Magnetic reversal for different shaped corners in sub-micron half-ring wires by mean phase analyses of magnetic force microscopy

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Abstract

In order to produce different types of domain wall or domain-wall pinning force on the corners of half-ring wires, three shapes of corners (rectangular, semi-circle and triangular) were fabricated. By means of real-time magnetic force microscopy (MFM) scanning, the hysteresis loops determined by mean phase values versus external magnetic fields can be obtained for the scanned regions at the corners. The samples with rectangular corners have the largest coercive field (~ 75 Oe) at two sides among three corner structures. This behavior is consistent with that determined from the magnetoresistance (MR) measurements. Thus, from the method of MFM mean phase analysis, the magnetization reversal phenomena at local regions can be observed. Furthermore, the regions in the sample that trigger the magnetization reversal can also be detected.

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The nucleation and propagation of domain walls (DWs) play an important role to dominate magnetization reversal in continuous thin films or patterned structures. The shape anisotropy in magnetic materials is usually used to produce different domains and domain walls. In some special designed wires [1–3] (such as the rings, zigzags, notches, etc.), their magnetization reversal process, with several effects such as the anisotropy properties, DWs contribution, and magnetic coherent rotation can be studied by the magnetoresistance (MR) or magneto-optical Kerr effect (MOKE). From the small steps (called Barkhausen jump) in the hysteresis loops, the domain walls nucleation and annihilation at certain external magnetic fields can be understood. However, it does not lead to probe the local behaviors in the patterns. The magnetic force microscopy (MFM), one of the useful scanning probe microscopy (SPM) for micromagnets, can offer many functions to investigate the changes of magnetization in the submicron

regions. One familiar function is to observe the domain structures of various regions and another function is to determine the local mean phase values (MPVs) from MFM operation software. The MPV is the average value for the phase shifts $\Delta\Phi$ [4] of total points that is proportional to the magnetic force gradient of the stray fields between the sample and the tip coated with the magnetic material. Comparing the MPV-to-field hysteresis loops for different chosen sections on the patterns, the switching fields at various regions in the samples can be acquired.

In this experiment, the submicron permalloy wires were made by electron beam lithography. The permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) films were first prepared with DC magnetron sputtering and then followed by lift-off technique to complete patterns. The wires consist of five half-ring units with four corners. Its inner radius is $0.5\mu\text{m}$ and the linewidth and thickness are $0.4\mu\text{m}$ and 25 nm , respectively. The samples with three different corner structures (rectangular (RT), semi-circle (SC) and triangular (TA)) have been fabricated. Each corner is connected with two half-ring wires at two sides, as shown in Fig. 1.

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After saturated with the longitudinal external magnetic field, the remnant states of the corners on half-ring wires will be the transverse states as indicated in Fig. 2; the magnetizations in the center of DWs are perpendicular to those on the two sides of the corners [5]. In this work, the purpose of designing different shapes of corners is to create different DW pinning force derived from the shape anisotropy field to counterforce the DW driven force by the external field.

Three different shapes of the corners were analyzed numerically by dividing the corner regions into four regions a–d. The positions marked with a and c in the diagrams of Fig. 1 were located at both sides of the corners. The right side of the corners is the head of the following half-ring wire, while the left side is the tail of another half-ring wire. Therefore, as indicated in Fig. 2, the magnetic states at two sides of the corners are just two independent and opposite magnetic poles with stronger stray fields. Their MPV-to-field loops were measured from real-time MFM scanning. The results are shown in Fig. 3. It is noted that the hysteresis behavior of the loops was

clearly identified in regions a and c. Besides, after comparing the hysteresis loops of regions a and c in Fig. 3, the samples with the rectangular corners have largest coercive field (~ 75 Oe) among three corner structures. The coercive fields are 30 and 5 Oe for the semi-circle corners and triangular corners, respectively. It implies that the wires with the rectangular corner structures have the most magnetic stable state to resist external magnetic field and the wires with the triangular-shape corners has the smallest nucleation field. The magnetoresistance (MR) measurements exhibited the similar behavior of the switching field [6] with our results.

Also in Fig. 3, the loops of regions b and d on RT, SC and TA-shaped corners do not show noticeable hysteretic effects and detectable coercive fields as the loops of regions a and c. The reason for such small MPVs is that the phase values for transverse domain walls are averaged. However, the variation between positive and negative saturated mean phase values for the loops of the TA-b and TA-d regions has been found to be different from those of regions b and

Fig. 1. Diagrams for the half-ring wires with three kinds of corner shapes that are (a) rectangular (b) semi-circle and (c) triangular. Four regions are selected to analyze their local magnetization reversal.

Fig. 3. The hysteresis loops (external magnetic fields versus mean phase values) for four selected regions a–d on rectangular, semi-circle and triangular corner shapes of the half-ring wires.

Fig. 2. Results of micromagnetic simulation for the domain wall structures in the magnetic remnant states of wires with (a) RT, (b) SC, and (c) TA shape corners.

d on other two shapes. The TA shape corners with sharp bottom have larger anisotropy field along the corners than other structures. Therefore, a tilted loop for TA-b and TA-d was observed, while the tilted behavior was not apparent in the loops for regions b and d of other shapes. From above descriptions of the anisotropy field, it suggests that those regions with larger anisotropy fields produce the domain wall nucleation more easily and results in smaller switching fields.

In summary, the hysteresis loops or reversal phenomena at local regions can be accurately obtained from the MFM mean phase analysis. Besides, the regions on the wires that dominate the magnetization reversal behavior can be directly identified.

References

- [1] X. Zhu, P. Grutter, V. Metlushko, Y. Hao, F.J. Castano, C.A. Ross, B. Ilic, H.I. Smith, *J. Appl. Phys.* 93 (2003) 8540.
- [2] T. Taniyama, I. Nakatani, T. Yakabe, Y. Yamazaki, *Appl. Phys. Lett.* 76 (2000) 613.
- [3] D. Lacour, J.A. Katine, L. Folks, T. Block, J.R. Childress, M.J. Carey, B.A. Gurney, *Appl. Phys. Lett.* 84 (2004) 1910.
- [4] Y.C. Chen, Y.D. Yao, S.F. Lee, Y. Liou, J.L. Tsai, Y.A. Lin, *Appl. Phys. Lett.* 86 (2005) 053111.
- [5] M. Kläui, C.A.F. Vaz, J.A.C. Bland, L.J. Heyderman, F. Nolting, A. Pavlovskaya, E. Bauer, S. Cherifi, S. Heun, A. Locatelli, *Appl. Phys. Lett.* 85 (2004) 5637.
- [6] Y.S. Chen, K.W. Cheng, C. Yu, S.F. Lee, D.C. Chen, S.H. Wu, M.T. Lin, Y. Liou, K.T. Wu, Y.D. Yao, *J. Appl. Phys.* 99 (2006) 08G516.