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TÍTULO PROYECTO : "SPIN TORQUE NANO-OscILLATORS, A MODEL THAT GOES BEYOND THE MACRO-SPIN APPROXIMATION"

DISCIPLINA PRINCIPAL : FISICA DE SOLIDOS
GRUPO DE ESTUDIO : FISICA TEORICA Y EXP
INVESTIGADOR(A) RESPONSABLE : RODRIGO ENRIQUE ARIAS FEDERICI
DIRECCIÓN :
COMUNA:
CIUDAD:
REGION : METROPOLITANA

FONDO NACIONAL DE DESARROLLO CIENTIFICO Y TECNOLOGICO (FONDECYT)
Moneda 1375, Santiago de Chile - casilla 297-V, Santiago 21
Telefono: 2435 4350 FAX 2365 4435
Email: informes.fondecyt@conicyt.cl
INFORME FINAL
PROYECTO FONDECYT REGULAR

MODIFICACIONES ACADÉMICAS

**Nuevas Solicitudes para Evaluación**

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**Otros Aspectos Importantes a Considerar**

Fondecyt, Estoy ingresando un artículo aceptado en Physical Review en relación directa al proyecto Fondecyt 1130192 para efectos de que se pueda incluir en el informe final.
The objective of the project ”Spin torque nano-oscillators, beyond the macro-spin approximation” was to study theoretically the magnetization dynamics of very thin ferromagnetic disks that are excited via spin transfer torques. Usually this has been studied under the so called ”macro-spin approximation”, i.e. it is assumed that the mode that enters into auto-oscillation is uniform, and its dynamics under spin transfer torque and dissipation is studied. The idea of the project was to go beyond the macro-spin approximation and examine when non uniform magnetization configurations are important in the magnetization dynamics of the system.

In this investigation the ferromagnetic disks considered form part of a nano-pillar structure, they correspond to the dynamically ”free” layer, made of soft ferromagnets. There is another ”fixed” ferromagnetic layer separated from the free layer by a metallic spacer: an electric current runs through the structure, it gets spin polarized in the fixed layer, it maintains its polarization in the short metallic spacer, and then it impinges on the free layer, transferring spin angular momentum to it. Under the action of a dc spin polarized current the free ferromagnetic disk enters into a self-oscillation regime when dissipation is counteracted by the energy transfer associated with the angular momentum transfer associated with the spin polarised current (there is also an applied magnetic field in plane). This is a self sustained oscillation with an amplitude that saturates due to non linear terms in the dynamics.

The results of the project were:

A) in an approximate model for the dynamics of the soft ferromagnetic disk, where the demagnetizing field is approximated by its main term, we determined the instability thresholds of spin wave modes when the uniform mode is in a self-oscillatory regime.

B) with an improved model that includes the full effect of the demagnetizing field (that then includes important finite size effects of the disk) we determined the instability thresholds of spin wave modes of the disk in the range where the lowest self-oscillatory mode is in oscillation, which in this case for nanometric radii corresponds to an edge mode.

C) using the model of part ii) we determined the spin wave modes of a very thin ferromagnetic disk, and we determined their excitation via different mechanisms. In particular we studied parametric resonance through the spin torque term.
Detailed results:

For all the results that we will present we developed a model of the dynamics of the magnetization of a very thin ferromagnetic disk that is appropriate to describe the circular geometry and the boundary conditions, and that is a natural selection for the model of study A) since it describes very directly the linear modes in that case. The ferromagnetic disk is magnetized in plane via an assumed applied in plane magnetic field.

First, we assumed that the thickness of the disk was close to the exchange length of the soft material (for practical evaluations we used Permalloy, with a 6nm exchange length), that justifies to assume that the static and dynamic magnetization are uniform over the thickness of the film. Then the problem is effectively a 2D problem, and given the circular geometry we used polar coordinates. The conservative dynamics of the magnetization was written in Hamiltonian form, using two variables \( a(\vec{x}, t), a^*(\vec{x}, t) \) to describe the dynamics, and that guarantee that the magnetization norm is conserved. Then we used a complete basis to describe the fields \( a, a^* \), that is a series in terms of Bessel functions that do satisfy the free boundary conditions that we imposed on the magnetization. Then the dynamic variables become the time dependent amplitudes of this expansion in terms of this basis. The conservative dynamics is still of Hamiltonian form in the new variables, since the associated transformation of variables is canonical, and it includes the Zeeman, exchange and demagnetizing fields. The non conservative terms were also considered in the model: spin-transfer torque, and Landau-Lifshitz dissipation.

Secondly, we describe the different studies:

A) In this study the demagnetizing field was approximated by the form that it takes for an infinite very thin film, i.e. its only component is perpendicular to the plane with the associated demagnetizing factor of a very flat film. Solving the model we obtained that beyond a critical dc current the uniform mode enters into a self oscillatory regime, the dynamics of non uniform modes was studied analytically. We determined the instability thresholds of these non uniform modes as a function of dc current and of the radii of the disks: beyond these thresholds the uniform mode may coexist with the excited non uniform, but this is left for a future study. These thresholds were obtained analytically considering that the uniform mode had attained a large amplitude, thus nonlinear terms of its dynamics were considered. The results show that the uniform mode self-oscillation is more stable for small radii.

We verified the theoretical results with numerical simulations of the dynamics of the lowest two modes.

B) We complemented the model of part A) by considering the full effect of the demag-
netizing field in the magnetization dynamics. The new terms of the demagnetizing field are proportional to the thickness of the film (i.e. it can be used as a small parameter in the theoretical analysis), and they consider the effect of magnetic volume and surface charges (the latter arise from the top and lower surfaces of the disk, as well as from the circular edge). The expression for the demagnetizing energy that enters the Hamiltonian dynamics takes an algebraic form in the amplitudes of the modes that are the dynamic variables (its coefficients depend on integrals that are calculated numerically once, and stored for the dynamic simulations). With the new Hamiltonian we determined the static equilibrium magnetization configuration: it corresponds to a magnetization mainly in the direction of the applied magnetic field, but that becomes curved near the circular edges of the sample (this happens in order to avoid surface charges on the edges). Then we determined the linear dynamics modes of this model, and we changed variables to describe the dynamics of the magnetization: we describe it in terms of the basis provided by the linear modes of the system. The amplitudes of the different linear modes become the dynamic variables (this is again a canonical transformation). Thus, a quadratic model of the Hamiltonian is diagonal in these amplitudes, with the diagonal coefficients corresponding to the frequencies of the different modes. Then, we wrote the nonlinear terms of the Hamiltonian in terms of the new amplitudes, as well the terms arising from the non conservative terms of the dynamics.

When the dynamics of this model was studied it happens that for radii in the range of 50nm (Permalloy) the mode that starts to auto-oscillate first is an edge mode that has a very close frequency to the quasi-uniform mode. We thus studied the range of dc current under which this mode auto-oscillates without another mode becoming unstable: it is a small range until the quasi-uniform starts growing. For higher currents it is expected a co-existence of auto-oscillation of these two modes, but this study was left for a future project.

C) The finite size effect of the disk on the demagnetizing field was considered in order to determine the spin wave modes of these very thin ferromagnetic films, as was explained in B). The equations of motion for the magnetization were linearized with respect to the equilibrium configuration of the magnetization, which is no longer purely uniform. We obtained the frequencies and shapes of the spin wave modes under free boundary conditions on the edges (the results agree well with previous micromagnetic simulations). The frequencies of all modes result appreciably higher than the corresponding values of case B). We also determined the excitation of these modes under an ac applied magnetic field, and under an ac current with associated Oersted and spin torque fields: all this under a forcing frequency similar to the frequencies of the modes. We also studied the case of parametric resonance of the
first modes via the spin torque term that is proportional to a time dependent current: in this case its ac part oscillates with a frequency that is approximately twice the natural frequency of the mode.

Present status of the studies:

The work detailed in A) was submitted to Phys. Rev. B in August 2015, we received response in September: although the Referees seemed in general to regard well the submission they were concerned about finite size effects of disk, that indeed exist for nanometric disks. Thus we decided to do in detail the study of part B) that includes the full effect of the demagnetizing field: this involved quite a bit of work so we resubmitted in February 15th 2016, and one month later we are still waiting response from one Referee that is busy.

With respect to the study C), the part on the determination of the linear modes was sketched in the previous submission, but we plan to submit a more complete version of it, together with the study of the excitation of modes, in the following months (the parametric resonance study is finished in terms of theoretical results and corroboration with numerical results, but we still need to verify if we can make contact with eventual experimental results on the subject).

Also, this project was the main research of the PhD thesis of Daniela Mancilla: the plan for her is to finish in the next 6 months, after submitting the study C) for publication, and then writing her thesis.
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<tr>
<td>Autor (a)(es/as) :</td>
<td>D. Mancilla-Almonacid, R.E. Arias</td>
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<td>Nombre Completo de la Revista :</td>
<td>Physical Review B</td>
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<td>Instabilities of spin torque driven auto-oscillations of a ferromagnetic disk magnetized in plane</td>
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<td>Mancilla, D.F.; Arias R.E.</td>
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OTRAS PUBLICACIONES / PRODUCTOS

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CONGRESOS

Nº : 1
Autor (a)(es/as) : Daniela Mancilla, Rodrigo Arias
Título (Idioma original) : "Inestabilidad de una auto-oscilacion de la magnetizacion en un disco ferromagnetico circular"
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1

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"Nano-osciladores por transferencia de spin, un modelo que va más allá de la aproximación macro-spin"

**Nombre y Apellidos del(de la) Alumno(a) :**

Daniela Mancilla Almonacid

**Nombre y Apellidos del(de la) Tutor(a) :**

Rodrigo Arias Federici

**Título Grado :**

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**Institución :**

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**País :**

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Nombre y Apellidos del(de la) Tutor(a): Rodrigo Arias Federici
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ANEXOS
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