Dipolar ferromagnetism, a ferromagnetic ground state for a fcc lattice of point dipoles, was theoretically predicted by Luttinger and Tisza [1]. Computer simulation has shown vortex domain structures with net magnetization in hexagonal arrays of magnetic nanodisks [2]. Magnetic force microscopy (MFM) has experimentally detected short-range net magnetization in 12 nm Co nanoparticle arrays at room temperature [3], however, the domain structures have been unclear because MFM is not sensitive enough to detect the in-plane component of magnetization in the array. Electron holography can directly detect the in-plane component at higher spatial resolution. Here we report the existence of dipolar ferromagnetic domain structures by electron holography.

We prepared 8 nm ε-Co nanoparticles in a high boiling-point solvent, and then transferred to carbon-coated TEM grids [4]. Observation were carried out with Philips CM200 TEM (200 kV) equipped with an electrostatic biprism and a Lorentz lens beneath a standard objective lens. Figure 1 shows the TEM image of the ε-Co monolayers with partial disordering. The average edge-to-edge separation between nanoparticles is 4.2 nm. To observe domain structures, we cooled the sample to 108 K with liquid nitrogen cooling holder in a zero field environment.

Figure 2 (a) shows a 7.5 μm wide region around edge of the sample. Eighteen frames are combined. We took a series of holograms and reference holograms at the same positions, and obtained the reconstructed phase distribution shown in Figure 2 (b). Vortex-like domain structures in micron scale were clearly observed near the sample edge. The previous simulation [2] predicted vortex structures due to magnetostatic interaction. Our result was similar to the simulation pattern around the edge. We applied a magnetic field to the sample in 108 K. The sample was tilted and the objective lens was turned on. After turning off the lens, the sample was tilted back to zero and imaged in remanence. As shown in Figure 2 (c), the vortex-like domain structures were shifted.
Shifting domain walls by a magnetic field has been observed in ordinary ferromagnetic materials [5]. A similar response occurred in the magnetic nanoparticle arrays without exchange coupling.

In conclusion, we experimentally showed the existence of long-range dipolar ferromagnetic ordering in the arrays, and observed the micron sized vortex-like domain structures and their response to the applied field. These observations would provide important information to clarify the detail of dipolar ferromagnetism.

We are grateful to Prof. David J. Smith for his valuable comments. We acknowledge the use of facilities within the John M. Cowley Center for High Resolution Electron Microscopy at Arizona State University.

References

FIG. 1 TEM image showing monolayer array of 8 nm ε-Co nanoparticles.

FIG. 2 Dipolar ferromagnetic domain structure after zero field cooling to 108 K; (a) TEM images near the sample edge. (b) Reconstructed phase distribution. Arrows indicate the direction of collective magnetization. (c) Reconstructed phase distribution after applying a magnetic field. The pattern was shifted.