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Fabrication of magnetic ring structures for Lorentz electron microscopy

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Abstract

We have fabricated three-quarter ring structures on silicon nitride membranes for magnetic domain imaging using Lorentz electron microscopy. The ring structures have linewidths of 100, 250, 350 and 700 nm, and outer diameters of 1.65 μm. Using the Foucault imaging mode, we have observed the magnetic domain configurations in ring structures with an inter-ring separation of 100 nm. Head-to-head transverse domain walls and vortices are seen depending on the ring geometry and stray field interactions between the rings. It is also possible to see contrast due to the stray field produced by transverse walls.

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The current interest in nanoscale magnetic elements is driven by both the interesting physics at reduced lateral dimensions and the possible industrial applications. For such applications, it is important to have precise control of the magnetic switching, which can be achieved when the magnetic elements have well-defined and reproducible remanent states and the switching processes are simple. The ring geometry has so far displayed these desired characteristics and has a good potential for use in high-density data storage [1,2] and bio-detection [3].

The rings have particularly simple magnetic states due to their high symmetry. In particular, in narrow rings there are two stable magnetic states [4–6]; the flux-closure vortex state, and the 'onion' state, accessible reversibly from saturation and characterised by the presence of two opposite head-to-head walls. These can either be transverse or vortex walls, schematically shown in Figs. 1a and b respectively, depending on the ring geometry [7]. Thus two transitions occur in the rings; at intermediate fields the rings switch from the onion to the vortex state and at high fields they switch from the vortex to the opposite onion state [4,8]. In order to fully understand the detailed magnetic behaviour of such rings, it is important to carry out direct observations of the magnetic domain structures. From such observations the dependence of the domain structures on the ring geometry can be determined, making it possible to tailor their magnetic properties. In addition to scanning

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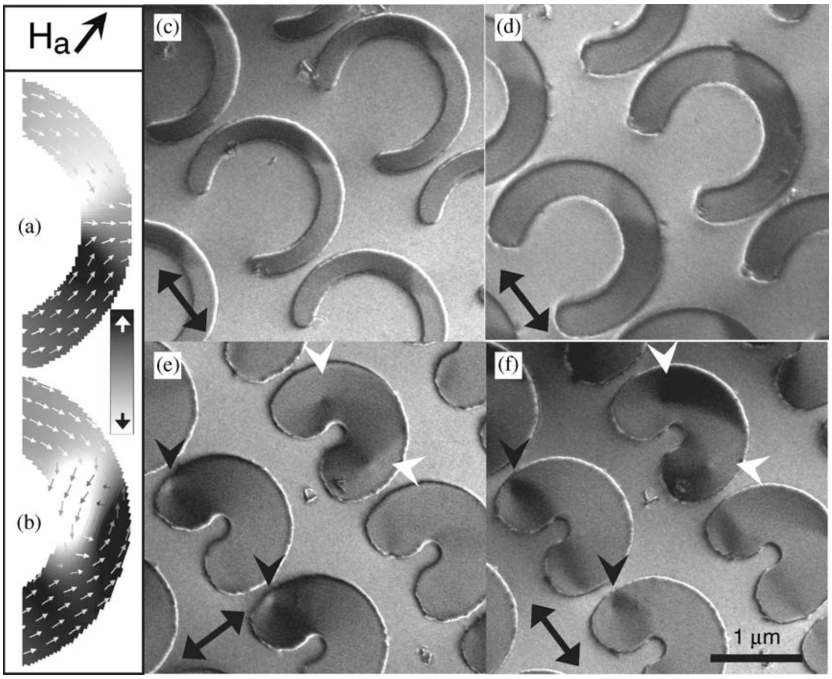

Fig. 1. (a,b) Schematic representations of magnetic spin structures and resulting magnetic contrast for a transverse and a vortex domain wall, respectively. (c–f) Foucault images of three-quarter rings after saturating the sample with an applied field, H_a, whose orientation is indicated: (c) $W = 250$ nm, (d) $W = 350$ nm and (e, f) pair of images for $W = 700$ nm with the positions of vortices indicated by the four single arrowheads. The images are sensitive to the direction of the magnetic induction component given by the double-headed arrows.

electron microscopy with polarisation analysis (SEMPA) and photoemission electron microscopy (PEEM) analysis [9], transmission electron microscopy (TEM) can provide detailed information on the magnetic spin structures. We have therefore fabricated ferromagnetic ring structures on substrates for Lorentz electron microscopy [10]. Here, a magnetic field can be applied to the sample using the objective lens field, which can be varied by changing the lens current or tilting the sample.

In order to produce samples suitable for TEM observations, the ferromagnetic rings must be fabricated on membranes to allow the transmission of electrons. While we have already shown that it is possible to prepare magnetic rings down to outer diameters of 90 nm using electron lithography with a lift-off process [11], the lift-off requires removal of the unwanted resist and magnetic material in an ultrasound bath. This is not compatible with membrane substrates because the membranes are too fragile to survive the ultrasound treatment. We report here on the fabrication of lift-off ring structures on membranes without the use of ultrasound and the observation of the magnetic domain structures using the Foucault imaging mode.

We employed electron beam lithography to fabricate magnetic rings on silicon nitride membrane substrates (from Silson Ltd, UK) suitable for TEM. The substrates have 500 µm square membranes with a thickness of 50 nm, back-coated with 5 nm Cr to minimise charging during the electron beam writing. The front side of the substrate was spin-coated with 100 nm of poly methylmethacrylate (PMMA) resist and the resist was patterned with ring structures using a Leica LION LV1 electron beam writer with the electron beam energy set to 2.5 keV to minimise the proximity effect. To write the ring structures, the electron beam follows a circular single pixel path along the ring and the linewidth is determined by the electron beam dose and defocus [12]. We created 6×6 arrays of full rings and three-quarter rings where a quarter of the ring was missing resulting in a horseshoe shape. These ring structures were produced with linewidths of $W = 100$, 250, 350 and 700 nm, and an outer diameter of 1.65 µm. The inter-ring spacing could be changed to vary the magnetic stray field interaction between the rings. 10 nm-thick polycrystalline permalloy (NiFe) films, with a 2 nm thick gold capping layer to prevent oxidation of the magnetic film, were deposited on the patterned resist by MBE evaporation in an ultra-high vacuum deposition chamber at a base pressure of 3×10^{-10} mbar [6]. The lift-off process involved removal of unwanted resist and magnetic material in acetone. For the full rings, the isolated centre of the ring did not lift off without the use