Advances in electromagnetic field observations using high-voltage electron holography

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The high penetration power of a high energy electron wave is crucial to observing magnetic structures, which exist only in thick samples. It is particularly crucial in three-dimensional (3D) observations, which require a series of sample observations with the sample increasingly tilted so that the projected sample thickness increases with the tilt angle. As an example of this, magnetic vortex cores confined in stacked ferromagnetic (Fe) discs were observed three-dimensionally by using vector-field electron tomography with a 1.0 MV holography electron microscope [1].

To invent new functional materials and devices for establishing a sustainable society, methods for controlling atomic arrangements in small areas such as interfaces have become important [2,3]. Electron holography is a powerful tool for analyzing the origins of functions by observing electromagnetic fields and strains at high resolutions. The advantages of high-voltage electron holography are high resolution and penetration power due to high energy electron waves. The quest for finding the ultimate resolution through continuous improvements on holography electron microscopes led to the development of an aberration corrected 1.2 MV holography electron microscope (Fig. 1) [4,5]. We describe recent results obtained by using the high-voltage electron holography.

Spatial resolution of 1.2 MV holography electron microscope reached 0.043 nm at high-resolution sample position [4]. Under the observation conditions, in which the sample was placed in a field-free position for observing a magnetic field, the spatial resolution reached 0.24 nm [5]. Although the spatial resolution of the TEM reached a subnanometer level, magnetic field observations at these resolutions have not yet been achieved because there were additional difficulties: improving magnetic phase sensitivity and separating the electrostatic and magnetic phases at high spatial resolutions. To overcome this, a pulse magnetization system was developed to reverse the magnetization in the sample without changing the geometrical configuration of the sample holder or stage referring to the electron beam. This resulted in sample drifts significantly smaller than those occurring with other separation methods.

To observe a subnanometer-resolution magnetic field, a multilayer consisting of Ta(5.0 nm)/CoFeB(0.5 nm)/Ta(3.0 nm)/CoFeB(1.0 nm)/Ta(3.0 nm)/CoFeB(2.0 nm)/Ta(6.0 nm) was prepared by using sputtering deposition. TEM observation revealed that the multilayer was intermixing at the CoFeB/Ta interfaces (Fig. 2a). Figure 2b shows the in-plane magnetic flux distributions, displayed by a cosine of the magnetic phase amplified 600 times with smoothing over a 1.43 nm length scale, parallel to the CoFeB layer. Spatial frequency perpendicular to the magnetic layer of 1/0.67 nm^{-1} was confirmed in the first Fourier transform (FFT) pattern. The successful separation of the electrostatic and magnetic phases provided data for analysis of the magnetic field as a function of the composition ratio of CoFeB to Ta. The results indicate that the magnetic field was not only affected by the mixing state, but also by a maximum composition ratio of CoFeB to Ta in the individual layer [6].

We developed a technique for exploring magnetic characteristics with high resolutions that can be used for various fundamental research and has practical applications for new industrial devices.

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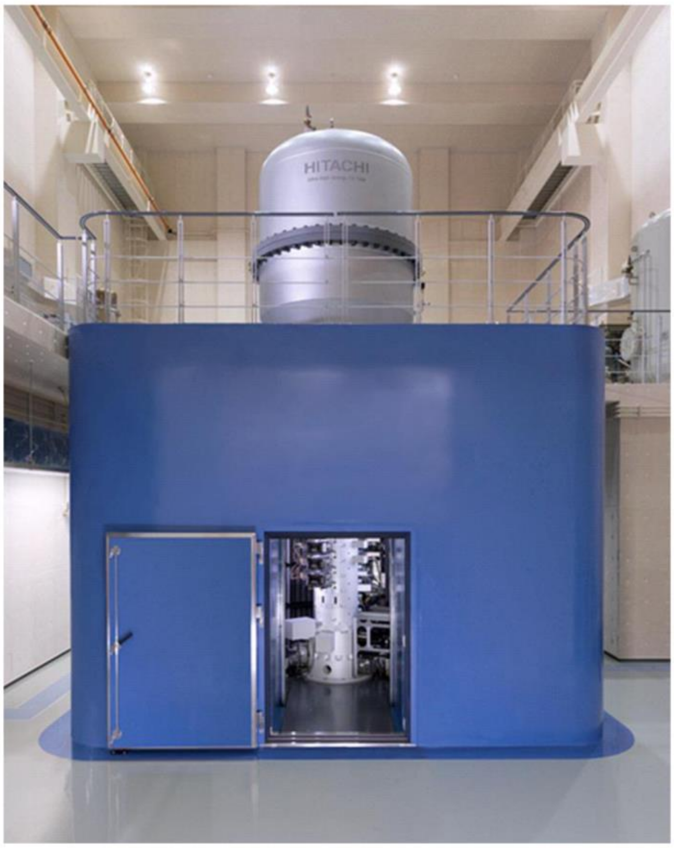

Fig. 1. An aberration corrected 1.2 MV holography electron microscope.

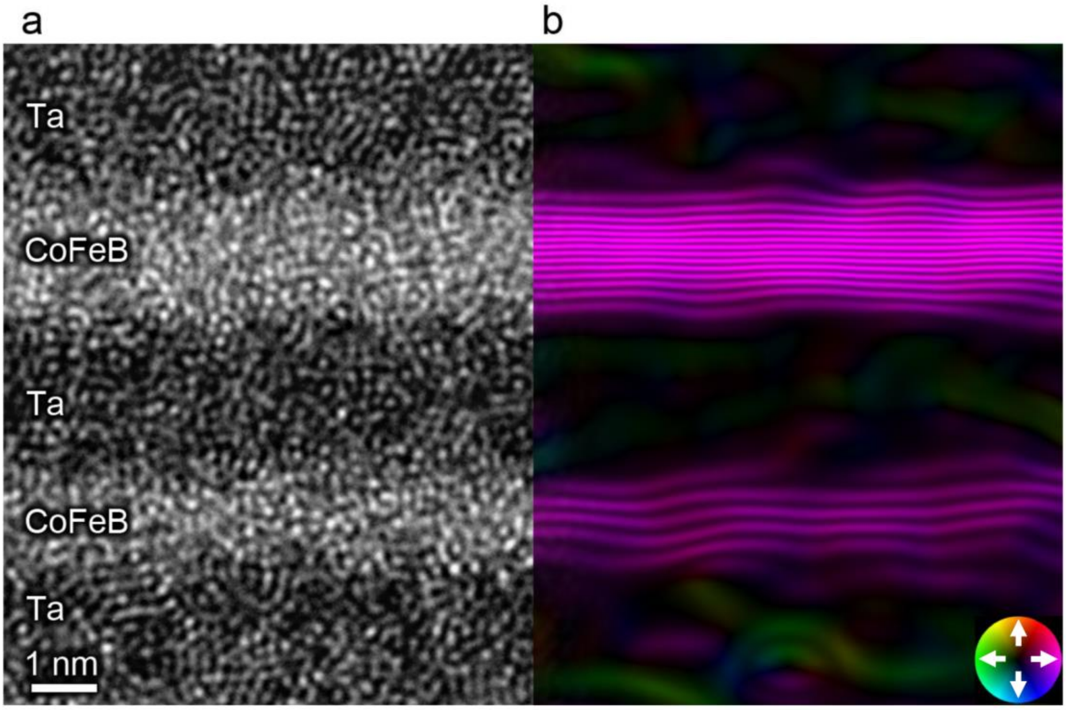

Fig. 2. (a) TEM image of CoFeB/Ta multilayer. (b) Magnetic flux distribution of CoFeB/Ta multilayer.