Physical Principles of Electron Microscopy

5. The Scanning Electron Microscope

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Smaller electron gun (30kV maximum): W, LaB6, Schottky, CFEG
Smaller and fewer lenses (30kV, no imaging lenses).
Image is generated serially (by scanning), as in STEM.
A bulk specimen (not thinned) can be used.
Principles of SEM imaging

Condenser lenses form a small (~ nm) “probe” on specimen. Final lens usually called the objective; it largely determines image resolution.

Sawtooth-wave scan generators deflect the probe in the form of a raster on the specimen. The same (x and y) scan signals are applied to the display device, so there is a 1:1 correspondence between point on the specimen and on the display (Maxwell’s first rule for imaging). Signal from an electron detector is amplified and used to modulate the local brightness of the display.
(a) Line scan deflects probe in $x$-direction, from A to B in Fig. (d), then rapid flyback takes probe to point C, where line scan is repeated.

(b) Frame scan displaces line scans in $y$-direction, up to point Z when frame-scan flyback returns probe to A. The entire frame is then repeated.

(c) Scan waveforms are usually digital (probe jumps from Y to Y$'$), with $m$ steps per line and $n$ lines per frame, giving $mn$ pixels in each image.
Principles of SEM

Image magnification: \( M = X/x = Y/y \)
where \( x, y \) are scan distances on specimen; \( X, Y \) are scan distances on display.

To increase \( M \), \( X, Y \) are kept fixed (constant image size) and \( x, y \) are reduced.

Display device was originally a cathode-ray tube (CRT) in which an electron beam moved in synchronism with the probe but over a much smaller distance. Nowadays a flat-panel computer monitor is used as the display; \( x \) and \( y \) signals make the computer select the appropriate pixel for brightness modulation.

The digital image is recorded in computer memory (then on disk etc.) by scanning once (slow scan) or many times (often at video rate).

The modulating signal is generated from any property of the specimen that changes when primary electrons arrive at the specimen.

Most commonly, secondary electrons (SE) used as the signal but backscattered primary electrons (BSE) can also be used.
Electron penetration into a bulk specimen

TEM uses primary electrons scattered elastically through small angles but as these electrons slow down (due to inelastic scattering) an increasing fraction are backscattered (through angles > 90deg) \( \rightarrow \) BSE signal of primary electrons emerging from the top surface of the specimen.

**Penetration depth** = electron range \( R \), where *empirically* (e.g. Reimer & Kohl)
\[
\rho R \approx a(E_0)^b
\]
where \( b \approx 1.35 \), \( a \approx 10 \mu g/cm^2 \) if \( E_0 \) is in keV, for any \( Z \).

Carbon: \( \rho \approx 2 \text{ g/cm}^3 \rightarrow R \approx 1 \mu m \) for \( E_0 = 10 \text{ keV} \)
Gold: \( \rho \approx 20 \text{ g/cm}^3 \rightarrow R \approx 0.2 \mu m \) for \( E_0 = 10 \text{ keV} \)
Monte-Carlo simulations (CASINO, Gauvin et al. 2001)

(a) 30 keV, (b) 10 keV, (c) 3 keV primary electrons penetrating Al (Z=13).
(d) 30 keV electrons penetrating Au (Z=79).
Secondary electrons

Inelastic scattering causes the primary electrons to slow down as they penetrate a solid. Much of the transferred energy is given to outer-shell atomic electrons and appears as kinetic energy of these secondary electrons (SE, secondaries). Average energy < 30eV so SE are themselves strongly scattered inelastically and they travel only a few nm. But if generated within the escape depth (~ 2nm) of the surface, they escape into vacuum and can be detected as a SE signal.

Average number of escaping secondaries per primary electron = SE yield $\delta$.

$0.1 < \delta < 10$ for most materials.

$\delta$ decreases with primary energy $E_0$.

$\delta$ increases with specimen tilt $\phi$ roughly as $1/\cos\phi$.
SEM topographical contrast

Volume from which secondaries can escape is $\pi (d/2)^2 \lambda$ in case A, $\pi (d/2)^2 (\lambda / \cos \phi)$ in case B, where $\lambda$ = escape depth.

The $\phi$-dependence gives topographical contrast.

Inclined regions (e.g. edges of particles or grooves) appear brighter than flat regions ($\phi=0$).

Asymmetry because SE detector is to the right.
Everhart-Thornley detector

Specimen often tilted towards detector to increase $\delta$

PMT gain $\approx (\delta)^n \approx 10^6$ for $n=8, d=4$

Accelerated SE generate visible photons at a scintillator (cathodoluminescence) and the photons are detected by a photomultiplier tube (PMT).

The PMT makes use of the photoelectric effect (photoelectrons released from a photocathode) and SE emission at $n$ dynodes.

With the $+10kV$ turned off, the device records BSE but not efficiently.
Through-lens detector

In some high-resolution SEMs, the objective lens has a small focal length (a few mm) and the specimen is placed very close to it, within the magnetic field of the lens (immersion-lens).

Secondary electrons emitted close to the optic axis follow helical trajectories, spiraling around the magnetic-field lines and emerging above the objective lens, where they are attracted toward a positively-biased detector.

Because the signal from such an in-lens detector (or through-the-lens detector) corresponds to secondaries emitted almost perpendicular to the specimen surface, positive and negative values of surface angle $\varphi$ provide equal signal.

Consequently, the SE image shows no directional or shadowing effects.
Effect of detector position

Compound eye of an insect, coated with gold to make the specimen conducting. (a) SE image recorded by a side-mounted detector (located toward the top) and showing a strong directional effect, including dark shadows visible below each dust particle. (b) SE image recorded by an in-lens detector, showing topographical contrast but very little directional or shadowing effect.
(a) Secondary-electron image of a small crystal, recorded with a side-mounted Everhart-Thornley detector is located toward the top of the image.

(b) Backscattered-electron image recorded by the same side-mounted detector, showing also topographical contrast and shadowing effects. Such contrast is much weaker for a BSE detector mounted directly above the specimen.
Backscattered-electron (BSE) images

Because the elastic scattering involves only a small energy exchange, most BSEs escape from the sample with energies not too far below the primary-beam energy.

The cross section for high-angle elastic scattering is proportional to $Z^2$, so BSE can be expected to give strong atomic-number contrast.

**Backscattering coefficient** $\eta =$ fraction of primary electrons that escape as BSE does increase with atomic number (*but almost linearly for low Z*).

BSE images show contrast due to variations in chemical composition of a specimen, whereas SE images reflect mainly its surface topography.

Another difference between the two kinds of image is the depth from which the information originates. In the case of a BSE image, the signal comes from a depth of up to about half the penetration depth (after being generated, each BSE must have enough energy to get out of the solid). For primary energies above 3 kV, this means tens or hundreds of nanometers, rather than the much smaller SE escape depth ($\approx 1$ nm).
Number of electrons emitted as a function of their kinetic energy, showing the conventional classification into secondary and backscattered components.
**BSE detectors**

Must have large solid angle (BSE have high energy, cannot be attracted by a positively-biased grid)

Robinson detector →

Solid-state (semiconductor) detector →

Axial location → mainly material contrast.
Other SEM modes

A **specimen-current image** is obtained by using a specimen holder that is insulated from ground and connected to the input terminal of a sensitive current amplifier.

Specimen current $I_s$ flowing to ground (through an amplifier) must equal the primary-beam current $I_p$ minus total emission current:

$$I_s = I_p - I_{BSE} - I_{SE} = I_p (1 - \eta - \delta)$$  [these currents are flow of negative charge]

Specimen-current image contains a mixture of Z-contrast and topographical information. To reduce the noise level of the image, the current amplifier must be limited in bandwidth, requiring that the specimen be scanned slowly (frame time of many seconds).

**Electron-beam induced conductivity (EBIC)** occurs when the primary-electron probe passes near a p-n junction in a semiconductor specimen such as a silicon integrated circuit (IC).

Additional electrons and holes are created, as in the case of a solid-state detector responding to backscattered electrons, resulting in current flow between two electrodes attached to the specimen surface. Using this current as the signal applied to the image display, the junction regions show up bright in the EBIC image.

The p-n junctions in ICs are buried below the surface, but if they lie within the penetration depth of the primary electrons, an EBIC signal will be generated. **It is even possible to use the dependence of penetration depth on primary energy $E_0$ to image junctions at different depths.**
**EBIC image**
showing perpendicular p-n junctions in a metal-oxide field-effect transistor (MOSFET).

(a) SE image

(b – f) EBIC images for increasing primary-electron energy $E_0$ and therefore increasing penetration depth.

Voltage-contrast images

Voltage contrast arises when voltages are applied to surface regions of a specimen, e.g. semiconductor IC chip. The secondary-electron yield is reduced in regions that are biased positive (lower-energy SE are attracted back to the specimen). Negative regions exhibit a higher SE yield because secondaries are repelled and have a higher probability of reaching the detector.

The voltage-contrast image is useful for checking whether supply voltages applied to an integrated circuit reach the appropriate locations. It can also be used to test whether a circuit is operating correctly, with signal voltages appearing in the right sequence.

Although most ICs operate at too high a frequency for the voltage cycles to be seen directly, this sequence can be slowed down and viewed in a TV-rate SEM image by use of a stroboscopic technique.

By applying a square-wave current to deflection coils installed in the SEM column, the electron beam can be scanned and intercepted by a suitably-placed aperture. If this chopping of the beam is performed at a frequency slightly different from the operational frequency of the IC, the voltage cycle appears in the SE image at the beat frequency (difference in chopping and IC frequencies), as low as 1 Hz.
Voltage-contrast image of an MOS transistor

Gate G at –6 volt, source S and drain D at 0 volt.

Gate G at –6 volt, source S and drain D at –15 volt.
Cathodoluminescence images

R, G and B phosphor dots in a color-TV screen, imaged using SE (a, c) and in CL mode (b, d) with no wavelength filtering.

The lower images (c, d) show individual grains of light-emitting phosphor at higher magnification.


Some CL images show the presence of electrical defects e.g. dislocations.
SEM operation

SEM is simpler than TEM, less to adjust, but there are some operating parameters.

**Accelerating voltage** (determines primary-electron energy $E_0$ and penetration depth)

**Working distance** (determines resolution, depth of field)

Change stage height and objective current. Since $M \ll 1$, WD $\sim$ focal length $f$.

Highest resolution (< 1nm obtained with an immersion lens, $f \sim$ few mm)

**Objective aperture** (determines depth of field, resolution)

**Focus and astigmatism controls** (determine resolution)

Particles on surface, objective current varied

astig. & focus correct
SEM objective focusing

\[ \alpha \sim \frac{D}{2\,WD} \]

\[ \text{depth of field} \sim \frac{\Delta r}{\alpha} \sim 2(\Delta r)(\frac{WD}{D}) \]

**Dynamic focusing** can correct for specimen tilt.
Comparison of SEM and light microscope images

(a) Low-magnification SEM image of a sea-urchin specimen, with specimen features at different height all approximately in focus.

(b) Light-microscope of the same area, with only one plane in focus. Other features (see arrows) appear blurred. From Reimer (1998).
Effect of accelerating voltage (1)

SE1 electrons are produced within escape depth by primary electrons. SE2 electrons are produced within escape depth by backscattered primaries. SE3 electrons are produced at SEM internal surfaces by backscattered primaries.

SE2 and SE3 produce mainly a background, reducing image contrast.
Effect of accelerating voltage (2)

Higher kV $\rightarrow$ more contribution from BSE $\rightarrow$ some depth information.

SE images of tridymite crystals and halite spheres on a gold surface, recorded with an SEM accelerating voltage of (a) 10 kV and (b) 30 kV. Note the higher transparency at higher incident energy. From Reimer (1998).
Low-voltage SEM

SEM specimens often coated with C or metal to prevent electrostatic charging. But insulator specimens can often be examined by reducing the primary energy $E_0$. Penalty: $C_c \rightarrow$ loss of resolution, minimised by FEG source, aberration correction.

$E_0 > E_2$: $\eta \& \delta$ low, required $I_s = I_p (1-\eta-\delta) > 0$. If 0, specimen charges negative.

$E_1 < E_0 < E_2$: $I_p (1-\eta-\delta) < 0 \rightarrow$ + charge but SE are attracted back and neutralize.

$E_0 < E_1$: $\eta \& \delta$ again low (penetration depth $<$ escape depth), negative charging.

1 keV $< E_2 < 10$ keV typically, $E_0$ is reduced until charging stops.
Environmental SEM (low-vacuum SEM)

Gas leak + differential pumping aperture $\rightarrow$ 0.01 atmos. in specimen chamber. Gas can be H$_2$O (SVP $\sim$ 3000 Pa at T = 25 C (less with PE-element cooling) which keeps a wet or biological specimen hydrated.

BSE or SE image (needs special detector, not E-T).

Primary electrons ionize gas molecules, +ions neutralise negative charging, so can use $E_0 > E_2$.

Penalty: e-scattering by gas molecules degrades spatial resolution.

The inner wall of the intestine of a mouse, imaged in an environmental SEM.

The width of the image is 0.7 mm.

Courtesy of ISI / Akashi Beam Corp.
Electron-beam lithography

Electrons can have a permanent effect on the specimen: radiation damage. In metals, high-angle “elastic” scattering causes atom displacement (defects). In insulators, inelastic scattering causes ionization damage (radiolysis).

In organic materials, this can be bond breakage or cross-linking between molecules, leading to positive or negative resists (where the product is easier or less easy to dissolve in a developer solution).

UV light and x-rays cause similar damage → lithography → IC manufacture. Electron beams are used in special cases, usually a special e-beam writer but an SEM (or TEM) can also be used.

Hydrocarbons present in a vacuum system can adsorb on internal surfaces (e.g. SEM or TEM specimen) and can be polymerized (by cross-linking) with much lower vapor pressure → e-beam contamination, which obscures the SEM or TEM image.
(a) Central region of a zone plate, fabricated by SEM lithography and imaged with secondary electrons. Bright rings are topographical contrast due to the step between bare Si substrate and PMMA-covered Si, but weak materials contrast is also present: the bare Si appears brighter because of its higher backscattering coefficient, giving a larger SE2 signal.

(b) Outer region of the zone plate, where the spatial resolution and accuracy of the pattern represent an engineering challenge.

Courtesy of Peng Li and Mirwais Aktary, Applied Nanotools Inc., Edmonton, Canada.
(a) Hydrocarbon-contamination line written onto a thin substrate by scanning a focused probe of 200-keV electrons in a TEM.

(b) A broader line transferred to polycrystalline bismuth by argon-ion etching. The arrow indicates the position of a grain boundary in the bismuth.

Courtesy of M. Malac, National Institute of Nanotechnology, Canada.