Magnetization Reversal in Nanostructured Permalloy Rings

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Abstract—Three different stable magnetization configurations of soft-type nanostructured permalloy rings are investigated in detail by micromagnetic simulation. During the reversal process, the abrupt change of the hysteresis loop corresponds to the evolution of these states. Beside the quasiuniform and circular states, we find a new pair-vortices state. We compare the magnetic pole density distributions transformed from the simulation patterns with the magnetic force microscopic (MFM) images and find very good agreement between them.

Index Terms—Magnetic force microscopy, magnetization reversal, micromagnetic simulation, nanostructured permalloy ring.

I. INTRODUCTION

THE development and application of ultrahigh density storage pattern media and various spintronic devices have attracted great attention to the investigation of the spin configurations and magnetization processes of nanostructured elements. As the promising magnetic random accessing memory (MRAM) progresses, the nanostructured rings become more and more important [1], [2] due to their efficiency in reducing the field leakage and enhancing the uniformity. The shape anisotropy of the ring-structured element causes a stable circular spin configuration inside the ring with closure flux loop, which avoids the field leakage and therefore raises the data storage density [1]. In this paper, we use micromagnetic simulations to study the spin configurations and magnetic reversal processes of permalloy rings. Further, we also compare the simulation results with the MFM experimental pictures and obtain very good agreement between them.

II. NUMERICAL SIMULATION

In our study, the outer diameter of the ring is 375 nm, and the inner diameter is 225 nm. The ring is 30 nm thick. We use the Landau-Lifshitz-Gilbert equation [3], [4] to investigate the spin configuration and magnetization reversal of the nano-structured ring. The parameters of the soft-type permalloy elements used in our micromagnetic simulations are exchange constant $C = 2A = 2 \times 10^{-6}$ erg/cm and saturation magnetization $M_s = 800$ emu/cm³. In addition, the uniaxial anisotropy constant K_1

is set to be 10^3 erg/cm³ [5], [6], which is too small to be of any significant influence on the total energy of the rings. The size of the meshed cell is chosen to be small in comparison with the exchange length of the permalloy material, namely, $R_0 = C^{1/2}/M_s = 17.7$ nm, to assure the precision of our simulation. In this study of the nanostructured ring element, the size of the cubic cell is set to be 7.5 nm, which is two times smaller than the exchange length. As the largest angular variation among spin directions of all cells is below 10^{-8} , the calculation is assumed to reach the equilibrium state of the system.

III. RESULTS AND DISCUSSION

Fig. 1 shows three different types of the reduced spin configurations of the ring from our simulation. As the external field is relaxed from saturation to 0 Oe, we obtain the magnetization configuration of Fig. 1(a). When the field is further decreased to -145 Oe, we obtain the magnetization configuration of Fig. 1(b). Two small vortices are nucleated at the two ends of the ring along the field direction because the quasiuniform state cannot exist in the vicinity of the two ends under the demagnetization field plus the negative external field. We call this the pair-vortices state. As we decrease the field to -440 Oe, we obtain the circular spin configuration, as shown in Fig. 1(c). When the field is further decreased to -1225 Oe, the magnetization is saturated to the left with spin configuration similar to Fig. 1(a) but with all arrows going in the opposite direction.

Fig. 2 represents the hysteresis loop of the ring from simulation result. In each sweeping down/up process of the hysteresis loop, we can find three obvious steps, which correspond to the transitions between the states in Fig. 1. The schematic pictures are used to represent the stable spin configurations corresponding to the plateaus. The spin configuration of Fig. 1(b) and its corresponding plateau in the hysteresis loop were not found in the recent investigation of Co(100) epitaxial ring magnets [2]. The circular state also appears in our simulation, although the permalloy ring used is symmetric, instead of an asymmetric ring used in the Co ring. This is different from the study of the Co(100) epitaxial ring magnets in [2].

We also investigate the ring structures that are two and three times larger than the previous one in the inner and outer diameters. Instead of the spin configuration in Fig. 1(a), we obtain their remanent states, which are similar to Fig. 1(b). Two vortices are nucleated in the two ends of the ring at remanent state because for larger linewidth, the vortex structure vastly reduces the demagnetization energy in either of the two ends, which is paid for in a lower increase of the exchange energy. In addition, we also study ring structures that are two times smaller than the previous one in the inner and outer diameters. We find that

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Fig. 1. Typical reduced ring patterns obtained by numerical simulation in permalloy rings. The external fields are 0 Oe, -145 Oe and -440 Oe for (a)–(c), respectively. Actual number of cubic cells is much larger in our simulation. The outer diameter, inner diameter, and thickness are 375, 225, and 30 nm, respectively.

Fig. 2. Hysteresis loops of permalloy ring. The schematic pictures are used to represent the stable states corresponding to the plateaus.

only the spin configuration of Fig. 1(a) can exist in smaller rings under arbitrary field. This is because that the ring is too narrow to possess any inhomogeneous reversal, which will cause huge

Fig. 3. (a)–(c) MFM images under different field in the sweeping down process. (d)–(f) Magnetic pole densities derived from the spin configurations of Fig. 1.

increase in the exchange energy; therefore, the whole spin configuration just rotates along the ring circumference, keeping the spin configuration the same throughout the reversal process. Therefore, we could only obtain one jump in the hysteresis loop of the ring with smaller linewidth.

The permalloy rings that have an outer diameter of $5\ \mu\text{m}$ and are $1\ \mu\text{m}$ wide and $45\ \text{nm}$ thick are made for MFM imaging. The patterns are fabricated using electron beam lithography with a lift-off technique. Fig. 3(a)–(c) shows the MFM images for different fields in the sweeping down process. Fig. 3(d)–(f) are the magnetic pole densities, which are the negative divergence of the spin configurations of Fig. 1(a)–(c), respectively. They can be compared with MFM images obtained from magnetic force gradient between the sample and the probe that is due to the magnetic pole density. The radii of the small circles appearing in Fig. 3(d)–(f) are proportional to the magnitude of the pole density. When the applied field is 300 Oe, we can obtain the MFM image of Fig. 3(a), which is similar to the pole density picture of Fig. 3(d), derived from the spin configuration of Fig. 1(a). When the experimental field is decreased to 34 Oe, the domain walls are nucleated with MFM image shown in Fig. 3(b). The image is nearly the same as the pole density in Fig. 3(e), which is derived from the spin configuration of Fig. 1(b). When the field is further decreased to -33 Oe, we find that the contrast

of the MFM image disappears, as shown in Fig. 3(c). This can be explained by the almost-zero pole density caused by the circular spin configuration. When we decrease the field further to -130 Oe, the domain wall is similar to Fig. 3(a) but with opposite polarity. When the field is swept in the opposite direction, we find that the MFM images and pole densities are repeatable.

Even though our simulation size is different from the experimental size, because the shape anisotropy dominates in the Permalloy ring structure, the micron-sized and submicron-sized elements have similar behavior. Due to the limited computing ability, it is still difficult to simulate magnetic thin films of large size and appreciable thickness.

IV. CONCLUSION

In summary, the magnetization reversal of the nano- and micron-sized permalloy ring is investigated by micromagnetic simulation and by MFM imaging. We find that three kinds of stable states can exist for different external fields, causing special features in the hysteresis loop. The magnetic pole density distributions from our simulations are in good agreement with the MFM images in our experiments.

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