{SE} = \frac{1}{\varepsilon} \int_{z_0}^{R} \frac{dE}{dz} 0.5 \exp\left(-\frac{z}{\lambda_d}\right) dz
\]
- SE yield: e/ion

**Escaping of e: diffusion**
\[
p(z) = A \exp\left(-\frac{z}{\lambda_d}\right)
\]
- Probability
- \( A \sim 0.5 \)
- The effective diffusion length

**\( \lambda_d \): Minimum resolvable feature, Ion < electron

**Excitation:**
- Conduction electrons
- Plamson
- Inner shell

**First principal**
- Partial wave expansion
- Empirically, by fitting

**For electron:** \( dE/ds = \text{constant} \)

**For He\(^+\):**
- \( v_{ion} \ll v_{Bohr} \)

\( dS \)
\( dE \)
\( SE \)
\( \varepsilon \)
\( \delta \)
\( A \)
\( \lambda_d \)
\( E_{SE} = \Delta E \)
2nd iSE imaging: topographical contrast

- Angle dependence
- Small interaction volume
- Dark region
- Lose sharpness
- Image fidelity

(a) 30 keV He ion
- 10 nm
- 1 μm

(b) 30 keV Ga ion
- 10 nm
- 1 μm

(c) 1 keV electron
- 10 nm
- 1 μm

Clearer Profile
SE2/SE1 ratio

Electron, $E = 25$ keV: $e_{SE2}/e_{SE1} > 1$

Poor resolution: SE2 emerges from a region equal to the full width of the interaction volume

He$^+$ ions: material/beam energy dependent
For $E > 50$ keV, $i_{SE2}/i_{SE1} <<$ electron case

$E_{\text{Backscattered ions}} < E_{\text{primary ions}}$

Optimized He$^+$ iSE: $> 100$ keV

- iSE yield +
- $i_{SE1}/i_{Se2} +$
- Beam energy +
- Gun brightness +

Fig. 8. The $i_{SE2}/i_{SE1}$ ratio computed by IONiSE for Al, Cu, Ag, and Au as a function of incident helium ion energy.
Appendix
The reduction of diffusion in LVSEM
Secondary ion imaging: compositional information with high spatial resolution

An understanding of the process of interaction between a primary ion beam and a solid target leading to the electron emission

• Clean targets
  • Contaminated surface: high yield
    • Low coverage: Change in work function – escape probability
    • High coverage: emission from the contaminates

• Two types of electron emission
  • Potential emission
    • Neutralization of the ion: Auger or resonance neutralization followed by Auger de-excitation – electron emission
    • Metal target: $E_{\text{max}} = \text{the first ionization energy of the ion – the work function of the target}$
    • For emission: $E_{\text{i}} - 2\phi > 0$ (Positive ions of inert gases, electronegative elements)
  • Kinetic emission
    • Transfer of the kinetic energy of a bombarding ion to the electrons of a projectile-target system