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Influence of shape imperfections on the magnetic states of permalloy nanodisks studied using off-axis electron holography

T. Weßels[1], S. Finizio[2], P. Diehle[1], J. Caron[1], A. Kovács[1], V. Migunov[1,3], S. Gliga[4], J. Raabe[2], R. Dunin-Borkowski[1]

[1]Forschungszentrum Jülich, Ernst Ruska-Centre for Microscopy and Spectroscopy with Electrons and Peter Grünberg Institute 5, Jülich, Germany
[2]Paul Scherrer Institute, Swiss Light Source, Villigen, Switzerland
[3]RWTH Aachen University, Central Facility for Electron Microscopy (GFE), Aachen, Germany
[4]University of Glasgow, SUPA, School of Physics and Astronomy, Glasgow, United Kingdom

Magnetic nanostructures are of interest from a fundamental perspective 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 (EH) and a model-based iterative reconstruction algorithm.

Permalloy disks with thicknesses of between 50 and 200 nm and diameters of up to 1.5 µm (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. Both the Fresnel mode of Lorentz TEM and off-axis EH were used to study the magnetic states of the permalloy disks. The latter technique is used to measure the magnetic contribution to the electron optical phase shift, which is sensitive to the projected in-plane component of the magnetic flux density within and around the sample and is separated from the electrostatic contribution to the recorded phase shift by turning the sample over inside the TEM using a dedicated holder and recording holograms of the same region of interest. Each pair of phase images was aligned and half of the difference between them was evaluated, in order to obtain the magnetic contribution to the phase shift (Figure 1b). The projected in-plane magnetisation was then reconstructed from the magnetic phase images by using a model-based iterative algorithm.

Both the magnetic phase images and the reconstructed magnetisation distributions reveal the presence of magnetic vortex states 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 is inferred to be 0.8 T, which is 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 smaller than its nominal value, in part because of slight oxidation.

Cross sections of the disks were also prepared using focused ion beam milling, revealing that they had slightly distorted bowl-like shapes, instead of being flat. The curvature of the disks was found to increase with their thickness. The three-dimensional nature of the magnetic structure and its relationship to the disk shapes will be discussed.

Fig. 1

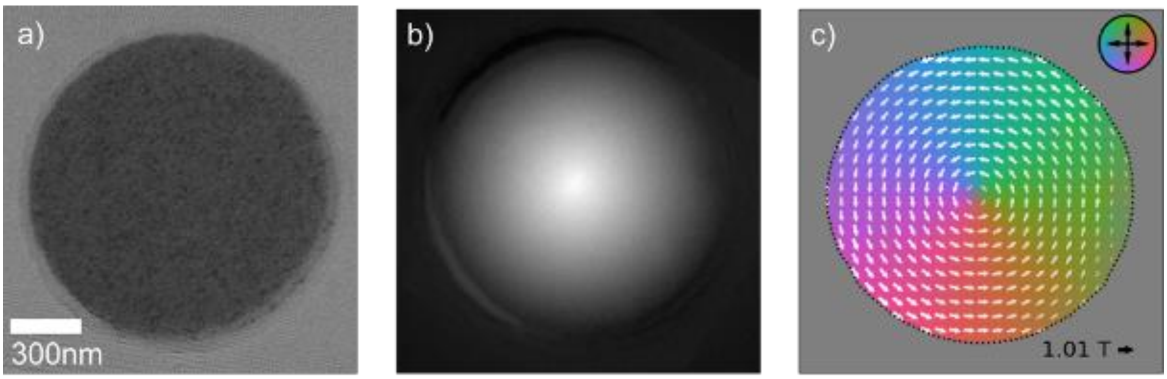

Figure 1. (a) Off-axis electron hologram of a permalloy disk of diameter 1250 nm and thickness 50 nm. (b) Magnetic contribution to the phase shift. (c) Reconstructed projected in-plane magnetisation showing a vortex state. The length of each arrow corresponds to the magnitude of the magnetisation.