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BACKSCATTERED ELECTRONS TOPOGRAPHIC MODE PROBLEMS IN THE SCANNING ELECTRON MICROSCOPE

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Abstract

The application of several backscattered electron (BSE) detectors makes it possible to separate topographic (TOPO) contrast and material (COMPO) contrast in a scanning electron microscope (SEM). The BSE signals from six p-i-n diodes were used to investigate some artifacts connected with the reconstruction of real topography. The location of these diodes has been predicted theoretically to obtain algebraic formulas for the appropriate mixing of the BSE signal from the detectors. The specimen surface was specially prepared for estimation of the surface reconstruction quality. The TOPO mode in the SEM was realized with the use of analog and digital methods. The experimental and theoretical analysis indicates that the signal difference from the detector placed at higher angles (in relation to the x-axis) is preferable for topography reconstruction. The goal of this paper is to discuss some ways for eliminating the artifact, that the structures parallel to the connection lines of diametral detectors can only be imaged with less contrast.

Key Words: Scanning electron microscopy, solid state detectors, backscattered electron signal, TOPO mode (topographic mode).

Introduction

The backscattered electron signal (BSE) has been widely used for the investigation of specimen surface in the scanning electron microscope (SEM) for many years [2, 5, 22, 23, 27, 34, 35]. The methods for separation of topographic (TOPO mode) and composition (COMPO mode) contrast have been frequently described [3, 4, 17, 30, 32-34]. For this purpose, both conventional configuration of detectors as well as multidetector systems have been applied [25, 26, 28, 29, 30, 33]. Experimental and theoretical analysis of microscopic images has been performed in order to visualize the specimen topography by using the BSE signal. Reconstruction of the real surface was, in this case, of the greatest importance [3, 4, 8, 15-17, 33]. In many studies, digital acquisition systems and digital image processing of BSE signals from SEM have been used [6, 7, 19, 24, 31].

The current paper is a result of several years of experience on utilizing BSE signals in the SEM for gaining information about topography and composition of specimen surface. The first study was focused on the separation of TOPO and COMPO modes with two symmetrically placed semiconductor detectors [9, 13]. Then, a multidetector system with properly tilted detector planes was studied [10, 11, 14]. The system (electron beam, specimen and detectors) was subjected to mathematical analysis [20, 21], and a system for analog BSE signal processing was then designed in order to confirm the conclusions resulting from the theoretical considerations [10, 11, 12]. The research showed the theoretically predicted possibility of TOPO and COMPO mode correction in the SEM by the proper mixing of signals from six semiconductor detectors [12, 21] to be correct. A computer system for acquisition and processing of the BSE signal in the SEM was the next important stage in the research [12].

Based on numerous theoretical and experimental investigations, it was stated that despite the use of digital image processing and introducing the TOPO mode correction (resulting from the applied theoretical model [20, 21]), some surface topography details with a particular orientation were reconstructed either inaccurately or not at all if the conventional detector system was used. Therefore, the examination of test specimens with a particular surface topography was undertaken with the BSE detector system,

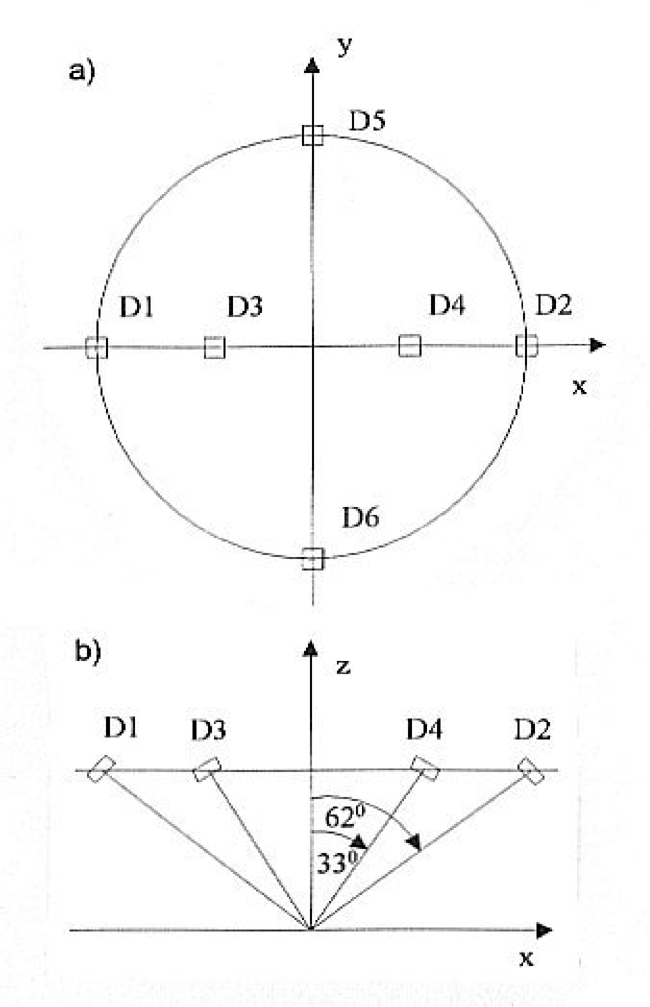


Figure 1. Detector arrangement in relation to the coordinate system x-y-z: (**a**) top view, and (**b**) detection angle quantity.

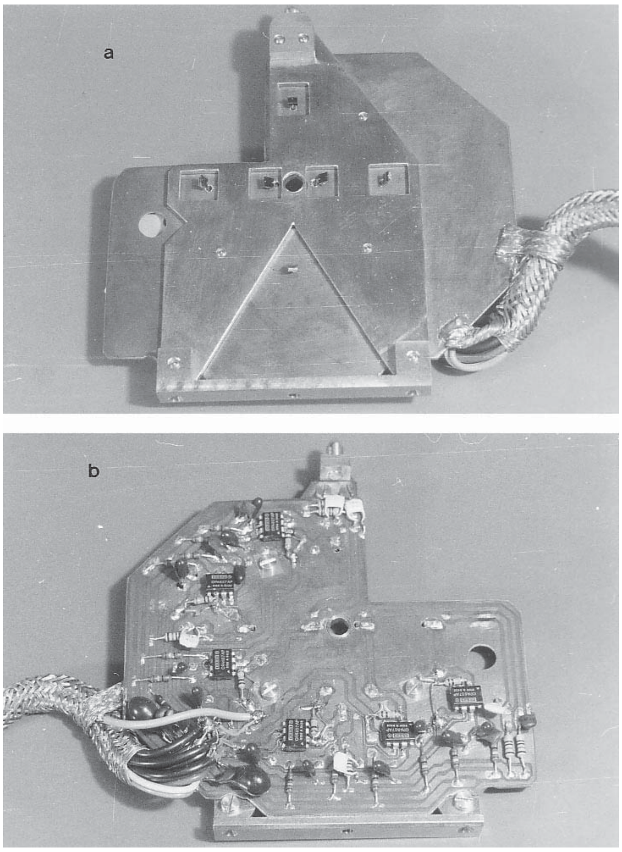


Figure 2. The detector system view from: (**a**) the p-i-n diodes side, and (**b**) the preamplifiers side.

allowing both analog and digital signal processing.

Detection System

The scanning electron microscope was equipped with six inclined p-i-n diodes mounted pair wise: four in the direction parallel to the scan line and the remaining two in the direction perpendicular to the scan line (Fig. 1) [10]. Each detector with a 16 mm^2 surface area covered approximately a 3.2 x 10^{-3} radians solid angle. Bare silicon diodes were used to reduce threshold energy of solid state detectors. The applied number of detectors was a result of the theoretical analysis presented in previous papers [20, 21].

The detector system consisted of BSE detectors (Fig. 2a) and six current preamplifiers (Fig. 2b) placed inside the vacuum chamber. All of these elements were mounted on one board. The main electronic circuit was located outside the vacuum chamber and consisted of the analog signal processing unit and a power supply. Six BSE signals produced by p-i-n diodes entered low pass filters and the next amplification stage in the signal conditioning circuit before they were sent to analog image processing. For digital image processing, the BSE signals were sent to a PC-based digital acquisition system and stored on a hard disk.

Experimental Results

Sample topography was studied using solid state detectors. The beam energy was 20 keV. Commonly, these detectors, which are placed at low take-off angles in relation to the specimen surface (for example, the detectors D1, D2, D5, D6 in Fig. 1), were used for investigation of topography. Detectors located at higher take-off angles towards the

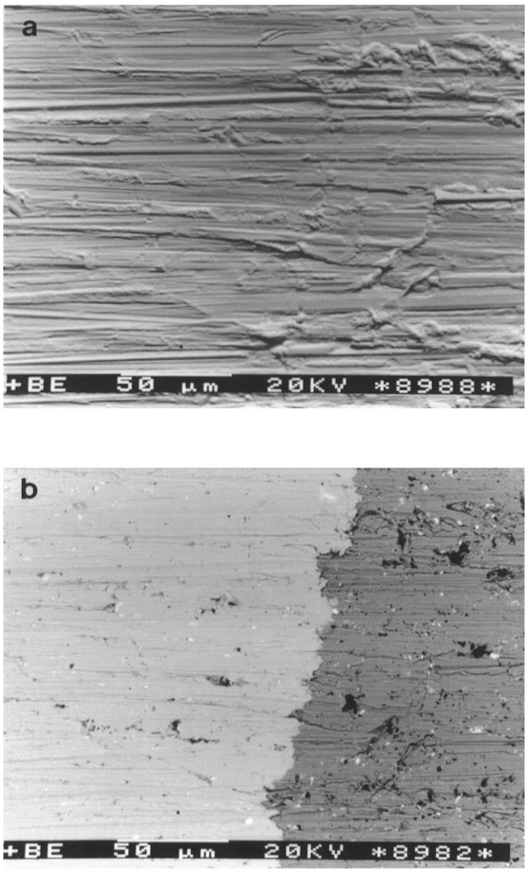


Figure 3. Scanning electron micrographs of Mo-Cu weld interface: (**a**) in TOPO mode (D1-D2), and (**b**) in COMPO mode (D3+D4). Bars = 20 µm.

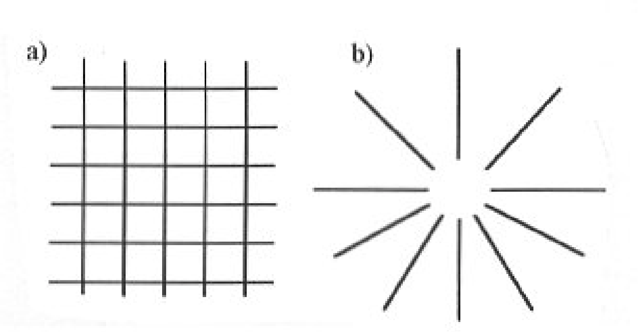


Figure 4. Schematic diagram of: (**a**) perpendicular, and (**b**) radial patterns produced for topography artifact study.

specimen surface (for example detectors D3 and D4) are usually used for composition investigation [1, 14, 18]. Some investigators only use the detectors placed at medium take-off angle [16, 33].

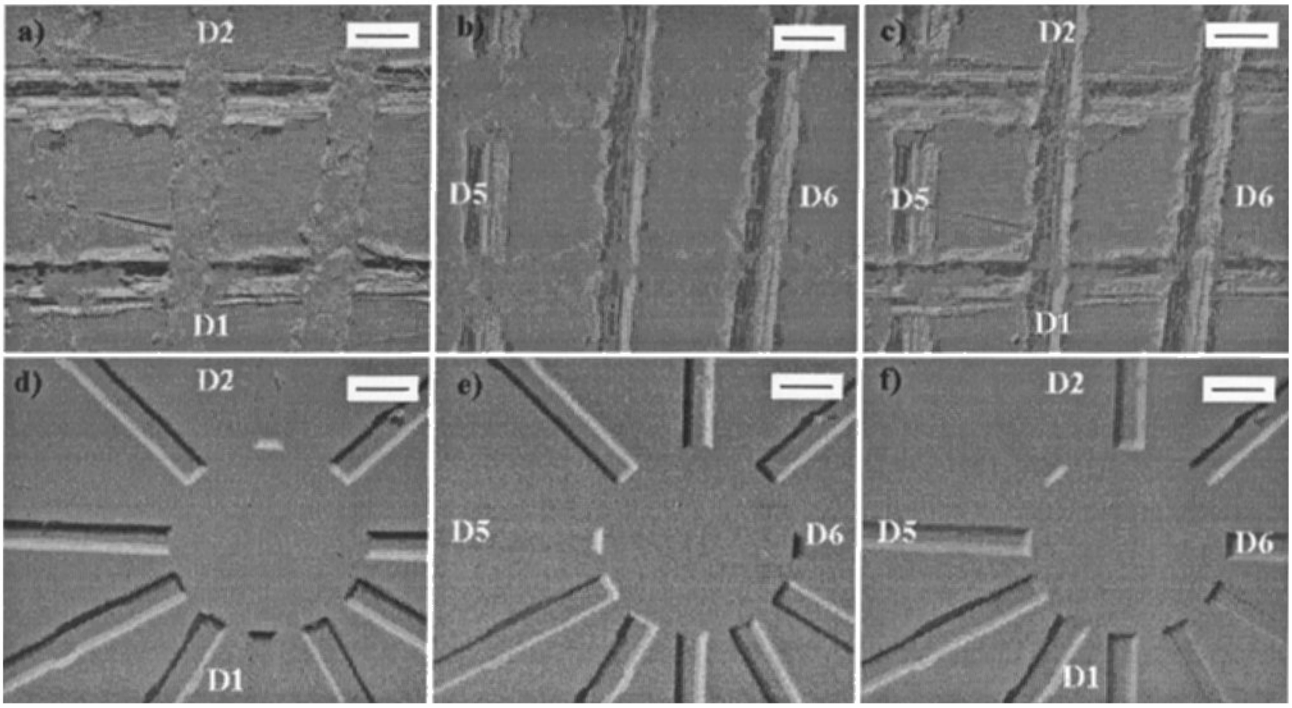
SEMs are often equipped with two semiconductor detectors placed opposite to each other. In this case, the TOPO mode is produced by subtraction of BSE signals coming from the detectors and COMPO mode by addition of these signals. These two cases are presented in Figure 3, which shows the surface of a Mo-Cu weld interface. The sample surface was mechanically polished. In Figure 3a, the specimen looks as if it were made of bulk material, while only horizontal scratches from the mechanical polishing are visible. Those scratches disappear in Figure 3b, where material contrast is enhanced with Mo on the left side and Cu on the right. However, the scratches made mechanically in the perpendicular direction are not visible in either Figure 3a or Figure 3b. This is clearly shown in the example of specifically prepared samples (Fig. 4). Crossing scratches were made on the surface of the Ta sample (Fig. 4a), whereas a set of radial grooves (Fig. 4b) were etched in the silicon sample.

Images in the TOPO mode were obtained in the conventional way by subtracting BSE signals from two detectors placed opposite to each other. In Figures 5a, 5b, 5d, 5e and 5f, it is shown how false images of real surface are obtained in this commonly used method. This is important because microscopes are often equipped with only two semiconductor detectors placed opposite to each other. As can be seen in Figures 5a and 5d, the images obtained by subtraction of signals from detectors D2 and D1, (D2-D1), do not show any scratches or grooves in the direction parallel to the line connecting these detectors. Similarly, the images obtained by subtraction of the signals from detectors D6 and D5, (D6-D5), do not show the horizontal grooves or scratches (Figs. 5b and 5e).

The simplest way of obtaining an image closer to real topography is the use of signals from four detectors situated perpendicular to each other. Addition of the different signals from the four detectors (D2-D1) + (D6-D5) results in an the image close to reality for the case of crossing scratches (Fig. 5c) located perpendicular to the direction pointed out by the two couples of detectors. Instead, Figure 5f shows that in the case of radial structures, the grooves located at an angle of 135° relative to the horizontal line are poorly visible.

Figure 6 shows that with the change in sequence of signal subtraction, (coming from different detectors), the grooves located at an angle of 45° towards the horizontal line are less distinct. Comparing the results from Figures 6a and 6b, various arrangements of shadows can be noticed. Grooves in Figure 6a look as if they were illuminated from the top, whereas in Figure 6b, they appear illuminated from the bottom. This can lead to a false interpretation of SEM images.

In order to examine various arrangements of detectors,



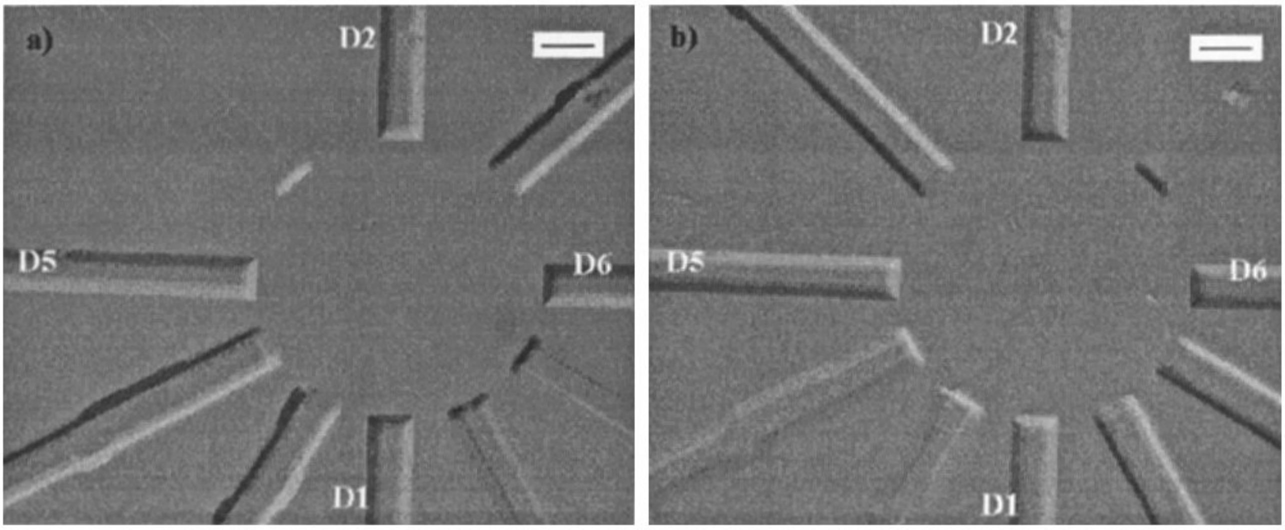


Figure 5. Surfaces digital images with crossing scratches and radial grooves: (**a**) and (**d**) images obtained as a result of BSE signal subtraction from detectors (D2-D1); (**b**) and (**e**) as above, but as a result of signal subtraction from detectors (D6-D5); and (**c**) and (**f**) as above, but in effect of addition of signal difference (D2-D1) + (D6-D5). Location of detectors has been marked on the particular images. Bars = 75 µm.

Figure 6. Surface digital images with radially located grooves in case when: (**a**) TOPO mode is produced according to the algorithm (D2-D1) + (D6-D5), (**b**) TOPO mode is produced according to the algorithm (D1-D2) + (D6 D5). Bars = 50 µm.

the detectors D3 and D4 located at high take-off angle in relation to the x-axis (Fig. 1b) were applied to produce the TOPO mode. In Figure 7, images of a section of specimen surface with crossing scratches were compared for the cases

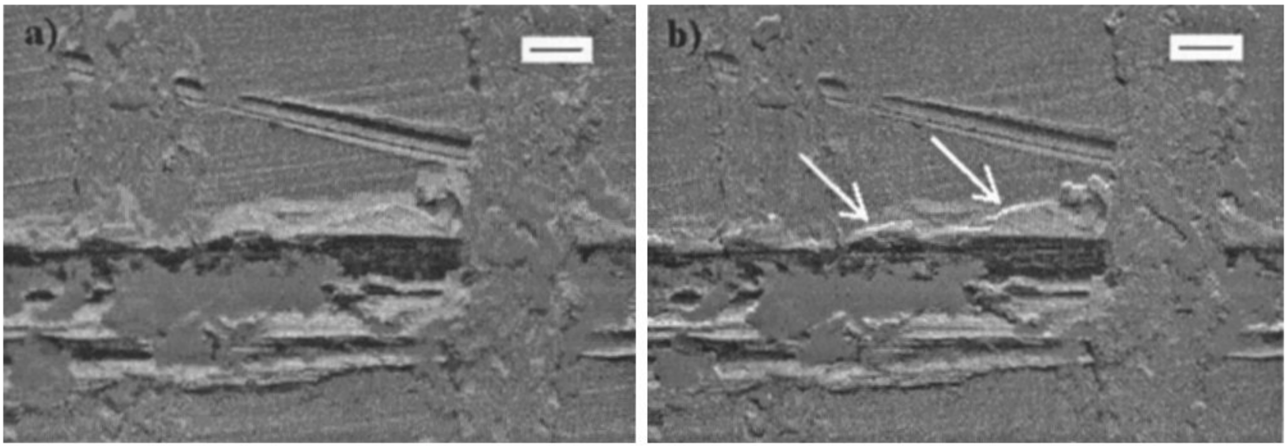


Figure 7. Digital image in TOPO mode obtained as: (**a**) (D2-D1), and (**b**) (D4-D3). Bars = 25 µm.

where the TOPO mode was produced as signal difference (D2-D1) or (D4-D3). In Figure 7b, especially at the points indicated by arrows, it can be seen that the steep slopes are particularly well imaged. In Figure 7a, the slopes can be seen as areas of similar greyness and therefore their image appears slightly blurred.

The experimental results presented above illustrate various artifacts which may occur during imaging of sample topography by different configurations of solid state detectors. In the following section, an attempt to explain the obtained results on the basis of backscattering phenomenon will be undertaken.

Analysis of Results

It is well known that BSE signals coming from two oppositely arranged detectors do not reconstruct the topographic details which are parallel to the axis along the location of the detectors. When the BSE signals from both detectors are similar, then the TOPO signal obtained by subtraction is mutually reduced (see Fig. 1 in [9]).

For specimen surface inspection in TOPO mode, asymmetry of the angular distribution of the differential electron backscattering ratio $d\eta/d\Omega$ is necessary in the direction of detection where η (the coefficient of backscattering) is defined as a ratio of BSE current to original beam current, Ω-solid angle [23]). The condition can be fulfilled by rotation and tilting of the specimen in relation to the detector system. Then, if the system consists of two detectors, a series of topographies of rotated samples should be taken. The structures located perpendicular to the line of the arrangement of the detectors are reproduced best in this case (see previous section).

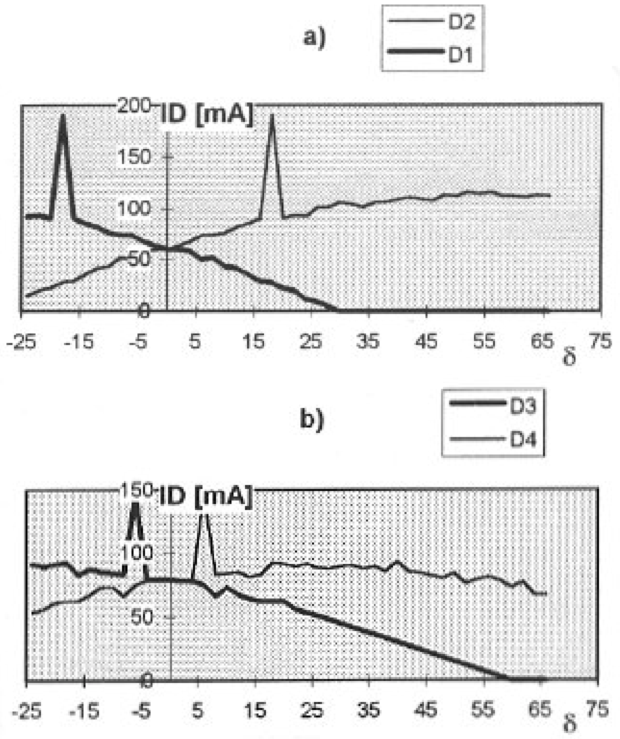


Figure 8. Dependence of BSE signals ID on the surface inclination angle of Au sample in the case of detectors: (**a**) D1, D2, and (**b**) D3, D4.

For the realization of the TOPO mode, the use of an internal pair of semiconductor detectors (D3, D4) has also been taken in consideration (Fig. 7b). Analysis of the results was performed on the basis of the dependence of the detector

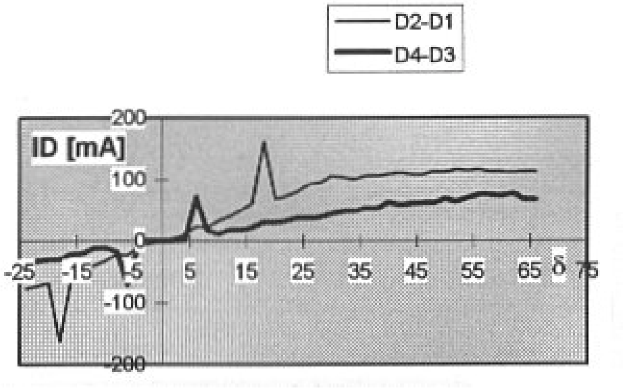


Figure 9. Dependence of detector current ID on the surface inclination angle of Au specimen in the case of TOPO mode realization as (D2-D1) and (D4-D3).

current (ID) coming from various BSE detectors on the angle of surface inclination (δ) in the case of a smooth Au surface. The digital BSE signal processing allowed computer averaging of the whole series of measurements made at one point for one particular value at an inclination angle δ. This made it possible to avoid randomness, connected with statistical noise distribution, which previously had caused problems. In Figures 8a and 8b, some plots of the BSE signal (ID) obtained from a Au specimen with the detectors D1 ÷ D4, versus surface inclination angle δ are shown. For the narrow range of δ angles at about half the angle between the detector and the axis of beam incidence, strong peaks of the signal were observed. The height of the peaks shown in the diagrams (Figs. 8a and 8b) was restricted during the measurements. The peaks may cause errors in the interpretation of micrographs. As can be seen from Figure 8a, the dependence of BSE signals on topography results, in the case of detectors D1 and D2, in a monotonic change in detector signal versus δ, and in the case of detectors D3 and D4 (Fig. 8b), the changes in BSE signal dependent on δ were negligible, as a result of a weak influence of topography on the signal from those detectors.

However, only the analysis of the run of differences in signal from the opposite detectors versus δ can be used to explain the results shown in Figure 7b. Figure 9 shows the difference signals, depicting the topographic contrasts: (D2-D1) and (D4-D3) versus δ.

From Figure 9, it can be concluded that the TOPO mode obtained in the form of a BSE signal difference from the detectors located at low take-off angle towards the specimen (i.e., (D2-D1)) is not able to distinguish the topographic details with a slope > 30° (for the detection system from Fig. 1b). The plot (D2-D1) = f(δ) has an inconveniently flat shape for angles > 30°. The run of signal from the detectors (D4-D3) placed at high angles in relation to the specimen is however monotonic in character for a wide range of δ angles (Fig. 9).

The analysis of BSE signals from Figures 8 and 9 can explain the differences occurring in the microscope images shown in Figures 7a and b. For the examination of a surface with developed topography, the placement of detectors at a higher angle over a specimen would be more useful. For such a configuration, the steep slopes would be better distinguished than in the case of conventionally arranged detectors for the TOPO mode.

In order to improve the separation of TOPO and COMPO in the conventional detector arrangement, a correction of the modes, resulting from a theoretical description of the system (electron beam, specimen and detector) could be applied [10, 20, 21]. This theory predicts the possibility of better separation of TOPO and COMPO modes by the compensation of the signal disturbance. As it follows from theoretical considerations [20], in the case of four detectors, the TOPO and COMPO signals mixed in the form of (D1-D2)(D3+D4) with opposite signs can be used for compensation of the disturbed TOPO mode. Then for one pair of detectors it follows that:

$$\text{undisturbed (D4 D3)} = \text{(D4-D3)} - \beta\text{(D4-D3)(D4+D3)} \quad \textbf{(1)}$$

where β is an experimental constant [21], i.e:

$$\text{undisturbed TOPO} = \text{TOPO} \;\; \beta\text{(TOPO)(COMPO)} \quad \textbf{(2)}$$

Conclusions

The paper describes different detection methods which can be used in the SEM for a correct reconstruction of surface topography with the use of the BSE signal. It aims at elaborating a universal method to obtain the TOPO mode in order to reconstruct a specimen surface. In the case of topography reconstruction, it is very important to have the BSE signal distinctly dependent on the local surface tilt. A too extensive shadowing effect contributing to the TOPO image can indeed disturb the correct topography reconstruction [33]. Particularly shadowing effects could be compensated as suggested in [29]. Numerous experimental results have resulted in the observation, that the difference of signals from the detectors placed at higher angles is more suitable for the reconstruction of the rough surface. As seen in Figure 9 and in reference [33], the detector angle defines the maximum surface slopes to be distinguished. A single detector placed at low take-off angle is more sensitive to the local inclination (Fig. 8) and could be preferred for the examination of topographical contrast.

The results indicate that a real topography of a specimen can be obtained if:

- the number of detectors is increased and their distribution in respect to the beam is optimized. It requires the application of an extended system of digital data acquisition and processing of BSE signals.
- digital processing of signals coming from two or four detectors according to the elaborated algorithm of mixing BSE signals is used.
- the specimen is rotated and tilted, when a standard two detector system is used.
- the detectors located at high take-off angles in relation to the x-axis are applied, and a correction improving the separation of topographic and material contrast is introduced.

At present, the research has led towards development of the algorithm enabling reproduction of real surface topography on the basis of analysis of signals from four detectors.

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Discussion with Reviewers

K. Murata: Have you investigated the contrast mechanism with the annular type of detectors divided into two parts? Could you speculate on the TOPO and COMPO contrasts with the annular detector on the basis of your results?
Z. Radzimski: How would the size of detectors affect your observations? Can we define the maximum solid angle of a detector which would give the proper separation of topographic and material contrasts?
M.M. El-Gomati: Detectors D1 and D2 resemble, in their position with respect to detectors D3 and D4, those for low energy loss electrons, and hence one should expect a higher surface topography from these detectors. Can you comment?
Author: I have not investigated the contrast mechanism of an annular type detector. Generally, it is more suitable to use small size detectors for topography reconstruction and large size ones for material contrast. With some simplification, it can be assumed that the sensitivity (s) of the detector for TOPO reconstruction $s_T \sim 1/\Omega$, and for COMPO mode $s_C \sim \Omega$ (where Ω is the solid angle of the detector). However, the signal to noise ratio is lower for the small detectors in comparison with annular detectors.

Z. Radzimski: What was a typical current in your experiment? How much does the current has to be increased in comparison with the scanning electron (SE) mode to get good quality images?
Author: The primary beam current used for experiment was about 1 nA. In comparison with the SE mode, the beam current had to be increased about 100 times to get good quality images.

H. Niedrig: What does "ID" mean in Figure 8?
Author: ID is the detector current directly dependent on the number of backscattered electrons (n) collected by the diode surface, so ID = K • n, where K is an amplification factor.

L. Reimer: It is not clear, where the peaks in Figures 8 and 9 are coming from. The occurrence at the half-angle between the detector and the axis of the beam can perhaps be explained by reflection of light from the cathode.
M.M. El-Gomati: What are the causes of the peaks shown in Figures 8 and 9.
K. Murata: In Figure 8, the peaks seem to be caused by the mirror reflection. Then the peaks exist at the surface inclination angles of 31 and 16.5 degrees, judging from Figure 1. Is my speculation correct?
Author: Yes, this speculation is correct. From the analysis of the system (specimen, electron beam and detector) presented in Figure 10, it follows that the peak appears at the angle of $\delta = \theta/2$ (where δ is the surface inclination angle, and θ is the detector angle). In Figure 10, the case is shown when $\beta = \theta/2 = \delta$. Only in this case ($\delta = \theta/2$), the mirror reflected backscattered electrons reach the detector D1. Thus, the peak is consistent with the reflection law, where the angle of incidence is equal to the angle of reflection. In order to confirm this statement the ID = f(δ) characteristics of BSE signals coming from the detectors placed at different angles have been examined. The results of this examination is shown in Figure 11.

It confirms the assumption concerning the angle of peak occurrence. These peaks can be the reason of incorrect interpretation of BSE images.

Z. Radzimski: The most attractive application for topography reconstruction using backscattered electrons is metrology of semiconductor devices. So far, however, due to rather poor performance of BSE detectors at low beam energy, the BSE imaging is not widely accepted. What is your prognosis for BSE detector developments which would address these issues?
Author: The solution to this problem is connected with material technology development. It concerns new materials (for instance, materials similar to heterostructures with variable threshold energy) sensitive to a wide energy spectrum. It could be also multichannel detectors.

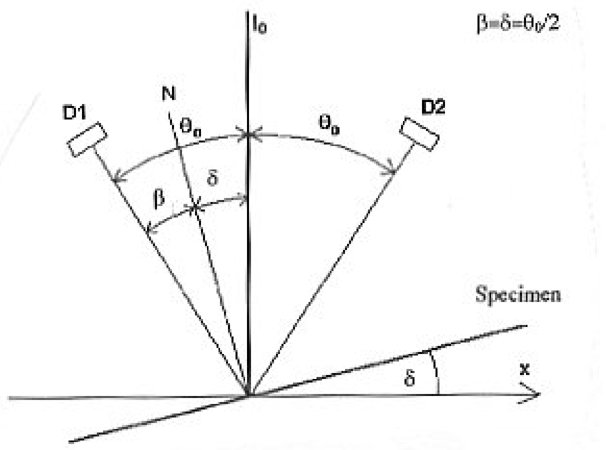

Figure 10. The system (specimen, electron beam and detectors).

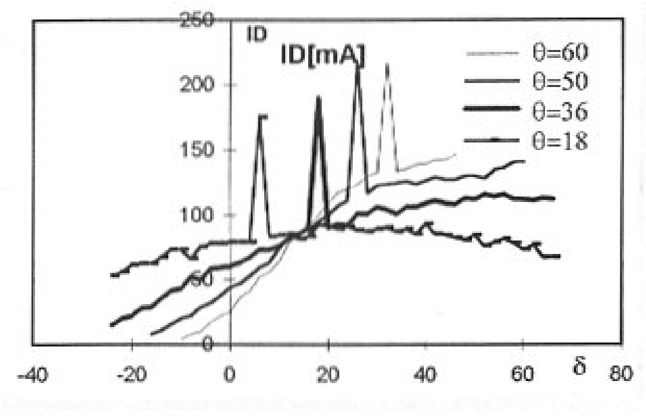

Figure 11. The ID = f(δ) characteristics obtained from Au specimen at the different angle θ of detector position.

L. Reimer: At the end of paper, it is not clear what undisturbed TOPO, for example, means?

Author: The improved TOPO mode due to a better separation of both the topographic and material contrasts in SEM has been called "undisturbed TOPO" [20, 21]. According to Murata [36], who has approximately determined angular BSE characteristics, the BSE current density after some transformations takes the form:

$$j(A,\alpha)=j_A dA+j_\alpha d\alpha+\frac{1}{2!}\left[\,j_{AA}(dA)^2+2\,j_{A\alpha}dA\,d\alpha+j_{\alpha\alpha}(d\alpha)^2\,\right] \qquad (3)$$

In Equation 3, the component $j_A dA$ contains the information about material in the dA factor. The component $j_\alpha(d\alpha)$ contains the information about topography in the dα factor. For the TOPO mode, when the signals from single detectors are subtracted, the terms containing α with the even power disappear. However, the term containing the factor dA•dα remains as a disturbance signal and it can be called the COMPO•TOPO. This disturbance term of the opposite sign has been used to obtain the "undisturbed TOPO" mode.

M.M. El-Gomati: Could you give some details regarding the fabrication of the samples of Figure 4, i.e., the height of the raised materials and the depth of the grooves?

Author: The height of the scratches was about 6 µm and the depth of the grooves was about 8 µm.

M.M. El-Gomati: In your conclusion, you suggest that as the number of detectors is increased one should get more accurate sample topography. Could you comment on the minimum number of detectors one needs to achieve this?

Author: Basing on my investigations I have stated that the minimum number of detectors to obtain an accurate image of a sample topography is four, but in the case of a sample composition, it is two.

K. Murata: Does your conclusion depend on the electron beam energy?

Author: Considering the fact that the angular distribution of BSE electrons does not vary drastically with primary beam energy, my conclusion does not depend on the beam energy. I have carried out my investigation at the energy of E_0 = 20 keV. From the angular distribution of the differential backscattering ratio dη/Ω with the energies of 102 keV and 9.3 keV [23], one can see that the characteristics are similar. It can be concluded that the η = f(δ) characteristics should be also similar in shape, but the peaks height would be different.

Additional Reference

[36] Murata K (1976) Exit angle dependence of penetration depth of backscattered electrons in the scanning electron microscope. Phys Stat Sol (a) **36**: 197-207.