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► **To cite this version:**

G. de Loubens, V. V. Naletov, Michel Viret, Olivier Klein, Hervé Hurdequint, et al.. Magnetic resonance spectroscopy of perpendicularly magnetized permalloy multilayer disks. 2006. hal-00113175v1

HAL Id: hal-00113175

<https://hal.science/hal-00113175v1>

Preprint submitted on 11 Nov 2006 (v1), last revised 12 Dec 2006 (v3)

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Magnetic resonance spectroscopy of perpendicularly magnetized permalloy multilayer disks

G. de Loubens, V. V. Naletov,* M. Viret, and O. Klein

Service de Physique de l'État Condensé,

CEA Orme des Merisiers, F-91191 Gif-Sur-Yvette

H. Hurdequint

Laboratoire de Physique des Solides,

Université Paris-Sud, F-91405 Orsay

J. Ben Youssef

Laboratoire de Magnétisme de Bretagne, 6 Av. Le Gorgeu, F-29285 Brest

F. Boust

ONERA, 29 avenue de la Division Leclerc, F-92322 Châtillon

N. Vukadinovic

Dassault Aviation, DGT/DTIAE, 78 quai Marcel Dassault, F-92552 Saint-Cloud

(Dated: November 12, 2006)

Abstract

Using a Magnetic Resonance Force Microscope, we compare the ferromagnetic resonance spectra of individual micron-size disks with identical diameter, $1 \mu\text{m}$, but different layer structures. For a disk composed of a single 43.3 nm thick permalloy (Py) layer, the lowest energy mode in the perpendicular configuration is the uniform precession. The higher energy modes are standing spin-waves confined along the diameter of the disk. For a Cu(30)/Py(100)/Cu(30) nm multilayer structure, the lowest energy mode becomes a precession localized at the Cu/Py interfaces. When the multilayer is changed to Py(100)/Cu(10)/Py(10) nm, this localized mode of the thick layer is coupled to the precession of the thin layer.

The dynamical properties of micron patterned ferromagnetic structures constitute new challenges and opportunities for novel magnetoelectronics devices¹. A recent focus is on the study of the exact nature of the normal modes in these tiny structures². Experimental works in the quasi-saturated^{3,4} and closure domain structures states^{5,6} have been recently reported. The interplay between the short-distance exchange and long-range dipolar interactions makes numerical simulations^{7,8} challenging. Moreover, the recently discovered spin diffusion mechanism^{9,10} makes the dynamical properties of such small structures still unsorted.

Ferromagnetic resonance (FMR) has been for a long time the principal tool to study the microwave susceptibility of magnetic samples¹¹. FMR uses a well-defined selection rule, where the excitation field preferentially couples to the most uniform mode in the sample. However, the sensitivity of standard FMR implies that it can only be performed on arrays of micron size disks, which statistically averages the spectra of many disks and makes it insensitive to individual differences. In this paper, we present ferromagnetic spectroscopy of *individual* micron size disks. It is shown that different multilayer structures yield different characteristics of the lowest energy mode.

To detect the FMR response of an individual microstructure, we exploit the high sensitivity of mechanical-FMR^{12,13}, a technique inspired by scanning probe techniques. As shown schematically in Fig. 1, the static part of the sample magnetization is coupled through the dipolar interaction to a magnetic sphere attached at the end of a very soft cantilever (spring constant 5 mN/m). Exciting the sample at a fixed frequency by a microwave field provided by a microwave antenna, the detected signal consists in measuring the cantilever motion as a function of the perpendicular dc applied field, H_{ext} . The variation of force on the cantilever is proportional to the variation of longitudinal magnetization (component along the precession axis) associated with the resonance¹⁴. In this experiment, the sphere diameter is 4 μm and its magnetic moment is $(5 \pm 0.5)10^{-9}$ emu. The center of the sphere is placed vertically (2.5 ± 0.1) μm away from the sample surface and laterally above the center of the disk. In this geometry, the perturbation induced by the stray field of the sphere on the FMR spectrum solely corresponds to a perturbation shift of 300 Oe of the whole spectrum¹³. To enhance the sensitivity of the measurement by the quality factor of the mechanical resonator ($Q = 4500$), we measure with a lock-in the response of the cantilever to a source modulation. The modulation frequency is set at the resonance frequency of the cantilever, which lies well

below all the relaxation rates in the spin system.

The excitation antenna is a $50\ \Omega$ microstrip circuit shorted at its extremity, a design allowing studies in a broad frequency range. The microstrip is a Ti/Au(150 nm) line deposited on a sapphire substrate. The disks studied in the present work have all the same diameter, $1\ \mu\text{m}$. They are patterned by electron-beam lithography and ion-milling techniques out of different multilayer thin films and are positioned at a magnetic field anti-node of the microstrip.

Fig. 2 shows the 5.6 GHz mechanical-FMR spectrum of an individual $\phi = 1\ \mu\text{m}$ disk composed of a single $t = 43.3\ \text{nm}$ thick Py layer sandwiched by two layers of Al_2O_3 (16 nm). The spectrum displayed on Fig. 2, as well as the ones of Fig. 3 and 4, has been recorded at a stabilized temperature $T = 280\ \text{K}$ and in the linear regime, where the peak amplitude remains proportional to the excitation power (*i.e.* precession angles limited to 1°). The most intense peak located at the highest field (lowest energy), $H_u \approx 10.5\ \text{kOe}$, is the uniform mode. Smaller amplitude modes at lower field (higher energy) correspond to standing magnetostatic modes with an increasing order m^{15} along the radial direction. Note that the linewidth (39 Oe) of the peaks is among the smallest reported at this frequency for Py. Such a regular spectrum has been also measured by mechanical-FMR on an individual ferrite microdisk¹³. It has also been observed using a cavity-FMR technique by Kakazei *et al.*¹⁵ on an *array* of Py disks of same diameter and similar thickness. The position of the magnetostatic modes can be calculated analytically¹⁵. Using the physical parameters characterizing our Py film deduced from X-band cavity-FMR performed on the extended film¹⁷ from which the disk was patterned out, we find that we have to introduce a small misalignment (5°) with respect to the perpendicular direction to fit our data, without any other fitting parameter.

Fig.3 shows the 5.6 GHz mechanical-FMR spectrum obtained for a thicker Py layer ($t = 100\text{nm}$) sandwiched by two Cu layers of 30nm. There are several important differences with the previous spectrum:

- i-* The peak of largest amplitude occurs at $H_u \approx 9.8\ \text{kOe}$ (red square symbol), which corresponds to the largest volume of precession (uniform mode). This lower value of the resonance field H_u is compatible with our previous measurement, since H_u decreases with increasing thickness. This is the consequence of the decrease of the internal field as the aspect ratio (t/ϕ) increases. The expected shift, $\approx -800\ \text{Oe}$, is close to the experimental one. The uniform mode is followed by small peaks at lower fields, whose amplitudes are

consistent with their magnetostatic nature.

ii- Another difference is the multiplicity of the peaks observed. While the spectrum in Fig.2 is very regular, we observe in Fig.3 some kind of mode splitting. As shown in ref.¹⁸, this effect is only apparent for spectra taken below 7 GHz. The reason behind is that we resolve the intrinsic broadening of the individual normal modes. Therefore at lower frequency (closer to the unsaturated regime), the mechanical-FMR resolve the individual imperfections of the sample in the disk shape or in the distribution of magnetization. A thorough analysis of the data¹⁸ indicates that the main contribution comes from the magnetization inhomogeneities in our disk, mainly due to a decrease of M_s near the Cu/Py interfaces, caused by interdiffusion between the Cu and Py layers and/or to roughness of the Cu/Py interfaces.

iii- The other striking feature is the appearance of a new intense mode at $H_l \approx 10.3$ kOe (green triangle) below the energy of the uniform mode. This new peak has been interpreted in ref.¹⁸ as a precession localized at the top and bottom Cu/Py interface near the disk center, in the region of minimum internal field. Indeed, spins excited in the minima region lead to a mode lower in energy than the core precession when the gain in demagnetizing energy exceeds the cost in exchange energy¹⁹. The first term depends on the aspect ratio while the second depends on the sample thickness. This explanation is consistent with the absence of the localized mode in the spectrum of Fig.2.

A cartography of the transverse component, obtained with a micromagnetic code⁷ in which the magnetic properties of our Py have been used and where the two Cu layers have been neglected, is displayed using a color code for the first three main modes. The largest peak corresponds to the so-called “uniform” mode where all the spins precess in phase in the bulk 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 same visualization of the lowest energy mode shows a precession localized at the minima of the internal field. Analytical models show that the characteristic length of precession in this localized mode is about 30 nm along the thickness of the layer²⁰.

Fig. 4 shows the 5.9 GHz mechanical-FMR spectrum for a double layer structure which consists of Py(100)/Cu(10)/Py(10) nm. It is directly deposited on the microstrip gold layer, and is capped by a 10 nm gold layer. This spectrum bears some strong resemblance with the one observed in Fig.3. This is expected since the main features should be dominated by the dynamics of the thick layer. In particular, we recognize the same large peak at $H_u = 9.8$ kOe

(red square), suggesting that this mode also corresponds to the uniform precession of the thick layer. However, the largest peak is now the localized precession mode at $H_l = 10.4$ kOe instead of the uniform mode, and a new group of peaks appears between those two modes. These two new features are likely related to the presence of the thin Py layer. Numerical simulations where the Cu spacer has been replaced by a vacuum layer have been performed on this structure. The simulated spectrum (not shown) gives the uniform mode of the thick layer as well as a higher field and higher amplitude mode. The latter corresponds to a localized precession of the thick layer coupled to the magnetization dynamics of the thin layer, shown in the inset of Fig. 4. One can understand that this mode may have a larger amplitude than the uniform precession since the top and bottom interfaces of the thick layer *and* the thin layer are now precessing at H_l . We emphasize that the simulation does not explain the new group of peaks observed between the coupled localized and the uniform modes. However, this high field feature must be related to the dynamics inside the thin layer (probably coupled to the dynamics of the thick layer), where the internal field inhomogeneity and the quantization of the spin-wave modes can give rise to several localized modes²⁰.

In conclusion, we have shown that different types of multilayer patterned into the same microstructure yield different FMR spectra. Importantly, the nature of the lowest energy mode depends on the thickness of the Py layer. It shifts from the uniform mode to a localized mode at the surfaces as the thickness increases. The influence of a thinner layer separated by a normal metal spacer has also been measured. We emphasize that the multiplicity of peaks for the two thicker disks reported above have been attributed to extrinsic effects¹⁸ and does not alter the main conclusions of this work. For a finer interpretation of the reported spectra, such effects should be taken into account, as well as the intrinsic effects associated to the diffusion of the microwave magnetization⁹ inside the whole metallic layered structure.

We are greatly indebted to A.N. Slavin, X. Waintal, and A.-L. Adenot for their help and support. This research was partially supported by the ANR grant PNANO06-0235.

* Also at Physics Department, Kazan State University, Kazan 420008 Russia

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Figures

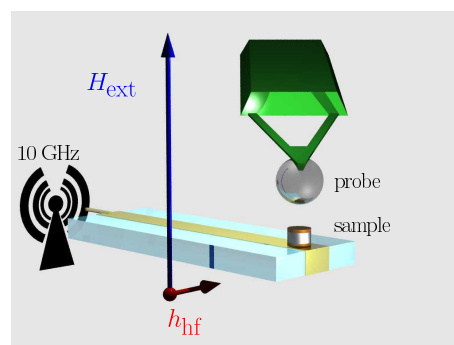


FIG. 1: Schematic of the mechanical-FMR.

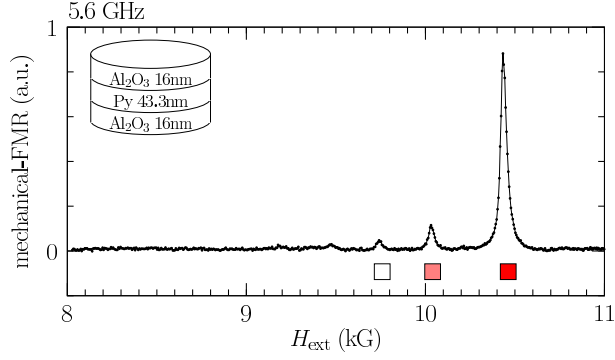


FIG. 2: Mechanical-FMR spectrum of a single $t = 43.3$ nm thick Py layer disk ($\phi = 1 \mu\text{m}$) at 5.6GHz. The lowest energy mode corresponds to the uniform precession. The experimental positions of the magnetostatic modes are shown as squares.

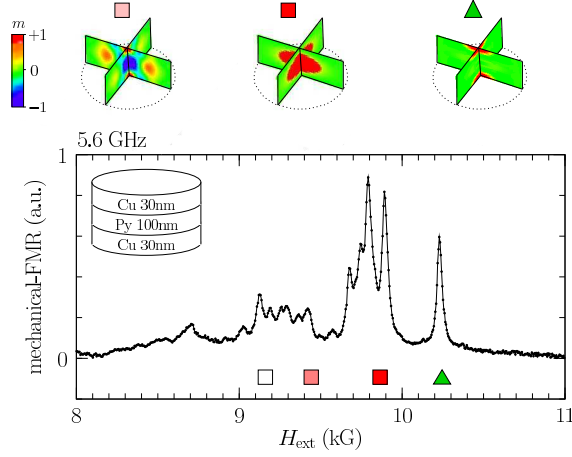


FIG. 3: Mechanical-FMR spectrum of a single $t = 100$ nm thick Py layer disk ($\phi = 1 \mu\text{m}$) at 5.6GHz. The lowest energy mode corresponds to a mode localized at the surface of the disk, shown as a triangle. Squares denote the uniform and magnetostatic modes. The top shows the transverse dynamics of the main modes represented in a color code, calculated using a micromagnetic simulation.

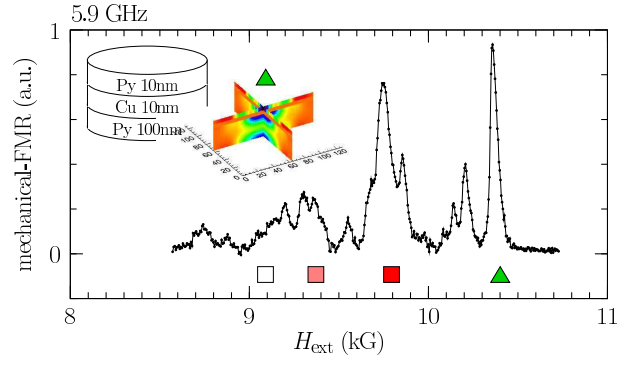


FIG. 4: Mechanical-FMR spectrum of a double layer Py disk ($\phi = 1 \mu\text{m}$) with thicknesses of 10 nm and 100 nm at 5.9 GHz. The spacer is a 10 nm thick Cu layer. The lowest energy mode corresponds to a coupled precession between the localized mode of the thick layer and the dynamics of the thin layer. The inset is a result of a micromagnetic simulation.