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ELECTRON DETECTORS USED FOR IMAGING IN THE SCANNING ELECTRON MICROSCOPE

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Abstract

Electron detectors used for imaging in the scanning electron microscope include those which detect secondary electrons, various portions of the backscattered electron signal, and the residual specimen current. The use of a different detector will often produce a different image of the same specimen. The information contained in these images depends upon the signal detected and the properties of the detector used. The choice of detector to be used depends upon the information desired.

KEY WORDS: Electron signals, secondary electron detectors, backscattered electron detectors, topography contrast, atomic number contrast, imaging.

Introduction

The image obtained from a scanning electron microscope (SEM) is not just a magnified presentation of the specimen being studied. Like all images, it is a transformed representation of the specimen. For example, at a magnification of x100, the optical microscope (OM) and SEM images of the same object may look very different. Both images are magnified representations of the specimen. Both are correct presentations and yet they may be very different. Such images are transformed representations of the specimen, where the transformation process is a function of the physics of the imaging technique.

In the SEM, this transform function depends upon the electron beam conditions, the scan circuitry, the specimen itself, the signal detected, the properties of the detector employed, signal processing and the linearity of the imaging system. For example, different accelerating voltages will produce different images of the same specimen. Essential to the production of the SEM image is the detector used to produce the image. Its properties, plus those of the signal detected, greatly influence the type of information that can be gained from the SEM image.

This paper discusses the electron detectors that are used, for imaging purposes, in SEMs. These are the secondary electron (SE) detectors, the backscattered electron (BSE) detectors, the low loss backscattered electron (LLBSE) detector and the specimen current (SC) detector. The information presented relates to the properties of the detectors as seen by the user, not just the properties of these detectors. This has been done to enable users to better understand the consequences of changing SEM operating parameters, when different detectors are employed.

The Electron Signals

Figure 1 illustrates the electron beam-specimen interaction, showing the various signals that are generated. Electrons from the beam enter the specimen, are scattered approximately as indicated and, within this scattering volume,

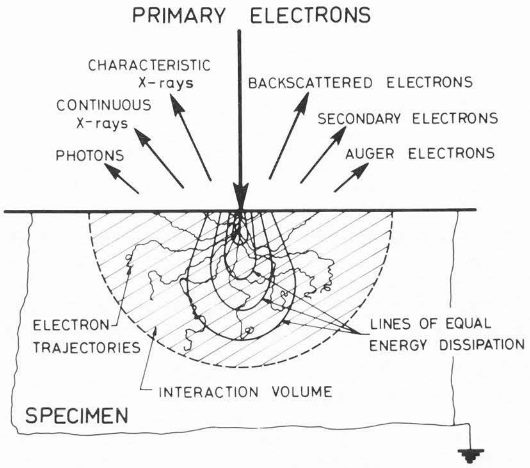


Figure 1. Schematic illustration of the electron-specimen interaction which gives rise to the signals detectable in SEM.

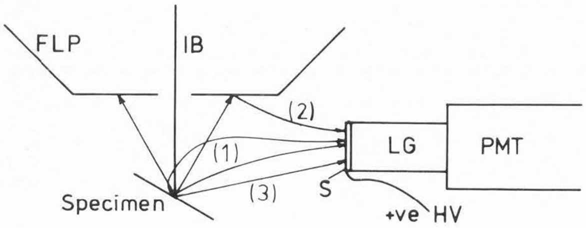


Figure 3. Schematic illustration of the construction of, and the electron contributions to, the signal output from an Everhart-Thornley detector.

they generate their signals. The signals of interest in this paper are only the backscattered electron (BSE), secondary electron (SE) and the specimen current (SC) signals.

Figure 2 shows the complete electron emission spectrum of all electrons emitted from a sample struck by high energy, say 20 keV, electrons vertically incident upon the various flat surfaces, as indicated. Figure 2a shows the complete spectrum. Figure 2b shows the detail at the low energy end of the spectrum, that is secondary electron emission. Figure 2c shows details at the high energy end, that is the elastically scattered end of the spectrum. Note that the vertical and horizontal scales are different in the separate figures. Although the height of the BSE peak is much lower than either the SE or elastically scattered BSE peaks, its much greater width makes it the largest signal emanating from the specimen (Robinson, 1973).

The three categories of electron detectors to be mentioned, each make use of one of these three signals, shown in Figure 2, namely SE detectors, Figure 2b, BSE detectors, Figure 2a and LLBSE detector, Figure 2c.

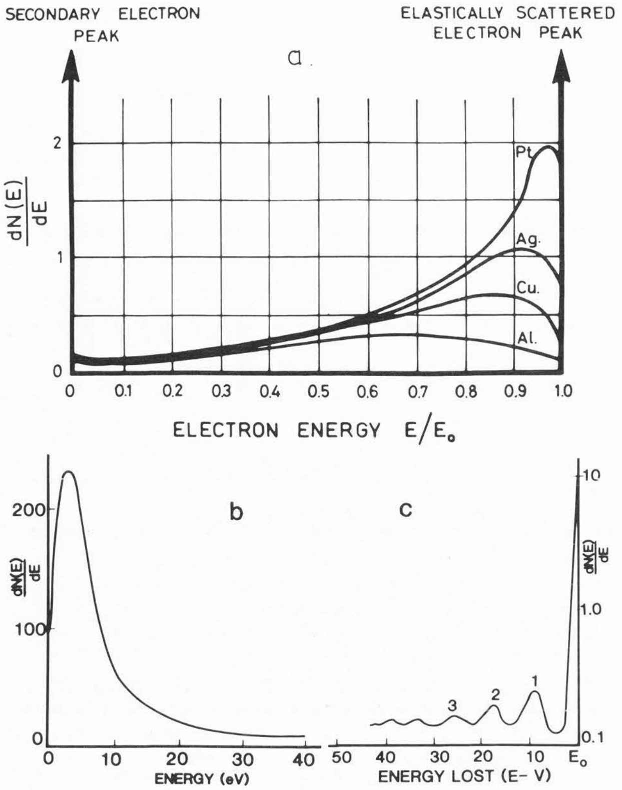


Figure 2. Electron energy emission spectra for an electron beam of energy E (> 5 keV) vertically incident upon a flat surface. (a) Total emission spectrum (after Kulenkampf and Spyra, 1954); (b) details at the low energy end of the spectrum (secondary electron emission after Kollath, 1947); (c) details at the high energy end (elastic scattering and plasmon loss, schematic).

Secondary Electron Detection

The most common form of secondary electron detector employed in SEMs is that due to Everhart and Thornley (1960). Its essential features are displayed in Figure 3. These consist of a scintillation surface (S), connected via a light guide (LG) to a photomultiplier tube (PMT). A positive high voltage (HV), usually of about +10 kV is applied to the scintillation surface and some form of electrostatic shielding is employed to ensure that the secondary electrons from the specimen impinge upon the scintillator surface, and not just the conductor supplying the positive high voltage. There are several variations of this shielding, involving the presence or absence of a positive low voltage, approximately +250V, grid between the scintillator and the specimen. Provided that the grid works properly, there is no noticeable performance difference between these different types of electrostatic attraction-shielding combinations.

These detectors work by providing an

electrostatic field strength of approximately +50 to +100V/cm at the surface of the specimen. This is sufficient to attract the SEs, typical energy +2V to +5V, towards the detector, without greatly influencing the primary beam. As they travel towards the scintillator, they are accelerated into it where they impinge with a high energy. They generate a number of photons, which are channelled through a light guide to the photomultiplier tube. Here they are converted to electrons and amplified. This complexity is used because it still gives the most noise free signal. This principle also ensures that every SE detected, gives the same signal output from an Everhart-Thornley (E-T) detector. As such the signal output of the detector, as seen by the operator, will depend very much upon the number of emitted secondary electrons.

Figure 3 also illustrates the method by which electrons contribute to the signal from the E-T detector. These are the signals from:-

(1) SEs released from the specimen as it is struck by the incident beam (Type I and Type II SEs)

(2) SEs released as BSEs strike the polepiece (Type III SEs).

(3) BSEs impinging directly upon the surface of the E-T detector.

Type III SEs account for approximately 15% to 20% of the E-T detector signal output (Moll et al., 1978, 1979), whilst the direct impingement of BEs into the E-T detector can contribute up to 2 - 5% of the total signal output. Of the SEs released from the specimen, approximately 80% are type II, i.e. those released as the scattered primary electrons pass out of the specimen surface (Robinson, 1974a; Wooldridge, 1939). It is easy to see from this that the signal output by the Everhart-Thornley detector contains a great deal of BSE information, as well as SE information. Figure 4 is a brief summary of properties of secondary electrons. Figure 4a shows variation of the secondary electron yield (δ) with atomic number (Z). Figure 4b shows the variation of the SE yield δ with accelerating voltage (kV). Figure 4c shows the variation of SE yield δ with sample tilt.

The uniformity of response of the E-T detector to each low energy electron, means that, to the user, the detector response with variations of atomic number, accelerating voltage and sample tilt are approximately the same as the variation in SE yield. That is, to increase secondary electron yield, use a higher atomic number sample, a lower accelerating voltage or a higher specimen tilt. Many SEM users will recognise the concept of gold or gold-palladium coating and operating with a 30 or 45 degree tilted specimen,to get a higher signal to noise ratio image. The additional contributions due to backscattered electrons are only such as to vary the absolute magnitude of the response of the detector away from the signal curves. They do not vary the intent or direction of any of these curves. As such, the variation in the signal output of an E-T detector with atomic number, accelerating voltage or specimen tilt will be similar to the SE yield curves shown in Figure 4.

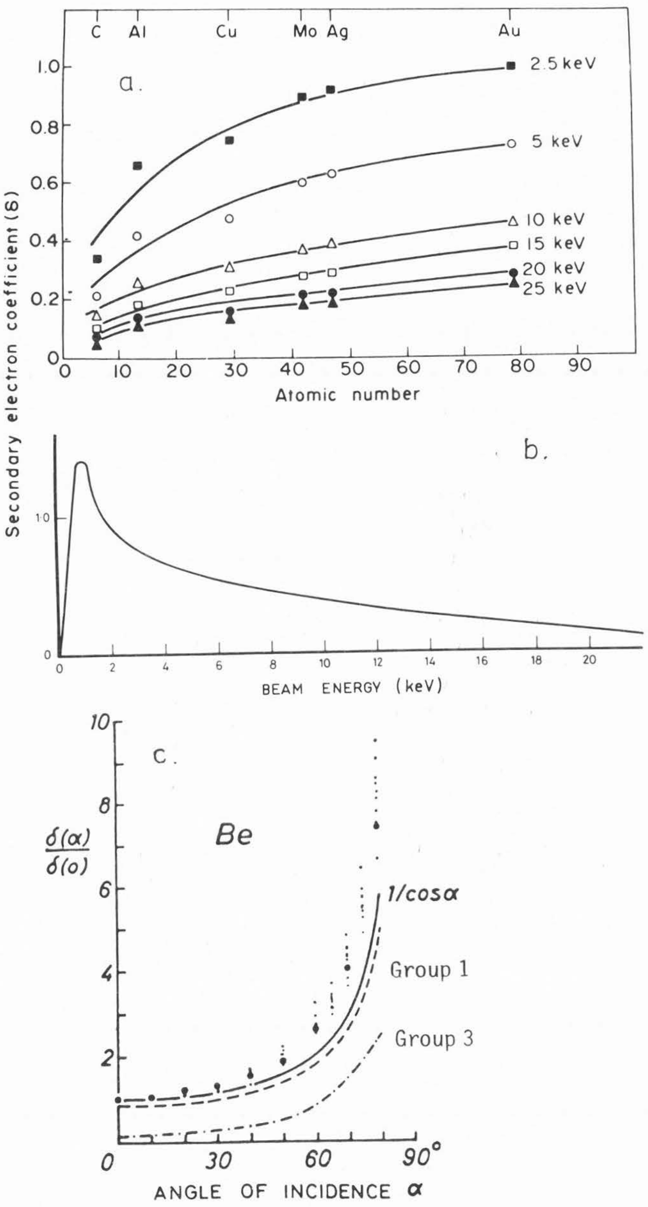
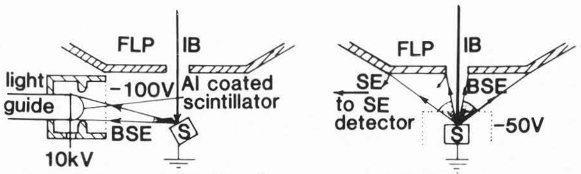


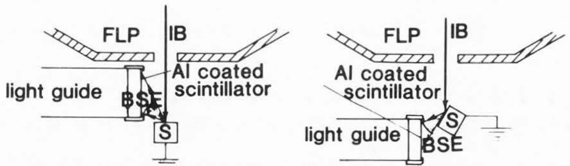
Figure 4. Variations of the secondary electron yield with (a) atomic number, (Moncrieff and Barker, 1978); (b) accelerating voltage (schematic); and (c) specimen tilt (after Drescher et al, 1970).

Another effect which has not been well studied, which makes quantitative results with E-T detectors difficult, is that due to the electrostatic attraction of secondary electrons reducing with increasing distance from the detector. This effect is easily seen on micrographs taken on flat, untilted surfaces at low magnification. It becomes more apparent when a side positioned E-T detector is used at short working distances.



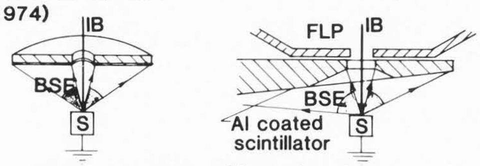
converted Everhart-Thornley (1960) detector

converted BSE detector after Moll et al. (1978)



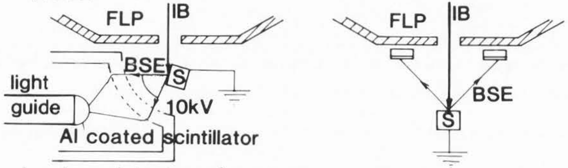
high take off angle detector after Wells (1970): Schur et al. (1974)

low take off angle detector after Wells (1970)



annular solid state detector after Wolf and Everhart (1969)

wide angle scintillator detector after Robinson (1974b)



low loss detector using energy filter after Wells (1971)

solid state pair detector after Kimoto and Hashimoto (1966)

Figure 5. Illustrations of the many different types of backscattered electron detectors. FLP = final lens pole-piece, IB = incident beam, S = specimen.

As the distance from the detector to the region of the sample where the secondary electrons are being emitted, is increased, the signal received diminishes. This effect can be quite large, encompassing some 10% to 20% change at low magnifications, i.e., the variation can be as much as 1% or 2% of the SE signal per mm. It can often be seen on micrographs taken of flat polished surface untilted at low magnification. Similarly, as the working distance is reduced, the secondary electron signal decreases. This is probably due to a drop off in the electrostatic potential at the surface of the specimen. These effects almost disappear when SEs are detected through the lens.

Until such time as there is a full investigation of these properties of the Everhart-Thornley detector, the obtaining of quantitative results using this detector will be difficult. It becomes even more difficult when additional effects are introduced, e.g. those due to charging artifacts, and edge brightness, i.e., strong SE emission from very small particles or from very close to the edge of heavily sloping surfaces. All of these effects have yet to be properly understood before quantitative results can be achieved, using the E-T secondary electron detector, over a wide range of surfaces.

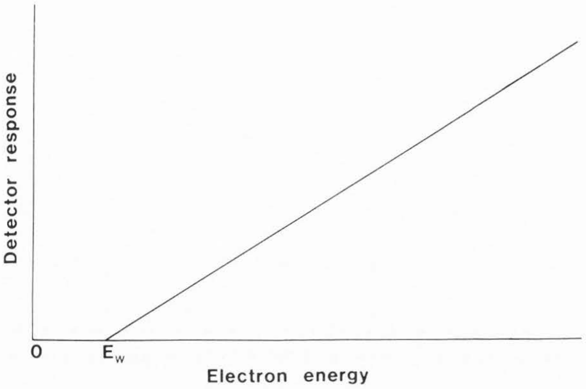


Figure 6. Variation of BSE detector response with energy of an incident electron.

Backscattered Electron Detectors

The second group of electrons that is widely used for imaging purposes in the SEM, is the backscattered electrons (BSEs), as shown in Figure 2a. These are the electrons that have suffered considerable energy loss, from a few eV to a few thousand eV. This group of electrons does not have a very high intensity at a given energy, compared to either the secondary electrons, or the elastically scattered electrons. However, it is extremely wide, spreading over greater than 99% of the energy of the electron beam, for beam energies greater than 10kV (Robinson, 1973). Its width makes it the most abundant type of electrons emitted from a specimen when struck by an electron beam, and it has by far the largest amount of energy associated with any electron emission group.

Over the years many fundamentally different types of backscattered electron detectors have been constructed to detect these electrons. Some have been based on the Everhart-Thornley detector, such as the unbiased detector, and the converted BSE detector due to Moll et al., (1978), Reimer and Volbert (1979). These are illustrated in Figure 5. Another group of detectors which has been employed is those which are specifically designed to detect only a certain fraction of the emitted BSE electrons. These include the solid state pair detector, after Kimoto and Hashimoto (1966), the high take-off angle detector, after Schur et al., (1974) and Wells (1970), the low take-off angle detector after Wells (1970), as well as some detectors made by SEM manufacturers specifically for their SEM. Several variations of these have been made, usually by extending the light guide of an E-T detector and placing an unbiased scintillator on the end of it (Zeldes and Tassa, 1979, Fitch et al., 1984).

The third type of detector is the non-directional BSE detector, that is the wide angle detector which is designed to detect as many BSEs as possible. The two different types are the silicon solid state, either surface barrier or the shallow diffused p-n junction (Wolf and Everhart, 1969; Stephen et al, 1975) and the wide angle scintillator type (Robinson, 1974b) detector.

All of these different types of BSE detectors have been summarised by Robinson (1980) and are illustrated in Figure 5. With the exception of the converted BSE detector, (Moll et al, 1978; Reimer and Volbert 1979), all other BSE detectors shown are passive detectors. That is, they rely entirely upon the energy of the BSEs themselves to give rise to the signal from the detector. They do not have an applied voltage as does the E-T detector. This means that, unlike the E-T detector, most BSE detectors give a different signal output response for electrons of different energies, as illustrated in Figure 6 (Robinson, 1975; Baumann and Reimer, 1981).

Another type of electron detector which is finding increasing use is the channel plate detector (Griffiths et al., 1972). It is useful for detecting both SEs and BSEs. The channel plate detector is not as sensitive to SEs as is the E-T detector, nor to high energy BSEs as are some scintillator type BSE detectors. However, it is a detector which is sensitive to low energy, less than 5 kV, BSEs. These detectors have been discussed by Russell (1984). They are of interest for the study of integrated circuits at low accelerating voltages. Figure 7 shows the variation in the backscattered electron yield (η) with changes in SEM parameters. Figure 7a shows the variation of η with atomic number (Z). Figure 7b shows the variation of η with accelerating voltage. Figure 7c shows the variation with specimen tilt. The response of a BSE detector is a combination of that fraction of the signal emitted, (see Figure 2a) that is detected by the detector, in conjunction with the response of the detector to the energy of the electrons, as shown in Figure 6, plus the properties of the backscattered electrons themselves as shown in Figure 7, plus variations in the shape of the curves shown in Figure 2a with variations of tilt. All in all a complex situation. However, all of these properties are either known or can be easily determined and quantitative calculations with BSEs can be performed. One example of this is the new technique of composition analysis in which the signal output of a BSE detector is matched to the composition or chemical formula of a specimen (Robinson et al., 1984).

To the user, BSE detectors have the following properties:-

(i) Greater signal output with increasing atomic number.
(ii) Greater signal output with increasing accelerating voltage. At voltages above approximately 18kV to 20kV, a good high collection efficiency scintillator type BSE detector will have a higher signal to noise (S/N) ratio output than the E-T detector, for the beam vertically incident upon a flat surface (Robinson, 1975; Baumann and Reimer, 1981). Below 15kV accelerating voltage, the E-T detector has higher S/N

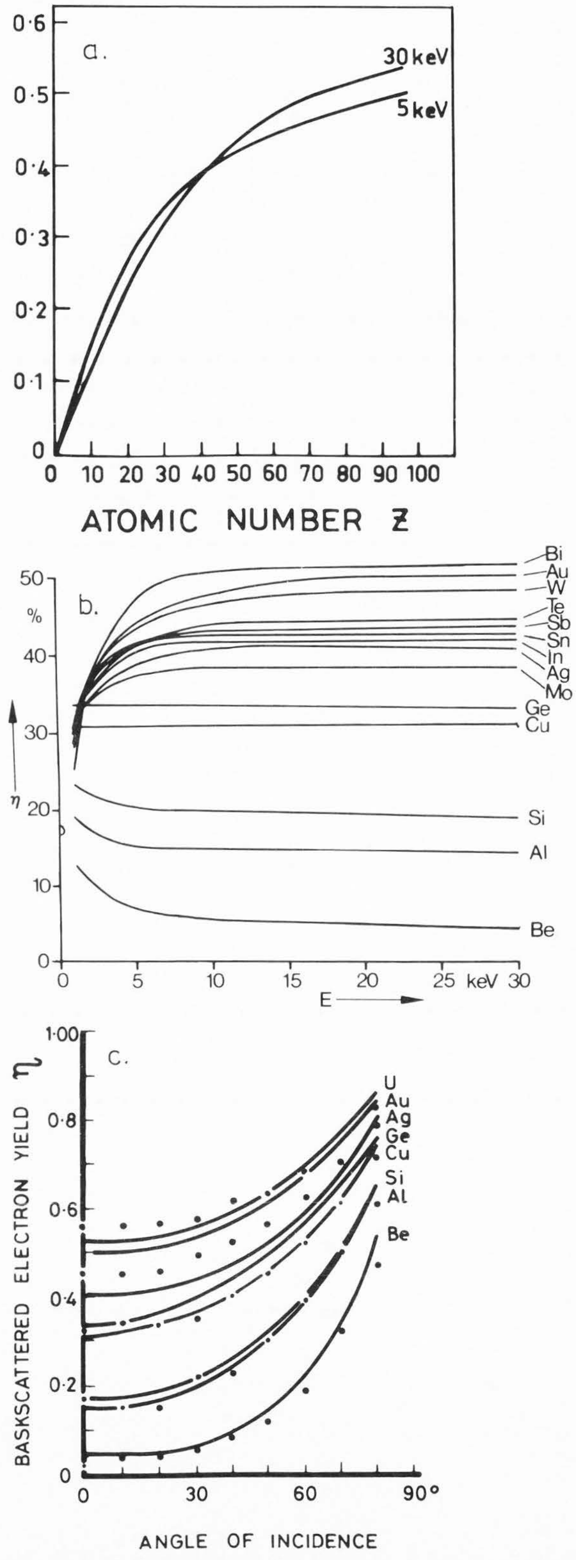


Figure 7. Variations of the backscattered electron yield with (a) atomic number (after Bishop, 1966, Colby, 1969); (b) accelerating voltage (after Reimer and Tolkamp, 1980) and; (c) sample tilt (after Drescher et al, 1970).

than a BSE detector. Below 10kV accelerating voltage, the performance of a scintillator type BSE detectors is seriously impaired. Below 5kV, it is essentially unworkable and at about 2kV it no longer functions. The relative merits of the different types of scintillator detectors have been summarised by Baumann and Reimer (1981). The solid state (silicon surface barrier or p-n junction) BSE detector show the same trends as the scintillator types but have a lower S/N ratio at the same operating conditions. The converted BSE detectors (Moll et al., 1978) have a high S/N at a low kV (Baumann and Reimer, 1981).

(iii) The variation of signal output with specimen tilt will depend upon the type of detector employed. Using a low take-off angle BSE detector and tilting the specimen towards the detector will increase the signal output. Tilting the specimen when a high take-off angle or wide angle detector is used will result in a decrease in signal output with increasing tilt because the BSEs are directed away from the detector.

Low Loss Backscattered Electron Detectors (LLBED)

These detectors are designed to detect the electrons shown in the spectrum in Figure 2c, i.e. the electrons which have gone into the sample and then scattered with little or no loss of energy. These electrons have undergone only one or two scattering events and have not penetrated very far into the surface. They constitute about 10^{-3}% of the emitted electron signal, making it a very weak signal. The only way which these electrons have been successfully detected has been by electrostatic suppression, i.e., allowing all of the electrons to enter an electrostatic field which is nearly as strong as the voltage of the incident beam (Wells 1971). The other electrons are then suppressed by the electrostatic filter and only those few electrons which have suffered little or no loss of energy are allowed through to a detector similar to the Everhart Thornley detector, as shown in figure 5. The work of Munro (1974) has shown that these electrons cannot be separated from the rest of the backscattered electrons, i.e. those which have lost a lot of energy, by the magnetic field of a pre or post specimen lens. These electrons are extremely sensitive to surface effects such as contamination and do not suffer from penetration effects as do the secondary electrons and other backscattered electrons. They do not show any subsurface features and are strictly surface imaging detectors (Wells, 1974). Despite these advantages, they have a low S/N ratio and are not widely used.

Specimen Current Imaging

The charge balance existing when incident beam electrons impinge upon a conducting specimen can be expressed mathematically by the equation:-

$$I_B = I_{SE} + I_{BSE} + I_{SC}$$

where I_B is the incident beam current, I_{SE} is the emitted secondary electron current, I_{BSE} is the emitted backscattered electron current and I_{SC} is the specimen current. Under most usual SEM operating conditions, accelerating voltage greater than 5 to 10 keV, $I_{SE} + I_{BSE} \neq I_B$ leaving a residual charge in the specimen. This can be conducted away to give a specimen current which has a reverse contrast to the SE + BSE contrast images, see for example Newbury (1977). This signal can be measured using a specimen current meter and amplified to form an image.

This mode of imaging can only be successfully employed with conducting specimens. It has the disadvantage of a low bandwidth. This is due to the inherently large capacitance of a specimen stub and holder. It requires long scan times for imaging purposes. It has been successfully used for channelling contrast studies (Coates, 1969) and the occasional atomic number and topography study. Specimen current imaging is not widely used.

Summary

Having described a number of different types of detectors and described their properties, as seen by the user, it is only fitting to describe the situations of what type of detector to use in particular applications. In commencing this, I should point out, that when you purchase a scanning electron microscope, the manufacturers have usually predetermined that you shall use an Everhart-Thornley detector for most situations. In the past few years, most manufacturers modified this a little by offering the option of one or two types of backscattered electron detectors as well. There are a number of laboratories where people have removed their Everhart-Thornley detector and do all imaging with a backscattered electron detector. When choosing a detector to use, there are two principal criteria to be invoked. (1) Available signal to noise; (2) the type of information you wish to detect. Baumann and Reimer (1981) have summarised the relative merits of the various scintillator type detectors used in scanning electron microscopes. For the sake of simplicity, I will categorise the types of information desired into three types; (1) atomic number contrast and topography contrast subdivided into (2) flat surface contrast and (3) edge contrast. Edge contrast is the type of contrast that you get when you have a surface such as pollen grains or micro-organisms which have a large number of very small, heavily curved surfaces.

For general topographic imaging purposes, the E-T detector is still the most widely used general purpose detector. It is so widely used, that there is a tendency to regard the SE image as the correct representation of the sample. Many users tend to forget that it is only one representation of the specimen. Figure 8 shows the wide angle BSE and SE images of an aluminium fracture surface, imaged simultaneously using a Robinson detector and an Everhart-Thornley detector respectively. These images have a very different appearance as each detector provides

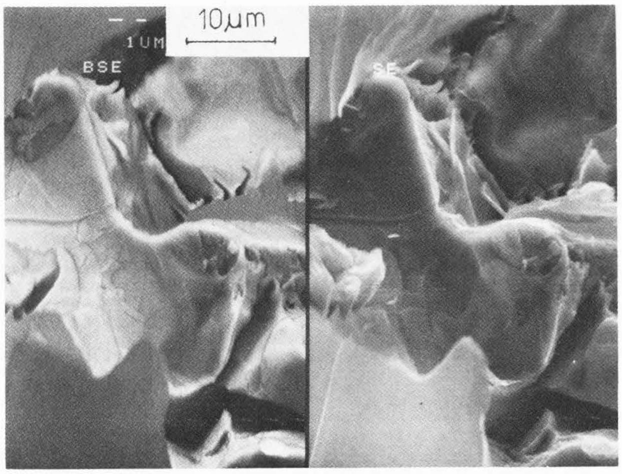


Figure 8. Wide angle BSE (Robinson) and SE (Everhart-Thornley) images of a fractured aluminium sample, 0 tilt, 25kV.

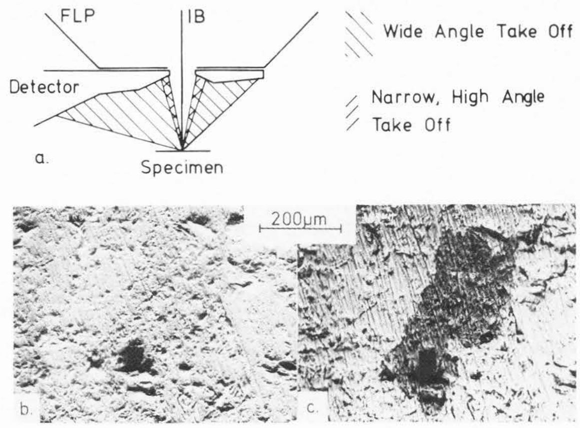


Figure 9. Schematic illustration of wide angle and narrow high take-off angle BSE detection (a) and micrographs of wide angle (b) and narrow, high, take-off (c) of a sample of a Cu, Fe and S containing ore, with a rough surface, 25kV, 0 tilt.

its own appropriate transformation to the image formation process. Both images are magnified transformations of the specimen. The SE image obtained with the E-T detector cannot be regarded as the sole accurate magnified representation of the specimen. A second transformation using a different detector to present a separate image is essential to avoid the situations where users consider properties of the transformation process as accurate representations of the specimen.

In many situations, the image obtained with the E-T detector will be an adequate representation of the specimen. This is particularly true of situations where the strong SE signal from edges is a desirable feature. This includes many high resolution topography imaging situations and studies of curved surfaces, such as cellular structures. In situations where the edge signal is too strong, a wide angle BSE detector placed above the specimen will not produce this strong edge signal and will produce images showing improved flat surface contrast. These detectors are also desirable when the E-T SE image displays charging artifacts.

The low take-off angle BSE detector with the specimen placed in the high field region of a condenser objective lens has shown itself to be useful for high resolution imaging of highly tilted specimens (Wells et al, 1973). Appropriately positioned and variable position high take-off angle BSE detectors have been successfully employed in studies of topography by providing the appropriate illumination conditions (Reimer et al, 1978; Schur et al, 1974).

If it is desired to observe atomic number contrast and the sample can withstand high voltages, > 15kV, then the best detector to use is a wide angle BSE detector. Wide angle BSE detectors give better S/N ratio images and will show smaller signal differences - smaller Z variations, than narrow angle detectors. The Everhart-Thornley detectors, detecting SEs, do not show as good a variation with Z as do BSE detectors. BSE detectors mounted to one side of the specimen do not show good signal variation with Z.

The one exception to this is if you have topography and atomic number contrast variations on the same sample and you wish to search for the smallest variation in atomic number that can be seen above the topography contrast. The best detector to use is a high take-off angle BSE detector which surrounds the beam and detects only those BSEs which have been scattered through close to 180 degrees, that is those electrons that have come down and been scattered back up towards the direction from which they just came. Electrons so scattered show very little response to changes in topography and as such the signal obtained from topography variations is quite small whilst the signal variations from variations in atomic number is still relatively large. This is illustrated in Fig. 9 which shows the wide angle BSE detector image and the narrow, high take-off angle BSE image of the same region of the same sample. Within these limitations, scintillator type BSE detectors tend to have a higher S/N ratio than the solid state type.

Electron channelling contrast has been best studied using either high take-off wide angle BSE detector or imaging in the specimen current mode. Crystallographic orientation effects have been best studied using a high take-off, narrow angle BSE detector. Magnetic and voltage contrast effects are beyond the scope of this paper.

Conclusions

Many different types of electron detectors are either available commercially or have been built for experimental purposes. The Everhart-Thornley detector is by far the most widely used detector for imaging purposes in the scanning electron microscope. There is a lot of additional information to be gained from using a second type of detector. Over the past few years, there has been an increase in the use of wide angle backscattered electron detectors, both the scintillator and solid state types.

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