Energy Filtered Scanning Electron Microscopy: applications to characterisation of semiconductors

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Abstract. It has been recognised previously that limiting the maximum energy of secondary electrons used for image formation in a scanning electron microscope (SEM) generates contrast not present in standard SEM images. Here we give examples how energy filtered SEM improve the usefulness of SEM in the characterisation of semiconductors.

1. The concept of energy filtering in Scanning Electron Microscopy

In Transmission Electron Microscopy (TEM) energy filtered imaging is now a widely used technique as it is recognised that energy filtered images contain additional information to that of an unfiltered image. It is therefore surprising that energy filtering has not gained much attention in scanning electron microscopy (SEM) applications, where additional information can also be gained. This has been demonstrated using Auger analysis where contrast sufficient to distinguish differently doped regions in a semiconductor was generated purely by energy filtering [1]. In a different application it was demonstrated that contrast between copper and brass can be obtained by secondary electron (SE) energy filtering (EF), whereas there is no contrast in the unfiltered image [2]. Presumably the lack of availability of technical solutions for user controlled EF in main stream SEM instruments is responsible for the lack of a more widespread use of EF SEM in materials characterisation. Here we describe a low pass energy filter integrated in the lens of a field emission SEMs (FEI Sirion / Philips XL30) and present examples for useful applications in particular in the field of semiconductor characterisation.

2. Description and characterisation of low pass energy filter in FEI Sirion / Philips XL30 SEM

The work described here was carried out in an FEI Sirion / Philips XL30 field emission SEM, equipped with a through-the-lens-detection (TTL) option. The TTL system consists of an extractor tube that can be positively biased (Tube bias, \( T \)). This is used to direct SEs escaping from the specimen towards deflection electrodes, consisting of three layers of electrodes of opposite potential. Each pair generates an electrostatic deflection field perpendicular to the optic axis. The function of the lowest layer is to deflect SEs towards the scintillation detector (Fig.1a). The strength of the deflection field can be adjusted by changing the deflector voltage, \( D \). Fig.1b is an acceptance diagram calculated for \( T=250V, D=60V \) at a working distance, \( WD=3mm \) (standard imaging). In the acceptance diagrams
black represent electrons that are detected and white represents no detection. Fig 1b demonstrates that SEs of all energies are detected, although for high energy SEs, detection is only possible for those emitted at angles larger than 40°. Fig 1c shows that reducing the deflector voltage to $D=6\text{V}$ prevents the detection of SEs with energies larger than 2.5 eV. Adjusting to $D=20\text{V}$ translates to a reduction of the maximum energy of SE to be detected to $10\text{eV}$ as can be seen from Figure 1d. Hence the TTL does work as a low pass energy filter.

Figure 1 a) Schematic cross-section of TTL detector (after Kazemian et al [3]), b) calculated acceptance diagram for SEs generated by 1keV incident beam, at $WD=3\text{mm}$, $T=250\text{V}$, $D=60\text{V}$, c) $D=6\text{V}$ d) $D=20\text{V}$.

3. Applications of EF in SEM

3.1 Voltage contrast:
Voltage contrast is used in the failure analysis of semiconductor devices. It is based on the principle that areas that have no conductive connection will charge and as result have a different potential. Here we demonstrate that EF can considerably enhance the contrast due to potential differences. This is evident by comparing the images in Fig. 2a and b. Both images were obtained from a silicon surface covered by native oxide using a 1keV primary beam, with identical imaging parameters such as working distance and beam current. A bias voltage in the form of a square wave was applied to the specimen during the scan. This is reflected in brighter and darker stripes in the image. The contrast between these stripes represents the contrast caused by a potential difference of 1 V. Fig 2a is an image collected with $D=20\text{ V}$ and Fig.2b is an image with $D=6\text{ V}$. The contrast between the regions biased with -0.5 V and +0.5V is improved by a factor of three with $D=6\text{V}$ compared to $D=20\text{V}$.
Figure 2 SEM images of a silicon specimen biased with square wave with amplitude alternating between -0.5V to +0.5 V. (a) $D=20$ V (b) $D=6$ V.

Figure 3 Plot of contrast of a biased copper specimen with respect to an unbiased specimen $C_{V0}$, for EF and unfiltered case and schematic representation of corresponding SE spectra. $C_{V0}=(I_V-I_0)/0.5(I_V+I_0)\times100$ where $I_V$ and $I_0$ represent the intensity in the biased and unbiased specimen images respectively.

To understand the origin of the substantial increase in sensitivity to potential differences in EF images, we first consider the effect of biasing a specimen on the SE energy spectrum. If a positive specimen bias is applied, the whole spectrum is shifted to lower energies (see insert in Fig 3). The application of a negative bias results in a shift of the entire SE spectrum to higher energies. The exact effect of this shift on the contrast as a result of specimen bias compared to the unbiased specimen, $C_{V0}$, depends therefore on the sign of the bias and its magnitude in relation to the shape of the spectrum, in particular the position of the peak. For most materials, the peak of the SE spectrum is located at several eV, with a 50% width of several eV (e.g. Silicon peak 4eV, width 6.5eV) [5]). An applied bias of +0.5 V will increase the number of SEs detected in the energy interval, 0-2.5eV (this interval corresponds to $D=6$V and is represented as $E_{\text{Max}}$ in Fig 3) resulting in an intensity increase in the EF image, and hence in a positive $C_{V0}$ (Fig 2b). In analogy, a negative bias will lead to a negative $C_{V0}$ in the EF image. This is confirmed by the experimental results shown in Fig 3.

Fig 3 also contains experimental results for the unfiltered case, where one would expect a small negative $C_{V0}$ for positive specimen bias, as SEs with very low energies are unable to leave the
specimen. For an ideal detector (detecting electrons of all energies and emission angles) we would expect $C_{V0} = 0$ for a negative specimen bias. However, we observe a small positive $C_{V0}$ as the negative bias affects the angular distribution of the emitted SE and the detector is non-ideal.

Fig 3 clearly demonstrates the superior sensitivity to potential contrast in an EF image, as long as the resulting shifts move the SE peak region in or out of the detected energy interval.

3.2 Dislocations in GaN
It is well known that Gallium nitride (GaN) has great potential for semiconductor devices especially when it comes to high power, low-noise and high-temperature operations. However, the electrical properties of GaN are strongly influenced by the presence of dislocations, and therefore the characterisation of potential changes associated with dislocations is of interest. Analysis is often carried out in TEM (Holography) which limits the analysis to small areas. As demonstrated above, small potential differences can be easily detected in energy filtered SEM and we show here that potential differences associated with dislocations can help to identify dislocations in the SEM. Fig 4 shows unfiltered (Fig. 4a) and filtered (Fig. 4b) images of the surface of p-type Gallium nitride. In the unfiltered image a number of dark spots (some marked by arrows) are visible. In the energy filtered image the contrast of the marked regions is reversed. The contrast reversal indicates that the marked regions have a different potential to the surrounding areas. As dislocations in GaN are known to be associated with potential differences, energy filtered SEM images could be used for easy identification of dislocations across large areas of wafer.

![Image](image_url)

Figure 4 SEM of p-type GaN surface dislocations marked by arrows (a) $D=60$ V, (b) EF: $D= 4$ V. Note that only the contrast related to dislocations is reversed while the overall contrast is not reversed.

4. Conclusion
We have demonstrated that EF SEM can be used to detect potential differences with very high sensitivity. This can be used to detect dislocations in GaN.

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