

Off-axis electron holography of magnetic nanoparticles, nanostructures and devices

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Off-axis electron holography is a powerful technique that can be used to characterize magnetic and electrostatic fields in materials in the transmission electron microscope with sub-10-nm spatial resolution. Here, we present several recent applications of the technique to the measurement of magnetic fields in a variety of different materials:

1. Linear arrays of magnetic nanocrystals are studied to understand the effect of crystallography, size, shape and spacing on the formation of remanent magnetic states. Interactions between neighboring crystals increase the critical size at which the transition from superparamagnetic to single domain behavior occurs and stabilize single domain states in crystals that would normally be expected to support multiple domains if they were isolated.
2. Self-assembled circular rings of nanoparticles, which support flux-closed magnetic states that would not be stable in disk-shaped elements of similar size, are studied using electron holography to understand magnetic switching in out-of-plane magnetic fields. Comparisons of experimental results with micromagnetic simulations suggest that complex metastable states form at intermediate applied fields.
3. The switching fields of the magnetic layers in individual sub-200-nm spin-valve elements are measured, and comparisons with micromagnetic simulations are used to infer the true magnetic thicknesses and widths of these layers. Inhomogeneities resulting from grain structure are observed to affect switching reproducibility.
4. Specimen holders that allow electrical contacts to be applied to magnetic devices in the electron microscope allow electron holography and the Fresnel mode of Lorentz microscopy to be used to study domain wall motion and transformations following the injection of current pulses along magnetic wires. Spin structure transformations due to Joule heating are observed and a set of indicators is devised to separate spin torque from heating effects.
5. Future developments in electron holography of magnetic materials may include approaches for increasing the sensitivity of the technique for measuring weak fields, improving its time resolution, understanding the effect of specimen preparation and electron irradiation on measurements of both magnetic and electrostatic fields, quantifying the magnetic moments of individual nanocrystals, and characterizing magnetic vector fields inside nanocrystals in three dimensions by combining electron tomography with electron holography.