Magnetic flux closure states in self-assembled nanoparticle rings

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The off-axis mode of electron holography is ideally suited to the characterization of magnetic fields in nanostructured materials because unwanted contributions to the measured phase shift from variations in composition and specimen thickness can be removed from a phase image more easily than from images recorded using other phase contrast techniques in the transmission electron microscope. Here, we present the application of electron holography to the characterization of rings of 20-nm-diameter Co nanoparticles. Such rings are appealing candidates for high density information storage applications because they are expected to form domain states that exhibit flux closure (FC). Such FC states have been proposed as elements in device architectures for magnetoresistive random-access memory [1]. As the magnetization directions of such rings cannot be reversed by applying an in-plane field to the sample using the microscope objective lens, phase images were obtained before and after turning the specimen over. The resulting pairs of phase images were aligned in position and angle, and their difference used to determine the magnetic contribution to the phase shift.

Figure 1a shows a bright-field image of the Co rings [2]. A variety of structures is visible, including five- and six-particle rings, chains and close-packed aggregates containing three or more particles. The particles are each encapsulated in a 3-4 nm oxide shell. Figures 1b-d show magnetic FC states in four rings, recorded using electron holography at room temperature in zero-field conditions [3]. The magnetic flux lines, which are formed from the cosine of 128 times the magnetic contribution to the measured phase shift, reveal the in-plane induction within each ring (integrated in the electron beam direction). Magnetic force microscopy confirmed the absence of magnetic vortex cores, such as those observed in planar magnetic disks [4]. The specimen contained an approximately 50:50 mixture of clockwise and counterclockwise ground-state configurations, to which the rings relaxed after exposure to a 2 T out-of-plane magnetic field. The stability and reproducibility of the states suggests that smaller particles may form stable FC states at room temperature, in contrast to vortex states in disks which are only stable for diameters of above ~100 nm [5]. The chirality of the states shown in Figure 1 can be switched using an out-of-plane magnetic field. Although the critical field strength for reversal remains to be determined, preliminary studies show that 4-to-7-membered rings can be reversed using an out-of-plane field of 1600 Oe [6].

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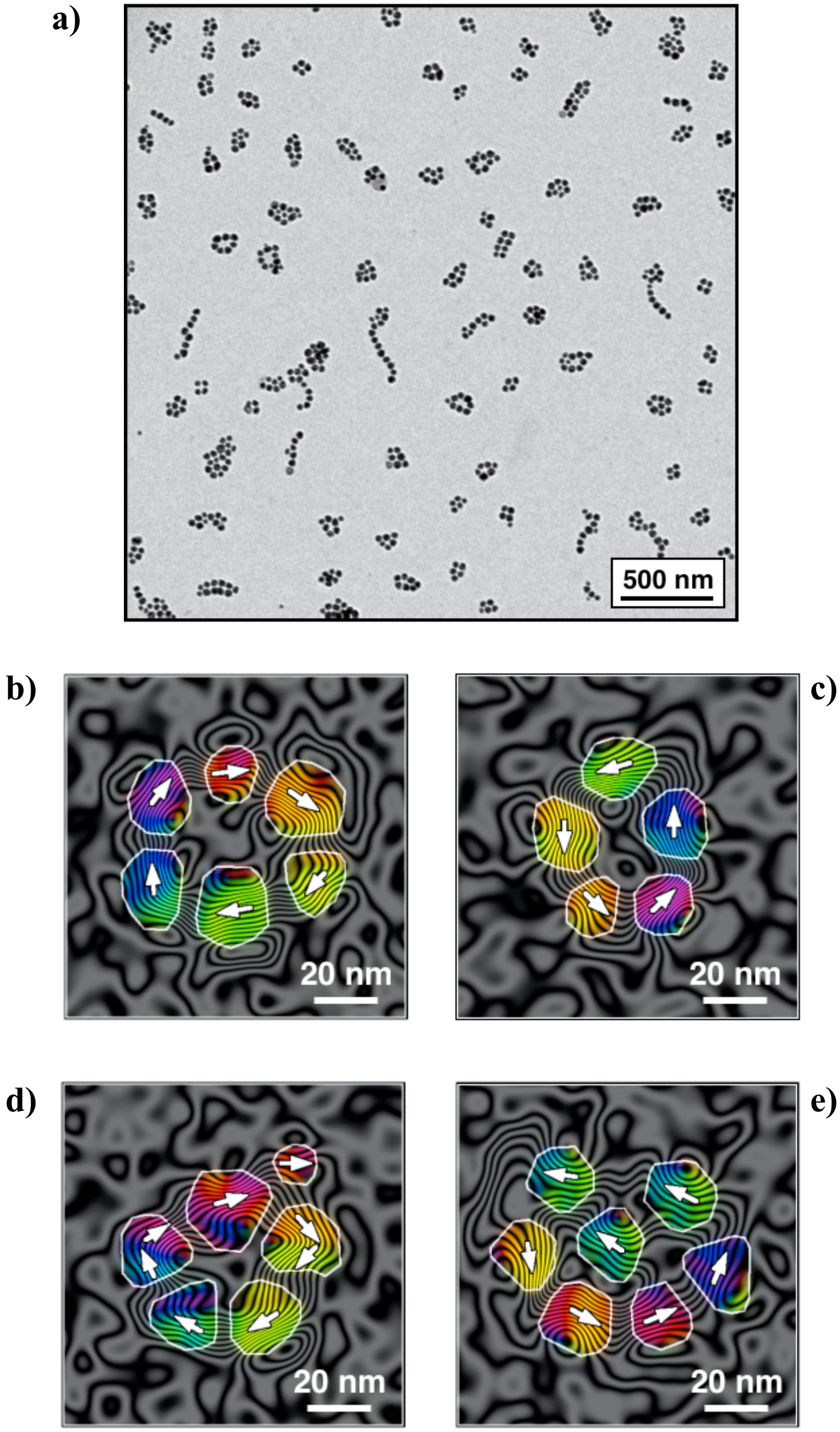

Figure 1. a) Low magnification bright-field image of self-assembled Co nanoparticle rings and chains deposited onto an amorphous carbon film. Each Co particle has a diameter of between 20 and 30 nm. b) - e) Magnetic phase contours (128 × amplification; 0.049 radian spacing), formed from the magnetic contribution to the measured phase shift, in four different nanoparticle rings. The outlines of the nanoparticles are marked in white, while the direction of the measured magnetic induction is indicated using arrows.