Quantitative analysis of magnetization reversal in patterned strip wire by magnetic force microscopy

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Abstract

Magnetic force microscopy (MFM) was used to investigate the magnetization reversal process in a patterned strip wire of permalloy thin film. The magnitude of the phase-shift of tapping mode MFM changed with the varying interactive magnetic force between the magnetic tip and the sample. By analyzing the change in values of the phase-shift, the behaviors of magnetization reversal of different local regions in a patterned strip wire can be quantitatively analyzed. The intensity of the phase-shift in the wider end is stronger than that in the narrower one. In contrast, due to a strong anisotropic effect, the coercive force in the narrower end (9 Oe) is larger than that in the wider one (8 Oe). Therefore, the H_c in the neck section could become strongly affected by the competition of the head-to-tail magnetic configurations in the two parts of the strip wire, and this results in a small H_c in the neck section. In addition, in a simple neck shape connection in a strip NiFe wire, a single domain configuration can be easily changed to a two single domain magnetic configuration.
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Keywords: Magnetic force microscopy; Magnetization reversal; Permalloy film

1. Introduction

Magnetic force microscopy (MFM) has been used for years to investigate magnetization reversal behaviors [1–6] because of not only its high resolution but also its ability to observe different local regions in a patterned sample (i.e. to separate the magnetic reversal processes in different respective sections in a submicron regime by In situ detection of MFM images with an applied magnetic field). The intensity of the phase-shift does not directly stand for the magnetization magnitude, but only reflects the vertical component of the magnetic flux straying out of magnetic thin films. Taking advantage of the phase analysis [7], one can locally investigate the magnetic reversal process in a patterned sample and even compare several different local sections.

In this study, we analyze the values of phases in tapping mode MFM to identify different configurations of magnetization in a patterned strip wire of permalloy thin film and to compare the magnetization reversal behaviors in different local sections.

2. Experiments

We fabricated the patterned permalloy thin film out of a combination of two strip wires with different widths by e-beam lithography and following sputtering deposition and lift-off techniques. The widths of the narrower wire and the wider one were 200 and 450 nm, respectively, and the lengths were 4500 and 5500 nm, respectively, while the thickness was 30 nm. The SEM image of the pattern is shown in Fig. 1.

Measurements were performed by AFM/MFM tapping mode to detect the topographic and magnetic images of the pattern at a simultaneously applied magnetic field of $-200\,\mathrm{Oe} \sim 200\,\mathrm{Oe}$ aligned to the longitudinal direction of the strip wires.

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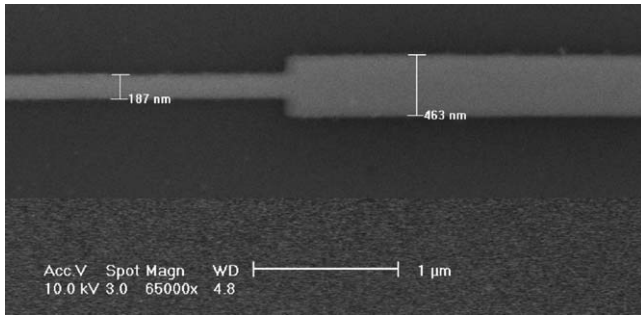 E-mail address: ydyao@phys.sinica.edu.tw (Y.D. Yao).

Fig. 1. An SEM image of the pattern with different widths of strip wire.

3. Results and discussion

Fig. 2.(a) shows AFM (upper diagram) and MFM (middle diagram) images, and the profile (lower diagram) of the phase of the line scan in the MFM image as well. This image was detected at a 140 Oe field which was initially at 200 Oe and varied to –200 Oe. The configuration of magnetization in the pattern (as shown in Fig. 2(b)) is briefly considered as macroscopic uniform, and in the same direction of magnetizations in both parts with different widths. Since only the vertical component of the interactively magnetic force between the MFM tip and the sample contributes to the signals of the MFM image, the relatively darker or brighter signals in the MFM image can only appear at the regions in which magnetic flux strays out of the film plane. In our case, these regions are at both ends of the pattern as well as in the section in which the width changes abruptly. Although the strong anisotropy in long strip wire causes a briefly uniform configuration, this section forms a geometric discontinuity (indicated as b in Fig. 2(b)) in the pattern, thus causing a locally different magnetic configuration and resulting in a stray field out of the film plane. It is reasonable to consider that the magnitude (absolute value) of the phase at the wider section (labelled **c**) is stronger than that at the narrower one (labelled **a**), because the quantity of the magnetic moment is proportional to the volume of the magnetic material, and the more moment the material contains, the stronger magnetic flux it radiates into an equal volume of space near the material. Furthermore, in this magnetic configuration, since the section **b** connects the wider and the narrower parts, which are supposed to have negative and positive values of phase, respectively, the totally combined value is negative (as shown in Fig. 2 (a), labeled **b**). Although it can be reasonably understood that peak **c** is stronger than peak b (in Fig. 2 (a), lower diagram), both in experimental results and theoretical prediction, here we still could not estimate or predict the certain relationship between peak a and peak **b** without further quantitative investigation of the relationship between the value of the phase and the magnitude of the stray field.

By measuring the completed magnetic reversal loop of the pattern, we analyzed the values of the phases. As shown in Fig. 3(a), the magnetic reversal behaviors in the three
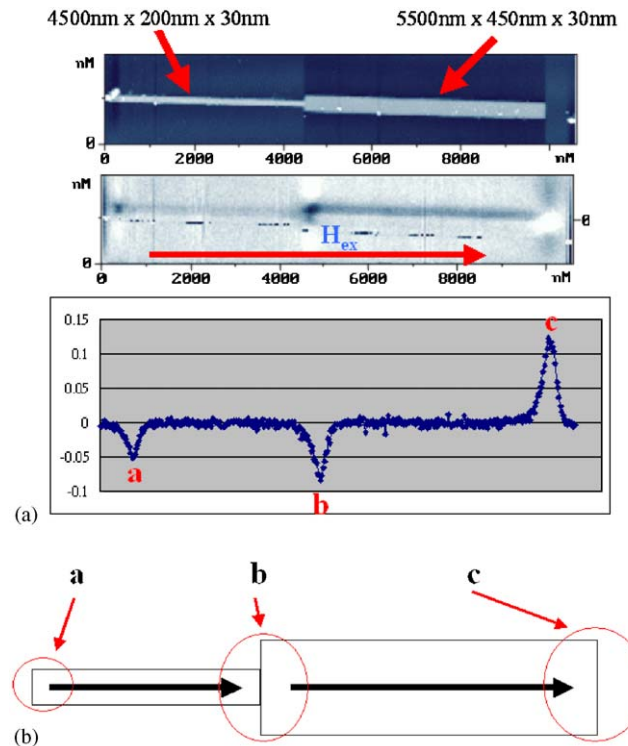

Fig. 2. (a) AFM image (upper), MFM image (middle) and a profile (lower) of line scan in MFM image which was observed at a 140 Oe field which was initially at 400 Oe and varied to –400 Oe. (b) A schematic diagram of the magnetic configuration in accordance with that in (a).

sections can be individually separated. During the process of changing in magnetization from field 200 to 15 Oe, the phase intensity remains roughly unchanged. During this process, the value of the phase in section **c** is positive, that of **b** is negative, and that of **a** is also negative. They retain a relationship of peak **c** > peak **b** > peak **a**. This also means that a certain configuration of magnetization which is in accordance with that in Fig. 2(b) is retained. While in the process of −20 to −200 Oe, the phase values respectively reverse to opposite signs, i.e., **c** negative, **b** positive, and **a** positive (shown in Fig. 3(c), lower diagram), but their absolute values still retain the same relationship mentioned in the previous process. The schematic diagram and MFM image of magnetic configuration during this process are shown in Figs. 3(b) and (c), respectively. This configuration is reasonably the opposite direction of that in the previous process.

The absolute values of the phases were presented with the longitudinal distance in the pattern, as shown in Fig. 4. As we mentioned above, phase-shift can obviously present only in the regions in which magnetic flux strays out of the film plane. Since sections **c**, **b**, and **a** radiate relatively strong magnetic fluxes, the phase intensities (absolute values) appear more evidently at the centers of these regions, and rapidly decrease at areas away from the centers. The result of analysis of phase intensity shows that the magnitude is about 0.05 in section **a**, 0.09 in **b**, and 0.117 in **c**. After normalization (choosing 0.117 as 1), we

Fig. 4. Phase Intensity (absolute value) varying with distance in the pattern near the magnetic saturation (20∼200 Oe and −20∼−200 Oe).
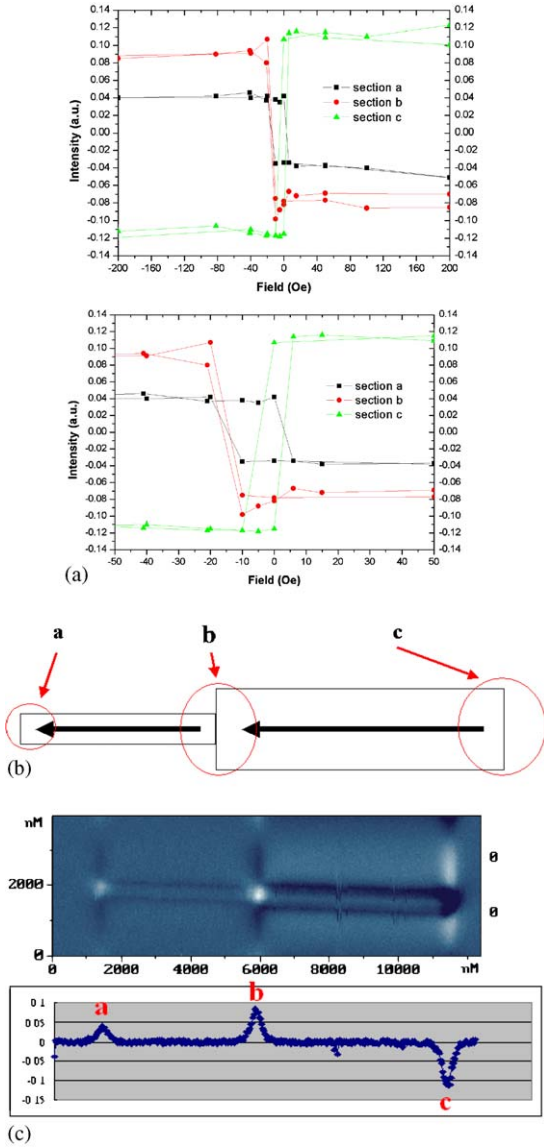

Fig. 3. (a) Magnetic hysteresis loops (upper) for different local sections presented in values of phase; its view amplified (lower). (b) Schematic diagram of the configuration of the magnetization in the magnetic process of –20 to –200 Oe. (c) MFM image (upper) at –200 Oe and profile (lower) of the line scan in the MFM image.

Fig. 5. The switching field (or coercive force) H_c for each individual local section

have 0.427 in **a**, 0.769 in **b**, and 1 in **c**. In addition, the width in section a is about 200 nm, and that in section **c** about 450 nm, hence the volume ratio of about 0.44. That means the ratio of the quantity of magnetic moment contained in sections a to c might be near 0.44, slightly in accordance with the value 0.427 (the ratio of phase intensity in sections **a** to **c**). Although we could not conclude that the phase intensity is proportional to the quantity of magnetic moment in this patterned sample with this magnetic configuration, systematically investigating the relationship between phase intensity and magnitude of magnetic moment by varying the width of the strip wires could be an achievable method.

Furthermore, the switching field (or coercive force) H_c for each individual local section is also analysed with the
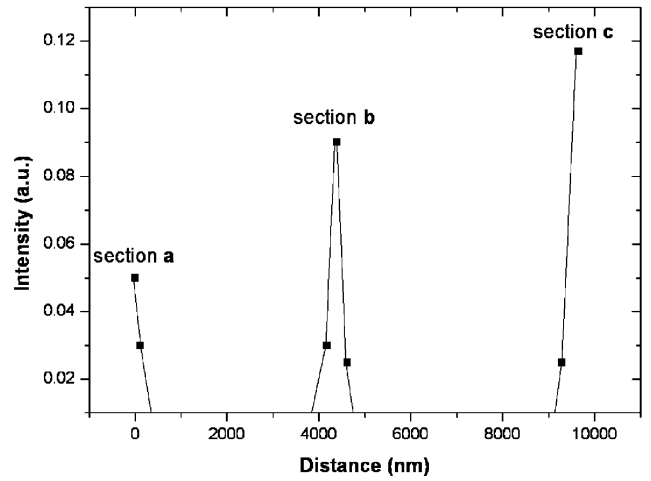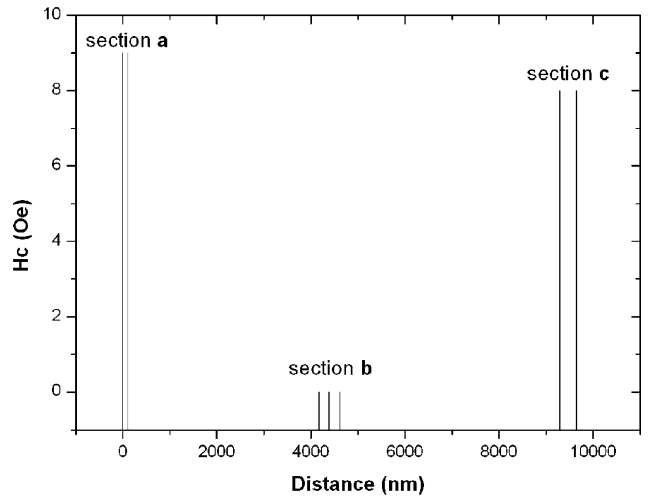
distance in the pattern, as shown in Fig. 5. The diagram shows that H_c in sections **a** and **c** are 9 and 8 Oe, which is much larger than that in section **b**, in which H_c is almost zero. Additionally, at the areas away from the centers of these sections, there is no so-called switching field, since at these areas there is not even an identifiable hysteresis loop observed. Our results are quite consistent with previous reports [8–10]. Due to the shape anisotropy, the value of the H_c should strongly depend on the width of the wire; therefore, we have quantitatively determined the H_c in sections **a**, **b**, and **c**.

4. Conclusion

We have demonstrated that the magnetic behaviors in different local sections of a patterned strip wire can be individually separated and compared with each other. The

intensity of the phase-shift in the wider end is stronger than that in the narrower one. In contrast, the coercive force (which is defined by the reverse in the signs of the values of phase-shifts) in the narrower end (9 Oe) is larger than that in the wider one (8 Oe). This is due to a strong anisotropic effect, and thus the H_c in the neck section (i.e. section **b**) could become strongly affected by the competition of the head-to-tail magnetic configurations in the two parts of the strip wire. This results in a small H_c in the neck section. Furthermore, with a simple neck shape connection in a strip NiFe wire, we can easily to change a single domain configuration to a two single domain magnetic configuration.

Acknowledgments

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