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BSE detector systems for imaging in a scanning electron microscope

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In this paper different detector systems for imaging in a scanning electron microscope (SEM) by using backscattered electrons have been presented. Owing to such detection systems the separation of topographic and material contrasts in SEM can be achieved. SEM images of different specimen surfaces obtained by means of the conventional scintillator detector of secondary electrons (SE) and backscattered electrons (BSE) detector have been compared.

1. Introduction

A scanning electron microscope (SEM) with additional detector systems for signals originating from a specimen makes possible the investigation of a solid state surface. In a SEM, the image processing with SE signals has been widely used due to scintillator detectors with the typical Everhart-Thornley detector [1]. The main advantage of SE images is a good resolution. Here, however, the superposition of topographic (TOPO) and material (COMPO) contrasts can be observed together with the edge effect occurring simultaneously. Hence, the interpretation of observed microscopic images is considerably difficult.

Therefore, in recent years backscattered electrons (BSE) have been used more frequently for surface investigation. Backscattered electrons are considered as the electrons of energies higher than 50 eV being emitted from the specimen due to collisions with solid state atoms.

The application of BSE detectors makes it possible to separate topographic and material contrasts which is very advantageous when the detailed interpretation of SEM images is required (electronics, metallurgy, medicine, chemistry, biology). The BSE signal is a useful tool for identification of elements on a specimen surface as well as for determination of surface topography, thin film thickness, crystal orientation and location of crystal lattice defects [2]-[4].

All the experiments have been done on JEOL/JSM-35 SEM.

2. BSE detectors in a SEM

In numerous applications of the BSE signal different detector systems, such as semiconductor detectors [5], scintillator detectors [6] and BSE to SE converters [7] can be used.

Great amplification, small dimensions and high signal-tonoise ratio (S/N) are the main features of semiconductor detectors. Their frequency band is usually about 100 kHz, although we can notice successful application of semiconductor detectors in the frequency range of a few MHz [8]. The active area is arranged either by the shallow p-i-n junction or by the Schottky junction with dimensions ranging from several to several hundreds mm^2. Semiconductor detectors, considering their construction (p-i-n junction depth, contact layer thickness), can detect BSE of energies over several keV.

Scintillator detectors are commonly used for SE signal detection in a SEM, as well as for BSE signal detection. They are characterized by a high frequency band (up to several GHz), great amplification (photomultiplier), high S/N ratio and high collection efficiency. We can distinguish directional detectors (e. g., Everhart–Thornley detector), wide angle detectors (e.g., Robinson detector [9]), and the detectors with the energy filter.

Another possibility is the detection (of BSE) by converting BSE to SE at a negatively biased converter plate coated with the material of a great secondary emission coefficient. The high frequency, high S/N ratio and high detection efficiency are the main advantages of the BSE detector systems containing a converter. This system can be used successfully at low accelerating voltages of electron beam (< 1 kV).

In the recent papers, we can notice a new tendency in electron microscopy towards a simultaneous application of signals coming from several different detectors. It makes possible the registration and observation of the sum and the difference of signals as well as the more complicated mixture of signals [10]–[12].

3. Detector system construction

At the Institute of Electron Technology, several types of BSE detector systems have been worked out as specialized systems for a SEM. The construction of the converter and multiple detector system has been presented in Figs. 1–3. The converter design

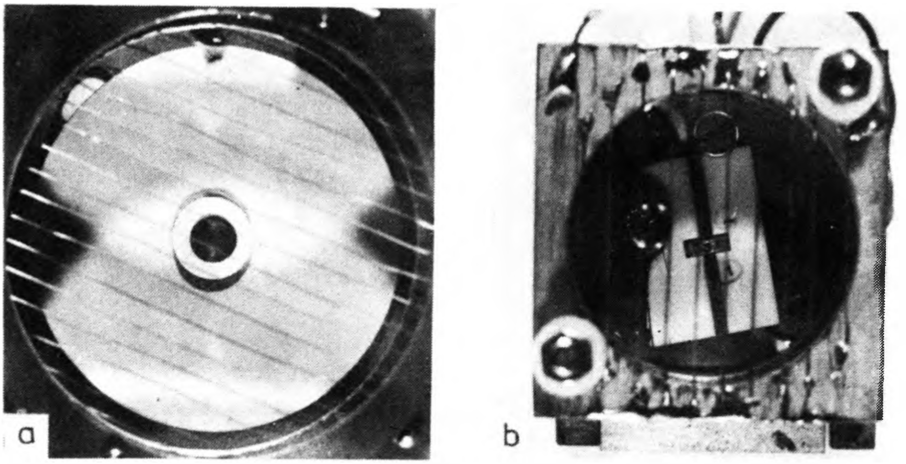

Fig. 1. Converter design (**a**) and specimen holder (**b**)

was based on the Reimer–Volbert construction [4] to which certain modifications were introduced. The converter consists of the copper-clad board coated with a thin MgO film and fixed to the polepiece. Below the plate the shield grid has been placed so as to make possible SEM imaging in the standard SE mode (Fig. 1**a**). The specimen holder with a grid separating secondary electrons is shown in Fig. 1**b**. The arrangement of four semiconductor detectors with the p-i-n junction of 25 mm^2 area on the ring below the SEM objective lens is presented in Fig. 2. It makes possible the BSE signal detection in three ranges of take-off angles: low (23°), medium (40°-58°) and high (78°). Take-off angles have been calculated upwards from specimen surface.

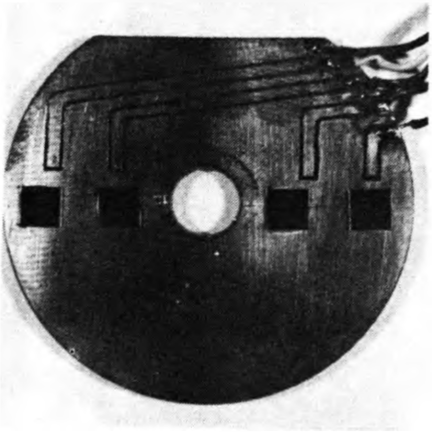

Fig. 2. Arrangement of four semiconductor detectors for BSE signal detection

In order to achieve BSE detection at larger solid angles, the detectors with the area of 100 mm^2 have been used. The arrangement of two semiconductor detectors for BSE detection in the range of low and high take-off angles is shown in Fig. 3. Semiconductor detectors with the p-i-n junction have been produced at the Institute of Electron Technology.

Current amplification characteristics for the detectors mentioned above are

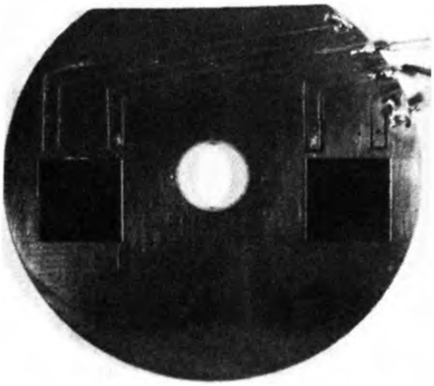

Fig. 3. Arrangement of two semiconductor detectors for BSE signal detection

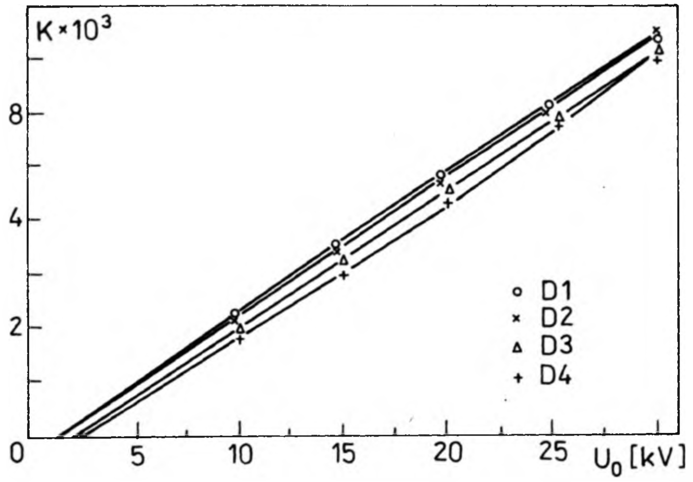

Fig. 4. Current amplification characteristics for detectors of 25 mm² area (U_0–accelerating voltage, K – detector amplification, $K = I_D/I$: I – current reaching a detector, I_D – current leaving a detector)

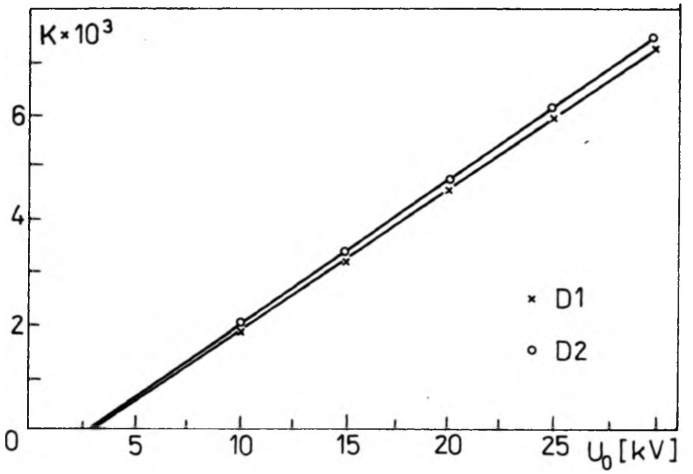

Fig. 5. Current amplification characteristics for detectors of 100 mm² area

presented in Figs. 4, 5. The average current amplification of detectors at the voltage $U_0 = 25$ kV was about 6000 fold. The measurement set-up has been prepared for processing the BSE signal coming from several detectors.This system consists, among other things, of pre-amplifiers which are able to rectify the possible differences in amplification of particular detectors.

4. Arrangement for measuring the BSE signal

The block diagram of a measuring system for the BSE signal originating from the specimen is shown in Fig. 6. The arrangement consists of four pre-amplifiers of signals coming from detectors, signal selector, systems accomplishing summation

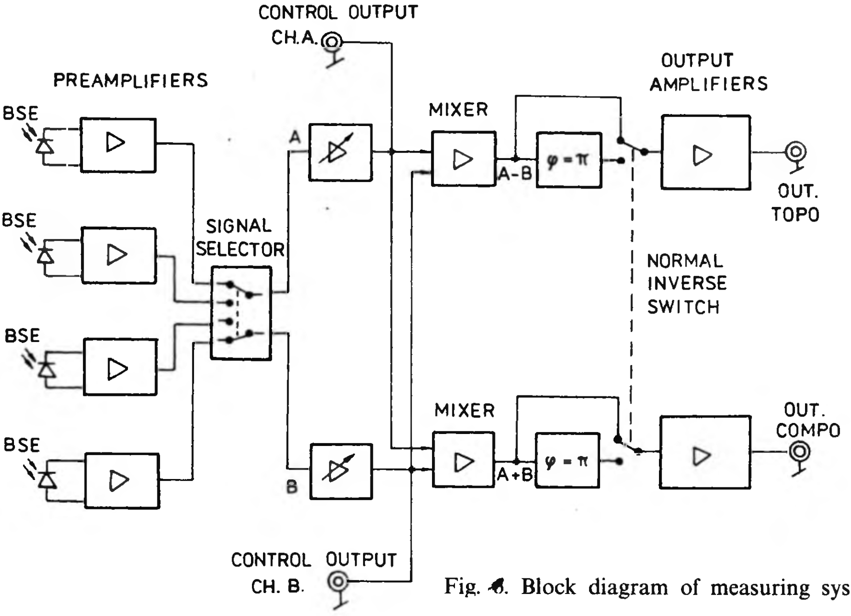

Fig. 4. Block diagram of measuring system

and substration of signals (mixer) and output amplifiers. This system has been designed and made at the Institute of Electron Technology. Particular functions realized by individual parts of the electronic system have been described below. Pre-amplifiers have been used in order to make easier the choice of various detection angles during surface investigation without necessity of aerating the microscope chamber and the respective on and off switching. The selector block makes possible the selection of two signals, which after having been amplified are subsequently led to control sockets. These both signals are directed to a block accomplishing either difference (A − B) their sum (A + B). Finally, TOP and COMPO signals are received and topographic and material contrast can be observed, respectively.

5. Results of surface investigation using SEM

Two main types of contrast namely topographic and material contrasts are most frequently applied in a SEM. The singal can be used in a SEM for observation of topographic contrast because the number of BSE leaving a specimen depends, among others, on the incidence angle of primary electron beam [6]. Based on the experimental results it has been confirmed that a better topographic contrast can be obtained when BSE are detected at low take-off angles. Such a signal can be obtained from detectors placed at a greater distance from the centre of a fastening ring (Fig. 2). It has been also stated that topographic contrast increases when there is the difference in signals coming from two opposite detectors, since then the background signal is almost completely reduced.

The BSE signal can be used for observation of material contrast in a SEM as also due to the fact that the number of BSE leaving a thick specimen depends almost linearly on the atomic number Z of the element [2]. The situation becomes more complicated when a non-homogeneous specimen with an extended surface is considered. In this case, the detection of the BSE signal from only one detector makes possible the observation of SEM images with superposition of topographic and material contrasts.

Based on the experimental results [13], it has been noticed that a better material contrast is observed during detection of the BSE signal at high take-off angles (60°–90°). Such a signal can be received from detectors placed closer to the centre of a fastening ring (Fig. 2). Moreover, the sum of signals coming from two opposite detectors is frequently used, especially to eliminate the topographic contrast to the highest degree.

BSE images of specimen surfaces obtained by means of the converter (arrangement from Fig. 1) and semiconductor detectors are shown in Figs. 8–11. The description of BSE images has been performed by introducing the following abbreviations:

SE – micrograph obtained by means of secondary electrons originating from a typical scintillator (normal mode),

BSE/SE – micrograph obtained from the BSE to SE converter,

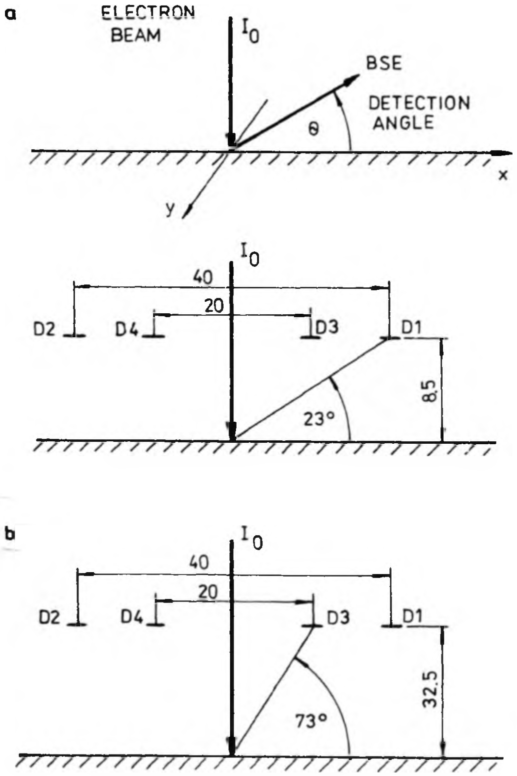

Fig. 7. Schematic illustration of the arrangement of four detectors on the ring with respect to the specimen: **a** – BSE detection at a low take-off angle, **b** – BSE detection at a high take-off angle

TOPO-micrograph due to the difference $S_1 - S_2$ of BSE signals coming from detectors D1 and D2 presented in Fig. 7**a**,

COMPO-micrograph due to the sum $(S_3 + S_4)$ of BSE signals coming from detectors D3 and D4 presented in Fig. 7**b**.

BSE images obtained by using SE and BSE/SE modes are presented in Fig. 8. Both the micrographs have been made under the same conditions. In the case of a normal SEM work (SE mode), the amplification level should be increased and contrast considerably improved. The signal received from the converter is about two times higher than that coming from the scintillator.

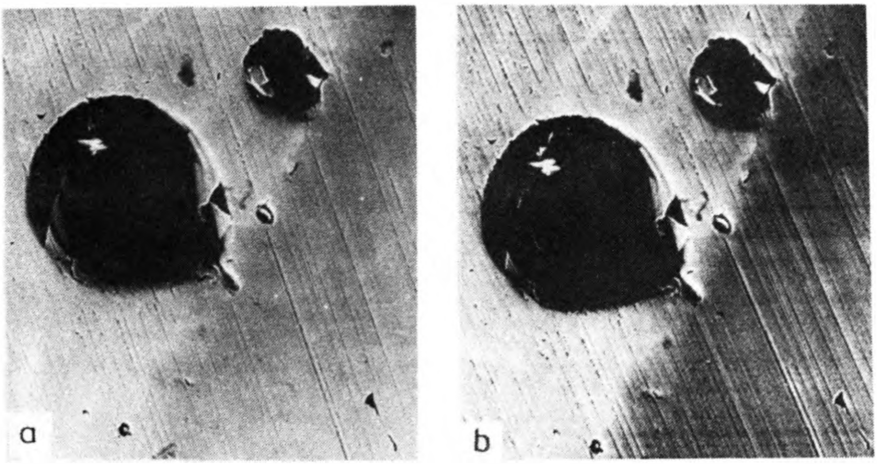

Fig. 8. BSE images of a grinded cross-section of Ta-Mo weld obtained using: **a** – scintillator (SE), and **b** – converter BSE/SE; 200 ×, $E_0 = 25$ keV

As shown in Figure 8**b**, the BSE/SE mode makes it possible to get the SEM image with material contrast considerably better in comparison with the SE mode. The converter can collect BSE only at a large solid angle and there is no possibility to separate entirely material and topographic contrasts. Such a possibility can be, however, given by detector systems consisting of several semiconductor detectors.

BSE images of the grinded cross-section of Cu-Ta weld with noticeable topographic and material contrasts are presented in Fig. 9. In the TOPO image the scratches arising from grinding are clearly seen but, the boundary of Cu-Ta weld penetration can be observed in the COMPO image (a bright area corresponds to Cu $(Z = 73)$).

BSE images of a sheet brass surface are shown in Fig. 10. We can notice the essential difference between the images obtained using SE, TOPO and COMPO modes. The superposition of topographic and material contrasts is noticeable in the SE image.

The influence of change of the detection angle θ for the BSE signal on the SEM image of the specimen surface is shown in Fig. 11. We can notice a much better

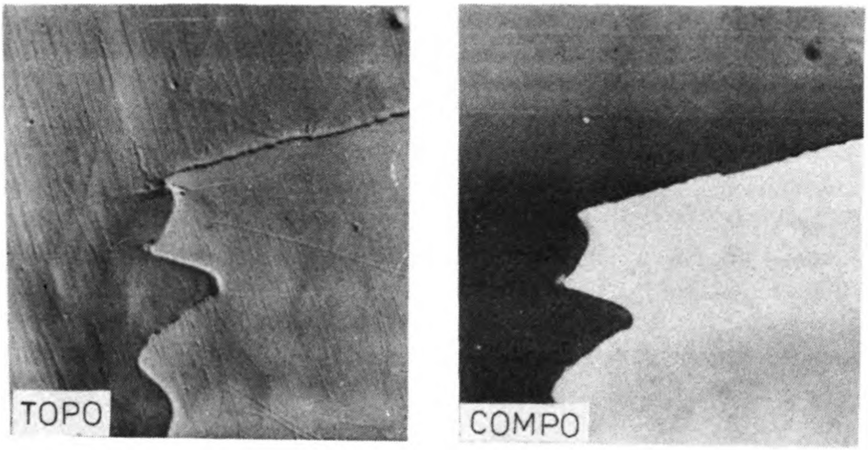

Fig. 9. SEM images of a grinded cross-section of Cu-Ta weld (200 ×)

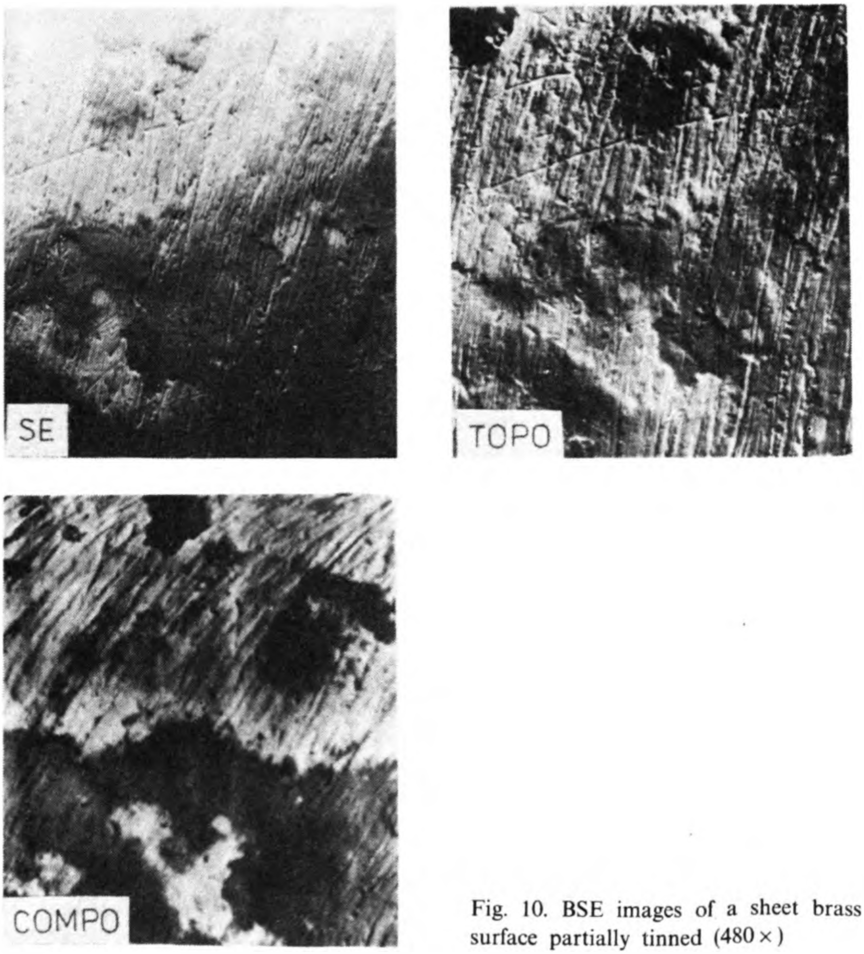

Fig. 10. BSE images of a sheet brass surface partially tinned (480 ×)

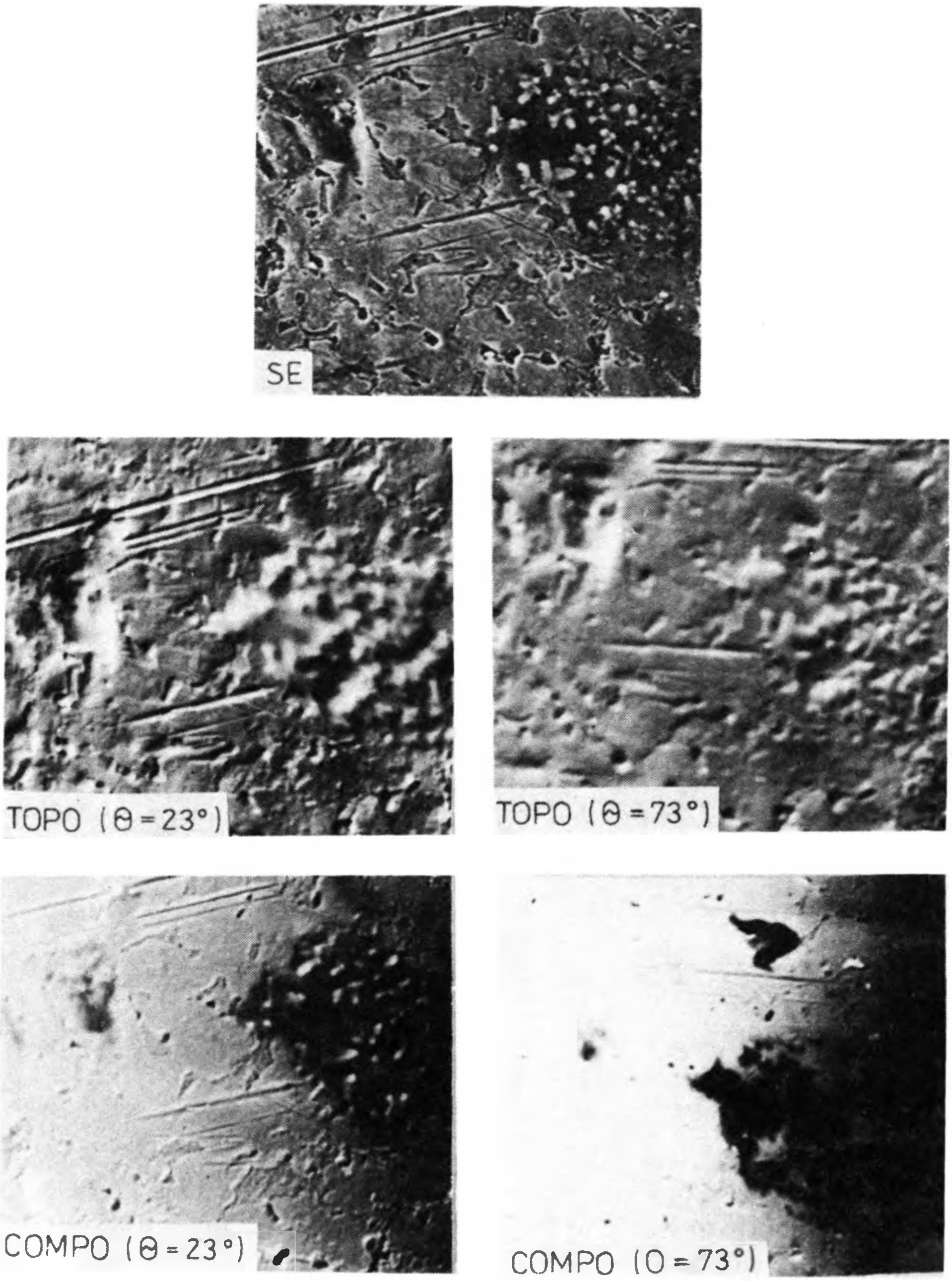

Fig. 11. BSE images of a brazen specimen surface obtained at different detection angles θ (540 ×)

topographic contrast at $\theta = 23$, but a more distinct material contrast at $\theta = 73$. The BSE image obtained from the scintillator contains both superposed contrasts. BSE images received using detector systems consisting of two semiconductor detectors at a large detection angle are presented in Fig. 12.

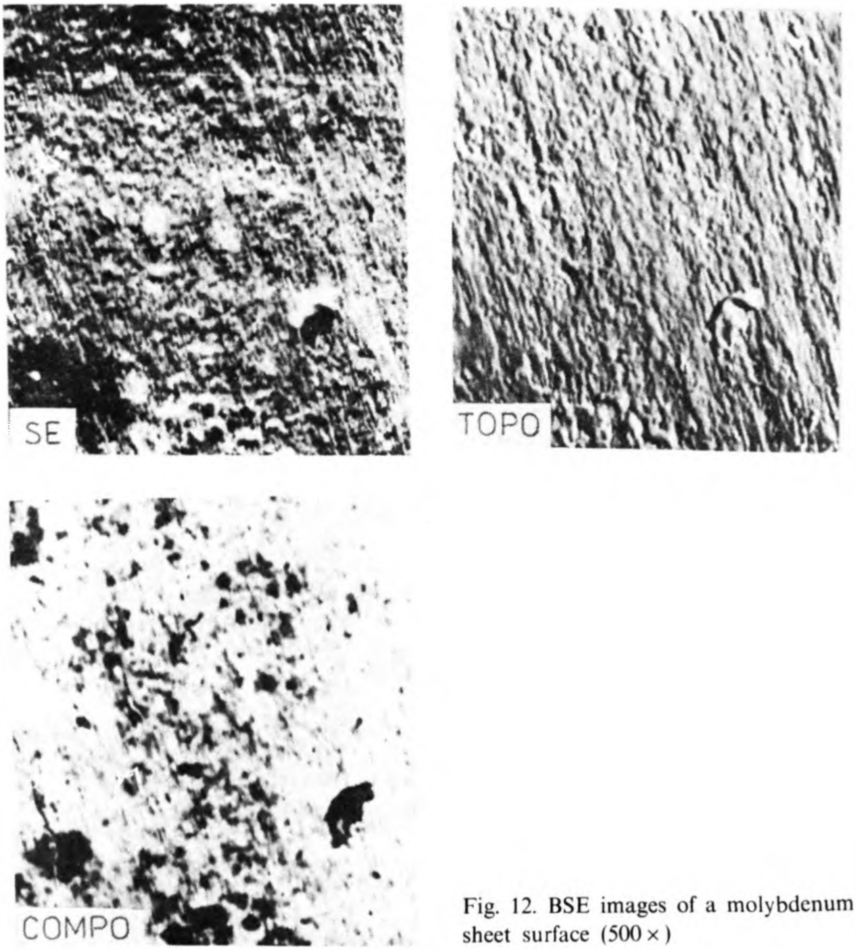

Fig. 12. BSE images of a molybdenum sheet surface (500 ×)

From the presented above BSE images it follows that the SE mode makes it possible to get the image of a specimen surface with a strong edge effect (artificially intense brighting of sharp edges). This effect does not occur in the images obtained by using the BSE mode.

6. Summary

The possibilities of utilization of the BSE signal in a SEM for investigation of material properties have been presented. Based on the experimental results we have shown the application ranges of two types of detector systems, i.e., the converter and semiconductor detectors. The electronic system for amplifying and processing BSE signals coming from several detectors has been also proposed. Both the types of detector systems can be easily set up in various types of scanning electron microscopes. This possibility extends the applicability of the above systems to different branches of science (e.g., medicine, biology, mineralogy, mechanics).

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Системы детектирования обратно рассеянных электронов для формирования изображения в сканирующем электронном микроскопе

В статье представлены различные системы, которые можно применять в сканирующем электронном микроскопе для формирования электронного изображения при помощи пучка обратно рассеянных электронов. Такие системы детектирования позволяют получить разделение материального и топографического контрастов. В настоящей работе сравнены также изображения поверхностей, полученных посредством конвенционального сцинтилляционного детектора вторичных электронов, а также детекторов обратно рассеянных электронов.