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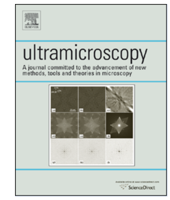

The development of a 200 kV monochromated field emission electron source

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ABSTRACT

We report the development of a monochromator for an intermediate-voltage aberration-corrected electron microscope suitable for operation in both STEM and TEM imaging modes. The monochromator consists of two Wien filters with a variable energy selecting slit located between them and is located prior to the accelerator. The second filter cancels the energy dispersion produced by the first filter and after energy selection forms a round monochromated, achromatic probe at the specimen plane. The ultimate achievable energy resolution has been measured as 36 meV at 200 kV and 26 meV at 80 kV. High-resolution Annular Dark Field STEM images recorded using a monochromated probe resolve Si–Si spacings of 135.8 pm using energy spreads of 218 meV at 200 kV and 217 meV at 80 kV respectively. In TEM mode an improvement in non-linear spatial resolution to 64 pm due to the reduction in the effects of partial temporal coherence has been demonstrated using broad beam illumination with an energy spread of 134 meV at 200 kV.

1. Introduction

In this paper we report the development and initial performance of a monochromator for a transmission electron microscope that enables a limiting energy resolution of 36 meV at 200 kV and 26 meV at 80 kV. The monochromator is an evolution of an earlier design based on a double focusing arrangement of two Wien filters [1]. This previously reported instrument has already been successfully used for observation of low energy loss features including measurement of the surface plasmon excitation in a LaB_6 nanoparticle in the infra-red region [2]. However, this instrument used an uncorrected objective lens limiting the minimum probe size to approximately 1 nm.

Developments in spherical aberration correction have dramatically improved the spatial resolution of electron microscopes in both Transmission (TEM) and Scanning Transmission (STEM) imaging modes [3–6]. Probes at atomic dimensions and with large currents can now be formed in STEM enabling elemental analysis at atomic resolution using either electron Energy loss Spectroscopy (EELS) [7–9] or Energy Dispersive X-Ray analysis (EDX) [10]. For phase contrast TEM imaging, a monochromated source improves the spatial resolution by reducing the effects of partial temporal coherence, which is particularly relevant to imaging at low accelerating voltages [11,12].

2. Optical design

Several optical designs of monochromators suitable for TEM/STEM operation have been previously proposed, including a retarding Wien filter [13], a single Wien filter [14], an electrostatic omega filter [15] and more recently a corrected magnetic alpha filter [16]. The former two geometries are distinguished by straight electron trajectories and since they are single stage energy filters, the crossover plane below the monochromator corresponds to the energy dispersive plane. Consequently, the virtual source at the specimen plane is the spectrum of the electron source, and the crossover at the specimen is an ellipse, extended in the energy dispersive direction. This leads to potential complications for high resolution phase contrast imaging where the effects due to spatial and temporal coherence are not simply multiplicative and a cross term must be included in image calculations [17]. The latter two geometries are two-stage energy filters and by locating an energy selection slit between the two filter elements, the electron trajectories inside the monochromator are symmetric with respect

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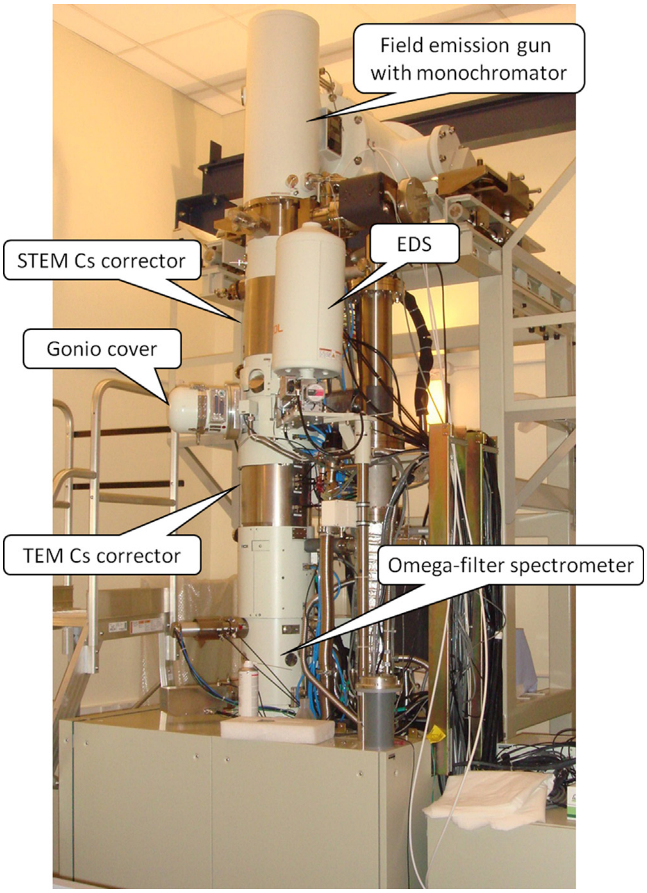

Fig. 1. Overview of the JEM-2200MCO equipped with the monochromator described.

to the plane of the energy selection slit. Consequently, the second filter cancels the energy dispersion at the slit plane and the crossover at the specimen plane is achromatic.

2.1. Monochromator design

Fig. 1 shows an overview of the instrument described in this paper (JEM-2200MCO). The microscope is based on a 200 kV column (JEM-2200FS) with an in-column omega energy filter spectrometer [18] and hexapole based third order spherical aberration correctors for the objective lens pre and post fields (CEOS GmbH) [4]. To achieve high energy resolution, the stability of the power supplies to the omega filter has been improved to better than 0.34 ppm/min peak to peak.

The monochromator is based on two dodecapole Wien filters with an energy selection slit located between the two filters and with straight electron trajectories inside the monochromator. Fig. 2 shows the top view of one dodecapole Wien filter together with the calculated fields in this element [19,20]. The multi-pole elements of the Wien filter introduce both dipole electric and magnetic fields, which are arranged to be mutually perpendicular at the dispersion plane. As a consequence of this arrangement, the Wien filter behaves as an energy filter.

Subsequently we denote energy dispersive direction of the Wien filter as x with the optical axis as z. The electric and magnetic potentials distributions can therefore be written as

$$\Phi(x,y,z) = U0 - E1 \cdot x - E2 \cdot (x^2 - y^2) - E3 \cdot x(x^2 - 3y^2) - \cdots \quad (1)$$

$$\Psi(x,y,z) = -B1 \cdot y - B2 \cdot 2xy - B3 \cdot y(3x^2 - y^2) - \cdots \quad (2)$$

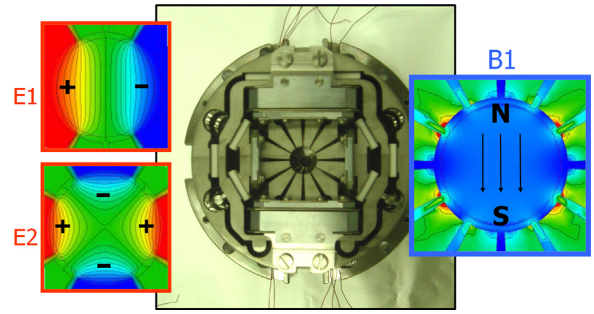

Fig. 2. Top view of a dodecapole type Wien filter element together with calculated dipole electric field (E1), dipole magnetic field (B1) and quadrupole electric field (E2).

where $\Phi(x,y,z)$ is the electrostatic potential, $\Psi(x,y,z)$ is the scalar magnetic potential, $U0$ is the potential along the optical axis and the quantities $E1$, $E2$, $E3$, $B1$, $B2$ and $B3$ are the dipole (1), quadrupole (2) and hexapole (3) components of the electric and magnetic fields, respectively. The monochromator is designed such that $U0$ of the axial potential is kept constant inside the Wien filter at 1000 eV. However, this optical geometry generates an additional, unwanted quadrupole field arising from any deviation between the center of the dipole field and the optical axis. To reduce this unwanted parasitic field the monochromator design includes an adjustable voltage in each electrostatic electrode and an adjustable current in each magnetic pole of the dodecapole elements. A further hexapole field is generated from any inhomogeneity in the dipole field and this is reduced using a homogeneous field around the dipole at an angle of 120° [21].

The electron trajectory equations to first order in the electric and magnetic fields given in (1) and (2) are now rewritten following [22–27] as

$$x'' + \frac{1}{U0}\left(\frac{E1^2}{4U0} + E2 - v_0 B2\right) \cdot x = -\frac{1}{2U0}(E1 - v_0 B1), \quad (3)$$

$$y'' + \frac{1}{U0}(E2 - v_0 B2) \cdot y = 0 \quad (4)$$

At the Wien condition

$$E1 = v_0 \cdot B1, \quad (5)$$

where v_0 is the velocity of the electron along the optical axis the right hand side of (3) vanishes. By suitable superimposition of dipole electric and magnetic fields, it is possible to generate the Wien condition on the optical axis of the filter with a straight beam path along the optic axis. However, it is important that the distribution of the dipole electric field should be equal to that of dipole magnetic field inside the Wien filter and also within the fringing field region and to ensure this shunts are incorporated at the entrance and exit of the Wien filter.

When the Wien condition is satisfied by superimposing the quadrupole electric field (E2), a stigmatic condition, giving a round beam at the crossover position, is produced. In this condition the Wien filter acts as a round lens described by (6)

$$\frac{E2}{E1} - \frac{B2}{B1} = -\frac{1}{4Rw}, \quad (6)$$

with Rw the cyclotron radius in the Wien filter.

The Wien filter design reported here does not include specific coils to generate a quadrupole magnetic field (B2) and hence the stigmatic condition of Eq. (6) is given by

$$\frac{E2}{E1} = -\frac{1}{4Rw} \quad (7)$$