Influence of the magnetostatic coupling in magnetization switching driven by spin-polarized current

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Abstract

The influence of the magnetostatic coupling (MC) on magnetization reversal processes driven by spin-polarized current has been studied by means of a micromagnetic model. The spin transfer torque is included as an additional term in the Gilbert equation, following previous theoretical calculations by Slonczewski. The MC plays a crucial role and it speeds the magnetization switching process.

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1. Introduction

The concept that a spin-polarized current (SPC) can transfer spin angular momentum to the local magnetization applying a torque was predicted by Slonczewski and Berger [1–4]. These spin-transfer effects have been observed experimentally, they give rise to domain reversal or spin waves excitation [5–8]. The SPC is generating interest as an alternative to the use of the magnetic field for switching elements in Magnetic Random Access Memory (MRAM). Urazhdin et al. [9,10] have shown as it is possible to partially control the magnetostatic coupling (MC) between the layers following different preparation procedures. The coupling between the MC and the Slonczewski torque produces a more symmetric switching processes, yielding absolute values of critical current closer to each other as shown by the experimental data [6–8]. In fact, with the inclusion of the MC, the critical currents to switch from parallel state (PS) to anti-parallel one (APS) are smaller, while the critical current to switch from APS to PS are slightly larger for short time current pulses and very close for long pulses [11]. Direct experimental estimation of the average of the MC can be done by means of the experimental loop of the resistance versus applied field [8]. In this paper, we present a micromagnetic study of the MC on the magnetization reversal dynamics of the free layer, pointing out the obtained results about one spin valve where the non-ferromagnetic layer thickness is between 2.5 and 10 nm. The MC was computed by a 3D micromagnetic simulation of the whole structures.

2. Model and numerical details

The nanostructures under investigation are nanopillars of Permalloy (PL) (10 nm)/Cu (x)/Permalloy (FL) (2.5 nm) with rectangular section of 60 nm × 20 nm × 2.5 nm, as shown in Fig. 1 (x = 2.5, 5, 7.5 and 10 nm).

The fixed layer is exchange-biased with the bottom layer using an 8 nm thick antiferromagnetic Ir 20 Mn 80 so we may consider the magnetization of the fixed layer along positive x-direction [12,13]. In order to take into account the effect of the SPC, an additional term as deduced by Slonczewski [1] should be added to the torque in the Gilbert equation, obtaining the following equivalent LLG equation with two new terms [14]:

\[
\frac{dM}{dt} = -\gamma'M \times H_{eff} - \frac{\sigma}{M} M \times (M \times H_{eff})
\]

\[
- \frac{2\mu_B J}{(1 + a^2)^2} g(M, P \times M) \times (M \times P)
\]

\[
+ \frac{2\mu_B a J}{(1 + a^2)^2} g(M, P) \times (M \times P)
\]

(1)

where \(M\) is the magnetization of the FL, \(H_{eff}\) the effective field, \(\gamma'=\gamma/(1 + a^2)\), \(\gamma\) the electron gyromagnetic ratio and \(a\) is the dimensionless damping parameter. Regarding the SPC term (two last right terms), \(\mu_B\) is the Bohr’s magneton, \(J\) the current density, \(d\) the thickness of the free layer, \(e\) the electron charge (positive

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Fig. 1. Sketch of the Py/Cu/Py nanopillar. The flowing of electrons for positive bias is also shown.

Scalar) and $P$ is the magnetization of the fixed layer. The scalar function $g(M, P)$ was deduced by Slonczewski [1]:

$$g(M, P) = \left[-4 + (1 + \eta)^3 \left(3 + \frac{M P}{|M|^2 s}\right)\right]^{-1}$$

with $\eta$ is the polarizing factor, which for Permalloy is $\eta = 0.3$ [1]. In our computations the effective field includes the following contributions:

$$H_{\text{eff}} = H_{\text{exch}} + H_{\text{ext}} + H_{\text{M}} + H_{\text{Amp}} + H_{\text{AF}}$$

being $H_{\text{exch}}, H_{\text{ext}}$ and $H_{\text{M}}$ the standard micromagnetic contributions from exchange, external and demagnetizing fields. $H_{\text{Amp}}$ and $H_{\text{AF}}$ are the ampere and the MC contributions, respectively.

The simulations are carried out by means of a 3D dynamic micromagnetic code developed by our group [14]. The Permalloy material parameters are $M_s = 8.6 \times 10^5 \text{ A/m}$, $A = 1.3 \times 10^{-11} \text{ J/m}^3$ and $\alpha = 0.02$. The simulations were performed for a nanopillar discretized with cubic cells of 2.5 nm$^3$.

3. Results and discussion

The simulations demonstrate the presence of the MC field influences the behavior of the dynamics in the nanostructure when an uniform electric current is applied along the $z$-axis. Furthermore, the same dynamics depend on the distance between the two ferromagnetic layers. Fig. 2 shows the configuration of the MC field between fixed (10 nm) and free layers (2.5 nm) for different copper spacers, 2.5, 5, 7.5 and 10 nm, respectively. For single-domain simulations the MC can be taken into account as an additive component to the effective field along $x$-direction only. As can be observed the $H_{\text{AF}}$ is uniform in the central region and there are inhomogeneties in the lateral regions of the rectangle. Obviously, the magnetostatic effect is minor when the distance between the ferromagnetic layers is large.

Fig. 3 shows the average of the absolute value of the MC versus the non-metallic spacer to the free layer due to a fixed layer of 10 nm (a), 20 nm (b) and 40 nm (c) of thickness, respectively. The $y$ and $z$ component of MC have mean value zero, but they play a crucial role for a magnetic dynamic as can be seen by micromagnetic model. This is due principally to the non-uniform distribution in the structure an idea about how it is can be done using the Fig. 3, and the ratio between the $x$ component and the $y$ and $z$ components, respectively.

The MC along the $y$-axis has a smaller value (dashed line) and MC along the $z$-axis has an intermediate value (dotted line). Naturally, in all cases, the values of the MC decrease with the distance from the PL.

The MC field changes the behavior of the magnetization dynamics. A previous work [11] describes how the MC changes the switching behavior of the Py(10 nm)/Cu(5 nm)/Py(2.5 nm) with no applied field. We have carried out the same simulation in different structures for three cases; no applied field and applied...
Fig. 4. Temporal evolution of $M_x$ for a rectangle nanostructure of Permalloy/Cu/Permalloy during the switching processes from PS to APS and backwards, with $H_{AF}$ (solid line) and without $H_{AF}$ (dashed line).

Field (along positive $x$-direction) of the same order and bigger of the average value of the MC. The results agree qualitatively with the ones presented in [11] also with applied field. Namely, the MC is able to speed the switching PS $\rightarrow$ APS (see Fig. 4 solid line), on the other hand, the MC delays the switching APS $\rightarrow$ PS for short pulse of current, but not changes the critical current for the long ones. However, applying a current pulse of amplitude that gives switching for both cases with and without the MC, in the former the switching process is faster either PS $\rightarrow$ APS and APS $\rightarrow$ PS (see Fig. 4). The interpretation of this effect can be found in the inhomogeneities of the MC in the lateral region of the rectangle, which are the cause of the accelerated reversal of the switching, as shown in Fig. 2.

In order to explain this kind of behavior the excited spatial modes configuration has been studied. This is achieved by means of a micromagnetic spectral mapping technique similar to that used in [13–15]. The procedure consists on performing the Fourier transform of the magnetization temporal evolution for each computational cell and then plotting the 2D spatial distribution of the spectral power at the specific frequency of the mode to be analyzed [15–17]. In particular, for the simulation of Fig. 4 the main mode ($12\,\text{GHz}$) excited in the first 0.25 ns of the structures is mapped in Fig. 5, (a) with the MC and (b) without the MC.

It can be seen how the MC helps the formation of an uniform distribution of the main excited mode in the boundary of the structure. Similar configurations of the excited modes can be seen for APS $\rightarrow$ PS switching process. Fig. 6 shows the dynamic of the magnetization $M_x$ considering an applied field $H_{ext} = 100\,\text{mT}$ and the critical current necessary for the switching in both cases PS $\rightarrow$ APS and vice versa. The critical current is $J_0 = -1 \times 10^8\,\text{A/cm}^2$; it can be observed that in the simulation without the $H_{AF}$ (dashed line), the transition PS $\rightarrow$ APS does not occur, whereas in the simulation taking into account the MC (solid line) the switching process is achieved. For the reverse transition (APS $\rightarrow$ PS), the required applied current to realize the switching of the magnetization is an order of magnitude lower, due to the asymmetric nature of the process. In fact, the critical current for the magnetization switching in the transition APS $\rightarrow$ PS (see Fig. 6b) is $J_0 = 0.1 \times 10^8\,\text{A/cm}^2$.

On the other hand, the switching occurs for the simulation without to take into account the MC contribution (dashed line) but it does not take place when we consider the magnetostatic coupling field. Therefore, for the transition APS $\rightarrow$ PS, the MC plays a different role if we apply a current minor or major with respect to the critical one for the switching process. In fact, the presence of the MC triggers the switching for applied current greater than the critical switching current; on the other hand, in order to obtain the switching of the magnetization, the MC enhances the value of this critical current.

From a more general point of view, when applying a dc current to simulate a complete dynamical stability diagram as the one reported in [8], it was observed that the magnetization dynamics achieved for several currents is very different including or not the MC in the simulation [18]. In particular, we point out the different behavior for the following value ($H_x = 100\,\text{mT}$, $J = -1 \times 10^8\,\text{A/cm}^2$). The presence of the MC gives rise to the PS $\rightarrow$ APS switching process differently without the MC we obtain a telegraph noise in the resistance. Fig. 7 shows the temporal evolution of the average of normalized resistance computed for each cell of the structure. The equation used is Ref. [8]:

$$NR = \frac{R(\theta) - R_{min}}{\Delta R_{max}}$$

(4)

Fig. 5. Spatial distribution of the main modes excited for the simulation of Fig. 4. (a) With the MC and (b) without the MC.

Fig. 6. Temporal evolution of $M_x$ for a rectangle nanostructure of Permalloy/Cu/Permalloy during the switching processes from PS to APS (a) and backwards (b) for $H_{AF} = 100\,\text{mT}$ and a critical switching applied current, with $H_{AF}$ (solid line) and without $H_{AF}$ (dashed line).
All the simulations have been performed with applied field and current; the answer of the magnetization is very similar to that without applied field as in Ref. [14].

In conclusion, we can affirm that the MC has to be taken into account in order to carry out micromagnetic computations correctly. Furthermore, the distance between the two ferromagnetic layers (FL and PL) has to be considered. Lastly, our results demonstrate that a ferromagnetic coupled system is faster with respect to the ferromagnetic uncoupled one; this is useful in order to design MRAM devices with smaller writing time.

References