Current-Induced Domain Wall Motion in TbFeCo micro wire

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Abstract. Current-induced domain wall motion in TbFeCo micro wire with perpendicular anisotropy has been observed by Kerr microscope. The critical current density in ferrimagnetic TbFeCo was found to be as low as $5.4 \times 10^{10}$ A/m$^2$, which is at least 1 order smaller than in other metallic materials reported so far. The results show that the critical current density can be reduced by controlling pinning sites in micro wire.

1. Introduction

Recently current-induced domain wall (DW) motion [1] has attracted attention because of its scientific importance and promising application in data storage [2]. To date, current-induced domain wall motion has mainly studied in Permalloy (NiFe) [3], which has an in-plane magnetization. In Permalloy, a high current density of approximately $10^{12}$ A/m$^2$ is needed to drive the DW. From the practical application point of view, the critical current density has to be decreased furthermore. In both experiment and simulation results, the possibility and superiority by using materials have perpendicular magnetic anisotropy for current induced domain wall motion has been reported [4][5]. In this article, we report on the current-induced domain wall motion in TbFeCo micro wire with perpendicular magnetic anisotropy. TbFeCo has very sharp DWs. The calculated domain wall width $\delta = \pi \sqrt{A/K_u}$ (A is the exchange stiffness and $K_u$ is the anisotropy constant) is less than 10 nm. Due to the large perpendicular anisotropy and low saturation magnetization ($K_u = 3 \times 10^6$ erg/cm$^3$, $M_s = 200$ emu/cm$^3$ for the TbFeCo films used in this experiment), high spin torque efficiency can be expected [5]. Furthermore, magnetic properties such as saturation of magnetization and anisotropy field of TbFeCo film can be manipulated in a wide range by controlling the film composition. Such properties make TbFeCo a prominent material both for application in spintronic devices and for fundamental research of current-induced domain wall motion.

2. Experiments
Tb$_{50}$Fe$_{58}$Co$_{12}$ layer with thickness 40 nm was lithographically patterned into Hall elements with 40 μm in width between a set of Au/Ti electrodes on thermally oxidized Si substrate by magnetron sputtering method. Electrodes were deposited for both pulse current injection and resistance measurement. Si$_3$N$_4$ layer with thickness 3 nm was deposited on TbFeCo film to protect the wire from oxidation. Fabricated sample is shown in Fig. 1(a). Then micro wire with 10 μm in width and 150 μm in length was structured by processing the sample in a focused ion beam (FIB) system as shown in Fig. 1(b). DWs were first nucleated in the pad regions and then propagated from the two ends to the centre through the micro wire when applying a negative saturating magnetic field followed by a positive field. DW propagation from the right end of the micro wire was successfully suppressed by means of etching the right end by ion beam (etching depth is 2 nm) so only one DW could be introduced into micro wire. After introducing a DW in to the wire, pulse currents were injected via electrode using a pulse generator under zero magnetic field. The pulse currents used in this experiment have width of 500 μs and frequency of 1 Hz. The amplitude of the pulse currents was set to increase step by step in sweep mode. The volt value when DW was moves was recorded as critical voltage and the critical current density was calculated from that value. The DW position before and after application of current pulse was imaged directly by MOKE microscope.

After that, to research the current density’s dependence on pinning sites, TbFeCo Hall elements with various thick (30 nm to 60 nm) were fabricated to controlled pinning sites and measured the critical current density by same way. The amount of pinning sites was measured from initial curve of M-H loop. To inspect the experimental result, micro magnetic simulation using OOMMF was performed.

3. Results and Discussion

MOKE microscope results show that DW was moved by the injection of pulse current and it’s direction depends on pulse direction. Fig.2 (a) shows initial DW position. One DW was introduced to the wire by external field. When the pulse current flows left side to right, DW was moved to left side as shown in Fig.2 (b). On the other hand, when the current flowing from right side to left, it can drive DW to right direction from initial position (Fig.2(c)). Moving direction is always same and depends on the flowing

![Fig. 1 Process of sample fabrication](image-url)

![Fig. 2 (a) Initial position of DW. (b) DW position after pulse.](image-url)
direction of current, so this result is not due to thermal effect. The critical current density is $5.4 \times 10^{10}$ (A/m$^2$).

Fig. 3 (a) shows the dependence of critical current density on pinning sites. We use the applied field on the rising point of initial curve of M-H loop as pinning field (Fig. 3 (b)). The critical current density decreases with the decrease of pinning field. Theoretically, It is known that critical current density is given by $J_c \propto \sqrt{V_o / \alpha}$ in material with strong pinning [6] and TbFeCo has strong pinning as

![Graph](image1)

**Fig. 3** The relation of the critical current density and de-pinning field is shown in (a). The numbers (30–60 nm) is the thickness of TbFeCo. Depinning field $H_p$ was shown in (b). The rising point of initial curve of M-H loop equals to pinning potential.

![Graph](image2)

![Graph](image3)

**Fig. 4** (a) The critical current density and number of pinning sites in OOMMF simulation. Numeral numbers is the mask used in simulation shown in (c). White dots were non-magnetic cell used as pinning site. (b) shows initial curve in simulation per the number of the pinning sites. De-pinning field is in promotion with number of the pinning sites.
shown in initial curve of M-H loop in Fig.3 (b). However, from the results, the decrease width of critical current density is not in proportion to a decrease width of pinning field. Those results suggest that depinning field is different qualitatively from pinning sites and current-induced domain wall motion with strong pinning is depends on hard-axis anisotropy or sample thickness [7, 8].

Fig.4 (a) shows the result of same experiment in micro magnetic simulation. In this case, opposite to the experimental result, pinning field and the critical current density were in direct proportion. This is the same result as Tatara’s theory with strong pinning [7]. From those results, it is hopeful that a reduced critical current density can be achieved by fabrication of smooth wire with few impurities.

4. Conclusion

DW was successfully driven by pulse current in TbFeCo micro wire. The current density needed to drive DW was found to $5.4 \times 10^{10}$ A/m$^2$, which is at least 1 order smaller than in Permalloy. The critical current density can be further reduced to $4.7 \times 10^{10}$ A/m$^2$ by controlling thickness of TbFeCo wires. Films with low pinning field show lower critical current density. Micromagnetic simulation results show that the critical current densities are in direct proportion to pinning field. Those results are in agreement with the theory of Tatara. The low critical current density found in TbFeCo films indicated the TbFeCo a potential candidate for domain wall memories.

References

[1] L Berger: J. Appl. Phys., 55, 1954(1984).
[2] S S P Parkin, M. Hayashi, and L. Thoms: Science, 320,190(2008)
[3] A Yamaguchi, T Ono, S Nasu, K Miyake, K Mibu, and T Shinjo: Phys. Rev. Lett., 92 077205(2004)
[4] H Tanigawa, K Kondou, T Koyama, K Nakano, S Kasai, N Ohshima, S Fukami, N Ishiwata, and T Ono: Appl. Phys. Express, 1 011301
[5] S W Jung, W Kim, T D Lee, and H W Lee: Appl. Phys. Lett., 92, 202508(2008)
[6] G. Tatara et al.: J. Phys. Soc. Jpn., 75, 64708 (2006)
[7] Gen Tatara, Hiroshi Kohno: Phys. Rev. Lett., 92, 086601(2004)
[8] A Yamaguchi, U Tanigawa, T Ono, S Nasu, K Miyake, K Mibu and T Shinjo: Journal of the Magnetics Society of Japan, 28, 343-346(2004)