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Fabrication of curved-line nanostructures on membranes for transmission electron microscopy investigations of domain walls

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Abstract

We have fabricated curved-line ferromagnetic nanostructures on membranes for transmission electron microscopy investigations of the equilibrium magnetic spin configurations. The magnetic elements were fabricated using electron-beam lithography and a lift-off procedure for pattern transfer. Due to the fragile nature of the membranes, the design of the elements was chosen to ensure that the lift-off was possible without using ultrasound. The elements included three-quarter rings, zig-zag lines and wavy lines with notches resulting in constrictions with widths down to 30 nm. Magnetic configurations were observed using electron holography and Lorentz microscopy. In particular, the details of the spin structure of vortex and transverse walls, and its dependence on the local geometry were obtained. While Lorentz microscopy provided qualitative information about magnetic spin orientations and the positions of domain walls, electron holography gave quantitative high-resolution images of the magnetic induction allowing the direct measurement of the stray field between adjacent domain walls.

Keywords: Ferromagnetic nanostructures; Electron holography; Lorentz microscopy

1. Introduction

The miniaturization of ferromagnetic elements down to the nanometer scale is of high interest both for research and for industry because it promises applications for data storage [1] and bio-detection [2]. For such applications it is essential to know the details of the magnetic spin structure present and to be able to control the switching process. It is therefore important to observe the spin structures present directly [3]. From such observations the dependence of the spin structures on the element geometry can be determined, making it possible to tailor their magnetic properties.

In the present work we fabricated different curved-line ferromagnetic elements on membrane substrates for direct observation of the magnetic spin structure using a transmission electron microscope (TEM). Curved-line elements such as rings are ideally suited for such experiments because it is possible to position the domain wall precisely using an externally applied field [4,5]. The domain wall can be either a vortex or transverse wall (see Fig. 2(a) and (b)), depending on the geometry of the element [6]. It is also of interest to study the influence of constrictions on the spin structure which can be correlated with magnetoresistance measurements [7] and current induced domain wall motion [8]. We employed electron holography and Lorentz micros-

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copy to probe the magnetic spin configurations in the curved-line elements and the interaction between ferromagnetic elements due to the presence of dipolar magnetic stray fields. In order to nucleate domain walls, a magnetic field can be applied to the sample using the objective lens field.

2. Fabrication of curved-line ferromagnetic structures on membranes

Curved-line ferromagnetic elements were fabricated using electron-beam lithography. First a Leica LION LV1 electron-beam writer was used to pattern a poly methylmethacrylate (PMMA) resist (50–100 nm thick), which was spin-coated on silicon nitride membrane substrates (from Silson Ltd., UK). To write curved lines, the electron beam follows a curved single pixel path and the line width is adjusted by changing the dose and the defocus of the electron beam. The electron-beam energy was set to 2.5 keV to minimize the proximity effect [9]. The substrates consist of 500 μm square membranes with a thickness of 50 nm (transparent to electrons in the TEM), and are back-coated with 5 nm Cr to minimize charging during electron-beam writing.

Pattern transfer was carried out using a lift-off process. A ferromagnetic film was deposited on the membrane with the patterned resist in an ultra-high vacuum molecular-beam epitaxy deposition chamber [3]. The magnetic film was either cobalt or permalloy with a thickness in the range of 5–30 nm. In a final lift-off step the unwanted resist and magnetic material were removed in acetone. In order not to damage the fragile membranes ultrasound was not used to assist the lift-off. It was therefore necessary to design open elements as, e.g., for closed ring elements the center does not lift out without the help of ultrasound [10]. The details for the three different element types fabricated are:

(i) *Three-quarter rings* (Fig. 1(a)). There is a gap in the ring to ensure that the lift-off works without ultrasound. Arrays of three-quarter rings were fabricated with different line widths, outer diameters and thicknesses. In addition, the edge-to-edge spacing was varied to study the interaction between domain walls in adjacent rings due to magnetic stray fields.

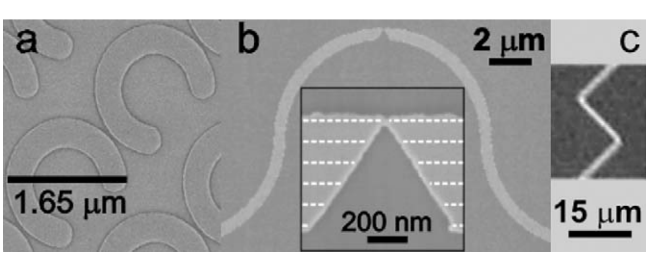

Fig. 1. SEM images of (a) an array of permalloy three-quarter rings with 350 nm linewidth, 1.65 μm outer diameter and 10 nm thickness; (b) part of a wavy line with a notch. The inset shows a magnified image of a constriction and the dashed lines indicate the beam path; (c) optical image of zig-zag lines with gold contacts.

(ii) *Wavy lines with notches* (Fig. 1(b)). These include a constriction in the curved section of the line. To achieve this, thin lines (with widths of the order of 50 nm) are combined together. The writing strategy is indicated by the dashed white lines in the inset which represent the electron-beam path. The path is adjusted, and can either be continuous or have a gap at the position of the notch, to give a certain width for the constriction. In order to maximize the effect of the constriction on the magnetic spin structure, the width of the constriction is made as small as possible. We have fabricated constrictions with widths down to 30 nm (see inset).

(iii) *Zig-zag lines* (Fig. 1(c)). These consist of 15 μm long and 100 to 500 nm wide line segments which are connected by quarter rings of different diameters. Contacts consisting of an 8 nm thick chromium layer and a 60 nm thick gold layer were added to each end of the line using an overlay procedure for magnetotransport investigations.

3. Observation of magnetic spin structures

In the following we report on TEM observations of some of the elements described above, exploiting different electron microscopy techniques for observation of magnetic spin structures.

First we observed stray field interactions between three-quarter rings and their influence on the magnetic spin structures, which depend on the distance between the neighbouring rings. Using Foucault imaging, qualitative information about the spin orientations is revealed [11]. The pairs of Foucault images in Fig. 2(c) and (d) show 10 nm thick permalloy three-quarter rings with an outer diameter of 1.65 μm and a line width of 350 nm and are sensitive to orthogonal directions of the magnetic induction, as given by the double headed arrows in the images.

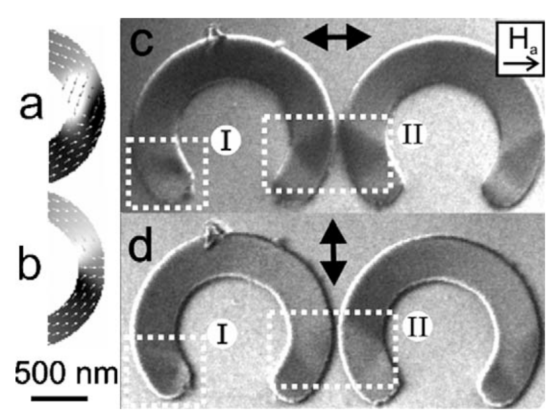

Fig. 2. Schematic diagram of (a) a vortex and (b) a transverse domain wall. (c, d) Pairs of Foucault images of three-quarter rings (as in Fig. 1(a)) after saturating the rings with an applied magnetic field H_a in the indicated direction. The images are sensitive to orthogonal directions of the magnetic induction component given by the double-headed arrows.

As indicated by the dashed regions, we can observe vortices (I) in the vicinity of the line ends and transverse walls (II). For comparison, schematic diagrams of vortex and transverse domain walls are given in Fig. 2(a) and (b), respectively. The vortex has a curled spin structure. The transverse walls are recognizable by the presence of a triangular shaped domain between domains with opposite magnetization. The transverse walls are favoured over vortices within the ring array because of stray field interactions between the transverse walls.

Detailed quantitative information about the magnetic spin configurations and stray fields can be obtained using electron holography [12]. A magnetic induction map recorded using electron holography from the same three-quarter rings as in Fig. 2 is shown in Fig. 3. This is combined with a bright field image to allow the magnetic flux to be correlated with the positions of the rings. The contours correspond to magnetic lines of force associated with the magnetic dipolar moments of the magnetic material. The direction and relative strength of the field is given by the direction and the density of the lines, respectively. The colour within the magnetic elements indicates the field direction and strength when compared with the colour wheel shown in Fig. 3.

We see three possible magnetic configurations in Fig. 3:

(A) *no domain walls present*: This is equivalent to a vortex state in full rings that do not contain domain walls. The stray field leaves at the end of each ring, and the magnetic flux is partly closed between the two ends of the three-quarter ring and partly between the ends of neighbouring rings.

(B) *vortices at line ends*: Here the spins try to align parallel to the edges, thus forming a curled spin structure with a vortex core inside. This configuration minimizes stray field energy but costs magnetic exchange energy to tilt the spins with respect to each other.

(C) *interacting transverse walls*: The triangular shape associated with the presence of a transverse wall and the stray field passing between them can be seen.

The positions of domain walls were revealed using Fresnel imaging [11]. Here, the image is defocused, and vortex

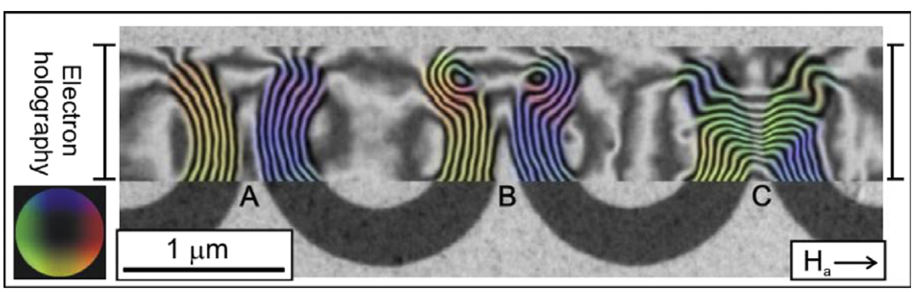

Fig. 3. Magnetic induction map recorded using electron holography placed over an equivalent bright field image to show the shape and position of three-quarter rings (as in Fig. 1(a) and 2 with a 70 nm spacing between them). A magnetic field H_a was applied along the indicated direction and relaxed to zero before recording the image (For interpretation of the references to colours in this figure, the reader is referred to the web version of this paper).

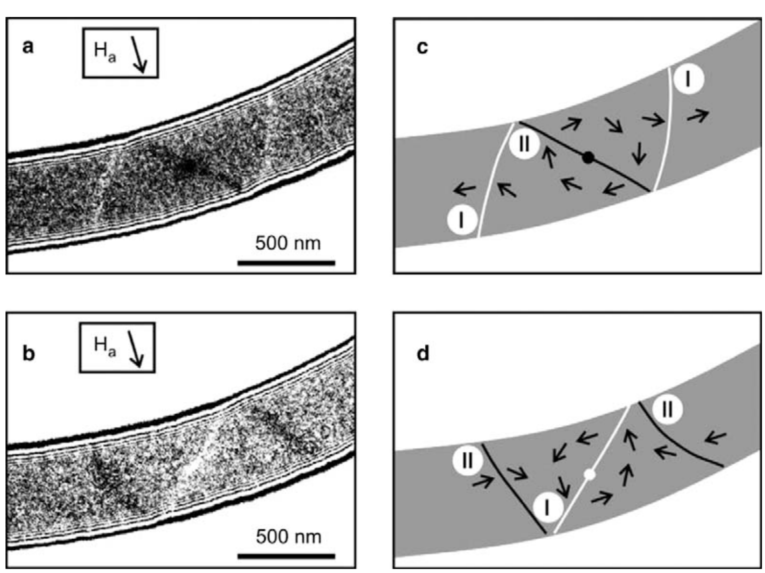

Fig. 4. (a, b) Fresnel images of curved section in zig-zag lines (permalloy, 23 nm thickness, 500 nm line width). (c, d) Schematic representation. The white (I) and black (II) contrasts are domain boundaries separating regions within the domain wall. The magnetization direction is indicated by the arrows.

walls in the curved sections of zig-zag lines are observed (Fig. 4(a) and (b)). Black or white contrast observed at the boundaries depends on the orientation of the magnetic spins in the areas on either side of the boundaries within the vortex wall. Schematic diagrams in Fig. 4(c) and (d) summarize this information by showing the domain boundaries (indicated by I and II) and the spin structure represented by arrows. The dots in the middle represent the locations of the vortex cores. Reverse contrast in the two walls in Fig. 4(a) and (b) indicates opposite circulation of magnetic spins within the vortex walls.

4. Conclusion

We have developed a method to fabricate curved-line ferromagnetic elements on membranes using electron-beam lithography combined with a lift-off procedure, and we are able to introduce constrictions in these elements which have widths down to 30 nm. We have employed various TEM techniques to observe the magnetic spin configurations present in these elements and the stray field interaction between neighbouring magnetic elements. In particular we have observed domain walls (transverse or vortex), and vortices at rounded line ends. The detailed spin structure depends on the lateral dimensions of each element and its thickness. While Lorentz microscopy gives a qualitative impression of the magnetic features present, using electron holography it was possible to obtain a quantitative map of the stray fields both inside and outside the elements.

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