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Abstract

Spin-wave spectra of perpendicularly magnetized disks consisting of a 100 nm permalloy (Py) layer sandwiched between two Cu layers of 30 nm are measured individually by a Magnetic Resonance Force Microscope (MRFM). Using 3D micromagnetic simulations, it is demonstrated that, for sub-micron size diameters, the lowest energy spin-wave mode of the saturated state is not spatially uniform, but rather is localized at the center of the Py/Cu interface in the region of the minimum demagnetizing field.

The detailed understanding of the spectrum and spatial structure of spin-wave eigenmodes in submicron-size patterned heterostructures [1, 2] introduces new challenges and opportunities for novel magnetoelectronics devices [3]. The exact nature of the lowest energy modes are of a particular interest as they are the most susceptible to spin transfer excitation. In the case of confined geometries, their identification can be quite challenging because of the interplay between short-range exchange and long-range dipolar interactions. Recent simulations predict that the lowest energy mode of nanomagnets in a zero applied field is a mode localized at the edges [4] instead of the uniform mode, that has the lowest energy in larger structures. Furthermore fundamental mechanisms specific to metallic multilayers (such has spin accumulation at the boundary of normal and ferromagnetic metals [5]) can play a significant role in the magnetization dynamics of multilayer metallic elements.

Ferromagnetic resonance (FMR) is regarded as the basic tool to study the microwave susceptibility of magnetic samples [6]. It uses a well-defined excitation symmetry, where the microwave field h couples to the most uniform mode in the sample. However, the limited sensitivity of standard FMR spectrometers implies that it can only be performed on arrays of micron-size samples [7], which statistically averages the spectra of each element and makes it insensitive to individual differences. This Letter reports on the FMR spectroscopy of *individual* submicron heterostructures. To detect their dynamical response, we exploit the high sensitivity of mechanical-FMR setup [8, 9]. As shown schematically in Fig.1(a), the static part of the sample magnetization, M_z, is coupled through the dipolar interaction to a magnetic sphere attached at the end of a soft cantilever (spring constant 5 mN/m). Exciting the sample at a fixed frequency, the spectrum is obtained by measuring the cantilever motion as a function of the perpendicular dc applied field, H_{ext}. The force on the cantilever is proportional to ΔM_z (the variation of the component along the precession axis associated with the resonance). The sphere is a metallic alloy whose principle constituents are Co (80 wt%) and Fe (10 wt%). It has a diameter of 4.0 μm and its magnetic moment is $(5 \pm 0.5)10^{-9}$ emu (saturated above 3.8 kOe). The center of the sphere is positioned above the center of the disk (3.1 ± 0.1) μm away from the sample surface. In this position, the distortion induced by the stray field of the sphere on the FMR spectrum corresponds to a shift of 300 ± 20 G of the whole spectrum [9]. To enhance the sensitivity by the quality factor of the cantilever ($Q = 4500$), a lock-in is used to measure the mechanical response to an amplitude modulated excitation, where the modulation frequency is set at the resonance frequency of the cantilever (well below all the relaxation rates in the spin system). It should be noted that the mechanical signal represents the energy *stored* in the spin-wave system, which is equal to the *absorbed* power ($P_{\text{abs}} \propto \chi''$, the microwave susceptibility) during the spin-lattice relaxation time. Thus the mechanical-FMR spectrum is composed of bell-shaped resonances, much like an absorption spectrum (χ'' vs. H_{ext}), except that the amplitude of each peak is renormalized by their respective relaxation rate [10].

The excitation antenna is a 50 Ω microstrip circuit shorted at its extremity. It is a Ti/Au(150 nm) line deposited on a sapphire substrate. Once completed, the microwave circuit is placed inside a sputtering chamber to deposit the metallic trilayer, which consists of a single Permalloy (Py) magnetic layer, t = 100 nm in thickness, sandwiched by two normal metal layers made of 30 nm thick Cu. Subsequently, several Cu/NiFe/Cu disks with diameters ranging from 2 μm down to 0.5 μm (*cf.* Fig.1(b)) are patterned by electron-beam lithography and ion-milling techniques out of the same thin film. All the disks are placed at a magnetic field anti-node of the microstrip. A 50 μm separation is set between them, so that any inter-disk coupling can be neglected.

We first characterize the properties of a $\phi = 1$ μm diameter disk. For all the mechanical-FMR measurements presented herein: (a) the data are collected at T=280 K in the linear regime, where the peak amplitude remains proportional to the excitation power *i.e.* precession angles limited to 1°. (b) The disks are almost saturated in the field range measured. (c) The shift introduced by the stray field of the probe has been subtracted from the spectra. Fig.2(a) shows the mechanical-FMR spectra of the same disk at four different frequencies. They substantially differ from the known FMR signature of thin disks perpendicularly magnetized in the saturated regime [9]. These spectra usually consist of an intense peak located at the highest field (lowest energy), the uniform mode, followed by harmonics at lower field (higher energy), which are standing spin-wave modes with an increasing order m along the radial direction. Such spectrum has been measured by cavity-FMR technique on arrays of single Py layer disks with smaller thickness (50 nm) [7]. This result has also been recently confirmed by our mechanical-FMR setup on similar disks patterned out of a 43.3 nm single Py layer [11].

Let us first concentrate on the FMR spectrum of Fig.2(a) measured at the highest frequency ($\omega/2\pi$ = 9.05 GHz), when the applied field is the largest, which insures that the magnetization is the most homogeneous. The main peak occurs at $H_u \approx 11.1$ kOe (red square). Because it is the largest peak, this mode corresponds to the largest volume of precession: the uniform (or $m = 1$) mode. It is followed by the first harmonic, $m = 2$, at 10.4 kOe (open square), whose size is consistent with its magnetostatic nature [11]. In a 2D picture, the $m = 2$ mode is characterized by a nodal circle (locus where the magnetization does not precess) and an outer cylindrical region precessing in opposition of phase with the center. The striking new feature is the appearance of an additional peak at H_l =11.4 kOe on the 9.05 GHz spectrum (blue triangle). This new lowest energy mode has an amplitude (volume of precession), which is about a factor of 5 smaller than the uniform mode. Repeating the measurement on a second 1 μm disk confirms the reproducibility of the spectral features (amplitude, position and linewidth) observed at the highest frequency. The positions of the peaks follow a linear frequency dependence in the measured range (see dashed lines in Fig.2(a)), a behavior consistent with the dynamics of a saturated sample. (A slight departure from the fully saturated configuration when $H_{\text{ext}} < 9.5$ kOe can be deduced from the 4.2 GHz spectrum, where the largest peaks occur below the red dashed line). The linewidth of the uniform mode ΔH_u (half width at half maximum) is only 28 Oe at 9.05 GHz. This is among the *smallest* reported for Py. Fig.2(c) shows the frequency dependence of the linewidth of the two lowest energy modes for our micron-size disk. It varies linearly with frequency and the slopes intercept with the origin. The zero intercept indicates that our instrument resolves the *intrinsic* broadening of the individual mode. While there is usually a single peak at the resonance field of the uniform precession [11], our main mode (red square) is split into at least two peaks. It becomes more obvious at lower frequency, where the peaks are narrower and the signal to noise ratio of the experiment improves. The same splitting of the largest peak is also observed in the high frequency spectrum of the second 1 μm disk. Such an observation points to the presence of significant magnetic inhomogeneities inside the film of the disk sample (and not to inhomogeneities in the lateral confinement, see below).

Quantitative prediction of the resonance field requires a detailed knowledge of the magnetic properties of the Py layer. A control thin film has been produced by placing a Si substrate inside the sputtering chamber during the deposition process of the trilayer. Two basic FMR studies have been performed on this Cu/NiFe/Cu extended film. The first one is a 9.59 GHz cavity-FMR experiment where the resonance field, H_0, is studied as a function of the orientation θ_H (angle with the film normal) of the static field H_{ext}. The second one is a stripline-FMR (thin film on top of a microwave stripline), where H_0 is studied as a function of frequency at $\theta_H = 0°$ (*cf.* Fig.1(d)). The analysis [12] of $H_0(\theta_H)$ gives a precise determination of our Py layer g-factor, $g = 2.134 \pm 0.003$ (*i.e.* a gyromagnetic ratio $\gamma = 1.87\ 10^7\ \mathrm{G}^{-1}.\mathrm{s}^{-1}$) and $4\pi M_s = 9801 \pm 1$ G for its saturation magnetization at 298 K. These values correspond to a $Ni_{81}Fe_{19}$ alloy, although a decrease of M_s should be assigned to the adjunction of normal metal layers [5].

This characterization can be used to understand the behavior observed in the 1 μm disk. We find that the slope $\gamma \partial H_{u,l}/\partial\omega = 1.03$ departs slightly from unity, what is attributed to a small misalignment of about 2° between the normal of the disk and H_{ext} in the mechanical-FMR experiment. This misalignment produces a shift down in field (≈ -70 G) of the spectra, which should be taken into account when comparing it with the exact perpendicular configuration. Following the same procedure as in Ref [7], we have calculated the resonance fields of the magnetostatic modes $m = 1, 2, ...$ at 9.05 GHz with a 2D analytical model, which neglects the thickness dependence of the demagnetizing field. The value of γ and M_s are inferred from the ones obtained on the extended film (no fitting parameter), where $4\pi M_s = 9.9$ kG is adjusted to the value at the temperature of the mechanical experiment (280 K). This model predicts that the mode $m = 1$ should resonate at 11.07 kOe and the mode $m = 2$ at 10.45 kOe. Finer adjustment could be obtained by fitting the pinning value of the magnetization at the disk periphery [13]. Despite the simplifying assumptions and the uncertainties of the precise experimental conditions (exact disk diameter, misalignment of the field or strayfield of the probe), it can account quite well for the main features observed in the low field part of the spectrum of the disk. But we also find that the 2D assumption is unable to predict the lowest energy mode (triangle). It requires a formalism which takes into account the variation of the demagnetizing field in all three dimensions of the sample.

To gain further insight, we have measured a smaller disk, 0.5 μm in diameter. This aspect ratio departs further from the ellipsoidal approximation used in the analytical model. The result is shown in Fig.3(a). For the 10.1 GHz spectrum, the largest peak (uniform mode) occurs here at 9.5 kOe (red square). There is again an additional mode which resonates at lower energy: the peak at $H_l = 10.2$ k0e on the same spectrum (triangle). Lower values of the resonance fields are consistent with a decrease of the demagnetizing field due to an increase of the aspect ratio (t/ϕ) and of the quantization of the spin-wave modes along the diameter. The positions of the peaks follow the same linear dependence on frequency above 7 GHz indicating that the onset of the fully saturated configuration is around 8 kOe for this aspect ratio.

To describe the dynamics of the 0.5 μm disk, we have performed a simulation of the dynamic susceptibility using the values of M_s, γ and damping (see below) measured experimentally. χ'' is determined using two 3D codes developed by the authors [14]. The first one calculates a stable configuration of the magnetization vector by solving the Landau-Lifshitz (LL) equation in the time domain. The second one computes the full dynamic susceptibility tensor from the linearization of the LL equation around the equilibrium configuration. A mesh with a cubic cell of size 6 nm gives a discrete representation of the sample. The role of the Cu interfaces is neglected. We have plotted in Fig.3(a) the amplitude of the dynamical susceptibility at 12, 9.5 and 6 GHz. The cartography of χ'' is displayed using a color code for the first three modes. The largest peak (the so-called "uniform" mode) corresponds to spins that all precess in phase in the volume of the sample. A nodal circle along the diameter appears in the next mode at lower field. The behavior in the median plan looks like the magnetostatic modes m described in the 2D model, although we note the apparition of two additional nodes across the sample thickness. The same visualization of the lowest energy mode indicates that the mode (l) corresponds to a precession localized near the top and bottom surfaces of the disk. The characteristic length scale of this precession along the thickness is about 30 nm. The upper left part of Fig.3 shows the calculated value of the z-component ($\| H_{\text{ext}}$) of the demagnetizing field for the saturated configuration as a function of the radial and thickness directions. The minima are located at the top and bottom surfaces near the disk center (indicated by yellow dots). Spins excited in the minima regions lead to a mode lower in energy than the core precession [15] because the gain in demagnetizing energy exceeds the cost in exchange energy. Our simulation computes precisely the competition between these two interactions, but it neglects spin diffusion effects. The good agreement with the data (no fitting parameters) indicates that these are indeed the dominant effects. This picture is consistent with the localized mode being absent of the spectrum of thinner samples, as the ones used of Ref. [7] (it is also absent from the simulation of a $t = 43.3$ nm disk of same diameter). One should note that both the measurements and the simulations indicate a more complex behavior as the unsaturated regime is approached (below 7 GHz). Part of the observed features (split peaks) should be linked to the imperfections identified in Fig.2(a).

Although this demagnetizing effect is clearly dependent on the thickness of the Py layer, the amplitude and position of the localized mode vary strongly with the lateral dimension of the disk. This is made evident in Fig.4 where one compares the spectra obtained at the same frequency (5.6 GHz) on three different diameters: 2, 1 and 0.5 μm. The separation between the uniform and localized modes increases when the diameter of the disk decreases, a behavior consistent with a lift of degeneracy that is due to the confined in-plane geometry. In summary, the detection of this localized mode requires also to use small (submicron)-size disks.

Finally, we come back on the measured linewidths. We observe in Fig.2 and Fig.3 that the linewidth of the localized mode, ΔH_l, is smaller than ΔH_u, the one of the uniform mode. Fig.2(c) compares their frequency dependence for the $\phi = 1$ μm disk. The difference comes from the slopes $\gamma\partial(\Delta H_{(u,l)})/\partial\omega$, which yields different damping coefficient α, respectively $(1\pm0.1)10^{-2}$ for the uniform mode and $(0.85\pm0.1)10^{-2}$ for the localized mode. Although the reason behind might be complicated, we point out that lower dissipation is consistent with the fact that the localized mode corresponds to the excitation of higher k-value spin-waves [16].

We have also investigated the cause of inhomogeneities in our disk. Fig.2(d) shows the frequency dependence of ΔH_0, the linewidth observed by stripline-FMR in the control film. The extrapolated value at zero frequency (23$\pm$2 G) shows the presence of an inhomogeneous broadening in the multilayer structure [12], absent in the nanostructures. The detection of the first volume spin-wave mode (370 Oe below the main mode) in the stripline-FMR spectra (*cf.* Fig.1(d)) indicates a dynamical pinning behavior that can be described by the volume inhomogeneity model [6] (a gradient of magnetization at the Cu/NiFe interface). This observation is consistent with a decrease of M_s by 25% in a $\approx$ 10 nm characteristic length scale at the interface. Although the study of the FMR spectrum of the control film, deposited on a Si substrate, clearly reveals the presence of such inhomogeneities, we indicate that the multilayer has been deposited on the microstrip Au layer (7 nm roughness). Further studies would be required to differentiate intrinsic contributions (*e.g.* spin diffusion into the normal metal layer [5]) to extrinsic ones, like interdiffusion of the atomic species at the Cu/NiFe boundary or surface roughness of the interfaces.

In conclusion, the above described mechanical-FMR technique has enabled to perform measurement of spin-wave spectra in individual submicron Cu/NiFe/Cu perpendicularly magnetized disks. Using 3D simulations, we have shown that the lowest energy mode in a

100 nm thick Py layer disk is localized in the region of the minimum effective magnetic field (at the center of the Cu/Py interface). Remarkably, the relaxation rate of this localized mode is substantially smaller than the relaxation rate of the uniform mode. In the case when the external bias field is fixed (*e.g.* in the case of spin-torque experiments) the localized mode has the lowest relaxation rate both because it has the lowest damping coefficient and because it is the lowest energy mode, and therefore it has the smallest precession frequency.

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Figures

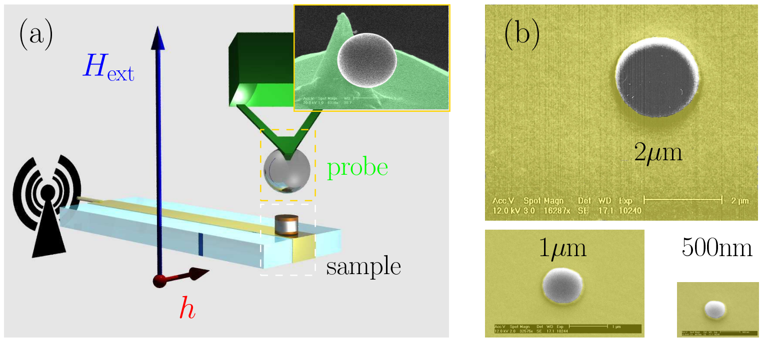

FIG. 1: (a) Schematic of the setup showing SEM images of the mechanical probe and (b) of the disks.

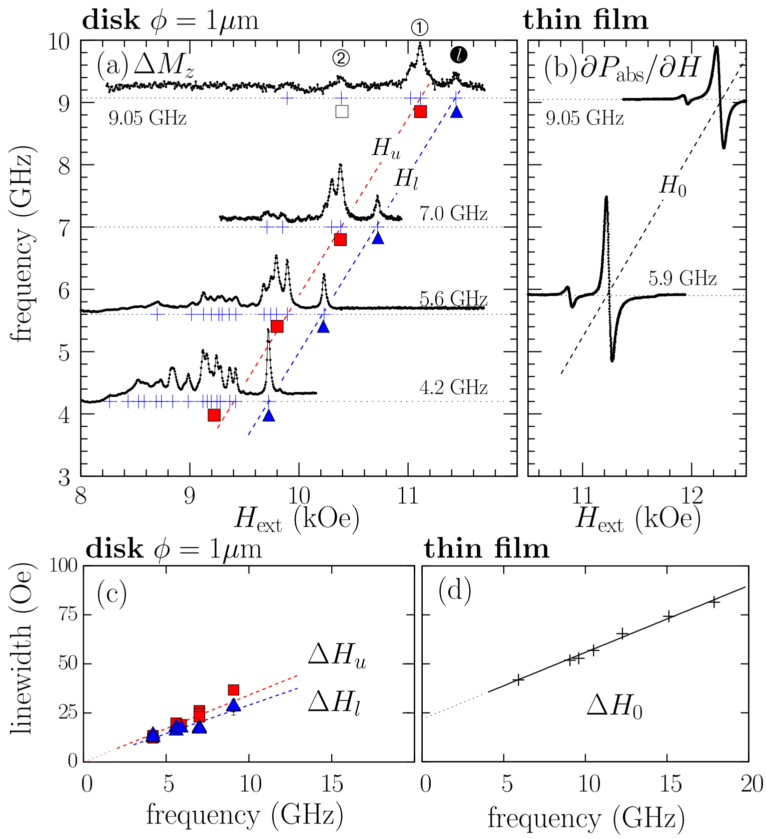

FIG. 2: (a) Mechanical-FMR spectra of the $\phi = 1$ μm disk for different frequencies. The experimental positions of the two lowest energy modes are shown as squares and triangles. (b) Stripline-FMR spectra of the control thin film on Si at two frequencies. The bottom figures show the linewidth versus frequency for the two lowest energy modes of the disk (c) and extended film (d).

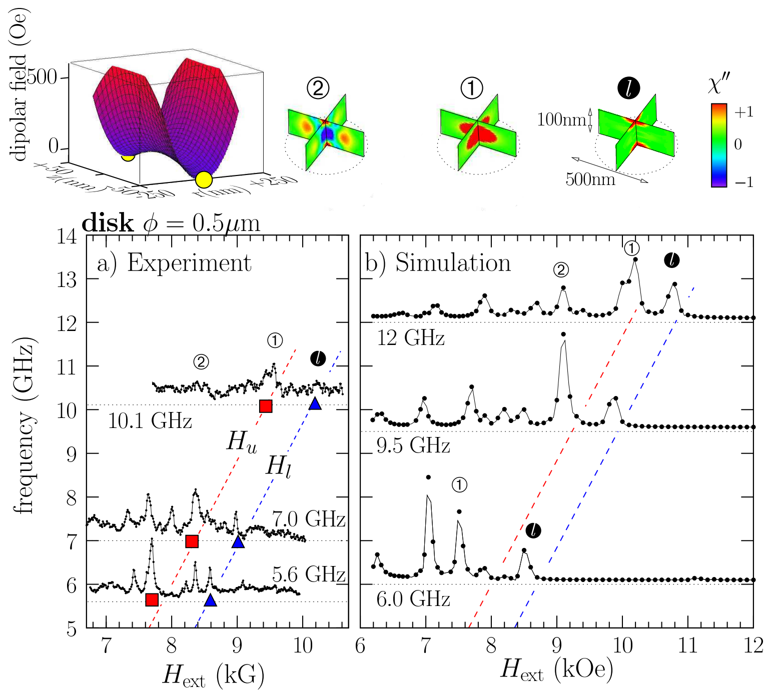

FIG. 3: (a) Mechanical-FMR spectra measured on the smallest disk ($\phi = 0.5$ μm). (b) 3D simulation of the dynamical susceptibility of a single Py layer disk ($t = 100$ nm, $\phi = 0.5$ μm). The top shows the spatial dependence (z, r) of the normal component of the demagnetizing field for the saturated configuration (shifted to zero at the disk center) and the transverse dynamics (χ'') of the main modes in a color code.

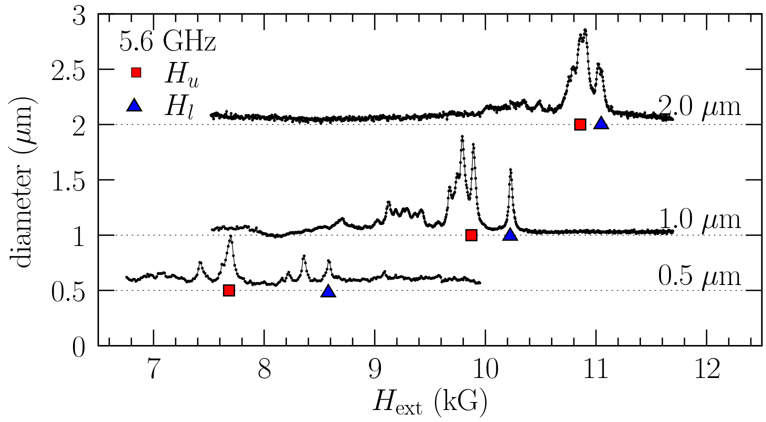

FIG. 4: Mechanical-FMR spectra of disks of different diameter at 5.6 GHz.