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Micromagnetic simulations of current-induced microwave excitations

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Spin-transfer effects on the magnetization motion are investigated in the free layer of a giant magnetoresistance device flooded with spin-polarized electrons, and more specifically microwave excitations in elliptical permalloy elements. The spin torque is found to excite at low current precessional trajectories compatible with the platelet eigenmodes. Then a forced regime is activated that is, characterized by trajectory broadening with increasing current and an almost spatially uniform power density. The effect of temperature on resonance frequencies and linewidth becomes negligible at high current. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1852434]

INTRODUCTION

The theoretical predictions of spin-polarized current-induced magnetization switching of Slonczewski[1] and Berger[2] arose considerable interest. Recent experiments[3–5] confirmed a key prediction of the theory stating that a dc current of spin-polarized electrons flowing across a ferromagnetic layer can drive microwave excitations as a consequence of the transfer of angular momentum to localized moments. More precisely, transport measurements in the frequency domain gave direct evidence for the existence of precessional magnetization trajectories, especially in the case where a large enough field is applied that impedes switching. However, several features observed in the spectral signature of the giant magnetoresistance (GMR) signal in nanopillar devices seem hardly consistent with the single spin approximation, notably the rather complex power spectral density (PSD) versus current behavior at high field, as illustrated in Figs. 2c–d of Ref. 3. The present paper addresses the question of spin transfer induced precession viewed from a micromagnetic perspective. For the sake of simplicity, simulations reported below describe the magnetization dynamics of the sole free layer of a current perpendicular to plane (CPP) spin-valve nanopillar device with elliptic cross section and typical dimensions of $114\times70\times2.5\ \text{nm}^3$, as sketched in the inset of Fig. 1(a). $\mathbf{e}_x$ (respectively $\mathbf{e}_y$), is the in-plane easy (respectively hard) magnetization axis. The magnetization distribution as a function of space and time $\mathbf{M}=\mathbf{M}(\mathbf{r},t)$ within the element is obtained through the integration of the Landau–Lifshitz–Gilbert equation augmented with the spin-torque term,[1,6]

$$\Gamma_{ST}=\frac{d\mathbf{M}}{dt}=-\gamma_0\frac{\hbar}{2}\frac{1}{\mu_0 M_S^2}\frac{J}{|e|d}P[\mathbf{M}\times(\mathbf{M}\times\mathbf{p})].$$

Here, d is the free-layer thickness, γ_0 is the gyromagnetic ratio ($\gamma_0>0$), e is the electron charge, M_S is the saturation magnetization, and P is the electron polarization pointing along unit vector $\mathbf{p}$. We assume a uniform polarization of 0.3 (a usual value for, e.g., CoFe) with $\mathbf{p}=-\mathbf{e}_x$ (electrons backscattered from the reference layer with $J>0$). On the top of the spin torque, the magnetization is subject to the effective micromagnetic field including the applied, exchange, and demagnetizing fields. Due account is made for the existence of the Oersted field, calculated for a 50-nm high pillar with elliptical cross section and uniform current

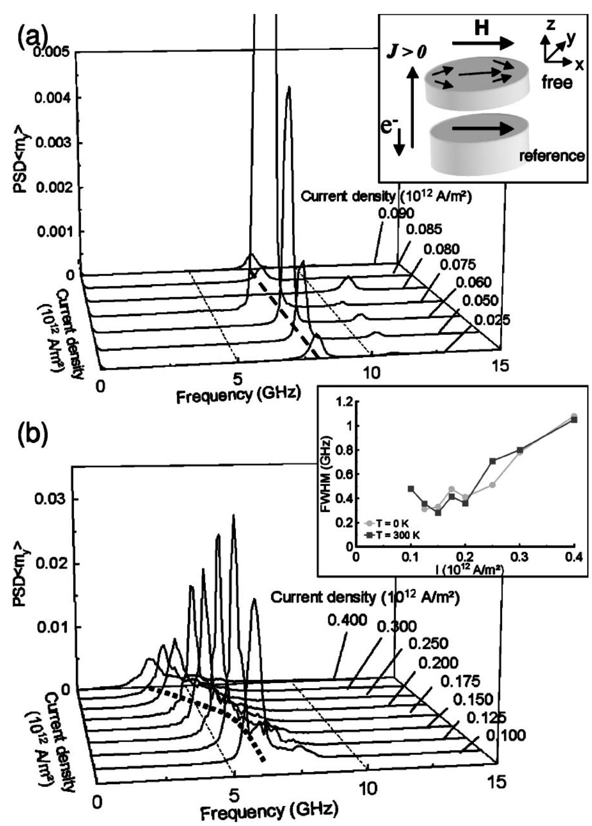

FIG. 1. Power spectrum density of $\langle m_y\rangle(t)$ at 300 K: (a) low current regime ($J<0.1\times10^{12}\ \text{A/m}^2$). Inset: spin-valve structure and signs convention for currents and fields; (b) high current regime. Inset: evolution of the linewidth as a function of current density for $T=0$ and 300 K.

[a)]Electronic mail: montigny@lps.u-psud.fr density, J. Lastly, thermal fluctuations are included through the addition of a Langevin stochastic field with the white-noise autocorrelation function,[7]

$$\langle \mathbf{H}_i(t_1) \, . \, \mathbf{H}_j(t_2) \rangle = \delta_{ij} \delta(t_1 - t_2) \frac{2k_B T \alpha}{V_{\text{cell}} M_S \gamma_0}.$$

All calculations have been performed for parameters illustrative of permalloy ($Ni_{81}Fe_{19}$): $M_S = 800$ kA/m, exchange constant $A = 1.0 \times 10^{-11}$ J/m, and a damping constant α set to 0.01 close to the bulk value. Crystalline or growth anisotropies are neglected whereas shape anisotropy amounts to $H_k \sim 19.5$ kA/m(245 Oe).

The present study is restricted to microwave excitation under a large applied field ($3^* H_k$), that stabilizes the initial magnetization direction along $+\mathbf{e}_x$. The applied field here grossly exceeds the Oersted field that scales roughly as 1.25 kA/m for a 10^{11} A/m^2 current density along the rim of the ellipse where it is largest.

PRECESSIONAL STATES

Similar to experimental data[3,4] and macrospin-type simulations,[8] precessional oscillations are here characterized by their PSD. The PSD is defined as the Fourrier transform of the autocorrelation function of **M** and is to be viewed as the power emitted by the system in the interval $(f, f+df)$.

Simulations have been performed for current densities ranging from 0.01 to 0.4×10^{12} A/m^2 and for temperatures from 0 to 400 K in order to account for Joule heating. Let us first examine results pertaining to the spatial average of the transverse magnetization component, $\langle m_y \rangle(t)$.

At low currents ($<0.1 \times 10^{12}$ A/m^2), two resonance peaks appear at 7.9 and 10.95 GHz at $T = 300$ K (8.1 and 11 GHz at 0 K, increasing the temperature induces a decrease of the apparent M_S hence a lower resonance frequency), respectively [Fig. 1(a)]. The current density solely affects the magnitude of these peaks. A maximum is reached for $J = 0.075 \times 10^{12}$ A/m^2. Increasing the current further leads to a sharp decrease in emitted power. A new regime appears upon further increase of the current density that is characterized by a redshift of the main resonance line with increasing current from 7 down to 3 GHz [Fig. 1(b)]. The magnitude of the peaks first increases with increasing current, up to $J = 0.125 \times 10^{12}$ A/m^2, then decreases, in a way that is reminiscent of results pertaining to point-contact geometry experiments.[4] Indeed, in the latter regime, similar to the single spin regime,[8] the spin-transfer torque leads to an opening of the mean magnetization trajectory into a large-angle elliptical orbit. At the highest current density, the in-plane angle of the magnetization with $\mathbf{e}_x$ typically ranges from $-120°$ to $+120°$ at 0 K whereas the out-of-plane excursion angle amounts to $\pm 30°$.

Several features deserve attention. On the one hand, the m_y PSD is at least one order of magnitude larger than the PSD of m_x, the latter being multiplied by a factor of 2 in frequency (not shown). This difference is not surprising because, if φ is the deviation angle from the easy axis, one gets $m_x \approx \cos(\varphi) \approx 1 - \varphi^2/2$ and $m_y \approx \sin(\varphi) \approx \varphi$. The frequency ratio follows directly. On the other hand, the linewidths of resonance peaks prove quite different from macrospin results.[8] The present micromagnetic simulations lead to linewidths at half maximum (FWHM) of about 0.4 GHz in the low current regime, irrespective of current density or temperature. FWHM's increase weakly with current density in the high current regime but remain essentially independent of temperature, as shown in the inset of Fig. 1(b). A high-frequency shoulder in the PSD is systematically observed in this regime. Moreover, the existence of two regimes with global features equivalent to those displayed in Figs. 1(a) and 1(b) is confirmed by simulations performed on ellipses with different aspect ratios and/or material parameters.[9]

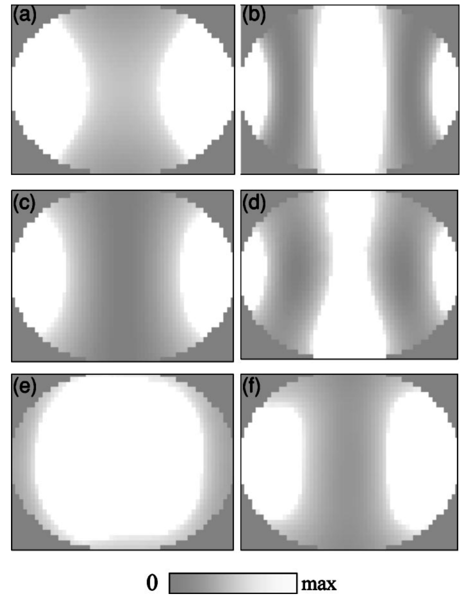

FIG. 2. Magnetic susceptibility χ_{yy} distribution at (a) $f = 8.2$ GHz and (b) $f = 11.2$ GHz. Kittel's frequency for the uniformly magnetized equivalent ellipsoid amounts to 9.18 GHz. $\langle m_y \rangle$ power spectrum density ($T = 300$ K) for $J = 0.075 \times 10^{12}$ A/m^2 at (c) $f = 7.9$ GHz and (d) $f = 10.95$ GHz. *Ibid* for $J = 0.125 \times 10^{12}$ A/m^2 at (e) $f = 5.4$ GHz and (f) $f = 6.8$ GHz. The static applied field is $H = 3^* H_k$ throughout.

INHOMOGENEOUS EXCITATIONS

In Fig. 2, we plot the PSD amplitude versus position for the m_y magnetization component for predefined frequencies. At low current density, for the first resonance (7.91 GHz), the apices of the ellipse are the regions that exhibit the largest excitation [Fig. 2(c)]. At 10.94 GHz, spin transfer triggers a higher rank mode [Fig. 2(d)]. At high current density, the situation is markedly different since spin transfer induces a nearly pure "volume" mode [Fig. 2(e)], where the central part of the ellipse oscillates coherently. At the shoulder frequency [Fig. 2(f)], however, an inhomogeneous state is excited that is reminiscent of first eigenmode in Figs. 2(a) and 2(c). In both regimes, higher-frequency modes are excited with a much smaller amplitude. Despite minor shifts in frequency, the modes at 0 and 300 K are found to be equal.

Additional information may be gained from the mapping of suitable components of the susceptibility tensor. The component $\chi_{\alpha\beta}$ of the tensor has been computed owing to a method directly inspired from Ref. 10. In this case study, we focus mainly on the χ_{yy} component because, for the initial magnetization distribution, the spin transfer acts as an effective field pulling the magnetization in the *y* direction. We identify two eigenmodes, one at 8.2 GHz and a weaker one at 11.2 GHz with mappings, as depicted in Figs. 2(a) and 2(b), respectively. From the similarity in intensity mappings and frequency, one immediately deduces that the first spin-transfer modes are eigenmodes of elliptical elements, hence the frequency invariance. On the other hand, we may not identify any eigenmode similar to the high current density redshift mode. Under prominent spin-transfer effect, whether at 0 K or higher temperature, the micromagnetic system enters a forced regime. As stated earlier, this regime is characterized by coherent excitations of the whole volume of the free layer except for the ellipse tips with almost uniform magnitude.

DISCUSSION

The magnetoresistance classically reads $\Delta R = \Delta R_{\max}[1 - \cos(\theta - \theta_{\text{ref}})]$ and is directly related to the projection of the free-layer magnetization onto the reference direction. Under such assumptions GMR mag-noise spectra should scale with the PSD's of the spatial average of the *x* magnetization component, $\langle m_x \rangle$, whereas the fundamental rf excitation frequency stems directly from the $\langle m_y \rangle$ PSD. In the point-contact geometry experiments of Rippard *et al.*,[4] the frequency spectra include f and $2f$ peaks with comparable amplitudes, implying some mixing of the contributions of $\langle m_x \rangle$ and $\langle m_y \rangle$ to the GMR response. Mixing has also been invoked by Kiselev *et al.*[3] in order to fit their experimental data. A plausible explanation might be the following: assume the field to be off axis with respect to the easy axis of the free layer; then, due to the difference in thickness and/or shape between the reference and free layers, shape anisotropy will exert different restoring torques on the magnetization of the two layers stack subject to the same applied field, hence the misorientation, notwithstanding the potential effect of the Oersted field on the reference layer. These arguments combined with the high $\langle m_x \rangle$ to $\langle m_y \rangle$ PSD ratio lead to the conclusion that the lowest observable frequency in the GMR response most likely corresponds to the fundamental rf excitation frequency. Provided the above conclusion be accepted, then simulations do predict that the first observable signal in nanopillars should correspond to the fundamental frequency of the first eigenmode of the free-layer element. Its frequency should be independent of the injection current within its existence domain, in agreement with the experimental data of Kiselev *et al.* (low current regime in Fig. 1d of Ref. 3). Increasing the current density leads to the onset of a forced regime characterized by a fast decrease of the resonance frequency in full analogy with experiments (e.g., Fig. 1c in Ref. 3) and single spin simulations.

However, in the macrospin model, peak linewidths should be very sensitive to temperature evolving from a Dirac peak at 0 K to a rather broad peak at 300 K. Because of the absence of any sizable dependence of the linewidth versus temperature, spin-transfer-induced disorder seems here to be preeminent over thermal broadening at high current densities.

As mentioned earlier, the Oersted field only plays a minor role in the present conditions. Such would not be the case if considering excitations and switching at low field ($H \ll H_k$). At large currents and low fields the Oersted field promotes the formation of a *C* state within the soft elliptical element and a possible distortion of the magnetization distribution within the hard/pinned layer.

Lastly, after linearization of the Landau–Lifshitz–Gilbert (LLG) equation, the threshold current leading to the onset of precessional states in the single spin limit reads

$$J_{\text{th}} = \frac{|e|}{P} \frac{\mu_0 M_S^2}{\hbar} d\alpha(1 + Q + 2h_a),$$

where Q and h_a are the reduced anisotropy and applied fields, respectively, normalized by M_S. With our parameters, $J_{\text{th}} = 0.115 \times 10^{12}\ \text{A/m}^2$ for a precession frequency roughly equal to 4.6 GHz. Although greatly simplifying the physics involved these values remain fairly representative of the transition between the low and high current regimes.

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