Trends in spin-transfer-driven magnetization dynamics of CoFe/AIO/Py and CoFe/MgO/Py magnetic tunnel junctions

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A spin-polarized current is able to excite magnetization dynamics in nanomagnets. A detailed theoretical study of dynamics in low and high field regimes in AIO and MgO magnetic tunnel junctions (MTJs) is presented, considering the maximum value of the applied current which comes from the breakdown voltage of the tunnel barrier. In low field regime, dynamics with a well-defined peak in frequency is observed. In high field regime, AIO MTJ presents the same behavior, while the magnetization in the MgO MTJ shows chaotic motion with a noisy spectrum. Lastly, an effect of the presence of a pinhole in the tunnel barrier is discussed. © 2006 American Institute of Physics. [DOI: 10.1063/1.2425017]

A spin-polarized current (SPC) flowing through a nanomagnet applies torque to its magnetization that can either induce magnetization reversal or excite persistent dynamics (self-oscillations) of magnetization.\textsuperscript{1,2} These behaviors have been experimentally observed in spin valves (SVs),\textsuperscript{3} magnetic tunnel junctions (MTJs),\textsuperscript{4} and point-contact geometries.\textsuperscript{5} Concerning the MTJs, they show promise as high performance magnetic random access memory and the classical Oersted field together with the standard effective field and change, Zeeman, anisotropy, and magnetostatic.\textsuperscript{6} We do not consider magnetocrystalline anisotropy for the Py. The polarization function \textit{g}_T, which modulates the spin-transfer torque, has been considered as proposed by Slonczewski in 2005.\textsuperscript{7} \textit{g}_T(\theta)=0.5 \eta_T (1+\eta_T^2 \cos(\theta))^{-1}, where \eta_T is the polarization factor. We also use \textit{M}_c=644 \times 10^3 \text{A/m} and \textit{M}_{sp} = 1.15 \times 10^6 \text{A/m} for the saturation magnetizations of the FL and the PL, respectively, a damping \alpha = 0.01, and an exchange constant \textit{A} = 1.3 \times 10^{-11} \text{J/m}. We consider a positive current when it flows from the PL to the FL. We consider the orange-peel coupling negligible.\textsuperscript{8}

From the theoretical point of view, it is well known that the MTJs (both with AIO or MgO tunnel barrier) exhibit a TMR that decreases when the applied voltage increases. On the other hand, current induced switching occurs at a large voltage, where the current must be spin polarized in order to exert a significant spin-transfer torque. A recent experimental study on MTJs with a MgO tunnel barrier shows that the polarization factor \eta_T is a constant function of the bias within a 10% uncertainty.\textsuperscript{9} Starting with this experimental remark that a decrease in TMR does not indicate a decrease in the spin polarization, we consider \eta_T to be constant for both positive and negative currents used for our simulations. With that further hypothesis, we obtain a symmetric torque, in agreement with most of the experimental data published so far.\textsuperscript{4,9} We use for the AIO MTJ \eta_T = 0.3: this has been computed by fitting the experimental critical currents of the most complex structure of Ref. [10]. For the MgO MTJ, we use \eta_T = 0.7: this value is smaller than the one obtained in the CoFe/MgO/CoFe MTJ. We consider a breakdown voltage of the tunnel barrier of 0.5 V for both the devices and a maximum resistances (APS state) of 1.7 (Ref. [10]) and 1.9 KΩ (Ref. [9]) for the AIO and MgO MTJs respectively, considering these values we apply maximum current densities of 1.2 \times 10^7 \text{A/(cm}^2\text{)} for AIO and 1.0 \times 10^7 \text{A/(cm}^2\text{)} for MgO.

In our calculations, we use a time step of 28 fs. Simulations performed with shorter time step gave the same results exactly. The samples where discretized into cells of 2.5 \times 2.5 \times 4.0 \text{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 \text{nm}^3, giving rise to

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of the average magnetization for an applied field. We performed calculations producing a chaotic behavior of the magnetization. Figure 1 top right shows the temporal evolution of the x component of the magnetostatic coupling with the PL contact geometries. Figure 2 shows the static loop computation of the critical current at zero temperature. These calculations produce $J_{C,AIO} = 1.15 \times 10^7 \text{ A/cm}^2$ and $J_{C,MgO} = 0.73 \times 10^7 \text{ A/cm}^2$, which are the same for both APS→PS and vice versa processes. The magnetization reversals obtained in both structures occur via nucleation process (not shown), likewise to recently time-resolved imaging at nanoscale of magnetization reversal in spin valves.

Furthermore, for both devices, we observe that currents lower than the critical one are able to drive magnetization dynamics. Figure 1(a) shows the temporal evolution of the x (solid line), y (dashed line), and z (dotted line) components of the average magnetization for an applied field $H=50 \text{ mT}$ and a current density $J = -0.97 \times 10^7 \text{ A/cm}^2$ (AIO MTJ). Figure 1 top right shows snapshots of magnetization configuration at three different points: A (x minimum, y maximum), B (x maximum, z maximum), and C (x minimum, y minimum). As can be noted, this persistent dynamics is given by the oscillation of the spins at the boundaries of the structure. A three-dimensional (3D) view of the average magnetization motion of the same process is displayed in Figure 1(b). A similar results for the MgO MTJ is obtained for a value of current density $J = -0.6 \times 10^7 \text{ A/cm}^2$. Figure 2(a) shows the plot of the frequency of microwave oscillations versus the applied field for AIO (solid line, $J = -0.97 \times 10^7 \text{ A/cm}^2$) and MgO (dashed line, $J = -0.6 \times 10^7 \text{ A/cm}^2$). In both cases, the frequency increases when the field increases (bliueshift). These results are in agreement with the experiments related to the microwave oscillations driven by SPC, when the field is applied in plane, in SVs and point-contact geometries. Figure 2(b) shows the static loop computed by numerically solving the Brown equation for both MTJs. We obtain a coercivity of 95 mT. We investigated the behavior of the devices at high field regime where the applied fields are larger than the coercivity. We performed simulations at fields of 100, 150, and 200 mT and current density range up to $-1.2 \times 10^7 \text{ A/cm}^2$ for AIO MTJ and up to $-1 \times 10^7 \text{ A/cm}^2$ for MgO MTJ. In the former MTJ, we observe persistent dynamics regime only at a field of 100 mT and a current density of $-1.2 \times 10^7 \text{ A/cm}^2$, it is similar to the one described at low field regime, in all the other cases we have the PS. Concerning the MgO MTJ, all our simulations show that when a current is able to excite microwave oscillations, we obtain a chaotic behavior of the magnetization. For example, Figure 3(a) shows the y component of the average magnetization due to a SPC $J = -0.3 \times 10^7 \text{ A/cm}^2$ and an applied field of 200 mT (MgO MTJ), while Fig. 3(b) shows the relative total power spectrum computed by means of the micromagnetic spectral mapping technique (MSMT). As can be noted, the spectrum is very noisy typical of a chaotic signal. We attribute this behavior to the complex domain configurations that we observe during the dynamic process, depending on the time range, there is an alternating of completely different configurations. For example, a vortex which moves in the device together with oscillations of the spins at the boundaries (Fig. 3 top right A), $180^\circ$ (Fig. 3 top right B) or $360^\circ$ (Fig. 3 top right C) domain configurations with the wall of the domain propagating through the structure.

Lastly, we performed a study of the influence of a pinhole (placed in the center of the insulator) in the magnetization dynamics [see Fig. 2(c)]. It is modeled as a square cross section (15 nm in side) perpendicular conducting channel through the tunnel barrier. We assumed that the current flows

![Figure 1](image1.png)  
**FIG. 1.** (Color online) (a) Temporal evolutions of the x (solid line), y (dashed line), and z (dotted line) components of the average magnetization for an applied field $H=50 \text{ mT}$ and a current density $J = -0.97 \times 10^7 \text{ A/cm}^2$ (AIO MTJ); (top right) snapshots of magnetization at three different points displayed in (a): A (x minimum, y maximum), B (x maximum, z maximum), and C (x minimum, y minimum); (b) 3D view of the average magnetization motion of the same process.

![Figure 2](image2.png)  
**FIG. 2.** (a) Plot of the frequency of microwave oscillations vs the applied field for AIO MTJ (solid line, $J = -0.97 \times 10^7 \text{ A/cm}^2$) and MgO MTJ (dashed line, $J = -0.6 \times 10^7 \text{ A/cm}^2$); (b) static hysteresis loop $(H,(m_x))$ computed by solving the Brown equation; (c) view of the pinhole location in the elliptical cross section of the MTJ.

![Figure 3](image3.png)  
**FIG. 3.** (Color online) (a) Temporal evolution of the y component of average magnetization for an applied field $H=50 \text{ mT}$ and a current density $J = -0.3 \times 10^7 \text{ A/cm}^2$ (MgO MTJ); (b) total spectrum of the above signal computed by means of the MSMT; (top right A–C) snapshots of three different domain configurations of the same dynamic above.
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13It consists on performing a fast Fourier transform of the temporal evolution of magnetization for each computational cell \( S(x_j, y_j, z_j, f) = \sum_{i=1}^{m} n_{i,j} e^{i \omega_{i,j} f} \), then the total spectrum is computed by the following: \( S(f) = 1/N \sum_{i=1}^{m} S(x_j, y_j, z_j, f) \) (component of magnetization) where the indices \( i, m \) and \( n \) a computational cell, \( f \) is the discretized time step, \( f \) is the frequency, and \( N \) is the total number of the cells.
16This current is the smaller which gives persistent magnetization dynamic at that field when a pinhole has been introduced in the device.