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Shape anisotropy in arrays of micrometric magnetic stripes: a Brillouin study

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Abstract

The uniaxial in-plane anisotropy of patterned arrays of micrometric magnetic stripes is observed through their magnetic Brillouin spectra: the analysis is based on the frequency variations and on the Stokes/anti-Stokes dissymmetry versus an external applied magnetic field **H**. The saturation field H_s is measured for **H** along the hard axis ($H_s = 200$ Oe with stripes of thickness 29 nm and of width 1 μm). For **H** along the easy axis a hysteresis loop is observed, allowing us to derive a coercive field approximately equal to 150 Oe for this array of stripes. A simple model provides a satisfactory interpretation: it stipulates that the anisotropy energy simply consists of a demagnetizing term related to an average demagnetizing field. The experimental determination lies within the interval provided by a panel of different plausible approximations.

1. Introduction

Thin magnetic stripes and dots have been abundantly studied using Brillouin scattering [1–4]. Nevertheless most of these studies generally involve a magnetic field **H** applied parallel to the plane of the studied structure and strong enough to align the static magnetization **M** along its own direction. The interest was often focused on the quantization of the wavevector in relation to the reduced size. With the above mentioned experimental conditions the anisotropy only weakly acts on the observed spectra, except when it is very large, as, for instance in Co patterned films [1]. However, rather small values of the anisotropy, presumably mainly arising from shape dipolar contributions, remain detectable, for instance in permalloy dots and stripes [2, 3]. In order to evaluate small anisotropy terms, an alternative approach consists in using applied fields with magnitude lying in a range where they continuously or abruptly monitor the direction of **M**. The related experimental protocol takes advantage of two properties: (i) the frequencies are expected to strongly depend on this direction, (ii) the Stokes/anti-Stokes intensity ratio is deeply modified by the reversal of **M** [5, 6]. It results that the dependence of the Brillouin spectrum upon the variation of a magnetic field of small amplitude can provide an imaging

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of the hysteresis cycle. Such a technique was recently employed by Han *et al* [7] in the case of a continuous permalloy thin film showing an in-plane uniaxial anisotropy induced by an elaboration process under an applied magnetic field. In the following we present and discuss results concerning Brillouin scattering of periodic arrays of permalloy thin stripes in which the anisotropy arises from the patterning and, consequently, is expected to be closely related to the demagnetizing field.

2. Experimental results and discussion

Periodic arrays of stripes were elaborated in our laboratory, starting from a continuous film of thickness $t = 29$ nm, using a technique combining electron beam lithography and ion beam sputtering which was presented elsewhere [8]: two values of the stripes width ($w = 0.5$ or 1 μm), were studied; the separation between two neighbouring stripes was chosen equal to 0.3 μm, thus providing a period of 0.8 μm or of 1.3 μm. The Brillouin magnetic spectra were obtained with a 2×3 passes tandem Fabry–Pérot interferometer, under a sweepable magnetic field lying in the plane of the studied periodic arrays, using two different geometrical arrangements: **H** perpendicular to the stripes or **H** parallel to the stripes. Backscattering geometry was used, with an angle of incidence α of 65°, which defines a surface wavevector $Q = 4\pi \sin[\alpha]/\lambda$ (where $\lambda = 514.5$ nm is the illuminating wavelength) large compared to π/w, thus ensuring that the above mentioned quantization effects can be neglected. Figure 1 shows some typical spectra. In figure 2 we present the observed frequency variations versus the field for the perpendicular (a) and the parallel (b) set-ups in stripes of width 1 μm. For convenience we assign negative values to the frequency f of the Stokes spectrum and positive ones to the anti-Stokes line. Notice (figure 1) that when the Stokes line clearly appears in the spectrum the anti-Stokes one shows a negligible intensity and vice versa.

Figures 2(a) and (b) are clearly reminiscent of hysteresis cycles in a sample showing uniaxial anisotropy under a magnetic field applied perpendicular and parallel to the easy axis, respectively. This can be rather simply justified in the following way. Let us denote by θ and ϕ, respectively, the angles of the static magnetization **M** and of the applied magnetic field **H** with the stripe direction and assume that the energy density writes as:

$$E = -HM\cos[\theta - \phi] + K\sin^2[\theta] \qquad \text{with } K > 0. \tag{1}$$

The first term is the Zeeman energy and the second one defines a plausible form for the anisotropy which will be discussed later. An homogenous solution for **M** is obtained by minimizing (1) versus θ:

(i) For the hard axis case ($f = p/2$) there is one minimum for $|H| > H_s = 2K/M$: **M** along **H** with the same direction and there are two equivalent minima for $|H| < 2K/M$, showing a magnetization non-collinear with **H** : $\sin[\theta] = HM/2K$. H_s represents the saturation field.

(ii) For the easy axis case ($\phi = 0$), there is one minimum for $|H| > H_s$: **M** along **H** with the same direction ($\theta = 0$ for $H > 0, \theta = \pi$ for $H < 0$) and there are two minima for $|H| < H_s$: **M** along **H** with the same direction or with the opposite direction. This situation can give rise to hysteresis loops with a coercive field H_c smaller than H_s.

A simple interpretation of the observed frequency variation can be given if one assumes that the anisotropy term in equation (1) derives from a demagnetizing field $\mathbf{H_d}$ normal to the stripes. We assume that:

$$K\sin^2[\theta] = -\mathbf{M}\cdot\mathbf{H_d}/2. \tag{2}$$

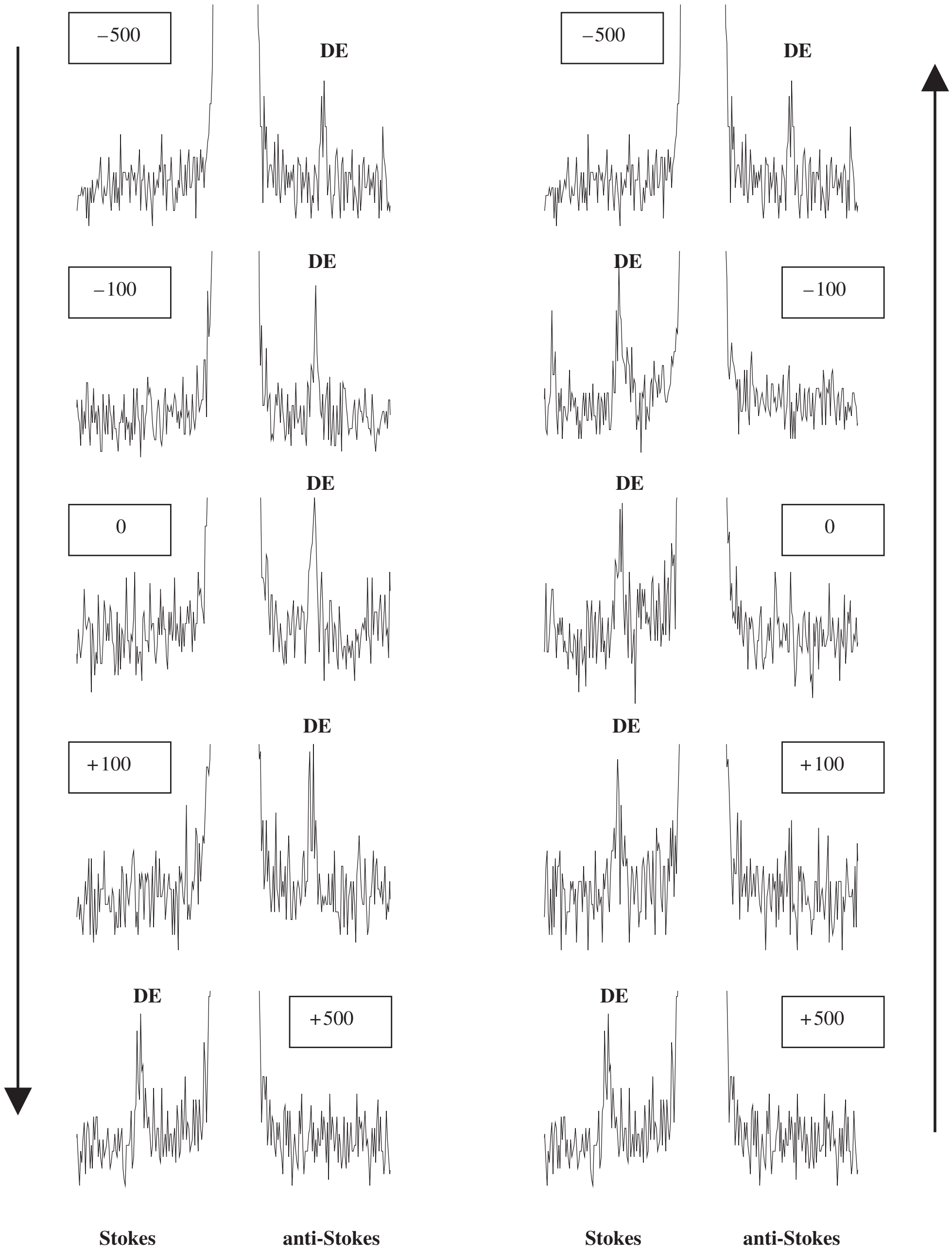

Figure 1. Brillouin spectra obtained with cycling fields applied along the easy axis. Left column: increasing field; right column: decreasing field. The field values are expressed in Oersteds.

The present discussion implicitly supposes that $\mathbf{M}$ and $\mathbf{H_d}$ are uniform, a hypothesis which, strictly speaking, cannot be realized exactly and will be commented on further. The absolute value H_d of the demagnetizing field is indeed proportional to the normal component $M\sin[\theta]$ of the magnetization and writes as:

$$H_d = aM|\sin[\theta]| \quad (3)$$

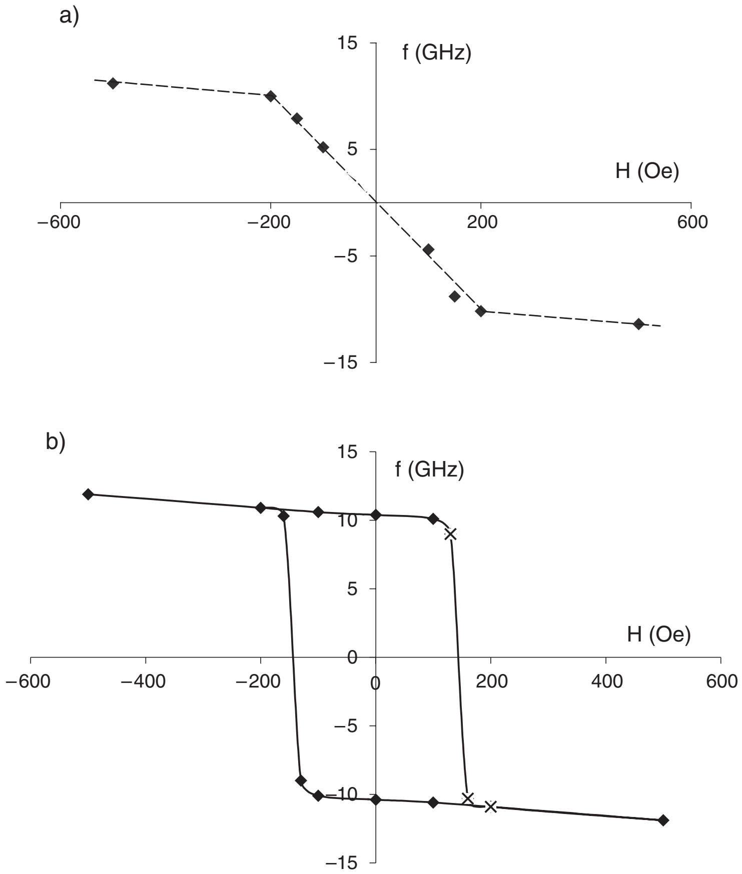

Figure 2. Frequency variation of the stronger DE Brillouin line versus the field (a) applied along the hard axis, (b) applied along the easy axis. Measured frequencies: ♦; the crosses (×) are frequencies deduced from symmetry arguments. The lines are guides for eyes.

where the positive coefficient a only depends on the geometrical configuration of the array of stripes. It results from equations (2) and (3) that:

$$K = aM^2/2. \tag{4}$$

It is easy to establish [9] that, in the dipolar approximation, the frequency f of the Damon–Eschbach like spin wave of wavevector Q is given by:

$$\left(\frac{2\pi f}{\gamma}\right)^2 = (2\pi M_\parallel + H_\mathrm{i})^2 - (2\pi M_\parallel)^2 \exp[-2Qt] \tag{5}$$

where H_i is the amplitude of the internal magnetic field $\mathbf{H}_\mathrm{i}$ ($\mathbf{H}_\mathrm{i} = \mathbf{H} + \mathbf{H_d}$) and where $M_\parallel$ is the (algebraic) component of $\mathbf{M}$ along $\mathbf{H_i}$.

In the hard axis geometry, it immediately results from equation (5) that:

for $|H| > H_\mathrm{s} = 2K/M = aM$:

$$\left(\frac{2\pi f}{\gamma}\right)^2 = (2\pi M(1 - a/2\pi) + |H|)^2 - (2\pi M)^2 \exp[-2Qt]$$

for $|H| < H_\mathrm{s} = aM$:

$$\left(\frac{2\pi f}{\gamma}\right)^2 = \left(\frac{2\pi}{a}\right)^2 (1 - \exp[-2Qt])H^2. \tag{6}$$

Table 1. Comparison between the calculated and the measured spin wave frequencies. Calculation performed using: $\gamma = 1.9 \times 10^7$ Hz Oe^{-1}; $4\pi M = 8000$ G; $Qt = 0.642$.

H (Oe)	$f_{calculated}$ (GHz)	$f_{measured}$ (GHz)
	Hard axis	
±500	11.3	11.2
±200	10.3	10.0
±150	7.7	7.9
±100	5.1	5.2
	Easy axis	
±500	12.0	11.7
±100	10.6[a]	10.5[a]
	9.9[b]	10.1[b]
0	10.3[c]	10.3[c]

[a] Experiment: $H > 0, M > 0$ or $H < 0, M < 0$.
[b] Experiment: $H > 0, M < 0$ or $H < 0, M > 0$.
[c] Experiment: $M > 0$ or $M < 0$.

In this last interval the frequency varies linearly versus the applied field. Due to the strong Stokes/anti-Stokes asymmetry, when increasing H, the observed line is expected to smoothly move from one side of the spectrum to the other, following the continuous sweeping of the applied magnetic field, as observed.

In the easy axis geometry:

$$\begin{aligned}
&\text{for } |H| > H_s = aM: \\
&\qquad \left(\frac{2\pi f}{\gamma}\right)^2 = (2\pi M + |H|)^2 - (2\pi M)^2 \exp[-2Qt] \\
&\text{for } |H| < H_s = aM: \\
&\qquad \left(\frac{2\pi f}{\gamma}\right)^2 = (2\pi M \pm |H|)^2 - (2\pi M)^2 \exp[-2Qt].
\end{aligned} \tag{7}$$

In the $[-aM, +aM]$ interval, the two available equilibrium positions provide two distinct frequencies. However, these two frequencies are close to each other since, as discussed below, the coefficient a is significantly smaller than 1 and, consequently, $|H| \ll 2\pi M$ in the concerned interval. The magnetization is expected to more or less abruptly jump during a cycling process, thus inducing a shift of the observed Brillouin line from the Stokes to the anti-Stokes side of the spectrum, or vice versa, without large frequency variation. However, as seen in table 1, this variation can be detected. Our model cannot give a detailed quantitative account of the hysteresis loop in this geometry, since the occurrence of distinct magnetic domains in the studied structure, which monitors the magnetization reversal, is not considered. However, it provides an upper limit to the coercive field H_c, namely: $H_c \leqslant H_s$, as experimentally observed: for $w = 1$ μm, we measure $H_s = 200$ Oe (see figure 2(a)) and $H_c = 150$ Oe (figure 2(b)). Finally, outside of the $[-aM, +aM]$ interval the spectrum is expected to only weakly differ from the observed one in the hard axis geometry. Notice, however, that a small frequency increase arising from the vanishing of the anisotropy field is detected.

Let us now come to the determination of the pertinent parameters. Experimentally, γ and M were evaluated from the study of the Brillouin spectrum variation of an unpatterned part of the sample versus the applied magnetic field. In this case the frequency is given by:

$$\left(\frac{2\pi f}{\gamma}\right)^2 = (2\pi M + |H|)^2 - (2\pi M)^2 \exp[-2Qt]$$

whatever the applied field. We found: $\gamma = 1.9 \times 10^7$ Hz Oe^{-1}; $4\pi M = 8000$ G. We verified that the above expression gives account of the Brillouin spectrum of a stripe array in the easy axis mounting for large applied fields. Finally, we determined the saturation field H_s from the study of the Brillouin spectra of the stripes arrays for small applied fields (see figure 2). In the case of 1 μm width the above mentioned 200 Oe determination of H_s provides $a = 0.31$. Using this value, the calculated frequencies satisfactorily agree with the measured ones (see table 1). This value has to be compared to theoretical evaluations. Even when assuming that the static magnetization is uniform, the demagnetizing field departs from uniformity: the demagnetizing field introduced above has to be considered as a 'mean' demagnetizing field. In a first approach, one can attempt to identify it as the demagnetizing field at the centre of a stripe belonging to a periodic array of stripes showing a uniform perpendicular magnetization. This approximation underestimates the required field since the calculation provides a value of 69 Oe. An alternative evaluation was obtained by calculating the mean value of the demagnetizing field through the entire volume of each uniformly magnetized stripe: the obtained result of 278 Oe only slightly overestimates the saturation field. We also calculated the true magnetic topography of a stripe and the resulting distribution of the demagnetizing field using a finite elements method: in regard to the residual discrepancies between our model and our experimental results we found that this 'exact' evaluation does not provide a real improvement. Finally, the stripes of 0.5 μm width show a similar experimental behaviour but, due to the weakness of the scattering intensity, the data are less exploitable. The saturation field is expected to increase by about a factor of two: it seems that these studied sharper stripes do not experimentally present such a large increase. This illustrates the only semi-quantitative validity of the above developed model.

3. Conclusion

The study of the Brillouin spectra in the presence of a small applied magnetic field allowed us to put into evidence the shape in-plane magnetic anisotropy induced by the patterning of continuous initially isotropic thin films. This technique is convenient to draw typical hysteresis loops. The experiments take advantage of the well known Stokes/anti-Stokes dissymmetry. The observed behaviour is attributed to demagnetizing effects. A simple proposed model provides a semi-quantitative interpretation.

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