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Foucault optical system by using a nondedicated conventional TEM

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We have constructed an electron optical system for both Foucault imaging and small-angle electron diffraction (SmAED) modes by using a nondedicated conventional transmission electron microscope. The objective lens is switched off as for Lorentz microscopy. An objective mini-lens is utilized in order to make a crossover on the plane where a selected area aperture is located. The aperture works for an angular selection in the Foucault mode. The present electron optical system has two advantages: one is the independent control of the illumination and the imaging optics, and the other is the application of external magnetic fields to the specimen parallel to the optical axis with the objective lens. In SmAED mode, the maximum camera length is estimated to be approximately 1300 m. We succeeded in the observation of magnetic domain structures and SmAED patterns of the rhombohedral phase of $La_{0.7}Sr_{0.3}MnO_3$ by using the present electron optical system. Copyright © 2016 John Wiley & Sons, Ltd.

Keywords: Foucault method; small-angle electron diffraction; transmission electron microscope; magnetic material

Introduction

Magnetic properties such as ferromagnetic, antiferromagnetic, and ferrimagnetic properties depend strongly on the microscopic interaction between spins at atomic sites.[1] Furthermore, there is an increasing interest in nanometric topological spin textures in magnets because they are expected to pave the way for the electric control of magnetism.[2] Magnetic microstructures such as magnetic bubbles and magnetic skyrmions usually have some influences on unusual physical properties such as the quantum Hall effect. Therefore, it is important to understand magnetic microstructures at the nanometric scale. The Lorentz transmission electron microscope (Lorentz TEM) is one of the most powerful tools to visualize magnetic domain structures with nanoscale spatial resolution.[3,4] The Lorentz TEM has two conventional observation modes: Fresnel (out-of-focus) mode and Foucault (in-focus) mode. In the Fresnel mode, magnetic domain walls can be observed as bright and dark lines. Conversely, in the Foucault mode, magnetic domains can be visualized as bright and dark contrasts. Recently, an electron optical system for observing Foucault images was constructed by using a conventional TEM without any special equipment.[5] In this electron optical system, the small-angle electron diffraction (SmAED) mode can be realized simultaneously, combined with the Foucault imaging mode. However, it was impossible to control the total amount of the electron beam flux and irradiation area on the specimen, because the condenser lens was fixed to make a crossover on the plane where the selected area aperture was located.

Here we report on an electron optical system for dual realization of SmAED and Foucault imaging modes by using a conventional TEM without any modification. In the present electron optical system, an objective mini-lens, which was installed just under an objective pole-piece, was used in order to make a crossover on the selected-area aperture plane. As a result, both illumination and imaging optical systems are controlled independently and the total amount of the electron beam on the observing specimen is adjusted adequately.

Electron optical system

Both Foucault imaging and SmAED modes were realized with a 200-kV thermal emission (LaB_6 filament) TEM (JEM-2010), which has an objective mini-lens. Figure 1 shows schematic illustrations of the constructed electron optical system for (a) SmAED and (b) Foucault imaging modes. The objective mini-lens and condenser lens are tuned in order to converge the electron beam on the selected-area aperture plane. The aperture enables the selection of an angular range in the Foucault imaging mode. Because the objective lens is switched off in the Lorentz observation mode, external magnetic fields are applied to the observed specimen with the objective lens. Because of magnetic hysteresis in the objective lens, a magnetic field of approximately 12–20 mT is still applied to the observed sample when the objective lens is switched off in the Lorentz observation mode. However, this residual magnetic field has no influence on magnetic domain structures of hard magnetic materials. When the objective lens is excited for the application of external magnetic fields, the current of the objective mini-lens has to be adjusted so as not to move the position of the crossover. The observation area to be visualized can be selected by using the objective aperture. The SmAED mode can be switched to the Foucault imaging mode by adjusting the current of the intermediate lens 1 without changing the illumination system. Total camera lengths and image magnifications are controlled with two image forming lenses: the intermediate lenses 2 and 3. In order to match the orientation of a Foucault image with that of the corresponding SmAED

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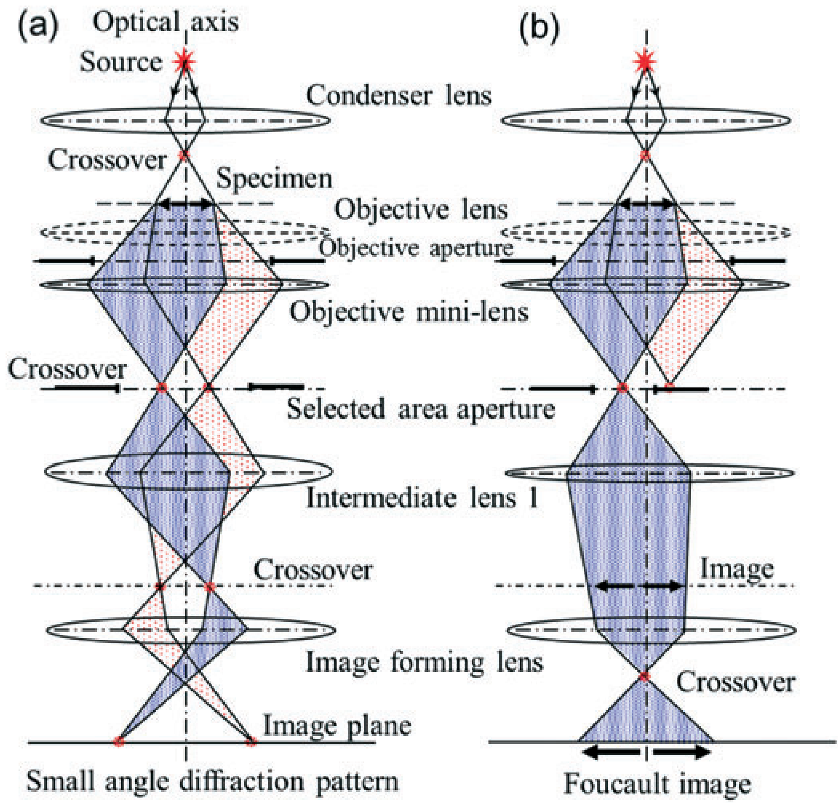

Figure 1. Schematic illustrations of the electron optical system: (a) SmAED mode and (b) Foucault imaging mode.

pattern, it is useful to use the intermediate lens 3 as well as the intermediate lens 1 when switching the SmAED mode to the Foucault mode.

Results

Evaluation of the electron optical system

The constructed electron optical system was evaluated by using a carbon replica grating with a lattice parameter of 500 nm, which was a similar way to evaluate the electron optical system as used in Ref..[6] Figure 2 shows the variation of the camera length in SmAED mode as a function of current (I_3) in the intermediate lens 3. The intermediate lenses 2 and 3 work as compound lenses and magnify the diffraction patterns and images projected with the intermediated lens 1. The camera length depends on the current in the intermediate lens 2. When a SmAED pattern is taken in the range of the camera lengths from 2 to 300 m, it is recommended that the current value of I_2 should be fixed to be 4 A. Conversely, I_2 should be fixed at $I_2 = 6$ or 8 A when employing camera lengths longer than 300 m, as seen in Fig. 2. In this electron optical system, the maximum value of the camera length was approximately 1300 m without exciting the objective lens.

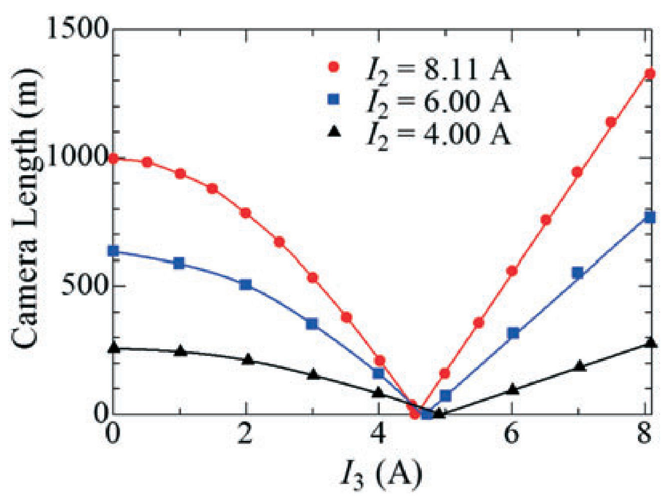

Figure 2. Variation of the camera length as a function of the current values I3 of the intermediate lens 3. The I2 and I3 represent the current values of the intermediate lens 2 and 3, respectively. Lines are guides to the eye.

Observation of magnetic domains in $La_{0.7}Sr_{0.3}MnO_3$

Figure 3 shows (a) the SmAED pattern and (b) the Fresnel image of the rhombohedral structure of $La_{0.7}Sr_{0.3}MnO_3$ at room temperature, both of which were obtained under the condition that the residual magnetic field of approximately 15 mT was applied to the observed sample. In the SmAED pattern (Fig. 3a) obtained with a camera length of 100 m, the splitting of the 000 spot is observed, which is due to the magnetic Lorentz deflection in 180° magnetic domains. In the Fresnel image of Fig. 3b, there are some straight lines with bright and dark contrasts corresponding to the 180° magnetic domain walls. Note that the defocus value was adjusted by changing the current of the intermediate lens 1. The 180° magnetic domain walls coincide with crystalline boundaries. As seen in Fig. 3a, the SmAED pattern has a streak between the two split magnetic deflection spots, indicating that the magnetic domain walls are Bloch-type. Note that the right side spot is elongated, which may be

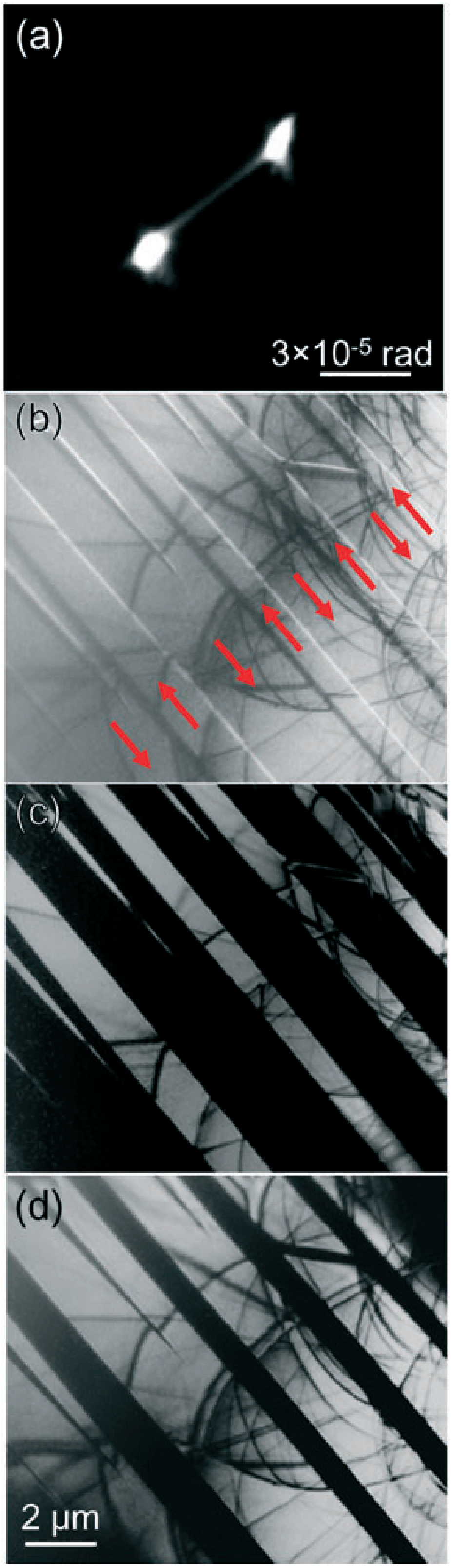

Figure 3. (a) SmAED pattern of $La_{0.7}Sr_{0.3}MnO_3$ and (b) Fresnel image obtained for a condition under focus. Foucault images obtained using (c) the lower left and (d) upper right spots in (a). The arrows show the direction of the magnetization in each magnetic domain.

ascribed to halation. The magnetic field induced by the magnetization is estimated from the separation of the split spots (5.8×10^{-5} rad) to be 0.48 T provided that the specimen thickness is 100 nm. The value of 0.48 T is almost consistent with that obtained in the previous study.[5] Figure 3c and 3d are the Foucault images obtained by using one of the two split 000 spots. Comparing the SmAED pattern (Fig. 3a) with the Foucault image (Fig. 3b), the directions of the magnetization in the 180° magnetic domains turn out to be oblique, and they are shown by arrows in Fig. 3b. The Foucault imaging mode combined with the SmAED mode provides some useful information about the direction and the magnitude of magnetization, types of magnetic domain walls, and morphology of magnetic domains.

Conclusions

An electron optical system with both Foucault imaging and SmAED modes has been constructed using a nondedicated conventional TEM. The system utilizes the objective mini-lens to make a crossover on the selected-area aperture plane. One of the advantages of this electron optical system is that the illuminating and the imaging electron optical systems can be controlled independently. The camera length can be set up to 1300 m. The present electron optical system can be applied to study nanoscale complex spin textures found in a variety of complex magnetic materials.

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