Microcantilever Torque Magnetometry Study of Patterned Magnetic Films

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Microcantilever torque magnetometry (MTM) is a sensitive tool to measure small magnetization changes in the sample. In this paper, we investigated a process for preparing patterned magnetic films on cantilevers and studied the magnetic interactions of a single pair of micrometer-sized $Ni_{80}Fe_{20}$ bars (7 μm $\times$ 3.5 μm $\times$ 30 nm) separated by 50 nm using MTM. The bars were prepared with focused ion-beam milling. The magnetic hysteresis loops show that the switching field of a single bar is larger than the reversing field of only one of the paired bars and less than that of both paired bars. This clearly indicates that the magnetostatic interaction exists between the bars.

***Index Terms*—Magnetization reversal, torque magnetometers.**

I. Introduction

The study of small, defined magnetic structures has attracted much attention due to interest in both technological applications and fundamental research in micromagnetism [1]–[3]. Microcantilever torque magnetometry (MTM) is a promising new experimental technique for measuring such small magnetic features due to their high sensitivity [4]–[10]. One challenge in using this technique is to place the sample on the cantilever. In this work, we develop a new process for preparing patterned magnetic films on the cantilever and study the magnetic interactions in a paired magnetic bar measured by MTM.

II. Experiment

In our early work, microcantilevers were fabricated with a multistep photolithography process in which film deposition is combined with the cantilever fabrication process [6], [10]. Fig. 1 shows the schematic diagram of the newly developed process of patterning the magnetic film on a cantilever. The process is: 1) depositing a thick Au (200 nm) layer on the cantilever; 2) patterning using focused ion beam (FIB) milling; c) depositing the magnetic film through a mask; and d) a lift-off process by a gold etchant. By using this method, either single or an array of nanostructures can be easily obtained.

The patterned magnetic film is characterized by MTM. The magnetic hysteresis loops are obtained by applying a dc magnetic field in the surface plane and a small ac magnetic field perpendicular to the surface of the film at the cantilever's resonant frequency. The measurements are done at ambient conditions.

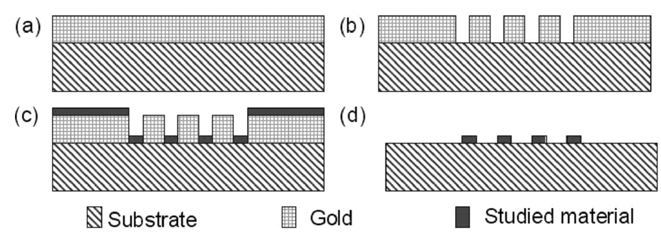

Fig. 1. Schematic diagram of the fabrication process of patterning the magnetic film on a cantilever: (a) depositing a thick Au (200 nm) layer on cantilever, (b) patterning using focused ion beam (FIB) milling, (c) depositing the magnetic film through a mask, and (d) a lift-off process by a gold etchant.

III. Results and Discussion

In order to investigate the magnetic interaction between a pair of bars, a 7 μm $\times$ 7 μm $\times$ 30 nm $Ni_{80}Fe_{20}$ film was put on the top left corner of the cantilever [Fig. 2(a)]. A 30-nm-thick Al layer is deposited on the top of the $Ni_{80}Fe_{20}$ film that prevents the possible poison of the magnetization with the Galium ions. The enlarged picture of the patterned $Ni_{80}Fe_{20}$ film is shown in Fig. 2(b). The $Ni_{80}Fe_{20}$ film was then patterned into two single 7 μm $\times$ 3.5 μm $\times$ 30-nm bars by cutting a 60-nm gap in the center of the film using an FIB [Fig. 2(c)]. The cut is made about 200 nm deep to ensure the two bars are unconnected.

The magnetic hysteresis loop is obtained by sweeping the external field from -40 kA/m to $+40$ kA/m and back. Fig. 3 shows the results in the field range of ± 6 kA/m for paired bars (the loop with open circles). The magnetization reversal occurs at -0.75 kA/m and -1.7 kA/m. The first jump at a field of -0.75 kA/m corresponds to the reversal of one of the paired bars. The second jump at a field of -1.7 kA/m corresponds to the reversal of the other one.

After the MTM measurement of the paired bar, the top bar of the same sample was removed with FIB. To make sure that the top bar is completely removed, the depth of the cut is about 500 nm which also removes some of the Si substrate. Fig. 2(d)

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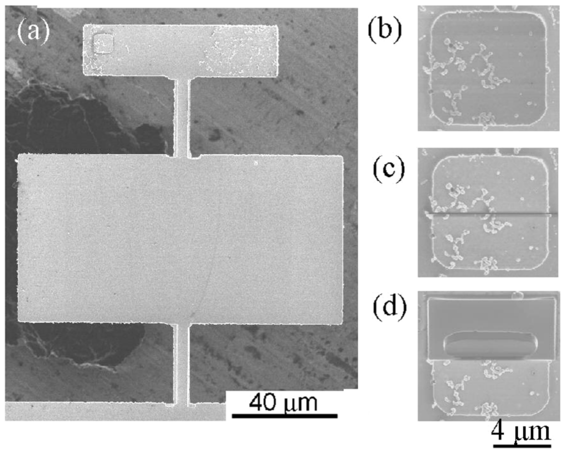

Fig. 2. (a) Microcantilever with a 7 μm $\times$ 7 μm $\times$ 30-nm $Ni_{80}Fe_{20}$ film deposited on the top left corner. (b) Magnified 7 μm $\times$ 7 μm $\times$ 30 nm $Ni_{80}Fe_{20}$ film. (c) Double 7 μm $\times$ 3.5 μm $\times$ 30-nm bars patterned with a focused ion beam on the 7 μm $\times$ 7 μm $\times$ 30 nm $Ni_{80}Fe_{20}$ film with a gap of 50 nm between adjacent bars. (d) Single 7 μm $\times$ 3.5 μm $\times$ 30-nm bar after removing the top bar with a focused ion beam.

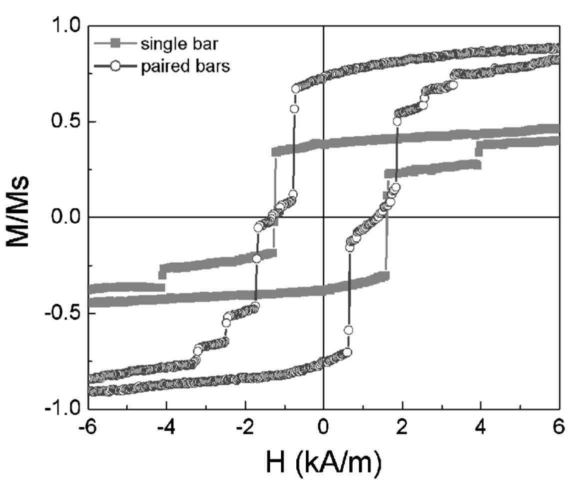

Fig. 3. Magnetic hysteresis loops of the single 6 μm $\times$ 3 μm $\times$ 30 nm $Ni_{80}Fe_{20}$ bar (solid squares) and same-size double bars (open dots) with a gap of 60 nm obtained with a microcantilever torque magnetometer (MTM).

shows only a single 7 μm $\times$ 3.5 μm $\times$ 30-nm bar is left on the cantilever. Fig. 3 shows the results in the field range of $\pm$ 6 kA/m for the single bar (solid squares). The magnetization reversal occurs around the coercive field of -1.23 kA/m. It is correlated to the domain wall propagating quickly through the bar. The smaller jump in magnetization at -4 kA/m may be caused by the annihilation of the small domain structure at the edge of the film.

Comparison of the magnetic hysteresis loops of the single and paired bars shows that the switching field of single bars is larger than the reversing field of only one of the paired bars and less than that of both paired bars. This indicates that magnetostatic interaction exists between the closely paired bars.

It has been shown by a micromagnetic simulation that the hysteresis loop for one set of paired $Ni_{80}Fe_{20}$ bars (300 nm $\times$ 1.5 μm $\times$ 32 nm) with a gap of 40 nm has two steps during the reversal [11]. The two steps observed in the hysteresis loop are caused by the magnetostatic interaction between the paired bars. In this study, the size of $Ni_{80}Fe_{20}$ bars is much larger than the size of 300 nm $\times$ 1.5 μm $\times$ 32 nm. The reversal process of a larger size bar may involve more domain wall motion than the small-size sample. Micromagnetic simulations were performed to study the magnetization reversal of 6 μm $\times$ 6 μm $\times$ 30 nm $Ni_{80}Fe_{20}$ bars using the Landau–Lifshitz–Gilbert solver software package developed by NIST [12]. The distance between the edges of two bars was taken to be 50 nm. The magnetization of $Ni_{80}Fe_{20}$ is 8×10^5 A/m, and the exchange stiffness constant is 1.3×10^{-13} J/m^3. The anisotropy of an ideal $Ni_{80}Fe_{20}$ alloy is extremely small; however, the measured film may have a substantial amount of inhomogeneity. Therefore, the following models of anisotropy are considered: 1) no anisotropy $\mathrm{K} = 0$, 2) random anisotropy with $\mathrm{K} = 10 \times 10^3$ J/m^3, and 3) random anisotropy with a distribution of anisotropy constants between 10×10^3 J/m^3 and 100×10^3 J/m^3. The random anisotropy is chosen to mimic the real thin-film medium.

For the single-square Permalloy film ($K = 0$, and no defects) with a side length of 6 μm, the simulation results show zero remanent magnetization. The film was initially magnetized along one side of the element relaxes to the vortex state at zero field. The reversal starts from the corners by creating vortices and consecutive motion of them. Experimental results show small coercivity with some features in the magnetization reversal curve. In order to introduce the coercivity, anisotropy should be introduced. Uniaxial anisotropy produces a square-like loop.

Nonuniform switching is characteristic of elements with large sizes and containing defects as shown in our experimental results. In order to model these films, we used a random anisotropy model with a distribution of uniaxial anisotropies in magnitude as well as easy axis. At moderate anisotropies, there is still a strong reduction of remanence magnetization with a complex domain structure at zero magnetic fields. A stronger anisotropy constant gives a picture similar to the experiment (i.e., there is large remanance magnetization and multiple steps in the hysteresis curve caused by pinning). For the paired bars system, the simulation results show that the switching is not independent for the ideal Permalloy film. After saturation, two bars form a symmetrically inversed C-state at the remanent state (no applied magnetic field). With a negative field applied, the magnetization reversal proceeds through the formation of two vortexes (end domains). Due to the broken symmetry (random anisotropy), the reversal of one of the bars happens first. Although the general picture of the reversal of this bar is similar to a single bar case, there are some deviations because of the interactions with the second bar. Due to the magnetostatic interactions, the system creates a closure for the magnetic field (magnetization of two bars is aligned in opposite directions). It is a metastable state for the system of two bars. Then, at a somewhat larger applied field, the system is forced out of this potential well and the second bar switches as well.

This picture is substantially different if we assume random anisotropy in the film. The two bars of Permalloy with disorder both in the direction of anisotropy and its magnitude are simulated as shown in Fig. 4. The average magnitude of K is taken to be 50×10^3 J/m^3. In this case, the magnetization reversal is quasi-independent for two bars. Both of them form a number of domains with edge domains to be switched last. Because of

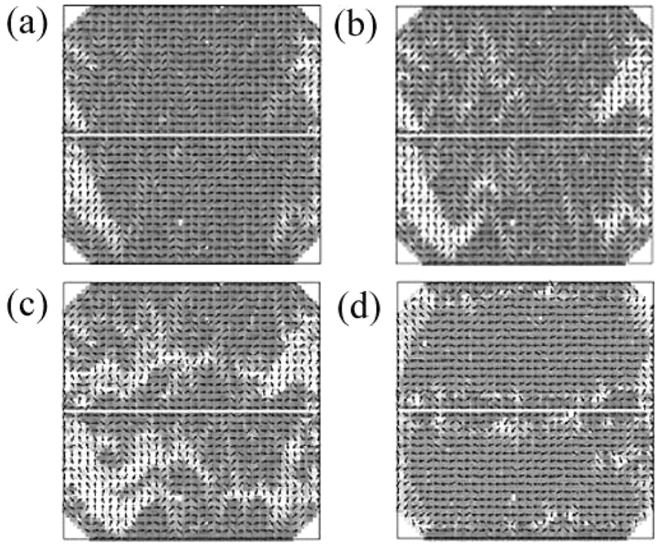

Fig. 4. Micromagnetic simulations were performed on the paired $Ni_{80}Fe_{20}$ bars (6 μm × 3 μm × 30 nm) with a gap of 50 nm. The sample was saturated along the long axis of the bars and then decreases to (a) -4.77 kA/m; (b) -20.69 kA/m; (c) -26.26 kA/m; and (d) -31.83 kA/m.

the two additional edges (due to the cut), the number of domains near the edges is twice the number as in the case of one square element. This results in a somewhat smaller remanent magnetization. There are multiple steps in the hysteresis loop. In the two-bar case, it is more pronounced. It can probably be attributed to the magnetostatic interaction between bars because it forms a domain structure which reduces the stray fields in the free space around the sample. Simulations show that a large number of domains near the edges of the feature are hard to push out. This energy barrier comes because of the closure of stray fields due to these domains. The formation of these domains is sensitive to the details of the reversal and should be strongly affected by the temperature. As a result, the reversal is not symmetric, especially if complete saturation was not achieved.

The above analysis shows that the reversal of the films in Fig. 3 can be understood, if a random anisotropy model with distribution of uniaxial anisotropies in magnitude as well as easy axis is assumed.

IV. Conclusion

A new process is developed to pattern magnetic films on an MTM cantilever. By using MTM, the magnetic interaction in a single pair of micrometer-sized magnetic samples is studied. The switching field of a single bar is larger than the reversing field of only one of the paired bars and less than that of both paired bars, which indicates that there exists magnetostatic interactions between the closely paired bars. This is correlated to a metastable state where the magnetization direction of the two bars is antiparallel to each other. The experimental results are consistent with micromagnetic simulations, if a random anisotropy model with distribution of uniaxial anisotropies in magnitude as well as of the easy axis is assumed. We show that MTM is a highly sensitive method for measuring magnetic interactions between closed small-size and shaped-defined magnetic elements with high resolution.

Acknowledgment

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