Control of domain patterns in square shaped nickel rings

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Magnetic rings in a square shape are studied by magnetic force microscopy with in situ in plane magnetic fields. Well defined domain structures are accessible by changing the orientation of the magnetic field. Magnetic domain wall can easily be trapped at corners. The domain patterns can be controlled by the magnetic field strength and field direction. © 2003 American Institute of Physics.

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I. INTRODUCTION

Recent microfabrication techniques allow us to fabricate magnetic elements in any desired shape. During the last decade, a rapidly growing number of studies of microfabricated magnetic elements have been conducted. For polycrystalline magnetic-soft materials, it is the shape induced anisotropy that determines the magnetic moment orientation, and different shapes result in different magnetic properties of the magnet elements.1 Understanding the influence of shape on the magnetic structure can help us design new nanostructured magnetic materials which possess unique magnetic properties and practical applications. The recent invention of magnetic logic devices based on controlling domain wall propagation is an excellent example.2

Rectangular or elliptical shaped nanoelements can form single domain states with magnetic moment aligned along the long axis.3 If the diameter of a magnetic disk is larger than a critical value, it forms a vortex state, otherwise it is single domain.4 For magnetic ring elements, a vortex state and an onion state can be formed.5 In zig–zag nanowires, controllable domain patterns can be formed depending on the magnetic field directions.6 In this paper, we study the domain pattern in square shaped rings by magnetic force microscopy (MFM). The reason that we study this structure is because the domain wall can be trapped at the corners, similar to zig–zag nanowires,5 and because this structure is a complete loop, similar to a circular ring structure.5 Our study indicates that the domain wall patterns are controllable in the elements by the magnetic field strength and direction.

II. EXPERIMENTAL TECHNIQUES

Square shaped Ni ring arrays were prepared by standard electron beam lithography followed by a lift off technique on a square lattice with a lattice constant of 4 μm. The nanowire is 200 nm wide and 10 nm thick, which forms a square shape with a side length of 2 μm, as shown in Fig. 1.

The magnetic domain structures were studied by a custom built vacuum MFM with in-plane in situ electromagnets. Commercial cantilevers sputtered coated with 30 nm Co71Pt12Cr17 were used as force sensors. To minimize MFM tip stray field induced irreversible distortion to the sample magnetization, the images were taken in the constant height mode.7 In this mode, the electrostatic force and van der Waals force only contribute a very small portion to the observed contrast, and the image is therefore mainly magnetic in origin. The magnetic fields were applied in the directions as indicated in Fig. 1. One direction H10 is slightly off the edge (<10°), while the other direction H45 is along the diagonal direction (~45°).

III. RESULTS AND DISCUSSION

A flux closure structure is the energetically stable state in square shaped magnetic elements.8 Even if the element is patterned into nanowires, as shown in Fig. 1, the flux closure state is still the energetic favorable state as it has the lowest

FIG. 1. Scanning electron microscopy image of Ni square shaped rings. The arrows indicate the magnetic field directions during the experiments.
magnetostatic energy. However, other domain patterns exist depending on the magnetic history. Figure 2 shows two typical magnetic moment states of square shaped nanowires obtained by micromagnetic simulation. If a large magnetic field is applied parallel to the edge direction, the element is magnetized into a single domain state, as shown in Fig. 2(a). The domain walls are formed as the magnetic field is removed, two transverse domain walls are formed in the middle of a nanowire segment, and the stray field above these domain walls is parallel to the field directions. On both sides of the transverse domain walls, the magnetic moments are head-to-head or tail-to-tail, and the stray field above these domain walls is perfect parallel to the magnetic field direction. The element has the same dimension as the real Ni square rings: 2 μm in size, 200 nm wide, and 10 nm thick.

However, if the magnetic field is slightly off the edge direction, as shown in Fig. 2(d), the domain patterns at remanence are different to Fig. 2(b). Figure 2(e) shows the remanent moment state. At two opposite corners, the magnetic moment gradually rotates by 90°. Such types of domain walls have recently been observed in zig-zag patterned Co wires. In addition to these domain walls, two transverse domain walls are formed in the middle of two of the nanowire segments, which are perpendicular to the field directions. On both sides of the transverse domain walls, the magnetic moments are head-to-head or tail-to-tail, and the stray field above these domain walls is therefore much larger than at the corners. Figure 2(c) shows the z component of the stray field of Fig. 2(b). The transverse domain walls show strong contrasts with one black spot and one white spot. Each corner of the square shows weak bright and dark contrasts.

However, if the magnetic field is slightly off the edge direction, as shown in Fig. 2(d), the domain patterns at remanence are different to Fig. 2(b). Figure 2(e) shows the remanent moment state. At two opposite corners, the magnetic moment gradually rotates by 90°. At the other two diagonal corners, the magnetic moments form transverse domain walls. The stray field contrast of the z component is shown in Fig. 2(f). As can be seen clearly, there is one white spot and one black spot at diagonal corners.

During our experiments, since the magnetic field is not perfectly parallel (perpendicular) to the nanowire segments, we only occasionally observe the transverse domain walls which are formed in the middle of a nanowire segment, and such transverse walls are easily dragged to the corners by the stray field from the MFM tip. Most of the MFM images show contrast similar to Fig. 2(f). Figure 3(a) is such an example. Micromagnetic simulation [Fig. 2(e)] and the experimental result [Fig. 3(a)] suggest that each of the four segments of the square shaped rings are nearly single domain states, as indicated by white arrows in Figs. 3(a)–3(e). Different orientation of these single domain states can form different domain patterns. The orientation of the moment states in these four segments can be controlled by the external magnetic fields. Figure 3 shows the magnetic moment state of a typical element at remanence as a function of external magnetic fields. All the images have one black spot and one white spot at the corners.

When a large field is applied and then reduced to zero, the magnetic state of Fig. 3(a) is formed. As an opposite magnetic field is applied, due to the shape anisotropy, the magnetic field can hardly switch the magnetic moment state in the segment which is almost perpendicular to the magnetic field direction [segments B and D in Fig. 3(a)]. The magnetic field, however, can switch the moment state in the segments which are almost parallel to the field direction [segments A and C in Fig. 3(a)]. When the magnetic field reaches the value of the domain wall pinning potential of the corner (H1), it can move the domain wall from one corner to another corner. Figures 3(b) and 3(c) show such processes. In Fig. 3(b), the segment A is switched, and the segment C is switched in Fig. 3(c). The two domain walls [the black spot and the white spot in Fig. 3(a)] have slightly different pinning potentials, and they are depinned and subsequently move at different magnetic fields.

When the magnetic field reaches another critical value (H2), the magnetic field can switch the magnetic moment
state in the segment $B$ and $D$, as shown in Figs. 3(d) and 3(e), respectively. Figure 3(e) is just the reversed moment state of Fig. 3(a). If an opposite magnetic field is applied, similar phenomena occur as shown in Figs. 3(f)–3(i).

Since $H_1 (~150$ Oe) and $H_2 (~250$ Oe) are widely separated, we can use this margin to control an element moment state. This can be demonstrated by studying an ensemble of elements. If a field strength is larger than $H_2$, the head–head domain walls appear at diagonal corners. However, if the field is reduced to a value in the range of $H_1$ and $H_2$ at the opposite direction, the head-to-head domain walls appear at the opposite diagonal corners. Figure 4 shows the example of ring arrays. After 500 Oe (~500 Oe) the magnetic field is applied, and the remanence states show the head–head domain walls at left and right corners as shown in Fig. 4(a) [Fig. 4(b)]. However, after ~180 Oe (180 Oe) the magnetic field is applied, and the remanence states show the head–head domain walls at up and down corners, as shown in Fig. 4(c) [Fig. 4(d)].

As the angle between the field direction and the edge increases ($\approx 45^\circ$), the margin between $H_1$ and $H_2$ will decrease. If the field is applied nearly along the diagonal direction ($45^\circ$), the magnetic field effect on the four different corners and the four segments is similar. Therefore, the margin between $H_1$ and $H_2$ disappears, and the switching behavior is different from those when the field is applied nearly parallel to the edges. A typical example of this is that the flux closure domain patterns can be formed in some elements, as shown in Figs. 5(b) and 5(c). We have not observed the ordered state as in Figs. 4(c) and 4(d). Similar ordered states as in Figs. 4(a) and 4(b), however, are observed when magnetic fields larger than $H_2$ are applied, as shown in Figs. 5(a) and 5(d).

In summary, the square shaped ring array shows well defined domain patterns. The magnetic patterns are controllable by the external magnetic field and its direction. As a magnetic field is applied nearly along the edge, the head-to-head domain can be formed at two diagonal corners. At the smaller field ($H_1$) they appear on one diagonal axis [Figs. 4(c) and 4(d)], while at the larger field ($H_2$), they appear on the other diagonal axis [Figs. 4(a) and 4(b)]. If the field is applied diagonally along the square, controllable head–head domain walls only appear at the diagonal corners which are parallel to the field direction. To get more insights in the switching process of the square shaped nanowires, a systematic study of the field direction dependence of $H_1$ and $H_2$ is in progress.

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9. Micromagnetic simulation is performed by a public available code from NIST. http://math.nist.gov/oommf. The element size is the same as the real sample. The unit cell is 5 nm.