Scanning Microscopy

Volume 2 | Number 2 Article 2

2-2-1988

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Scanning Microscopy, Vol. 2, No. 2, 1988 (Pages 633-638) 0891-7035/88$3.00+.00
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

SIGNAL MIXING TECHNIQUE FOR BACKSCATTERED ELECTRONS IN THE SCANNING ELECTRON MICROSCOPE

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(Received for publication August 12, 1987, and in revised form February 02, 1988)

Abstract

Signal mixing technique using asymetrically placed backscattered electron detectors in a scanning electron microscope is presented in this paper. Two types of detectors have been used: a low-take off angle ring scintillation detector (placed around the specimen) and a wide-angle semiconductor detector (placed above the specimen). It has been shown that the discussed configuration gives good "real" topography in all directions on the specimen surface and also reduces significantly the pseudo-topography effect of flat grain boundaries.

KEY WORDS: scanning electron microscopy, backscattered electrons, signal mixing, ring detector, semiconductor detector, topographic contrast, pseudo-topographic effect.

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Introduction

Imaging of "true" topography or "surface reconstruction" of a specimen is still a problem in SEM that has not been completely solved. It has been shown that backscattered electrons (BSE) are very useful for this purpose. Due to their high energy they have straight trajectories when travelling from a specimen toward a detector. That is why BSE micrographs, obtained when a detector collects only BSE emitted to one side of the specimen, have the more pronounced and sharper shadowing effects than secondary electrons (SE) micrographs. Moreover, the straight trajectories of BSE allow easier surface reconstruction. The disadvantages of using the SE signal for topography are: its sensitivity to surface states (contamination, corrosion, dirt, etc.) which requires the surface be very clean, its sensitivity to edges, incompletely understood relationship between brightness and tilt angle, effect of detector geometry and detector voltage, etc.

Micrographs taken either in SE or BSE mode contain information about both topography and composition of the specimen surface. But often it is desirable to obtain topography and morphology information separately. Topographic and atomic number contrast can be separated by changing the take off angle of the BSE detector, but the best results are obtained by either analog or digital signal mixing . The most popular and most often used SEM technique for separation of compositional and topographic contrast is that developed by Kimoto and Hashimoto (1966). This technique uses two detectors A and B symmetrically placed on opposite sides of electron beam (Fig 1a). Detectors A and B produce opposite surface tilt or shadow contrast. To increase topographic and decrease compositional contrast the A-B signal is taken. Kimoto and Hashimoto proposed this method for backscattered electrons and they used two semiannular semiconductor detectors placed below the polepiece. Volbert and Reimer (1980) applied this method for secondary electrons (SE) by using two oppositely mounted Everhart -Thornley detectors. The disadvantage of this method is that not only the compositional contrast is decreased. Features which produce similar signals in both detectors A and B (e.g., steps parallel to the line connecting the detectors) also disappear on the micrographs. Moreover, the method may introduce some artifacts such as pseudo-topographic contrast on flat multicomponent heterogeneous specimens, with grain sizes much larger then interaction volume of electron beam.

Signal difference can also be used to determine surface orientation or to reconstruct the surface profile along a line parallel to the line connecting the detectors (Reimer and Riepenhausen, 1985). Three dimensional reconstruction requires a four detector system placed above the specimen around electron beam (Carlsen, 1985; Lebiedzik and White,

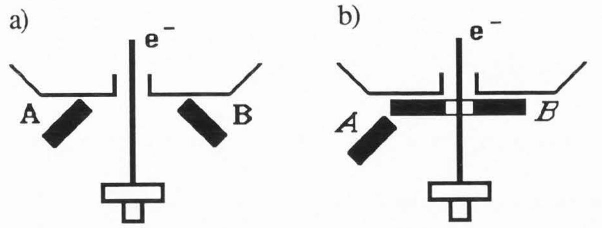

Fig. 1. Two main configurations of detectors (A and B) for signal mixing purposes, with (a) symmetric and (b) unsymmetrical arrangement.

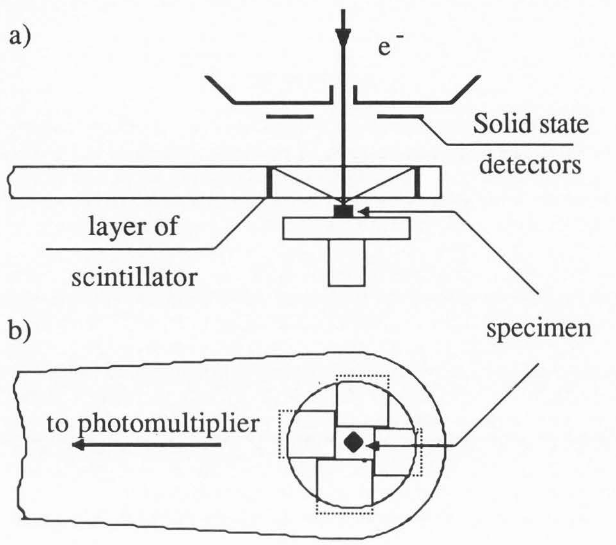

Fig. 2. Detection system of BSE consisting of the ring scintillation detector and wide-angle semiconductor detector. (a) - cross section, (b) - bottom view.

1975; Kuypers and Lichtenegger, 1980).

Another technique of signal mixing which avoids loss of information in one direction is the use of an asymmetrical detector arrangement. As mentioned previously, a detector placed at the side of the electron beam gives a good impression of surface topography. The signal from this detector also contains information about surface morphology, which can be subtracted. Resulting from the angular distribution of BSE, a large solid angle detector placed above the specimen gives almost pure compositional contrast. If this signal is subtracted from the signal of the detector placed to one side of the beam (Fig. 1), the difference will give only information about topography. The signal difference can be in the forms: SE-k·BSE or BSE-k·BSE, corresponding to either a SE or a BSE detector placed to the side, respectively. The first way of signal mixing was done by Volbert (1982) who used the signals of a multifunction detector for SE. BSE signal mixing was proposed by Hejna et al. (1985) who used the signals of a semiconductor detector and a BSE to SE converter. In this paper a modification of the latter system is proposed. The BSE to SE converter has been replaced by a ring scintillation detector for BSE's (Hejna 1987), avoiding some of the disadvantages of the BSE to SE converter. The converter has the same sensitivity for BSE's of different energies. Low energy BSE's, which penetrated large distances in the specimen, contribute to the signal and degrade the image resolution. The converter is also sensitive to specimen charging when the built-in voltage exceeds the bias voltage of the mesh or ring placed over the specimen. The ring detector does not have these disadvantages, and enables one to obtain images with better resolution, free of charging effects.

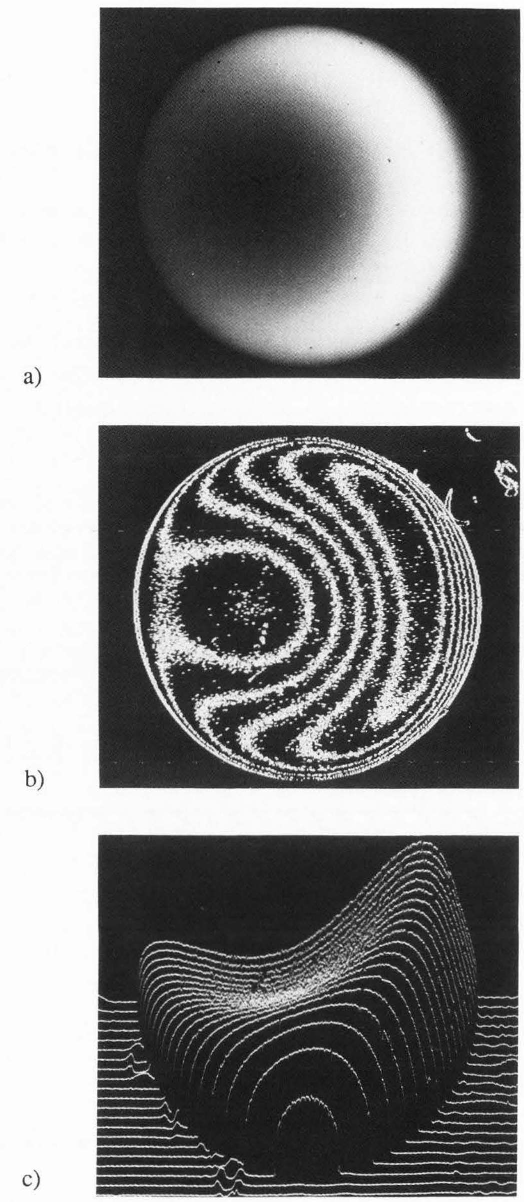

Fig. 3. BSE images of a 0.9 mm steel ball taken with ring scintillation detector (a); (b) isodensities, (c) Y modulation of a lower half of the ball. Eo = 20 keV, WD = 15 mm.

Detection System

A system with an asymmetrical arrangement of BSE detectors is shown in Fig. 2. It contains a ring detector, with 25 mm diameter hole, surrounding the specimen with a semiconductor detector placed over it. The inner surface of the hole is painted with a solution of scintillation plastic in toluene. The detector replaces the standard photomultiplier of

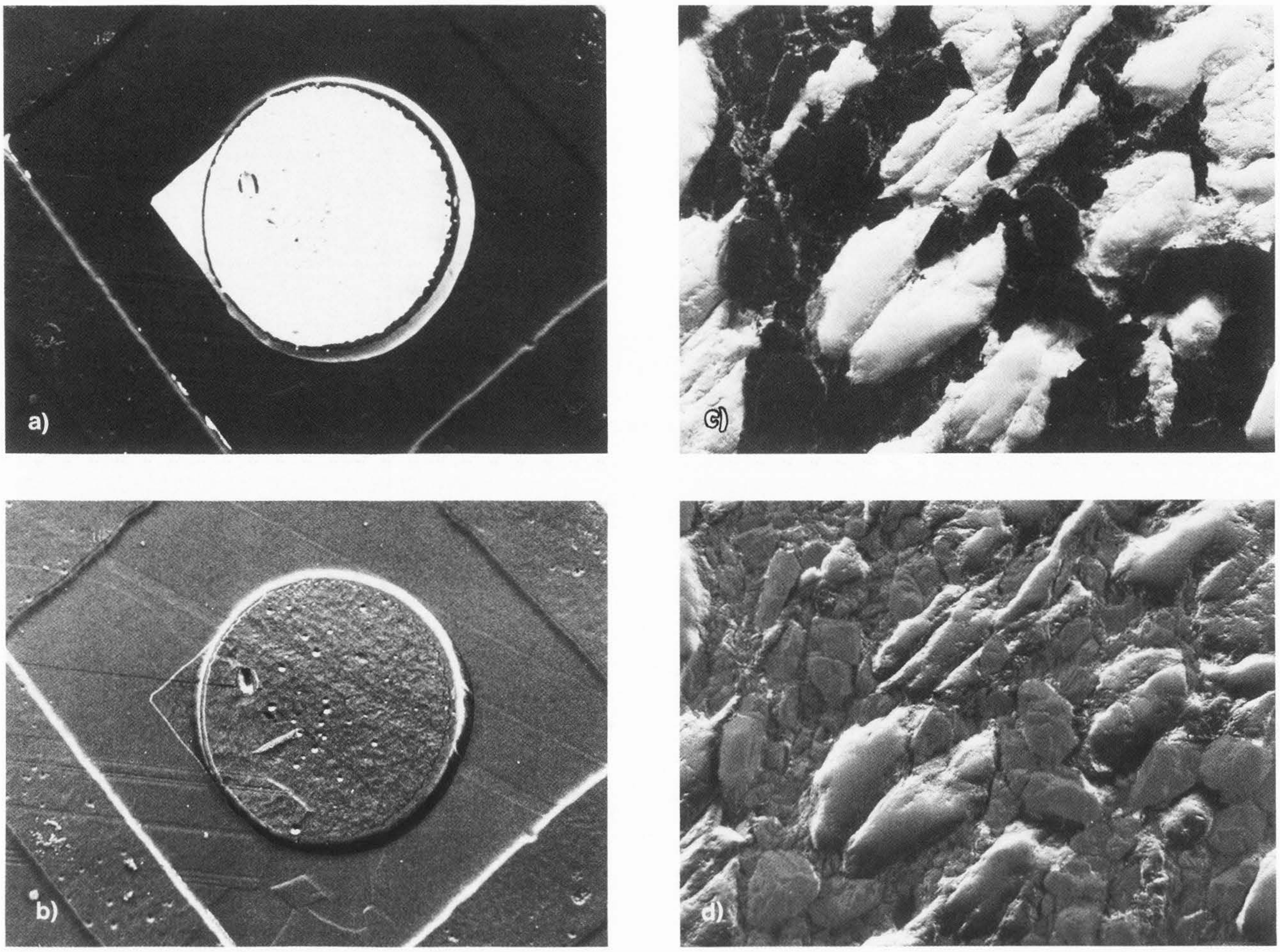

Fig. 4. Micrographs taken with detector system shown in Fig. 2. (a) and (b) - surface of silicon diode structure, (c) and (d) - tungsten-diamond composite, (a) and (c) images obtained with the ring detector, (b) and (d) images obtained with the difference signal of the ring detector and the wide-angle semiconductor detector. Primary beam energy 20 keV. Horizontal field view = 0.2 mm.

an Everhart-Thornley detector. The ring detector works like a detector placed at the side of the electron beam, because the highest contribution to the signal originates in that part of the hole nearest to the photomultiplier. This affect is shown in Fig. 3 by the isodensities and Y modulation image of a steel ball. The semiconductor detector consists of four silicon diodes, 10x10 mm^2 each. The diodes with contact metal ring around the uncoated active area have a 3 keV threshold energy and a gain of about 5000 for 20 keV electrons. The semiconductor detector with its large solid acceptance angle placed above the specimen gives mostly compositional information. After amplification the signals from the ring and semiconductor detectors are fed to a mixing unit, where the material contribution in the signal of the ring detector is compensated.

The detection system was mounted in a Cambridge Stereoscan 180 SEM, in which a thermionic tungsten cathode was use as an electron source.

Examples of Application

When studying surface topography, images which provide a good three dimensional impression and which reveal fine structures on a nearly flat surface are required. As discussed earlier, the ring detector fits these requirements. Examples of micrographs obtained with the ring detector are shown by Figs. 4a and 4c. One specimen is a semiconductor diode structure fabricated in polycrystalline silicon with a gold coated contact area, and the second specimen is tungsten-diamond composite. The ring detector gives both topographic and compositional information, but by mixing its signal with the signal from a wide angle semiconductor detector the compositional information has been subtracted in images 4b and 4d, and only topographic contrast remains. These images show that the proposed method of signal mixing is suitable for studying nearly flat surfaces because of the good sensitivity of the ring detector to small differences in inclination of a surface (see structure of polycrystalline silicone), and for studying rough surfaces where images with good three-dimensional impressions are required.

One of the problems of signal mixing techniques based on subtraction of BSE signals is a pseudo-topographic effect on flat multicomponent specimens caused by anisotropic electron scattering at material boundaries. Due to this effect, steps on flat surfaces may appear which may not represent the real topographic features on the surface. Monte-Carlo studies (Reimer, 1985) show that this effect decreases with decreasing primary beam energy. We studied this effect using a polished sample consisting of ZrO_2 inclusions in a glass and corundum matrix with two detector systems, one described

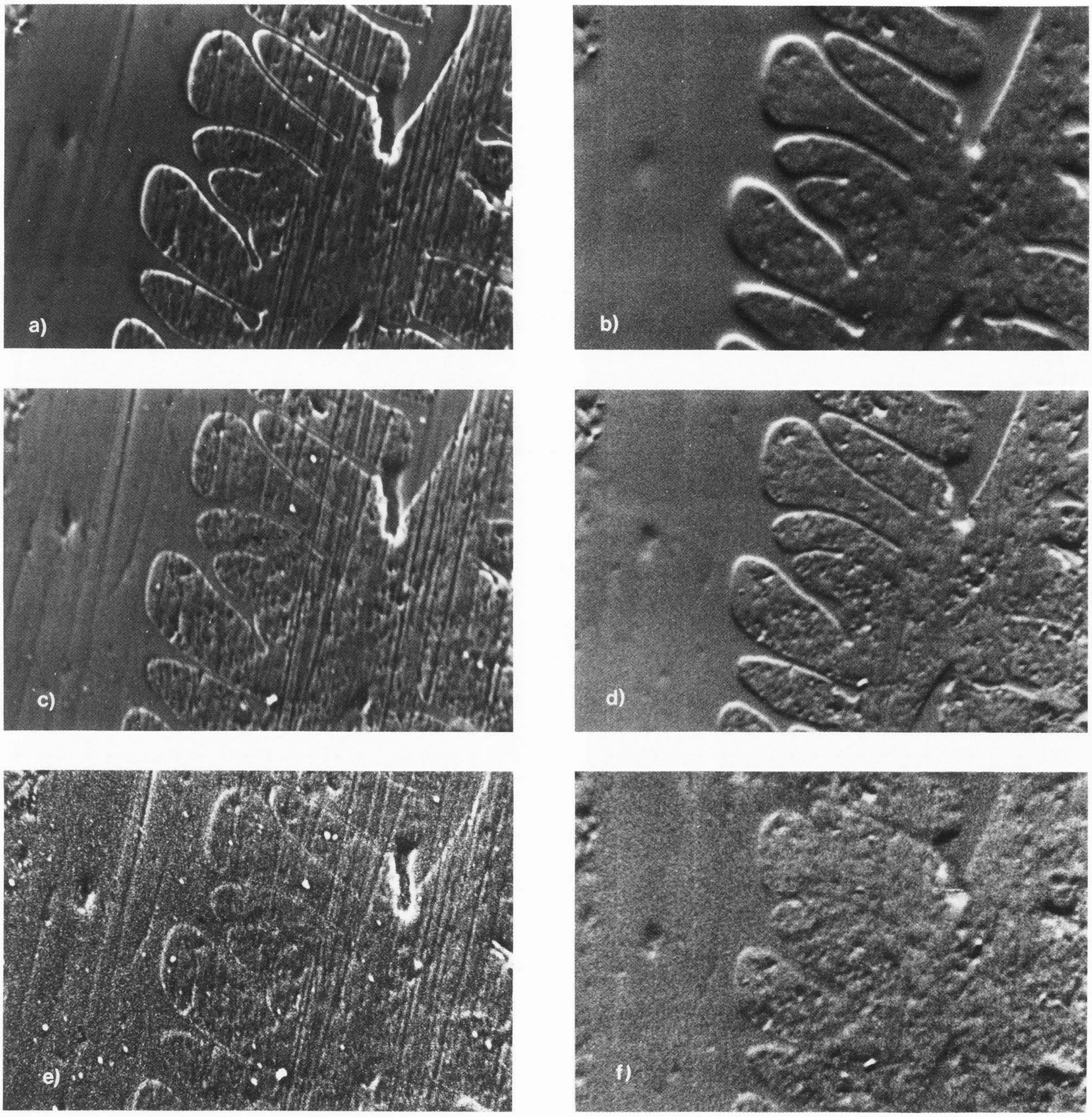

Fig. 5. Topography of a carbon coated specimen containing ZrO_2 inclusions in a glass and corundum matrix obtained by two methods of signal mixing. Left column images obtained with the difference signal of the ring detector and wide-angle semiconductor detector. Right column images obtained with the difference signal of two semiconductor diodes placed symmetrically at two sides of a primary beam. (a) and (b) 25 keV; (c) and (d) 15 keV; (e) and (f) 8 keV. Horizontal field view = 0.15 mm.

above and the other with two semiconductor diodes placed symmetrically on opposite sides of the primary electron beam. Fig. 5 shows micrographs obtained for 8, 15 and 25 keV primary electrons. As expected the pseudo-topography effect nearly disappears for the low energy electron beam (Figs 5c and 5f). At 25 keV this effect is enhanced and is different for both systems. The subtraction of the signal from the symmetrical system results in an asymmetric shadow effect very similar to topographical steps. In the asymmetrical system all grain boundaries have similar contrast and the pseudo-topographic effect is significantly reduced.

A qualitative explanation of pseudo-topography is shown in Fig. 6 for both of the systems discussed. Signal A in Fig. 6a has a maximum at the left grain boundary because electrons scattered in the heavier element penetrate to the lighter element and produce a larger signal in detector A. The signal of detec-

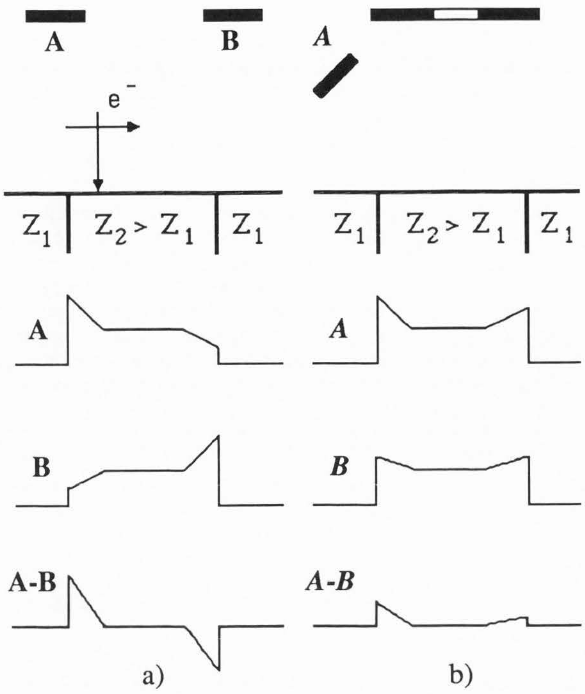

Fig. 6. Explanation of the origin of pseudo-topographic effect in the case of two detector arrangements: (a) - symmetric arrangement containing two BSE detectors placed at both sides of the primary beam; (b) - unsymmetrical arrangement containing the ring detector and wide-angle detector over the specimen.

tor B drops at that boundary because of the escape of electrons to the lighter element and scattering predominantly results in the direction of detector A. At the right boundary there is maximum in the B signal and a drop in the A signal. The signal A-B in the case of a symmetric detector arrangement shows bright and dark bands at material boundaries. Depending on the orientation of the detectors the areas with higher Z look like protrusions or indentations in the flat surface (for example in Fig. 5b). Signal *B* from the wide-angle semiconductor detector in Fig. 6b is an (A+B) type signal and it shows small maxima at both boundaries. The *A* signal of the ring detector is similar, however the maxima at the grain boundaries are different because of the directional properties of this detector (Fig. 3). The maximum at the boundary facing the photomultiplier is higher, and as a result the difference signal (*A-B*) shows only maxima at boundaries of different materials, which on the micrographs are seen as bright bands (Fig. 5a).

Comparing pairs of micrographs from the two different detector systems, taken at the same beam energy, shows that the "real" topography of the surface is much better represented with the asymmetrical detector system. Scratches visible in all micrographs taken using the unsymmetrical detector system are hardly visible in micrographs taken with the symmetrical system. The scratches are oriented so that they are nearly parallel to the line connecting detectors A and B. Also, particles of a polishing powder remaining on the surface are more visible for the asymmetrical system. Moreover the smaller pseudo-topography effect of this system makes it possible to distinguish real topographic features at the grain boundary, like a depression in the surface highlighted by the arrow in Fig. 5a, which is hardly visible on micrographs taken with a symmetric system. The depression is clearly visible for an 8 keV primary beam energy (Fig. 5e), is slightly less visible at 15 keV (Fig. 5c) and becomes nearly invisible for 25 keV electrons (Fig. 5b) where pseudo-topographic contrast dominates. Therefore it is necessary to use as low a primary beam energy as possible in the BSE (A-B) mode to image the "real" topography of a multicomponent heterogeneous specimen.

Conclusions

It has been shown that mixing of BSE signals from non-symmetrically placed detectors reduces artifacts introduced by the symmetrical detection system. The difference of signals from wide solid angle semiconductor detectors and low take-off angle ring type detectors always gives good "real" topography in all directions on the specimen surface, and reduces the pseudo-topographic effect of flat grain boundaries.

Acknowledgments

The authors wishes to thank Prof. R. Blaschke for providing the sample consisting of ZrO_2 inclusions in a glass and corundum matrix and Dr A. Jaworski for providing the tungsten-diamond composite sample.

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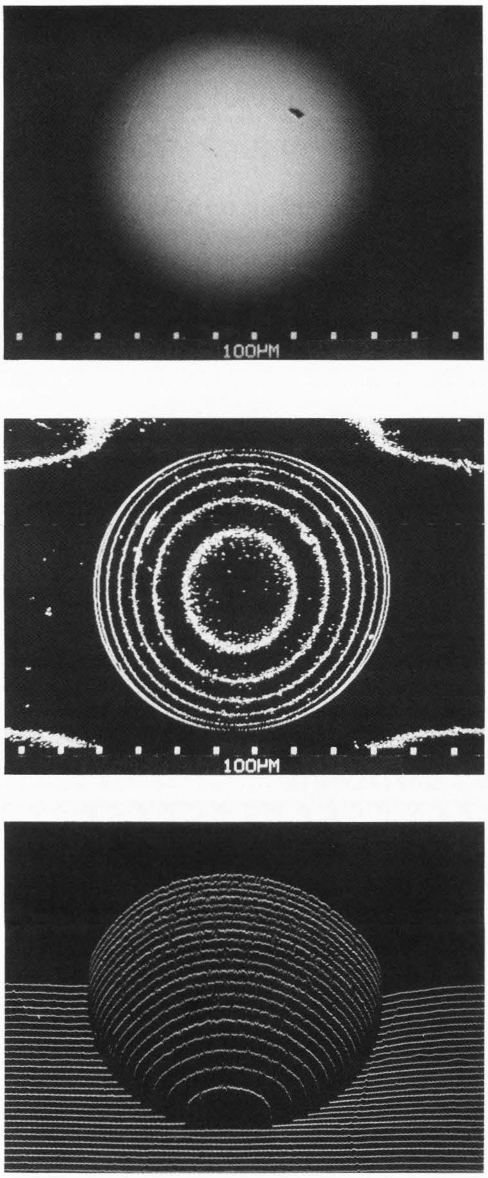
Discussion with Reviewers

P.S.D. Lin: Would the authors also show us the BSE image taken by the solid state detector for the steel ball shown in Fig.3?

Authors: The images of the steel ball taken by the wide angle semiconductor detector (see Fig.7 below) show the nondirectional character of this type detector when placed just above the specimen. The images support the schematic explanation presented in Fig. 6.b (*B*).



a) b) c)

Fig. 7. BSE images of a 0.9 mm steel ball taken with wide angle semiconductor detector (a); (b) isodensities, (c) Y modulation of a lower half of the ball. Eo = 20 keV, WD = 15 mm.

V.N.E. Robinson: "Resulting from angular distribution of BSE, a large solid angle detector placed above the specimen, gives almost pure compositional contrast." Not entirely true. I have been building this type of detector for over ten years, and I get very good topographic contrast with just such a detector. So do over 1000 users. I think they probably mean a narrow angle detector above the specimen.

Authors: Of course we have to agree with the reviewer as well as with those 1000 users. The backscattering coefficient is not only a function of atomic number, but it depends also on the incident angle of the electron beam. The cited sentence was intended to emphasize that the wide solid angle detector is less sensitive to surface topography than the small detector placed at side of electron beam.

D.C. Joy: Do you foresee any problem in image interpretation resulting from the fact that the energy response of your detectors are not the same? Particularly at low beam energies (near the threshold for the solid state diodes) this might cause artifacts in the micrograph.

Authors: This is an interesting question and a detailed explanation requires an additional study using simulation techniques. A detailed study of the solid state detector response to BSE was recently presented by one of the authors (see Z.Radzimski. (1987) Scanning electron microscope solid state detectors, Scanning Microscopy, 1, 975-982). Because the output signal of both detectors depend on the energy of BSE, i.e., is higher for higher energies, they give an enhanced compositional contrast. That is why the resulting signal difference may introduce some artifacts for samples containing materials with large difference in atomic number and with smooth topographic features.

The threshold energies resulting from "dead" silicon layer of the semiconductor detector and the thin aluminium layer of the scintillator detector are similar and equal about 2 keV. We foresee problems with imaging below 5 keV because of low SNR.

V.N.E. Robinson: Figure 6 and it's associated explanation is a little misleading. For example, the geometry of detector A in Fig. 6.a is similar to detector *A* in Fig. 6.b. The curves for A and *A* should be the same in both cases, closer to what is shown in Fig. 6.b (A). The authors have illustrated the effect of increased emission at the high Z side of a high/low transition, but have not shown the reverse effect of electron capture on the low Z side of a high/low transition (see for example, Robinson and George, Atomic number intensity profiles in the SEM, J. Microscopy, 107, 85-91 (1976)).

Authors: The detectors A (Fig 6.a) and *A* (Fig.6.b) have different angular collection characteristics. The detector A (as in the system proposed by Kimoto and Hashimoto) is a small solid angle detector place below the polepiece at the side of the electron beam. Detector *A* (Fig. 6.b) represents ring detector which collects BSE with very low exit angles around the electron beam. However because of the higher collection efficiency from the photomultiplier side we presented it as a detector placed at side of electron beam. The explanation corresponding to these configurations are well supported by images presented in Fig. 5, i.e., by bright and dark "edges" in the case of configuration A-B (see Fig. 5a) and bright and brighter "edges" in the case of configuration *A-B* (see Fig. 5b).

D.C.Joy: Is your signal mixing done in "real time" or do you optimize the subtraction coefficient k by working on stored images? Is your k-coefficient always the same value, and typically what is its value?

Authors: This is an analog signal mixing technique. The signals from the detectors are fed to a differential amplifier through two separate preamplifiers with variable amplification. Then the differential amplifier input signal from solid state detector is adjusted to minimize compositional contrast. The k value is approximately between 1 and 2.

V.N.E. Robinson: Have you checked that the regions in Fig. 5 do indeed contain no topography variation, e.g., by producing stereo pairs?

Authors: No we did not. To reduce the topography effect the specimen was metallurgically polished.