Experimental Study of Thermally Activated Magnetization Reversal With a Spin-Transfer Torque in a Nanowire

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The current-induced domain-wall depinning in ferromagnetic nanowires with perpendicular magnetic anisotropy is investigated. The nanowire patterns with 500-nm width are fabricated from 8-nm-thick Co-Re-Pt alloy films on 1-nm-thick Ta underlayer. By injecting the current into the nanowire, the domain wall motion via depinning from extrinsic structural pinning sites is observed. The depinning time ranging over 1 μs–1 s is found to be exponentially dependent on the current density. Based on generalized Néel–Brown formula, the slope of the exponential dependence is analyzed to estimate the depinning energy barrier as a function of the current density under a constant bias magnetic field.

***Index Terms*—Nanowire, perpendicular magnetic anisotropy, spin-transfer torque (STT), thermally activated magnetization reversal.**

I. Introduction

RECENTLY, theoretical [1]–[5] and experimental [6]–[11] studies on spin-transfer torque (STT) have been intensively conducted in viewpoints of its application as well as fundamental of physics. The STT phenomena such as current-induced magnetization switching (CIMS) and current-induced domain wall motion (CIDWM) have triggered the prospective spintronic devices such as STT magnetic random access memory and magnetic race-track memory. These phenomena are essentially accompanied with the spin temperature rising caused by spin injection together with the lattice temperature rising caused by Joule heating [6], [8], [11] and thus, clear distinction between the two effects is essential for in-depth understanding of the phenomena.

The effective spin temperature was introduced by Li and Zhang to extend the Néel–Brown (NB) formula for activation energy including the STT effect [12]. Based on their theory, the effective spin temperature T^* is dependent on the injected current density J as given by

$$T^* = T\left(1 - \frac{J}{J_C}\right)^{-1} \quad (1)$$

where J_C is the critical current density and T is the lattice temperature. The thermally assisted switching time τ is then given by $\tau = \tau_0 \exp(E_\mathrm{b}(H)/k_\mathrm{B}T^*)$, where τ_0 is the inverse of the attempt frequency, $E_\mathrm{b}(H)$ is the energy barrier as a function of applied field H, and k_B is the Boltzmann constant. The concept of the effective spin temperature has been well explained in the experimental observation of CIMS in nanopillar structure [12]. This work was motivated to verify the theory for the case of CIDWM in nanowire structure. For this study, we fabricated a Co-Re-Pt alloy nanowire with perpendicular magnetic anisotropy (PMA) and measured current-induced domain-wall depinning time of domain wall in the nanowire. The results are analyzed based on the theory.

II. Experiments

E-beam resist (ER; 950 PMMA A4) patterns of 500-nm-wide nanowires were prepared on a thermally oxidized Si-wafer by e-beam lithography. 8-nm-thick Co-Re-Pt alloy films with PMA were deposited on 1-nm Ta underlayer and covered by 1-nm Ta capping layer using a DC magnetron sputter system. Then, it was followed by removal of ER through lift-off process in acetone. On the top of the nanowire we deposited Ta(5 nm)/Au(100 nm) as electrodes using photolithography method as shown in Fig. 1. Note that the underlayer and the capping layer were minimized to avoid the shunt current through the layers.

Saturation magnetization M_s was measured using a vibrating sample magnetometer (VSM) and perpendicular magnetic anisotropy was estimated from hard-axis hysteresis loop with

Digital Object Identifier 10.1109/TMAG.2008.2002419

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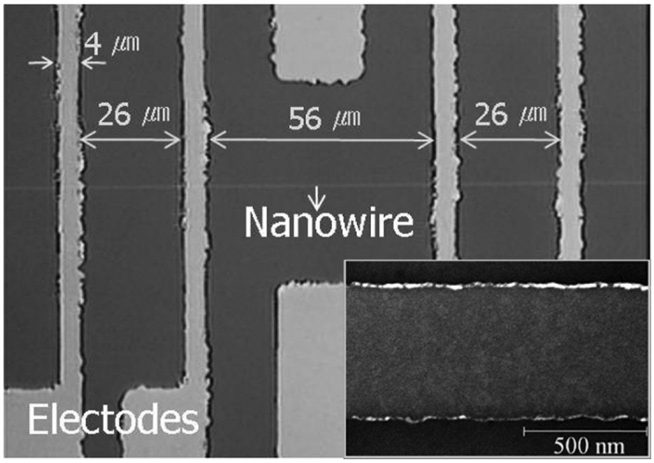

Fig. 1. Optical microscope image of a 500-nm-wide nanowire patterned by E-beam lithography with Ta/Au electrodes [inset: extended SEM image of the nanowire].

the areal method from a continuous film. In addition, the crystal structure of the films was confirmed by x-ray diffraction (XRD) patterns. A magneto-optical Kerr effect (MOKE) system was used for the hysteresis loops measurement in perpendicular direction for unpatterned films and patterned nanowires.

The magnetization reversal process by domain wall motion was monitored by a nanosecond magneto-optical microscopy magnetometer (NS-MOMM). In the experiment, the nanowire was first saturated to one direction and then, reversed domain at a specific area between the electrodes was formed by heat-assisted field writing under a small reversed bias field. The domain wall pinning at a specific pinning site was confirmed for every experiments. After that, by injecting current into the wire we triggered the domain wall depinning from the pinning site and monitored the depinning time with respect to the injected current density. The experiments were done for several constant bias fields.

III. Results and Discussion

Magnetic properties of the continuous film showed saturation magnetization of 450 emu/cm^3 and perpendicular anisotropy of 2.2×10^6 erg/cm^3 [Fig. 2(a)]. Besides this, magnetically easy axis to the perpendicular direction of the films could be confirmed by the in-plane hysteresis loops and (0002) HCP plane of XRD patterns. Uniformity of magnetic properties through out the film was confirmed by MOKE at ten different positions. There were less than 5% differences in coercivity. The easy axis and squareness remained unchanged after patterning as shown in Fig. 2(b), except the coercivity enhancement possibly caused by strong pinning at the rough wire edge. The overall curved envelop is ascribed to the mechanical stability of the probe stage under the applied magnetic field.

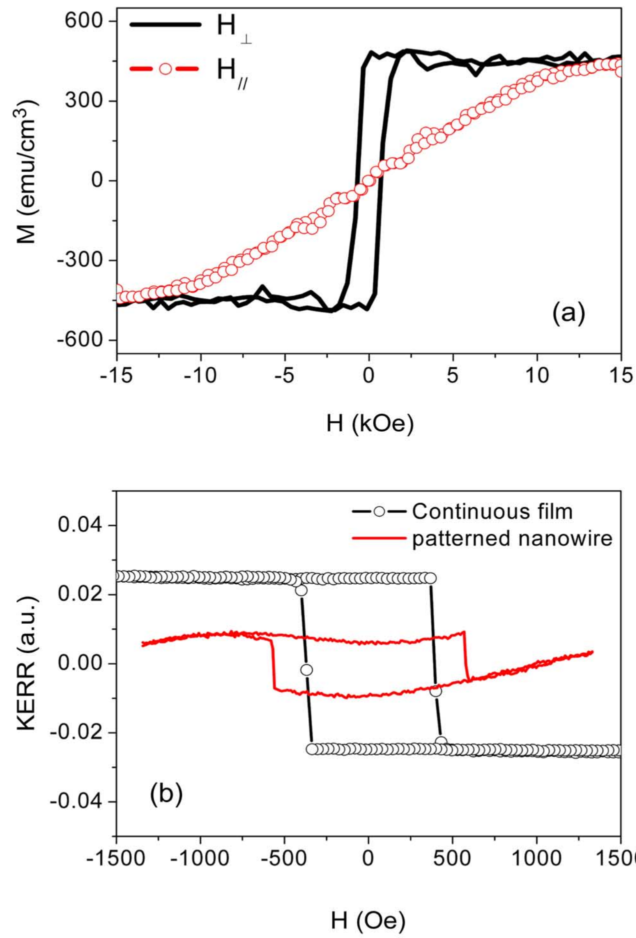

Fig. 2. Hysteresis loops measured by (a) VSM for a continuous film in perpendicular and in-plane direction, and (b) MOKE for a continuous film and a 500-nm-wide nanowire of Co-Re-Pt alloy in perpendicular direction.

Based on the temperature-dependent electric resistance change [11], [14], the temperature rising by the Joule heating was estimated to be less than several tens of degree since the resistance change of the nanowire was less 2.2%.9m

The current-induced domain-wall depinning was triggered by 5-μs $\sim$ 5-s current pulse with the density ranging from 2.0×10^7 to 3.5×10^7 A/cm^2. The bias field was set to be smaller than the coercive field (580 Oe). As shown in Fig. 3, the depinning time clearly showed the exponential dependence with current density. The slope and the intercept to y-axis give the estimated value of J_c as 4.2×10^7 A/cm^2 and the detailed values for each curve are listed in the Table I. The exponential dependence could be well explained by the NB theory. Based on the theory [(1)], the temperature was estimated to be 600$\sim$1800 K, which is extraordinarily higher than the lattice temperature estimated from the electric resistance. We thus conjecture that the temperature corresponds to the effective spin temperature as proposed the generalized NB theory.

The slope was proportional to the energy barrier determined by the strength of the bias field. For quantitative analysis, we adopted the activation energy described

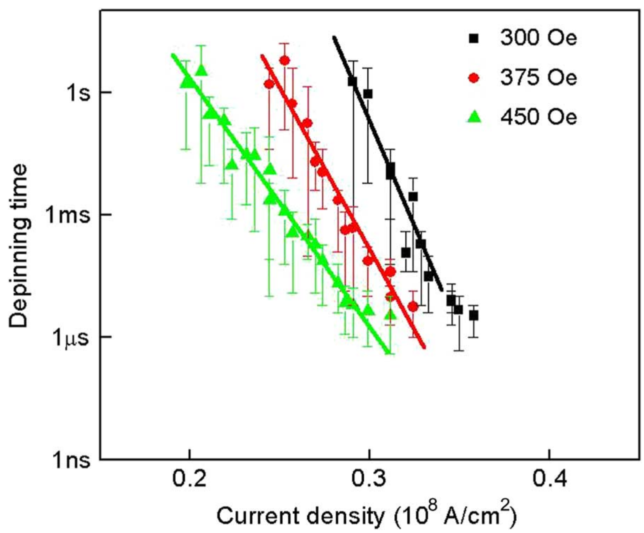

Fig. 3. Measured depinning time (τ) as a function of current density (J) with various applied magnetic field (H).

TABLE I
ESTIMATED VALUES FROM FIG. 3

H [Oe]	Slope [10^{-8} cm^2/A-sec]	E_b(H) [eV]
300	-238	2.52
375	-183	1.94
450	-140	1.49

in [12]

$$E_b(H) = E_0 \left(1 - \frac{H}{H_p}\right)^{\beta} \quad (2)$$

where H_p is the pinning field, E_0 is the energy barrier without magnetic field, and β is a constant. Although β is 1.5$\sim$2 for the magnetization reversal of the single domain [12], [13], it is well fitted to be 1 for the domain wall propagation like our system. The value reflects the analogy with the results in [15] and [16].

Using these parameters, E_0 was estimated to be 4.56 eV and H_p was 664 Oe. H_p is relatively larger than the result of other work [17]. H_p originates from the intrinsic and extrinsic properties of the selected positions of the nanowire, such as rough edge or surface problems in E-beam lithography process [inset of Fig. 1] and dispersive coercivity distribution in the nanowire. In the view of energy barrier variation, for the applied field 300 Oe and current density 3×10^7 A/cm^2, E_0 was estimated to have 45% and 29% reduction, respectively. Namely, it is clear that our experimental results can be well explained by the generalized NB formula, which exhibits the thermal effect of the spin torque by the modification of the energy barrier.

IV. CONCLUSION

We measured the STT effect at the magnetic nanowire with PMA. In this nanowire magnetization reversal for the thermal effect of STT was investigated by varying injected current and applied field. The exponential dependence of the depinning time on the current density at a constant bias field was observed. Based on the Néel–Brown formula, the temperature was estimated to be 600$\sim$1800 K, which possibly corresponds to the effective spin temperature.

ACKNOWLEDGMENT

This work was supported in part by the Tera-level Nano-devices (TND) Frontier Project funded by KISTEP and in part by the Korea Science and Engineering Foundation through the NRL Program (R0A-2007-000-20032-0).

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