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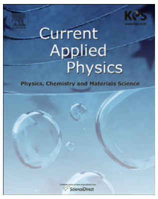

Domain wall movement in a rhombic Co thin film ring

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ABSTRACT

The magnetization switching of micron-scale thin film Co rhombic rings is studied by magnetic force microscopy and electrical measurements. The rhombic rings have a 1.4 μm/0.7 μm major/minor diameter with 200 nm width. A magnetic field ranged from 130 Oe to 200 Oe causes motion of domain walls (DWs) around the ring in a direction controlled by the magnetic field orientation. In addition to the well-known 'onion' and 'vortex' states, intermediate states such as horseshoe and hard-axis onion states were formed for certain field cycles, in agreement with micromagnetic simulations and anisotropic magnetoresistance calculations. DWs induce a 0.4% resistance change when the external magnetic field is cycled.

1. Introduction

Magnetic domain walls (DWs) in thin film magnetic wires and other patterned structures may be used to represent, store and manipulate data [1,2] in addition to producing localized stray fields that can, for example, attract and displace magnetic particles [3,4]. In such structures, magnetization reversal often occurs via DW nucleation and propagation, and understanding the motion of DWs and the effect of geometrical structures such as corners as pinning sites for DWs is critical. DWs can be injected into nanowire structures from a wide pad or by using the Oersted field generated from a pulsed high current in an adjacent conductor [1,5]. DWs can be also formed at specific positions in magnetic nanostructures such as Y-junctions, zigzag wires, and L-shapes at remanence after saturation in a magnetic field [6–8]. Magnetic rings provide a particularly convenient geometry for studies of domain walls in thin film wires with in-plane anisotropy, because in-plane saturation of the ring forms a remanent 'onion' state in which two domain walls are present at opposite ends of a diameter along the magnetic field direction [9–11]. In circular rings the DWs can be translated around the ring by small in-plane fields [10,11] but for rings with corners, such as square or rhombic rings, the corners can provide pinning sites and the direction of DW motion can be controlled via the angle of the sides of the ring with respect to the field direction.

In this paper we describe the behavior of DWs in a single layer rhombic ring to understand anisotropic magnetoresistance changes as a function of an applied magnetic field. There has been study of square and rectangular rings [12–14], but little work on the behavior of rhombic rings in which adjacent corners enclose different angles [9,15]. Square and rectangular rings show two different intermediate states, either a vortex or a horseshoe state between the onion and reverse onion states [12–14]. The intermediate state is dependent on the reversal path via DW motion [14]. Unlike square and rectangular rings, the elongated rhombic shape enabled control of DW motion to form either hard-axis or easy-axis onion states, in addition to horseshoe and vortex states. The DW position was detected by magnetic force microscope (MFM) and electrical anisotropic magnetoresistance measurements (AMR) to determine which arm switches first and where DWs are located at remanence. Micromagnetic simulations and AMR calculations predicted the dependence of the reversal path on the magnetic field direction.

2. Experimental details

Rectangular rhombic rings with stack composition Ta(2 nm)/Co(10 nm)/Ta(3 nm) were fabricated on silicon wafers using electron beam lithography with a polymethylmethacrylate resist and lift-off processes. The Co layer was deposited by ion-beam sputtering at an Ar pressure of 2×10^{-5} Torr, a beam current of 35 mA

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and a beam voltage of 1000 V and the Ta layer was deposited with DC triode sputtering at a working pressure of 1 mTorr. The rhombic rings had a 1.4 μm/0.7 μm major/minor diameter with 200 nm width (angle at the sharp end = 52°) and the arms were labeled P, Q, R, and S as shown in Fig. 1(a). The magnetic configurations of the rings were imaged at remanence using a Digital Instruments Nanoscope MFM with a low moment tip at a scan height of 60 nm.

Electrical contacts made from Ta(5 nm)/Au(80 nm) films were overlaid on the rings by a second electron beam lithography and lift-off process. AMR measurements were performed with a standard lock-in technique with four-point probes at an AC current of 10 μA.

Micromagnetic simulations were carried out using the 2D NIST OOMMF code [16], where the simulated ring (angle at the sharp end = 62°) was discretized into 4 nm × 4 nm × 10 nm cells with exchange constant $A = 3 \times 10^{-6}$ erg cm^{-1}, saturation moment $M_s = 1400$ emu cm^{-3}, random uniaxial anisotropy $K_1 = 5.2 \times 10^6$ erg cm^{-3} and damping constant = 0.5 for quasistatic simulation. The simulated ring had rough edges to approximate the experiment. AMR ratio was calculated from the simulated magnetic configuration using a method similar to Ref. [17] using $\rho = \rho_\perp + (\rho_{||} - \rho_\perp)\cos^2\theta$, where θ is an angle between current and magnetization direction in each cell and $\rho_{||}$ and $\rho_\perp$ represent the resistivities at $\theta = 0°$ and 90°, respectively.

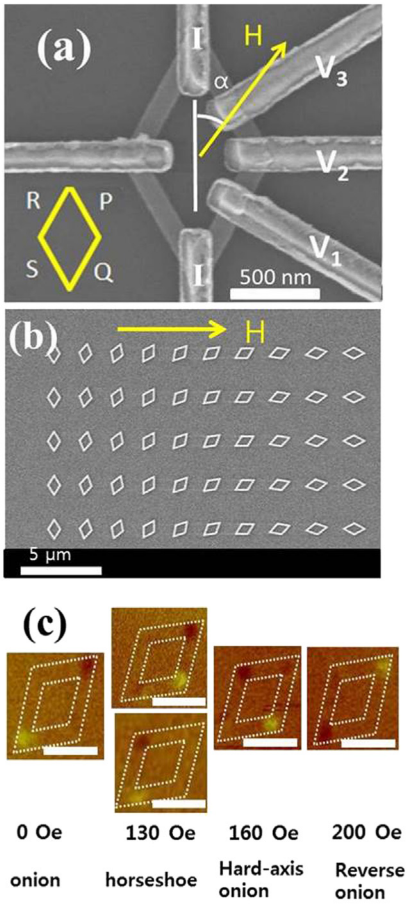

Fig. 1. (a) SEM image of the rhombic ring consisting of four arms of P, Q, R and S with current and voltage electrodes, where α corresponds to the angle between the applied field and the long axis of the ring. (b) SEM image of an array of rhombic rings with angles varying in 10° steps. (c) MFM images of the rhombic ring for α = 40° at remanence with sequential applied fields, where the scale bar is 500 nm.

3. Results and discussions

The shape anisotropy of the rhombic ring provides a control for the direction of DW motion (except for the symmetrical cases of α = 0 and 90°), though it does not predict which of the two DWs depins first. We focus on the case of α = 40° to show which path the reversal followed, where α defines the angle between the major axis of the rhombic ring and the magnetic field direction. Six electrodes were placed on the rhombic ring to independently probe the P and Q arms as shown in Fig. 1(a). The sensing AC current was injected through oppositely placed electrodes along the long axis of the rhombic ring. Voltage measurements were performed with three electrodes (V_1, V_2, and V_3), and V_{12} and V_{23} represent voltages measured across parts of the Q and P arms, respectively. Since the current divides between the two sides of the ring, RS and PQ, V_{12} and V_{23} are also sensitive to changes in magnetic configuration elsewhere in the ring [18]. In the configuration of this experiment, since the length of P and Q enclosed by contacts V_1–V_2 and V_2–V_3 respectively was less than 10% of the total ring circumference, the changes of magnetoresistance in sections of the ring outside sections V_1–V_2 and V_2–V_3 had only a small effect on the measured voltages V_{12} and V_{23}. At α = 40°, the Q or R arms were expected to switch first by counterclockwise motion of the DWs in the onion state, followed by reversal of the P or S arms at higher field.

To demonstrate the preferred arm switching, the MFM measurements were performed on an array of rings at the remanent state after an application of the magnetic field as shown in Fig. 1(b) and (c). An array of rhombic rings is shown in Fig. 1(b), where each column of rings had a different angle (α) between the long axis of the rhombus and the applied magnetic field direction increasing in 10° steps. The edge-to-edge spacing in an array of rhombic rings was 2 μm to avoid significant magnetostatic interaction. Hereafter, the discussions are focused on the sample for α = 40° to clarify the AMR change based on DW motions measured from MFM.

After negative saturation, the remanent state shows two DWs at the long axis corners in the onion state, as shown in Fig. 1(c). Although the direction of the applied field for α = 40° was not parallel to the long axis of the rhombic ring, DWs in the remanent state are present along the long axis due to the shape anisotropy. At a reverse field of 130 Oe, the two intermediate states (horseshoe states) are randomly observed in Fig. 1(c), indicating that there was no preferred selection of which arm switched first, Q or R, but in both cases the walls moved counter-clockwise. The microstructural variations or defects from the fabrication process would lead to different depinning strength from the two long axis corners in the switching process [19]. Thus, two different intermediate horseshoe states are observed in the MFM measurements depending on which DW moves first from the onion state. At a reverse field of 160 Oe, two DWs were present at the hard axis corners, forming the hard-axis onion state. Eventually, the reverse onion state is formed at 200 Oe by movement of both walls to the long axis corners.

Fig. 2 shows AMR measurements after positive saturation for α = 40°. The AMR measurements of V_{12} in Fig. 2(a) show a flat background signal because the magnetic moment in Q is parallel to the current direction regardless of the field strength. A drop in resistance corresponds to the presence of a DW or other region where the magnetization is no longer parallel to the current direction. In the upper plot in Fig. 2(a), the small drop in resistance at −120 Oe is attributed to the passage of a DW along Q (in a counterclockwise direction). In the lower plot in Fig. 2(a), a lower resistance was evident over a wider field range (−80 to −170 Oe). This is attributed to the distortion of magnetic moments in Q by the magnetic field, in cases where the domain walls moved in R but not in Q [20].

Fig. 2(b) shows AMR changes in terms of the applied field for the