Dependence of magnetization process in a Ni-Fe nanowire on the width of the nanowire

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Abstract. We investigated the dependence of the magnetization process in 30-nm-thick Ni-Fe nanowires on the width of the nanowire using the magnetic field sweeping (MFS) - magnetic force microscopy (MFM), which measures phase changes (stray field changes) using a MFM tip as a detector. The phase changes are dependent on the width of the nanowire; hysteresis loops of the phase and plateau areas of the phase are observed at local points for the widths between 100 - 600 nm, while local points, each, display the hysteresis loops of the phase and the valleys of the phase for the width of 800 nm. These results demonstrate that the dominant factor in the magnetization process of 30-nm-thick Ni-Fe nanowires changes from “domain wall motion and domain wall pinning” to “domain wall motion with increasing the width of the nanowires”.

1. Introduction

The control of domain walls in nanosized magnets has been studied intensively from both fundamental and applied points of view [1-3]. In particular, much attention has been focused on the studies of domain walls in magnetic nanowires [4-10] because several groups reported that inducing a magnetic field [8] or current [9] can control their domain wall motion and that the domain wall trapping occurs by introducing an artificial neck into them [7,10]. For these studies, the electric resistance measurement is mainly used to observe the domain wall formed in magnetic nanowires, because of high measurement sensitivity in giant magnetoresistance (GMR) effect [11,12]. However, the detailed magnetic configurations of the domain walls in a magnetic nanowire cannot be determined. Thus, an experimental technique that can directly observe the details of magnetic configuration of the domain walls in a magnetic nanowire is required.

Recently, we have proposed a new magnetization measurement method, the magnetic field sweeping (MFS)-magnetic force microscopy (MFM) [13-16], which employs a MFM tip as a detector while sweeping the magnetic field. The MFS-MFM has an advantage that the precise magnetic state in a local point of a single nanosized magnet can be directly observed at room temperature within 1 min. Until now, we have successfully observed the detailed magnetization process in a magnetic dot with various shapes [13] and domain wall trapping in a Ni constriction structure [14] using the MFS-
MFM. In this paper, we observed the magnetic state at local points in 30-nm-thick Ni-Fe nanowires using the MFS-MFM, and investigated the dependence of the magnetization process in the nanowire on the width of the nanowire in detail.

2. Experimental Procedure
Ni-20at.\% (Ni-Fe) nanowires were fabricated by electron-beam lithography, DC magnetron sputtering, and a lift-off technique onto thermally oxidized Si(100) substrates. The thickness and the length of the nanowires were 30 and 2100 nm, respectively, while the widths varied between 100 - 800 nm. The shape of the nanowires was observed by scanning electron microscopy (SEM). As can be seen in figure 1, the shape of each nanowire is clearly linear near center, but is slightly rounded at both edges. The magnetization process of the arrayed nanowires was observed by magneto-optical Kerr effect (MOKE) measurements, while the magnetic state of nanowires was investigated by our proposed measurement method, namely, MFS-MFM. The details of the MFS-MFM have been described elsewhere [13-16].

![Figure 1. SEM images of 30-nm-thick Ni-Fe nanowires (length = 2100 nm) with the width of (a) 300 nm, (b) 500 nm, and (c) 800 nm.](image)

3. Results and Discussion
In order to clarify the dependence of magnetization process in a Ni-Fe nanowire on the width of the nanowire in detail, the phase curves vs. magnetic field (H) at various points in 30-nm-thick Ni-Fe nanowires with various widths were measured by the MFS-MFM. Figure 2 shows these results in Ni-Fe nanowires with the widths of (a) 300, (b) 500 and (c) 800 nm when the magnetic field is applied in the longitudinal direction of the nanowire. Here, figures 2(a-1), 2(b-1) and 2(c-1) show MFM images at zero field of isolated Ni-Fe nanowires with the widths of 300, 500 and 800 nm, which are composed of several domains, S-shape state, and double closure state [17], respectively. The location of each measured point is denoted in figures 2(a-1), 2(b-1) and 2(c-1). Points 1-4 indicate measured points within the nanowire. For each nanowire with the widths of 300 and 500 nm, points 1 and 4 [figures 2(a-2), 2(a-5), 2(b-2) and 2(b-5)] each show a hysteresis loop of the phase. These hysteresis loops are attributed to the magnetization reversal at the edge of the nanowire. The magnetic field at which the phase increase or decreases is observed apparently coincides with the switching field of each arrayed nanowire. At points 2 and 3 [figures 2(a-3), 2(a-4), 2(b-3) and 2(b-4)], either one or two sharp plateau areas of the phase are observed, which originate from the domain wall motion and domain wall pinning (the nucleation and annihilation of Bloch wall within the nanowire). The ranges of magnetic field in which the plateau areas of the phase are observed are different each other; their ranges are -0.04 - -0.08 kOe and/or +0.04 - +0.08 kOe for the nanowire with the width of 300 nm, while are -0.04 - -0.13 kOe and/or +0.01 - +0.08 kOe for the nanowire with the width of 500 nm. These ranges are similar to the switching field range of each arrayed nanowire measured by MOKE. These results are confirmed in 30-nm-thick Ni-Fe nanowires with other widths less than 600 nm. On the other hand, for the nanowire with the width of 800 nm, points 1 and 4 [figures 2(c-2) and 2(c-5)] each displays hysteresis loops. These loops are derived from the magnetization reversal at the edge of the nanowire. The magnetic field at which the phase increase or decreases is observed apparently coincides with the
switching field of the arrayed nanowire. At points 2 and 3 [figures 2(c-3) and 2(c-4)], a valley of the phase is observed between 0.05 – 0.20 or + 0.05 – - 0.10 kOe as the magnetic field is changed from negative to positive or vice versa, which are similar to that in a Ni-Fe circular dot [16]. These are attributed to only the domain wall motion, namely, the motion of the cores in the double closure domain state [figure 2(c-1)]. Thus, these results reveal that the change in domain wall within an

**Figure 2.** MFM images in a zero field of 30-nm-thick Ni-Fe nanowires with the widths of (a-1) 300, (b-1) 500, and (c-1) 800 nm. Points 1-4 indicate measured points within the nanowire. Curves of phase vs. magnetic field ($H$) for various points in the Ni-Fe nanowires with the widths of (a-2)-(a-5) 300, (b-2)-(b-5) 500, and (c-2)-(c-5) 800 nm measured by MFS-MFM. The magnetic field is applied in the longitudinal direction of the nanowire.
isolated nanowire can be directly observed using the MFS-MFM. These results also mean that the domain wall motion and the domain wall pinning are dominant in the magnetization process of nanowires with the widths between 100 – 600 nm and that the domain wall motion plays an important role in the magnetization process of nanowires with the width of 800 nm.

The magnetic fields ($H_{\text{MFS-MFM}}$) at which the phase increase or decrease are observed in the hysteresis loop of the phase by the MFS-MFM and the switching fields ($H_{sw}$) of arrayed nanowires by MOKE are summarized in Fig. 3 as a function of the width of the nanowire. The $H_{\text{MFS-MFM}}$ and $H_{sw}$ markedly decreases as the width of the nanowire increases. This is due to the fact that the magnetostatic energy is reduced with increasing the width of the nanowire [18]. The $H_{\text{MFS-MFM}}$ and $H_{sw}$ differs each other. The reason for this is that $H_{sw}$ means the average value of the switching fields in the arrayed nanowires and $H_{sw}$ of each nanowire is widely distributed in the MOKE loop. This result means that the switching field of an isolated nanowire can be directly measured by the MFS-MFM.

4. Conclusions
The details of the magnetization process in a 30-nm-thick Ni-Fe nanowire with various widths between 100 – 800 nm were observed using the MFS-MFM. The phase changes at nanowire edges are independent of the width of the nanowire, and show a hysteresis loop. In contrast, the phase changes around the center of the nanowire markedly depend on the width of the nanowire, and change from sharp plateau areas of the phase to valleys of the phase with increasing the width of the nanowire. On the basis of these results, it is found that the domain wall motion and the domain wall pinning within the nanowire play an important role in the magnetization process of a 30-nm-thick Ni-Fe nanowire with the widths between 100 – 600 nm, and that the domain wall motion within the nanowire is mainly dominant in the magnetization process of a 30-nm-thick Ni-Fe nanowire with the width of 800 nm. Hence, it is concluded that the change in domain wall within an isolated nanowire can be directly observed using the MFS-MFM.

Acknowledgments
This work was partly supported by a Grant-in-Aid for Scientific Research (S), Exploratory Research and Encouragement of Young Scientists (B) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. This study was supported by Priority Assistance for the Formation of Worldwide Renowned Centers of Research - The Global COE Program (Project: Center of Excellence for Advanced Structural and Functional Materials Design) from MEXT, Japan.
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