Current-Induced Domain-Wall Motion in [CoFe/Pt]$_5$ Nanowire With Perpendicular Magnetic Anisotropy

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We experimentally demonstrate the current-induced domain wall motion in [CoFe/Pt]$_5$ nanowire with perpendicular magnetic anisotropy. By use of the scanning MOKE measurement, we observe that two domain walls are moved simultaneously by spin polarized current at the current density of 1.43×10^{12} A/m^2. The domain wall speed is estimated to be about 1.5 m/s, determined by the domain wall displacement (750 nm) and the current pulse duration (500 ns). From *in situ* resistance measurement, the temperature of the nanowire rises up to 700 K when the domain wall moves at such the high current density.

***Index Terms*—Current induced, domain wall motion, perpendicular magnetic anisotropy, spin transfer torque, thermal activation.**

I. INTRODUCTION

CURRENT-INDUCED domain-wall motion in ferromagnetic nanowires is intensively investigated due to the prospective applications to next generation memory and logic devices [1], [2]. These novel devices are operated by the successive domain wall movement along the nanowires. It is thus important to understand the dynamic mechanism of the current-driven domain-wall motion. Many theoretical and experimental studies have been carried out mostly with Permalloy nanowires which have in-plane magnetic anisotropy [3]–[8]. Despite successful progresses with Permalloy nanowires, however, there remain several technological barriers such as the high critical current density and the large domain wall width. Very recently, it has been theoretically proposed that the nanowires with perpendicular magnetic anisotropy might exhibit much lower critical current density [9] and smaller domain wall width [10], [11]. However, the experimental verification has been lacking yet, partly because the perpendicular magnetic anisotropy films in general have strong scattered pinning sites which act as energy barriers for the domain wall propagation [12]. From this reason, only several particular structures such as spin valves [13] and magnetic semiconductors [14] have been examined to exhibit a low critical current density, but few experiments have been introduced for metallic nanowires [15]–[17]. In this study, we present the experimental observation of the current-induced domain wall motion in [CoFe/Pt]$_5$ nanowires with perpendicular magnetic anisotropy.

II. EXPERIMENTAL PROCEDURE

For this study, 50-Å Ta/25-Å Pt/[5-Å Co$_{90}$Fe$_{10}$/10-Å Pt]$_5$ multilayered films are deposited on Si substrate with natural SiO$_2$ layer by dc-magnetron sputtering in ultrahigh vacuum environment. The film exhibits a squared hysteresis loop with the coercive field about 700 Oe along the out-of-plane axis. 10-μm-long nanowires with 230-nm width are then patterned by electron-beam lithography and ion milling. The secondary electron microscopy (SEM) image of the patterned structure is shown in Fig. 1. The tapered ends are introduced to avoid the edge domain formation and easy annihilation of domain walls.

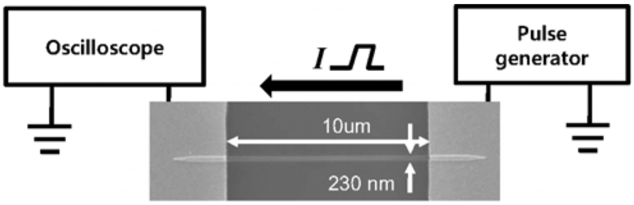

Fig. 1. Secondary electron microscope (SEM) image with schematic diagram of measurement setup.

The current-induced domain-wall motion is monitored by a scanning magneto-optical Kerr effect (MOKE) microscope [18]. The nanowire is first saturated under a sufficiently large magnetic field and then, a reversed domain is formed by thermo-magnetic writing process. The thermo-magnetic writing is carried out by focusing high power laser (7.5 mW, 300 ns) onto a small spot (~500 nm) under a small reversed field ($H < 0.5H_C$). The current pulse is then injected into the nanowire by a pulse generator under zero field bias. The current pulse flows through the nanowire from the right to the left and thus, the electrons flow from the left to the right. The typical current pulse profile with 20-ns duration is depicted in Fig. 2. To minimize the Joule heating, we inject several current pulses of 20-ns duration successively, rather than inject a single pulse of long duration [19].

The typical MOKE hysteresis loop measured on the local spot of the nanowire is plotted in Fig. 3. The coercive field is confirmed to be almost unchanged with respect to the film. The maximum MOKE signal amplitude is about 30 mV. The magnetic domain structure along the nanowire is then obtained by

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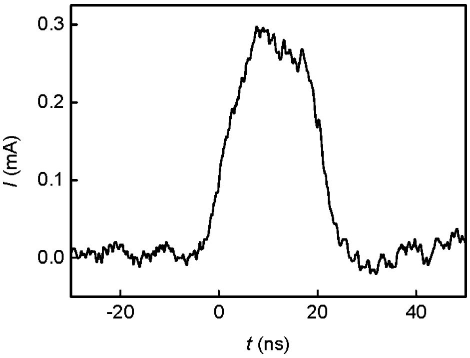

Fig. 2. The current pulse profile.

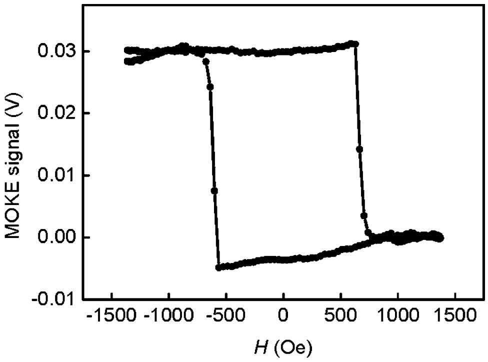

Fig. 3. Typical hysteresis loop of the nanowire.

monitoring the MOKE signal by scanning the detection spot along the nanowire from the left to the right. The background noise from topographical artifact is subtracted by the reference signal, which is obtained from the saturated magnetization state of nanowire.

III. Results and Discussion

Fig. 4(a) shows the initial state of the magnetic domain structure along the nanowire. In the middle of the nanowire, it has a reversed domain—typically 1-μm wide, formed by the thermo-magnetic writing process. The area of the reversed domain is shaded by a dark background in the figure for easy distinction. The signal difference between the reversed and unreversed domains is basically the same with the full MOKE signal amplitude in the hysteresis loop shown in Fig. 3, manifesting that the magnetization is fully reversed inside the region of the reversed domain.

By injecting the current pulses into the nanowire, we successfully move the reversed domain (i.e., the two domain walls) to a side. Fig. 4(b) and (c) show the successive domain patterns after injecting the current pulses. Here, the current pulses with 20-ns duration are injected repeatedly by 25 times, resulting effectively 500 ns pulses between each scan of the domain patterns. The peak current density is 1.43×10^{12} A/m^2. It is clear from the figure that the domain walls are shifted to the right in the direction of the electrons flow. The domain wall speed is estimated to be 1.5 m/s, by measuring the domain wall displacement (~750 nm). We confirm that such the domain wall motion is reproducible from several repeated measurements. We thus conclude that the domain wall motion in [CoFe/Pt]$_5$ nanowire is triggered by injection of the spin polarized current.

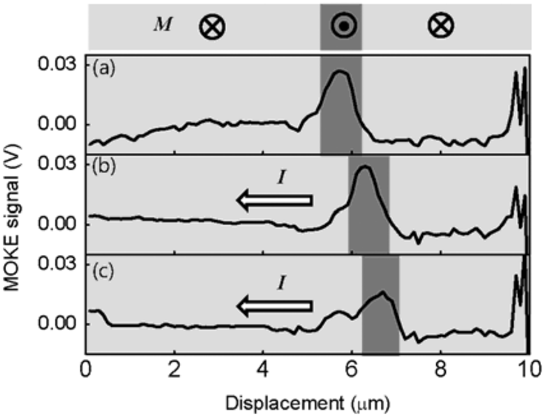

Fig. 4. Domain configuration of the nanowire. (a) After thermo-magnetic domain writing. (b) After the current pulse injection into the nanowire. (c) After second current injection into the nanowire. All figures are obtained after background subtraction.

Looking into the details of the domain wall motion, we find that the two domain walls behave differently—the right domain wall moves consistently with the current injection, whereas the left domain wall seems to be impeded. The impeded domain wall motion might be caused by the domain wall pinning at a pinning site at an edge of the nanowire, where the pinning site is created by the natural edge roughness. Once the domain wall is pinned at the pinning site on an edge of the nanowire, the domain wall is bent rather than depinned when the injected current density is smaller than the depinning threshold. The domain wall is then elongated to a side, which is possibly evidenced by the blunting of the left domain wall with the current pulse injection. We are unable to depin the left domain wall with the current up to ~1.6×10^{12} A/m^2. It demonstrates that the edge roughness plays a crucial role in determining the critical current density for domain wall displacement [12].

Finally, we check the temperature of the nanowire during the current pulse injection. To do this, every current pulse profile is recorded by an oscilloscope during the experiment, followed by measuring the electric resistance of nanowires from the pulse profile [19]. The temperature is then estimated in comparison with temperature-dependent electric resistance, which is preliminarily measured in a cryostat. The temperature-dependent electric resistance is shown in Fig. 5. From this measurement, we estimate the temperature of the nanowire with respect to the current density and the results are summarized in Fig. 6. It is worthwhile to note that the temperature at the current density of 1.43×10^{12} A/m^2 is revealed to be about 700 K. One can thus conclude that, even though the clear directionality of the domain wall motion is certainly ascribed to the spin transfer torque effect, the motion is largely involved with a significant thermal effect.

IV. Conclusion

The current-induced domain wall motion is experimentally investigated in a ferromagnetic [CoFe/Pt]$_5$ nanowire with perpendicular magnetic anisotropy. The two domain walls move

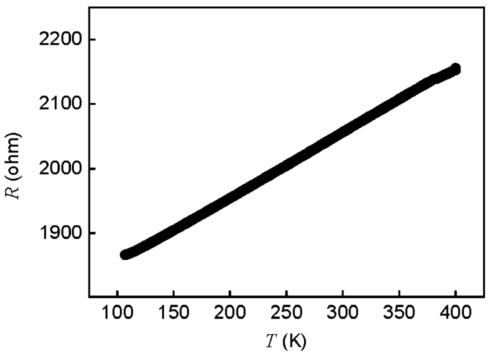

Fig. 5. The temperature dependence of resistance measured in a cryostat.

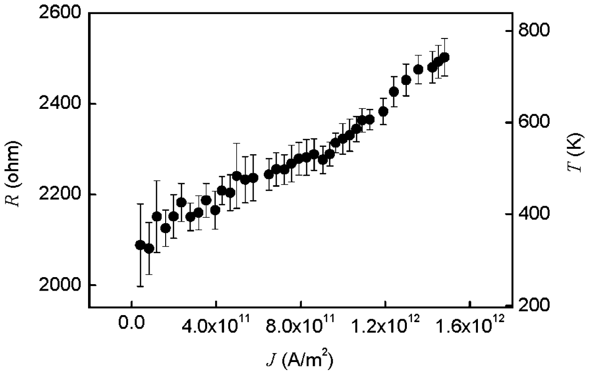

Fig. 6. The resistance and corresponding temperature of nanowire with respect to the current density.

simultaneously and the speed is up to 1.5 m/s. From the *in situ* temperature measurement, we demonstrate that there exists significant thermal effect on the domain wall motion.

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