Quantitative measurements of magnetic states in patterned permalloy disks using off-axis electron holography and model-based reconstruction of magnetisation

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Magnetic nanostructures are of interest both fundamentally and for applications that include data storage, medical imaging and drug delivery. As new applications require nanostructures that have ever smaller dimensions, the characterisation of their structural, chemical and magnetic properties becomes increasingly challenging. Here, the intrinsic magnetisation of lithographically patterned, circular permalloy elements is determined quantitatively using off-axis electron holography and a model-based iterative algorithm.

Permalloy disks with a nominal thickness of 50 nm and varying diameters of up to 1.5 m (Figure 1a) were fabricated on silicon nitride membranes using electron beam lithography, thermal evaporation of permalloy, and lift-off. Transmission electron microscopy (TEM) was used to study the structures, compositions and magnetic fields of the disks quantitatively with high spatial resolution. For magnetic characterisation, the samples were studied in magnetic-field-free conditions in Lorentz mode in an aberration corrected FEI Titan TEM operated at 300 kV. We used both the Fresnel mode of Lorentz TEM and off-axis electron holography to study the magnetic states of the permalloy disks. The projected in-plane component of the magnetic flux density within and around the disks was determined by separating the magnetic from the electrostatic contribution to the phase shift measured using off-axis electron holography. This separation was achieved by using a TEM specimen holder that allowed the sample to be turned over inside the microscope, leaving its magnetic state unaffected by external magnetic fields. The resulting phase images were aligned and half of the difference between them was evaluated, in order to obtain the magnetic contribution to the phase shift of the permalloy elements (Figure 1b). The projected in-plane magnetisation in the disks was then reconstructed from the magnetic phase images using a model-based iterative algorithm.

Both the magnetic contribution to the phase and the reconstructed magnetisation reveal the presence of a vortex state in permalloy elements that have a diameter of 1250 nm and a nominal thickness of 50 nm (Figures 1b, c). The vortex core is estimated to have a diameter of 15 nm. On the assumption that the nominal specimen thickness is correct, the average magnitude of the in-plane magnetisation was inferred to be 0.8 T, which is apparently smaller than the value of 1 T expected for permalloy. This difference is expected to result from the fact that the true magnetic thickness of the disk is slightly smaller than its nominal value, in part because of slight oxidation. Interestingly, a more complex magnetic state, namely perpendicular magnetisation, was observed in permalloy disks above a critical thickness using scanning transmission X-ray microscopy (STXM). Ongoing studies are being used to correlated and combine magnetic information of permalloy disks with various thicknesses measured by both STXM and off-axis electron holography.

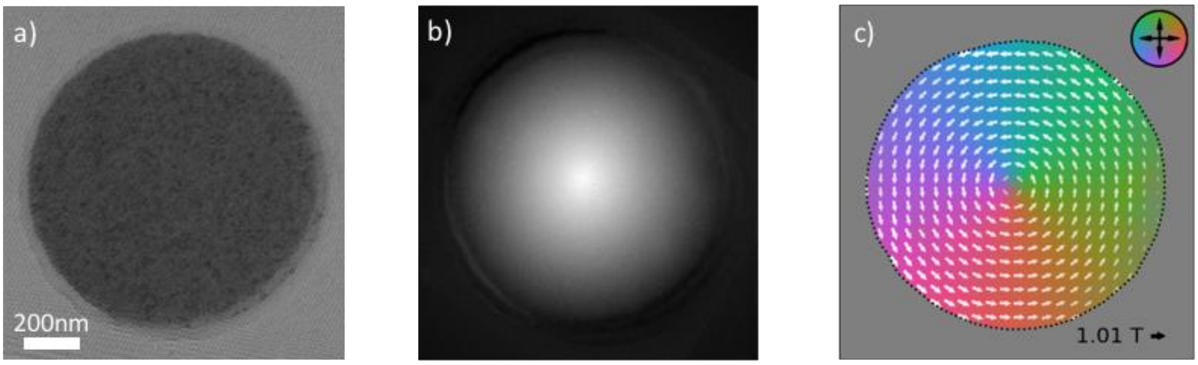

Figure 1. (a) Off-axis electron hologram of a permalloy disk of diameter 1250 nm. (b) Magnetic contribution to the phase shift. (c) Reconstructed projected in-plane magnetisation showing a vortex state. The length of each arrow corresponds to the magnitude of the magnetisation.

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