Scanning Electron Microscopy: an introduction

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In this article, aimed at the non-specialist microscopist rather than the experienced user, we introduce the fundamentals of Scanning Electron Microscopy and the information that can be gained from this technique. A companion article on Transmission Electron Microscopy will follow in a future issue.

The maximum useful magnification obtainable in a conventional optical microscope is about 1000x. For better resolution (and higher useful magnification) the wavelength of the imaging radiation must be decreased. In electron microscopy the electrons are usually accelerated to high energies of between 2 and 1000 keV (i.e. wavelengths of 0.027-0.0009 nm).

There are many possible interactions between the high-energy electron beam and the atoms in the specimen (see Figure 1). If the specimen is very thin, then electrons may be transmitted through it unabsorbed and used to form the image in TEM. If the specimen is thicker, then electrons are no longer transmitted so only particles (e.g. electrons, x-rays and photons) emerging from the surface can give us information. These are the signals used in a conventional SEM.

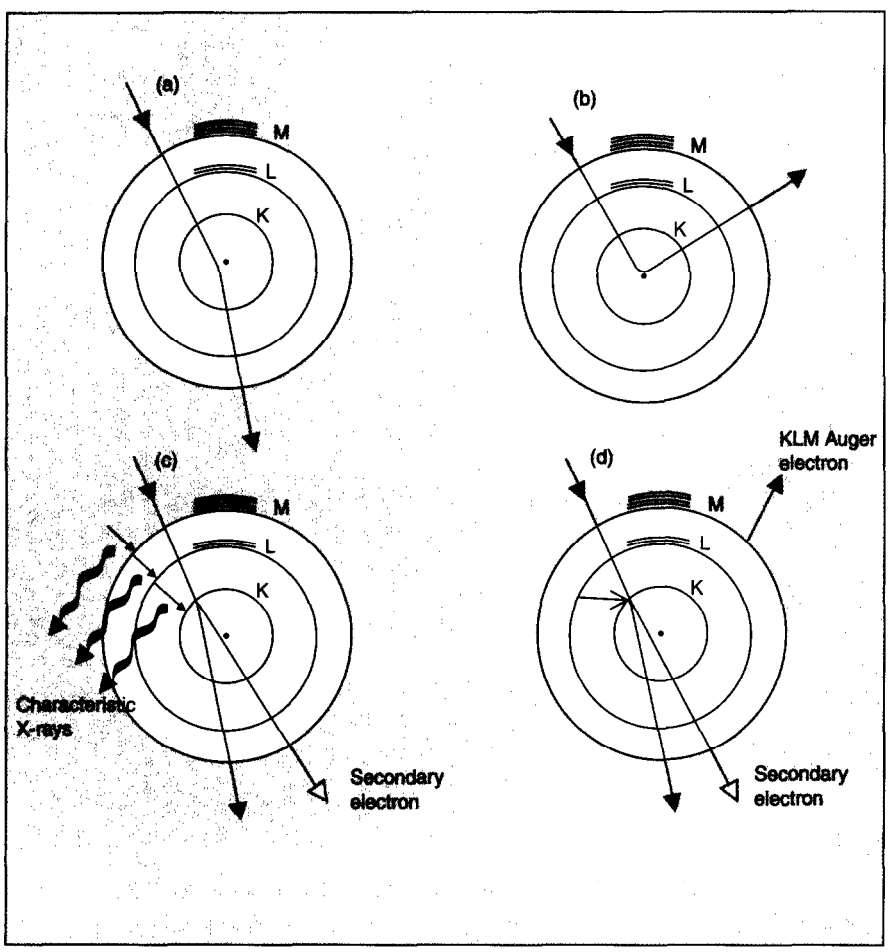

Figure 1. Some atom-high energy electron interactions. The inner electron shells of atoms are labelled according to standard notation (the innermost states are K, L etc). The incident particle is arrowed.
(a) Low-angle scattering - electrons scattered in this way pass to the next layer of atoms with very little loss of energy; (b) Back (or high-angle) scattering; (c) Emission of a secondary electron and characteristic x-rays; (d) Emission of a secondary electron and an Auger electron.

Why scanning electron miscroscopy?

SEM can provide information on surface topography, crystalline structure, chemical composition and electrical behaviour of the top 1 μm or so of specimen. Various specialised stages (e.g. hot, cold or designed to permit ***in situ*** mechanical testing) can be attached to enable behaviour under various conditions to be examined. For example, cathodoluminescence (emission of light) at temperatures near absolute zero is much stronger than at room temperature, so images formed from the light emitted by a cold specimen are much less noisy.

Further advantages of SEM over optical microscopy include:

- SEM benefits from a large depth of field so most of the specimen surface is simultaneously in focus whatever the surface roughness. Optical microscopes operating at high magnification have a very small depth of

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field so image quality is very dependent on the surface being smooth.

• Much higher magnifications can be achieved (up to 1,000,000x), with an ultimate resolution of 1 nm. The maximum useful magnification in an optical microscope is around 1000x.

• The possibility of getting more information than just the surface topography, e.g. crystal structure, chemical composition and electrical properties. Switching between different imaging techniques enables information to be cross-correlated with confidence.

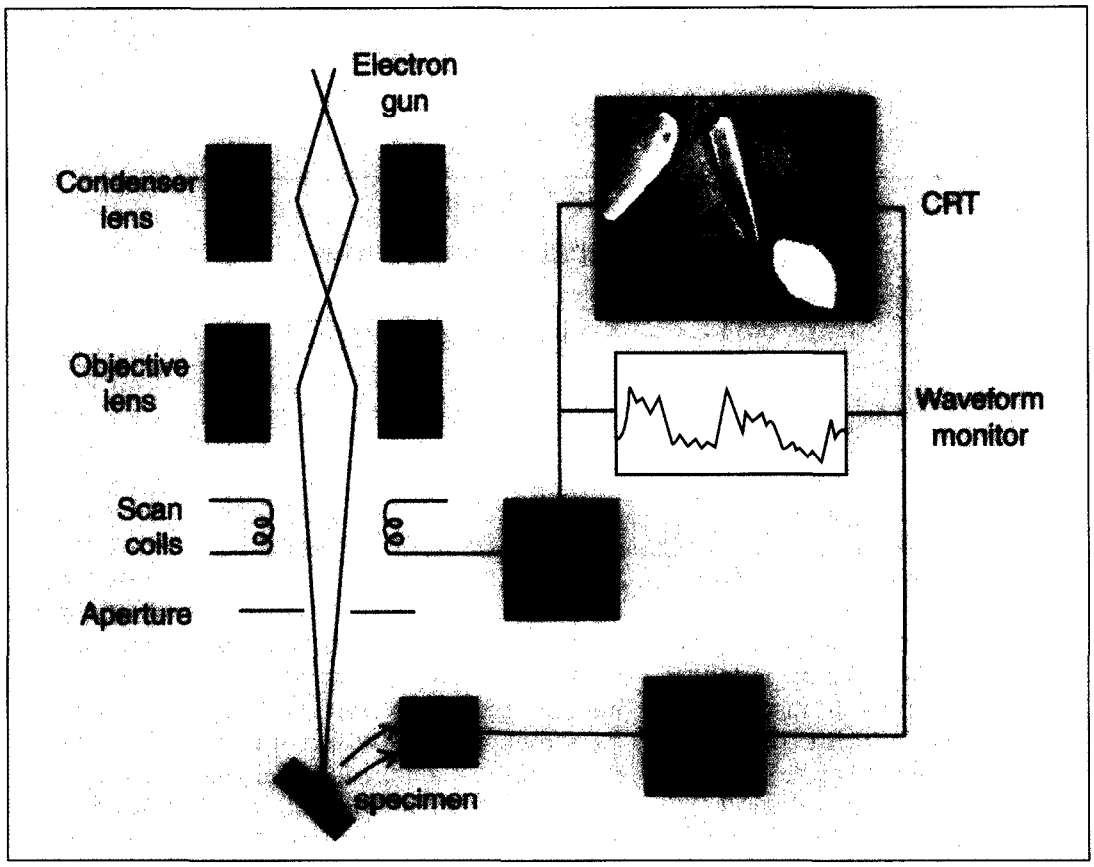

Figure 2. Schematic diagram showing the main components of a scanning electron microscope. After P J Goodhew and F J Humphreys

Advantages of SEM over TEM include:

• Large specimens (200 mm diameter wafers, or even larger in specially adapted SEMs), compared to just 2.3 mm or 3 mm in diameter for TEM.

• SEM permits non-destructive evaluation of the specimen (TEM is effectively a destructive technique because of the specimen preparation required).

• Very short specimen preparation time (maybe only a few seconds) while the specimen is attached to a "stub" (specimen holder). TEM specimen preparation is more complex and time-consuming.

Basic SEM optics and operation

In an SEM the incident electrons (from an electron gun) typically have energies of 2-40 keV. There are three types of electron gun in general use:

• The most common is the tungsten hairpin filament which is heated (by passing a current through it) to over 2500°C to produce thermal emission of electrons from its tip.

• Lanthanum hexaboride (LaB_6) filaments also work by thermionic emission, but advantages include a larger maximum beam current, i.e. a "brighter" beam (because LaB_6 has a lower work function than tungsten) and a longer working lifetime. However, these filaments are more expensive.

• Field emission guns (not heated, so also known as "cold cathode" emitters) provide the brightest beam with very small deviations in electron energy by applying a very high electric field to a finely pointed tip until quantum mechanical tunnelling of electrons occurs. Whereas thermionic guns need a vacuum near the gun of only 10^{-6} Torr, field emission guns need better than 10^{-10} Torr to preserve the tip, increasing the cost of FEG microscopes.

Two or three electromagnetic condenser lenses demagnify the electron beam into a fine probe which is scanned across a selected area of the specimen surface in a raster by scan coils. The electrons penetrate the specimen in a teardrop-shaped volume whose overall dimensions are determined by the energy of the electron beam, the atomic masses of elements in the specimen and the angle at which the electron beam hits the specimen. The "penetration depth" increases with higher electron-beam energy, incidence angle, and lighter atomic mass, e.g. 1μm into GaAs for 20 keV electrons and normal incidence.

The interaction of the electron beam with the specimen produces secondary, backscattered and Auger electrons, x-rays and perhaps light (see Figure 1), collected by various detectors in

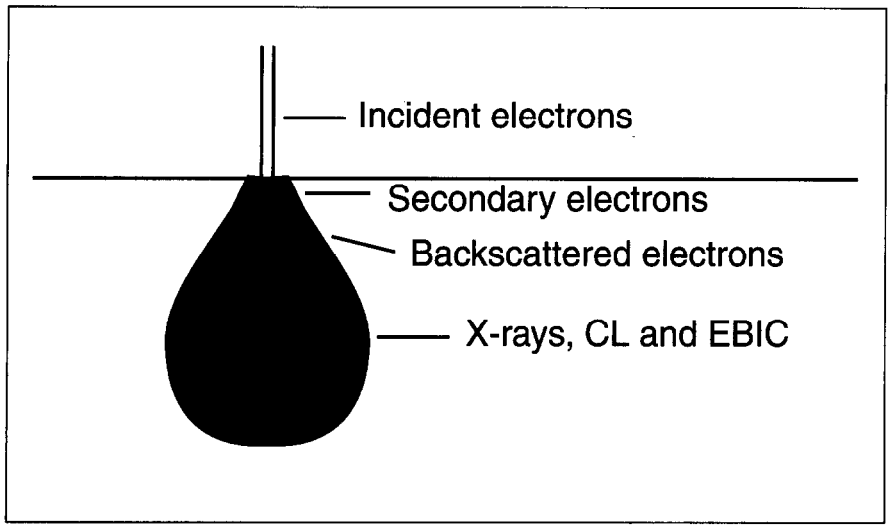

Figure 3. The specimen-beam interaction volume and the regions from which backscattered electrons and x-rays may be emitted.

the specimen chamber. The signal from each detector can be fed to a monitor, which is rastered in synchronisation with the electron beam (see Figure 2). The magnification of the image is determined by the ratio of the side length of the monitor display to the side length of the raster on the specimen. The best resolution for secondary electron images achieved in FEG SEMs is about 1 nm, but is typically only 5 nm or so for LaB_6 and W filaments.

Specimen preparation

For semiconductors, no special specimen preparation is required. The surface to be examined is mounted on a special SEM stub with electrically conducting pads. If the specimen is mounted on an insulator then to prevent the specimen from charging (which distorts the image) a conduction path to ground is required. If EBIC or voltage contrast is being used, then suitable electrical connections are also required.

Signals available in the SEM

Various signals from the specimen can be collected and used to form images. The interaction volumes from which the signals arise are shown in Figure 3. The following comments on imaging modes apply specifically to semiconductor materials.

1. Secondary Electron (SE) images

"Secondary electrons" are those that escape from the specimen with energies below 50 eV, mainly knocked out of their orbits around an atom by an incident electron (see Figure 1). These provide the highest spatial resolution images, as they can only escape from a very shallow, near-surface layer of material and the signal comes from an area about the size of the electron probe. Primarily, they give topographic information but, since a few back-scattered electrons are collected by the secondary electron detector, some compositional contrast is also present. Secondary electrons give rise to doping contrast by a mechanism akin to voltage contrast imaging (see below) - see Figure 4 for comparison with a backscattered electron image.

2. Backscattered Electron (BSE) images

Backscattered electrons are those incident electrons that approach the nucleus of an atom sufficiently closely to be scattered through a large angle and re-emerge from the surface. They are not as numerous as secondary electrons, but have much higher energies. Images have slightly less resolution than secondary electron images because they come from slightly deeper in the specimen, so the area giving rise to the signal is larger than the probe size. Mostly, they provide compositional information: elements of higher atomic mass give brighter contrast. Backscattered electrons can also provide crystallographic information, as electron channelling occurs (similar to ion channelling during ion implantation).

Electron backscattered diffraction pattern analysis has been used for strain measurements in semiconductors, and its use in studying

Figure 4. Identical-area SEM images of a GaAs/AlGaAs heterostructure imaged by (a) backscattered electrons at 30 kV (only the GaAs/$Al_{0.5}Ga_{0.5}As$ superlattice is visible) and (b) secondary electrons at 20 kV (both the superlattice and doped regions can be seen). From M R Castell, D D Perovic, A Howie, D A Ritchie, C Lavoie and T Tiedje, Inst. Phys. Conf. Ser. No. 146 pp 281-284 (1995)

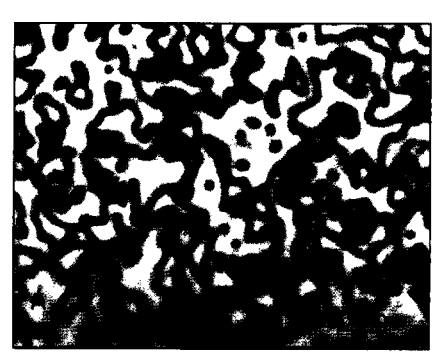

Figure 5. EBIC micrograph showing antiphase boundaries in a GaAs/Ge solar cell. Courtesy Professor D B Holt, Imperial College, London

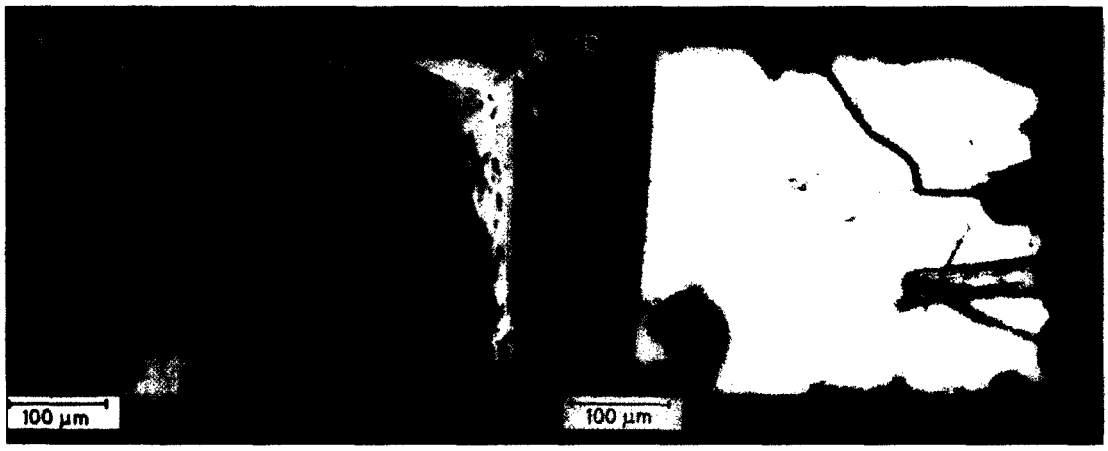

Figure 6. Micrographs of a GaAs/AlGaAs double heterostructure laser: (a) secondary electron image; (b) CL image using monochromatic λ = 790 nm light with the specimen cooled to 6.2K. Courtesy Professor D B Holt, Imperial College, London

the epitaxy of GaN on sapphire is being explored.

Electron channelling contrast is an alternative method for gaining crystallographic information that gives better angular resolution at the cost of decreased spatial resolution.

3. Electron beam induced current (EBIC)

Every incident electron generates hundreds of electron-hole pairs in the specimen. Normally, most recombine within about 10^{-12} s. However, if an electric field (e.g. from a p-n junction) separates the electrons and holes before they can recombine, an induced current flow between the electrodes will occur, forming an EBIC image. A related technique, EBIV, displays the spatial variation of the induced voltage.

The current flowing from (or voltage across) each point will depend on the conductivity of the specimen at that point, the lifetime of the electrons and holes, and their mobilities. This technique can be used for mapping varying concentrations of electrically active defects, and determining failure points in devices. Figure 5 shows anti-phase domain boundaries in GaAs/Ge solar cells imaged by EBIC.

4. Cathodoluminescence (CL)

When the electron-hole pairs generated by the incident electron beam recombine they may emit light. The wavelength depends on the bandgap energy of the specimen and, therefore, on the composition. The signal may be passed through a spectrometer before being measured by a suitable detector. This technique is excellent for revealing defects that degrade radiative properties. Cathodoluminescence signals come from the entire specimen-beam interaction volume, so have a resolution of about 1 µm.

Figure 6 compares (a) the secondary electron image and (b) a CL micrograph (taken using emitted light of 790 nm wavelength with the specimen cooled to 6.2K) of a GaAs/AlGaAs double heterostructure laser.

5. Voltage-contrast imaging

When a voltage is applied across a semiconductor in the SEM, the secondary electron image will be different from that with no voltage: the potential developed across the active regions changes the number of secondary (low energy) electrons emitted from those areas. More electrons can escape from active regions where a negative voltage develops, so these appear brighter regions where a positive voltage develops.

This is another technique that is useful in failure analysis. Figure 7 shows an LS 138 multiplexer chip: (a) is the secondary electron image without an external electrical connection to the chip; (b) when a voltage is applied. The circuit pathways display different intensity levels, related to the applied voltage across each region of the device.

Figure 7. Secondary electron micrographs of a LS 138 multiplexer chip: (a) without a voltage; (b) an operating voltage applied, showing the effects of voltage contrast. From R S Cornell, JEOL Inc.

6. Auger electrons and x-rays

Auger electrons are emitted from atomic layers very close to the surface and give valuable information about the surface chemistry. Because of the low numbers of Auger electrons and the need to measure their energies

with precision, Auger electron imaging is usually performed in dedicated instruments and requires advanced detectors and instrumentation.

Characteristic x-rays are generated by atoms when the incident high-energy particle knocks out an inner-shell electron and an outer-shell electron moves into the empty orbit (see Figure 1(c)). There is now a progression of electron jumps from higher to lower energy states (e.g. from L to K, then M to L etc) until all the electron states are refilled. At each stage, x-rays are emitted to conserve energy.

Measurement of the energies (or wavelengths) of these x-rays gives information about the chemical composition of the specimen. Characteristic x-rays are emitted from the entire specimen-beam interaction volume, so resolution is no better than 1 μm or so. The x-rays are detected by either an energy-dispersive or a wavelength-dispersive spectrometer. Energy dispersive x-ray spectroscopy (EDS or EDX) is the more common attachment to SEMs as it provides rapid qualitative analysis of the specimen. Semi-quantitative analysis can be obtained with care, but accurate microanalysis requires a wavelength-dispersive spectrometer and use of standards to allow for x-ray absorption in the specimen and fluorescence (the excitation of lower-energy x-rays by higher-energy ones). An "Electron Microprobe" is a scanning electron microscope fitted with wavelength-dispersive x-ray spectrometers and analysis software and is dedicated to this type of chemical analysis.

Summary

Scanning electron microscopy can provide a variety of imaging techniques with resolutions in the range 1 μm to 1 nm, depending on the microscope and the signal used to form the image. Information about electrically active defects can be obtained using techniques such as EBIC and CL, and these data can be correlated with the microstructure obtained in secondary electron images.

Further reading

"Electron Microscopy and Analysis" by P J Goodhew and F J Humphreys

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