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Characterization of the fundamental spin-wave modes in submicron NiFe disk.

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Abstract

Using a Magnetic Resonance Force Microscope, we have measured the ferromagnetic resonance spectrum of individual nonellipsoidal disk in the saturated regime. Studying the spectrum both as a function of frequency and disk diameter, we find that the lowest energy mode of samples, whose length scale along the field is 100nm, is not the uniform precession but instead a mode localized at the surface. This is supported by 3D simulations, which predicts a resonance in the region of minimum internal field.

New challenges and opportunities are emerging out of the dynamical properties of magnetic heterostructures. Current interest resides in the study of submicron-scale patterned structures [1, 2, 3], where the exact nature of the normal modes remains an open question. Recent simulations of the dynamics of nanometer-scale ellipsoids predict that the fundamental mode at zero field corresponds to a precession localized at the edge of the sample instead of the uniform motion [4]. Furthermore the adjunction of normal metal layers substantially alters the magnetization dynamics near the interface and the role of the spins accumulated in the adjacent normal metal still remains unclear [5].

Thorough comprehension of the high-frequency response requires to use a well-defined excitation method. Ferromagnetic resonance (FMR) has been for a long time the basic tool to study the microwave susceptibility of magnetic samples [6]. The FMR selection rules are set by the symmetry of the microwave excitation field, which preferentially couples to the most uniform modes in the sample. This Letter reports the first attempt to perform ferromagnetic resonance of an *individual* submicron disk perpendicularly magnetized.

To detect the FMR response, we exploit the high sensitivity of mechanical-FMR [7, 8], a novel technique inspired by local probe techniques. The disk magnetization is coupled through the dipolar interaction to a magnetic probe attached at the end of a soft cantilever whose spring constant is 5mN/m (Fig.1(a)). This mechanical oscillator amplifies the FMR signal by $Q = 4500$ when the microwave power is source-modulated at the resonance frequency of its first flexural mode. The probe is a magnetic sphere of diameter $4\mu\text{m}$, glued at the apex of the tip as shown in the insert of Fig.1(a). Its magnetic moment, $(5 \pm 0.5)10^{-9}$ emu, is mechanically measured by applying a reference field gradient. In our experiment, the center of the sphere is placed vertically $(3 \pm 0.1)\mu\text{m}$ away from the upper surface of the disk, which ensures that the probe and the sample are in the weak coupling regime [7]. Laterally, the sphere center is placed precisely on the axial symmetry axis. In this case, the spectral distortion induced by the stray field of the sphere corresponds solely to a well defined shift of 300G of the entire spectrum [7].

The excitation antenna is a 50Ω microstrip circuit, shorted at its extremity, a design allowing studies on a broad frequency range. The microstrip is a Ti/Au(150nm) line deposited on a monocrystalline sapphire substrate, chosen for its high dielectric and good thermal conductive properties. Once completed, the microwave circuit is placed inside a sputtering chamber to deposit the magnetic trilayer, which consists of a single permalloy

(Py) magnetic layer, $t = 100\text{nm}$ in thickness, sandwiched by two normal metal layers made of 30nm thick Cu. Subsequently, several Cu/NiFe/Cu disks with diameters ranging from $2\mu\text{m}$ down to 500nm (*cf.* Fig.1(b)) are patterned by electron-beam lithography and ion-milling techniques out of the same thin film at a magnetic field anti-node of the microstrip. A $50\mu\text{m}$ separation is set between disks, which is large enough to neglect any inter-disk coupling.

Fig.1(c) shows the mechanical-FMR spectra of the $\phi = 1\mu\text{m}$ diameter disk measured at four different frequencies (the 300G shift introduced by the stray field of the probe is from now on subtracted). All the measurements displayed on this figure are collected at room temperature in the linear regime, where the peak amplitude remains proportional to the excitation power (*i.e.* precession angles limited to 1°). The mechanical signal measures the decrease of the longitudinal magnetization (component along the precession axis) associated with the precession. This quantity is proportional to the total number of magnons created by the FMR excitation or the energy stored in the spin-wave system. There exists a simple relationship between the mechanical-FMR and the induction coil-FMR measurements, since the dissipated power (energy stored times the spin-lattice relaxation rate) must be equal to the absorbed power, P_{abs} [9], which represents the number of magnons that couple coherently to the excitation. Thus the shape of the mechanically detected spectrum is proportional to the coil-FMR spectrum measuring the dynamical susceptibility χ'' , where the amplitude of each peak is renormalized by their intrinsic relaxation time [10].

The normal modes of arrays of $t = 50\text{nm}$ Py disks (thinner thickness but similar aspect ratio) has been recently measured by Kakazei *et al.* [11] with a cavity-FMR technique. It consists of an intense peak located at high field (low energy), the uniform mode, followed by harmonics at lower field (higher energy), which are standing spin-wave modes with an increasing order m [11] along the radial direction. The same shape has also been observed on ferrite disks of smaller aspect ratio [7]. For our thicker Py disk ($t = 100\text{nm}$), the spectrum in Fig.1(c) is substantially different. In the saturated regime (9.07GHz), the largest peak is observed at $H_u \approx 11.1\text{kG}$ (square symbol). Because of the symmetry of the excitation field, this mode should be assigned to the largest volume of precession (the uniform mode). It is followed by small peaks at lower field, whose sizes are consistent with their magnetostatic nature. For our detection scheme, the amplitude of second mode ($m = 2$) is an order of magnitude smaller than the uniform mode ($m = 1$). The peak positions follow a linear frequency dependence in the measured range (see dashed lines in Fig.1(c)), although we

observe a multiplication of peaks as one approaches the unsaturated regime. The striking new feature is the appearance of a new mode at H_l (green triangle) below the energy of the uniform mode.

To gain further insight, we have repeated the measurements on disks of diameters 2 and $0.5\mu\text{m}$. Fig.2 compares the spectra obtained at the same frequency: $\omega/2\pi = 5.6\text{ GHz}$. The resonance field H_u of the largest peak (squares) decreases with diameter. This is the consequence of the decrease of the internal field with the increase of the aspect ratio t/ϕ and of the quantization of the spin-wave modes along the diameter. In each case, an additional mode (triangle) resonates at H_l , higher field (lower energy) than H_u . The separation between these two modes decreases with the aspect ratio of the sample, a behavior also consistent with a lift of degeneracy that is due to the confined in-plane geometry.

Quantitative prediction of the resonance field requires a detailed knowledge of the magnetic properties of the sample. 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 at room temperature on the Cu/NiFe/Cu control film. The first one corresponds to an 9.59GHz 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 corresponds to a stripline-FMR (thin film on top of a microwave stripline), where H_0 , is studied as a function of frequency at $\theta_H = 0^\circ$ (*cf.* Fig.1(d)). The analysis [12] of $H_0(\theta_H)$ enables one to determine precisely the Py layer g -factor and its total uniaxial perpendicular anisotropy field (completely dominated by the demagnetizing field). We find $g = 2.134 \pm 0.003$ (*i.e.* a gyromagnetic ratio $\gamma = 1.87 \cdot 10^7 \text{G}^{-1} \cdot \text{s}^{-1}$) and $4\pi M_s = 9801 \pm 1\text{G}$ for the saturation magnetization of our Py at 25°C . These values correspond to the expected ones for a $\text{Ni}_{81}\text{Fe}_{19}$ alloy, although a decrease of M_s should be assigned to the adjunction of normal metal layers. For completeness, cavity-FMR experiments are also performed in two orthogonal configurations of H_{ext} in the parallel geometry ($\theta_H = 90^\circ$). They enable to deduce the small uniaxial in-plane anisotropy field of this Py film, found to be $4.2 \pm 0.1\text{G}$. A linear fit of $H_0(\omega)$ between 5.9 and 17.9GHz yields also values for γ and M_s , which are in agreement with those obtained above. This result can be compared to the behavior observe in the $1\mu\text{m}$ disk. We find that the slope $\gamma\partial H_{u,l}/\partial\omega = 1.03$ departs slightly from unity, what is attributed to a slight misalignment of about 2° in average between the normal of the disk and H_{ext} , which should be included in the model.

Using the same procedure as in Ref [11], we have plotted in Fig.2 an analytical prediction for $H_u(\phi)$ ($m = 1$). In this calculation, the radial dependence of the demagnetizing factor is renormalized by the mode profile before being injected into the dipole-exchange dispersion relation for perpendicularly magnetized thin films developed by Kalinikos and Slavin [13] assuming total pinning at the disk periphery. The value of γ is the one obtained on the control film (no fitting parameter). The value of the magnetization used in the model is $4\pi M_s = 9.9\text{kG}$ (taking into account that the sample is temperature stabilized at 6°C). We have also plotted the predictions of the first magnetostatic modes. Despite the simplifying assumptions of the analytical model (homogeneous magnetic state) and the uncertainties of the precise experimental conditions (exact disk diameter, misalignment of the field, strayfield of the probe), it accounts well for the main features observed in the low field part of the spectrum of the largest disks. The model cannot explain, however, the lowest energy mode (triangle). It cannot also describe the spectrum of the smallest disk, which has the largest nonellipsoidal shape.

To describe the dynamics of the smallest disk ($\phi = 500\text{nm}$), we have performed a micro-magnetic simulation of the dynamical transverse susceptibility. A 3D mesh ($128 \times 128 \times 16$) gives a discrete representation of the sample with a cubic cell of size 6nm. For each static field value, the equilibrium magnetic configuration is calculated. We have plotted in Fig.3(a) the amplitude of the dynamical susceptibility at 12 and 9.5 GHz of each of these configurations. In the simulations, the stray field of the probe is neglected, as well as the Cu interfaces. The simulated spectrum reproduces some of the main features observed experimentally at the highest frequency (7GHz) on the smallest disk. The cartography of the transverse component is displayed using a color code for the first three modes. The largest peak is the $m = 1$ mode. It corresponds to the so-called “uniform” mode because all the spins precess in phase in the volume of the sample. The modes at lower field correspond to the apparition of lines of nodes along the diameter and of regions precessing in opposition of phase with the core. The color code for the $m = 2$ mode indicates also two nodes across the sample thickness: a mixing between spin-waves propagating along and perpendicular to M . The high field mode (l) corresponds to a mode localized at the top and bottom surfaces of the disk. The upper part of Fig.3 shows the internal field inhomogeneity both along the radial and thickness directions. The minima are located at the top and bottom surfaces near the disk center. Spins excited in the minima region lead to a mode lower in energy than the

core precession [14] when the gain in demagnetizing energy exceeds the cost in exchange energy. The first term depends on the aspect ratio while the second depends on the sample thickness. This result is consistent with the localized mode being absent of the spectrum of samples whose size along the field is below the 100nm length scale, as the ones used by Kakazei *et al.* [11]. Simulations have also been performed at 6GHz. The position of H_u is predicted to occur at 7.5kG close to the ones observed experimentally in Fig.2 although comparisons are less reliable at lower frequencies where the dynamics is more sensitive to inhomogeneities in the confinement potential of spin-waves and two localized modes [15] are observed experimentally in the 5.6GHz (Fig.2) spectrum of the smallest disk.

Besides the resonance field, the other main characteristic of the FMR spectrum is the resonance linewidth, ΔH (full width at half maximum). Fig.4(a) shows the frequency dependence of the linewidth of our $\phi = 1\mu\text{m}$ disk measured for both the uniform, ΔH_u , and localized mode, ΔH_l . The behavior is compared to ΔH_0 , the linewidth observed by stripline-FMR in the control film at $\theta_H = 0^\circ$. ΔH_u varies linearly with frequency and the slopes, which yield to $\alpha = \gamma\partial(\Delta H_u/2)/\partial\omega = (1 \pm 0.1)10^{-2}$, are parallel between the film and the disk, indicating that the homogeneous part of the relaxation of the uniform precession is unchanged in the patterned structure. The same analysis performed on the localized mode (triangles) gives a lower value: $\alpha = (0.85 \pm 0.1)10^{-2}$. Lower dissipation is consistent with the fact that the localized mode corresponds to the excitation of higher k -value spin-waves [9]. The extrapolated value at zero frequency corresponds to the inhomogeneous part of the broadening [12]. For the $\theta_H = 0^\circ$ orientation, the $45 \pm 3\text{G}$ inhomogeneities observed in our Cu/NiFe/Cu control film are dominated by a variation in M_s across the thickness of the Py layer. This is supported by the characteristics of the first volume spin-wave mode observed in the stripline-FMR spectra (*cf.* Fig.1(d)), whose pinning behavior can be described by the volume inhomogeneity model [6]. In contrast, the slopes of $\Delta H_{u,l}(\omega)$ intercept the origin for the disk. It suggests that the inhomogeneous broadening of the control film corresponds to the existence of several nearby peaks in the confined structure, which lifts degeneracies. It illustrates the sensitivity of FMR-spectroscopy of submicron objects to details in the confinement potential but it also emphasizes the importance of doing measurement on *individual* samples rather than on arrays of dots.

In conclusion, using a novel technique we have performed the first FMR measurement of individual Cu/NiFe/Cu disks perpendicularly magnetized. Using both an analytical calcu-

lation and 3D simulations, we show that the lowest energy mode of 100nm thick Py disks corresponds to spin-waves that are localized near the surface adjacent to the normal metals. Other effects that might enhance this localization is the presence of Cu layers or the fact that the spins at the surface experience a lower magnetization than the bulk in our sample. These inhomogeneities are due to interdiffusion of the atomic species at the Cu/NiFe boundary, but also to the surface roughness of the interfaces. This effect is certainly more pronounced in the patterned structure, where the Cu/NiFe/Cu film is deposited on a thick Au layer instead of a flat substrate. More elaborated models should incorporate this pinning behavior in the simulations to predict more accurately the details of the observed spectrum when one approaches the unsaturated regime.

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Figures

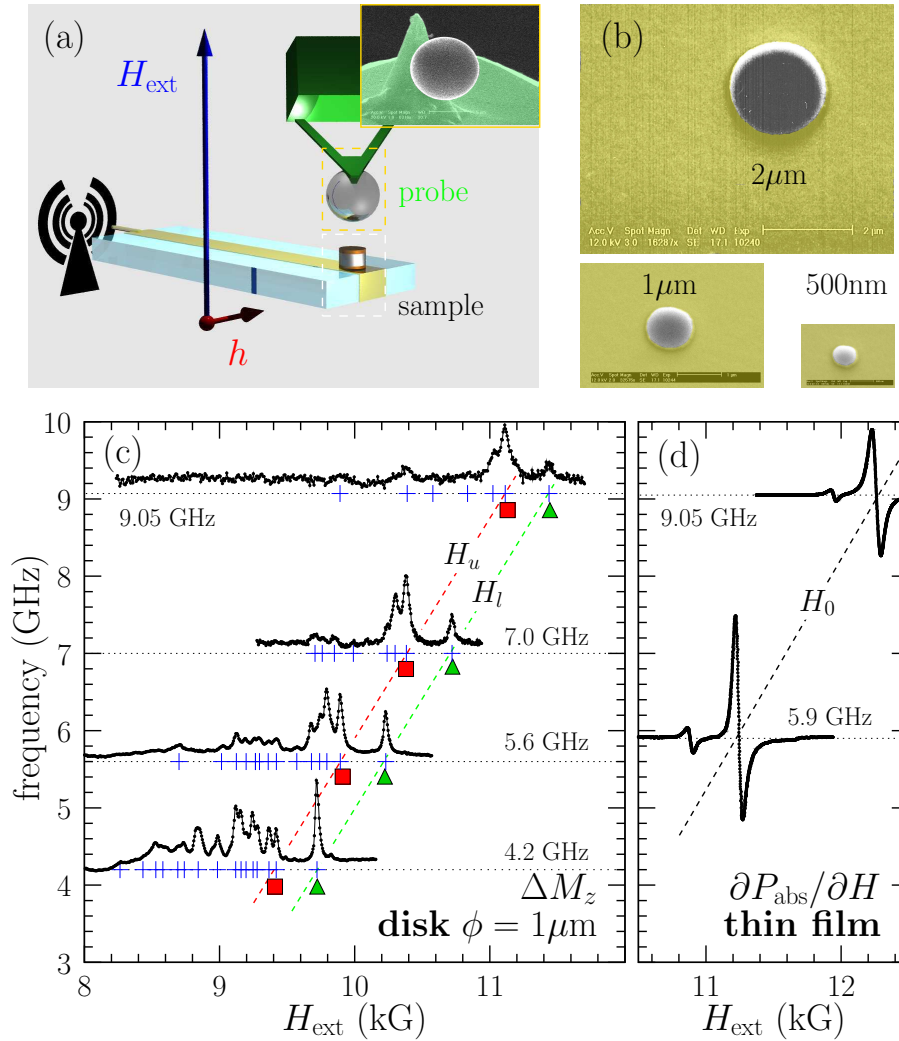


FIG. 1: (a) Schematic of the setup showing SEM images of the mechanical probe and (b) of the disks. The structure of the trilayer is Cu(30nm)/ NiFe(100nm)/Cu(30nm). (c) Mechanical-FMR spectra of the $\phi = 1 \mu\text{m}$ disk for different frequencies. The experimental positions of the two lowest energy modes are shown as squares and triangles. (d) Stripline-FMR spectra of the control thin film on Si at two frequencies.

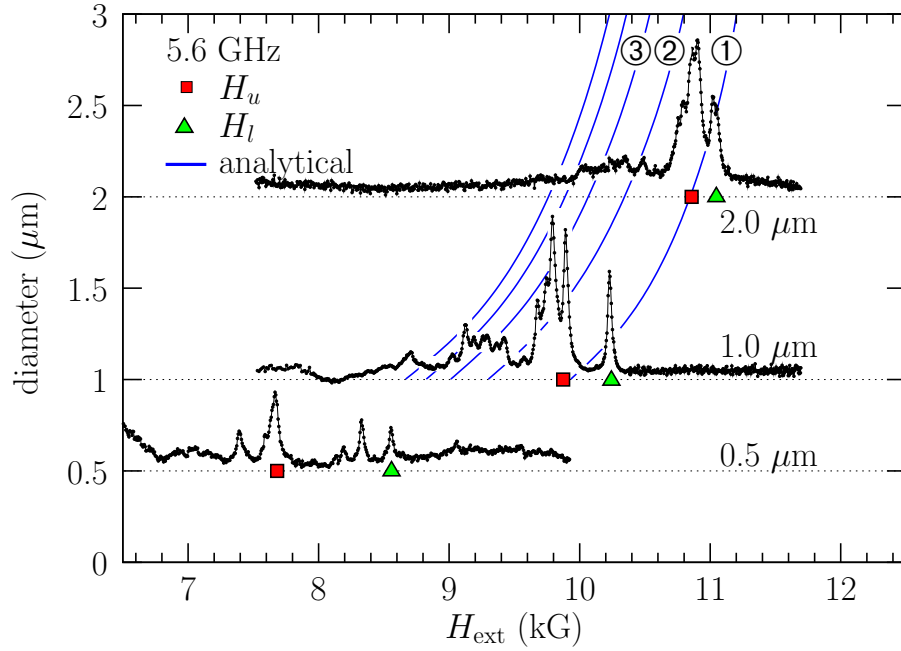


FIG. 2: Mechanical-FMR spectra of different diameter disks at 5.6GHz. The solid lines are the location of the resonance fields calculated analytically for the first magnetostatic modes ($m = 1$ to 5).

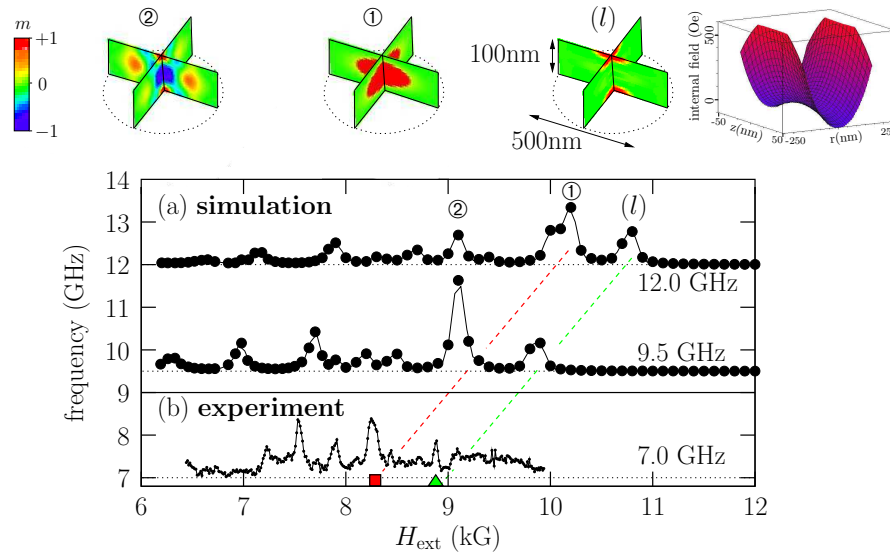


FIG. 3: (a) 3D simulation of the magnetization dynamics of a $t = 100\text{nm}$, $\phi = 500\text{nm}$ Py disk at 12 and 9.5GHz. The top shows the transverse dynamics of the main modes represented in a color code and the spatial inhomogeneity of the internal field in this nonellipsoidal element (it has been shifted to zero at the disk center). (b) Mechanical-FMR measured on the smallest disk at 7GHz.

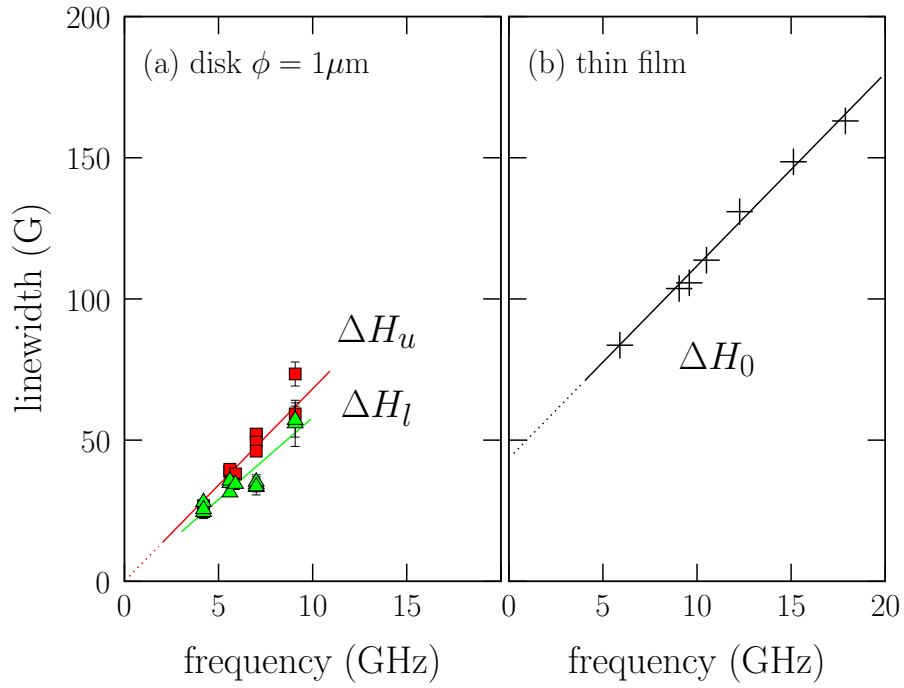


FIG. 4: (a) Variation of the linewidth versus frequency for the uniform (squares) and localized (triangles) modes of the $\phi = 1\mu\text{m}$ disk measured by mechanical-FMR. (b) Idem for the control thin film on Si measured by stripline-FMR.