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Local Probing of Magnetization Reversal in Ni–Fe Elliptical Dots With Variable Geometry

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We have investigated the detailed magnetization reversal in 10-nm-thick Ni–Fe elliptical dots with several dot sizes using magnetic field sweeping (MFS)-magnetic force microscopy (MFM). At the dot edges, the shape of the phase (the stray field) curve versus magnetic field changes from a stepped hysteresis loop to a almost nonstepped hysteresis loop with increasing dot size. On the other hand, at the center within the dot, sharp or weak decreases in phase are observed as the magnetic field is varied. From these results, it is found that, in the magnetization reversal of a 10-nm-thick Ni–Fe elliptical dot with several dot sizes, the dominant factor changes from the change in the magnetic domain configuration to the domain wall motion as the length of major axis increases.

***Index Terms*—Magnetic elliptical dot, magnetic force microscopy (MFM), magnetization reversal.**

I. Introduction

MAGNETIC DOTS are attractive as promising materials for practical applications, including nonvolatile magnetic random access memory (MRAM) [1], [2], magnetic storage media [3], [4], magnetic logic gate (MLG) [5]–[7], and so on. In addition, they have been studied intensively from a micromagnetic point of view [8], e.g., a magnetic state of a single dot, its magnetization reversal, and so on. In particular, the understanding of a magnetization reversal in a single magnetic dot is very important from both fundamental and applied points of view. An experimental technique to directly observe the detailed magnetization reversal in a single magnetic dot is required.

Recently, we have proposed a new magnetization measurement method, the magnetic field sweeping (MFS)-magnetic force microscopy (MFM) [9]–[11], which uses an MFM tip as a detector while the magnetic filed is swept. In MFS-MFM, the precise magnetic state of a local point in a single magnetic dot or a single magnetic nanowire can be directly observed at room temperature within one minute. Until now, we have successfully applied MFS-MFM to study the detailed magnetization reversal in a circular dot and the effect on the dipole–dipole interaction between the adjacent elliptical dots [9], [11]. We have also observed the domain wall trapping in an Ni constrictive structure and found the dominant contribution to the magnetization reversal process in an Ni–Fe nanowire with various thicknesses and sizes [10], [11]. In this paper, we report, using MFS-MFM, a detailed magnetization reversal in a single Ni–Fe elliptical dot with several dot sizes.

II. Experimental Procedure

Ni-20 at.%Fe(Ni–Fe) elliptical dot arrays were fabricated by electron-beam lithography, electron-beam evaporator, and a liftoff technique onto thermally oxidized Si (100) substrates. During the film evaporation, a magnetic field of around 40 kA/m was applied to the major axis direction of elliptical dots, to induce unidirectional anisotropy. The thickness of the elliptical dots was fixed at 10 nm, the aspect ratio between major and minor axis was 2 : 1, and the length of major axis was varied from 200 to 1600 nm. The major axial distance between adjacent dots was 200 nm.

The shape of the dot arrays was observed by scanning electron microcopy (SEM). The magnetization process of the dot arrays was investigated using magnetooptical Kerr effect (MOKE) magnetometry, while the magnetic state of a single dot was observed using our proposed measurement method, namely, MFS-MFM.

In MFS-MFM, an MFM tip is used as a detector as the magnetic field is swept between $+40$ and -40 kA/m, so that the magnetic state of a local point in a single dot or a single nanowire can be directly observed by measuring the change in phase (i.e., the change in stray field). The MFM tip used in this method is an Si cantilever coated with a 30-nm-thick CoCrPt film, which has a low magnetic moment and is initially magnetized in the perpendicular direction. This tip is fixed 10 nm above the surface at a point of interest within the dot, which is at a height much lower than that in a conventional MFM measurement. This condition guarantees the signal pickup process within the range of 20 nm [12]. MFS-MFM was carried out at room temperature in a vacuum near 10^{-1} Pa.

III. Results and Discussions

Fig. 1 shows SEM and MFM images of 10-nm-thick Ni–Fe elliptical dot arrays with the length of major axis of 400 and 1000 nm. The shape of each dot is linear near the center and is clearly rounded at both edges [Figs. 1(a) and (b)]. For the dot arrays with the major axis of 400 nm [Fig. 1(c)], the dark and the bright areas are observed at the dot edge, or reverse in either upper or lower part of dot. This demonstrates that the magnetic domain configuration is either a single domain or a closure domain at a zero field. On the other hand, for the dot arrays with the major axis of 1000 nm [Fig. 1(d)], the dark and the bright areas are observed not only at both edges, but also

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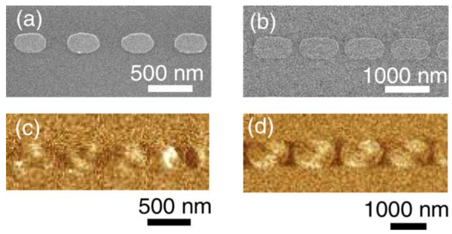

Fig. 1. (a), (b) SEM images of 10-nm-thick Ni–Fe elliptical dot arrays with the major axis of (a) 400 nm and (b) 1000 nm. (c), (d) MFM images at a zero field of 10-nm-thick Ni–Fe elliptical dot arrays with the major axis of (c) 400 nm and (d) 1000 nm.

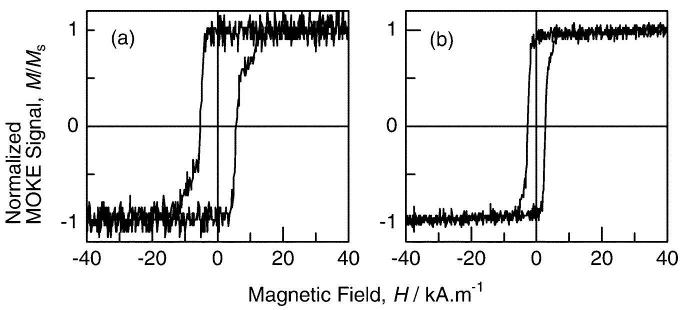

Fig. 2. MOKE hysteresis loop of 10-nm-thick Ni–Fe elliptical dot arrays with the major axis of (a) 400 nm and (b) 1000 nm. Magnetic field is applied in the major axis direction of the elliptical dot.

within each dot. These results reveal that several domain walls exist within the dot at zero field. Thus, it is revealed that the magnetic domain configuration of the dot changes as the dot size increases.

Fig. 2 shows the MOKE hysteresis loop of the 10-nm-thick Ni–Fe elliptical dot arrays with the major axis of 400 and 1000 nm. The magnetic field is applied in the major axis direction of the dot. As can be observed, the shape of the MOKE loop becomes narrower as the length of major axis of the dot increases. This result is in agreement with the MFM images of the Ni–Fe dot array in Fig. 1, which present variation in magnetic domain configuration within the dot as the size increases. This change has been confirmed by a micromagnetics simulation published elsewhere [13], which also shows that the shape of a magnetization loop in an elliptical dot becomes narrower as the length of major axis increases. This result reveals that the magnetization reversal in a single dot differs according to the dot size.

In order to clarify the difference observed in the magnetization reversal of a single dot as the dot sizes increases, the curves of the phase versus magnetic field (H) at various points within the 10-nm-thick Ni–Fe elliptical dots were measured using MFS-MFM. Fig. 3 shows their results when the sweeping magnetic field is applied in the major axis direction of the elliptical dot. Here, Figs. 3(a-1) and 1(b-1) presents the AFM image of a 400- and 1000-nm major axis elliptical dot and the position where each measurement was carried out is denoted with points 1–3. For the dot with the major axis of 400 nm, the measurements carried out at points 1 and 3 displayed stepped hysteresis loop of the phase [Figs. 3(a-2) and (a-4)]. These loops represent the magnetization reversal around the dot edge, i.e., when the magnetic domain configuration changes from a single domain to a closure domain and back to an opposite single domain, following the direction of the sweeping magnetic

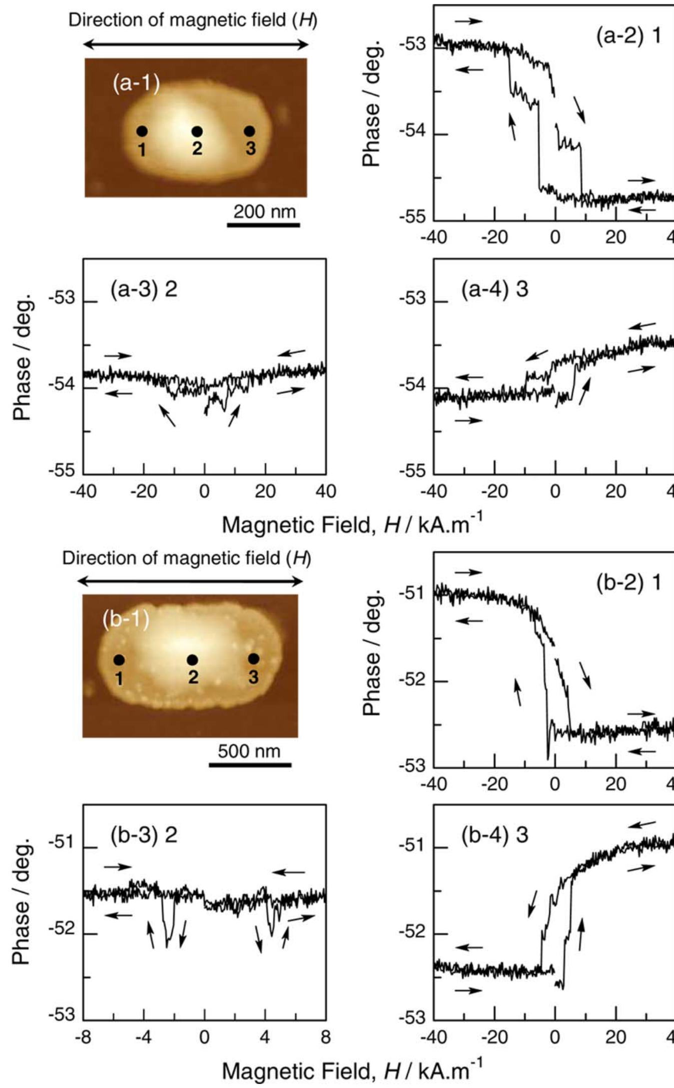

Fig. 3. Images of 10-nm-thick Ni–Fe elliptical dots with the major axis of (a-1) 400 and (b-1) 1000 nm. Points 1-3 indicate measured points within the dot. Curves of phase versus magnetic field (H) for various points in the Ni–Fe elliptical dots with the major axis of (a-2)-(a-4) 400 and (b-2)-(b-4) 1000 nm measured by MFS-MFM. The magnetic field is applied in the major axis direction of the elliptical dot.

field. The magnetic fields at which these changes in the phase saturate in these loops are similar to the switching field for the dot array measured by MOKE. In the measurement carried out at point 2 [see Fig. 3(a-3)], weak phase decreases are observed at approximately 8 and -8 kA/m. This behavior might be due to the presence of the core of a closure domain at the center of the dot, as reported in [9] and [11]. The magnetic fields at which the phase decreases are observed are similar to the coercivity of the dot array measured by MOKE. These results reveal that the magnetization reversal within the dot originates from the change from the single domain to the closure domain configuration.

On the other hand, for the dots with the major axis of 1000 nm, the measurements carried out at points 1 and 3 [Figs. 3(b-2) and (b-4)] displayed nonstepped hysteresis loop of the phase. These loops are attributed to the magnetization reversal taking place at the dot edge. The magnetic fields at

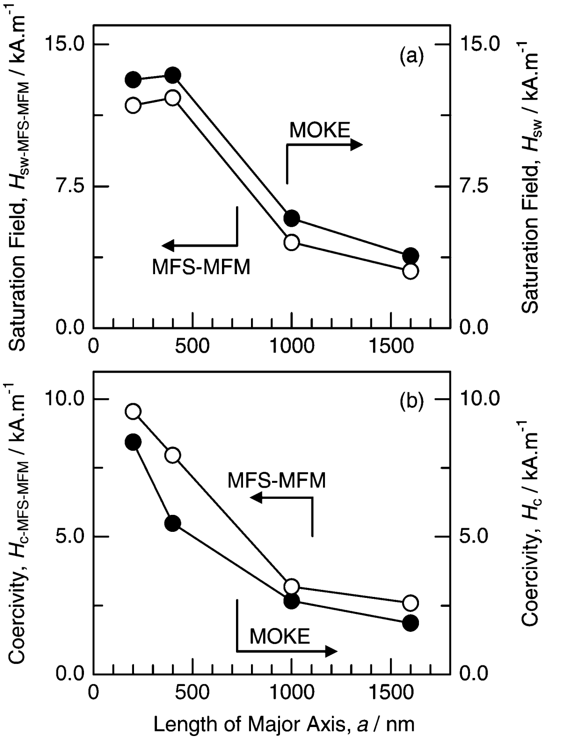

Fig. 4. (a) Relationship between magnetic fields $(H_{\mathrm{sw\_MFS-MFM}})$ at which the changes in phase saturate in the hysteresis loop measured with MFS-MFM and the switching field (H_{sw}) obtained by MOKE. (•) and (○) : $H_{\mathrm{sw\_MFS-MFM}}$ and H_{sw}, respectively. (b) Relationship between magnetic fields $(H_{\mathrm{c\_MFS-MFM}})$ at which the weak or sharp phase decreases are observed by MFS-MFM and the switching field (H_{sw}) obtained by MOKE. The x axis indicates the length of major axis of the elliptical dot. (•) and (○) : $H_{\mathrm{c\_MFS-MFM}}$ and H_{c}, respectively.

which a decrease or an increase in the phase is observed in these hysteresis loops are similar to the switching field observed for a dot array measured by MOKE. In the measurement carried out at point 2[Fig. 3(b-3)], sharp jumps of the phase are observed at approximately 4 and -2 kA/m. These sharp decreases in the phase are similar to those observed in the Ni–Fe nanowires reported in [11] and are ascribed to the domain wall motion within the dot. The magnetic fields at which the phase decrease is observed are similar to the coercivity of each dot array measured by MOKE. These results reveal that the magnetization reversal in the dot originates from the domain wall motion. Thus, these results demonstrate that the details of magnetization reversal in a single Ni–Fe elliptical dot can be observed using MFS-MFM. Note that the intermittent curves of phase versus magnetic field [e.g., Figs. 3(a-2), (a-4), (b-2), and (b-4)] might be attributed to the slight drift of the dot with sweeping the magnetic field but does not influence the magnetic properties of the dot.

These results have been confirmed in 10-nm-thick Ni–Fe elliptical dots with several dot sizes. The magnetic fields at which the changes in phase saturate in the hysteresis loop measured with MFS-MFM $(H_{\mathrm{sw\_MFS-MFM}})$ and the magnetic fields at which the weak or sharp decreases in the phase $(H_{\mathrm{c\_MFS-MFM}})$, both measured by MFS-MFM, are summarized in Fig. 4, as a function of the length of major axis of the elliptical dot. In this figure, the switching field (H_{sw}) and coercivity (H_{c}) of the 10-nm-thick Ni–Fe elliptical dot array obtained by MOKE are shown. As can be observed, each field decreases as the length of major axis of the dot increases. This happens because the magnetostatic energy is reduced when the length of major axis of the dot increases [14]. The values of $H_{\mathrm{sw\_MFS-MFM}}, H_{\mathrm{sw}}$ and those of $H_{\mathrm{c\_MFS-MFM}}, H_{\mathrm{c}}$ are in good agreement because H_{sw} and H_{c} are the average values of several dots. On the other hand, H_{sw} and H_{c} of each dot shows a wide distributed value in the MOKE loop. These results mean that the coercivity as well as the switching field of a single dot can be determined by MFS-MFM. As a consequence, it has been found that the magnetization reversal in a single 10-nm-thick Ni–Fe elliptical dot differs according to the dot size, that is, the change in the magnetic domain configuration plays an important role in the magnetization reversal of the dot with smaller dot size, while the domain wall motion mainly dominates in the magnetization reversal of the dot with larger dot size.

IV. Conclusion

Local probing of the magnetization reversal in single Ni–Fe elliptical dots with several dot sizes has been studied using MFS-MFM. The detailed magnetization reversal at local points in these dots can be successfully observed. These results demonstrate that the dominant factor changes from the change in the magnetic domain configuration to domain wall motion with increasing dot size in the magnetization reversal of the 10-nm-thick Ni–Fe elliptical dot. Hence, it is concluded that MFS-MFM directly provides information of magnetization reversal at local points in a Ni–Fe elliptical dot with several sizes, allowing further fundamental insight into the nanomagnetism.

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