Magnetization dynamics in CoFe/AlO/Permalloy and CoFe/MgO/Permalloy magnetic tunnel junctions

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This paper presents a theoretical study about the effect of nonidealities in the shape of elliptical cross sectional area of magnetic tunnel junctions on the magnetization dynamics driven by spin-polarized currents (no applied field). The set of nonideal shapes has been computed from scanning electron microscopy images directly. The polarization function deduced by Slonczewski in 2005 ([Phys. Rev. B 71, 024411 (2005)]) has been used for the simulations, considering the polarization factor independent of the bias. Depending on the shape, results of micromagnetic simulations show that the main steps of the magnetization dynamics do not change qualitatively, but in contrast, (a) other modes (defect modes) are excited, (b) a shift in the excited main mode is observed, and (c) the spatial distribution of the main mode changes. © 2007 American Institute of Physics. [DOI: 10.1063/1.2713711]

The tunneling magnetoresistance (TMR) effect in a magnetic tunnel junction (MTJ) is currently of great interest for its potential for device applications such as magnetic random access memories (MRAMs), magnetic sensors, or radio frequency detector.1–4 The advantage of the next generations of MTJ-based MRAMs is the magnetization switching driven by spin-polarized currents (no applied field). The set of nonideal shapes has been computed from scanning electron microscopy images directly. The polarization function deduced by Slonczewski in 2005 ([Phys. Rev. B 71, 024411 (2005)]) has been used for the simulations, considering the polarization factor independent of the bias. Depending on the shape, results of micromagnetic simulations show that the main steps of the magnetization dynamics do not change qualitatively, but in contrast, (a) other modes (defect modes) are excited, (b) a shift in the excited main mode is observed, and (c) the spatial distribution of the main mode changes. © 2007 American Institute of Physics. [DOI: 10.1063/1.2713711]

In this paper, we present micromagnetic simulations of magnetization dynamics driven by SPC, at zero applied field, in MTJs consisting of CoFe(8 nm)/Al2O3(0.8 nm)/Py(4 nm) (Py denotes Permalloy) and CoFe(8 nm)/MgO(0.8 nm)/Py(4 nm) with an elliptical cross section (90 × 35 nm2). CoFe is the pinned layer (PL) and Py is the free layer (FL). We introduce a system of Cartesian unit vectors (x, y, z) where the easy axis of the ellipse is the x axis and the hard in-plane axis is the y axis. We consider a positive current when it flows from the PL to the FL (+z). Different from other works,10 we present a theoretical study of the magnetization dynamics, when the thermal effect is not taken into account, considering the presence of the nonidealities in the shape of samples with elliptical cross sectional area. The set of nonideal shapes [Fig. 1(a), right panel] has been computed from scanning electron microscopy (SEM) images directly [Fig. 1(a), left panel]. In order to figure out the discretized nonideal shape, we consider the larger axis of the SEM image of 90 nm while the smaller axis is 35 nm, then we use an algorithm which approximates the SEM images using square cells of 2.5 × 2.5 nm2.

The simulations have been performed by solving the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation,8,11 considering the standard contributions of the effective field together with both the magnetostatic coupling between the PL and the FL and the classical Ampere field.11 We do not consider magneto crystalline anisotropy for Py. The polarization function gT is the one proposed by Slonczewski in 2005:12

\[ g_T(\theta) = 0.5 \eta_T [1 + \eta_T^2 \cos(\theta)]^{-1}, \]

where ηT is the polarization factor. We also use \( M_s = 644 \times 10^5 \) A/m and \( M_{sp} = 1.15 \times 10^6 \) A/m for the saturation magnetization of the FL and the PL, respectively, a damping parameter α=0.01, and an exchange constant of 1.3 × 10⁻¹¹ J/m.

From theoretical point of view, it is well known that the MTJs (both with AlO or MgO tunnel barrier) exhibit a TMR that decreases when the applied voltage increases. Recently, a study on MTJs with a MgO tunnel barrier showed that the polarization factor ηT is a constant function of the bias within a 10% uncertainty.13 Starting from this experimental remark and considering that a decrease in TMR does not indicate a large decrease in the spin polarization, we consider ηT constant. We use ηT=0.3 for the AlO MTJ (value com-

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The magnetostatic coupling has been computed by means of the three-dimensional (3D) static simulation of the whole device for all the shapes; its average value changes in the range of 54–58 mT.

For the study of the magnetization dynamics, we consider a uniform spatial distribution of current density. The initial configuration of the magnetization has been computed by solving the Brown equation for the antiparallel state. A time step of 28 fs has been used; simulations performed with shorter time step gave the same results exactly. The samples were discretized into cells of $2.5 \times 2.5 \times 4.0$ nm$^3$. Simulations have also been performed with cells of $2.0 \times 2.0 \times 2.0$ and $2.5 \times 2.5 \times 2.0$ nm$^3$, giving rise to very similar results, where the magnetization dynamics varies by less than 5%.

Figure 1(b) shows the 3D view of the persistent magnetization dynamics in an AlO MTJ [for an ideal ellipse (I) and the three nonideal shapes (A, B, and C)] driven by a current density of $J=1.2 \times 10^7$ A/cm$^2$. Smaller current densities do not excite persistent dynamics; we do not simulate larger values in order to have voltage smaller than the breakdown voltage (a value of 0.5 V is considered; the value for magnetoresistance is taken from Ref. 7). As can be noted in Fig. 1(b), the dynamics does not change qualitatively considering the average magnetization. In all of the simulated shapes it goes through four main points: 1 (y-max), 2 (x-min, z-min), 3 (y-min), 4 (x-min, z-max). By analyzing the spatial distribution of the magnetization, we observe that the dynamics occurs by rotation of the spins (no nucleation). Figure 2 shows the snapshots of the main steps of the magnetization dynamics of Fig. 1(b) for the ideal ellipse. The spins rotate from a magnetization configuration 1I to 2I, after that to 3I, and lastly the spins go back to 1I through the configuration 4I.

The nonidealities introduce a distribution of the spins which is less uniform in the space. This can be observed in Fig. 3, where the configuration 1 (y-maximum) for the three nonideal shapes (top, A; center, B; bottom, C) is displayed. Another effect of the nonideal shapes can be seen by analyzing the total spectrum computed by means of the micromagnetic spectral mapping technique (MSPT). It consists...
in performing a fast Fourier transform (FFT) of the temporal evolution of magnetization for each computational cell
\[ S_X(x_i, y_m, z_n, f) = \sum_m |S_X(x_i, y_m, z_n, f)|^2 \], \(^\text{Ideal} \), where the indexes \( i, m, \) and \( n \) identify a computational cell, \( t_k \) is the discretized time step, \( f \) is the frequency, and \( N \) is the total number of the cells. \(^\text{15}\) We computed the FFT of the \( x \) component of the magnetization since it is the one related to the magnetoresistance signal (the magnetization of the PL is pinned along the \(+z\) direction).

Figure 4 shows the total spectrum (a.u.) of the \( x \) component of the magnetization of the process of Fig. 1(b) for the ideal ellipse together with the nonideal shapes (an offset has been added). For that current density a main mode (\( f_M \)) is excited, which changes in the range 8–10 GHz. Concerning the ideal ellipse, the edge roughness due to the discretization introduces high harmonics at \( 2f_M, 3f_M \), etc. Simulations performed using a smaller cell size \( 2 \times 2 \times 4 \) \( \mu \)m\(^2\), show that the frequency of the main peak is shifted by less than 3\%, and the amplitudes of higher harmonics are smaller. In contrast, the effects of nonidealities are as follows: (a) other modes (defect modes) are excited, (b) a shift in the main mode (\( f_M \)) is observed (in the simulated cases it changes in the range 8–10 GHz), and (c) the spatial distribution of the main mode \(^\text{16}\) changes, becoming asymmetric. Figure 5 shows an example of the spatial distribution of the main mode of the process of Fig. 1(b) for the ideal ellipse (\( f_M = 8.1 \text{ GHz} \)) (top) and for the shape C (\( f_M = 8.2 \text{ GHz} \)) (bottom). As can be noted, the former is symmetric, while the latter is asymmetric. Similar results have been obtained for the MgO MTJ in a range of current density of \( 0.22 \times 10^7 - 0.45 \times 10^7 \) A/\( \mu \)m\(^2\). In the latter value, a reversal from the antiparallel state to the parallel is achieved.

In summary, we have presented magnetization dynamics driven by a SPC in MTJs when no field is applied. We performed a computational study about the effect of nonidealities in the elliptical cross sectional area on the magnetization dynamics. We observe that the frequency of the main peak differs from the value of the ideal ellipse; in particular, for the simulated shapes and currents the frequency increases. The MSMT reveals that the spatial distribution of the main mode is symmetric in the ideal shape and asymmetric in the nonideal ones. Lastly, the presence of the edge roughness excites other modes.

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