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A new monochromator with multiple offset cylindrical lenses

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A B S T R A C T

This article presents the optics and performance of a new monochromator (MC) with multiple offset cylindrical lenses (CLs). From ray trace simulations and a regression analysis, a single-offset CL is described in first-order matrix expressions. Based on the matrix, a new optics using multiple CLs is constituted. It is capable of energy filtering internally and forms stigmatic and non-energy dispersive images at the exit. It consists of an offset CL doublet located at a specified distance. It is also equipped with two transfer lenses and two apertures. From simulations, an energy dispersion of 23 μm/eV and an energy resolution better than 10 meV for 4 keV incident energy are achieved. Compared to previous MCs with multi-pole optics, the proposed MC has the additional advantage of a simplified structure. This MC realizes improvements in spatial resolutions for transmission electron microscopy, scanning transmission electron microscopy, and scanning electron microscopy and in energy resolutions for electron energy loss spectroscopy.

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1. Introduction

Monochromators (MCs) are important optical components for advanced charged particle beam instruments. By filtering the charged particle beam with energy differences, narrower energy spread beams are achieved. These monochromatic beams improve the spatial resolution for transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM), and scanning electron microscopy (SEM). They also enhance the energy resolution for electron energy loss spectroscopy (EELS) in microscopes with energy analyzers. Thus far, various types of MCs have been proposed, evaluated and commercialized.

Historically, MCs have frequently been used in the field of surface science, especially in phonon physics. The technique known as high-resolution electron energy loss spectroscopy (HREELS) utilizes low-energy electron beams of several eV to analyze specimen surfaces in the reflection mode. By adopting MCs, energy resolutions better than a few meV can resolve phonon signals from energy loss spectrums [1]. For relatively high energy beam instruments used in thin specimen analysis by transparent electrons, 4–6 meV at 25 keV has been obtained by the retarding Wien filter MCs [2]. By applying high voltage to the filter to decelerate the electron beams, the energy dispersion is increased and a high resolution is achieved. The same type of MC has been integrated into TEM optics, with an achievement of several tens of meV at 60 keV for a spatial area of 100 nm after optimizing the configurations of the filters [3,4]. Also, the retarding field MCs in gun regions in focused electron and ion beam systems have been proposed to improve the probe sizes [5].

Later, MCs using a thin Wien filter placed in the gun region were proposed, evaluated and applied to STEM [6–8]. An energy resolution of 61 meV at 100 keV was achieved. Similarly, various types of gun Wien filters have been proposed, evaluated and commercialized, as follows: a relatively longer type [9], those with double-Wien filters [10,11], and those with quad-Wien filters [12]. The progress related to Wien filters, including their application to MCs, has been reviewed and summarized [13,14].

As a different concept, pure electrostatic deflectors in the gun region have been proposed. MCs with Ω-shaped four toroidal deflectors have been proposed, evaluated and applied to TEM [15–17]. This symmetric optical configuration can cancel not only the energy dispersion but also all second-order geometric aberrations at the exit plane of the MCs. An energy resolution of about 40 meV at 200 keV was confirmed by TEM with an imaging energy filter. Another electrostatic MC with a hemispherical analyzer with deflection of 180° was also investigated [18].

Recently, ground potential MCs with α-shaped configuration of four magnetic sectors have been proposed and utilized in STEM-EELS [19,20]. Multi-poles placed between the sectors increase the energy dispersion even for high-energy beams. As an initial evaluation, the highest energy resolution of 12 meV at 60 keV and a probe size of 1.2 Å at an energy spread of 100 meV were achieved.

These MCs improved the (S)TEM spatial resolution by eliminating the contributions of the chromatic terms, especially in the lower energy region, where the radiation damage to specimens

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can be reduced. They also improved the energy resolution in EELS, revealing new information on the bandgaps, excitons, and dielectric properties of materials on the nanometer scale [20,21].

As applications of MCs to SEM after Troyon's proposal [5], estimations of the probe sizes with a reduction of the chromatic terms and an improvement in the size in the low-energy region have been discussed based on D50 methods [22]. Later, an MC with a modified condenser lens was proposed and commercialized [23,24]. It also includes two off-axis apertures and a deflector. By selecting an off-axial portion of an emitted beam with an aperture, energy dispersion occurs due to the off-axial chromatic aberration of the condenser lens. By selecting the dispersed beam with another aperture behind the lens, energy filtering is realized. The monochromated beams are deflected back to the optical axis of the microscope by the deflector. The energy spread of 0.15 eV for Schottky emitters is obtained and sub-nm SEM image resolutions are achieved in low-energy regions around 1 keV. This MC is considered as a modification of the Möllenstedt energy analyzer used frequently during the early stages of EELS studies owing to their high energy resolutions [25,26]. In these analyzers, configurations of electrodes known as a cylindrical lens (CL) are adopted.

As described above, many varieties of MCs have been proposed and realized thus far. They have drastically enhanced (S) TEM, SEM and EELS performance levels. Therefore, the MC is regarded as an essential component in the latest microscopes. It is important to investigate new MCs to achieve further improvements for the next generations of these instruments.

Here, we propose a new MC with multiple offset cylindrical lenses (CLs) which is assessed in simulations. The CLs are highly excited to generate a high energy dispersion, which results in high performance with a simple configuration. The MC is based on the same principle used in Möllenstedt energy analyzers [25,26]. The MC can be used as a gun MC for (S)TEM or as a ground potential MC for SEM. The optics and performance will be discussed in detail in the following sections.

2. Simulation methods and models

To investigate the optics of MCs with multiple CLs, it is difficult to use conventional paraxial approximation methods because the optical axis passes through a non-uniform and complicated electric field distribution in the off-axis region of the CLs. Thus, we take a new approach to study this. First, we perform direct ray trace simulations for a single CL to determine its optical axis and paraxial rays. By analyzing the results, we deduce the optical parameters and first-order matrix expressions. Based on the matrix, we establish new optics for a MC with multiple CLs. Then, the performances of the MCs are investigated by combined calculations of ray trace and matrix methods, including the contributions from higher order aberrations.

In this study, the simulations are done with the charged-particle optics software EO-3D by MEBS Ltd. It can calculate 3D electrostatic fields for various electrodes by the finite difference method and trajectories by the ray trace method based on these fields. For the analysis of the trajectories, the regression analysis functions of Microsoft Excel are used.

In this study, the cylindrical lens (CL) is our main concern. It consists of three electrodes with rectangular openings in their centers. Applying high voltage to the center electrode creates a stronger focusing effect in the direction of the shorter side of the opening and a weaker focusing effect in the other direction of the longer side. The schematics are shown in Fig. 1. Here, a Cartesian coordinate is introduced as (X, Y, Z). The Z axis is defined as the travel direction of the charged particles, and it passes through the center of the rectangle openings of the electrodes. The X axis is adopted as the stronger focusing direction and the Y axis is chosen as the weaker focusing direction. The detailed dimensions of the lenses are as follows: the thickness of the electrodes is 10 mm, the gap between the electrodes is 10 mm, the shorter side of the opening is 10 mm, and the longer side of the opening is 100 mm. The same parameters are adopted for all three electrodes of the CL

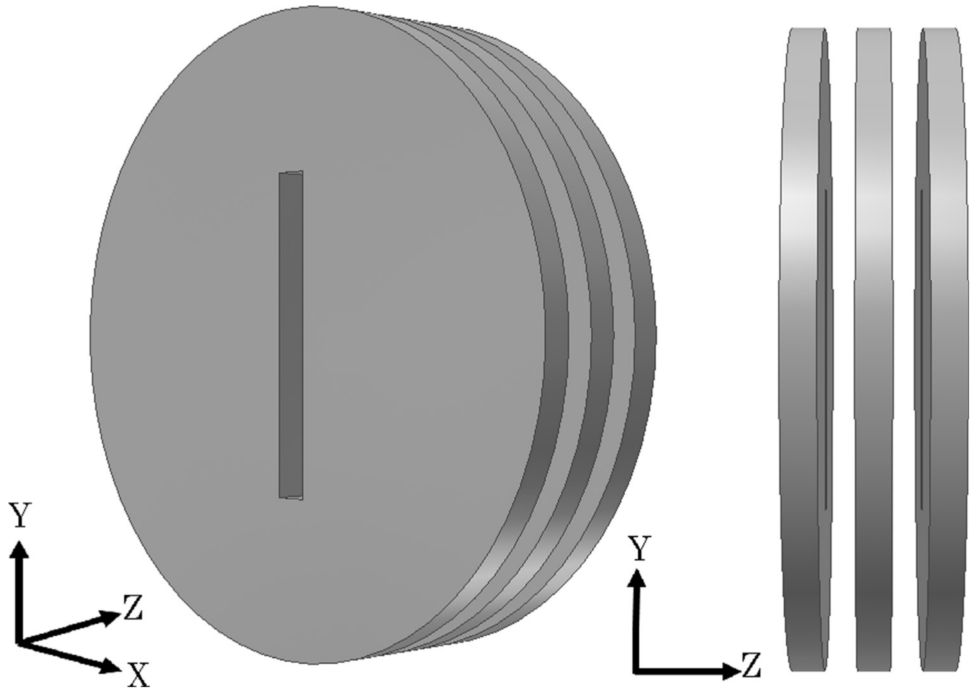

Fig. 1. Configuration of the cylindrical lens: the thickness of the electrodes is 10 mm, the gap between the electrodes is 10 mm, the shorter side of the opening is 10 mm, and the longer side of the opening is 100 mm.

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