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Passive Mirror Imaging through a Solid-State Back-Scattered Electron Detector

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Introduction

The scanning electron microscope (SEM) is commonly used to obtain images of a wide variety of samples within a wide range of magnification factors from the order of 10 up to about $10^5\times$ [1]. This technique is usually applied, but not limited to, the investigation of conductive samples. This is because the interaction of the scanning beam with the sample generates a net charge on the sample surface. Thus, if the sample is conductive, the charge can be quickly disposed of to ground, away from the beam spot. If the sample in non-conductive, the sample becomes locally charged, giving rise to a distortion of the primary beam. In certain conditions, the charge stored on the sample is able to reflect back the incoming electrons, much like an electrostatic mirror. The phenomenon is called the electron mirror effect (EME). Evidence of this phenomenon has been given since the 1970's by SEM users [2,3]. Recently a similar effect involving ions in a focused ion beam microscope (FIB) has been observed by us [4].

Methods

The charging process of an insulating sample is typically obtained by rastering it with high energy electrons (in the range: 10 to 30 keV). In these conditions, the number of secondary electrons produced per incident primary electron, σ , can be smaller than unity thus leading to negative charging of the sample surface [5-7].

The charging process dynamics is exponential with time constant τ_e and saturates to a value Q_e^∞. These two quantities are related by the equation [4,8-11]:

$$\tau_e = \frac{Q_e^\infty}{[1-\sigma(\Delta V_s)]I_e} \quad \text{(Eq. 1)}$$

where $\sigma(\Delta V_s)$ is the secondary electron yield depending on the scanning potential ΔV_s and I_e is the current of the primary beam.

When the sample contains a trapped negative charge, the incoming electrons are repulsed by Coulomb interaction, thus electrons with sufficiently small kinetic energy are reflected back to different points in the microscope chamber, depending on the incoming direction, beam parameters and the amount of the trapped charge [2-4,11,12].

The process to get a conventional EME image involves the fact that the reflected electrons eventually hit the chamber walls and different objects within the chamber, giving rise to secondary electron emission with a rate determined by the materials hit by the electrons and the electron velocity. If a biased detector, like a channel detection electron multiplier (CDEM) or an Everhart-Thornley detector (ETD), is utilized as an active sensor, most of these electrons are attracted and detected, providing a mirror image of the inside of the microscope. This can be referred to as active mirror imaging (AMI). The comparison of an EME image with a photograph of the inside of the microscope chamber can easily reveal its different elements (Fig. 1).

In Fig.1 a comparison between a conventional AMI image obtained through the active CDEM sensor and a photograph of the inside of the FIB/SEM chamber is shown. It's easy to recognize all the elements within the microscope (see figure caption for details). The image is obtained after charging a PE sample by rastering with 20 keV electrons with a current of 0.6 nA and a dwell time of 50 μs, thus providing an injected charge of about 30 nC and an actual saturated charge estimated to be about 3 nC. Successive observation is made with 2 keV electrons with a dwell time of 50 μs through the CDEM sensor biased at a potential of 250 V.

In the present article, the process involved in the detection of electrons through the passive backscattered electron detector is investigated. In this case, when the electrons are reflected back by

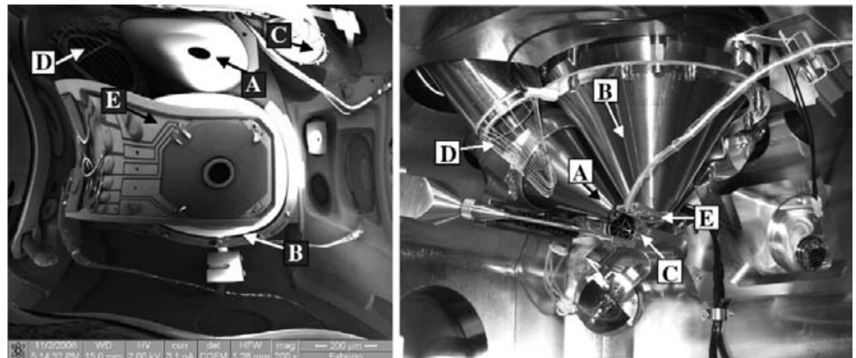

Fig. 1. AMI from a Polyethylene sample vs. photograph of the FIB/SEM chamber. In both cases the principal components can be clearly identified: (A) ion gun, IG; (B) electron gun, EG; (C) channel detection electron multiplier, CDEM; (D) Everhart-Thornley detector, ETD; (E) solid-state back-scattered electron detector, SSBSD.

the electrostatic mirror they hit the different components within the chamber and interact with the materials by producing secondary electrons that are weakly collected by the passive sensor, because they are not attracted to the sensor due to the absence of an Everhart-Thornley type biased grid. Only the electrons that impinge directly on the passive sensor are able to give a significant signal. These electrons are directed straight at the detector and have essentially the same energy they had upon exiting the electron gun (*i.e.* about 2 keV), while the secondary electrons produced all around the chamber have a much smaller energy (order of 100 eV) and the majority of them are not directed toward the SSBSD sensor. Therefore, only the primary reflected electrons contribute to image formation. This can be referred to as passive mirror imaging (PMI). The paths of electrons that are detected by the SSBSD detector can be described in four steps (the sample is previously charged):

- the electrons are accelerated by the scanning potential in the electron column, acquiring a kinetic energy $E_c = q_e\ \Delta V_s$, and are directed to the charged sample,
- the electrons are stopped at some distance from the sample surface by the Coulomb repulsion generated by the trapped charge, acquiring an electrostatic potential energy equal to the lost kinetic energy,
- the electrons are accelerated backwards,
- the electrons on a path straight toward the SSBSD detector, strike the detector with a kinetic energy that is essentially the same of step 1.

Of course, there is a probability that a secondary electron generated at some point in the microscope chamber, impinges on the passive detector, but that electron's contribution to the signal is negligible.

It's worth pointing out the difference of this mechanism with respect to what happens to a secondary electron detected by the

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biased grid of an Everhart-Thornley detector. In this case, the biased grid actually attracts most of the secondary electrons generated inside the chamber, providing information about points that are not geometrically accessible to the detector. However, electrons generated from surfaces oriented toward the detector are more likely to be collected, giving rise to an apparent illumination of the image (see Fig.1a) as if 'light' comes from the active detector.

Results

In Fig.2, a comparison between two images obtained in the EME conditions, but through different detectors is shown. For both images the sample was a Polyethylene (PE) film previously charged as detailed before.

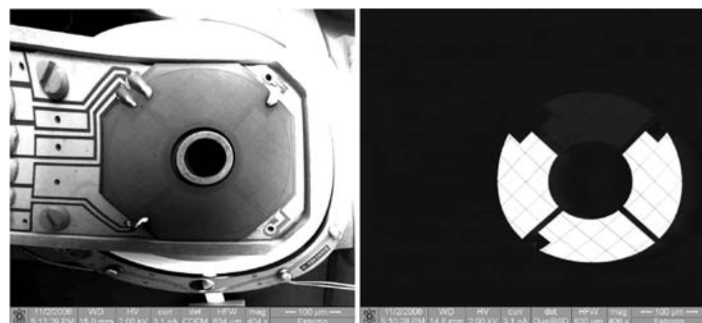

Fig. 2. Two images obtained in EME conditions with a previously charged Polyethylene sample. (a) AMI obtained through the CDEM detector. (b) PMI obtained through the SSBSD detector (A+B modality). From the latter it's easy to note that the upper sector is not working properly.

Fig. 2(a) is obtained through the CDEM detector and shows a typical AMI image where the SSBSD detector is observed in detail. The electrons coming from the gun are reflected back by the charged sample and hit the SSBSD detector generating secondary electrons collected by the CDEM sensor. Different gray levels correspond to different secondary electron yields, which depend both on the type of the hit material and on the angle between the hit surface and the primary electron direction. For example, while the SSBSD detector is reached by electrons moving nearly perpendicularly to its surface, the electron column is hit by electrons at less than 10°, yielding a much stronger secondary electron emission.

Fig. 2(b) shows a PMI image obtained through the SSBSD detector itself. In this case the reflected electrons are collected directly from the passive SSBSD detector, as explained before, thus providing an image of the working areas of the detector. Essentially no electron directed outside the detector area is collected so that the rest of the image is dark.

Fig. 2(b) is obtained in the so called '*Z* contrast' modality in which the signal coming from all four sectors of the sensor is summed. It is easy to detect that the upper sector was not working correctly at the time. Of course, in the EME condition, no information about the sample surface can be obtained from the two images, other than information about the amount of the trapped charge or trapping charge properties as already demonstrated in literature [4,6].

In Fig. 3, two PMI images, obtained through the SSBSD detector working in the two different modalities, are shown. The signal coming from the four sectors is electrically acquired as the sum of two neighbor sectors, thus providing two distinct signals that can be summed or subtracted. In conventional imaging, sum (A+B modality) provides information about the atomic mass number of the sample materials (*Z*-contrast), while subtraction (A–B modality) provides information about sample profile (profile-contrast). As

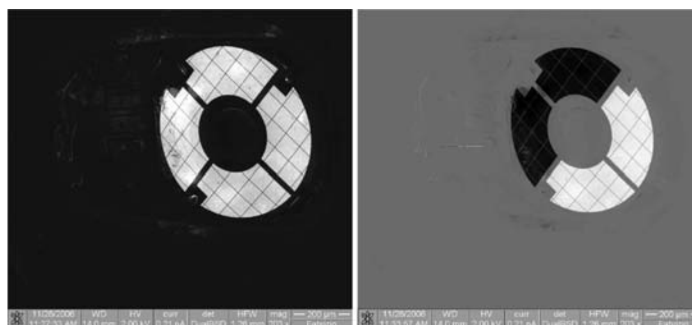

Fig. 3. PMI images obtained observing a Polyethylene sample through the SSBSD detector after its repair: (a) A+B modality and (b) A–B modality.

discussed, in the EME conditions, no information about the sample surface can be given, however these two images can clarify the working modalities of the SSBSD detector. The two images of Fig. 2 have been obtained after the detector repair, as can be seen.

Concluding Remarks

In the present article the acquisition of EME images through the passive SSBSD detector is discussed. To get the EME conditions, a non conductive PE sample is irradiated with high energy electrons and eventually the sample is observed with lower energy electrons. The charge accumulated onto the sample in the first step is able to reflect back the slow primary electrons of step two, some of which are sent directly to the passive detector. These electrons give rise to an image of the active zones of the detector itself, referred to as passive mirror imaging. This is helpful in understanding the working modalities of the SSBSD sensor and also to check if the sensor is working properly. ■

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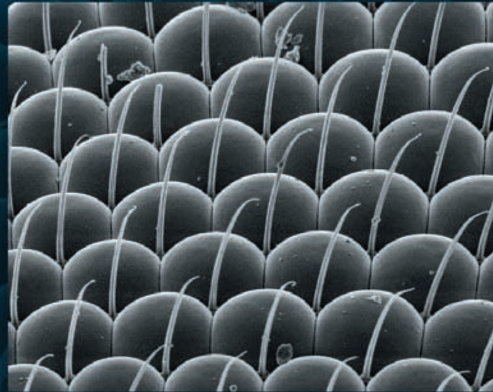

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