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A RING SCINTILLATION DETECTOR FOR DETECTION OF BACKSCATTERED ELECTRONS IN THE SCANNING ELECTRON MICROSCOPE

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Abstract

A backscattered electron detector with a cylindrical detecting surface has been constructed and installed in a scanning electron microscope. The detector surrounds the specimen and accepts electrons emitted into a specific range of zenith angles. In the case of untilted specimens it collects electrons emerging from the specimen surface at low exit angles relating to it. This enables us to obtain a good resolution of images of untilted specimens. Moreover, the detector gives very high level of topographic contrast and good three-dimensional impression of the specimen shape.

KEY WORDS: Scanning electron microscopy, backscattered electrons, electron detector, topographic contrast, resolution.

Introduction

Many different backscattered electron (BSE) detectors have been constructed for the use in a scanning electron microscope (SEM). They differ in a collecting angle, a response to electrons with different energies, a uniformity of the detection efficiency over a detector surface. They can be differently situated in relation to an electron beam and a specimen. They give different information about the specimen surface. The detectors have been reviewed by Robinson (1980, 1984). The most popular ones are wide angle detectors placed above the specimen. They show mainly material contrast. The topographic contrast is low and the information depth (thickness of a layer in which a signal originates) is large because electrons reaching the detector mainly diffuse through the specimen. The topographic contrast is more pronounced when the detector is placed at one side of the electron beam. Scintillation detectors are mainly used in such a case. They subtend different collecting angles and are located at different take-off angles. The decrease of the take-off angle (measured between a specimen surface and the direction from the specimen to the detector) increases a topographic contribution to the obtained contrast. In a specific case, when the specimen is highly tilted and the take-off angle is low, the topographic contrast dominates and the information depth is small (Wells, 1970). However, because of a foreshortening of images and strong shadowing effect, such configuration is not widely used.

In the present paper a ring scintillation detector for BSEs is proposed. It surrounds the specimen and accepts electrons emitted into a specific range of zenith angles. In the case of untilted specimens it collects electrons which emerge at low exit angles from the specimen surface. Between such electrons, there are many which have lost small amounts of their initial energies and penetrated a thin layer below the surface. We can expect that in the case of the ring detector the material contrast will be suppressed, the resolution of images will be improved and the shadowing effect, in comparison to the case when a disc detector is placed at one side of the specimen, will be reduced. The problem of detection of electrons with a ring detector has been studied theoretically by other authors. George and Robinson (1977) found that detection of BSEs emerging from the surface at low angles enables one to detect small topographic features on untilted specimens. Reimer and Riepenhausen (1985) found that the ring detector gives very high levels of topographic contrast. They studied the case when topographic features are larger than the interaction volume of the electron beam, i.e., in low and medium magnification ranges.

Experimental arrangement of the ring detector

The detector design is shown in Fig. 1. It consists of a cylindrical hole, 25 mm in diameter, in a glass light guide. The inner surface of the hole is covered with a plastic scintillator by painting the surface with the solution of scintillator material in toluene. The whole light guide, except for the surface facing photomultiplier, is coated with a thin layer of aluminium. The aluminium coating prevents charging of the light guide surface and maximizes the light output from the light guide.

The specimen is placed at the centre of the hole. Its position in z direction is adjusted to fit the required range of angles accepted by the detector. When the specimen surface coincides with the bottom plane of the light guide (working distance WD= 15 mm), electrons leaving the specimen surface at take-off angles from 0^o to 20^o are collected by the detector. This is the best condition for detection of the small topographic features on the surface of a flat, untilted specimen (George and Robinson, 1977) and the topographic contrast is very high (Reimer and Riepenhausen, 1985). A shadowing effect will occur if there are deep depressions in the specimen surface. When we place the specimen below the bottom plane of the light guide, the range of take-off angles collected by the detector will change. For instance, when the specimen surface is situated 2 mm below the bottom plane of the light guide (WD= 17 mm) the detector accepts electrons leaving the surface at angles from 10^o to 30^o. In such a case the topographic contrast decreases, the resolution worsens but the shadowing effect is less pronounced. At normal incidence of the primary beam an angular distribution of BSEs fulfils a

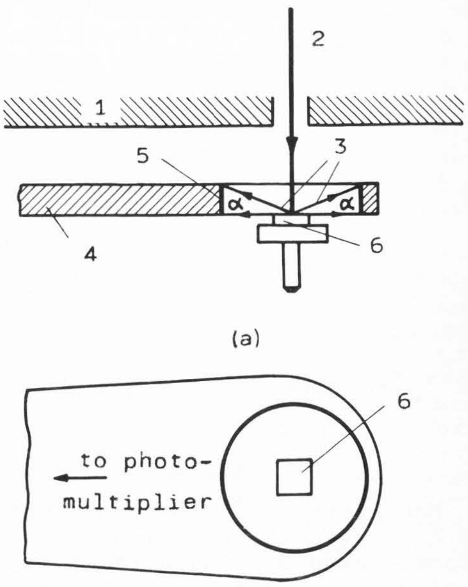

Fig. 1 Schematic diagram of the ring detector (a) - cross section, (b) - top view. 1- microscope lens, 2- primary beam, 3- backscattered electrons, 4- light guide, 5- layer of scintillator, 6- specimen. α is an acceptance angle of the detector.

cosine law and for this, the number of electrons reaching the detector increases with an increase of the take-off angle. Shifting the range of angles accepted by the detector to higher values causes an increase of the mean value of the signal. In the case of a normal incidence of a primary beam, backscattered electrons emitted in the range of zenith angles from 0^o to 20^o are equal to about 11.7 % of the total number of BSEs emitted from the specimen. By shifting angles accepted by the detector to the range from 10^o to 30^o we increase this value to about 22 % of the total number of BSEs.

A light collection efficiency of the light guide, i.e., the amount of light generated at a certain point of the hole and reaching a photomultiplier is not uniform over the detector surface. The highest contribution to the signal originates in the part of the hole nearest to the photomultiplier, the lowest contribution originates at the opposite side. Therefore the detector is a directional one. This will be an inconvenience when we intend to obtain quantitative results but it will become an advantage when we perform qualitative assessment of the topography. Micrographs taken with the directional detector are more similar to those we meet in our daily experiences when we observe things illuminated by light (Reimer et al., 1984).

The detector was installed in a Cambridge Stereoscan 180 SEM. It was mounted in the place of a standard Everhart-Thornley (E.T.) detector for secondary electrons (SEs). Changing from BSE to SE imaging was performed by replacing the detectors. A thermionic W cathode was used as an electron source in the microscope.

Experimental results

In order to evaluate the usefulness of the ring detector, we recorded micrographs of different specimens. Fig. 2 shows a high magnification image of a magnetic tape. A resolution (as a gap between two grains) of 20 nm is shown and a better one can be claimed. This is a satisfactory result in the case of a relatively high beam current of $5 \cdot 10^{-10}$ A. It has been mentioned earlier that BSEs emerging from the surface at angles from 0^o to 20^o are only about 11.7 % of the

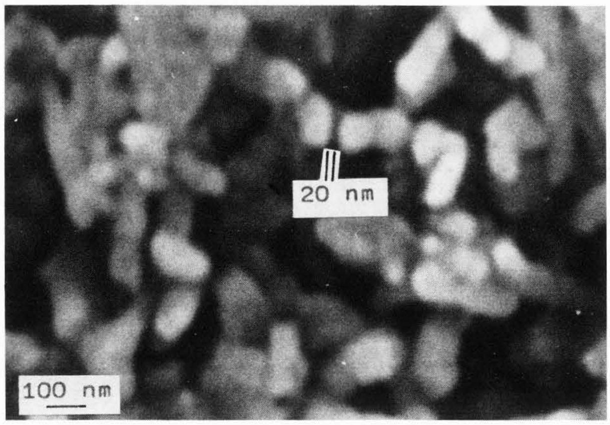

Fig. 2 An image of a gold coated magnetic tape taken with the ring detector. U_o= 40 kV, I_o= $5 \cdot 10^{-10}$ A, untilted specimen, WD= 15 mm.

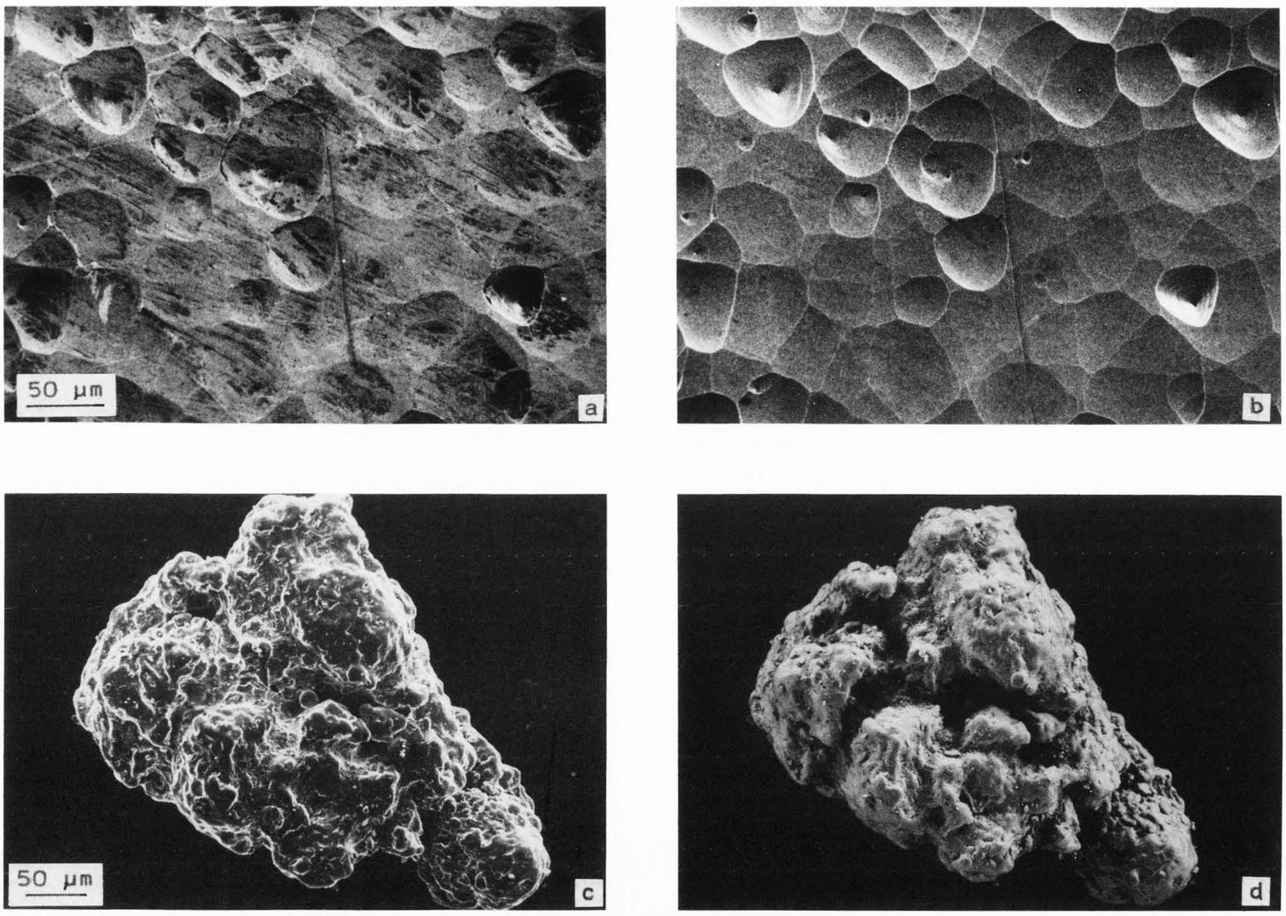

Fig. 3 A comparison of images taken with the ring detector for BSEs and the E.T.detector for SEs. (a) and (c) - SE images, (b) and (d) - BSE images, (a) and (b) - a surface of chemically etched GaAs wafer, (c) and (d) - an iron grain. U_o= 20 kV, I_o=$4 \cdot 10^{-10}$ A, untilted specimens, WD= 17 mm.

total number of BSEs emitted from the specimen. Assuming normal incidence of the primary beam and backscattering coefficient $\eta = 0.3$ we obtain a value of $1.8 \cdot 10^{-11}$ A for the electron current reaching the detector. This fact does not enable one to use a low beam current and obtain a low beam diameter. With an increase of a beam voltage the beam parameters improve (beam current increases and beam diameter decreases) but an available contrast decreases because of a larger penetration volume of an electron beam. An accelerating voltage of 40 kV was a balance between improving of beam parameters and worsening of the contrast.

In Fig. 3, BSE images taken with the ring detector and SE images taken with an E.T. detector are compared. In the topographic contrast we can distinguish two contributions. One depends on the number of electrons emitted from the specimen surface as a function of its roughness (emission contrast), the second depends on the number of detected electrons as a function of their exit momenta (collection contrast). In the case of the E.T. detector an emission contrast predominates, while in the case of the ring detector a collection contrast plays an important part. For this reason, the ring detector is more sensitive to small variations in the inclination of the specimen surface (compare apparently flat regions in Fig. 3a with the same regions in Fig. 3b). Moreover, BSEs are not so sensitive to a contamination of the surface as SEs. Comparing the images of an iron grain (Figs. 3c and 3d) we can notice that the ring detector gives images with better three-dimensional (3D) impression of the shape of the specimen. The strong edge effect in SE images defines exactly an extension of the feature but it leads to a wrong interpretation of the specimen shape.

Discussion and conclusions

It is clear from the examples shown that the ring detector can be very useful in observing different specimens. It should be added that similar to other BSE detectors it is less sensitive to the specimen charging and can be used to the study of uncoated specimens.

Its main disadvantages are a low signal level which implies the use of relatively high beam currents and a limitation of the space at the specimen. The first disadvantage is a common one for all BSE detectors used for imaging of a specimen topography of untilted specimens. It should be pointed out that the present construction enables us to detect electrons at low take-off angle with relatively high efficiency, compared to other detectors. The signal level of a ring detector can be increased to some extent by using a better scintillator material (e.g., YAG crystal). The standard E.T. detector cannot be placed simultaneously with the ring detector. A new E.T. detector needs to be constructed. Both detectors could be coupled to the same photomultiplier, similarly as in Autrata's double detector system (Autrata, 1984), or to separate photomultipliers. Another possibility, limited only to microscopes with an open polepiece bore geometry, is to place the SE detector above an objective lens of the microscope (Kawamoto et al., 1984). The space at the specimen can be enlarged by increasing the diameter of the hole in the detector. The detector can be divided into segments and coupled to the photomultiplier by means of flexible light guides.

The performances of the detector were checked with untilted specimens. Sometimes, we need to look at a specimen from particular direction by tilting the specimen. It can be done in the present construction, but in order to increase the signal from tilted specimens they should be placed at the top of the hole.

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Discussion with Reviewers

R. Autrata: Your detector is placed at a great distance from the polepiece so that WD may be shorter than 15 mm. The sample

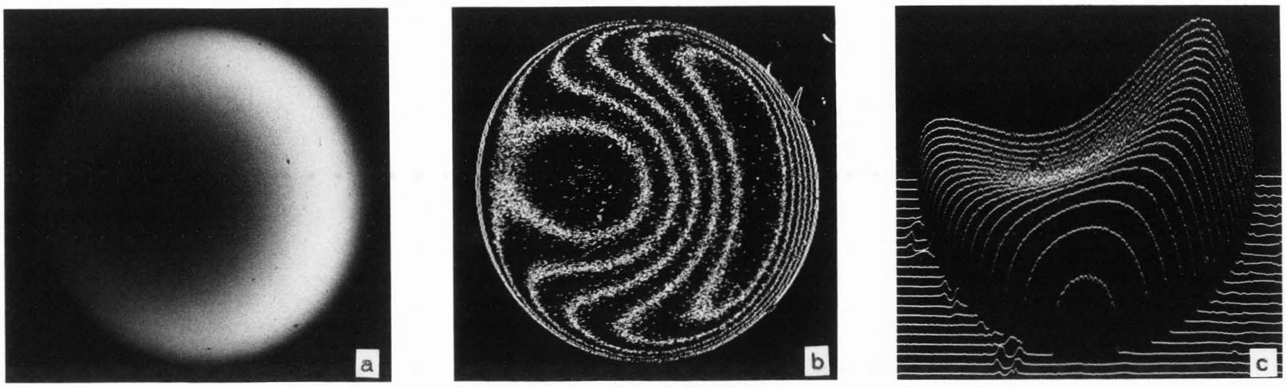

Fig. 4 Images of a 0.9 mm steel ball taken with a ring detector for BSEs. (a) - normal image, (b) - isodensities, (c) - Y-modulation image of a lower half of the ball. U_0=20 kV, WD=15 mm.

may be then tilted in the direction to the photomultiplier or away from it. In this way it is possible to measure the directivity of your detector. Could you evaluate the efficiency of light collection from the side of the detector facing the photomultiplier or from that diverted from the PMT?

Author: The directivity of the detector can be also evaluated by making micrographs of a ball. Such specimen scatters electrons in all directions. In Fig. 4 images of 0.9 mm steel ball are shown. From the linescan across a ball centre we can evaluate the efficiency of light collection from the side of the detector diverted from the photomultiplier as equal to 0.4 of that from the side facing the photomultiplier.

D.C. Joy: The spatial resolution of the image could be further improved by restricting the detector to only high energy electrons- i.e. those which have lost little or no energy in the sample. Have you experimented with either a metal coating on the scintillator, or even a retarding field, to try and achieve this result ?

Author: I have not done such experiments. I think that a metal coating on the scintillator would not be a good solution because it would cause a decrease of the signal strength. A retarding field analyser seems to be a very useful device in a ring detector system.

R. Autrata: The plastic scintillator has a very low electron radiation damage resistance. And this resistance decreases with increasing the energy of the primary beam and consequently also the energy of BSEs. You used E_0= 40 keV, which is rather a high value, or E_0= 20 keV. Can you give the dependence of converse efficiency of your thin film scintillator on time ?

Author: I have not studied a resistance of my scintillator to an electron radiation damage. We can expect that the resistance is rather low and replacing a plastic scintillator with a monocrystalline scintillator would improve performances of the detector. I used a thin film plastic scintillator because of simplicity of its preparation.

D.C. Joy: Would it be possible to put two, or even three, such rings one above another so that you could switch to which ever gave the most useful contrast ?

Author: There is such a possibility but it would need an optical switch between detectors and the photomultiplier to connect only one detector with the PMT. I have mentioned in the paper that, to some extent, the range of angles accepted by the detector can be changed by varying a position of the specimen in z direction. Additionally, a movable screen, in the form of a tube, can be inserted into the hole of the detector. Setting the heights of the specimen and the screen we would be able to choose the best conditions for obtaining the most useful contrast.

R. Autrata: Our experiments have shown that by coating the light guide with aluminium the light signal output strength is affected. The reasons are imperfect reflectivity of light by aluminium and increased absorption due to multiple reflections. What is your experience with the uncoated or Al-coated light guide ?

Author: The reason for Al coating of my detector was its complicated shape. Without such a coating, the amount of light generated at the side of the detector diverted from the photomultiplier and reaching the PMT would be very small. I have not used an uncoated light guide in the present construction.