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Vortex state in magnetic rings

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Abstract

Recent studies on cobalt and permalloy rings have shown that a totally flux-closed magnetic vortex structure is stable at remanence. The two chiralities of the vortex, clockwise and anti-clockwise, have been proposed as the carriers for the stored information that could be read in a magneto-resistance-based device. Here, we present the results of systematic characterization of arrays of micron size narrow permalloy ring elements of different symmetry with magnetic force microscopy (MFM) to determine the magnetic patterns inside the rings and to visualize the reversal process during a magnetization cycle. Those experimental data are in a good agreement with the results of micromagnetic calculations.

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Keywords: Magnetic rings; Magnetization; Micromagnetic simulations

1. Introduction

The magnetic properties of circular ring structures (Fig. 1) have drawn a considerable amount of attention in the last few years [1–5]. Prinz et al. [6] proposed a design for high-density magnetic random access memory (MRAM) which used the "vortex" or flux closure states in circular ring structures to store data with clockwise rotation of magnetization corresponding to "1", and counterclockwise magnetization corresponding to "0". They estimated that the ultimate area density for the MRAM with circular magnetization could reach 400 Gbits/in.^{2} [6].

The most important aspects of the design of an MRAM are that the stable remanent states used to store the data have to be repeatable. The switching between stable states has to be simple and uniform. The switching process observed in circular rings is very simple [1–3]. At remanence, a stable bi-domain state, with a head-to-head and a tail-to-tail domain wall, called the "onion" state is observed. The onion state corresponds to opposite circulation of magnetization in each half of the ring. During switching, one of the two domain walls de-pins first and moves toward the other ultimately forming a flux closure state inside the ring (Fig. 2).

At higher fields, the vortex state annihilates, resulting in the formation of another onion state of

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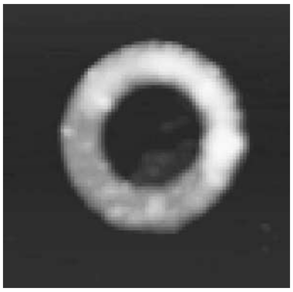


Fig. 1. Atomic force microscopy image of a circular permalloy ring with 2.0 μm outer diameter and thickness of 25 nm.

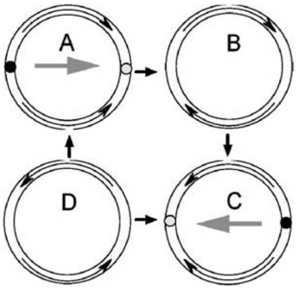
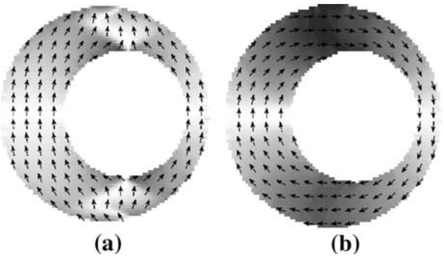


Fig. 2. Schematics of the magnetization reversal process in ring magnetic element. Two "onion" states (A) and (C) and two "vortex" states (B) and (D).



(a) (b)

Fig. 3. Micromagnetic simulations based on OOMMF code of the onion state (a) and vortex state (b) in asymmetric circular ring.

opposite polarity. Micromagnetic simulations based on OOMMF code from NIST [7] though do not reproduce this switching phenomenon for symmetric rings. Introducing small asymmetry in the rings, unavoidable in the real fabrication process, produces these results as shown in Fig. 3a and b.

2. Fabrication

A standard 4 in. silicon wafer (1 0 0) with a 100-nm thick, thermally grown SiO_2 insulating layer was spin coated with 0.4 μm double-layer resist and baked. The substrate was then placed in an industrial e-beam writer and the desired pattern was written. Using e-beam evaporation in vacuum chamber with a typical evaporation rate of 0.1 Å/s, a 25 nm permalloy film was deposited onto the holes in photoresist. After lift-off in acetone the array of rings was obtained. Both square and rectangular rings were fabricated using the same process. MFM measurements were done using lift mode magnetic force microscopy, at remanence, on a modified DI Nanoscope III AFM/STM. Standard magnetic force etched silicon probes were used for the measurement. The lift height used was 50 nm. The samples containing the rings were magnetized using two SmCo block magnets. The field between the two magnets was tabulated as a function of the distance of separation between them.

3. Results and discussion

3.1. Square rings

We found that in circular rings, small variations in the direction of external field produced by MFM tip can move the domain walls in the onion state along the ring. As a result, the onion state may not always be perfectly along a diameter. In a square ring the domain walls can be pinned at the corners formed by the sides of the square. This will ensure that there is no undesirable movement of domain walls. We studied the magnetic switching characteristics of permalloy square rings to see if these rings exhibited behavior similar to those of the circular rings and to explore the possibility of using the magnetic states in squares for data storage. Permalloy square rings of size 2.0 μm × 2.0 μm with a thickness of 250 nm and line width of 250 nm were fabricated. Similar to circular rings, two stable bi-domain onion states are observed. These onion states were experimentally verified to be stable at remanence. The magnetic properties and switching behavior of square rings were studied using magnetic force microscopy.

The experimental results were compared with micromagnetic calculations done with the NIST developed OOMMF software. The size of the squares used for the simulations was the same as the ones used for experimental measurements and the cell size was 10 nm. The micromagnetic calculations reproduced the experimental results when asymmetry was introduced in the square. This again is consistent with the experiments because a small anisotropy is always present in the squares due to fabrication. The results of the micromagnetic calculations are shown in Fig. 4a–c.

First a high field of about 600 G was applied along the direction of one of the sides of the square and MFM imaging was done at remanence. An onion state was uniformly observed in this case. The head-to-head and tail-to-tail domain walls of the onion state are seen as bright and dark spots in an MFM image (Fig. 5a). This is due to the stray field components in the direction perpendicular to the surface being maximum at these two points.

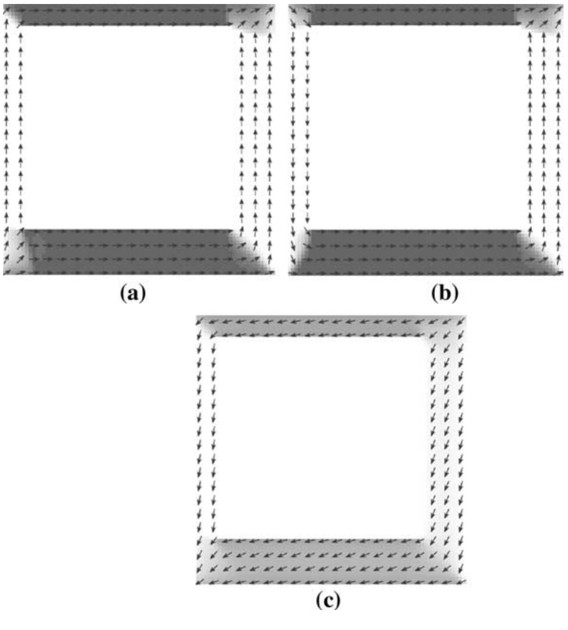


Fig. 4. Micromagnetic simulations of the forward onion (a), the horseshoe (b) and the reverse onion (c) states in asymmetric square ring.

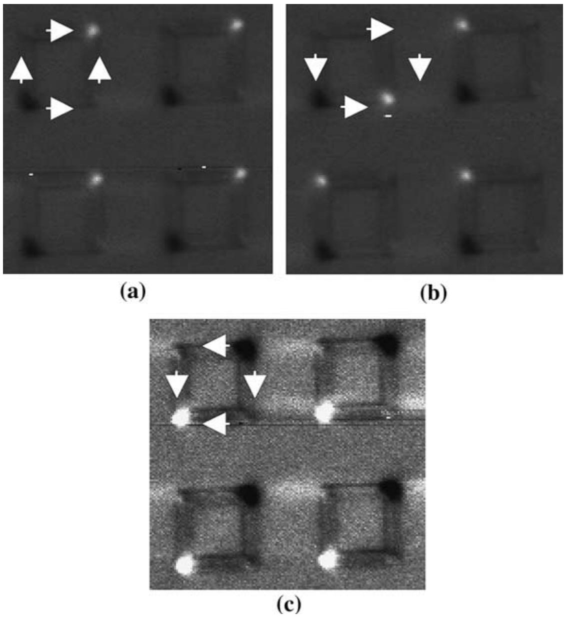


Fig. 5. Magnetic force microscopy images of the forward onion (a), the horseshoe (b) and the reverse onion states (c) in permalloy 2.0 μm × 2.0 μm nm square ring. White arrows indicate magnetic moment orientation in each segment of the ring.

Next, a field in the opposite direction is applied. First, a very low field of about 50 G is applied. This field is not strong enough to switch the moments in all the sides of the squares. It switches the moments only in one arm of the square. This gives an appearance that one of the domain walls has moved forming a state that resembles a ‘horseshoe’ in shape (Fig. 5b). The asymmetry in the sides of the square that are introduced during the fabrication process decides which domain wall de-pins. The appearance of the horseshoe state is quite unique. This state was first shown to occur in square shaped Nickel nanowires [8]. This state is difficult to isolate in practice. Though MFM is an invasive technique because the stray fields in the tips can distort metastable states, we were able to capture this intermediate horseshoe state in our MFM measurements. We can clearly see the dark and the bright spots arranged to give the impression of a horseshoe. Upon further increasing the field, the moments switch to form another intermediate horseshoe state and finally switch to the reverse onion state. It is clearly seen from micromagnetic calculations and magnetic force microscopy measurements that switching in square rings does not occur through the formation of a vortex state like in circular rings. The switching phenomenon observed is very unique and occurs through the formation of an intermediate ‘horseshoe’ state by domain wall movement.

3.2. Rectangular rings

Rectangular rings were studied as they have an inherent asymmetry in the geometry. This also provided an advantage over the circular ring as the asymmetry of the rectangular rings predominated over the asymmetry due to the fabrication process. Permalloy rectangular rings of size 1.5 μm × 1 μm with a thickness of 250 nm and line width of 250 nm were fabricated (Fig. 6).

The magnetic behavior of the rings under the influence of an externally applied field was studied using the Lift Mode MFM technique at remanence. The rectangular rings were magnetized along the diagonal and scanned along the same diagonal to minimize the effect of the tip stray field. Initially, a field of 860 G was applied and the imaging was done at remanence. The stable states observed were onion states that were seen as bright and dark spots along the corners of the diagonal of the rectangular ring (Fig. 7a). The spots correspond to the formation of head-to-head and tail-to-tail domain walls. A small field was then applied in the opposite direction. This field intensity was increased in steps till switching occurred. At about 380 G, the rectangular ring switched to a vortex state (Fig. 7c). This state was caused by the nucleation of the opposing domain walls and it was stable over a range of reverse fields. On further increase of the reverse field, the moments switch to the reverse onion state (Fig. 7d). As in circular rings, the switching of moments in the rectangular rings took place through the intermediate ‘vortex’ state. However, in circular rings, the switching between the forward and reverse onion states took place only through the ‘vortex’ state. In rectangular rings, the switching from the forward onion state to the ‘vortex’ state went through the ‘horseshoe’ state. These ‘horseshoe’ states were unstable and were very difficult to capture, because the moments switched with a slight increase in the field. In closely packed rectangular rings, a few unstable ‘horseshoe’ states were also captured during the transition to a vortex state (Fig. 7b) at a reverse field of about 280 G. This was probably due to the interactions between the rings.

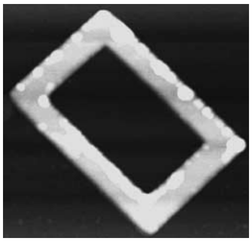


Fig. 6. Atomic force microscopy image of a rectangular permalloy 1.5 μm × 1.0 μm ring.

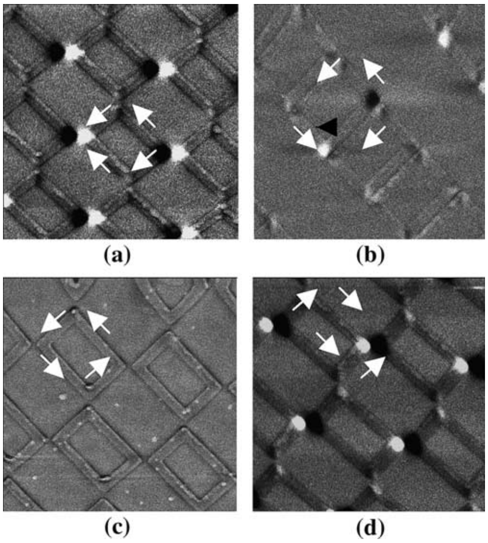


Fig. 7. Magnetic force microscopy images of the forward onion (a), the horseshoe (b), vortex (c) and the reverse onion (d) states in arrays of 1.5 μm × 1.0 μm rectangular rings. White arrows indicate magnetic moment orientation in each segment of the ring.

Micromagnetic simulations were done using OOMMF. The parameters set for the simulations were the same as the experiments, with identical field range and direction of magnetization. The experimental results closely matched the simulation results. The images of the onion, horseshoe and vortex states obtained from the simulation are shown in Fig. 8a–d.

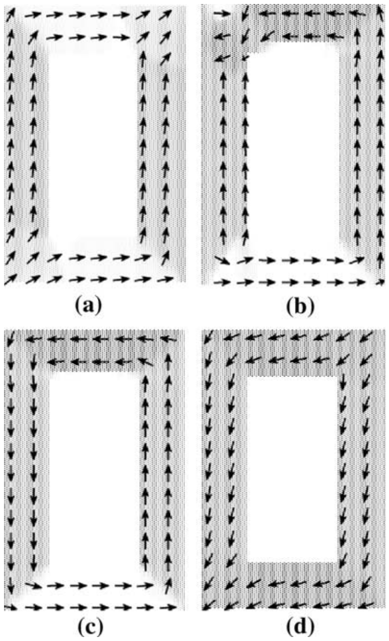


Fig. 8. Micromagnetic simulations of the forward onion (a), the horseshoe (b), the vortex (c) and the reverse onion (d) states in rectangular ring.

4. Conclusions

It has been shown that square and rectangular rings exhibit two stable states of opposite polarity at remanence that can be used for data storage. It has also been shown that unlike circular rings that switch only through the vortex state the square and rectangular rings also exhibit a unique intermediate horseshoe state depending on the direction of magnetization. The choice of the stable intermediate state and thus the switching mechanism, in the square and rectangular rings, can be controlled. This offers a good platform for the development of the magnetic storage technology.

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