Micromagnetic Investigation of Precession Dynamics in Magnetic Nanopillars

Mario Carpentieri¹, Luis Torres², Giovanni Finocchio¹, Bruno Azzerboni¹, and Luis Lopez-Diaz²

¹Dipartimento di Fisica della Materia e Tecnologie Fisiche Avanzate, University of Messina, Messina I-98166, Italy
²Departamento de Fisica Aplicada, University of Salamanca, Salamanca E-37008, Spain

This paper interprets and reproduces, by means of full micromagnetic simulations, the pioneering experimental data on magnetization dynamics driven by spin polarized current of the experiment by Kiselev et al. The effect of the spatial dependence of the polarization function together with either nonuniform magnetostatic coupling from the fixed layer and classical Ampere field are shown to play a fundamental role in the magnetization dynamics. A detailed study of the stable magnetization self-oscillations shows that for high field and high current regimes, the dynamics is localized in the sides of the structure, where the energy dissipated by damping and the energy provided by the spin flow compensate exactly.

Index Terms—Magnetization dynamics, micromagnetic modeling, nanopillar, spin torque.

I. INTRODUCTION

SLOWCZESKI [1] and Berger [2] demonstrated a new mechanism for exciting the magnetic state of a ferromagnet at nanometer scale which opened important perspectives because of potential applications in devices like magnetic memories and microwave oscillators [3]. Recently [4]–[6], full micromagnetic (FMM) simulations have been performed trying to mimic the pioneering experimental data by the Cornell group [3]. These studies use a spin polarized current (SPC) transfer torque “αJ” assumed to be spatial and angular independent and they try to fit the experimental data by adequate magnetic parameters [5], [6] or by making a detailed analysis of the polycrystalline microstructure and including the effect of the thermal fluctuations [6]. Furthermore, those theoretical works show some discrepancies between experimental and computed frequencies [4]–[6]. In our study, we intend to reproduce by FMM the dynamical stability diagram at T = 0 K of the nanostructure reported in [3] and [6] (40 nm Co (pinned layer (PL))/10 nm Cu/3 nm Co (free layer (FL)) and elliptical cross-sectional area (130 nm × 70 nm)), using the same magnetic parameters when the spatial dependent polarization function “g(M(i,j,k),P)” proposed by Slonczewski is computed for each computational cell [7].

A micromagnetic 3-D dynamic code developed by our research group which takes into account the effect of the SPC [8] has been used to perform the simulations. It includes the Slonczewski (S) term in the Gilbert equation which gives rise to two terms in the equivalent Landau Lifshitz Gilbert (LLG) equation [8], [9]. The LLG can be written as follows:

\[
\frac{dM}{dt} = -\gamma M \times H_{\text{eff}} + \frac{2\mu_P J}{(1 + \alpha^2)\tau} g(M, P) M \times P - \frac{\alpha \gamma}{M_s} M \times (M \times H_{\text{eff}}) - \frac{2\mu_B J}{(1 + \alpha^2)\tau} g(M, P) M \times (M \times P).
\]

(1)

The scalar function \(g(M, P)\) is [1] \(g(M, P) = [-4 + (1 + \eta)^3(3 + MP/M_p^2)/4\eta^2/\gamma J/2]^\alpha\), where the polarization factor \(\eta\) is 0.35 for Co [1].

The effective field includes \(H_{\text{exch}}, H_{\text{ext}}, H_M\), and \(H_{\text{Anis}}\) that are the standard micromagnetic contributions from exchange, external, demagnetization, and uniaxial anisotropy fields, \(H_{\text{Amp}}\) and \(H_{\text{AF}}\) that are the Ampere field and the magnetostatic coupling between FL and PL. As pointed out previously, no polycrystalline microstructure, shape defects or finite temperature will be considered. The standard Cobalt magnetic parameters \(M_p = 1.4 \times 10^6 A/m, A = 1.3 \times 10^{-11} J/m, K_u = 89387 J/m^3\), and \(\alpha = 0.014\) have been used. Computational cells of 2.5 × 2.5 × 3.0 nm³ have been used, the FMM simulations were carried out during 50 ns using a time step of 40 fs. In this framework, the current is considered positive for a flow of electrons from the PL towards the FL; positive \(J\) will produce a torque which pushes the magnetization \(M\) towards the direction of \(P\). On the contrary, negative \(J\) will bring \(M\) out of the direction of \(P\). More modeling details can be found in [8].

II. STABILITY DIAGRAM AND DISCUSSION

Fig. 1 shows the phase stability diagram of the dynamical modes related to the Kiselev nanostructure [3]. The diagram shows the simulations (at \(T = 0 K\)) in the range we studied; the
applied fields run from 0 to 300 mT at steps of 10 mT and the applied currents are always negative from 0 to $-1 \times 10^9$ A/cm$^2$ at steps of $-0.2 \times 10^8$ A/cm$^2$. We performed simulations where the initial configuration of the magnetization is the parallel state. In order to compare the diagrams with those of previous works [3]–[6], the absolute values of the applied currents are depicted in the figure. The regions labelled “PS” and “APS” denote the zones where the magnetization either remains or switches to one of the two stable static states (“fixed points” of the dynamics [8]). The zone “L” is characterized by a noisy oscillation of the magnetization between the stable PS and APS states, corresponding with the region “L” of [3].

Neither were clear traces of telegraph noise observed nor did characteristic frequencies arise in the fast Fourier transform (FFT) power spectrum in this zone. A detailed description can be found in [7]. Moreover, the regions marked as “W” present well defined peaks in frequencies indicating a persistent stable magnetization dynamics. These oscillations could be thought to correspond to periodic solutions like the ones found in uniform magnetization models [10], but the FMM computations show that, in this case, they are associated to a nonuniform persistent oscillation involving the formation of “$-M_r$” domains. Last, a narrow linear region of small precessional points is found, carrying out dynamics as that reported in Fig. 2. Since the stability diagram has been computed starting from the parallel state, the bistability P/AP region of [3] is not displayed in Fig. 1. That can be computed by performing simulations starting by the antiparallel state [7].

In order to establish if the magnetization dynamics for each applied field and current belongs to a noisy or precessional behavior, the following computation is carried out: 1) FFT of the temporal evolution of the magnetization and 2) mean and standard deviation of the FFT computed by using a Matlab toolbox. A characteristic constant is obtained by dividing these values, the gap obtained in the series of values of this constant indicates the separation of noisy and precessional zones. In this framework, we focus our attention in the two precessional regimes, low applied field and low current and high applied field and high current, labelled in the diagram of Fig. 1 as “Small” and “W,” respectively. These regimes are characterized by different frequency behavior as described in the following.

The “Small” precessional zone represents quite critical magnetization dynamics. For each magnetic field, just a single current gives rise to this precessional state. This zone corresponds to a narrow strip. Fig. 2 shows the temporal evolution of the magnetization dynamics due to an applied field of 180 mT and a current density of $-6.44 \times 10^7$ A/cm$^2$, as can be noted, the amplitude of the oscillations the $x$-component of the magnetization is very small. The inset of Fig. 2 displays the frequency spectrum where it can be found that the frequency of the main peak is $f = 17$ GHz. The precession frequency is in good agreement with the Kittel equation for a magnetic film [11]

$$f(H) = (\gamma/2\pi)\sqrt{(H_{\text{ext}} + H_{\text{AF}})(H_{\text{ext}} + H_M + H_{\text{AF}})}.$$  

The behavior of the magnetization dynamics in the “W” region is shown in Fig. 3 for $H_{\text{app}} = 300$ mT and $J_{\text{app}} = -9 \times 10^8$ A/cm$^2$.

The 3-D plot of the average magnetization is presented together with some snapshots of the magnetization configuration which correspond approximately to the points marked in the trajectory. It can be seen how the oscillation involves the formation of two “$-M_r$” and “$+M_r$” domains which appear in the left and right part of the structure. In this case, the energy dissipated by damping and the energy provided by the spin flow compensate exactly. We point out that for the first time (to the best of our knowledge) micromagnetic simulations are able to reproduce the “W” region. In our FMM computations, the nonuniformities in the magnetization dynamics come from the magnetostatic coupling, the amperian field, and spatial and temporal dependence of the polarization function “$g(M, P)$.” The latter has been computed for each computational cell considering the angular dependence of $g(M(\hat{\mathbf{i}}, \hat{\mathbf{j}}, \hat{\mathbf{k}}), P)$. When a nonuniform pattern of the magnetization (see Fig. 3) is present, this angular dependence is different for each computational cell so that for calculating the phase diagrams the spatial and angular dependence of “$g(M(\hat{\mathbf{i}}, \hat{\mathbf{j}}, \hat{\mathbf{k}}), P)$” has been employed.

Typical precession frequencies for the two regimes are quite different; the small amplitude oscillations run in a frequency range between 16 and 20 GHz [see Fig. 4(a)] depending on the applied field. For this kind of oscillation, the dependence on
the applied current is negligible, since the current differences among the various oscillation points are very small. The frequency range of the W precession is typically smaller with respect to the small precession and runs between 1–4 GHz, as shown in Fig. 4(b). The diagram of Fig. 4(b) shows the frequencies of the excited modes versus current density for several applied fields. It can be noted, that the oscillation frequency decreases when the current increases and it increases when the applied field increases. Fig. 4(c) shows the FFT of the 2-component of the magnetization.

A comparison of our results to the experiments of [3] yields some differences as expected from the ideal character of our simulations. We do not find large amplitude uniform precessions signals enduring over the 50 ns of computation. On the other hand, our region “W” could be identified with the “W” region of [3] and [5] and, in our case, it is due to domain motion. No vortex formation and annihilation is detected differently to the FMM computations reported in [5]. However, the experimental frequencies are in agreement with our FMM simulations. The discrepancies between the W precession frequency of the experimental results [3] (typically in a range of 2–7 GHz) and the ones simulated in [6] (about 10 GHz) are attributed to the following reasons:

- In our computation, we consider in the effective field both the magnetostatic coupling between the two Cobalt layers and the ampere field that are nonuniform [9], [12]. In [3], the MC has not been taken into account, and this component of the effective field decreases the oscillation frequency.
- As previously discussed in this paper and demonstrated in [7], we computed the polarization factor $g(M, i, j, k, P)$ found by Slonczewski [1] for each computational cell taking into account the spatial and angular dependence of the function; in fact, the full dependence changes the frequency spectrum, which is the most reliable characteristic of experiments [6].

In summary, we found a complete dynamical stability diagram of the experiment by Kiselev et al. We take into account all the components of the effective field together with the effect of the spatial dependence of the polarization function. A detailed study of the stable magnetization self-oscillations shows that for high field and current regime, the dynamics is localized in the sides of the structure. We described two precessional regions in that device. Last, we provide a possible justification on the discrepancy between the experimental “W” precessional frequency and that simulated by Berkov et al. [6].

REFERENCES


Manuscript received January 30, 2007 (e-mail: carpentieri@ingegneria.unime.it).