Theoretical analysis of thermally-activated spin-transfer-torque switching in a conically-magnetized free layer

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Faster spin-transfer-torque (STT) switching with lower threshold current (I_{sw}) is theoretically expected in a spin-valve nano-pillar having a conically magnetized free layer (c-FL) [1] compared with that having a perpendicularly magnetized free layer (p-FL). In c-FL, the angle (θ) of a magnetization ($\boldsymbol{m}$) is determined by energetic competition between the first-order and second-order magnetic anisotropies ($K_{u1,eff}$ and K_{u2}), and θ is tilted by $\theta_0 = \sin^{-1}(-K_{u1,eff}/2K_{u2})^{1/2}$ from z-direction (see inset of Fig. 1).

In this study [2], we theoretically analyzed the thermally-activated STT switching of c-FL by solving the Fokker-Planck equation to describe the current (I) dependence of the switching barrier (Δ), which is essential for evaluating the thermal stability factor Δ_0 (Δ for I = 0) from switching probability (P_{sw}) measured at ambient temperature. The system we studied is shown in the inset of Fig. 1. In the case of c-FL, we found that Δ is expressed as

$$\Delta = (-1/3)^{1/2}\,\Delta_0\,[A_-^{2/3} - A_+^{2/3} - 2\xi(A_-^{1/3} - A_+^{1/3})],$$

where $A_\pm = \xi \pm (\xi^2 - 1)^{1/2}$, $\xi = I/I_{sw}$, and I_{sw} is the switching current at 0 K. Figure 1 shows I/I_{sw} dependence of Δ/Δ_0 for c-FL and p-FL. We also found that Δ/Δ_0 of c-FL exhibits a more gentle slope than that of p-FL which is given by $\Delta/\Delta_0 = (1 - I/I_{sw})^2$ [3, 4]. By fitting Δ/Δ_0 of c-FL to a function: $(1 - I/I_{sw})^b$, where b is a fitting parameter, we obtained $b = 1.53 \pm 4.90\times10^{-4}$. Therefore, in c-FL, P_{sw} can be expressed by

$$P_{sw} \approx 1 - \exp\{-c_{12}\,t_p \exp[-\Delta_0\,(1 - I/I_{sw})^{1.53}]\},$$

where c_{12} is an attempt frequency, and t_p is a current-pulse width. The results enable us to evaluate Δ_0 of c-FL from P_{sw} measured at ambient temperature.

This work was partially supported by the NEDO Normally Off Computing project.

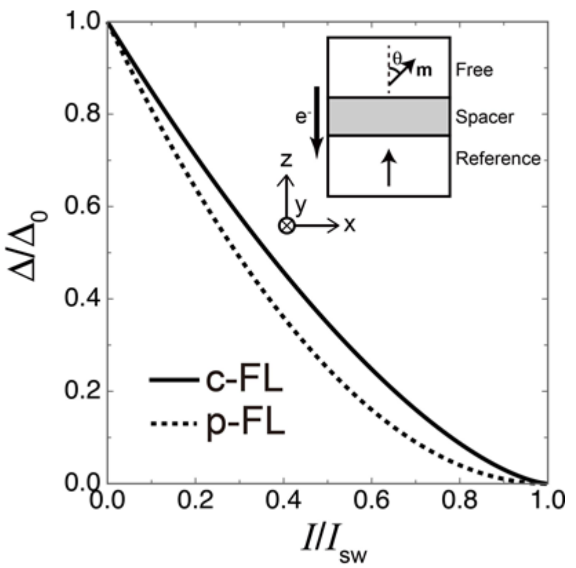

Fig. 1 I/I_{sw} dependence of Δ/Δ_0. Solid (dotted) line represents Δ/Δ_0 of c-FL (p-FL).
Inset: Schematic illustration of the system we studied. The positive I is defined as electrons (e^-) flowing from the free layer to the reference layer.

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[2] R. Matsumoto *et al.*, PRB **92**, 140409(R) (2015).
[3] Y. Suzuki *et al.*, Nanomagnetism and Spintronics 1st ed. (Amsterdam: Elsevier) Chap. 3, (2008).
[4] Here, p-FL satisfies $K_{u1,eff} > 0$ and $K_{u2} = 0$.