Development of a magnetic force microscopy for magnetically soft materials

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Abstract. We propose a magnetic force imaging technique based on MFS. This method is directly visualize a two dimensional motion of the domain structure of the sample, without a disturbance of the magnetic structure of the sample by MFM tip stray field, and improve the interpretation of the result of MFS. Magnetic force imaging by MFS is useful to investigate magnetic domain structures and magnetization switching mechanism of magnetically soft materials.

1. Introduction
Magnetic force microscopy (MFM) [1] is one of the most powerful techniques to study magnetic phenomena for logic functionality such as magnetic logistic gate [2], magnetic domain wall logic element [3]. In general, magnetically soft materials are used for these elements.

There are two important issues in the imaging of magnetically soft structures by MFM: (1) an effect of the magnetic stray field from the MFM tip and (2) a cross-talk between the topography and the magnetic force image [4]. To reduce these effects, several operation modes are developed, the most common of which are a constant-height mode and a tapping/lift mode.

The constant-height mode maintains the tip position on constant height value in the non-contact region. Thus the MFM tip stray field does not disturb the magnetic structure on the sample surface. However obtained image reflects not only the magnetic structure but also the topography of the sample. The tapping/lift mode obtains the topography and magnetic force image separately. The topography is obtained in the tapping mode, whereas the magnetic force image is obtained by tracing the surface with constant offset height which is determined from the topography. Therefore the tapping/lift mode can reduce the cross-talk between the topography and the magnetic force image. However, during the topographic measurement, the MFM tip contacts to the sample surface and the magnetic stray field from the MFM tip disturbs the magnetic structures of the sample [4].

Recently, Y. Endo, et al proposed a Magnetic field sweeping (MFS) MFM, which employs a MFM tip as a magnetic interaction force detector while sweeping the external magnetic field [5]. By using this method, we can eliminate an effect of the magnetic stray field from the MFM tip and a cross-talk between the topography and the magnetic force image, simultaneously. However, MFS only measure a single point of the sample, and interpretation of the result is still difficult.

In this study, we propose a magnetic force imaging technique based on MFS. This method is directly visualize the two dimensional motion of the domain structure of the sample and improve the interpretation of the result of MFS.
2. Magnetic force imaging by MFS

![Figure 1](image)

**Figure 1.** Schematic diagram of magnetic force imaging by MFS. We implemented the MFS technique in a magnetic force imaging. The procedure for this method include the following step: First, to obtain the topography, the tip scans the surface by tapping mode AFM (Fig. 1(a)). Second, to separate the van del Waals interaction force and magnetic interaction force, the tip is lift-up to a constant lift-height above the previously recorded topography, where the long range magnetic interaction force is dominant and the van del Waals interaction force becomes constant value (Fig. 1(b)). Third, to eliminate the disturbance of the magnetic state of the sample by the MFM tip stray field, the magnetization state of the sample is initialized by applying a large external magnetic field (Fig. 1(c)). Finally, MFS measurement is performed to measure the magnetization process of the sample by sweeping the external magnetic field (Fig. 1(d)). The magnetic force image in each external magnetic field is restructured from MFS curve and x-y location information of each MFS measurements (Fig. 1(e)). To minimize the effect of the thermal drift of the tip-sample distance, this procedure is performed per each scan point.

3. Experimental Procedure

As a sample, Ni-Fe nanowires with constriction was fabricated on thermally oxidized Si(100) substrates by electron-beam lithography, DC magnetron sputtering, and a lift-off technique. All experiments were performed in vacuum condition with a commercial AFM (SII-A300) at room temperature. The probe we used was a CoPtCr-coted cantilever (SI-MF40LM) with spring constant of \( k = 36 \text{ N/m} \), a free resonance frequency of 295.840 kHz, and Q factor of 3462. The topography was measured at free amplitude of 72 nm, amplitude shift of 8.2 nm. In magnetic force image measurement by MFS, the free amplitude of the MFM cantilever was 14 nm and a lift-height was 10 nm. The magnetization state of the sample was initialized by applying an external field of -500 Oe, and then the external magnetic field was increased from -500 Oe to +500 Oe (256 points). The scan area and the number of measuring points are 1000 nm \( \times \) 2000 nm and 20 points \( \times \) 40 points, respectively.

4. Results and Discussions

![Figure 2](image)

**Figure 2.** Topography of Ni-Fe nanowire with constriction by tapping mode AFM. (5\( \mu \text{m} \) \( \times \) 5\( \mu \text{m} \))
Figure 2 shows the topography of the Ni-Fe nanowire with constriction by tapping mode AFM (5µm × 5µm). Typical dimension of Ni-Fe nanowires are a length of 2080 nm, a width of 380 nm and constriction width of 325 nm. Magnetic force image by MFS was performed with the nanowire indicated by dots-lines.

![Figure 2](image)

**Figure 3.** Magnetic force image of Ni-Fe nanowire with constriction by MFS in a zero field. (a) raw image, (b) calculated thermal drift of the phase signal (c) thermal drift compensated image.

Figure 3(a) shows a raw magnetic force image of the Ni-Fe nanowire with constriction by MFS in a zero field. In Fig. 3(a) we can see the corrugation which originates in the thermal drift of the phase signal of the MFM cantilever. To eliminate the effect of the thermal drift in the phase signal, we calculated and subtract the thermal drift of the phase signal by averaging the phase signal in the external magnetic field of -500 Oe to -360 Oe and +360 Oe to 500 Oe at each scan points, where the sample magnetization states were saturated (Fig. 3(b)). As a result, we can clearly see that the magnetic stray field from the sample at (A) the lower-end, (B) the constriction structure and (C) the upper-end of the nanowire, respectively (Fig. 3(c)) without disturbance of the magnetic structure of the sample by MFM tip stray field.

![Figure 3](image)

**Figure 4.** Magnetic force image of Ni-Fe nanowire with constriction by MFS. The external magnetic field increases from +160 Oe to +313 Oe.
Figures 4 show drift compensated magnetic force image of the Ni-Fe nanowire with constriction by MFS. The external magnetic field was increased from -313 Oe to +313 Oe. The magnetization state of (A) the lower-end, (B) the constriction structure and (C) the upper-end of the nanowire are switched in the external magnetic field from (A') +180 Oe to (A'') +270 Oe, from (B') + 234 Oe to (B'') +266 Oe, and from (C') 242 Oe to (C'') + 305 Oe, respectively. The switching process was observed in order of the lower-end, constriction structure and upper-end of the nanowire. These results show that the two dimensional motion of the domain structure in Ni-Fe nanowire can be directly observed using magnetic force image by MFS.

5. Conclusion
We performed a magnetic force imaging technique based on MFS with Ni-Fe nanowire with constriction. This method is directly visualize the two dimensional motion of the domain structure of the sample without the disturbance of the magnetic structure of the sample by MFM tip stray field, and improve the interpretation of the result of MFS. Magnetic force imaging by MFS is useful to investigate magnetic domain structures and magnetization switching mechanism of magnetically soft materials.

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