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Backscattered electrons topographic mode problems in the scanning electron microscope

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The application of several backscattered electron (BSE) detectors makes it possible to separate topographic (TOPO) contrasts and material (COMPO) contrasts 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 had 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 x axis) is preferable for topography reconstruction. The goal of this paper is to discuss some ways of eliminating the artifact that the structures parallel to the connection lines of diametral detectors can only be imaged with less contrast.

1. Introduction

The backscattered electron (BSE) signal has been widely used for the investigation of specimen surface in the scanning electron microscope (SEM) for many years [1]–[7]. The methods for separation of topographic (TOPO mode) and composition (COMPO mode) contrast have been frequently described [6], [8]–[13]. For this purpose, both conventional configuration of detectors as well as multidetector systems have been applied [11], [13]–[17]. 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 [8]–[10], [13], [18]–[20]. In many studies, digital acquisition systems and digital image processing of BSE signals from SEM have been used [21]–[25].

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 [26]. Then, a multidetector system with properly tilted detector planes was studied [27]–[29]. The system: electron beam–specimen–detectors was subjected to mathematical analysis [27], [30], [31] and a system for analog BSE signal processing was then designed in order to confirm the conclusions resulting from the theoretical considerations [28], [32], [33]. 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 [27], [31], [33] 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 [33].

Based on numerous theoretical and experimental investigations, it was stated that despite using digital image processing and introducing the TOPO mode correction, (resulting from the theoretical model applied [27]), 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, allowing both analog and digital signal processing.

2. 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) [28]. Each detector with a 16 mm^2 surface area covered approximately 3.2×10^{-3} radians solid angle. Bare silicon diodes were used to reduce threshold energy of solid state detectors. The applied number of detectors was the result of the theoretical analysis presented in the previous paper [27].

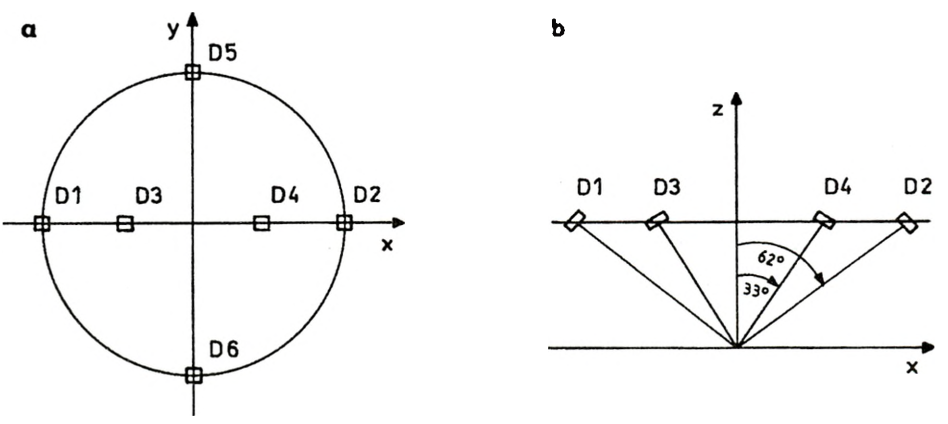

Fig. 1. Arrangement of detectors in relation to the coordinate system x-y-z: a — top view, b — detection angles quantity.

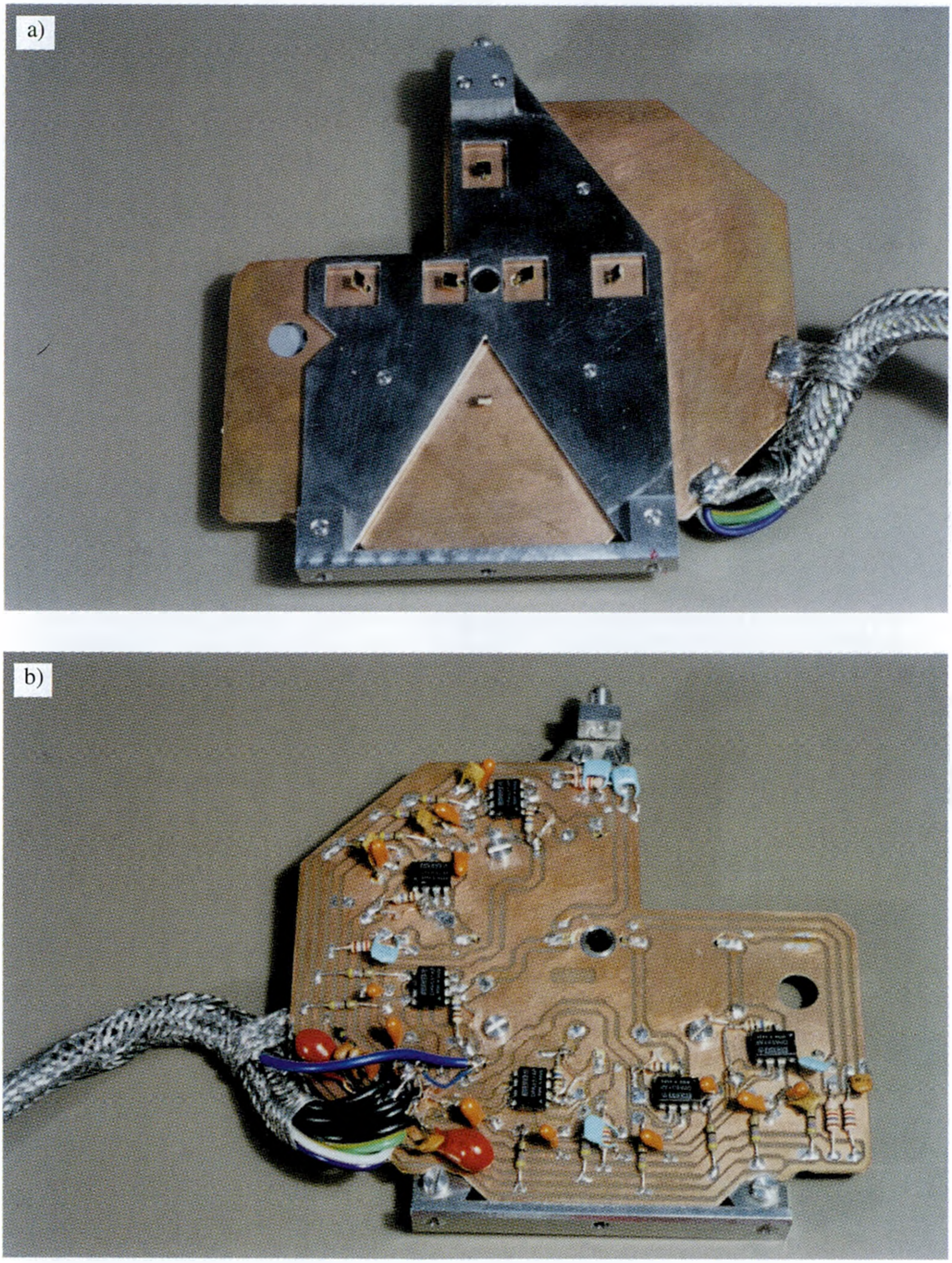

Fig. 2. The detector system view from: a) the p-i-n diodes side; b) the preamplifiers side

The detector system consisted of BSE detectors (Fig. 2**a**), and six current preamplifiers (Fig. 2**b**) 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 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 PC-based digital acquisition system and stored on a hard disk.

3. Experimental results

Sample topography was studied using solid state detectors. The beam energy was 20 keV. Commonly, the 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 specimen surface (for example, detectors D3 and D4) are usually used for composition investigation [29], [34], [35]. Some reaserchers only use the detectors placed at medium take-off angle [13], [20].

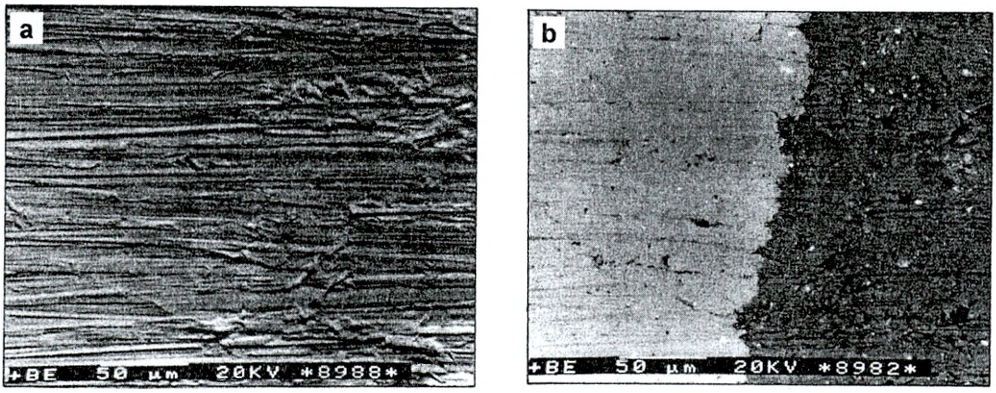

Fig. 3. Scanning electron micrographs of Mo – Cu weld interface: **a** – in TPO mode (D1 – D2), **b** – in COMPO mode (D3 + D4).

The SEMs are often equipped with two semiconductor detectors placed opposite each other. In this case, the TOPO mode was produced by subtraction of BSE signals coming from the detectors and COMPO mode by addition of these signals. These two cases are presented in Fig. 3, which shows the surface of Mo – Cu weld interface. The sample surface was mechanically polished. In Figure 3**a**, 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 Fig. 3**b**, 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 Fig. 3**a** or **b**. This is clearly shown in the example of specifically prepared samples (Fig. 4). Crossing scratches were made on the surface of Ta sample (Fig. 4**a**), whereas a set of radial grooves (Fig. 4**b**) were etched in the silicon sample.

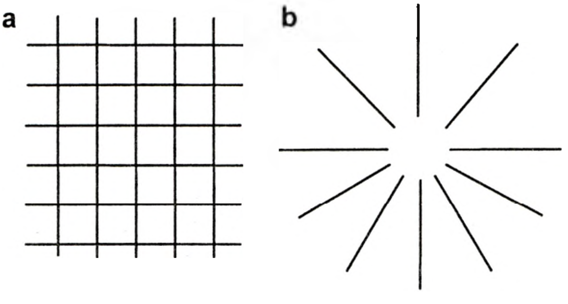

Fig. 4. Schematic diagram of: **a** — perpendicular, and **b** — radial patterns produced for topography artifact study.

Images in TOPO mode were obtained in the conventional way by subtracting BSE signals from two detectors placed opposite each other. In Figure 5**a**, **b** and **d**, **e**, **f**, 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 each other. As can be seen in Fig. 5**a** and 5**d**, 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 (Fig. 5**b**, **e**).

The simplest way of obtaining an image closer to real topography is by using 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 image close to reality for the case of crossing scratches (Fig. 5**c**) located perpendicular to the direction pointed out by the two couples of detectors. Instead, Fig. 5**f** 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 Fig. 6**a** and **b**, various arrangements of shadows can be noticed. Grooves in Fig. 6**a** look as if they were illuminated from the top, whereas in Fig. 6**b**, they appear illuminated from the bottom. This may lead to a false interpretation of SEM images.

In order to examine the various arrangements of detectors, the detectors D3 and D4, located at high take-off angle in relation to x axis (Fig. 1**b**), were applied to produce the TOPO mode. In Figure 7, images of a section of specimen surface with crossing scratches were compared in the cases where the TOPO mode was produced as signal difference (D2−D1) or (D4−D3). In Figure 7**b**, especially at the points indicated by arrows, it can be seen that the steep slopes are particularly well imaged.

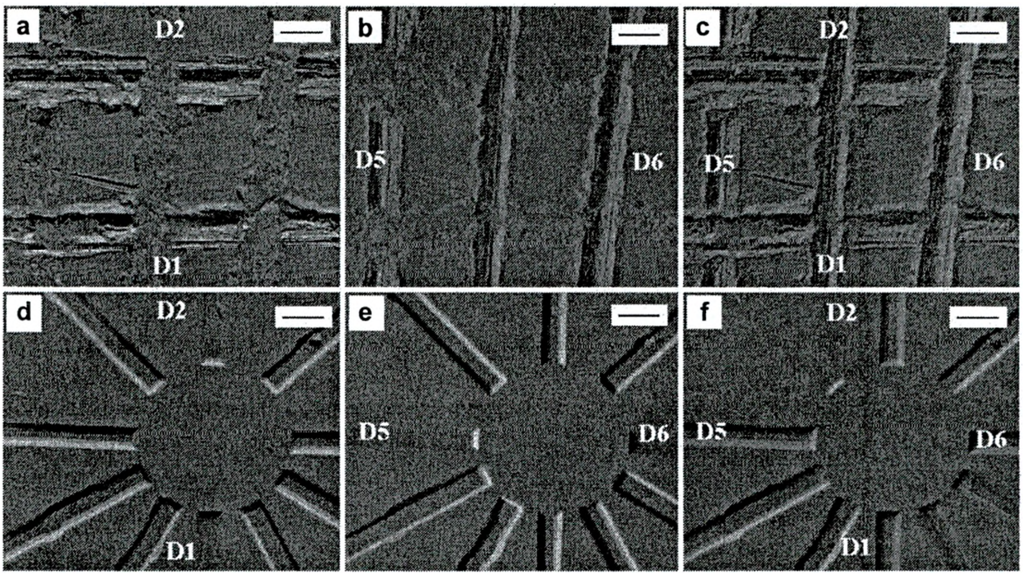

Fig. 5. Surface digital images with crossing scratches and radial grooves: **a**, **d** – images obtained as a result of BSE signal subtraction from detectors (D2−D1), **b**, **e** – as above, but as a result of signal subtraction from detectors (D6−D5), **c**, **f** – as above, but in effect of addition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

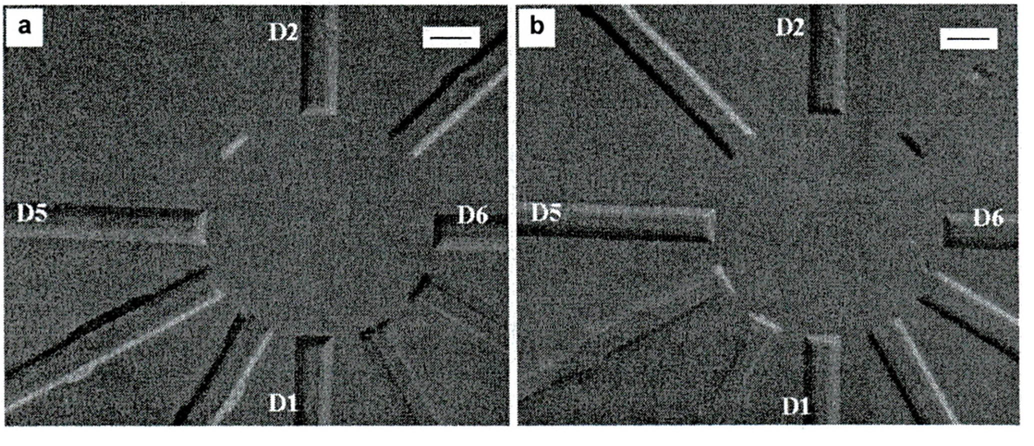

Fig. 6. Surface digital images with radially located grooves in case where: **a** – TOPO mode is produced according to the algorithm (D2−D1)+(D6−D5), **b** – TOPO mode is produced according to the algorithm (D1−D2)+(D6−D5) (bar = 50 μm).

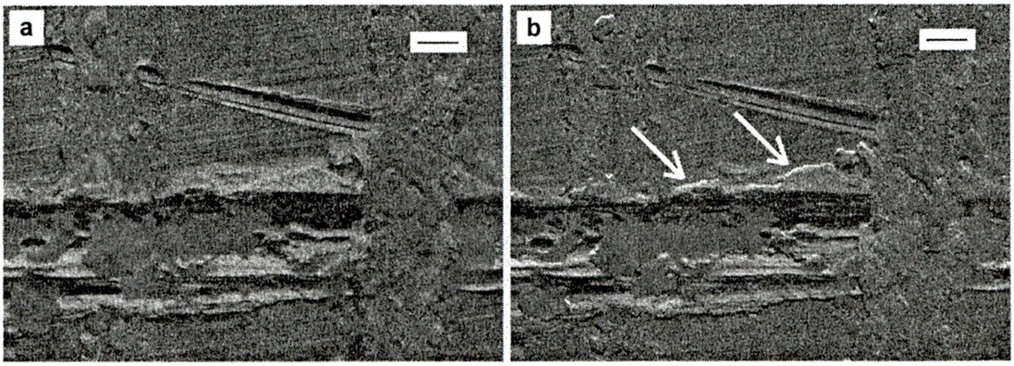

Fig. 7. Digital image in TOPO mode obtained as: a – (D2–D1), b – (D4–D3) (bar = 25 μm).

In the case of Fig. 7**a**, 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.

4. Analysis of results

It is well known that BSE signals coming from two detectors arranged in opposite manner 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.

For specimen surface inspection in TOPO mode, asymmetry of 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 the ratio of BSE current to original beam current, Ω – solid angle [4]. The condition can be fulfilled by rotating and tilting 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 the previous section).

For realization of the TOPO mode, the use of an internal pair of semiconductor detectors (D3, D4) has also been taken into consideration (Fig. 7**b**). The results were analysed based on the dependence of the 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 enabled 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 Figure 8**a** and **b**, some plots of BSE current ID obtained from an Au specimen with the detectors from D1 to 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 signal were observed. The height of the peaks shown in the diagrams (Fig. 8**a**,**b**) was restricted during the measurements. The peaks may cause errors

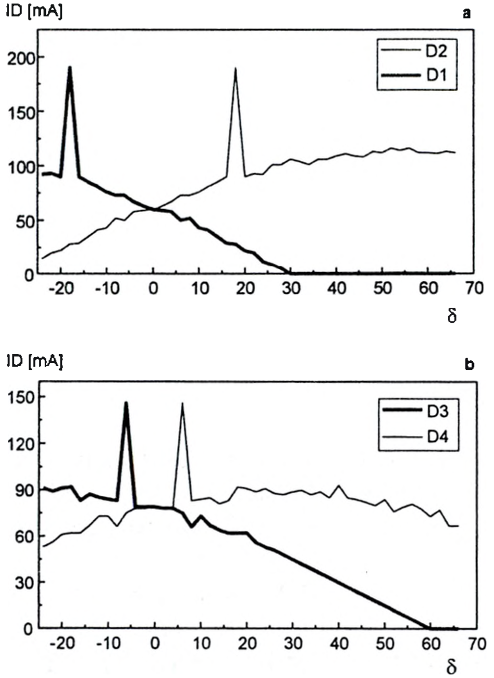

Fig. 8. Dependence of BSE current ID on the surface inclination angle δ of Au sample in the case of detectors: **a** – D1, D2, **b** – D3, D4.

in the interpretation of microphotographs. As can be seen from Fig. 8**a**, the dependence of BSE current 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. 8**b**), the changes in BSE current dependent on δ were negligible, as a result of the weak influence of topography on the signal from those detectors.

However, only the analysis of the run of differences in signals from the opposite detectors versus δ can be used to explain the results shown in Fig. 7**b**. 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 the slope $>30°$ (for the detection system from Fig. 1**b**). The plot $(D2-D1)=f(\delta)$ 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 Fig. 8 and 9 can explain the differences occurring in the microscope images shown in Fig. 7**a** and **b**. For the examination of

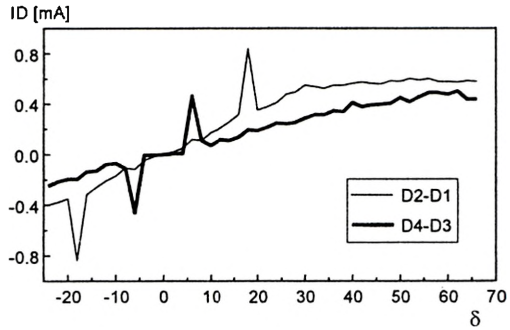

Fig. 9. Dependence of detector current ID on the surface inclination angle δ of Au specimen in the case of TOPO mode realization as $(D2-D1)$ and $(D4-D3)$.

a surface with developed topography, the placement of detectors at higher angle over a specimen would be more useful. In such 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 theoretical description of the system electron beam – specimen – detector, could be applied [27], [30], [31]. This theory predicted the possibility of better separation of TOPO and COMPO modes by compensating the signal disturbance. As it follows from theoretical considerations [27], 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:

– undisturbed $(D4-D3)=(D4-D3)-\beta(D4-D3)(D4+D3)$ (1)

where β is an experimental constant [27], *i.e.*,

– undisturbed TOPO = TOPO $-\beta$(TOPO)(COMPO). (2)

5. Summary

The paper describes different detection methods which can be used in the SEM for correct reconstruction of surface topography with the use of 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 [13]. Particularly shadowing effects could be compensated as suggested in [17]. Numerous experimental outcomes 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 Fig. 9 and in reference [13], 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 with respect to a 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 x axis are applied, and a correction improving the separation of topographic and material contrast is introduced.

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

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