Dependence of critical current of spin transfer torque-driven magnetization dynamics on free layer thickness

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(Dated: February 3, 2009)

The dependence of the critical current of spin transfer torque-driven magnetization dynamics on the free-layer thickness was studied by taking into account both the finite penetration depth of the transverse spin current and spin pumping. We showed that the critical current remains finite in the zero-thickness limit of the free layer for both parallel and anti-parallel alignments. We also showed that the remaining value of the critical current of parallel to anti-parallel switching is larger than that of anti-parallel to parallel switching.

PACS numbers: Valid PACS appear here

Spin transfer torque (STT)-driven magnetization dynamics is a promising technique to operate spin-electronics devices such as a non-volatile magnetic random access memory (MRAM) and a microwave generator \cite{1,2}. STT is the torque due to the transfer of the transverse (perpendicular to magnetization) spin angular momentum from the conducting electrons to the magnetization of the ferromagnetic metal. One of the most important quantities of STT-driven magnetization dynamics is the critical current over which the dynamics of the magnetization is induced. The typical value of the critical current density is on the order of $10^{9} \text{A/cm}^2$ \cite{3,4,5}. Control of the value of the critical current is required to reduce the energy consumption of spin-electronics devices.

In Slonczewski’s theory of STT \cite{11,12,13,14}, the critical current of P-to-AP (AP-to-P) switching is expressed as \cite{6,7}

$$I_{c}^{\text{P} \rightarrow \text{AP}}(\text{AP} \rightarrow \text{P}) = \frac{2eMSd}{\hbar\gamma\eta_{\text{P}(\text{AP})}}\alpha_{0}\omega_{\text{P}(\text{AP})},$$

(1)

where $e$ is the absolute value of the electron charge, $\hbar$ is the Dirac constant, and $M$, $\gamma$, $S$, $d$ and $\omega_{0}$ are the magnetization, gyromagnetic ratio, cross section area, thickness and the intrinsic Gilbert damping constant of the free layer, respectively \cite{8,9,10}. $\omega_{\text{P}(\text{AP})}$ is the angular frequency of the magnetization around the equilibrium point. The coefficient $\eta_{\text{P},\text{AP}}$ characterizes the strength of STT, and depends only on the relative angle of the magnetizations of the fixed and free layer \cite{11,12,13}. According to Eq. (1), the critical current vanishes in the zero-thickness limit of the free layer, $d \rightarrow 0$.

However, recently, Chen et al. \cite{8} reported that the critical current of STT-driven magnetization dynamics of a CPP-GMR spin valve remains finite even in the zero-thickness limit of the free layer. What are missed in the above naive considerations based on Slonczewski’s theory are the effects of the finite penetration depth of the transverse spin current, $\lambda_{t}$, \cite{8,9,10} and of spin pumping \cite{11,12,13,14}. We investigated the current of STT-driven magnetization switching from AP to P alignment by taking into account both the finite penetration depth of the transverse spin current and the spin pumping, and showed that the critical current remains finite in the zero-thickness limit of the free layer \cite{14}. We also showed that the remaining value of the critical current is mainly determined by spin pumping. Although our results \cite{14} agree well with the experimental results of Chen et al. \cite{8}, we investigated only the critical current of AP-to-P switching, $I_{c}^{\text{AP} \rightarrow \text{P}}$. For the manipulation of spin-electronics devices, the thickness dependence of the critical current of P-to-AP switching, $I_{c}^{\text{P} \rightarrow \text{AP}}$, should also be investigated.

In this paper, we study the critical current of STT-driven magnetization switching both from P to AP alignment and from AP to P alignment by taking into account both the finite penetration depth of the transverse spin current and the spin pumping. We show that both critical currents, $I_{c}^{\text{P} \rightarrow \text{AP}}$ and $I_{c}^{\text{AP} \rightarrow \text{P}}$, remain finite in the zero-thickness of the free layer. We also show that $I_{c}^{\text{P} \rightarrow \text{AP}}$ is larger than $I_{c}^{\text{AP} \rightarrow \text{P}}$ over the whole range of the free layer thickness, and thus, the remaining value of $I_{c}^{\text{P} \rightarrow \text{AP}}$ is larger than that of $I_{c}^{\text{AP} \rightarrow \text{P}}$. The difference between the remaining values of the critical currents, $I_{c}^{\text{P} \rightarrow \text{AP}}$ and $I_{c}^{\text{AP} \rightarrow \text{P}}$, can be explained by considering how the strength of STT, $\eta_{\text{i}}$, depends on the magnetic alignment.

A schematic view of the system we consider is shown

FIG. 1: The schematic view of the nonmagnetic (N) / ferromagnetic (F) multilayer. $I$ and $I_{\text{pump}}$ are the electric current and pumped spin current, respectively. $I_{\text{c}}^{\text{N}(F) / \text{N}}$ is the spin current induced by the spin accumulations in each layer. $\mathbf{m}_{i}(k = 1, 2)$ is the unit vector pointing the direction of the magnetization of the $F_{k}$ layer.
Two ferromagnetic layers (F₁ and F₂) are sandwiched by the nonmagnetic layers Nᵢ (i = 1 – 7). The F₁ and F₂ layers correspond to the free and fixed layers, respectively. \( m_k \) (k = 1, 2) is the unit vector pointing in the direction of the magnetization of the Fᵢ layer. \( I \) is the electric current flowing perpendicular to the film plane.

The electric current and pumped spin current at the Fₖ/Nᵢ interface (into Nᵢ) is obtained by using the circuit theory [10, 16].

\[
I_{p/N_i}^{F_k} = \frac{eg}{2\hbar} \{2(\mu_{F_k} - \mu_{N_i}) + pm_{k}(\mu_{F_k} - \mu_{N_i})\},
\]

\[
I_{p}^{\text{pump}} = \frac{h}{4\pi} \left( g_{s}^{\uparrow\downarrow} m_{1} \times \frac{dm_{1}}{dt} + g_{t}^{\uparrow\downarrow} \frac{dm_{1}}{dt} \right),
\]

where \( h = 2\pi\hbar \) is the Planck constant, \( g = g^{\uparrow\downarrow} + g^{\downarrow\uparrow} \) is the sum of the spin-up and spin-down conductances, \( p = (g^{\uparrow\downarrow} - g^{\downarrow\uparrow})/(g^{\uparrow\downarrow} + g^{\downarrow\uparrow}) \) is the spin polarization of the conductances, and \( g_{s}^{\uparrow\downarrow} \) is the real (imaginary) part of the mixing conductance. \( \mu_{N_i,F_k} \) and \( \mu_{N_j,F_k} \) are the charge and spin accumulation, respectively. The spin current at each Fₖ/Nᵢ and Nᵢ/Nⱼ interface (into Nᵢ) is given by

\[
I_{s}^{F_k/N_i} = \frac{1}{4\pi} \left[ g \left( \frac{p(\mu_{F_k} - \mu_{N_i})}{2} m_{k}(\mu_{F_k} - \mu_{N_i}) \right) m_{k}
- g^{\uparrow\downarrow}_{t}(m_{N,i} \times m_{k}) - g^{\downarrow\uparrow}_{t}(m_{N,i} \times m_{k})
+ t^{\uparrow\downarrow}_{t}(m_{F_k} \times m_{k}) + t^{\downarrow\uparrow}_{t}(m_{F_k} \times m_{k}) \right],
\]

\[
I_{s}^{N_i/N_j} = -\frac{g_{N_i,N_j}}{4\pi} (m_{N,i} - m_{N,j}),
\]

where \( t^{\uparrow\downarrow}_{t} \) is the real (imaginary) part of the transmission mixing conductance at the Fₖ/Nᵢ interface and \( g_{N_i,N_j} \) is the conductance of the one spin channel at the Nᵢ/Nⱼ interface.

The spin accumulations in the N and F layer obey the diffusion equation [8, 10, 17]. The spin accumulation in the N layer, \( \mu_{N} \), decays exponentially with the spin diffusion length \( \lambda_{sd(N)} \). The longitudinal and transverse spin accumulations in the F layer are defined as \( (m_{F} \mu_{F} m) \) and \( m \times (\mu_{F} \times m) \), respectively. The longitudinal and transverse spin accumulations decay exponentially with the spin diffusion length \( \lambda_{sd(F_L)} \) and with the penetration depth of the transverse spin current \( \lambda_{t} \), respectively.

The total spin currents across the Nᵢ/F₁ and F₁/Nⱼ interfaces, i.e., \( I_{s}^{(1)} = I_{s}^{\text{pump}} + I_{s}^{F_1/N_i} \) and \( I_{s}^{(2)} = I_{s}^{\text{pump}} + I_{s}^{F_1/N_j} \), exert the torque \( \tau = m_{1} \times \{ (I_{s}^{(1)} + I_{s}^{(2)}) \times m_{1} \} \) on the magnetization \( m_{1} \). In order to obtain the spin current \( I_{s}^{(1,2)} \), we solve the diffusion equation of spin accumulation in each layer. The boundary conditions are as follows. We assume that the thicknesses of the N₁ and N₇ layer are much larger than their spin diffusion length, and that the spin current is zero at the outer boundary of the N₁ and N₇ layer. We also assume that the spin current is continuous at all interfaces and that the electric current is constant through the entire structure.

The critical current densities of P-to-AP switching (\( I_{c}^{\text{P→AP}} \)) and AP-to-P switching (\( I_{c}^{\text{AP→P}} \)) in STT-driven magnetization dynamics are shown against the free layer thickness.

The torque \( \tau \) modifies the Landau-Lifshitz-Gilbert (LLG) equation of magnetization \( \textbf{m}_1 \) as

\[
\frac{dm_1}{dt} = -\gamma \textbf{m}_1 \times \textbf{B}_{\text{eff}} + \frac{\gamma}{2M_S} \tau + \alpha_0 m_1 \times \frac{dm_1}{dt} = -\gamma \text{eff} m_1 \times \textbf{B}_{\text{eff}} + \frac{\gamma \alpha}{\gamma} (\alpha_0 + \alpha') m_1 \times \frac{dm_1}{dt},
\]

where \( \textbf{B}_{\text{eff}} \) is the effective magnetic field, and \( \alpha' = \alpha + \alpha_{\text{pump}} \) is the enhancement of the Gilbert damping constant. The enhancement \( \alpha_0 \) is proportional to the electric current and independent of the pumped spin current. The enhancement \( \alpha_{\text{pump}} \) represents the contribution from the pumped spin current and is independent of the electric current. The enhancement of the gyromagnetic ratio, \( \gamma_{\text{eff}}/\gamma \), is a function of both the electric current and the pumped spin current.

The current critical of the STT-driven magnetization dynamics is defined by the electric current that satisfies the condition, \( \alpha_0 + \alpha_c + \alpha_{\text{pump}} = 0 \), and given by

\[
I_{c}^{\text{P→AP}(\text{AP→P})} = \frac{2eM_S d}{h\gamma_{\text{eff}}\gamma_{\text{P}}}(\alpha_0 + \alpha_{\text{pump}})\gamma_{\text{P}}(\text{AP}),
\]

where the coefficient \( \gamma_{\text{P,AP}} \) characterizes the strength of STT due to the electric current, and is determined by the diffusion equations of the spin accumulations. Thus, \( \gamma_{\text{P,AP}} \) is the function of \( d/\lambda_{sd(F_L)} \), \( d/\lambda_{t} \) and the relative angle of the magnetizations of the F₁ and F₂ layers.

We performed numerical calculation to obtain the critical currents \( I_{c}^{\text{P→AP}} \) and \( I_{c}^{\text{AP→P}} \). The system consists of nine layers as shown in Fig. 7, where F₁ and F₂ are Co, N₁, N₃, N₄, N₅, N₆, and N₇ are Cu, and N₂ and N₆ are Pt. The thicknesses of the N₃, N₄ and N₅ layers are 10 nm, the thicknesses of the N₂ and N₆ layers are 3 nm and the thickness of the F₂ layer is 12 nm [8]. The thickness of the N₁ and N₇ layers are taken to be 10 μm. The spin diffusion length of Cu and Pt are 1000 and 14 nm, respectively [18]. The conductance at the Cu/Pt interface is 35 nm²/A [18]. The magnetization, the intrinsic Gilbert damping constant and the gyromagnetic ratio of Co are
and thus, the remaining value of $I_c^{\text{AP} \rightarrow \text{P}}$. As shown in Ref. [15], the remaining value of the critical current is mainly determined by spin pumping. It should be noted that the magnitude of the enhancement of the Gilbert damping constant due to spin pumping, $\alpha_{\text{pump}}$, is the same for both P-to-AP switching and AP-to-P switching [13, 14]. Thus, the fact that the remaining values $I_c^{\text{P} \rightarrow \text{AP}}$ and $I_c^{\text{AP} \rightarrow \text{P}}$ are different from each other implies that the strength of STT, $\tilde{\eta}_{\text{P,AP}}$, depends on the alignment of the magnetizations. As shown in Fig. 3, $\tilde{\eta}_{\text{P,AP}}$ decreases with a decreasing free layer thickness. On the other hand, the number of localized magnetic moments in the free layer, and therefore the STT per magnetic moment, is inversely proportional to the free layer thickness $d$. According to Eq. (7), the remaining value of the critical current is proportional to $(\tilde{\eta}_{\text{P,AP}}/d)^{-1}$ with $d \rightarrow 0$, where $\tilde{\eta}_P/d \simeq 0.44$ nm$^{-1}$ and $\tilde{\eta}_{\text{AP}}/d \simeq 1.47$ nm$^{-1}$ in the limit of $d \rightarrow 0$ are estimated by Fig. 3. Thus, the remaining value of $I_c^{\text{AP} \rightarrow \text{P}}$ is larger than that of $I_c^{\text{P} \rightarrow \text{AP}}$.

In summary, we studied the critical current of STT-driven magnetization dynamics by taking into account the finite penetration depth of the transverse spin current and spin pumping for both P and AP magnetic alignments. We showed that the critical current remains finite in the zero thickness limit of the free layer for both P-to-AP and AP-to-P switching. We also showed that the critical current for P-to-AP switching is larger than that for AP-to-P switching over the whole range of the free layer thickness.

The authors would like to acknowledge the valuable discussions they had with K. Matsushita, J. Sato and N. Yokoshi. This work was supported by JSPS and NEDO.

FIG. 3: The coefficient $\tilde{\eta}$ in the P state ($\tilde{\eta}_P$) and AP state ($\tilde{\eta}_{\text{AP}}$), against the free layer thickness.

0.14 T, 0.008 and 1.89 x $10^{11}$ Hz/T, respectively. The polarization $p$ is taken to be 0.46 for Co [18]. The spin diffusion length of Co is 40 nm [18]. The conductances at the Co/Cu interface, $g/S$, $g_{\text{S}}^{\text{P} \rightarrow \text{AP}}/S$ and $g_{\text{S}}^{\text{AP} \rightarrow \text{P}}/S$, are 50, 27 and 0.4 nm$^{-2}$, respectively [12, 13]. We assume that $t_r = t_0$ where $t_r,i/S$ at the Co/Cu interface is taken to be 6.0 nm$^{-2}$. The angular frequency is $\omega_{\text{P,AP}} = \gamma[B_{\text{appi}} - (+)4\pi M]$ where the strength of the applied magnetic field $B_{\text{appi}}$ is 7 T [5].

Figure 2 shows the dependence of the critical current density of Eq. (7) for P-to-AP switching, $I_c^{\text{P} \rightarrow \text{AP}}/S$, and AP-to-P switching, $I_c^{\text{AP} \rightarrow \text{P}}/S$, on the free layer thickness, $d$. As shown in Fig. 2 both $I_c^{\text{P} \rightarrow \text{AP}}$ and $I_c^{\text{AP} \rightarrow \text{P}}$ remain finite in the zero-thickness limit of the free layer. We show that the critical current $I_c^{\text{P} \rightarrow \text{AP}}$ is larger than $I_c^{\text{AP} \rightarrow \text{P}}$ over the whole range of the free layer thickness, and thus, the remaining value of $I_c^{\text{P} \rightarrow \text{AP}}$ is larger than

\[ I_c^{\text{P} \rightarrow \text{AP}} \]

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