Journal of Magnetics 13(4), 167-169 (2008)

Variation of the Switching Field of Composite Nanowires with Different Widths

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(Received 7 November 2008, Received in final form 28 November 2008, Accepted 28 November 2008)

The switching field of a 300 nm wide nanowire has been controlled by attaching a wide wire to it. The width of the wide wires varies from 700 nm to 2000 nm. While the connection of the two wires does not affect the switching field of the wide wires, it strongly affects the 300 nm-wire, resulting in a decrease of the switching field of the isolated wire from 175 Oe to 54 Oe when the 2000 nm-wire is connected to it. This result clearly shows that the switching field of the nanowire can be engineered by attaching a nucleation pad that has a different magnetic anisotropy.

Keywords : nanowire, domain-wall, switching field, connected nanowire

1. Introduction

Ferromagnetic nanowires have been extensively studied over the last decade because of their potential application. Recently a new concept of devices, such as magnetic storage and magnetic logic devices has been proposed based on magnetic nanowires [1-3]. These concepts also offer new phenomena, such as magnetic single domain state and magnetic domain wall motion along the wire. The magnetic domain wall, which separates two domains that have opposite magnetizations in a nanowire, can be moved by applying an external magnetic field or current pulse [4-9].

Ferromagnetic nanowires have a well defined magnetic anisotropy because of their shape. As the width of the wire decreases, the magnetic anisotropy becomes stronger, which results in a high switching field for magnetization reversal of the nanowire. This is not practical in real device applications, such as those of sensor or device. Recent reports have shown that attaching a nucleation pad to a nanowire can decrease the switching field of the nanowires [10-12], which is explained by the domain wall injection into the nanowire. The domain wall is formed at the junction because of the difference in switching fields between the nanowires. The magnetization of the nanowire is then reversed due to the movement of the domain wall.

In this work, the switching field of the nanowire has been engineered. For this purpose we have fabricated an artificial structure, which is connected by two nanowires that have different widths. The width of the wide wire varies while that of the narrow wire is fixed, which systematically changes the anisotropy constant of the wide wire.

2. Experiment

The connected magnetic nanowires, in which two nanowires of different widths were connected, were fabricated on a Si substrate by using electron beam lithography and the lift-off method. The nanowires are comprised of capping layers of 10 nm thick Cu, 20 nm thick $Ni_{80}Fe_{20}$, and 3 nm thick Cu. These materials were evaporated onto the Si substrate, which was patterned with PMMA. The chamber pressure during evaporation was $\sim 5 \times 10^{-8}$ Torr.

The magnetic hysteresis loops were measured by using longitudinal magneto-optic Kerr effect (MOKE) equipment. For MOKE equipment, the s-polarized HeNe laser (wavelength 633 nm) was incident at 45° to the surface normal. The reflected beam was detected by the photodiode. The incident beam was focused into a spot by using an objective lens (50×) in order to measure the MOKE signal from the nanowires. A magnetic force

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ⓒ 2008 Journal of Magnetics

microscope (MFM) was used to take magnetic domain images at the remanent state.

3. Result & Discussion

Fig. 1(a) shows an AFM image of nanowires that have two different widths. The width of the narrow wires, including the bottom, wire is 300 nm and the widths of the four wide wires are 2000, 1500, 1000, and 700 nm, respectively. The length of the narrow wires is 50 μm and that of the wide wire is 20 μm. The center to center distance between the composited wires is 8 μm, which is large enough to ignore the magnetostatic interaction between the wires. The bottom wire is 300 nm wide and 50 μm long and is used as a standard sample for switching field measurement. Fig. 1(b) shows an MFM image of the above sample, which was taken simultaneously with the AFM image. These images are taken at the remanent state after saturating the sample magnetically along the wire axis. Bright contrasts can be seen at the left end of the wide wires and dark contrasts can be seen at the connected part between the wires. With the exception of these two parts, no magnetic contrast is observed. The bottom wire shows a bright contrast only at the left end. While it is not shown here, a dark contrast is also observed at the right ends of all wires. These dark and bright contrasts are due to the magnetic flux entering and exiting from the wire end and connecting part. Since the wires are saturated along one direction, the polarity of the connected part of the wire is opposite to that of the left end of the wide wires. From these observations, it can be seen that all wires are mostly in the single domain state at remanence even though we cannot exclude the possibility of the edge domain formation. If the wires are in the multi-domain state with a measurable size, then bright and/or dark contrasts must be observed within the wire and the observed contrast within the wire indicates the position of the domain wall.

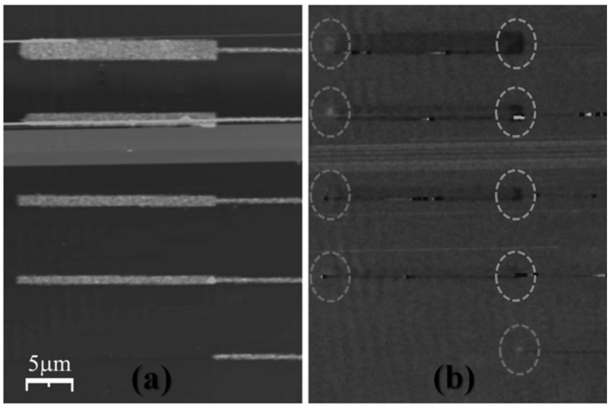

Fig. 1. (a) AFM image of nanowires that have two different widths. (b) MFM image of nanowires that have two different widths. The red circles, including the bottom circle, show the bright spots at the end of the wire, while the blue circles show the dark spots at the junction of the wire.

Fig. 2 shows the magnetic hysteresis loops measured at the wide (a) and narrow (b) parts of the connected wires. The width (w) of the wide wires is marked in the figure. Both parts show abrupt magnetic reversal behavior at each switching field. This may indicate the typical magnetization reversal process, in which the magnetization is reversed due to the domain wall traveling along the wire after the nucleation of the reversed domain at the end of the wide wire. Fig. 2(a) shows that, as is well known, the switching field of the wide wires increases as the width decreases [13, 14]. The switching field of the narrow wires is greatly affected by the connection. The isolated 300-nm wire is shown at the bottom of Fig. 2(b) for reference. Even though the width of the narrow wires is fixed, the switching field of the narrow wires decreases dramatically as the width of the connected wires increases. The switching field of the narrow wires is very close to that of the connected wires.

Fig. 3 shows a summary of the variation of the switching field as a function of the width of the wide wires. The switching field of the narrow wires decreases dramatically once the wide wire is attached. While the magnetization reversal of the isolated 300 nm wire occurs at 175 Oe, it occurs at 54 Oe once the 2000 nm wire is attached. This value is slightly larger (~9 Oe) than the switching field of the connected 2000-nm wire. While the switching field of the narrow wires is slightly larger than that of the connected wire at $w = 1500$ and 2000 nm, no difference in the switching field is observed between the two wires

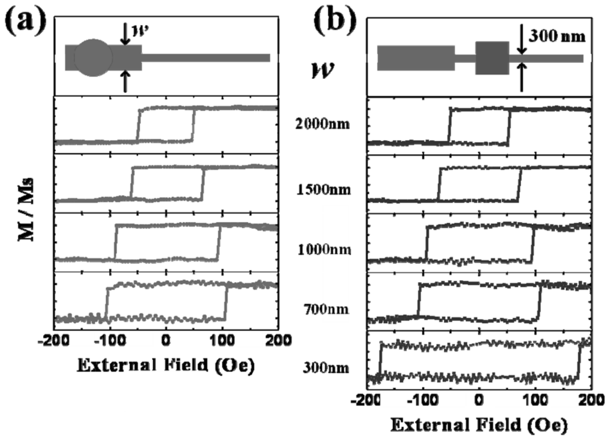

Fig. 2. Magnetic hysteresis loops measured at the wide (a) and narrow (b) parts of the connected wires for various widths (w) of the wide wires.

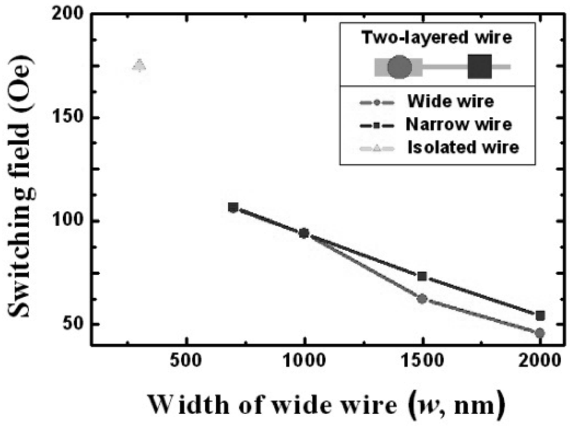

Fig. 3. Variation of the switching field as a function of *w*. The square (circle) is the switching field of the narrow (wide) part of the connected wire. The triangle is the switching field of the isolated 300 nm-wire.

within experimental accuracy if the widths of the connected wires are 500 and 1000 nm. The minimum field step in Fig. 2 is 8 Oe.

It is well known that the switching field of the nanowire can be decreased by attaching a nucleation pad to it. This is because the domain wall can be moved at a very low field once the domain wall is formed [7]. If the reverse field is applied to the magnetically saturated sample that has a nucleation pad, the reverse domain is formed in the nucleation pad at a low field. Furthermore, the domain wall travels through the pad and stops at the junction between the nucleation pad and the narrow wire. A domain wall is thereby formed at the junction [10-12]. In order to inject the domain wall into the narrow wire, an additional field is required. This additional field is known to be proportional to the difference between the magnetic anisotropy constants of the two structures and is expressed as [15]

$$\Delta H_C = \frac{K_2 - K_1}{2\mu_0 M_S}. \tag{1}$$

After the domain wall has been injected into the narrow wire, it travels through the wire at a very low field. Therefore, the difference in the switching field between the two structures is the field required to inject the domain wall into the wire. In this experiment, the wide wires act as nucleation pads and their magnetization is reversed at the low field because their anisotropy constant is smaller than that of the narrow wire. We have calculated the required injection field when the 2000-nm wide wire is connected to the 300-nm wire. For simplicity, in this calculation both of the wires are assumed to be elliptic structures. The material parameters for permalloy are the saturation magnetization $M_s = 800$ emu/cm^3, the magnetic anisotropy constant of the 2000-nm wide wire $K_1 = 2.55 \times 10^3$ erg/cm^3, and the magnetic anisotropy constant of the 300-nm narrow wire $K_2 = 1.67 \times 10^4$ erg/cm^3 [16]. The calculation shows that a 9-Oe additional field is required for domain wall injection into the 300-nm wire.

4. Conclusion

In this study, the results are presented of an engineering switching field of a 300-nm wire by attaching a wide wire to it. The switching field of a 300-nm wire decreases to 1/3 of that of the isolated wires. This method can be applied to other magnetic nanowires that require a low switching field in their application.

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