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Sub-Nanometer-Resolution Magnetic Field Observation Using Aberration-Corrected 1.2-MV Holography Electron Microscope with Pulse Magnetization System

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Sub-nanometer scale magnetization is important for fundamental science and application of magnetic materials, and electron holography is a promising method for observing it. Although the spatial resolutions of holography electron microscopes in field-free mode have reached sub-nanometer scale through the use of aberration correctors [1–3], magnetic field observations have so far been performed at 1-nm resolution [4]. To achieve sub-nanometer resolution by improving magnetic phase sensitivity and subtracting electrostatic phases at high spatial resolution, we developed a pulse magnetization system (Figure 1) for use with an aberration-corrected 1.2-MV holography electron microscope. The system automatically acquires a set of holograms with opposite magnetization states to obtain a high-resolution magnetic phase with a high signal-to-noise ratio. The magnetic phase noise in a thin oxide magnet (Ba_2FeMoO_6) was reduced to ±0.0021 (2π/2990) rad [5]. This paper reports the achievement of sub-nanometer-resolution magnetic field observations of a magnetic multilayer.

A multilayer of Ta(5.0 nm)/Co-Fe-B(0.5 nm)/Ta(3.0 nm)/Co-Fe-B(1.0 nm)/Ta(3.0 nm)/Co-Fe-B(2.0 nm)/Ta(6.0 nm) was prepared by sputtering deposition. The structures of this Co-Fe-B layers and Ta layers were amorphous. A thin sample (45 nm thick) was observed by electron holography. A pulse magnetic field of 207 kA/m was used to reverse the sample magnetization. The hologram fringe spacing was set to 0.22 nm, and the reconstruction aperture was set to enable spatial information greater than 0.66 nm to pass through. The reconstructed phase images were aligned, and the averaged phases were decomposed into the electrostatic and magnetic phases, as shown in Figures 2(a) and (b), respectively.

A spatial resolution of 0.67 nm was attained in the phase image and Fourier transform pattern. Phase steps attributed to the in-plane magnetic fields were observed for the 2.0- and 1.0-nm-thick Co-Fe-B multilayers but not for the 0.5-nm-thick one (Figure 2(b)). The absence of the magnetic phase step for the 0.5-nm-thick layer is consistent with the finding that spontaneous magnetization was not discerned in vibrating sample magnetometer (VSM) measurements in the in-plane mode. The strength of the magnetic field at the center of the 2.0-nm-thick Co-Fe-B multilayer was 1.45 T (Figure 2(c)). This is comparable to the VSM results of 1.50 T. The amount of the noise in the magnetic field measurement was 0.02 T (standard deviation of the profile for the Ta area).

These results demonstrate that sub-nanometer-resolution observation of a magnetic field can be performed with high accuracy. We believe that the developed systems and techniques can be used for various types of fundamental research and development for practical applications and industrial devices.

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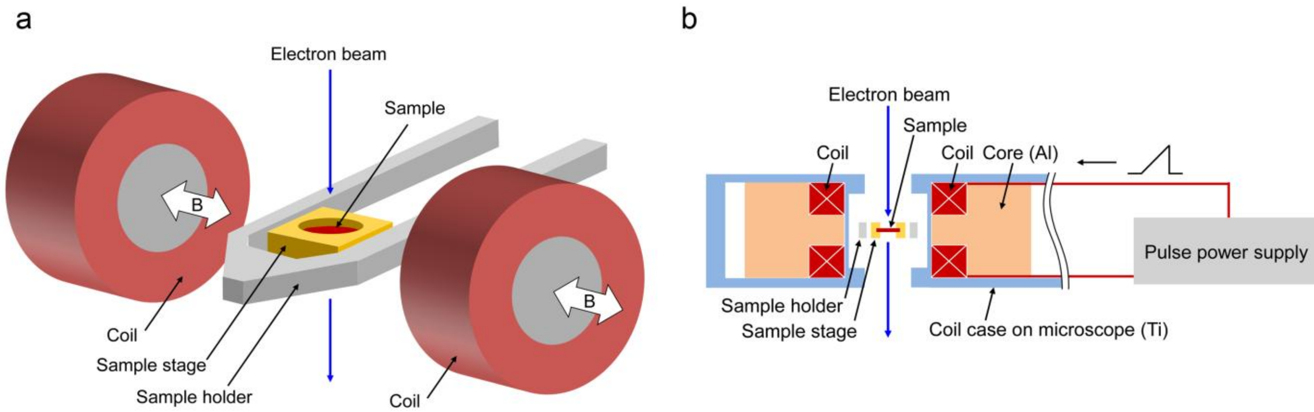

Figure 1. (a) Schematic and (b) cross-section of pulse magnetization system.

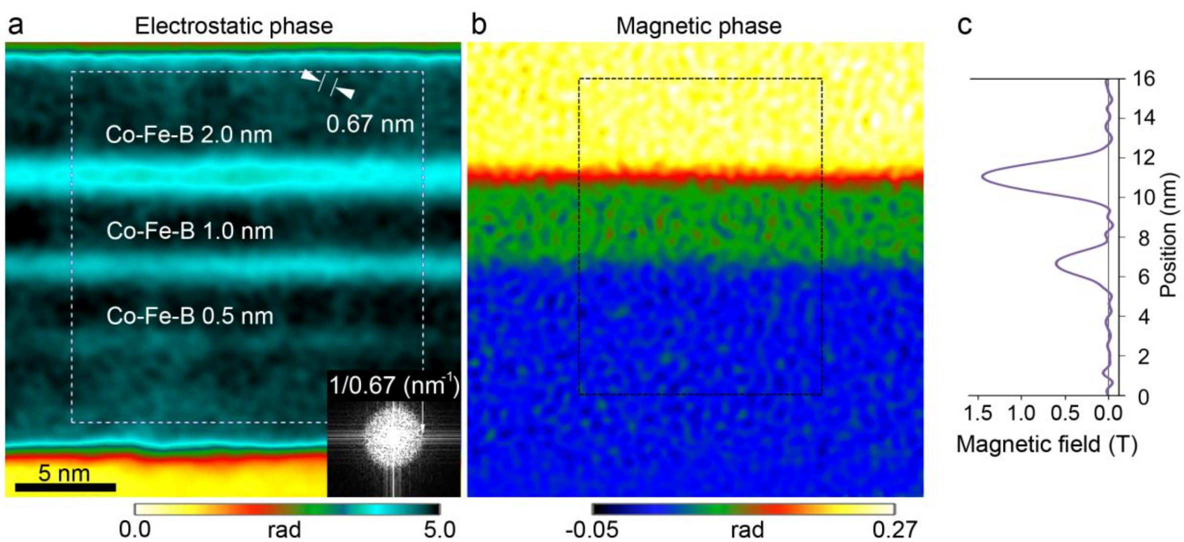

Figure 2. (a) Electrostatic and (b) magnetic phase of Co-Fe-B multilayer. Inset in (a) shows Fourier transform pattern of area indicated by white dashed square. (c) Magnetic field profile of black dashed area.