Spin-Transfer Torque Switching in Magnetic Multilayers

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In this paper, we point out how the magnetization switching depends on the nanostructure geometry and on the material parameters. The micromagnetic study is carried out on multilayer nanodevices constituted by Permalloy(Py)/Cu/Py and Co/Cu/Co with different cross-sections. Results show that the switching time is strongly dependent on the magnetization of the material.

Index Terms—Critical current, micromagnetic modeling, MRAM, spin-transfer torque, switching times.

I. INTRODUCTION

R
cent developments in the physics of spin electronics have enabled the emergence of a new class of non-volatile memories, magnetic random access memories (MRAM). The "spin-transfer torque" consists on passing a current in a magnetic multilayer composed by two alternating magnetic layers (a thin free layer FL and a thick pinned layer PL) and a non-magnetic. The magnetization switching occurs when the applied electrical current carries a spin flow that, depending on its intensity and polarity, can induce a reversal of the FL magnetization direction. This effect, usually called spin polarized current (SPC) driven-switching, has been predicted theoretically \cite{1}–\cite{4} and observed experimentally \cite{5}–\cite{10}.

In this paper, we study the magnetization switching in spin valves by means of a 3-D dynamic micromagnetic simulation code developed by our group \cite{11}. The structures under investigation are nanodevices composed by a Co-Py(10 nm)/Cu(5 nm)/Co-Py(2.5 nm) trilayer of two different cross-sections, S\textsubscript{1} (ellipse 130 nm × 70 nm), and S\textsubscript{2} (ellipse 130 nm × 40 nm) as shown in Fig. 1.

The aim of this paper is to point out how the switching time is related to the geometry of the nanodevice and to the material saturation magnetization. Similar investigations have been carried out experimentally using other kind of structures, showing a dependence of the critical current on the saturation magnetization and the sample geometry to be consistent with the spin transfer torque model \cite{12}–\cite{14}.

Following these experimental works, we emphasize, by means of a micromagnetic study, how the choice of materials, sizes and shape of the sample is fundamental in the design of MRAM cell. In fact, one of the most important requirements in this research field is the decreasing of the critical current values needed to perform a complete switching process.

II. MICROMAGNETIC MODEL DETAILS

Our code is based on the numerical integration of the equivalent Landau–Lifshitz–Gilbert (LLG) by means of a second-order predictor-corrector solver \cite{15}. The system under study is dissipative, therefore, it tends to minimum energy states naturally and the dynamics corresponds to reversible processes. In the equation are present two terms: the first one is called precessional term, in fact it corresponds to a motion of precession of \( \mathbf{M} \) around \( \mathbf{H}_{\text{eff}} \); the second one is the dissipation that is introduced in the theory by means of a phenomenological term. The complex structure of the LLG equation does not allow to perform a simple analytical study of the dynamical processes. In general, it is possible to solve this non-linear equation numerically only, this implies to change the continue problem where the magnetization is a vector field \( \mathbf{M} \) to a discrete problem in both space and time. A time domain finite differences technique is used and the magnetization is assumed to be uniform in each cell. Furthermore, in order to take into account the torque effect due to the SPC, an additional term, as deduced by Slonczewski \cite{1}, is added to the original formulation of the Gilbert equation \cite{16}. 

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{Fig_1.png}
\caption{Sketch of the nanopillar structure under investigation.}
\end{figure}
In this way, the modified LLG presents two new terms related to the SPC and it can be written as follows:

$$\frac{dM}{dt} = -\gamma M \times H_{\text{eff}} - \frac{\alpha \gamma}{M_s} M \times (M \times H_{\text{eff}})$$

$$- \frac{2\mu_B J}{(1 + \alpha^2)M_s^2} g(M,P)M \times (M \times P)$$

$$+ \frac{2\mu_B G_0 J}{(1 + \alpha^2)M_s^2} g(M,P)M \times P$$

(1)

where $M$ is the magnetization of the FL, $H_{\text{eff}}$ is the effective field, $M_s$ is the saturation magnetization, $\gamma = \gamma/(1 + \alpha^2)$, $\gamma$ is the electron gyromagnetic ratio, and $\alpha$ is the dimensionless damping parameter. Regarding the SPC term (two last terms), $\mu_B$ is the Bohr’s magneton, $J$ the current density, $d$ the thickness of the FL, $e$ the electron charge (positive scalar), and $P$ the magnetization of the PL.

The scalar function $g(M,P)$ is the term introduced by Slonczewski [1] and it summarizes the efficiency in the conversion of electric current into torque

$$g(M,P) = \left[-4 + (1 + \eta)^3(3 + MP/M_s^2)/4\eta^3/2\right]^{-1}$$

(2)

with $\eta$ the polarizing factor, which for Permalloy and Cobalt are $\eta = 0.30$ and $\eta = 0.35$, respectively. The effective field is calculated as the sum of a number of contributions which includes

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

(3)

being $H_{\text{exch}}$, $H_{\text{ext}}$, and $H_M$ the standard micromagnetic contributions from exchange, external, and demagnetizing fields. $H_{\text{ Amp}}$ and $H_{\text{ AF}}$ are the Ampere field and the magnetostatic coupling between FL and PL. $H_{\text{ Ani}}$ is the anisotropy field. No crystalline anisotropy has been considered for Py-based nanostructures, as corresponds for this material; the considered anisotropy is just the shape one. On the other side, for Co nanodevices an uniaxial anisotropy of $1.37 \times 10^5$ J/m$^3$ has been included.

The simulations were performed using discretized cubic cells of 2.5 nm in side. We checked that the results were independent of the discretization; in fact increasing the number of the discretization cells, the magnetization configuration does not show quantitative changes. This aspect reflects the agreement with the standard criterion in micromagnetism which consists on using cell sizes smaller than the exchange length (5.7 nm for Py and 7 nm for Co).

The constant time step of 50 fs is small enough to achieve numerical stability and sufficient accuracy. Smaller time steps were tested producing exactly the same solutions.

In order to consider the temperature effects, a thermal field must be included in the effective field computation and it becomes necessary to solve the stochastic Langevin-LLG equation and to average over a large number of realizations. To evaluate the effects induced by the temperature, we have carried out some tests at $T = 300$ K and at $T = 0$ K obtaining qualitatively the same results. It means that this contribution is probably small compared to the other ones involved in our simulation. For this reason, although our code is able to perform these computations [17], all the results of this work have been obtained without taking into account the effect of the temperature ($T = 0$ K).

The next section will present main results of our investigation into the switching dynamics and the switching times as a function of the saturation magnetization value and of the nanopillar geometry.

### III. RESULTS AND DISCUSSION

The possibility to act on the $M_S$ parameter only, without affecting all of the other magnetic values substantially, has been experimentally validated by Rippard et al. [13], [14]. From this experimental point of view, the $M_S$ value of the FL (for both Py and Co) can be varied by diluting or adding to the ferromagnetic layers some amount of Cu and other specific paramagnetic materials.

Since several valid definitions about switching times have been presented in literature, in our simulations we consider that the switching from Parallel to Antiparallel State (PS → AP), between the magnetization of the FL and PL, occurs when the normalized magnetization $M_F/M_S$ changes its value from 1 to 0.9.

Fig. 2 shows the temporal evolution of the x-component of the magnetization, for the S2 structure and Py material, when three different values of $M_S$ are considered.

As it is evident in figure, the switching time is strongly dependent of the $M_S$ value. In fact, considering the standard $M_S$ value of the Permalloy (solid line), the switching time is 0.4 ns. Increasing the $M_S$ value of a magnitude order (dashed line), in the same initial conditions, the SPC is not able to carry out the switching in the considered range ($0 \div 0.5$ ns). Viceversa, decreasing the $M_S$ value (dotted line), the switching occurs in 0.04 ns, a switching time one magnitude order smaller than for the standard case.

Moreover, we considered the temporal evolution of the x-component of the magnetization, for both S1 and S2 structures and for both different materials (Py and Co).

We studied the dynamics of $M_F$ when an external static magnetic field $H_{\text{app}} = 100$ mT and a current perpendicular to the plane $J_{\text{app}} = -1.2 \times 10^8$ A/cm$^2$ are simultaneously applied. In Fig. 3(a) we show the results of the investigation for Permalloy material and for the structures S1 and S2, while Fig. 3(b) is related to the Cobalt case. It can be observed that the larger
device is slightly faster (the greater aspect ratio reflects a greater shape anisotropy contribution which helps the alignment of the magnetization to the easy-axis direction); this advantage is more evident when we consider the Cobalt. Therefore, the advantage on the use of Cobalt is evident for the design of fast magnetic memories. In fact, although the \( M_S \) value is higher in the Cobalt, the magneto-crystalline anisotropy contribution triggers the magnetization switching in a shorter time with respect to the Permalloy.

Systematic simulations were carried out in order to measure the minimum amplitude (\( J_{app} \)) of the write pulse required to the switching as a function of the switching time in some different configurations.

Fig. 4 shows the phase diagram that is a summary of all our simulations, where a switching event is a 180° reversal of the magnetization of the FL. In particular, in Fig. 4 we report the minimum applied currents (for us this is the critical current) in order to obtain the switching within 0.5 ns for both of the materials (Py and Co) and the structures under investigation (S1 and S2). Furthermore, three different \( M_S \) values are used for each analyzed structure. In particular, the parameters used are the saturation magnetization values of the Permalloy and Cobalt (\( M_S = 800 \cdot 10^5 \) A/m and \( M_S = 140 \cdot 10^4 \) A/m, respectively) and for each material two values corresponding at an order of magnitude greater and smaller with respect to the standard value.

Analyzing the structures, our expectation was that for the larger device the amplitude of the critical current should be an order of magnitude greater than the smaller one. In fact, whereas for the S2 structure (for both materials and \( M_S \) values) the critical current is in the range between \( J_{app} = -1 \cdot 10^6 \) A/cm² and \( J_{app} = -2.2 \cdot 10^9 \) A/cm², for the S1 structure the critical current is in the range between \( J_{app} = -3.1 \cdot 10^6 \) A/cm² and \( J_{app} = -2 \cdot 10^{10} \) A/cm².

In all cases, the switching process of both S1 and S2 structures is strongly dependent on the \( M_S \) parameter value. In order to be able to understand and justify this behavior, one possible (and efficient) way is to analyze the spatial distribution of the magnetization as a function of the time.
Without loss of generality, we refer to the dynamics observed for Cobalt in the S1 structure for two values of $M_S(M_S = 1.4 \cdot 10^5$ A/m and $M_S = 1.4 \cdot 10^4$ A/m). By considering the value of $M_S = 1.4 \cdot 10^5$ A/m, when the current is applied (in this case the critical current value was $J_{app} = -4 \cdot 10^8$ A/cm$^2$) an reversal of the spin at the boundary of the structure starts and there is the formation of four domains in the sides and a main central domain that keeps the magnetization in the parallel state [see Fig. 5(A)]. The four little domains at the sides of the structure expand quickly while the central domain size decreases with time until the central domain is completely destroyed.

On the other hand, in the case of $M_S = 1.4 \cdot 10^4$ A/m (critical current $J_{app} = -2 \cdot 10^9$ A/cm$^2$), it can be noted [see Fig. 5(C)] that two domains only are formed at the boundaries. These domains expand in time and the expulsion of the inner domains occurs from the center to the boundary of the structure [see Fig. 5(D)].

In summary, the magnetization switching dynamics is a very complex process which occurs through domain nucleation due to a combined effect of both Ampere field, anisotropy field (shape and magneto-crystalline) and torque of SPC. At high applied current values both of the Ampere field and the torque due to the spin-polarized effect are large too, and in particular the Ampere field plays a crucial role at the boundaries of the structure [16].

An alternative way to study the switching dynamics could be the analytical approach like the one presented in [18]. In this case, the analytical solution obtained by means of the use of the perturbation (Melnikov) theory, gives us the possibility to delineate our stability diagram and to determine an estimation of the switching-time value for each geometry under investigation, but this is beyond the scope of this paper.

IV. CONCLUSION

The magnetic properties of a material play a significant role in triggering the spin-polarized-current driven switching processes. The possibility to act on the saturation magnetization value allows us to propose a strategy to decrease the switching time and to design MRAM devices with faster writing rates. The main result of the micromagnetic simulations presented here shows how diminishing the saturation magnetization produces a significant lowering in the switching time. It is also demonstrated by our computations that this is due to the different mechanism in the domains expulsion process.

REFERENCES


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