Switching of $\pm 360^\circ$ domain wall states in a nanoring by an azimuthal Oersted field

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Abstract
We demonstrate magnetic switching between two $360^\circ$ domain wall vortex states in cobalt nanorings, which are candidate magnetic states for robust and low power magnetoresistive random access memory (MRAM) devices. These $360^\circ$ domain wall (DW) or ‘twisted onion’ states can have clockwise or counterclockwise circulation, the two states for data storage. Reliable switching between the states is necessary for any realistic device. We accomplish this switching by applying a circular Oersted field created by passing current through a metal atomic force microscope tip placed at the center of the ring. After initializing in an onion state, we rotate the DWs to one side of the ring by passing a current through the center, and can switch between the two twisted states by reversing the current, causing the DWs to split and meet again on the opposite side of the ring. A larger current will annihilate the DWs and create a perfect vortex state in the rings.

(Some figures may appear in colour only in the online journal)

1. Introduction

Magnetoresistive random access memory (MRAM) could serve as a non-volatile random access memory, replacing hard drives, DRAM, and SRAM if a suitably robust, low power, and dense element can be developed. A variety of proposals exist with some commercial realization [1]. One promising candidate is to use magnetic nanorings, with the storage bit consisting of the vortex state in which the moments align circumferentially in the clockwise (CW) or counterclockwise (CCW) direction [2]. The ring geometry is relatively insensitive to small geometric variations and the vortex state has no stray field, leading to robust switching characteristics and dense packing. The initial proposal [2] suffered from requiring relatively high currents to switch fully from one vortex circulation to the opposite. The current can be reduced by using a slightly different state, called a twisted onion or a $360^\circ$ DW state, in which the ring is primarily in the clockwise or counterclockwise vortex, but a single $360^\circ$ DW remains [1, 3, 4] (see figure 1). Spin torque transfer can further reduce this switching current [1, 3]. Further reported results suggested that the spin torque efficiency decreases as the temperature increases, though the applied field required to switch states is lowered [5].

Ferromagnetic nanorings have attracted attention in the research community, in part due to the unique closed-flux vortex state [1, 2, 6–8]. Considerable work on simple single layer structures allowed direct imaging of the magnetization, but manipulation of the magnetic states is limited to uniform external fields, making control of the vortex circulation challenging. Introducing asymmetry to the ring enables control over the circulation with a uniform applied field [9].

In this paper, we demonstrate proof of principle control over switching between a twisted onion or $360^\circ$ DW vortex state and the opposite circulation state by passing a current through the center of a ring using an atomic force microscope (AFM) tip and imaging the resulting state with magnetic force microscopy (MFM). The vortex circulation is determined by the Oersted field created by the current through the tip. Previously, we have demonstrated motion of $180^\circ$ DWs and direct vortex to vortex switching in permalloy nanorings [10]. Here we are able to ‘unpeel’ a $360^\circ$ DW and recombine the two $180^\circ$ DWs on the opposite side of the ring, demonstrating a switching between states that will lower the switching current [3, 4] for MRAM devices.

Direct switching of one vortex circulation to the opposite one in thin and narrow nanorings requires DW nucleation and motion. Nucleating a DW requires larger external field than...
coherent rotation or movement of a DW. An alternative method to switching the vortex circulation in thin and narrow nanorings is shown in figure 1. Figure 1 plots the simulated hysteresis, showing vorticity versus current, simulated using OOMMF. We apply a magnetic field that results from a current through the center of the ring, modeled as an infinite wire with a diameter of 100 nm, and calculate the resulting vorticity of the magnetization. Vorticity is the degree to which the ring is in a perfect vortex state, defined by

\[ V = \frac{1}{A} \oint_A (\mathbf{r} \times \mathbf{M}) \cdot dA \] (1)

where \( A \) is the area of the ring and a vorticity of +1 corresponds to a perfect CCW vortex, and −1 to a perfect CW vortex. The ring is in the CCW state with a single 360° DW at +4 mA, with the corresponding magnetization shown in the upper right inset of figure 1. As the current is lowered and reversed, the DW widens (upper left inset) and unpeels, reversing the vorticity of the ring (lower right inset).

The nanorings are fabricated by standard electron beam lithography, using a JEOL JSM-7001 F SEM. A double layer MMA/PMMA resist is spin coated on top of a gold coated silicon wafer substrate. After e-beam exposure, the samples are developed in a solution of methyl isobutyl ketone and isopropyl alcohol. The desired thickness of cobalt is then deposited by electron beam evaporation, followed by an acetone soak and a sonication ‘lift-off’ procedure. A thin protective platinum layer of ∼4 nm is then deposited by thermal evaporation on the ring structure to prevent oxidization of the cobalt.

All AFM images and manipulation are performed with an Asylum Research MFP-3D atomic force microscope. A schematic of the experimental technique is shown in figure 2(a) and can also be found elsewhere [10]. Our procedure consists of three steps. First, we apply a uniform in-plane field of about ±2500 Oe to the nanoring sample, removing it to obtain the remanent state. We image this state with a low moment magnetic tip (Asylum Research ASYMFMML). Next, we switch the magnetic tip to a solid platinum metal tip (Rocky Mountain Nanotechnology LLC, tip radius ∼25 nm) and locate the same rings imaged with the magnetic tip in the first step. Finally, we bring the tip into contact with the surface at the center of a ring and pass the desired amount of current through the tip, without contacting the ring arm.

We measure the voltage across a 100 Ω resistor in series with the tip to determine the current. A typical current versus voltage plot is shown in figure 2(b), demonstrating our ability to pass up to 50 mA through the solid metal tip, which we can consistently do 10–20 times without losing our ability to topographically image with the metal tip, despite the high current density. The passing current into the substrate was taken to be positive, while the passing current out of the substrate was taken to be negative, with the polarity of the current determining the CW and CCW circulation of the field by the right hand rule. The strength of the applied circular field can be calculated by Ampere’s law using the radius of the ring material itself (resulting in a smaller field for the same current, but also enabling spin torque transfer contributions to lower the switching current) has been proposed by Zhu et al [1, 3].

2. Experimental technique

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applied circular field. Figure 3(a) is the height image of their positions, shown by the MFM image in figure 3(c). We state.

MFM image shows the magnetic configuration of the onion indicates the direction of the applied circular field. Figure3(d) assuming a 25 nm tip radius. The red arrow around the cartoon

Figure 3 shows onion–360◦ DW–vortex switching under the applied circular field. Figure 3(a) is the height image of two symmetric cobalt nanorings with the same arm width of 140 nm and different outer diameters of 900 nm (top) and 1050 nm (bottom). The nanorings are 20 nm thick. We initialize the rings in a uniform 2500 Oe in-plane field pointing toward the bottom of the image. The MFM image in figure 3(b) reveals the onion state in both the rings with 300 Oe in-plane field, with dark contrast and bright contrast corresponding to the T–T and H–H 180◦ DWs. The cartoon on the top of the MFM image shows the magnetic configuration of the onion state.

When the applied field is reduced to zero, the DWs shift their positions, shown by the MFM image in figure 3(c). We applied the circular field to only the top ring, indicated by the dashed red circle, by passing current through a solid platinum tip as described above. A CCW field resulted from the dashed red circle, by passing current through a solid platinum tip that is unavoidable due to the substantial wear on the metal coated tip that is unavoidable due to the substantial topographic imaging required to locate the identical rings.

A higher resolution MFM image of the top ring (figure 3(e)) clearly shows the dark and bright contrasts of the 360◦ DW (or two combined 180◦ DWs). We next increase the field strength by passing a higher current (−48 mA = 225 Oe CCW) through the same ring. The double red arrow around the cartoon indicates the higher circular field strength and direction. Figure 3(f) shows the resulting magnetic states after passing higher current/applying higher field. The top ring now shows no contrast, indicating the annihilation of the 360◦ DW–vortex state. The cartoon on the right of the MFM image shows the magnetic configuration of the rings. Overall, the two 180◦ DWs formed initially in the onion state were forced toward one another by the applied circular field to form a 360◦ DW and then annihilated by increasing the field strength. This demonstrates the ability to create the 360◦ DW, which has been reported by other groups [10, 12–14], and to annihilate the DWs with a sufficiently strong field. We next demonstrate the proposed switching mechanism from one vortex circulation to the other, keeping the 360◦ DW.

Figure 4 shows the experimental implementation of onion–CW 360◦ DW–CCW 360◦ DW switching with an applied circular field. The ring has an outer diameter of 900 nm, thickness of 15 nm and width of 100 nm. Figure 4(a)

and the current passed through the tip. Last, we switch back to the magnetic tip to observe the change of the magnetization in the individual ring due to the applied circular field. All measurements were made at room temperature. If the applied circular field was too weak to change the magnetization, then we repeated the second two steps, increasing the applied current until the resulting field was strong enough to change the magnetic state of the nanoring.

3. Results and discussion

Figure 3 shows onion–360◦ DW–vortex switching under the applied circular field. Figure 3(a) is the height image of two symmetric rings with 900 nm (top) and 1050 nm outer diameter with ring arm of 140 nm and thickness of 20 nm. (b) MFM image of the rings at 300 Oe in-plane magnetic field showing the onion state. Dark and bright contrasts correspond to tail-to-tail (T–T) and head-to-head (H–H) 180◦ DWs. (c) MFM images when the field was reduced to zero, showing that the rings are in the onion state. The circled ring was chosen to apply the circular field. (d) MFM image after the applied circular field and (e) the zoomed MFM image of the top ring after the applied circular field. (f) MFM images of the rings after application of a stronger circular field on the top ring.
shows the initial onion state of the nanoring at remanence, in which the dark and bright contrasts indicate the T–T and H–H domain walls, respectively. A CW circular field was applied by passing current (40 mA = 188 Oe) through the center of the ring. Figure 4(b) reveals the resulting magnetic state. The two 180° DWs moved toward one another forming the twisted or 360° state with CW vortex circulation, as controlled by the applied circular field. The T–T DW appears to be pinned and the H–H DW moves near the T–T DW. The pinning could be due to topographical defects in the nanoring through the fabrication and the strength of the applied field was insufficient to move the pinned DW (T–T). The cartoon below the MFM image sketches the magnetic state of the nanoring. Instead of applying a higher field in the same direction as before in figure 3(e), we applied a reverse circular field (CCW direction) by changing the direction of the current (−45 mA = −211 Oe) through the center of the ring. Figure 4(c) shows the MFM image after the reverse circular field was applied. The two combined 180° DWs pulled apart, moved to the opposite side of the ring and recombined to form a CCW vortex circulation, again following the direction of the applied field.

Figure 5 is a micromagnetic simulation of a ring with identical geometry to the ring in the experiment, using physical parameters for cobalt carried out with OOMMF; the micromagnetic software package developed by NIST (see footnote 3). The magnetization states are shown on top, with the cartoon inside each figure schematically showing the magnetic states to aid in interpretation. The corresponding MFM images: (a) initial onion state; (b) CW 360° state; (c) CCW 360° state.

4. Conclusion

In conclusion, we experimentally demonstrate control over ±360° DW magnetic states in thin cobalt nanorings by applying a circular magnetic field generated by passing current through the ring center with an AFM tip. The 360° DW vortex states can be easily switched back and forth by reversing the direction of the current passed through the ring. These states are suitable for MRAM devices, as previously proposed [3, 4]. We estimate the applied current density to be around 10^8 A cm⁻², which would be smaller if our AFM tip filled the entire center of the ring. The switching field can be further reduced by decreasing the thickness and width of the ring [4]. In our case the DW motion is due to the circular field and not due to spin torque transfer. Passing current through the ring material in addition to the center of the ring would further decrease the critical switching field/pinning field [5].

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