Minimization of the Switching Time of a Synthetic Free Layer in Thermally Assisted Spin Torque Switching

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We theoretically studied the thermally assisted spin torque switching of a synthetic free layer and showed that the switching time is minimized if the condition \( H_s = |H_f|/(2\alpha) \) is satisfied, where \( H_s, H_f, \) and \( \alpha \) are the coupling field of two ferromagnetic layers, the amplitude of the spin torque, and the Gilbert damping constant, respectively. We also showed that the coupling field of the synthetic free layer can be determined from the resonance frequencies of the spin-torque diode effect. © 2011 The Japan Society of Applied Physics

Spin random access memory (Spin RAM) using the tunneling magnetoresistance (TMR) effect and spin torque switching is one of the important spin-electronics devices for future nanotechnology. For Spin RAM application, it is highly desired to realize the magnetic tunnel junction (MTJ) with high thermal stability \( \Delta_0 \), a low spin-torque switching current \( I_c \), and a fast switching time. Recently, large thermal stabilities have been observed in anti-ferromagnetically coupled SyF layers in MgO-based MTJs. In particular, the ferromagnetically coupled SyF layer is a remarkable structure because it shows thermal stability of more than 100 with a low switching current.

Since the coupling between the ferromagnetic layers in the SyF layer is indirect exchange coupling, we can systematically vary the sign and strength of the coupling field by changing the spacer thickness between the two ferromagnetic layers. As shown in ref. 8, the thermal switching probability of the SyF layer is a double exponential function of the coupling field, and a tiny change in the coupling field can significantly increase or decrease the switching time. Therefore, it is of interest to physical science to study the dependence of the thermal switching time on the coupling field.

In this paper, we theoretically studied the spin-current-induced dynamics of magnetizations in an SyF layer of an MTJ. We found the optimum condition of the coupling field, which minimizes the thermally assisted spin torque switching time. We showed that the coupling field of the two ferromagnetic layers in the SyF layer can be determined by using the spin torque diode effect.

Let us first briefly describe the thermal switching of the SyF layer in the weak coupling limit, \( K V \gg J S \), where \( K, J, V \), and \( S \) are the uniaxial anisotropy energy per unit volume, the coupling energy per unit area, and the volume and cross-sectional area of the single ferromagnetic layer, respectively. For simplicity, we assume that all the material parameters of the two ferromagnetic layers (F1 and F2) in the SyF layer are identical. A typical MTJ with an SyF layer is structured as a pinned layer/MgO barrier/ferromagnetic (F1) layer/nonmagnetic spacer/ferromagnetic (F2) layer (see Fig. 1), where the F1 and F2 layers are ferromagnetically coupled due to the interlayer exchange coupling. The F1 and F2 layers have uniaxial anisotropy along the z axis and two energy minima at \( m_i = \pm \epsilon_0 \), where \( m_i \) is the unit vector pointing in the direction of the magnetization of the Fi layer. The spin current injected from the pinned layer to the Fi layer exerts spin torque on the magnetization of the Fi layer. Then, the magnetization of the Fi layer switches its direction due to the spin torque, after which the magnetization of the F2 layer switches its direction due to coupling. By increasing the coupling field, the potential height of the Fi (F2) layer for the switching becomes high (low), which makes the switching time of the Fi (F2) layer long (short). Then, a minimum of the total switching time appears at a certain coupling field, as we shall show below.

The switching probability from the parallel (P) to antiparallel (AP) alignment of the pinned and free layer magnetizations is given by

\[
P = 1 - \frac{\nu_{F1} e^{-\nu_{F1} t} - \nu_{F2} e^{-\nu_{F2} t}}{\nu_{F1} - \nu_{F2}},
\]

where \( \nu_{F1} = f_0 \exp(-\Delta_{F1}) \) is the switching rate of the Fi layer. The attempt frequency is given by \( f_0 = f_0 \delta \), where \( f_0 = [\gamma H_m/(1 + \alpha^2)]^{1/2}/\pi, \delta_1 = [1 - (H + H_J + H_s/\alpha^3)/H_{an}]^{1/2}, \) and \( \delta_2 = [1 - (H - H_J)^2/H_{an}^2][1 + (H - H_J)/H_{an}] \). A, \( \gamma \), \( H \), \( H_m = 2K/M \), \( H_J = J/(Md) \), and \( \Delta_0 = KV/(k_B T) \) are the Gilbert damping constant, gyromagnetic ratio, applied field, uniaxial anisotropy field, coupling field, and thermal stability, respectively, and \( d \) is the ferromagnetic layer thickness. \( \Delta_{F1} \) is given by

\[
\Delta_{F1} = \Delta_0 \left[ 1 + \frac{(H + H_J + H_s/\alpha)}{H_{an}} \right]^2,
\]

\[
\Delta_{F2} = \Delta_0 \left( 1 + \frac{H - H_J}{H_{an}} \right)^2.
\]

\( \Delta_{F1} \) is the potential height of the F1 layer before the F2 layer switches its magnetization while \( \Delta_{F2} \) is the potential height of the F2 layer after the F1 layer switches its magnetization. \( H_s = \eta I/(2eMsd) \) is the amplitude of the spin torque in the unit of the magnetic field, where \( \eta \) is the spin polarization of the current \( I \). The positive current corresponds to the electron flow from the pinned layer to the free layer. H represents the applied field.
$H_{an} < 1$ and $|H - H_J|/H_{an} < 1$ because eq. (1) is valid in the thermal switching region. In particular, $|H + H_J + H/|H_{an}/H_{an} < 1$ means that $|l| < |I_l|$. The effect of the field like torque is neglected in eq. (2) because its magnitude, $\beta H_j$ where the beta term satisfies $\beta < 1$, is less than 1 Oe in the thermal switching region and thus, negligible.

Figure 2 shows the dependencies of the switching times at $P = 0.50$ and $P = 0.95$ on the coupling field with the currents (a) $-8$, (b) $-9$, and (c) $-10 \mu A$. The values of the parameters are taken to be $\alpha = 0.007$, $\gamma = 17.32 \text{MHz/Oe}$, $H_{an} = 200 \text{Oe}$, $M = 995 \text{emu/cm}^3$, $S = \pi \times 80 \times 35 \text{nm}^2$, $d = 2 \text{nm}$, and $T = 300 \text{K}$. The values of $H$ and $\eta$ are taken to be $-65$ Oe and 0.5, respectively. The value of $H$ is chosen so as to make the potential heights for the switching low as much as possible $(|H + H_J + H/|H_{an} < 1$ and $|H - H_J|/H_{an} < 1)$. As shown in Fig. 2, the switching time is minimized at a certain coupling field. We call this $H_J$ as the optimum coupling field for the fast thermally assisted spin torque switching.

Let us estimate the optimum coupling field. For a small $H_J$, the switching time of the F2 layer is the main determinant of the total switching time; thus, eq. (1) can be approximated as $P \simeq 1 - e^{-9.5}$. By increasing $H_J$, $v_{F2}$ increases and the switching time $(1/v_{F2})$ decreases. Fast switching is achieved for $v_{F2} \sim v_{F1}$ in this region. On the other hand, for a large $H_J$, the switching time of the F1 layer dominates, and eq. (1) is approximated as $P \simeq 1 - e^{-9.5}$. The switching time $(1/v_{F2})$ decreases with decreasing $H_J$. Fast switching in this region is also achieved for $v_{F1} \sim v_{F2}$. The switching rate $v_{F1}$ is mainly determined by $\Delta F_1$. By putting $\Delta F_1 = \Delta F_2$, the optimum coupling field is obtained as

$$H_J = \frac{|H_I|}{2\alpha}.$$ (4)

This is the main result of this paper. The values obtained with eq. (4) for $I = -8, -9, and -10 \mu A$ are 53.7, 60.5, and 67.2 Oe, respectively, which show good agreement with Fig. 2.

The condition $v_{F1} \simeq v_{F2}$ means that the most efficient switching can be realized when both switching processes of the F1 and F2 layers occur with the same rate. $v_{F1} > v_{F2}$ means that the magnetization of the F2 layer can easily switch due to a large spin torque. However, the system should stay in this state for a long time because of a small switching rate of the F2 layer. On the other hand, when $v_{F1} < v_{F2}$, it takes a long time to switch the magnetization of the F1 layer. Thus, when $v_{F1}$ and $v_{F2}$ are different, the system stays in an unswitched state of the F1 or F2 layer for a long time, and the total switching time becomes long. For thermally assisted field switching, we cannot find the optimum condition of the switching time because the switching probabilities of the F1 and F2 layers are the same. Factor 2 in eq. (4) arises from the fact that $H_J$ affects the switchings of both the F1 and F2 layers, while $H_0$ assists that of only the F1 layer. When $H_J \ll |H_I|/(2\alpha)$, the total switching time is independent of the current strength, because the total switching time in this region is mainly determined by the switching time of the F2 layer, which is independent of the current. In the strong coupling limit, $K/V \ll JS$, two magnetizations switch simultaneously, and the switching time is independent of the coupling field.

For the AP-to-P switching, the factors $\delta_1$ and $\Delta F_2$ are given by $\delta_1 = [1 - (H - H_J + H/\alpha)]^2/H_{an}^2$$[1 - (H - H_J + H/\alpha)/H_{an}]$, and $\Delta F_2 = \Delta F_1 = \Delta F_1 = [1 - (H + H_J)/H_{an}]^2$. In this case, a positive current ($H_J > 0$) induces the switching. By setting $\Delta F_2 = \Delta F_1$, the optimum coupling field is obtained as $H_J = (H_I)/(2\alpha)$. Thus, for both P-to-AP and AP-to-P switchings, the optimum coupling field is expressed as $H_J = |H_I|/(2\alpha)$.

In the case of the anti-ferromagnetically coupled SyF layer, $H_J$ and $H_H$ and $H - H_J$ in eqs. (2) and (3) should be replaced by $H + |H_I|$ and $-H - |H_I|$, respectively, where the sign of the coupling field is negative ($H_J < 0$). The optimum condition is given by $|H_J| = -H + |H_I|/(2\alpha)$, where the negative current is assumed to enhance the switching of the F1 layer. For a sufficiently large positive field $H > |H_I|/(2\alpha)$, this condition cannot be satisfied because $v_{F1}$ is always smaller than $v_{F2}$.

One might notice that the condition $\Delta F_1 = \Delta F_2$, for the ferromagnetically coupled SyF layer has another solution $|H_I|/(2\alpha) = H + H_{an}$, which is independent of the coupling field. We exclude this solution because such $H$ and $H_J$ cannot satisfy the conditions for the thermal switching regions $H + H_J + H/\alpha < H_{an}$ and $|H - H_J| < H_{an}$ simultaneously. Similarly, for the anti-ferromagnetically coupled SyF layer, we exclude the solution $|H_I|/(2\alpha) = H_{an}$ obtained from $\Delta F_1 = \Delta F_2$.

The natural question from the above discussion is how large the coupling field is. The coupling field of a large plane film can be determined from two ferromagnetic resonance (FMR) frequencies11,12 corresponding to the acoustic and optical modes, which depend on $H_J$. The antiferromagnetic coupling field can also be determined by the magnetization curve,61 in which finite magnetization appears when the applied field exceeds the saturation field $H_s = -2H_J$. These methods are, however, not applicable to nanostructured ferromagnets such as the Spin RAM cells because the signal intensity is proportional to the volume of the ferromagnet, and thus, the intensity from the Spin RAM cell is negligibly small. It is desirable to measure the coupling field of each cell because $H_J$ strongly depends on the surface state and may differ significantly among the cells obtained from a single film plane.

Here, we propose that the coupling field can be determined by using the spin torque diode effect13-15 of

Fig. 2. Dependencies of the switching time at $P = 0.50$ (solid lines) and $0.95$ (dotted lines) on the coupling field $H_J$ with currents $I = -8$ (yellow), $-9$ (blue), and $-10$ (red) $\mu A$. 
the SyF layer. This method is applicable to a nanostructured ferromagnet, although the basic idea is similar to that of FMR measurement.

The spin torque diode effect is measured by applying an alternating current $I_{ac} \cos(2\pi f t)$ to an MTJ, which induces oscillating spin torque on the magnetization of the F1 layer. The free layer magnetizations oscillate due to the oscillating spin torque and the coupling, which lead to the oscillation of the TMR (dotted) and anti-ferromagnetically (dashed) coupled SyF layers on the applied current frequency calculated by solving the LLG equations of the F and AF coupled SyF layers on the coupling field. We found that the switching time is minimized if the condition of $H_{J} = |H_{J}| / (2\alpha)$ is satisfied. We showed that the coupling field can be determined from the resonance frequecy of the spin torque diode effect.

In summary, we theoretically studied the dependence of the thermally assisted spin torque switching time of a SyF layer on the coupling field. We found that the switching time is minimized if the condition of $H_{J} = |H_{J}| / (2\alpha)$ is satisfied. We showed that the coupling field can be determined from the resonance frequency of the spin torque diode effect.

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