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Suri, Ashish, Pratt, Andrew orcid.org/0000-0002-0795-2640, Tear, Steven Philip orcid.org/0000-0002-1535-1327 et al. (2 more authors) (2017) Characterization of a Miniature Electron Energy Analyzer for Scanning Electron Microscopes. Journal of Physics: Conference Series. 012017. ISSN 1742-6596

https://doi.org/10.1088/1742-6596/902/1/012017

Journal of Physics: Conference Series

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To cite this article: Ashish Suri *et al* 2017 *J. Phys.: Conf. Ser.* **902** 012017

Characterization of a Miniature Electron Energy Analyzer for Scanning Electron Microscopes.

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Abstract. We report the design and experimental characterisation of a miniature detector for the scanning electron microscope based on the Bessel Box (BB) electron energy analyser which has a simple cylindrical geometry. We report on the simulation and operation of a prototype BB. The energy resolution of a single BB has been numerically calculated and experimentally characterised to be < 1%. This miniature electron detector is designed to be used close to the sample, alleviating the effects of the ambient electrostatic and magnetic fields.

1. Introduction

Advancements in scanning electron microscopy (SEM) have been one of the major nanotechnology enablers. A magnified image of the sample is generated in the SEM by bombarding it with an electron beam and detecting the electrons that scatter off the surface along with the electrons that are generated in the sample [1]. In conventional SEMs, the generated secondary electrons (SEs) are detected by the widely adopted Everhart-Thornley detector via a positively biased input-grid [2]. However, in doing so, the energy and angular information of the SEs are lost. This detector also collects other tertiary electrons that are generated from the specimen chamber walls by energetic backscattered electrons, thus reducing the signal quality obtained. Preserving the energy and angular information of the SEs is crucial to interpret the SEM image of the sample under study. Thus, a small-scale detector is required that can preserve this information and the performance of which is little affected under the influence of ambient electrostatic and magnetic fields inherent to electron microscopes. In this work we propose the use of the lesser known Bessel box (BB) electron energy analyser (EEA) [3]. We examine the operation of the Bessel box using SIMION 8.1 [4] simulations and experimentally test a prototype.

The BB has a very simple cylindrical geometry consisting of 3 electrodes: a central cylinder and two end caps/plates with input and output apertures (figure 1). The electric field generated by the voltages on these electrodes allow the BB to act as a band pass filter. Allen et al. [5] used a BB with annular ring input and output apertures whilst grounding the input and output electrodes. The major drawback of this design was the existence of multiple electron trajectories within the analyser. This problem was addressed by Stalder et al. by introducing a stopper on the optical axis inside the BB [6]. An alternative solution was recently introduced by Schwietz et al. by negatively biasing the output electrode at the same potential as the central cylinder electrode. This suppressed the higher modes from being detected and only the trajectories that are cylindrically symmetric can be detected [3].

2. Simulations

2.1. The Bessel Box

In this work we operate the BB in the retarding configuration very similar to Schiwietz et al. [3], wherein the central and output electrodes are shorted and negatively biased. The input electrode is grounded. The band pass filtering action is demonstrated in figure 1. A primary beam with a conical distribution (half angle = 14^{o}), is incident at the input electrode, whereby electrons experience the retarding radial and axial fields inside the BB. Electrons with energies less than the BB energy are repelled back as they are unable to overcome the energy barrier of the BB axial fields (figure 1(b)). This field decreases from a maximum at the central BB electrode walls to a minimum at the BB optic axis, thus causing the focussing action. For electron energies greater than the peak pass energy, the BB is unable to focus these at the output aperture, and only the on-axis electrons are detected as shown in figure 1(c). Electrons with energies closer to the peak pass energies are focussed at the output aperture (figure 1(a)) and can be detected at the collector plate. Simulations are carried out for a BB with internal diameter of 3 mm, length 6 mm and i/o aperture diameters which are 10 % of the BB diameter.

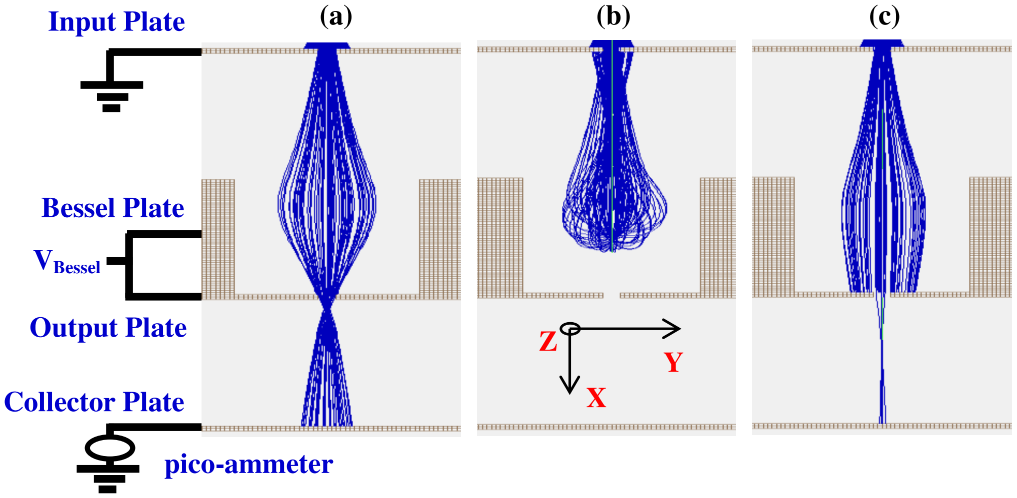

Figure 1. Simulation of electron trajectories in the BB. (a) For a given set of voltages the BB focusses electrons at the output aperture which are then collected. (b) Lower energy electrons have insufficient energy to reach the collector. (c) The BB is not able to focus higher energy electrons, however on-axis electrons do pass through.

2.2. Physics of operation: dispersion

The energy dispersion in the analyser leads to electrons being either stopped by the BB walls or collected through the output electrode (figure 2(a)). The electric field retards the electron velocity until it reduces to zero. To collect electrons within a narrow energy band, one has to define an output aperture. In this study the output aperture is placed on the optic axis at the output electrode. Figure 2(a) shows simulations of electrons entering at 11.2^{o} to the optic axis and their energy is varied from 10.01 eV to 12 eV in equal steps. The plot of Y-coordinates on the output electrode with respect to the energy (figure 2(b)) enables calculation of the energy resolution ($\Delta E/E*100$). For the output aperture which is 10% of the BB diameter, the pass-band energy window is calculated to be 0.22 eV, which gives a resolution of 2%. This can be improved to 0.95% by reducing the output aperture to 5% of the BB diameter. However, this results in the trade-off between the energy resolution of the analyser and its collection efficiency.

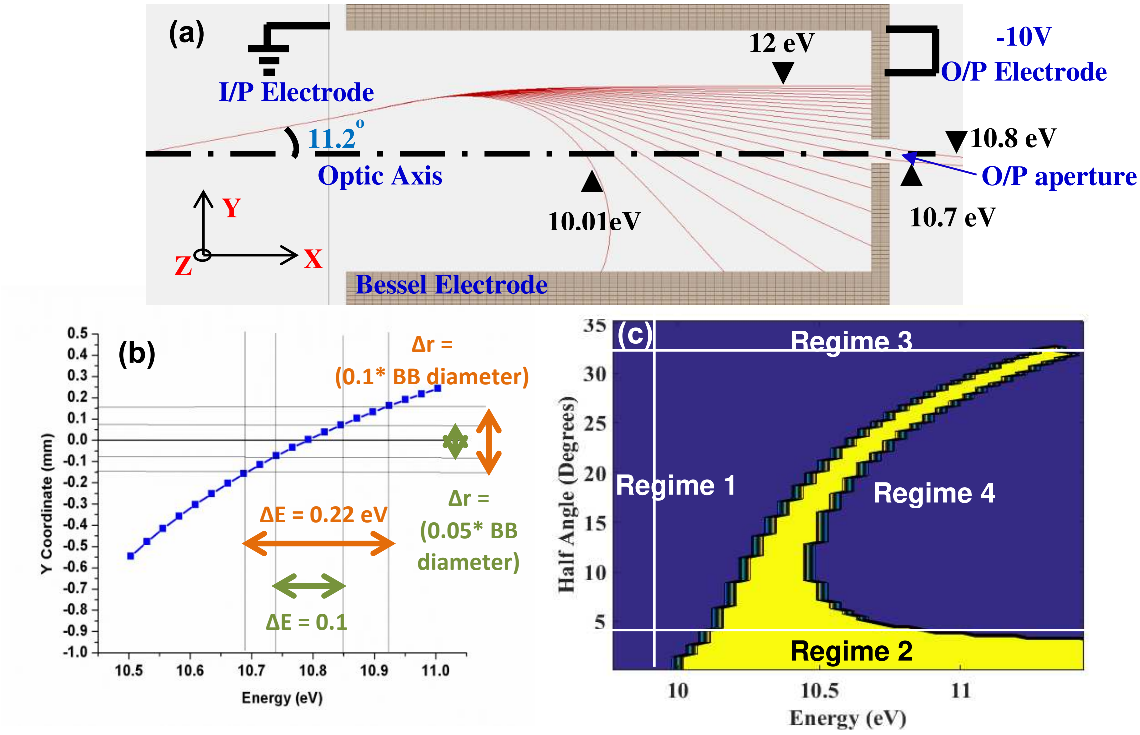

Figure 2. (a) The BB disperses the energies of the incident electrons. (b) The definition of the output aperture diameter results in the trade-off between collection and the resolution of the device. (c) The dispersion depends on the incident angle: yellow = electron detected, blue = no detection.

2.3. Physics of operation: angular dependence

So far the BB performance is assessed when the primary beam does not have any angular dispersion, which means all electrons are incident at the same angle. Practically this is never the case. An energy-angle convoluted surface-plot in figure 2(c) shows the detected electrons for a given a set of energies and angles, and the plot is divided into 4 regimes. Regime 1: Corresponds to lower energy electrons than the BB energy. Electrons with energies and angles within this regime are repelled back because axial velocity reversal takes place. Regime 2: The BB is unable to alter the on-axis electron trajectories as a result of which they go undeflected and are collected by the detector. For the BB to act as band-pass filter, the on-axis must be avoided. Regime 3: Corresponds to electron angles which are blocked by the geometrical design. Regime 4: This regime shows the focusing regime of the BB. There are two important points to be noted: firstly, electrons detected at higher incident angles are of higher energy, and secondly, the band-pass energy decreases with the increase in the incident angle.

3. Experimental Characterisation

A prototype BB was fabricated using 10mm x 10mm aluminium metal plates, which have thickness 5mm for the central cylinder and 0.2mm for the end caps and collector. The plates were biased using a high voltage operational amplifier (Kepco OPS 2000) controlled by a low voltage DC power supply (Keithley 2460). The BB was placed into a dedicated ultra-high vacuum chamber furnished with a hot cathode electron gun to directly illuminate the BB with a range of primary beam energies.

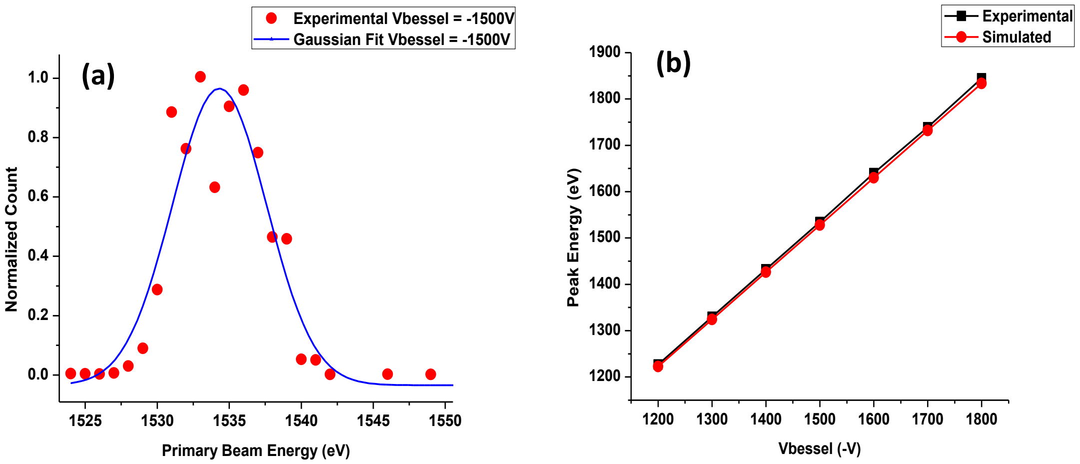

Figure 3. (a) Experimental Normalized Collector Currents (to peak value) for a BB at -1500V. The error in the counts is estimated to be about 10% of the count. An experimental peak energy of 1534eV is observed. (b) Peak Pass energy can be tuned linearly varying the Bessel voltage.

SIMION simulations were also performed for the described setup. Figure 3(a) demonstrates the band-pass action. A peak energy of 1534eV was obtained experimentally with a resolution less than 1%. The error in the count for each point is estimated to be about 10%. An offset between the BB energy (1500 eV) and the peak energy (1534 eV) is due to a convolution of the electron energy and the incident angle demonstrated in figure 2(c). Furthermore, the peak pass energy can be controlled by varying the voltages on the Bessel and output plates. A linear relationship between the peak pass energy and the applied Bessel voltage can be seen in experimental and simulated results of figure 3(b).

4. Conclusion

The simulation and preliminary results of a new SEM electron detector based on a Bessel box (BB) electron energy analyser is presented. The detector is of the band-pass configuration and shows an energy resolution of less than 1%, which should prove useful detecting the energy and angular distribution of secondary electrons. Further work is underway where an array of such BBs is being investigated. The small size of the BB makes it an attractive detector to add-on existing SEM and with better signal-to-noise ratio than the conventional ET detector.

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Acknowledgments

The authors would like to acknowledge the support of SIMDALEE2 consortium, FP7-PEOPLE-2013-ITN (Grant agreement No. 606988).