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Exchange-dominated eigenmodes in sub-100 nm permalloy dots: a micromagnetic study at finite temperature

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ABSTRACT

Micromagnetic simulations at room temperature (300 K) have been carried out in order to analyse the magnetic eigenmodes (frequency and spatial profile) in elliptical dots with sub-100 nm lateral size. Features are found that are qualitatively different from those typical of larger dots because of the dominant role played by the exchange-energy. These features can be understood most simply in terms of nodal planes defined relative to the orientation of the static magnetization. A new, generalized labeling scheme is proposed that simplifies discussion and comparison of modes from different geometries. It is shown that the lowest-frequency mode for small dots is characterized by an in-phase precession of spins, without nodal planes, but with a maximum amplitude at the edges. This mode softens at an applied switching field with magnitude comparable to the coercive field, and determines specific aspects of magnetization reversal. This characteristic behavior can be relevant for optimization of microwave assisting switching as well as for maximizing interdot coupling in dense arrays of dots.

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I. INTRODUCTION

Progress in nanofabrication techniques makes it possible to realize magnetic dots with a lateral size as small as a few tens of nanometers.[1] These are expected to behave as single-domain particles and are key elements for the design of either high-density storage media or nanomagnetic logic circuits.[2] Knowledge of the spin dynamics in these dots is relevant because the small size is comparable with the exchange correlation length and can lead to significant effects on the spin-wave eigenmodes. Spin-wave excitations occur in the GHz range and can be a serious source of noise in real devices, and affect potential rates of data writing or processing.[3]

In this work, we perform a computational study of the spectrum of eigenmodes of sub-100 nm elliptical permalloy ($Ni_{80}Fe_{20}$) dots at room temperature (300 K) obtained by solving stochastic Landau-Lifshitz-Gilbert (LLG) equations. The temporal evolution of the magnetization of each single cell is recorded while the magnetization oscillates in response to thermal fluctuations. By means of a local temporal Fourier transform analysis we are able to calculate both the complete spectrum of excitations of the dot and the spatial profiles of the corresponding eigenmodes. This is different from any approach where the temporal Fourier transform of the average magnetization is calculated, which only gives access to a subset of eigenmodes, namely those with a non-zero average magnetization profile. Moreover, the present method, based on thermal activation of the system, allows one to overcome the well-known limitation, connected to the fact that the excitation of the dot by a field pulse permits to reveal only those modes that have the proper pulse-symmetry.[4,5,6] For the considered dots, having sub-100 nm lateral dimensions, we find that the exchange energy makes the dominant contribution to the frequency of all eigenmodes. As a consequence, some features of the modes are qualitatively different from those typical of larger dots.[7] A rationalized labeling scheme is proposed for the modes, based upon the presence of nodal planes in the direction parallel or perpendicular to the static magnetization. Moreover, we investigate the evolution of the mode frequencies as the external field is increased to near where reversal occurs, showing that, due to the considered small lateral dimensions, the softening of the fundamental mode occurs, suggesting novel opportunities in the design of microwave assisted switches or spintronic and magnonic devices.

DETAILS OF THE CALCULATIONS

Micromagnetic simulations have been carried on using a customized version of the commercial software MICROMAGUS. Details about the code and its characteristics can be found elsewhere.[8] The elliptical dot, having dimensions were 100×60×5 nm^3, was discretized in cells with size of 1×1×5 nm^3 (the small lateral size was chosen in order to better mimic the dot curvature). A stochastic magnetic field was used to model thermal fluctuations using the stochastic LLG option, thereby simulating thermal reduction of the magnetization at finite temperatures. The magnetic parameters of polycrystalline Permalloy have been used, with $^3 = 1.76\times10^7\, rad\cdot(Oe\cdot s)^{-1}$ as the gyromagnetic ratio, ±=0.02 for the phenomenological damping constant, M_s=860 G for the saturation magnetization, A= 1. 3×10^{-6} erg/cm for the exchange stiffness, and a moderate uniaxial anisotropy (K_1=1×10^5 erg/cm^3) directed along the major axis of the ellipse (x-axis). The trajectory of the magnetization of each discretized cell at T=300 K is recorded for 200 nanoseconds, at a constant value of the external field applied along the major axis. This data was used to determine the frequency and the spatial profile of the eigenmodes using a local Fourier-transform analysis. The power spectrum $P_{i,j}(f)$, of the magnetization was calculated for each discretization cell located at (i,j). Then, the average power spectrum is calculated as the sum of the power spectra of each single cell. The two dimensional spatial distribution of the dynamical magnetization for each eigenmode is determined from the Fourier coefficients of the corresponding eigenfrequency. Such profiles are presented as bidimensional plots of modulus and phase of the components of the time varying magnetization.

RESULTS AND DISCUSSION

Fig. 1 (left panel) shows the spectra calculated at room temperature for different values of an external field H applied along the major axis of the ellipse. In order to avoid artifacts at unstable maxima, the field is applied at about 2 degrees from the x axis. It can be seen that there are several modes whose position in frequency evolves with the applied field intensity. It is important to notice that because simulations are performed with random thermal fields at 300 K all the eigenmodes of the dot are simultaneously excited. Each mode is labeled with two integer indices (*m*,*n*) whose values correspond to the number of nodal planes. The number of nodal lines perpendicular to the major axis of the ellipse are given by "*m*" and the number perpendicular to the minor axis are given by "*n*". Example results are depicted in the right panel of Fig. 1, where the spatial profile of both the intensity and the phase of the perpendicular magnetization component is illustrated for a number of low frequency modes.

It can be seen that all modes display nodal planes, with the exception of the (0,0) one. The (0,0) mode would be the only mode present in the spectrum if one calculates the Fourier transform of the time averaged magnetization, as shown in the bottom spectrum of Fig. 1. Therefore, from the experimental point of view, the (0,0) mode is a sort of fundamental mode, that would be the only one detected in either a ferromagnetic resonance or a Brillouin light scattering experiment at normal incidence.

This labeling scheme has advantages over schemes used in previous studies of larger dots.[9,10,11] Previous studies identify the mode with the largest average magnetization as the fundamental (F) one: it normally has maximum amplitude in the dot center and is not the lowest frequency mode. At frequencies lower than the F mode, several end-modes (*n*-EM) can exist, followed by *m*-BA (backward) modes: i.e. dipolar modes with *m* nodal lines perpendicular to H. At larger frequencies with respect to the F mode, *n*-DE (Damon–Eshbach) modes can exist, corresponding to modes with *n* nodal lines parallel to the direction of H. The distinction between parallel and perpendicular nodal lines is significant, but the terminology "backward" and "Damon-Eschbach" are historically derived from competing magnetostatic and exchange energies, and can be misleading for small geometries where magnetostatic contributions are minimal.

Compared to the above phenomenology, typical of previously studied submicrometric dots, the situation is rather different here. As illustrated in Fig. 2, the present "fundamental" (0,0) mode is the mode at the lowest frequency. Magnetostatic effects appear in the fact that the (0,0) mode amplitude is larger at the edges than the dot center. Interestingly, there are no true edge modes localized to the dot boundaries at frequencies below that of the fundamental mode, as in micrometric dots. Additionally, there is no decrease of the frequency for (*m,0*) modes on increasing *m*, which is again different from the BA modes discussed in larger dots. The reason for this is the dominant role of exchange energy in the small dot is due to its sub-100 nm lateral dimensions which are comparable to the exchange correlation length (about 5 nm in permalloy), so that exchange energy dominates over magnetostatic contributions. Of course, the frequency increase of modes (*m*, *n*) and (0, *n*) is more rapid than that of the (*m,0*) modes, as seen in Fig. 2, because of the smaller lateral dimension of the dot along the short axis. In fact, in the exchange-dominated regime, one expects a quadratic increase of the spin-wave frequency with the effective wavenumber.[6]

In Fig. 3 the evolution of the eigenmodes with external field is shown. The frequency decreases with decreasing external field. When the field is reversed and its value approaches that of the coercive field (H_x=-630 Oe), the (0,0) mode softens, coinciding with the reversal of the dot magnetization.[12] This is another important aspect, typical of the present sub-100 nm dot for which reversal is a relatively uniform process. In larger dots, either the edges reverse first, before the dot center, or the reversal proceeds through a sequence of complex intermediate states (e.g. vortices). In this latter case one of either an EM or BA mode becomes soft and triggers the magnetization reversal.[10] In this way the symmetry of the mode is correlated with the initial path of the reversal process. For the small dots discussed here, reversal approximates that of a block spin, and corresponds to softening of the (0,0) mode which has no nodal planes.

It is interesting to note that the (0,0) mode is also efficiently excited by a uniform magnetic field pulse (as are, to a less extent, the (2,0), (4,0) and (0,2) modes, whose average dynamical magnetization is substantially different from zero). This can be seen in Fig. 3 where full circles indicate the modes that are excited by a uniform perpendicular field pulse with the corresponding spectrum shown in the inset. Therefore, in our dot the (0,0) mode has three distinct characteristics with respect to the other modes: (i) it has the largest average magnetization, (ii) it becomes soft in proximity of the magnetization reversal and (iii) it exhibits a pronounced localization at the dot boundaries. The simultaneous combination of these features makes it attracting for different classes of problems. First, in the context of microwave assisted switching, (i) and (ii) represent a clear advantage to achieve efficient switching with an external RF field. In second place, (i) and (iii) correspond to a more efficient interdot coupling which can be key in in dense arrays of dots for applications as magnonic crystals,[13] nano-magnetic logic gates,[2] and artificial spin ices.[14]

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FIGURES CAPTIONS

Fig. 1. (Left panel) Simulated eigenmodes spectra of the elliptical dot under investigation for different values of the external field H, applied along the major axis of the ellipse. The three upper spectra are calculated as the average from the spectra of the discretized cells, while bottom spectrum is relative to the average magnetization of the dot. (Right panel**)** **c**alculated spatial profiles of the intensity and the phase for a number of relevant eigenmodes.

Fig. 2 Evolution of the frequency of the different eigenmodes (*m*,*n*) at remanence (i.e. in absence of any external field) as a function of the mode index *m* and/or *n*. The dotted lines are guide to the eyes.

Fig.3 Evolution of the eigenmodes frequency with the intensity of the magnetic field, applied along the major axis of the elliptical dot, from +700 Oe to -625 Oe. The full circles correspond to the four modes that can be excited with a perpendicular field pulse and the corresponding spectrum is reported as a bottom inset.