Magnetic excitation in weak stripe domains: Ferromagnetic resonance and Brillouin light scattering studies

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Abstract. Ferromagnetic films with perpendicular anisotropy and above a critical thickness exhibit weak stripe magnetic domains. The dynamic response of such systems with inhomogeneous state under moderate applied field can then be a probe of the local as of the macroscopic magnetization evolution. The static properties of Permalloy (Py) films of different thicknesses are obtained by VSM and MFM. Then the dynamic response is both investigated with a micro-stripe line device (FMR) and by Brillouin light scattering (BLS). For thick Py films three modes are observed below saturation which merge into a single one in the saturated state. Micromagnetic simulations have been performed to get the various resonance frequencies and the spatial distribution of the modulus of the dynamic magnetization for each mode. BLS spectra also show frequency multi-modes (at low q) in the non saturated state.

1 Introduction
Ferromagnetic films with a small perpendicular magnetic anisotropy are very interesting class of materials. Under certain conditions, periodic weak stripes domains can appear above a critical thickness [1]. The dynamical response of such systems with inhomogeneous magnetization state even for moderate applied magnetic field can then be a probe of the local as of the effective macroscopic magnetization modifications.

The purpose of this paper is to investigate the dynamical properties of Permalloy films exhibiting a stripe pattern structure. The paper is organised as follows. Section 2 provides a description of the static properties of the samples used. The dynamical responses obtained by FMR and BLS are given in section 3 while an analysis based on 2d micromagnetic simulations is proposed. Finally, in section 4, some outlooks are briefly drawn from the obtained results.

2 Static magnetic properties
Various Permalloy thin films with different thicknesses obtained by rf pulverisation on Si substrate and exhibiting magnetic stripe pattern have been studied. In the main, such pattern occurs in thin films which possess a uniaxial anisotropy whose axis is perpendicular to the film plane. The competition between anisotropy and demagnetizing energies leads, according to the thickness of the sample, either to a succession of up and down domains found in high Q bubble garnets or, as observed in our NiFe films with moderate anisotropy and thickness, to a piling-up of vortices with alternate chirality [2]. In a first step, the static magnetic properties are obtained using a vibrating sample magnetometer from which the remnant magnetization $M_r$, the saturation magnetization $M_{sat}$ and the saturation field $H_{sat}$ are extracted. On the other hand, the domain pattern is observed with a magnetic force microscope (MFM) that enables us to follow the variation of the width of the stripe versus an in

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plane applied field along the direction of elongation of the pattern (OZ axis). Figures 1 illustrate the experimental results of the present analysis for a 415nm thick Permalloy film (labelled sample A in the following). Looking at figure 1 (right part) and starting from a positive saturation, when decreasing the field, the stripe are nucleated first. A further decrease of the field increases the period of the stripe till, in negative field, the reversal of the direction of polarization of the vortices occurs what corresponds to a huge decrease of the period of the stripe and simultaneously to a large jump in the hysteresis loop. The remnant stable configurations and their field evolutions are numerically determined using a 2d micromagnetic model [2]. From the analysis of BLS and FMR results in the saturated state the following set of magnetic parameters: $4\pi M=10200$ G and $A=1.06 \times 10^{-6}$ erg/cm have been extracted. The numerical calculations obtained by 2d micromagnetic simulations are reported in fig. 1 (color: red lines) assuming a uniaxial perpendicular anisotropy $K=9.0 \times 10^4$ erg/cm$^3$. One may notice a reasonable agreement between experiments and simulations.

3 Dynamic response

Ferromagnetic resonance and Brillouin light scattering are complementary techniques conventionally used to study the small amplitude dynamic response of a magnetic system to obtain the spectrum of the fundamental excitations with (by BLS) or without (by FMR) momentum transfer.

3.1 FMR results

The dynamic response in the presence of a static magnetic field applied along the stripe domains is investigated with a ferromagnetic resonance device made of a micro-stripe line (FMR-MS). Contrary to the classical FMR technique with a cavity and a nearly fixed resonance frequency, the FMR-MS device enables us to study the dynamic response of the film for a variable frequency under a static and constant magnetic field that preserves the magnetic pattern during the experiment. According to the thickness of the film several modes are observed below saturation that merge into a single one in the saturated state which corresponds to the usual uniform mode. Such a behavior has been already observed in reference [1]. Figure 2 exhibits the results for sample A when the rf pumping field is applied in-plane and normal to the stripe direction of elongation (OX axis). Starting from the remnant stripe pattern in zero field till the saturation is reached, three modes are observed which are localized modes due to the non-homogeneous state of the magnetization. Numerical calculations of the dynamical permeability [details of the method can be found in ref.3] have been performed for various values of the applied field and provides us the nature of the mode and its localization (domain modes and surface modes). One example is given for $H=0$ in fig.3, for sample A, showing the evolution of the imaginary part of the permeability: $\mu''_x$. The corresponding spatial distribution of the modulus of the dynamic permeability within one period of the stripe is shown at each resonance frequency in the color insets. For the lowest frequency mode, the resonance arises from spin localized within the central part of the domain wall or more precisely, according to fig.3 left, in the vicinity of the vortex-like pattern. The second mode is associated with surface areas located in between the closure domains.
3.2 Brillouin light scattering results

Complementary, we have investigated by BLS the spin wave excitations supported by stripe domains. BLS corresponds to scattering photons from thermally excited travelling spinwaves. We use the backscattering geometry for which the in-plane wavevector $q$ of the excitations is defined by the relation $q = \frac{2\pi}{\lambda} \sin \theta$, where $\theta$ is the angle of incidence of the light with wavelength $\lambda=514$ nm. Spin waves can be probed following distinct geometric configurations according to the directions of $q$ and $H$ with respect to the elongation direction of the stripe. In zero field, we notice first a dispersion of the modes propagating along the stripe (OZ axis). Let us notice that the number of pics increases with $q$ like a progressive splitting of various excitation levels. Such phenomenom which may recall longitudinal wall undulations is out of the scope of the present communication and will be discussed elsewhere. Now, when $q$ is perpendicular to the stripe few modes are observed (see fig.4 a) showing a slight dispersion with $q$. In this last geometry, an for a given $q$ value, we have followed the evolution of the frequency lines versus $H_Z$. Two main features are evidenced: i) low frequency multi-modes appear in low field (fig.4a) ii) In increasing field and just before saturation is reached the low frequency modes disappear (fig.5). On the contrary, the highest frequency mode is preserved. It
undergoes a slight softening behavior near $H_{sat}$. Above the saturation field this mode corresponds to the usual Damon-Eshbach mode (DE) as shown in fig.4b and 5. The evolution of the pseudo-DE mode is influenced by the non-uniform distribution of the static magnetization typical of the non-saturated state. Its width at half height decreases with increasing field till saturation is reached.

Figure 4. Brillouin spectra obtained for different values of the applied field: a) remnant state $H=0$ and b) saturated state, $H=150$ 0e. In both cases q is perpendicular to the stripe.

More experimental works are presently done to analyse in detail the various modes observed in the non saturated state when the wave vector $q$ is perpendicular to the stripe in order to know whether or not non-dispersive modes may be definitely assigned to the patterning of the magnetization distribution (i.e. periodic magnetic structure) similar to what already mentioned for isolated permalloy wires [5].

Figure 5. Brillouin frequencies of localized and pseudo-DE modes versus $H$ applied parallel to the stripes ($q$ is perpendicular to the stripe).

4 Conclusion

The static and dynamic properties of Py films supporting a weak stripe pattern have been investigated both experimentally and numerically. The signatures of the magnetic domains are clearly observed in the FMR and Brillouin resonance spectra and explained via 2d micromagnetic simulations. Additional BLS experiments in order to reveal low frequency modes similar to those obtained by FMR are in progress.

5 References

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