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In-Plane Magnetic Field Evaluation with 0.47-nm Resolution by Aberration-Corrected 1.2-MV Holography Electron Microscope

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Electron holography is a powerful tool for analyzing the origins of functions by observing electromagnetic fields at high resolution. The quest for finding the ultimate resolution through continuous improvements on holography electron microscope leads to the development of an aberration corrected 1.2-MV holography electron microscope [1,2]. The resolutions of this microscope are 0.043 nm in the HR mode [1] and 0.24 nm in the field-free mode [2]. To realize high-resolution magnetic field observations, a pulse magnetization system was developed to reverse the magnetization in the sample without changing the geometrical configuration of the sample holder and stage referring to the electron beam. Using this system, the magnetic fields in CoFeB/Ta layers were observed at 0.67-nm resolution [3]. However, due to the experimental residual aberrations, the atomic-resolution has not been achieved. Here, we show the atomic-layer in-plane magnetic field analysis with 0.47-nm resolution using post-aberration correction for reconstructed electron wave.

A rectangular shape thin (47 nm) TEM sample was prepared from single crystal Ba_2FeMoO_6 with double perovskite structure [4] by using focused ion beam instruments. The surface damage layers were cleaned by Ar ion beam. Figure 1 shows schematics of the crystal structure and in-plane magnetization direction due to the rectangular sample shape along to (111) lattice plane.

A pulse magnetic field of 207 kA/m was used to reverse the sample magnetization. The hologram fringe spacing was set to 0.078 nm, and the reconstruction aperture was set so as to enable spatial information greater than 0.234 nm to pass through. Holography observations were performed for four different positions at room temperature without magnetic field and 10 pairs of hologram set with reversed magnetizations were acquired for each position. After the reconstruction of the holograms, the residual aberrations of C1, A1, C3, and C5 estimated by Thon diagrams [5] were corrected. The aberration corrected images were aligned, and the averaged phases were decomposed into the electrostatic and magnetic phases by using the non-magnetic surface carbon layer for the alignment of the pair images with reversed magnetization.

Figures 2(a) and (b) show electrostatic phase and derivative of magnetic phase, respectively; the latter reflects the in-plane magnetic field in the sample. The magnetic phase information with 0.47 nm spacing corresponding to the (111) lattice were obtained. By the multi-slice simulation including atomic-scale magnetic field derived by the Vienna Ab initio simulation package (VASP) calculation, it is shown that the observed result does reflect the atomic-layer in-plane magnetic field distributions.

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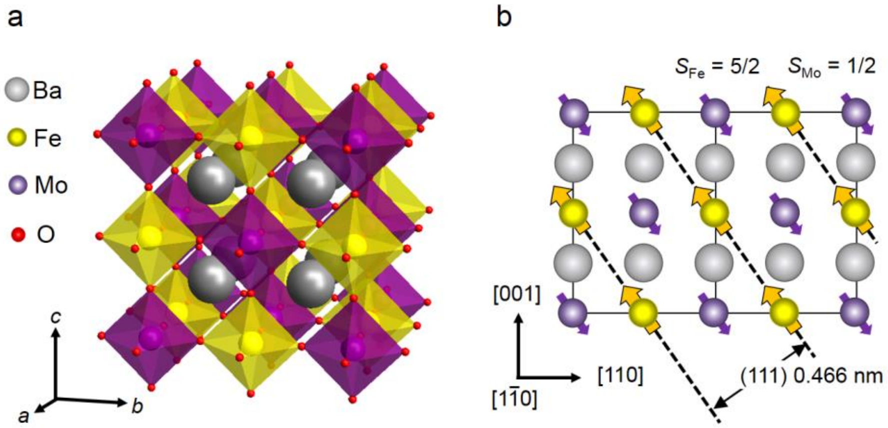

Figure 1. (a) Crystal structure of Ba_2FeMoO_6. (b) Atomic-scale spin distribution in [1-10] projection.

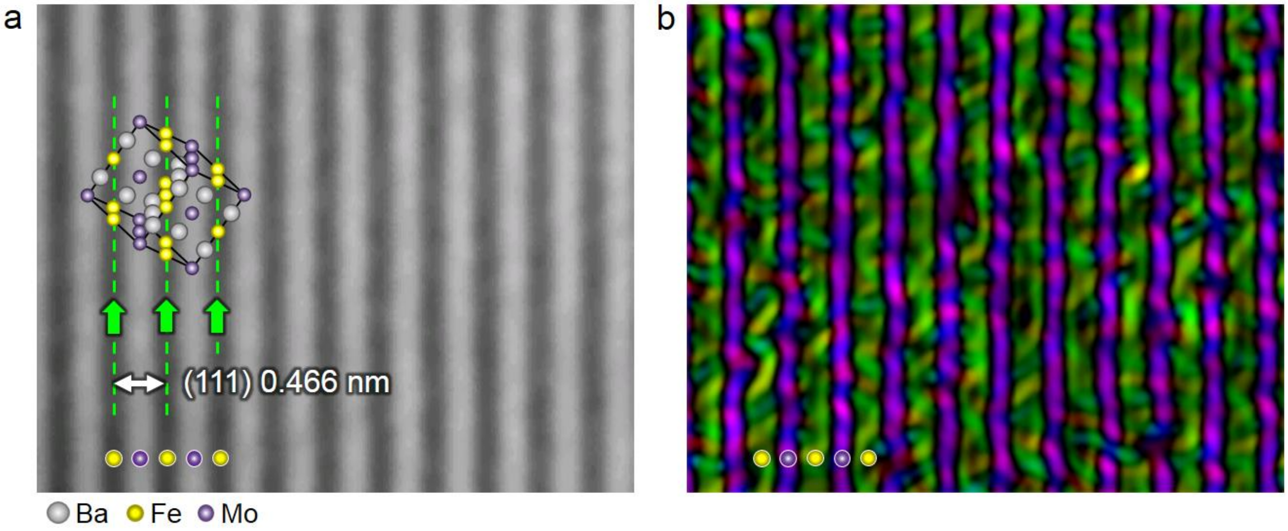

Figure 2. (a) Averaged electrostatic phase. (b) Derivative of averaged magnetic phase.