Construction of hysteresis loops of single domain elements and coupled permalloy ring arrays by magnetic force microscopy

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(Presented on 15 November 2002)

Magnetic structure and magnetization reversal of permalloy ring arrays and elongated permalloy particle array were studied by magnetic force microscopy (MFM). For single domain permalloy particles, the hysteresis loop is constructed by counting the percentage of switched elements imaged at remanence. For permalloy ring elements, two different states are energetically stable: a vortex state and an onion state. Their hysteresis loop is obtained by MFM imaging at a field between the switching fields of these two states. The magnetostatic coupling among these ring elements is directly revealed. [DOI: 10.1063/1.1540129]

I. INTRODUCTION

Magnetic force microscopy (MFM) is a powerful tool for studying submicron elements due to its high sensitivity, high spatial resolution, low cost, and its versatility. MFM can be used to image and manipulate a magnetic moment state. In spectroscopical mode, it can be used to study the switching behavior of individual elements. The collective switching behavior of an array can also be determined by constructing a hysteresis loop. The hysteresis loop is obtained constructed by counting the percentage of switched elements as a function of the external magnetic field. One needs to be aware of the fact that the combined effects of the MFM tip stray field and the external magnetic field can make the particle switch at different field during imaging.[1,2] In this article, we study two different particle arrays to demonstrate how to obtain the precise switching field of submicron elements and how to construct a hysteresis loop by MFM.

II. EXPERIMENTAL TECHNIQUES

Arrays of widely spaced elongated permalloy particles as well as coupled rings were studied in this paper. The elongated permalloy elements with lateral dimensions of 240 nm$\times$90 nm and a thickness of 10 nm were prepared by interference lithography.[3] Permalloy ring elements with outer and inner diameter of 700 and 350 nm, respectively, and a thickness of 25 nm, were prepared on a 1 μm square lattice were prepared by standard electron beam lithography.[4]

Images were taken with a custom built vacuum MFM operating in the constant height mode in order to minimize irreversible distortion of the sample magnetization induced by the tip stray field.[2] Vacuum operation was used to increase sensitivity. Commercial cantilevers sputter coated with a thin film of $Co_{71}Pt_{12}Cr_{17}$ were used as force sensors. The cantilever frequency signal is decoded by a digital phase locked loop from NanoSurf.[5]

III. RESULTS AND DISCUSSION

A. Elongated permalloy elements

As the magnetic particle becomes smaller and thinner, the vortex state is not favorable due to the cost of the exchange energy. Thus, a single domain state is formed as shown in Figs. 1(a) and 1(b). The experiments were performed at remanence after the field was ramped to different values. In this case, reversible magnetization behavior of the elements can not be revealed, but irreversible magnetization behavior, such as switching, can be clearly observed. Distortions during imaging due to the tip stray field can be minimized by using a low moment tip and using a tip–sample separation.[2]

Figures 1(a) and 1(b) show the magnetic states at remanence after applying magnetic fields of −304 and −510 Oe, respectively. The remanent hysteresis loop is constructed by

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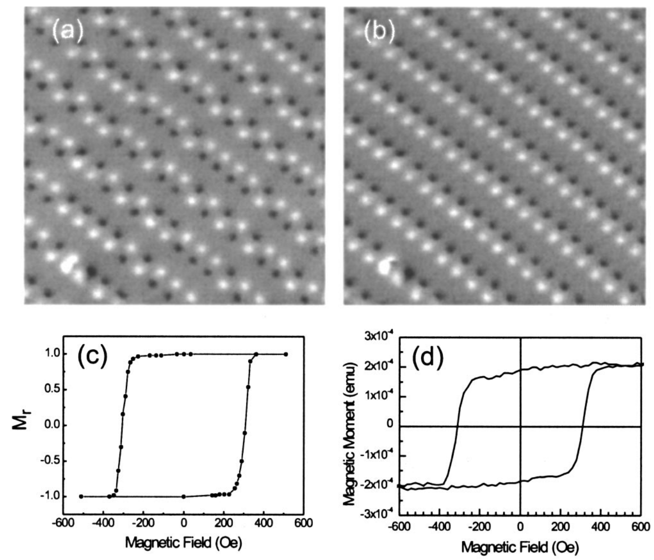

FIG. 1. (a) MFM image at remanence after applying −304 Oe along the long axis of the element; (b) after applying −510 Oe; (c) remanent hysteresis loop constructed from MFM images; and (d) hysteresis loop obtained by alternating gradient magnetometery. The images were taken in the constant height mode, with a tip sample separation of 100 nm. Element size: 240 nm×90 nm×10 nm. Gray scale: force gradient of 1.0×10^{-5} N/m; cantilever spring constant: $k=0.08$ N/m; resonance frequency: 22.6 kHz; tip: 50 nm CoPtCr; $P=1.4\times10^{-5}$ mbar.

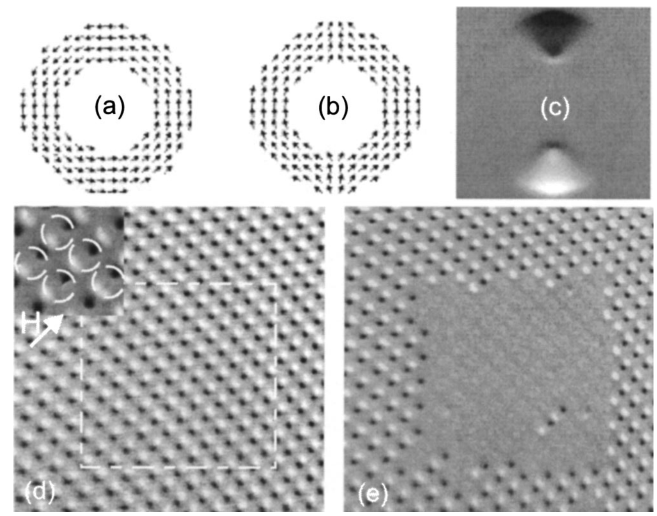

FIG. 2. Magnetic moment orientation of (a) vortex state and (b) onion state by micromagnetic simulations (see Ref. 10); (c) the *z* component of the stray field of (b) in a plane 40 nm above the ring; (d) MFM image at an external field of 60 Oe after a field of 300 Oe is applied; (e) MFM image at a field of 60 Oe after scanning the square area indicated in (d) at remanence. Scan area: 15 μm. Inset of (d) shows a smaller scan area, allowing comparison with (a) and (c). The arrow in (d) indicates the direction of the applied field. Tip: 30 nm CoPtCr; $f_0=97.8$ kHz; tip sample separation: 100±20 nm. Constant height images in vacuum. Inset in (d) shows an image in small scan size, and the white box in (d) is the 10 μm scan area at remanence.

counting the percentage of switched elements as a function of external magnetic field, as shown in Fig. 1(c). The observed remanent hysteresis loop can be directly compared to the hysteresis loop obtained by alternating gradient magnetometery, shown in Fig. 1(d). The coercivities (310 Oe) obtained by both methods agree very well, which demonstrates the capability of using MFM to characterize the switching behavior of nanomagnets. The advantage of obtaining a hysteresis loop from MFM images is that it builds a bridge between an individual element and the ensemble, whereas the macroscopic technique can only give an average switching behavior.

B. Coupled permalloy ring array

The prerequisite for constructing a remanent hysteresis loop is that the MFM tip stray field cannot irreversibly switch the remanent particle state. However, in some circumstances such distortions are unavoidable. Recent studies show that magnetic ring structures have two different stable states: a vortex state and a ''single domain like'' state.[6–8] The vortex state (i.e., a circular magnetization), as shown in Fig. 2(a), is the most energetically stable state.[9] The ''single domain like'' state is known as the ''onion state'' due to the fact that each half of a ring has the same moment orientation, forming head to head and tail to tail domain walls where opposite flux meets, as shown in Figs. 2(b) and 2(c).[6–8] There are two different transition fields for permalloy ring elements: one transition from the onion state to the vortex state occurs at a lower field H_n, and the other from the vortex state to the onion state occurs at a higher field H_s. Usually H_n is very small, and the MFM tip stray field can easily switch the particle moment state.[7] Figures 2(d) and 2(e) show such an example. Figure 2(d) shows a MFM image (15 μm) in a 60 Oe magnetic field after a field of 300 Oe was applied. The onion states in the image are clearly visible. In this case, the tip stray field cannot flip the ring's moment due to the offset field. However, distortion due to the tip stray field is obvious if the center area (10 μm) is rescanned at remanence since there are observable jumps in individual scan lines (not shown). This can also be demonstrated by rescanning the 15 μm area in an external field of 60 Oe, as shown in Fig. 2(e). The permalloy ring elements in the center region are now in the vortex state.

It is challenging to obtain the ring switching field from images, since the tip stray field can induce irreversible distortion at remanence. To obtain the switching field of rings or dots, one can assume that the MFM tip contributes a constant field offset. However, many effects such as the unknown in-plane and out-of-plane tip field component and the potential change of the tip stray field in the external field lead to major uncertainties. To obtain an accurate switching field,[11] one needs to perform the MFM experiments at a field of $\pm H_p$ ($H_n<H_p<H_s$) after the external field is ramped to a designated value H.[12] The ring will maintain its previous state at the field H_p or $-H_p$. The prerequisite to a reliable and accurate determination of the switching field is that H_p combined with the tip stray field cannot induce reversal. This can be experimentally achieved by using low moment tips and operating in the constant height mode.[12] Figure 3 shows a series of images where a field was applied in the (100) direction as indicated in the inset of Fig. 2(d). No tip stray field induced reversal can be observed.

By counting the percentage of switched elements based on Figs. 3(a)–3(f), a hysteresis loop is constructed as shown

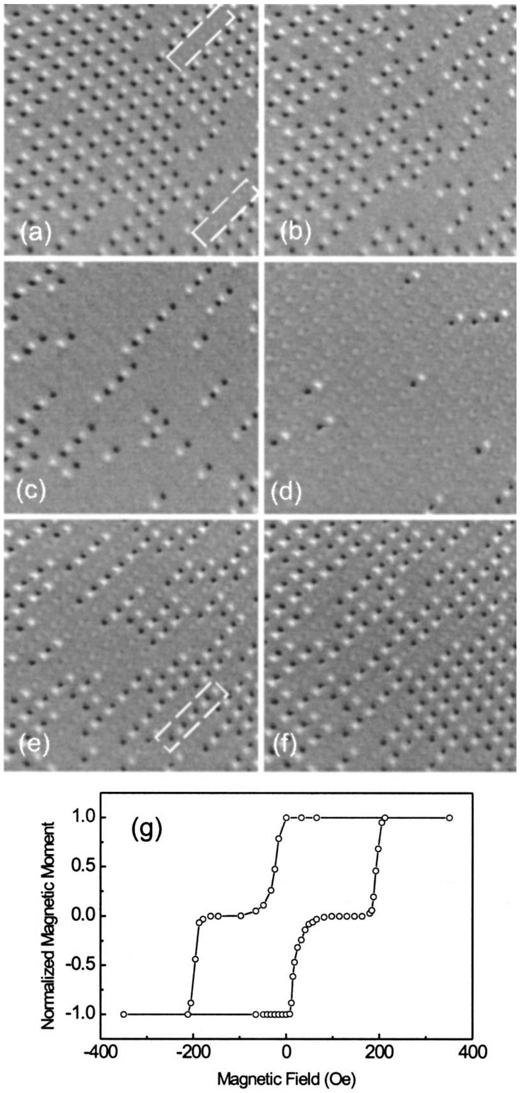

FIG. 3. MFM images of coupled rings after the magnetic field was ramped to a value of: (a) 11.6 Oe; (b) 14.7 Oe; (c) 32.6 Oe; (d) 183.5 Oe; (e) 192.3 Oe; and (f) 197.4 Oe. The magnetic field direction is along the (100) direction as is indicated in the inset of Fig. 2(d). (g) hysteresis loop obtained by MFM of the coupled permalloy ring array. The images of (a)–(c) were taken in a magnetic field of −60 Oe, and the images of (d)–(f) were taken in a magnetic field of +60 Oe. Experimental parameters are the same as in Figs. 2(d) and 2(e) with a tip sample separation of 80 nm.

in Fig. 3(g). Two different sharp transitions are observed in the curve. The average switching field H_n is only 15 Oe, and the average switching field H_s is approximately 195 Oe. The sharp transition shows that the switching field distribution is very narrow. One reason is that the edge roughness, a dominant factor determining the switching field variability of single domain elements, plays a less significant role for switching field variations in ring structures.[8] A second reason is that the ring elements are correlated due to their close separations. Switched elements help other elements to be switched. Such correlation can be directly observed in the MFM images, as the switched elements form chain structures (Fig. 3). However, the chain correlation length is limited due to the competition between the magnetostatic coupling and the variations in individual element switching fields.

IV. CONCLUSION

The MFM tip stray field can irreversibly distort a particle's magnetic moment state. Therefore, it is not trivial to obtain the precise switching field and to construct an hysteresis loop. If the MFM tip stray field is smaller than a switching field of the magnetic element (e.g., of a single domain element) then the imaging can be performed at remanence after the magnetic field is ramped to a predesignated value. The hysteresis loop is constructed by determining the percentage of switched elements as a function of the external magnetic field. However, if the MFM tip stray field is bigger than the switching field, special care needs to be taken in order to obtain the switching field. One solution is to image the magnetic state at a fixed field value after ramping the field to a predetermined value. At this fixed field, the magnetic moment state of the element is not irreversibly changed, and the combined effect of the tip stray field and the external field cannot induce switching of the particle.

ACKNOWLEDGMENTS

This work at McGill was supported by grants from the NSERC and FCAR. The work at UIC was supported by the U.S. National Science Foundation, Grant No. ECS-0202780 (VM).

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