Effect of angular dependence of spin-orbit spin transfer torque on magnetization switching and domain wall motion of perpendicular magnetic layer

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Spin-orbit spin transfer torque (SOT) induced perpendicular magnetization switching in ferromagnet/heavy metal bilayers is of great interest due to its efficiency and ability to separate read and write paths in memory devices [1]. Recently, a general expression of SOT was proposed based on space and time inversion symmetry arguments [2], where the damping-like SOT is given as

$$\mathbf{T} = \gamma c_J \left[\mathbf{m} \times (\mathbf{m} \times \mathbf{y}) + \chi_2 m_x \mathbf{m} \times \mathbf{z} + \chi_4 m_x (\mathbf{m} \times \mathbf{z})^3 \right], \quad (1)$$

where c_J is the magnitude of damping-like SOT, **m** is the unit vector along the magnetization, **z** is film normal, **y** is perpendicular to both **z** and current direction, and χ_2 and χ_4 describe additional angular dependences. Experimental measurements of SOT vectors found that χ_2 and χ_4 are in general nonnegligible [2, 3]. We note that the bulk spin Hall effect theory predicts no additional angular dependence [4] whereas Rashba spin-orbit coupling (RSOC) effect shows strong angular dependence when RSOC is comparable to sd exchange coupling at interface [5].

In this work, we investigate effect of additional angular dependence on magnetization switching by SOT. Assuming $\chi_2 << 1$ and $\chi_4 = 0$, we first derive an analytic threshold of c_J for switching as

$$c_J^c = H_k \frac{\Gamma - h^4 + \frac{h^6}{4}\chi_2 + \frac{(-8 - 3\Gamma + h^2(3\Gamma - 28))\chi_2}{8 + h^2} - \frac{1}{4}h^2((\Gamma + 4)\chi_2 - 80)}{4\sqrt{2}\sqrt{20h^2 - h^4 + \Gamma}}, \quad (2)$$

where h = Hx/Hk, Hx is the external field applied along the current direction, Hk is the effective perpendicular anisotropy field, and Γ =8-h(8+h^2)^(3/2). Eq. (2) shows that the switching current decreases with increasing χ_2 when $\chi_2 > 0$. We next perform micromagnetic simulations and find that numerical results are consistent with the analytic solution (Fig. 1). We also find that a positive x_4 reduces the switching current further.

Our results show that the additional angular dependence with a specific sign (i.e., positive χ_2 and χ_4) is beneficial for low power operation of SOT memory devices. As it would be related to the interfacial RSOC [5], interface engineering and its relationship to the angular dependence of SOT are necessary to reach full potential of SOT devices. In the presentation, effect of angular dependence of field-like torque will be also discussed.

References

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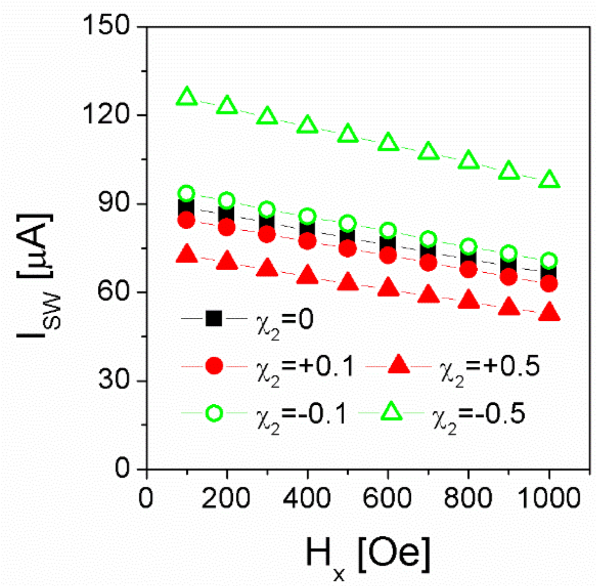

Fig. 1. Switching current with external in-plane field H_x. (parameters : α = 0.1, M_S = 1000 *emu/cm*^{3}, effective Θ_{SH} = 0.3, diameter of ferromagnet = 30 *nm*, thickness of ferromagnet = 1 *nm*, current pulse = 5 *ns*, and current rise time = 0.5 *ns*, $H_{k,eff}$ = 5000 Oe).