In situ visualization of local magnetic field using low-acceleration electron beam in scanning electron microscope

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Visualization of the local magnetic field is essential for understanding the spintronic behavior predicted to occur on grapheme. Electron beam holography is a powerful tool that could be used to visualize the local magnetic field through the detection of the magnetic vector potential, but the local magnetic field needed to induce the necessary phase shift in the electron wave for the imaging is far larger than the local spin polarization. Magnetic force microscopy (MFM) is an alternative for visualizing the local magnetization, but the visualization of a field distribution around a free-standing nanosized specimen is a crucial issue. Here, we demonstrate magnetic-field visualization using a beam of weakly accelerated electrons deflected by the local magnetic field of the nanospecimen.

Our visualizing principle [1,2], shown in Fig. 1, is based on a simple concept in which a low-acceleration electron beam (typically 1 to 5 keV) is deflected by the local magnetic field of a specimen. The deflection angle θ is defined by $\tan\theta = eBl / m_e v_e$, where m_e is the mass of the electron, B is the magnetic flux density, e is the elementary charge, v_e is the velocity of the electron, and l is the effective thickness of the magnetic field. Here, we placed a gold grid array at a distance of ~10 mm downstream of the specimen and detected the secondary electrons emitted by the incident deflected primary electrons; these secondary electrons generate bright contour lines that are simultaneously superimposed on the scanning electron microscope (SEM) image. The model specimen was a magnet strip array constructed of rectangular cobalt thin film (10 μm long, 2 μm wide, and 5 nm thick). Thus, the shape anisotropy produces a remnant magnetization of about 500 G and a multi-domain structure. The deflection direction is determined by the Lorentz force $F_e = e\vec{v} \times \vec{B}$, and therefore, electron beams incident at positions A and C are deflected to the same grid line, even though the beams are deflected in opposite directions. In addition, the deflection of the beam incident at position B is directed to the same grid line, since the magnetic flux density at this position is smaller than that at A and C. The secondary electrons emitted from the detection grid created curved contours that were almost equivalent to the local magnetic flux lines, as shown in Fig. 1. However, it should be noted that the contours are created from beams deflected from positions that have the same tangential component of the magnetic field density. The deflection angle is inversely proportional to the electron velocity, and thus a higher detection sensitivity can be obtained with a lower accelerating voltage, as shown in Fig. 2; this image was obtained with an incident electron beam energy of 2 keV. The contour line at position A is equivalent to a deflection of about 10 μm, and the primary electron beam passed the edge of the magnet at a distance of about 3 μm, suggesting that the local magnetic field was about 230 G. In contrast, the weak deflection at position B was estimated to be induced by a field of about 3 G. The sensitivity of this visualization technique depends on the electron acceleration energy, as shown in Fig. 3. In this image, the specimen was a standard MFM probe tip coated with a cobalt film. The weak deformation of the contour line at 5 keV changes remarkably to allow for a detailed field distribution at lower acceleration energies. The apex of the MFM tip is polarized, and thus magnetic flux was emitted and/or converged at the apex, generating a maximum flux density at this position. The magnetic flux on both sides has the same flux density, but the tangential component of the flux creates a split in the contour, as shown in Fig. 4. Based on the splitting of the gap width, we estimated the local flux density to be about 300 G at the tip apex.

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References

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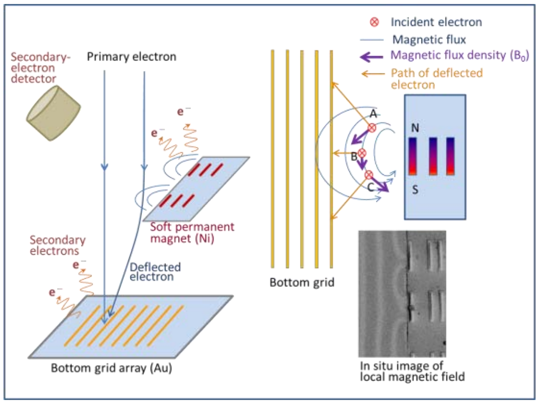

Figure 1: Schematic of the magnetic-field visualization.

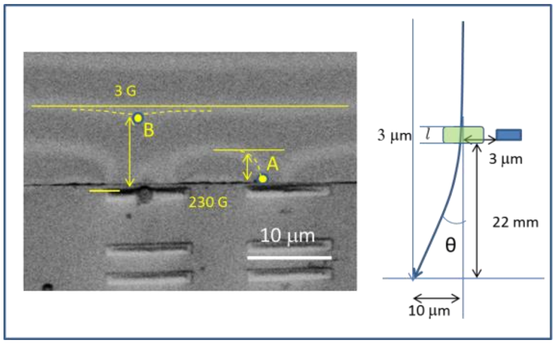

Figure 2: Evaluation of the local magnetic field.

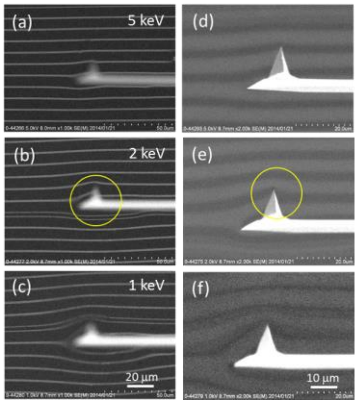

Figure 3: Acceleration energy dependency of the magnetic field imaging.

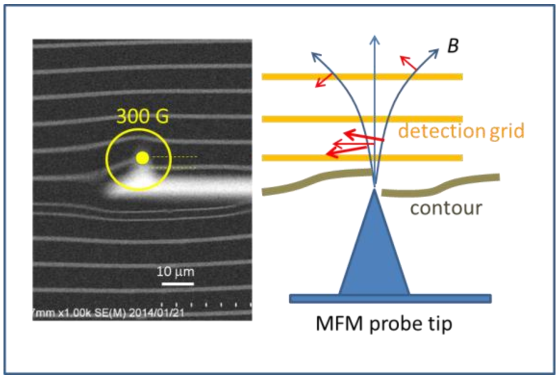

Figure 4: Image and deflection at the MFM tip.