Role of the spin transfer in the ferromagnetic resonance response of thin films

P. Landeros,[1] R. A. Gallardo,[2] O. Posth,[3] J. Lindner,[3] and D. L. Mills[4]

[1]*Departamento de Física, Universidad Técnica Federico Santa María, Av. España 1680, 2340000 Valparaíso, Chile*

[2]*Instituto de Física, Pontificia Universidad Católica de Valparaíso, Av. Parque Sur 330, Curauma, Valparaíso, Chile*

[3]*Fakultät für Physik and Center for Nanointegration (CeNIDE), AG Farle, Universität Duisburg-Essen, Lotharstr. 1, 47048 Duisburg, Germany*

[4]*Department of Physics and Astronomy, University of California, Irvine, California 92697, USA*

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We develop a theory to describe the ferromagnetic resonance response of layered structures composed of two ferromagnetic thin films separated by a nonferromagnetic spacer layer, when spin-polarized current emanates from one layer and is injected into the second. The resulting spin torque influences both the frequency and the linewidth of the ferromagnetic resonance response of the film into which the current is injected. We derive explicit formulas that describe such effects, for arbitrary orientations of an external magnetic field and directions of the magnetization of the polarizing ferromagnetic layer. This enables us to calculate the effect of the spin-transfer torque on characteristic quantities such as the high-frequency susceptibility, ferromagnetic resonance linewidth, ferromagnetic resonance frequency, and the equilibrium magnetization orientation. The results demonstrate that ferromagnetic resonance investigations provide access to spin-transfer torque effects by analyzing both the resonance frequency as well as the resonance linewidth. The latter can be used as a very sensitive measure of spin-torque physics in the regime of small current densities, i.e., at the onset of spin-transfer-torque-driven dynamics. The theory is compared quantitatively to experimental results obtained on Py/Cu/Co-trilayer structures.

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I. INTRODUCTION

When an electric current emerges from a metallic ferromagnetic (FM) layer with defined magnetization direction, it exhibits a spin polarization along that direction. If such a spin-polarized current is then injected into a second ferromagnetic film, the electrons will exert a torque on the magnetization of the second layer. This effect is called spin-transfer torque and was predicted theoretically by Slonczewski[1] and Berger[2] in 1996 and observed by several groups.[3–5] The research on the spin-torque effect within magnetic nanostructures has become a focus of recent interest in the field of nanomagnetism, mainly because of its relevance for applications in technological devices such as magnetic random access memory elements or high-frequency devices.[6] It has been argued that the spin-torque effect may be used to replace external magnetic fields as a means of manipulating the magnetization in a film integrated in a device. Detailed review articles of the topic including extensive bibliographies can be found elsewhere.[6–9]

A spin-polarized current has two effects on the magnetization of a free layer. It transfers angular momentum to the magnetization through the exchange field generated by the polarized spins associated with the current, and in addition there is a classical Oersted field present as well. Both effects induce a torque on the magnetization. In this context, the Oersted field might, in principle, induce a multidomain structure in the magnetic layers. However, since we are interested in the ferromagnetic resonance (FMR) response in the presence of the current, a static applied Zeeman field is also present. Under typical FMR conditions, this static field is much larger than the Oersted field so that monodomain behavior of the magnetic moments in the sample is ensured even for larger structure sizes. This fact can be viewed as an advantage of using FMR to detect the spin-transfer-torque-driven effects by a measurement of the dynamic response of the specimen (changes in the high-frequency susceptibility) as opposed to measurements of static properties such as the dc electrical resistance.

Another property of the Oersted field is that by reversing the direction of the electrical current only the *direction* and not the magnitude of this field is changed. The Oersted field is in general inhomogeneous; with the consequence that it leads to a broadening of the FMR line *independent* of current direction. On the contrary, the spin-transfer torque efficiency is highly anisotropic relative to the current flow direction, which is reflected by the critical current densities for magnetization reversal being different for the two current directions.[3–5] As discussed below, this asymmetry results in a decrease in the FMR linewidth for one current direction while an increase is expected when the current is reversed. As a consequence, the distinctly different effects of the Oersted field and the spin-transfer torque can be well distinguished in an FMR experiment.

In this paper, we focus our attention on the description of a trilayer structure like those fabricated by Posth *et al.*[10] These pillars contain two FM metallic layers separated by a nonmagnetic metallic spacer. One magnetic layer (called the polarizer in the following) is assumed to be either pinned along a given direction or free to follow the applied field. A pinned polarizer may be achieved by exchange bias due to direct contact with an antiferromagnet, by in-plane anisotropy of the polarizer, which creates preferential magnetization directions, or by an external magnetic field applied along a certain direction. Since the latter is necessarily present in an FMR measurement, the requirement of polarizer pinning is achieved by the external magnetic field. We will see that large external fields do not hinder the detection of the spin-transfer torque effects when employing FMR to examine the response of the free layer, in our samples.

The degree of spin polarization realized in an electric current traversing the polarizer would be influenced by spin-dependent scattering at the interface and spin-flip scattering within the bulk of the polarizing material. Although, depending on the material of the polarizer, the spin polarization might be either parallel or antiparallel to the polarizer's magnetization (the latter may occur in case of preferential interface reflection and bulk scattering of majority electrons with spin orientation *parallel* to the magnetization direction, see, e.g., Ref. 11), we assume in the following the more common case that the minority spins are scattered more strongly so that the current will become spin polarized parallel to the magnetization of the polarizer.

The spacer layer is assumed to be sufficiently thick that one can neglect interlayer exchange coupling. In this limit and as a first approach, the FM layers can be treated as independent from each other and thus they can be characterized by different magnetic parameters. Hence, when an external field is applied, the two magnetizations will respond differently to the field. In general, this will lead to a nonparallel alignment of both magnetizations in case of different anisotropies (shape and/or magnetocrystalline) in each film. However, when polycrystalline materials are used and so in-plane anisotropy is negligible, due to the shape of the trilayer stack, both magnetizations will, in equilibrium, align parallel to the in-plane external magnetic field direction.

To exert a torque on the second magnetic layer (called free layer) a nonvanishing angle between polarizer and free layer is required. In many investigations, this is achieved by introducing in-plane shape anisotropy into the trilayer, e.g., by fabricating structures with elliptical or square shape, rather than circular cross section. This reduction in symmetry in turn results in a preferential direction for the in-plane orientation of the magnetization with origin in shape anisotropy. If the two magnetic layers consist of different materials or have different thicknesses, they will respond differently to an external magnetic field applied off-axis to the high-symmetry direction of the ellipse or the edge of the square. This leads to a nonzero angle between the magnetization of two layers and induces a nonzero torque of the spin-polarized current on the free layer. Another advantage of FMR detection of spin-torque effects is that the requirement of an angle between the two magnetic layers is not needed, as we shall see. This is because in FMR one excites a precession of the magnetization about the static equilibrium orientation. In case of different ferromagnetic materials such as Py and Co, the precession frequency is material specific. Thus, only the free layer will undergo precession when excited in resonance while the polarizer does not. Then, however, the dynamic excitation will introduce an angle between the two magnetizations that induces a spin-transfer torque despite the same *static* equilibrium angles of the two magnetic layers.

We finally emphasize that it is the *dynamical* response of the free layer that includes information on the spin-torque effect within an FMR experiment. No change in the static equilibrium orientation is necessary for one to probe spin-torque physics with this method. It is the case that this technique is extremely sensitive and suitable for small current densities, and it probes the system below the onset of the spin-torque-driven magnetization reversal. In this regime, since there is very little change in the static orientation, other methods suffer from sensitivity problems. The reader should note that the experimental approach we consider here assumes a classical microwave-driven FMR experiment to which the spin torque enters as a quantity that influences the precessional orbit which in turn can be detected due to changes in the FMR linewidth. The linear regime for small current densities is considered for which the spin torque acts as a positive or negative damping instead of driving a magnetic mode itself. Such an experiment is conceptually different from the so-called spin-torque FMR that employs spin-polarized ac currents in the gigahertz range to drive FMR (see, e.g., Refs. 12 and 13 for details).

As far as we know there is no complete theoretical description of how an external Zeeman field out of the film plane affects the FMR response in the presence of a spin-polarized current. We mention that spin-torque effects on the linewidth in the linear response regime were shortly discussed already by Rezende *et al.*[14] while this work focused on the nonlinear regime. In papers published so far the effect of spin-transfer torque on the dynamics and the magnetization reversal in spin-valve pillars has been investigated only for the case where the applied field is parallel to the film plane.[15,16] Peng-Bin He *et al.*[17] consider an in-plane applied field also but extend the theoretical description of the trilayer structures by introducing tilted anisotropy in the polarizing layer. Thus, an arbitrary orientation of the magnetization of the polarizer is addressed in this paper. From the experimental point of view, a more convenient way to tune the direction of the polarizer is by variation in the direction of an external field.[10] Our goal in the present paper is to describe the effect of the spin torque on the FMR response of trilayer structures for applied fields along arbitrary directions in the film plane as well as out of the film plane. We also provide the reader with simple analytical formulas to model the FMR response through calculations of the FMR frequency, resonance field, and FMR linewidth. We illustrate the predictions of the theory by calculations performed for realistic experimental parameters that assume a Co/Cu/Py system. We moreover discuss the static behavior of the equilibrium magnetization in presence of applied magnetic fields and spin currents. Finally, we calculate the dynamical high frequency response of the system and compare our results with experimental data.

II. THEORETICAL DISCUSSION

The geometry we consider is displayed in Fig. 1. The magnetization $\mathbf{M}_S$ of the free layer points along the z direction, which is not in general parallel to the film plane. The y axis lies in the plane spanned by the magnetization of the free layer and the normal $\hat{\mathbf{n}}$ to the surface of the free layer. The x axis is oriented parallel to the surface. The magnetization $\mathbf{M}_S$, the applied Zeeman field $\mathbf{H}^0$, and the polarization $\hat{\mathbf{p}}$ of the injected spin current are oriented out of plane, given by the polar angles ϕ, ϕ_H, and ϕ_P with respect to the plane

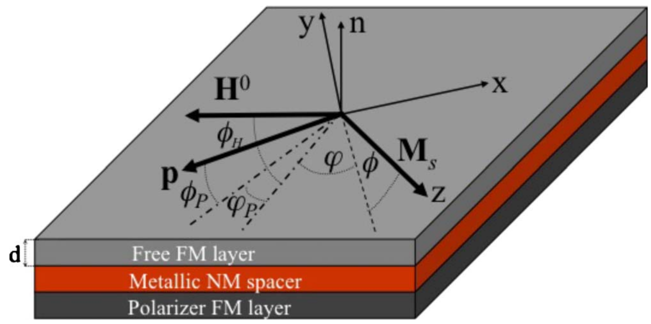

FIG. 1. (Color online) An illustration of the geometry used in the present paper. $\mathbf{H}^0$ is the externally applied magnetic field and $\mathbf{M}_S$ the magnetization. The z axis points along the equilibrium magnetization direction while the x axis is chosen to be always in the film plane.

of the film. The azimuthal angles φ and φ_P are the angles between the projections of $\mathbf{M}_S$ and $\hat{\mathbf{p}}$ onto the film plane and the projection of the Zeeman field $\mathbf{H}^0$. The free FM layer magnetization $\mathbf{M}_S$ will experience a torque whose effect on the FMR response and static magnetization is analyzed. Our interest will be focused to the following two situations: (i) the magnetization of the polarizing FM layer (being oriented parallel to the direction of $\hat{\mathbf{p}}$) is fixed along a chosen direction, independent of the direction and magnitude of $\mathbf{H}^0$. This means that the polarizer is fixed, e.g., by being coupled to a pinning layer. (ii) The magnetization of the polarizing layer ($\mathbf{M}^P = M_S^P \hat{\mathbf{p}}$) is free and may respond to the applied magnetic field. For this case, we calculate the equilibrium orientation of both magnetizations and explore the linear spin dynamics of the free layer with respect to its FMR response in presence of a spin-polarized current.

In the presence of an external field, the equilibrium magnetization of both magnetic layers can be obtained by setting the static torque on the magnetization to zero, i.e., we require $d\mathbf{M}/dt=0$. We assume that the magnetization of the polarizing layer is not influenced by the spin torque and the equilibrium magnetization for a free polarizing layer is given by $\varphi_P=0$ and ϕ_P which has to be determined by the relation:[18,19] $2H_0 \sin(\phi_H - \phi_P) = M^P \sin(2\phi_P)$, where H_0 is the magnitude of the dc field and the effective magnetization for the polarizing layer is defined by $M^P \equiv H_a^P + 4\pi M_S^P$ with H_a^P being a uniaxial anisotropy field.

A. Linearization of the equations of motion

In this section, we write down the basic equations of motion for the magnetization of the free layer. We will then derive the condition from which one deduces the equilibrium orientation of the magnetization and then discuss the nature of the ferromagnetic resonance response of the film. We begin with the phenomenological Landau-Lifshitz-Gilbert (LLG) equation including spin torque. This reads[6,8,9]

$$\dot{\mathbf{M}} = -\gamma \mathbf{M} \times (\mathbf{H}^{\mathrm{e}} + b\hat{\mathbf{p}}) + \frac{\alpha}{M_S}\mathbf{M} \times \dot{\mathbf{M}} + \frac{\gamma\beta}{M_S}\mathbf{M} \times (\mathbf{M} \times \hat{\mathbf{p}}), \tag{1}$$

where $\mathbf{H}^{\mathrm{e}}$ is the effective field, $\gamma > 0$ is the absolute value of the gyromagnetic ratio, α is the Gilbert damping constant, M_S is the saturation magnetization of the free layer, and $\beta = \hbar JP/(2eM_S d)$ is a spin torque parameter which has the dimension of a magnetic field.[6] The term $b\hat{\mathbf{p}}$ is the spin-torque effective field derived by Zhang *et al.*[20] While this term is quantitatively small for the films that we address later in the paper, we include it for completeness. The current density J is positive if the electrons flow from the free layer to the pinned one. P is the spin polarization of the current injected into the free layer.[6] Then d is the thickness of the free layer and $e > 0$ is the absolute value of the electron charge. For the sake of simplicity and as a first approach, we ignore the spatial variation and the magnetization dependence of P, which may considerably complicate the analysis.[6] The effective field is given by $\mathbf{H}^{\mathrm{e}} = (D/M_S)\nabla^2\mathbf{M} + \mathbf{H} + \mathbf{H}^d + \mathbf{H}^a$ with $D = 2A/M_S$ being the exchange stiffness. Here $\mathbf{H} = \mathbf{H}^0 + \mathbf{h}(\mathbf{r};t)$ is the applied magnetic field, where the static dc field is $\mathbf{H}^0 = H_0(\eta_x, \eta_y, \eta_z)$ with $\eta_x = -\sin\varphi \cos\phi_H$, $\eta_y = \cos\phi \sin\phi_H - \cos\varphi \sin\phi \cos\phi_H$ and $\eta_z = \sin\phi \sin\phi_H + \cos\varphi \cos\phi \cos\phi_H$. The small driving ac field is written as $\mathbf{h}(\mathbf{r};t) = (h_x, h_y, h_z)$. The dipole field is $\mathbf{H}^d = \mathbf{H}^{d0} + \mathbf{h}^d(\mathbf{r};t)$, where the static part is $\mathbf{H}^{d0} = -4\pi M_S \sin\phi(0, \cos\phi, \sin\phi)$ and the dynamic dipole field is $\mathbf{h}^d(\mathbf{r};t) = (h_x^d, h_y^d, h_z^d)$. The surface (or uniaxial) anisotropy field is given by $\mathbf{H}^a = \mathbf{H}^{a0} + \mathbf{h}^a(\mathbf{r};t)$ with $\mathbf{H}^{a0} = -H_a \sin\phi(0, \cos\phi, \sin\phi)$ and $\mathbf{h}^a(\mathbf{r};t) = -(H_a \cos\phi/M_S)(0, \cos\phi, \sin\phi) m_y(\mathbf{r};t)$. Finally, the spin current polarization vector is written as $\hat{\mathbf{p}} = (p_x, p_y, p_z)$ with $p_x = -\sin(\varphi + \varphi_P)\cos\phi_P$, $p_y = \cos\phi \sin\phi_P - \cos(\varphi + \varphi_P)\sin\phi \cos\phi_P$, and $p_z = \sin\phi \sin\phi_P + \cos(\varphi + \varphi_P)\cos\phi \cos\phi_P$.

To linearize the equations of motion, we write the magnetization of the free layer as $\mathbf{M}(\mathbf{r},t) = M_S\hat{\mathbf{z}} + m_x(\mathbf{r},t)\hat{\mathbf{x}} + m_y(\mathbf{r},t)\hat{\mathbf{y}}$, such that the $\hat{\mathbf{z}}$ axis is always oriented parallel to the equilibrium magnetization direction and $m_{x,y} \ll M_S$. We write the effective magnetic field as $\mathbf{H}^{\mathrm{e}} = \mathbf{H}^{\mathrm{e}0} + \mathbf{h}^{\mathrm{e}}(m_{x,y})$ with $\mathbf{H}^{\mathrm{e}0} = (H_x^{\mathrm{e}0}, H_y^{\mathrm{e}0}, H_z^{\mathrm{e}0})$ including the zero-order contributions and $\mathbf{h}^{\mathrm{e}}(m_{x,y}) = (h_x^{\mathrm{e}}, h_y^{\mathrm{e}}, h_z^{\mathrm{e}})$ containing the first-order contributions proportional to $m_{x,y}$. Thus, in the linear regime we can write,

$$\dot{m}_x = -\gamma m_y H_z^{\mathrm{e}0} + \gamma M_S h_y^{\mathrm{e}} - \alpha \dot{m}_y + \gamma\beta p_z m_x, \tag{2a}$$

$$\dot{m}_y = \gamma m_x H_z^{\mathrm{e}0} - \gamma M_S h_x^{\mathrm{e}} + \alpha \dot{m}_x + \gamma\beta p_z m_y. \tag{2b}$$

Here, $H_z^{\mathrm{e}0} = H_0\eta_z - M\sin^2\phi$, where $M \equiv 4\pi M_S + H_a$ is the effective magnetization of the free layer. From the requirement that the equilibrium orientation of the magnetization must have a form with vanishing zero order terms in the above equations, we extract the equilibrium conditions for the magnetization of the free layer. We have two conditions,

$$H_y^{\mathrm{e}0} - \beta p_x = 0 \tag{3a}$$

and

$$H_x^{\mathrm{e}0} + \beta p_y = 0, \tag{3b}$$

using $H_x^{\mathrm{e}0} = H_0\eta_x$ and $H_y^{\mathrm{e}0} = H_0\eta_y - M\sin\phi\cos\phi$. We further assume that the driving ac field has a harmonic dependence

$h_{x,y}(\mathbf{r};t)=h_{x,y}(\mathbf{r})e^{-i\Omega t}$ with Ω as the angular frequency. Then, it follows that $m_{x,y}(\mathbf{r};t)=m_{x,y}(\mathbf{r})e^{-i\Omega t}$ and the dipole field can be also written as $h^d_{x,y}(\mathbf{r};t)=h^d_{x,y}(\mathbf{r})e^{-i\Omega t}$. We are interested here in the limit of vanishing wave vector. It can be shown[19] that in this case, the dipole field components become $h^d_x(\mathbf{r})=0$ and $h^d_y(\mathbf{r})=-4\pi m_y(\mathbf{r})\cos^2\phi$. Thus, the dynamic components of the effective field can be cast into the form $h^e_x(\mathbf{r})=h_x$ and $h^e_y(\mathbf{r})=h_y-(M/M_S)m_y(\mathbf{r})\cos^2\phi$. Our attention is directed toward the uniform mode of the film so that exchange does not enter. With the above considerations, we can write the equations of motion for $m_{x,y}(\mathbf{r})$ in matrix form $\tilde{\mathbf{A}}\tilde{\mathbf{m}}=M_S\tilde{\mathbf{h}}$ with $A_{xx}=W_x-i\alpha\Omega/\gamma$, $A_{xy}=\beta p_z+i\Omega/\gamma=-A_{yx}$, and $A_{yy}=W_y-i\alpha\Omega/\gamma$. We have defined $W_x\equiv H^{e0}_z$ and $W_y\equiv H^{e0}_z+M\cos^2\phi$. After some minor manipulations and neglecting the term $(\alpha\Omega)^2$, the susceptibility tensor $\tilde{\boldsymbol{\chi}}=M_S\tilde{\mathbf{A}}^{-1}$ is therefore given by

$$\tilde{\boldsymbol{\chi}}=\frac{\gamma M_S(\Omega^2_{\mathrm{FMR}}-\Omega^2-i\Lambda)}{(\Omega^2_{\mathrm{FMR}}-\Omega^2)^2+\Lambda^2}\begin{pmatrix}\gamma W_y-i\alpha\Omega & -\gamma\beta p_z-i\Omega\\ \gamma\beta p_z+i\Omega & \gamma W_x-i\alpha\Omega\end{pmatrix},\tag{4}$$

using $\Lambda\equiv\alpha(W_x+W_y)\gamma\Omega-2\beta p_z\gamma\Omega$. Then, we find that the resonance frequency Ω_{FMR} in presence of the spin current can be expressed as

$$\Omega_{\mathrm{FMR}}=\gamma\sqrt{W_xW_y+\beta^2p_z^2}.\tag{5}$$

One should notice that the presence of the spin-polarized current enters into the resonance frequency of the film. Thus, at least in principle, one may also modulate or control the FMR resonance frequency by injecting spin-polarized currents. We will discuss this issue later in the paper.

The matrix elements χ_{xx} and χ_{xy} of the susceptibility tensor can be generally written as

$$\chi_{xx}=\gamma M_S\frac{\gamma W_y(\Omega^2_{\mathrm{FMR}}-\Omega^2)+\alpha\Omega\Lambda+i\{\gamma W_y\Lambda-\alpha\Omega(\Omega^2_{\mathrm{FMR}}-\Omega^2)\}}{(\Omega^2_{\mathrm{FMR}}-\Omega^2)^2+\Lambda^2},\tag{6a}$$

$$\chi_{xy}=-\gamma M_S\frac{\gamma\beta p_z(\Omega^2_{\mathrm{FMR}}-\Omega^2)+\Omega\Lambda+i\{\Omega(\Omega^2_{\mathrm{FMR}}-\Omega^2)-\gamma\beta p_z\Lambda\}}{(\Omega^2_{\mathrm{FMR}}-\Omega^2)^2+\Lambda^2}.\tag{6b}$$

The power absorbed is proportional to the imaginary part of the susceptibility,

$$\mathrm{Im}\{\chi_{xx}\}=\gamma M_S\frac{\gamma W_y\Lambda-\alpha\Omega(\Omega^2_{\mathrm{FMR}}-\Omega^2)}{(\Omega^2_{\mathrm{FMR}}-\Omega^2)^2+\Lambda^2},\tag{7a}$$

$$\mathrm{Im}\{\chi_{xy}\}=\gamma M_S\frac{\gamma\beta p_z\Lambda-\Omega(\Omega^2_{\mathrm{FMR}}-\Omega^2)}{(\Omega^2_{\mathrm{FMR}}-\Omega^2)^2+\Lambda^2}.\tag{7b}$$

B. Influence of spin-polarized current on the FMR linewidth

At this point, we need to link the susceptibility to the linewidth which will be the experimentally measured quantity that we will compare with theory later in the paper. In the experiment, the driving angular frequency Ω is fixed and the dc field H_0 is varied and swept through resonance. In essence the factor Ω_{FMR} is swept through Ω by varying H_0. Suppose the applied field is close to resonance, i.e., $H_0=H_0^{(r)}+\Delta H$, where $H_0^{(r)}$ is the resonance field (where $\Omega_{\mathrm{FMR}}=\Omega$). When ΔH is small, we expand Ω^2_{FMR} obtaining the following expression:

$$\Omega^2_{\mathrm{FMR}}-\Omega^2=\gamma^2\left(W_x\frac{dW_y}{dH_0}+W_y\frac{dW_x}{dH_0}+2\beta^2p_z\frac{dp_z}{dH_0}\right)\Delta H.\tag{8}$$

From the denominator of the susceptibility [Eq. (4)], we obtain the FMR linewidth defined as the half width at half maximum of the Lorentzian absorption line,

$$\Delta H=\frac{\alpha\Omega}{\gamma\Xi}-\frac{2\Omega\beta p_z}{\gamma\Xi(W_x+W_y)},\tag{9}$$

where Ξ is the so-called dragging function,[21]

$$\Xi\equiv\frac{W_x\frac{dW_y}{dH_0}+W_y\frac{dW_x}{dH_0}+2\beta^2p_z\frac{dp_z}{dH_0}}{W_x+W_y}.\tag{10}$$

Note that in order to obtain the peak-to-peak linewidth in the derivative of the absorption line, we need to multiply ΔH by a factor $2/\sqrt{3}$ (assuming a Lorentzian line shape with ΔH being the half width at half maximum linewidth). To calculate the linewidth, we need the dragging function, and the total derivatives of the quantities W_x, W_y, and p_z which have to be calculated taking into account the variation in the angles ϕ, φ, and ϕ_P, φ_P (in case of unpinned polarizer) with the applied field H_0. This can be obtained by an appropriate use of the equilibrium conditions given by Eq. (3) in the section above. In principle, one can obtain an analytic expression for the dragging function, as described in Eq. (6) of Ref. 21. In the case of a pinned polarizer, the dragging function becomes

$$\Xi\equiv\eta_z+H_0\left(\eta_y\frac{d\phi}{dH_0}+\eta_x\cos\phi\frac{d\varphi}{dH_0}\right)+\frac{2\beta^2p_z}{W_x+W_y}\left(p_y\frac{d\phi}{dH_0}+p_x\cos\phi\frac{d\varphi}{dH_0}\right).\tag{11}$$

However, in the case of an unpinned polarizer, the dragging function becomes a more complicated expression and for the sake of simplicity, we omit a more complete expression for the linewidth of the unpinned polarizer.

The above equations represent the main theoretical results presented in this paper. At first, the equations of motion [Eq. (2)] allow us to obtain the macrospin dynamics of the magnetization in the linear regime. Equation (3) gives us the orientation of the magnetization at equilibrium. The general structure of the susceptibility tensor is provided by Eqs. (4), (6), and (7) whereas the FMR resonance frequency and resonance field can be obtained from Eq. (5). Finally, the FMR linewidth is given by Eqs. (9)–(11).

III. RESULTS AND DISCUSSION

The analytical expressions we have obtained above allow us to calculate the dependence of the FMR linewidth and resonance frequency on the spin current. The expressions are quite general and permit the analysis of the problem in a rather general way and for any orientation of the dc external magnetic field. Note that the relevant quantities such as the susceptibility, the linewidth, the resonance field, the resonance frequency, and the magnetization depend on the magnitude of the spin current density and on the properties of the polarizing layer.

In the following, we will present the results of calculations based on the formulas above. The purpose of these is to explore the influence of polarized current on the FMR response, for various geometries. Thus we discuss some special cases of interest. We refer to case 1 as the situation for which the polarizer magnetization is constrained to the film plane and oriented parallel to the projection of the applied magnetic field onto the film plane. Case 1 corresponds to $\phi_P=0$. We also discuss the case 2 for which the polarizer magnetization is oriented perpendicular to the film plane, which means $\phi_P=\pi/2$.

We have also fitted our theory to the FMR experiments performed at a frequency of 9.3 GHz. The measurements were carried out with a commercial Bruker spectrometer and at a temperature of 300 K. The sample is prepared by electron-beam lithography in a multistep process in which we fabricate an array of 420 pillar structures with a size of $4\times4\ \mu m^2$ and all structures are connected in series to increase the current density (compared to a parallel connection) and to guarantee enough magnetic material for the FMR measurement.[10] The pillars consist of 20 nm Co, 10 nm Cu, and 10 nm of Py. Since the upper electrical contact for each pillar has a lateral size of $1\times1\ \mu m^2$ being smaller than the lateral size of the pillar, we assume that the current flows only in the volume of the pillar which is below the upper contact. With this assumption, a maximum current density of $3.6\times10^6\ A/cm^2$ results. Within the FMR measurement, the heating of the sample due to the high current density is avoided by a cooling setup, consequently the magnetic parameters (e.g., the saturation magnetization) do not change too much. The following parameters are found by the measurements: the saturation magnetization is $\mu_0 M_S=857$ mT and the effective magnetization $\mu_0 M=920$ mT. The damping parameter α has a value of 0.0193 and the gyromagnetic ratio is $\gamma=186.2$ GHz/T. We estimate the field associated to the spin transfer to be $\beta=0.45PJ$. Using the polarization factor P of 0.4, we get a maximum spin torque field of about 0.65 mT.

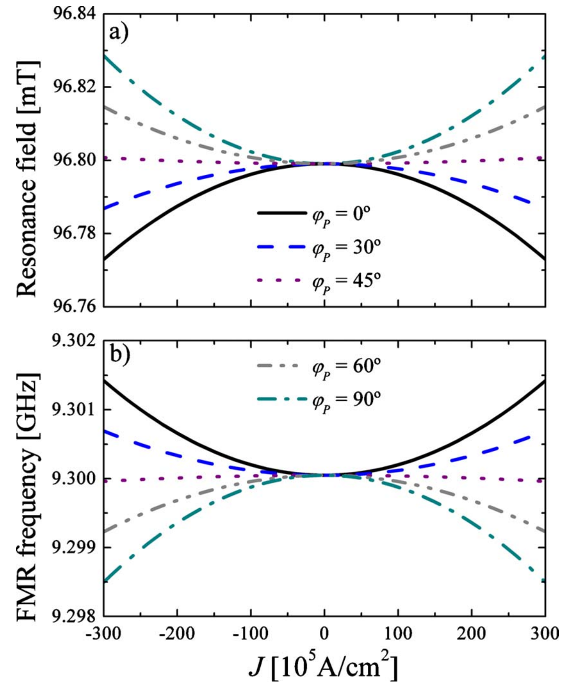

FIG. 2. (Color online) In-plane angular dependence of the resonance field (a) and FMR frequency (b) vs current density for case 1 and some orientations of the polarizer within the plane.

Figure 2 shows the resonance field (a) and the FMR frequency (b) calculated from Eq. (5) as a function of the spin current density and for different in-plane directions of the polarizer with respect to the applied field that is applied in the film plane. This example corresponds to case 1 where the magnetization of the polarizer is pinned and will not follow the external field. A small shift in the resonance field and in the resonance frequency is predicted if the current density is increased. Note that the sign of this shift changes with the angle between the external field and the direction of the polarizer.

It can be seen that for the current densities we are interested in this paper (at most $10^6\ A/cm^2$), the spin-torque term has a very small effect on the equilibrium magnetization of the free layer. This can be easily understood by noting that the spin transfer enters in the equilibrium conditions for the magnetization through the terms βp_x and βp_y, which are in the order of 0.65 mT or less. Thus, in this limit, the spin torque cannot compete with the effective field components in Eq. (3).

Compared to the relatively small effect in the resonance field and frequency, the FMR linewidth changes considerably due to the spin torque. Notice that the linewidth in Eq. (9) contains two contributions. The first results from the Gilbert damping and the second from the spin-torque effect. We find that the magnitude of the term resulting from spin torque [proportional to $2\beta p_z/(W_x+W_y)$] is comparable to the term having its origin from Gilbert damping (proportional to α) and, therefore, the linewidth can be manipulated and tuned with a proper control of the current density. Moreover, by an

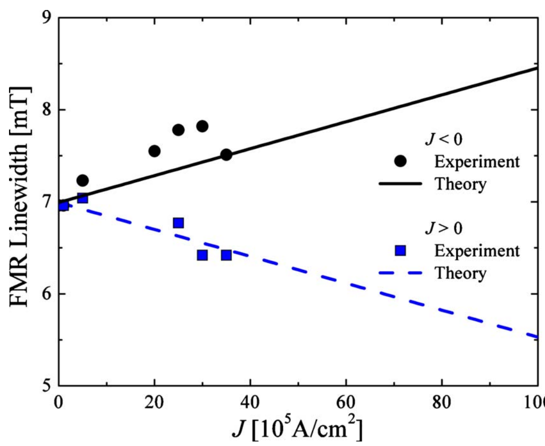

FIG. 3. (Color online) In-plane FMR linewidth vs current density (case 1). Points represent the experimental data, and the solid and dashed lines correspond to our theory for negative and positive current densities, respectively.

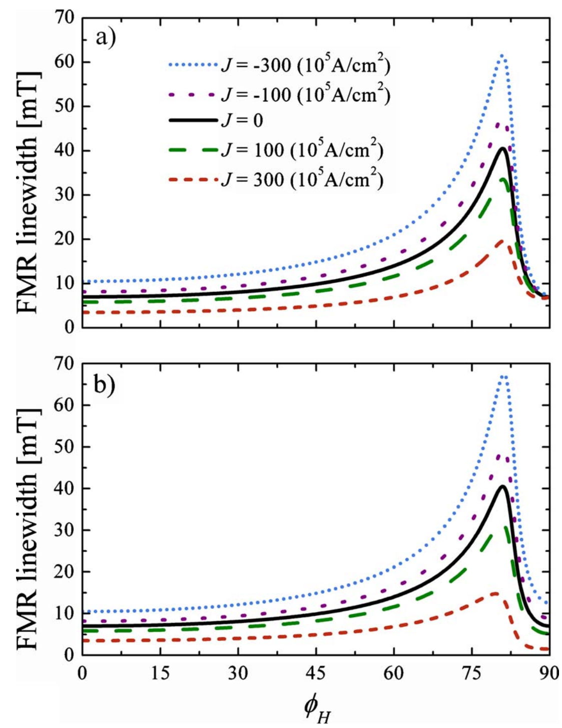

FIG. 4. (Color online) FMR linewidth vs field angle for case 1 and different current densities. The solid lines correspond to zero current density while the lines above (below) the solid line correspond to negative (positive) currents as depicted in the figure. In (a) the polarizer is pinned at $\phi_P = \varphi_P = 0$, and in (b) the polarizer is free to follow the applied field.

inversion of the direction of the current the variation in the linewidth can change in sign, meaning the linewidth increases for negative current densities and decreases for positive current densities as illustrated in Fig. 3. Here the points represent the experimental data, the solid line corresponds to negative current densities (electrons flowing from the pinned layer to the free one), and the dashed line corresponds to positive current densities. This plot represents the simplest situation in which the polarizer magnetization is parallel to the applied field lying in the film plane. One can see that the experimental data fit very well to the calculated values for the linewidth.

We turn now to discuss the *angular* dependence of the FMR linewidth in presence of spin-transfer torque. In Fig. 4, we show calculations of the linewidth vs the out-of-plane angle of the applied field for different current densities, as shown in the inset. We first observe that negative (positive) currents increase (decrease) the linewidth for the overall angular dependence and not just in the in-plane case of Fig. 3. The peak in Figs. 4(a) and 4(b) is a consequence of the dragging of the magnetization and occurs for approximately 81° independent of the current. In Fig. 4(a), the polarizer magnetization is held fixed in the plane while in Fig. 4(b), the polarizer magnetization is free to follow the applied field. The difference in linewidth between pinned and unpinned polarizers is small whenever the orientation of the applied field is close to the film plane. However, as the field is tipped out of the plane, the differences in linewidth are more important, as one can see in the limit of an applied field perpendicular to the plane. In this limit, and for a pinned polarizer, we observe from Fig. 4(a) that the linewidth is almost independent of the current density. Otherwise, in the unpinned regime, the linewidth for $\phi_H \rightarrow 90°$ depends considerably on the current density, as shown in Fig. 4(b). This fact can be easily understood from Eq. (9). It can be shown that for $\phi_H = 90°$ the denominator of the linewidth is almost independent of the current and the dependence of the linewidth with J is controlled by the numerator of Eq. (9), $\alpha\Omega - 2\Omega\beta p_z/(W_x + W_y)$. Then it follows that the difference we observe in Fig. 4 resides in the factor $p_z = \sin\phi \sin\phi_P + \cos\varphi \cos\phi \cos\phi_P$. In the pinned case, we have $\phi_P = 0$, then $p_z = \cos\varphi \cos\phi$ and when the applied field is close to the normal, the magnetization is aligned with the field ($\phi = \pi/2$) and $p_z \rightarrow 0$ making the linewidth independent of the current density. On the other hand, in the unpinned regime, and for an applied field close to the normal, we also have $\phi = \pi/2$ but now ϕ_P is different from zero making $p_z = \sin\phi_P$ nonzero and the linewidth depends on the current density as shown in Fig. 4(b).

We have also calculated the dependence of the FMR linewidth under the presence of a spin-polarized current for different directions of the applied field. In Fig. 5, the polarizer is pinned *parallel* to the film and in Fig. 6 it is pinned *perpendicular* to the film plane. We observe that the linewidth is practically linear with the current and the slope depends on the direction of the applied field and on the orientation of the polarizer. In both cases, the linewidth is maximum near $\phi_H = 81°$, corresponding to the linewidth peaks in Fig. 4.

We have also solved numerically the equations of motion [Eq. (2)] in order to illustrate the influence of the spin-polarized current on the precessional orbits of the magnetization, induced by the microwave field. These orbits are displayed in Fig. 7, where the top panel corresponds to a positive current density $J = 50 \times 10^5$ A/cm^2, the central panel to zero current, and the bottom panel corresponds to a negative current density $J = -50 \times 10^5$ A/cm^2. The polarizer is pinned along the direction of the applied field, which is parallel to the plane and fulfill the resonance condition. Here

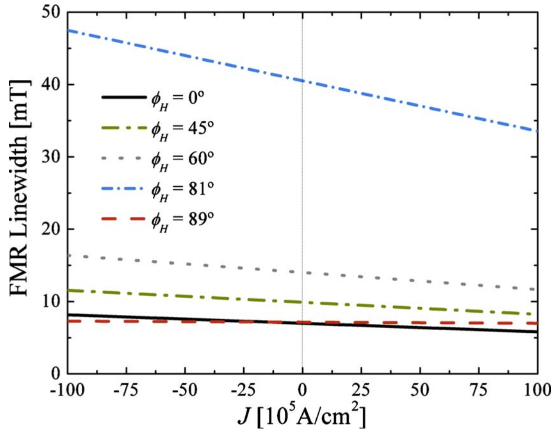

FIG. 5. (Color online) FMR linewidth vs current density for case that the polarizer is pinned parallel to the film. Different lines represent different orientations of the applied field.

we have fixed the initial condition to a magnetization almost aligned with the resonance field. The magnetization evolves to a stable elliptic orbit, whose area is a measure of the magnetic damping. Note that this ellipticity would be even present without spin-torque contribution due to the presence of magnetic anisotropy in the system. For $J<0$, the area of the stable orbit is reduced compared to the case without current. This means that the damping increases for negative currents in agreement with Fig. 3. On the other hand, for positive current, the radius of the orbit increases in relation to the zero current case, implying that the damping decreases.

IV. FINAL REMARKS

In this paper, we have investigated the effect of a spin-polarized current on the ferromagnetic resonance response of magnetic thin films. We have formulated the problem analytically and in a rather general way, such that the theory allows the reader to calculate the overall angular dependence of characteristic FMR quantities such as the high frequency susceptibility, FMR linewidth, and FMR frequency. Besides, the theory enables us to consider a polarizer layer either free or fixed. The spin torque influences the frequency and the linewidth of the FMR response of the film and depending on the direction of the electron flow, the additional damping associated to the spin current can play the role of damping or antidamping, in nice agreement with experimental results. Finally we can conclude that ferromagnetic resonance is a powerful tool to detect spin-transfer torque effects in the small current limit, at the onset of spin-transfer-driven dynamics.

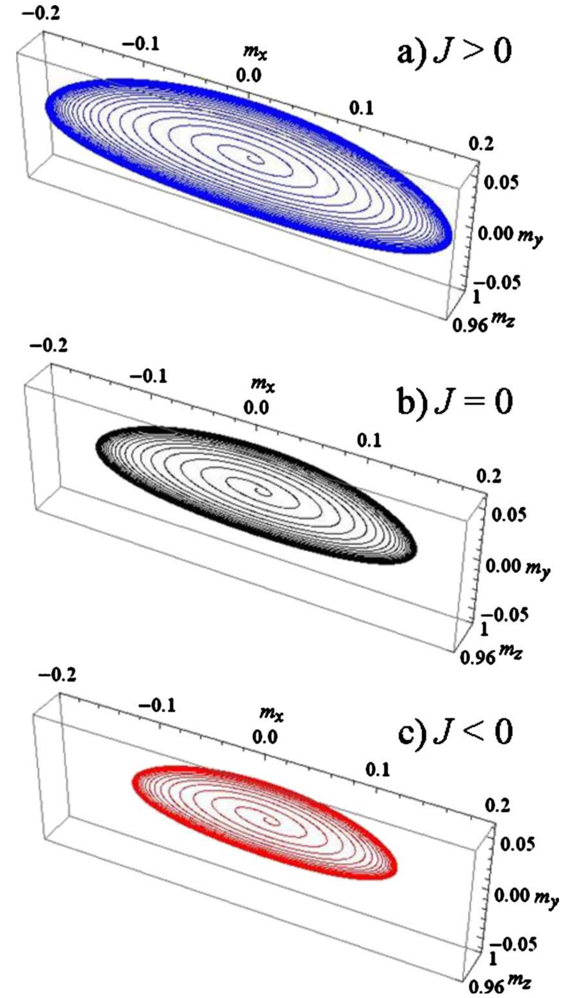

FIG. 7. (Color online) Precessional orbits of the magnetization for positive (top panel), zero (middle panel), and negative (bottom panel) current densities. The polarizer magnetization has been pinned parallel to the in-plane resonance field. The absolute value of the current density for cases (a) and (c) is $J=50\times10^5$ A/cm^2. This figure illustrate that the spin-transfer torque can play the role of damping for negative currents and antidamping for positive currents.

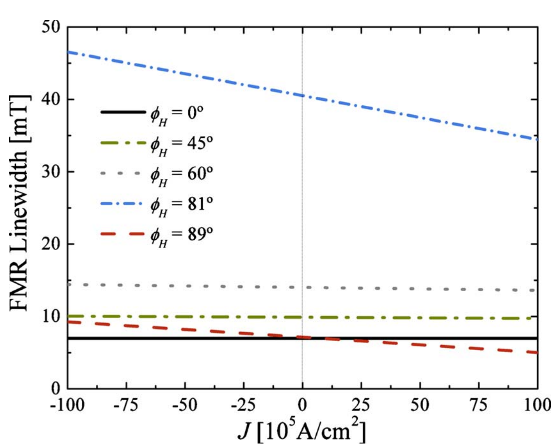

FIG. 6. (Color online) FMR linewidth vs current density for case that polarizer is pinned perpendicular to the film. Different lines represent different orientations of the applied field.

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