EFFICIENCY OF SPIN TRANSFER TORQUE SWITCHING IN A PERPENDICULARLY MAGNETIZED FREE LAYER WITH THE FIRST- AND SECOND-ORDER UNIAXIAL MAGNETIC ANISOTROPIES

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I. INTRODUCTION

Second-order perpendicular magnetic anisotropy (K_{u2}) has been attracting a great deal of attention because faster spin-transfer-torque (STT) switching with higher STT-switching efficiency (κ) is theoretically expected [2] in the case of a conically magnetized free layer (c-FL) [3] compared with the case of a conventional perpendicularly magnetized free layer (p-FL) without K_{u2}. Here, κ is defined as $\kappa \equiv \Delta_0/I_{sw}$ where Δ_0 is the thermal stability factor and I_{sw} is switching current. In c-FL, the angle (θ) of a magnetization ($\boldsymbol{m}$) is tilted from z-direction (see Fig. 1(a)) due to the energetic competition between the first- and second-order magnetic anisotropies ($K_{u1,eff}$ and K_{u2}). κ of c-FL ($\kappa^{(c)}$) can be about 1.3 times larger than that of the conventional p-FL ($\kappa^{(p0)}$). In this study [4], we theoretically expect the further enhancement of κ in p-FL with finite K_{u2}.

II. MODEL

The system we consider is illustrated in Fig. 1(a). The magnetic energy density (g_L) and the effective potential (Φ) of the free layer is given by

$$g_L = K_{u1,eff} \sin^2 \theta + K_{u2} \sin^4 \theta, \quad (1)$$

$$\Phi = g_L + M_s (a_J/\alpha) \cos \theta. \quad (2)$$

Here, $K_{u1,eff}$ and K_{u2} are the first- and second-order magnetic anisotropy constants. In $K_{u1,eff}$, demagnetization energy is subtracted. M_s and α are the saturation magnetization and the Gilbert damping constant of the free layer. (a_J/α) represents the effective field by STT and a_J is defined as $a_J = hIP/(4\pi e M_s V)$. h is the Planck constant, P is the spin polarization, I is the applied current, e (> 0) is the elementary charge, and V is the volume of the free layer.

The equilibrium direction of $\boldsymbol{m}$ is determined by minimizing $g_L(\theta)$. The phase diagram of the equilibrium direction is shown in Fig. 1(b). We assume $K_{u1,eff} \geq 0$ and the perpendicular state is stable or metastable.

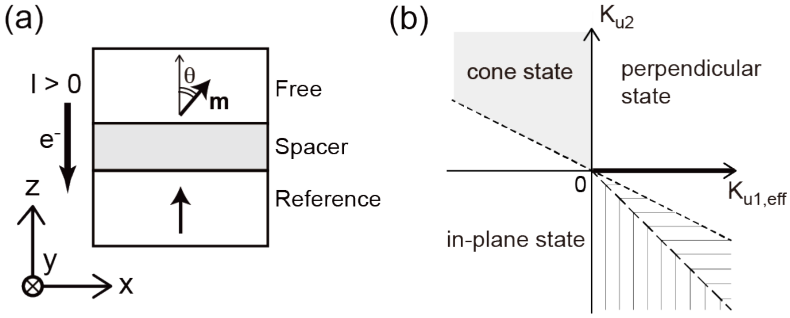

Fig. 1 (a) Schematic illustration of the system we considered. Positive I is defined as electrons (e-) flowing from the free layer to the reference layer. (b) Phase diagram of equilibrium direction of $\boldsymbol{m}$. The conventional perpendicular state with $K_{u2} = 0$ is

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indicated by the thick solid line. Metastable regions are hatched.

III. RESULTS AND DISCUSSIONS

κ of the free layer can be calculated by analyzing Δ_0 from Eq. (1) and I_{sw} from Eq. (2). By normalizing Δ_0 with I_{sw}, the dependence of κ on $K_{u1,eff}$ and K_{u2} is obtained as

$$\kappa/\kappa^{(p0)} = (3\cdot 6^{1/2}/2)\, r_K^{1/2}\,(1+r_K)/(1+2\,r_K)^{3/2} \qquad \text{for } r_K > 1/4, \qquad (3)$$

$$\kappa/\kappa^{(p0)} = 1+r_K \qquad \text{for } -1/2 \le r_K \le 1/4, \qquad (4)$$

$$\kappa/\kappa^{(p0)} = -1/(4r_K) \qquad \text{for } r_K < -1/2. \qquad (5)$$

Here, κ is normalized by $\kappa^{(p0)}$, and r_K represents the ratio of K_{u2} to $K_{u1,eff}$, that is $r_K = K_{u2}/K_{u1,eff}$. In Fig. 2, the normalized switching efficiency ($\kappa/\kappa^{(p0)}$) of the p-FL given in Eqs. (3) - (5) is plotted as a function of r_K. It should be noted that $\kappa/\kappa^{(p0)}$ is larger than unity for a positive r_K and takes a maximum value of $2^{1/2}$ at r_K =1.

IV. CONCLUSIONS

The analytical expression of the STT-switching efficiency is derived for the perpendicularly magnetized free layer with the second-order uniaxial magnetic anisotropy. The switching efficiency is maximized at $K_{u1,eff} = K_{u2}$. $\kappa/\kappa^{(p0)}$ in the p-FL with the positive K_{u2} can be larger than those in the p-FL without K_{u2} and in the c-FL.

IV. ACKNOWLEDGMENTS

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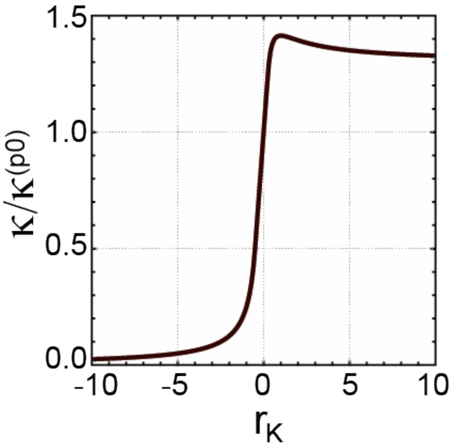

Fig. 2 r_K dependence of the normalized switching efficiency ($\kappa/\kappa^{(p0)}$).