Switching phenomena in magnetic materials and devices studied using electron holography

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We describe the application of off-axis electron holography in the transmission electron microscope (TEM) to the study of magnetic switching phenomena in nanostructured materials and devices with sub-10-nm spatial resolution. Our measurements are facilitated by the ability to apply external magnetic fields and voltages to electron-transparent specimens in the TEM, as well as to vary the specimen temperature. Here, we concentrate on three distinct specimen geometries:

1. Magnetic remanent states in two-dimensional and linear arrangements of lithographically patterned nanostructures are studied. Rectangular arrays of 75 nm x 280 nm NiFe/Cu/Co pseudo-spin-valve elements are prepared for TEM examination in plan-view geometry using focused ion-beam milling. The magnetic switching fields of the Co and NiFe layers in individual elements are measured, and comparisons with micromagnetic simulations are used to infer the true magnetic thicknesses and widths of these layers. Remanent magnetic states in linear arrays of electrodeposited Ni pillars with diameters of 57–120 nm and aspect ratios of up to 2 are also characterized. Inhomogeneities in the Ni, resulting from its grain structure, are observed to perturb the axial uniformity of the magnetization.

2. The effect of crystallography, size, shape and spacing on the formation and switching of magnetic states in isolated and closely-spaced sub-50-nm magnetic nanocrystals is studied. The change in the direction of magnetization of an isolated equidimensional magnetite crystal with decreasing temperature is imaged directly. Interactions between neighboring magnetite nanocrystals are observed to increase the critical size at which the transition from superparamagnetic to single domain behavior occurs. Tapering magnetic catalyst particles that are encapsulated in carbon nanotubes are also studied in order to examine the effect of shape anisotropy on magnetic remanent states. The combined effects of shape, crystallography and inter-particle interactions are found to stabilize single domain states in crystals that would normally be expected to support multiple domains, if they were isolated.

3. Both electron holography and the Fresnel mode of Lorentz electron microscopy are used to study domain wall motion and transformations following the injection of current pulses along zigzag permalloy structures that are patterned lithographically on electron-transparent silicon nitride windows. Spin structure transformations due to Joule heating are observed following the injection of current pulses, and a set of indicators is devised to separate spin torque effects from heating. By using additional metal layers, the structures are cooled sufficiently to demonstrate current-induced domain wall motion due to spin torque.