Proceedings of the Seventh International Conference on Charged Particle Optics

The energy dispersion characteristics of a magnetic beam separator

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Received 9 July 2008; received in revised form 9 July 2008; accepted 9 July 2008

Abstract

This paper presents an energy spectrometer design for scanning electron microscopy, where the spectrum of secondary, Auger and backscattered electrons can be captured at the same time. The spectrometer is based upon the use of a magnetic sector beam separator that deflects the primary beam while dispersing the scattered electrons. A series of retarding field magnetic sector post-deflectors is used to focus the scattered electrons on to a multi-channel detector plane. Initial simulation results predict that pre-focusing the scattered electrons into the beam separator via a transfer lens will significantly reduce the effect of angular dispersion and improve the beam separator spectrometer’s energy resolution.

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PACS: 79.20.Uv

Keywords: Electron energy loss spectroscopy; Energy dispersion; Magnetic separator

1. Introduction

Recently, a “Spectroscopic SEM” proposal made by Khursheed et al. [1,2] describes the possibility of redesigning the SEM so that it can capture the entire energy range of scattered electrons that leave the specimen. The new design, depicted in Fig. 1, is based upon the use of a magnetic sector deflector as a beam separator which bends the primary beam through a large angle, typically 90 degrees. The primary beam then enters a mixed field electric/magnetic immersion lens. The scattered electrons travel back through the objective lens, and are focused into the beam separator by a transfer lens. The beam separator now acts as the first stage of an energy spectrometer. Subsequent first-order focusing on to multi-channel detectors can be achieved through the use of additional magnetic sector/retarding field units. In the present paper, the energy dispersive characteristics of the beam separator are analyzed for a spectrometer designed to acquire the energy spectrum of secondary, Auger and backscattered electrons in parallel.

The beam separator consists of circular magnetic sector plates, which is able to both deflect the primary electron beam and act like a round lens, a feature known as “stigmatic focusing”. The primary beam aberrations of the beam separator have been analyzed in detail, and they are predicted to lie in the sub-nanometer range for SEM.
applications [3]. These predictions have recently been verified by experiment, and they are the subject of another paper presented at CPO-7 [4].

![Diagram of beam separator](image)

**Fig. 1. Schematic layout of beam separator energy dispersion action.**

BSEs, AEs and SEs denote backscattered, Auger and secondary electrons respectively.

**2. Field distribution simulations**

Simulation of the spectrometer’s characteristics requires accurate ray tracing of electron trajectory paths through curved magnetic sector plates. Since magnetic sector field distributions are inherently three-dimensional in nature, and in this case involve curved boundaries, direct ray tracing of electrons through them is a non-trivial task. Numerical field solving techniques such as the finite element method do not in general provide enough accuracy to extract aberration coefficients from the trajectory paths of focused beams in three dimensions. This is because numerical meshes in three dimensions that model complex shaped boundaries typically need over a million free nodes, requiring prohibitively large amounts of computer memory and unmanageably long program run times. The situation is made even more difficult for retarding sector units where an electric field is overlaid onto the deflecting magnetic field in order to slow down electrons to very low energies (a few eV). Another disadvantage of using a fully finite element approach is that high-order interpolation methods are needed to extract accurate field information from nodal potentials. While not impossible to carry out, this is quite a challenging task in 3D where the mesh density is relatively low. For all for these reasons, mesh-less methods are preferred. In the following work, a semi-analytical approach is taken, one which uses a modified two-dimensional finite element solution in combination with a Fourier-series expansion. This approach avoids the direct use of a fully three-dimensional finite element solution, and has the desirable feature of not requiring a mesh in the region where electron trajectories are to be plotted.

![Diagram of sector plates](image)

**Fig. 2.** Schematic layouts of sector plates having odd and even symmetry planes. The scalar potential $\Psi(x,y,z)$ represents magnetic fields in the case of odd symmetry and electric fields in the case of even symmetry. Consider a box with dimensions $a, b, L$ and in the $x, y$ and $z$ directions. A finite element solution in the plane of the plates, $\Psi(x,y,L)=g(x,y)$, is used as the potential distribution on top of the box region. In the case of magnetic deflectors, where $z = 0$ represents the odd-symmetry plane and the other sides have zero magnetic potential, as shown in Fig. 2a, the magnetic potential inside the box can be expressed as a double Fourier-series:
\[ \Psi(x, y, z) = \sum_{m,n} \frac{4}{ab\sinh(q_{mn}L)} \int_0^b g(x, y) \sin(k_m x) \sin(k_n y) dx dy \]

where \( k_m = \frac{m\pi}{a} \), \( k_n = \frac{n\pi}{b} \), \( q_{mn} = \sqrt{k_m^2 + k_n^2} \) and \( C_{mn} = \frac{4}{ab\sinh(q_{mn}L)} \int_0^b g(x, y) \sin(k_m x) \sin(k_n y) dx dy \)

For electric retarding field units, where \( z = 0 \) represents the even-symmetry plane and the other sides have zero electric potential, as shown in Fig.2b, the electric potential inside the box can be expressed as the following double Fourier series:

\[ \Psi(x, y, z) = \sum_{m,n} C_{mn} \sin(k_m x) \sin(k_n y) \cosh(q_{mn} z) \]

where \( k_m = \frac{m\pi}{a} \), \( k_n = \frac{n\pi}{b} \), \( q_{mn} = \sqrt{k_m^2 + k_n^2} \) and \( C_{mn} = \frac{4}{ab\cosh(q_{mn}L)} \int_0^b g(x, y) \sin(k_m x) \sin(k_n y) dx dy \)

The magnetic and electric fields in both cases can be simply obtained by differentiating equations (1) and (2).

A two dimensional finite-element solution capable of modeling curved boundaries is first performed in the plane of the sector plates (x-y plane), as illustrated in Fig. 3. In this example, circular sector plates have an inner sector plate, an outer sector plate, and an outer round casing. The outer sector plate is set to unity potential, while the inner sector and casing is set to zero potential. Fig. 3a shows the numerical mesh, Fig. 3b shows the initial 2D finite element solution, and Fig. 3c shows a modified 2D finite element solution for the central nodal coefficient \( P_0 \) adjusted by a factor of \( \left(1 + \frac{h^2}{2d^2}\right) \), where \( h \) is the mesh size in the x-y plane, and \( d \) is the distance to a zero potential odd-symmetry plane in the out-of-plane direction (z-direction). In this example, \( d = 1 \) mm, and \( h = 0.25 \) mm. As expected, the influence of the zero-volt odd-symmetry plane causes equipotential lines to bunch towards the sector plate edges. No adjustment of the 2D finite-element solution is required for the electrostatic distribution (even symmetry boundary).

A Fourier-series expansion then integrates the potential in the plane of the boundary and calculates field values for any point inside the sector unit. This semi-analytical solution provides reasonably high accuracy when compared to the full three dimensional solution, which in this case, can be calculated accurately by a rotationally symmetric finite-element program, since the in-plane geometry is circular. Fig. 4 illustrates the accuracy of the semi-analytical approach for electric field values in the x-y plane 0.1 mm above the zero-potential odd-symmetry plane (10% of the distance from the plates to the odd-symmetry plane). The accuracy is plot as a function of the number of terms used in the Fourier-series. The maximum electric field variation is divided by the maximum field strength value along a line running through the centre of the sector unit. Fig. 4 shows that only 90 terms are required to reduce the percentage electric field error to smaller than 0.1 %.
Fig. 3. Finite-element solution in the plane of circular sector plates
(a) 81 by 81 mesh (b) 2D solution (c) Modified solution to account for nearby zero-potential symmetry boundary located 1mm away

Fig. 4. Accuracy of electric field values along the x-y plane for z = 0.1mm. Distance from plane of plates to odd-symmetry boundary is 1 mm.

The beam separator is designed to have the same focusing properties on primary beam electrons traveling both “in-plane” (in the plane of deflection, (x-y) plane), and “out-of-plane” (perpendicular to it, (x-z) plane). This is achieved by segmenting the beam separator into two sections, a pair of inner plates and a pair of outer plates, as shown in Fig. 3. For the following spectrometer simulations, the beam separator shown in Fig. 3 is scaled by a factor of five, so that the diameter of the beam separator is 100 mm, and the gap between each pair of sector plates in the out-of plane direction (z direction) is 10 mm. The excitations on the inner and outer plates necessary to provide stigmatic focusing of a 10 keV primary beam deflected through 90 degrees are 85.85 AT and -12.14 AT respectively, see Ref. [3] for more details on simulating the primary beam aberrations through this beam separator for stigmatic focusing.

3. Direct ray tracing

Figs. 5 and 6 depict trajectory paths of scattered electrons that leave a -5 kV specimen and travel through a beam separator spectrometer layout that is designed to capture a wide-range of energies. Three magnetic sector post-deflectors separate scattered electrons having emission energies of 3, 500, 1000, 2000, 3000 and 5000 eV from one another. Due to the -5 kV biasing of the specimen, these electrons have kinetic energies of 5.003, 5.5, 6, 7, 8 and 10 keV respectively as they travel through the beam separator. Note that the 3 eV secondary electrons are mirrored back into the beam separator for a second pass. In Fig. 5, all scattered electrons are assumed to enter the beam separator with diverging ± 5 mrad angles emanating from a point source located 50 mm below it. In Fig. 6, they enter the beam separator with ± 5 mrad angles that converge directed towards the beam separator centre.
On comparing Figs. 5 and 6, it is clear that angular dispersion is greatly reduced where a transfer lens is used to focus the scattered electrons towards the beam separator centre. This effect is quantified by noting the exit angular dispersion at the detector plane, presented in Tables 1a and 1b. Also apparent from these Tables is the greater output spread angular spread for the secondary and backscattered electrons compared to the Auger electrons; they are typically an order of magnitude greater. This comes mainly from the design of the post-deflector magnetic sector units, which were designed to provide good dispersion (separation) of scattered electrons across the entire spectrum. They may well be other post-deflector designs that produce smaller angular dispersion for the secondary and backscattered electrons.

Table 1a
Output angular dispersion at the detector plane. Input rays are assumed to be diverging with angles $\pm 5$ mrad, emanating from a point 50 mm below the beam separator.

| Emission energy (eV) | 3   | 500 | 1000 | 2000 | 3000 | 5000 |
|----------------------|-----|-----|------|------|------|------|
| $\Delta \theta_1$ (mrad) | 220.01 | 20.50 | 23.10 | 26.91 | 30.74 | 304.39 |
| $\Delta \theta_2$ (mrad) | 141.20 | 23.90 | 21.91 | 24.28 | 28.62 | 216.25 |

Table 1b
Output angular dispersion at the detector plane. Input rays converge towards the centre of the beam separator with $0, \pm 5$ mrad angles.

| Emission energy (eV) | 3   | 500 | 1000 | 2000 | 3000 | 5000 |
|----------------------|-----|-----|------|------|------|------|
| $\Delta \theta_1$ (mrad) | 77.06 | 3.28 | 3.67 | 4.31 | 4.39 | 47.33 |
| $\Delta \theta_2$ (mrad) | 69.88 | 3.41 | 3.61 | 4.16 | 4.52 | 43.18 |

Table 1c
Output angular dispersion at the detector plane. Input rays converge towards a point 40 mm below the centre of the beam separator with $0, \pm 5$ mrad angles.

| Emission energy (eV) | 3   | 500 | 1000 | 2000 | 3000 | 5000 |
|----------------------|-----|-----|------|------|------|------|
| $\Delta \theta_1$ (mrad) | 257.13 | 7.70 | 7.32 | 7.68 | 7.82 | 68.18 |
| $\Delta \theta_2$ (mrad) | 232.13 | 6.72 | 7.62 | 8.33 | 8.91 | 75.52 |

Table 1d
Output angular dispersion at the detector plane. Input rays converge towards a point 20 mm above the centre of the beam separator with $0, \pm 5$ mrad angles.

| Emission energy (eV) | 3   | 500 | 1000 | 2000 | 3000 | 5000 |
|----------------------|-----|-----|------|------|------|------|
| $\Delta \theta_1$ (mrad) | 215.52 | 8.00 | 9.32 | 10.72 | 12.19 | 115.64 |
| $\Delta \theta_2$ (mrad) | 194.38 | 9.01 | 8.95 | 9.83 | 10.58 | 94.76 |
Tables 1c and 1d show the change in output angular dispersion when the input rays converge to different points, 40 mm below the beam separator centre in the case of Table 1c, and 20 mm above it in the case of Table 1d. They show that despite over-focusing by 40 mm at the beam separator input, the output angular dispersion for the Auger and backscattered electrons only goes up by a factor of 1.5 to 2. For the secondary electrons, it is similar to the diverging input case. This is an important result, since most the scattered electrons have energies well below the primary beam energy, they will be over-focused by the transfer lens. Tables 1c and 1d indicate that there is a relatively wide range of converging input angle conditions for which the output angular dispersion is relatively small, and therefore predicts that the beam separator spectrometer will have good focusing properties for parallel detection across the full range of emission energies. Obviously more detailed simulations are required which take into account the objective and transfer lenses, however, the early indications are that the beam separator will allow for parallel energy spectrum acquisition in the SEM.

In order to obtain energy resolution estimates, trajectory rays around the detection plane were examined and the standard practice of taking the energy resolution to be equal to half the dispersion created by input angular spread was taken. Preliminary results are shown in Table 2. Note that in the case of 5 mrad secondary electrons an energy resolution estimate was not made, since the rays were too divergent to be deflected and focused by the postdeflector layout depicted in Figs. 5 and 6. The simulation results show that pre-focusing the scattered electrons is expected to greatly improve the energy resolution: by approximately a factor of 5 for the 3 eV secondary electrons, around 20 for the 2 keV Auger electrons, and about 10 for the 5 keV backscattered electrons. Future work will calculate the energy resolution for specific objective/transfer lens designs and relate them to the number of electrons that reach the detector plane. In the present context, these simulation results illustrate how the beam separator spectrometer energy resolution changes with respect to angular dispersion at its entrance, this helps in designing the transfer lens for a given source of electron emission.

Table 2
Simulated energy resolution

| Emission energy (eV) | Kinetic energy at detector plane (eV) | Input angle conditions | Energy resolution (eV) |
|---------------------|--------------------------------------|------------------------|-----------------------|
| 3                   | 5003                                 | ± 3 mrad diverging      | 0.8                   |
| 3                   | 5003                                 | ± 3 mrad converging     | 0.15                  |
| 3                   | 5003                                 | ± 5 mrad diverging      | 0.23                  |
| 3                   | 5003                                 | ± 5 mrad converging     | 3.6                   |
| 2000                | 7000                                 | ± 3 mrad diverging      | 0.19                  |
| 2000                | 7000                                 | ± 3 mrad converging     | 5.4                   |
| 2000                | 7000                                 | ± 5 mrad converging     | 0.25                  |
| 5000                | 10,000                               | ± 3 mrad diverging      | 8.7                   |
| 5000                | 10,000                               | ± 3 mrad converging     | 0.7                   |
| 5000                | 10,000                               | ± 5 mrad diverging      | 10.4                  |
| 5000                | 10,000                               | ± 5 mrad converging     | 0.9                   |

Acknowledgement

The authors would like to acknowledge support of the Singapore Ministry of Education Research Project WBS 263-000-382-112

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