Energy width reduction using an electrostatic Ω-monochromator

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Abstract

An electrostatic electron monochromator consisting of four hemispherical condensers and having an Ω-shaped curved optic axis was improved and tested. The principle of operation and initial experiments were already published by Huber, Bärtle and Plies (Nucl. Instr. And Meth. A519 (2004) 320). In the meantime the performance of the monochromator was enhanced by a dedicated magnetic shielding and the home-made gun/transfer lens set-up was improved by a redesign. The native energy width (FWHM) of the used ZrO/W Schottky field emitter (0.6–0.8 eV) could be reduced to 0.2 eV or less.

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1. Introduction

Light-optical monochromators are well known in light-optical microscopy as well as X-ray monochromators in X-ray applications. In the past electron monochromators have mainly been used in surface science for HREELS (High Resolution Electron Energy Loss Spectroscopy) investigations of a sample [1]. One or two monochromators are arranged between the electron emitter and the sample to reduce the energy width of the primary electrons with an energy up to a few hundred eV to some meV (< 10 meV). Consequently the energy resolution of the analyzer between the backscattering sample and the electron detector is not limited by the large energy width of the electron gun. For these surface investigations the lateral resolution, i.e., the diameter of the electron probe is rather poor (~1 mm).

The incorporation of an electron monochromator in a modern TEM (Transmission Electron Microscope) is very promising. A monochromator which reduces the native energy width of an electron emitter to 0.1 – 0.2 eV may be used advantageously

- to further enhance the lateral resolution of a spherically corrected TEM (SCTEM) because in such a TEM the resolution is limited by the chromatic aberration (of first order) whose simultaneous correction is rather complicated;

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• to improve the energy resolution in an energy filtering TEM (EFTEM) where the energy resolution of the spectrometer (EELS analyzer or imaging energy filter) should not be limited by the energy width of the primary electrons;

• and to increase the temporal coherence and the information limit in advanced electron holography.

We should mention that the incorporation of a gun monochromator is also one way to further enhance the resolution in a modern low-voltage scanning electron microscope (LVSEM). In contrast to HREELS mentioned above the electron probe size should now be 1 nm or less but the energy width reduction is not so stringent.

Several proposals for electron monochromators for electron microscopy have been made in the past such as Wien filters [2-7], filter lenses [8-10] and electrostatic sector fields [11-16]. The specific sector fields are cylindrical mirror analysers [11], hemispherical condensers [12, 16] and toroidal condensers [13-15]. Substantial energy width reductions have been demonstrated using Wien filter or sector field monochromators. For example, Benner et al. [15] have integrated an Ω-type monochromator with 4 toroidal condensers [13, 14] into a SCTEM and a reduction of the energy width of a Schottky field emission gun from 0.8 eV down to 0.3 eV has been observed thus allowing a resolution improvement to about 0.1 nm.

2. Principle

The monochromator already introduced in [16] is of the Ω-type proposed by Rose [12]. Fig. 1 shows the principle of our monochromator set-up together with the unrolled course of the fundamental rays in both principal sections. For a schematic view of the monochromator with the Ω-shape of the optic axis and for a view into the open monochromator with the 4 electrostatic deflectors, the fringing field clamps, etc., see [16]. Due to the high symmetry of the deflection fields of the 4 identical hemispherical condensers (C1 - C4) and the fundamental rays (x₀, xᵢ, xₑ in the radial “horizontal” section and yᵦ, yₛ in the perpendicular “vertical” section) the whole monochromator provides a virtual stigmatic image of the source, introduces no dispersion or angular dispersion and is free of second-order aperture aberrations. A real stigmatic and dispersed image is formed by the first group of 2 deflectors in the energy selection plane (ESS), i.e. the symmetry plane. Table 1 contains some principal data of the monochromator, together with the measured minimum energy width (FWHM). For simulation and design details of the monochromator, e.g. the design of field clamps, etc., see [16, 17].

![Fundamental rays in the monochromator set-up](image)

Fig. 1. The unrolled course of the fundamental rays in the radial x,z section and in the perpendicular y,z-section of the monochromator set-up. x₀, yᵦ = axial rays; xᵢ, yₛ = field rays; xₑ = dispersion ray; z = coordinate of the curved optic axis, i.e. the arc length; R = radius of the optic axis in the hemispherical condensers C1 – C4.
Table 1
Main data of the monochromator set-up.

| Parameter                                    | Value  |
|----------------------------------------------|--------|
| beam energy $e_{Ua}$                         | 3 keV  |
| radius $R$ of the optical axis in the deflectors | 60 mm  |
| deflection angle $\Phi$ of the deflectors     | 180°   |
| dispersion $D$ in the energy selection plane $z_S$ | 80 $\mu$m/eV |
| virtual source size of the FE gun            | 20 nm  |
| source size in the energy selection plane $z_S$ | 1 $\mu$m |
| initial energy width                         | 0.6 eV |
| minimum energy width (theory)                | 13 meV |
| minimum energy width (experiment)            | 150 meV|
| number of intermediate stigmatic crossovers   | 5      |
| increased length of the optical axis         | $= 900$ mm |

3. Test set-up and improvements

Fig. 1 shows our set-up in principle and Fig. 2 the Möllenstedt analyzer [18] in more detail. The latter is used to measure the inherent energy distribution of the Schottky field emitter (no energy selection slit ESS of the monochromator in action) and the reduced energy distribution when the ESS is partially closed. Following the path of the electrons we will mention the improvements made since our last report [16]. We exchanged the extractor electrode (redesign of the bore) which is also the first electrode of the three-electrode transfer lens of immersion type (4.5 - 5.5 keV input and 3 keV output). We also renewed the electric contact to the extractor. In a field-free region of the long middle electrode (focusing electrode) of the home-made transfer lens the non-adjustable aperture is positioned and also acts as a differential diaphragm to separate the UHV region of the gun and the HV region of the lower part of the set-up. This aperture was replaced by a larger one of 200 $\mu$m diameter. The UHV ionization gauge was dismounted and the pressure is now measured solely using the current of the ion getter pump.

Fig. 2. (a) The Möllenstedt analyzer consists of the analyzer slit, the analyzer itself and a deflector used to shift the obtained spectrum across the scintillator. There, the spectrum is converted to a light signal that is imaged onto a CCD by a light-optical transfer system [19]. From the available light signal generated by an electron energy spectrum, only 10% are imaged onto the CCD. Binning is used to enhance the signal. (b) Simulation of electron rays in the analyzer without using the analyzer slit. The electron signal on a screen at the exit of the analyzer is simulated as well as a line scan produced by 1000 electrons. By placing the analyzer slit at the appropriate position above the analyzer lens itself, the caustic part is selected, resulting in a high intensity peak on the left or the right side. The generated intensity distribution contains the desired energy width [18]. This selection implies a loss of the available beam current of 80%.
In the HV region, we rearranged the vacuum gauge and improved the magnetic shielding of the monochromator itself: inside between the 4 hemispherical condensers and the housing and also outside the housing. We removed the electrostatic deflectors for beam alignment between C2 and ESS and also between ESS and C3 because they are not necessary. Finally, we exchanged the alignment deflectors below the Ω-monochromator and we replaced the analyzer slit of the Möllenstedt analyzer by an improved one.

As already mentioned, the energy width of the electron beam is measured using a Möllenstedt analyzer [18] arranged adjacent to the monochromator and the magnetic objective lens (second transfer lens). The generated spectrum is first converted using a scintillator and then light-optically imaged onto a CCD camera attached below, see Fig. 2. Between the objective lens and the slit of the Möllenstedt analyzer one can insert a Faraday cup to measure the beam current below the monochromator.

4. Results and conclusion

We found the native energy width of the ZrO/W Schottky emitter in our set-up to be about 0.6 – 0.8 eV (FWHM) depending on the individual emitter as well as on the emission current. An energy width reduction to 0.2 eV by means of the Ω-monochromator is possible, see Fig. 3. Typical probe currents before energy width reduction were up to some 10 nA, the final reduced beam current was always well below 1 nA. Due to the intensity losses in the Möllenstedt analyzer as well as in the light-optical part of the set-up (for details see caption to Fig. 2), an energy width reduction below 150 meV down to the theoretical limit of 13 meV was not possible. Nevertheless, some interesting facts concerning the Boersch effect can be confirmed: the previously observed [16] robustness of the overall energy width concerning the amount of stigmatic crossovers in the monochromator and the increased optical length by the monochromator was observed again in the beam current regime available.

The construction and operation of an electrostatic electron monochromator of the Ω-type with low energy electrons is very demanding. Special care was taken concerning power supplies, grounding, magnetic shielding and alignment to finally reach the desired energy width of 0.2 eV. An even better energy width should be possible and measurable using a better suited analyzer, e.g. a retarding field analyzer which does not exhibit such a high intensity loss.

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