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Three-Dimensional Magnetic Vortex Cores Visualized by Electron Holographic Vector Field Tomography

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Spintronics, which uses electron spins, is expected to become a widely used device technology because it has advantages in terms of nonvolatility, data processing speed, electric power consumption, and integration densities compared with conventional semiconductor technologies. Since the functions of spintronics devices are controlled by changing the spin configuration, i.e., by changing the magnetic field vector distribution, their direct observation is important for understanding the mechanisms of spintronics devices. Vector field electron tomography (VFET) using a transmission electron microscope (TEM) is a powerful technique for visualizing three-dimensional (3D) magnetic vector distributions on the nanometer scale [1,2]. Here we report 3D magnetic vortices in stacked ferromagnetic discs in a nanoscale pillar using a 1 MV electron holography microscope and a dual-axis 360° rotation sample holder for the VFET [3].

The 1 MV holography electron microscope with high penetration power, which has been used to observe vortex behavior in high-Tc superconductors [4], is a promising instrument for observing practical spintronics devices because it does not require changing their inherent magnetic structures by sample thinning. The dual-axis 360º rotation sample holder can eliminate artifacts due to missing wedges while performing the VFET [5]. These electron microscopic technologies have been used to unveil 3D magnetic vortices in stacked ferromagnetic discs in a nanoscale pillar (Figure 1).

Figure 2 shows 3D view of the reconstructed magnetic vortex cores. The obtained 3D magnetic vectors in the stacked magnetic discs clearly show counter clockwise (CCW) magnetic flux flows in both the upper and lower discs. The z direction of the magnetic vectors at the vortex core of the upper disc was up while that of the lower disc was down. These opposite z directions are indicated by coloring in blue and red. The tail-to-tail vortex cores were mutually repulsive and thus stabilized at a position offset from the structural center of the discs. Comparison of the observed 3D magnetic field vector distributions in the magnetic vortex cores with the results of micromagnetic simulations based on the Landau-Lifshitz-Gilbert equation showed that tail-to-tail vortex configurations are one of the stable magnetization states.

In conclusion, 3D magnetic field vector distributions in the stacked ferromagnetic discs were visualized using the electron holographic VFET performed using the 1 MV holography electron microscope with high penetration power and the dual-axis 360º rotation sample holder that prevented missing wedges. The obtained results demonstrate that the proposed electron holographic VFET is a promising technique for direct 3D visualization of the spin configurations in magnetic materials and spintronics devices.

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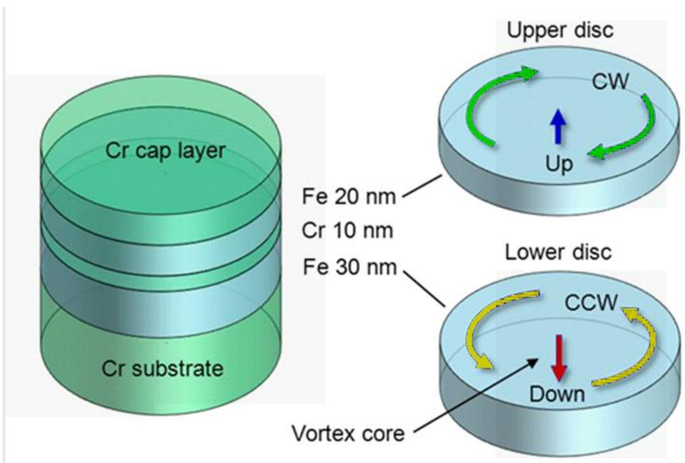

Figure 1. Schematic diagrams of stacked ferromagnetic discs and axes used for 360º observations. Two Fe discs (light blue) with thicknesses of 20 nm (upper) and 30 nm (lower) were separated by a 10 nm Cr disk (green). The direction of the magnetic vortices in the disc is either clockwise (CW) or counter clockwise (CCW). At the magnetic vortex core, the direction of the magnetic vectors is either up or down.

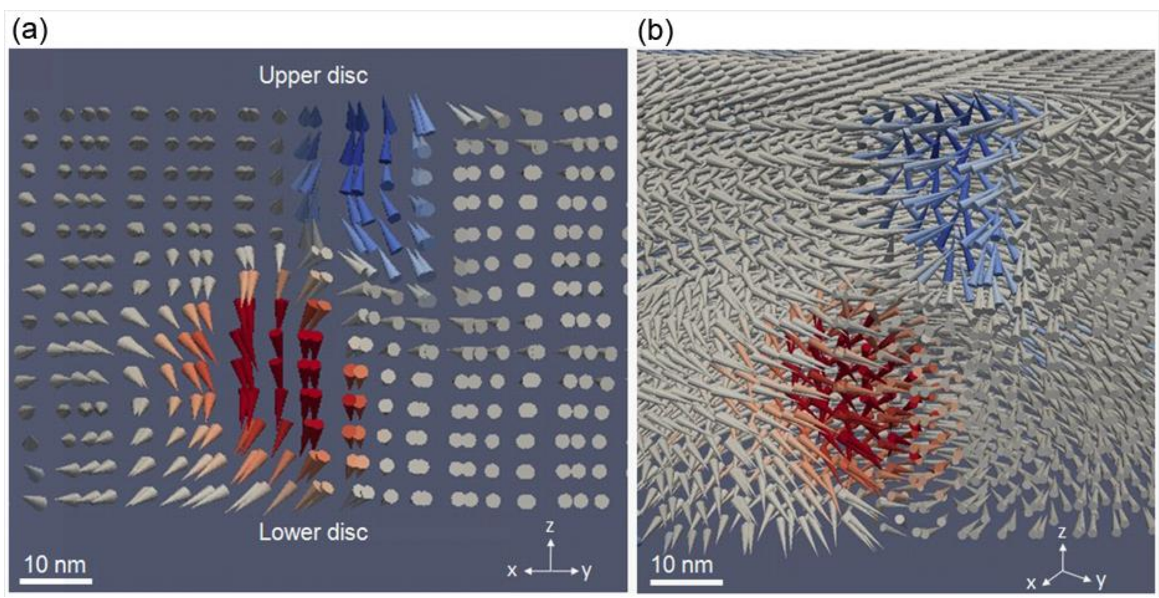

Figure 2. Three-dimensional (3D) view of the reconstructed magnetic vortex cores. The z-directional components are indicated by blue (+z) or red (−z). (a) The cross-sectional magnetic vectors. The magnetic vectors for the upper and lower vortex cores had opposite z directions. (b) 3D view of the tail-to-tail vortex cores.