Absence of stable collinear configurations in Ni(001) ultrathin films: canted domain structure as ground state

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Brillouin light scattering (BLS) measurements were performed for (17-120)Å-thick Cu/Ni/Cu/Si(001) films. A monotonic dependence of the frequency of the uniform mode on an in-plane magnetic field was observed both on increasing and on decreasing H in the range (2-14) kOe, suggesting the absence of a metastable collinear ground state. Further investigation by magneto-optical vector magnetometry (MOKE-VM) in an unconventional canted-field geometry provided evidence for a domain structure where the magnetization is canted with respect to the perpendicular to the film. Spin wave calculations confirm the absence of stable collinear configurations.

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I. INTRODUCTION

The determination of the magnetic phase of thin films can require a subtle analysis owing to the presence of many different competing anisotropies. Furthermore, metastable phenomena can be present, so that the magnetic history of the sample must be considered. For example, when the magnetization is perpendicular to the film plane, a monodomain state is suggested from remanent magnetization and a frequency Ω0 is the angle between the magnetization and the normal to the film plane). A phase with canted (0 < θ < π/2) magnetization has been used to observed close to the reorientation transition between perpendicular and in-plane magnetization in a very narrow range of film thickness, t, and/or temperature. This phase is usually related to a domain structure as experimentally observed by microscopic techniques.

It is generally agreed that epitaxial Cu/Ni/Cu/Si(001) films present a collinear phase magnetized perpendicularly to the film plane in a wide range of Ni thickness, 17 Å ≤ t ≤ 120 Å. Assuming the perpendicular to be stable, the frequency Ω0 of the uniform mode versus Hc, an external magnetic field applied within the film plane, is predicted to have a minimum at a critical field Hc. In a previous paper, we reported Brillouin light scattering (BLS) experiments in Cu/Ni/Cu/Si(001) films, which, in the thickness range 17 Å ≤ t ≤ 80 Å, showed a monotonic decrease of the frequency of the uniform mode on decreasing the in-plane field down to 2 kOe, with a clear change in slope at field values H∗ ≈ (5-8) kOe, depending on the film thickness. (A similar behavior was observed also in other systems: Co/Au ultrathin films, Co/Pd multilayers, and Co/Au multilayers) We attributed such a discrepancy between our data and theoretical predictions to the breakdown of the collinear ground state and to the onset of a domain configuration. As a matter of fact, spin-wave theory predicts such an instability at a field value H∗ = Hc + ∆Hc (see Section V for the definitions of Hc and ∆Hc) and at a finite wavevector k||, whose inverse sets the initial size of the domains. In our previous paper, we attributed strong evidence for the presence of domains was provided by magneto-optical vector-magnetometry (MOKE-VM) data. A direct visualization of up and down perpendicular domains in these specimens for zero applied field is presented by Hug et al.; unfortunately, our present attempts to visualize - using magnetic force microscopy - the domain structure while applying an in-plane magnetic field were unsuccessful due to the weak magnetic signal from the sample and to the interference with the strong external field.

If the system is saturated in the z (perpendicular) direction and the in-plane field H is increased from 0 to Hc, a collinear ground state with a canting angle θ increasing from 0 to π/2 is expected, and the spin-wave frequency is predicted to decrease until, at a field value H∗ ≈ Hc − ∆Hc/2, a “lower” instability (quite similar to the “upper” one at H∗) is expected. The fact that, on decreasing H, the Brillouin light scattering data did not show any indication for the low field phase might be interpreted as due to a metastability phenomenon.
The aim of the present paper is to definitively investigate the possible occurrence of the above mentioned metastability and to achieve a detailed understanding of the ground state and of both the static and dynamic magnetization properties. New BLS data taken by increasing the in-plane field $H$ are presented and discussed. Moreover, MOKE-VM data in a new canted-field geometry are presented in order to analyze the collinear ground state.

II. BRILLOUIN LIGHT SCATTERING DATA

Our new measurements of BLS spectra are reported in Fig. 1 for the Cu/Ni/Cu/Si(001) sample with Ni thickness $t = 60$ Å for several values of the external magnetic field $H$ applied within the film plane (similar results are obtained for other thicknesses in the range 17Å-80Å). The details of the film growth and structural characterization have been published elsewhere, but a brief description is necessary here. The films were grown in a molecular beam epitaxy (MBE) chamber by e-beam evaporation. The base pressure was less than $2 \times 10^{-8}$ Torr during deposition. About 150 mW of P-polarized light, from an Ar$^+$-ion laser operated in single longitudinal mode on the 5145-Å line, was focused onto the sample surface, at an incidence angle of 45°, by a camera objective of numerical aperture 2 and focal length 50 mm. The sample was placed between the poles of an electromagnet used to produce a d.c. magnetic field, with a maximum intensity of 15.0 kOe, applied parallel to the film surface and perpendicular to the plane of incidence of light. Since light scattered by magnons has its plane of polarization rotated through 90°, an analyzer was used to remove unwanted back-reflections from the objective lens and light scattered by acoustic phonons. The spectra, recorded at room temperature, were stored in 512 channels, each with a gate length of 1 ms. A few thousand interferometer scans were necessary to record spectra with a good signal-to-noise ratio.

III. MODEL

From the measured spectra in Fig. 1, one obtains the field dependence of the frequency of the Damon-Eschbach mode reported in Fig. 2. A detailed theoretical analysis of these data is performed in terms of the following spin Hamiltonian

$$
\mathcal{H} = -J \sum_{i \neq \delta} \mathbf{S}_i \cdot \mathbf{S}_{i+\delta} - g \mu_B \mathbf{H} \cdot \sum_i \mathbf{S}_i - K_2 \sum_i (S^z_i)^2 \\
+ \frac{1}{2} K^\parallel_4 \sum_i (S^z_i)^4 + \frac{1}{2} K^\perp_4 \sum_i ((S^z_i)^4 + (S^y_i)^4) \\
+ \frac{1}{2} (g \mu_B)^2 \sum_{i \neq j} \left[ \frac{\mathbf{S}_i \cdot \mathbf{S}_j}{r_{ij}^3} - 3 \frac{(\mathbf{S}_i \cdot \mathbf{r}_{ij})(\mathbf{S}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5} \right]
$$

(1)

where $J > 0$ is the nearest neighbour ferromagnetic exchange constant; $H$ is an external field; $K_2 > 0$ is a uniaxial anisotropy favouring the $z$ direction, normal to the film; $K^\parallel_4 > 0$ and $K^\perp_4$ are quartic anisotropies. The former favours the film plane, $xy$; the latter, when the spins are in plane, favours them to lie along the in-plane diagonal [110]; finally, the last term in Eq. (1) is the magnetostatic dipole-dipole interaction. The presence of a quartic in-plane anisotropy is required since the BLS data, performed for field applied in plane along the easy [110] and the hard [100] direction respectively, show a small difference in frequency (see the inset in Fig. 2). For sufficiently high fields ($H > H^\circ_{\perp}$), the spins are aligned in plane along the field direction and the frequency of the uniform mode is

$$
\Omega_0|_{[110]} = \gamma \sqrt{(H - H_{K^\parallel} - \frac{1}{2} H_{K^\perp}^4)(H + H_{K^\perp}^4)}
$$

(2a)

$$
\Omega_0|_{[100]} = \gamma \sqrt{(H - H_{K^\parallel} - H_{K^\perp}^4)(H - H_{K^\perp}^4)}
$$

(2b)

for $H$ along the easy and hard in-plane axis, respectively ($\gamma$ is the gyromagnetic factor). Above and in the following we put $H_{K^\parallel} = H_{K^\perp} - H_{dip}$, where $g \mu_B H_{K^\parallel} = 2 K^\parallel_2 S$ is the uniaxial anisotropy field and $H_{dip} = 4 \pi M_0 c_1$ is the dipolar field ($M_0$ is the bulk magnetization) and $c_1 = f/\sqrt{2}$ is a thickness dependent coefficient. $g \mu_B H_{K^\perp}^4 = 2 K^\perp_4 S^3$ and $g \mu_B H_{K^\perp}^4 = 2 K^\perp_4 S^3$ are the quartic anisotropy fields. The former is estimated to be $H_{K^\perp}^4 \approx 1$ kOe from the frequency difference in the BLS data ($\Delta \nu \approx (2-3)$ GHz for $H \gtrsim 10$ kOe), while a fit of $\Omega_0(H)$ at high fields along [110], using Eq. (2a), yields an estimate for the effective anisotropy field $H_{K^\parallel}^4 \approx 2.5$ kOe. Finally, we define the exchange field $g \mu_B H_{ex} = 2JS$ which - though not appearing in Eqs. (2a,b), since they are written for zero wavevector - will be useful in the following. The results of our new BLS measurements in Fig. 2 clearly show that almost the same curve $\Omega_0$ versus $H$ is obtained on increasing as well as on decreasing the in-plane field $H$ in the range (2-14) kOe. We conclude

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that the collinear perpendicular state is a very weakly metastable state or that it is plainly unstable, i.e. the system does not present a perpendicularly magnetized phase. Even more important, BLS data exclude a ground state with domains magnetized perpendicularly to the film plane as well. In fact, for \( H = 0 \) and negligible quartic anisotropies, the energy gap of the spin-wave excitations with respect to a ground state with striped domains perpendicularly magnetized is estimated to be

\[
\Omega_0|_{\perp,\text{stripe}} = \gamma(H_K - H_{\text{dip}}N_{zz})
\]

where \( N_{zz} < 1 \) is the demagnetization factor. Thus, in a perpendicular striped domain structure, the gap would be higher than in the case of spin waves excited from a uniform perpendicular ground state (i.e. with \( N_{zz} = 1 \))

\[
\Omega_0|_{\text{uniform}} = \gamma(H_K - H_{\text{dip}}).
\]

Since, using the value of \( H_{K_4} \) deduced before, the latter frequency is estimated to be at least 7 GHz, the hypothesis of a perpendicular striped domain structure in the low field region (\( H < 2 \) kOe) appears to be inconsistent with the high field (\( H > 10 \) kOe) results. This problem can be solved assuming the system to have a quartic perpendicular anisotropy \( K_4^\perp > 0 \), i.e. competing with \( K_3^\parallel \) and leading to a canted collinear configuration for \( H = 0 \). Neglecting the small in-plane quartic anisotropy, the zero-field canting angle \( \theta_0 \) is given by \( \cos^2 \theta_0 = H_{K_3} / H_{K_4} \) (see Eq. (A4) in the Appendix). In this way, the problem of the inconsistency between low and high field BLS data is removed because, for \( H \rightarrow 0 \), the spectrum of the excitations with respect to such a canted collinear ground state has a Goldstone mode (\( \Omega_0 = 0 \)) as a consequence of the translational invariance around the z axis. In the presence of a small quartic in-plane anisotropy, the gap at zero field is slightly greater than zero, but small enough to make our argument still valid.

\[\text{IV. MOKE-VM DATA}\]

In order to reveal the possible occurrence of a canted magnetization we use the magneto-optic Kerr vector-magnetometry (MOKE-VM) technique in a novel canted-field geometry. The field is applied within the plane formed by \( z = [001] \), the normal to the film, and \( x = [110] \), the in-plane easy axis; the field direction formed a canting angle \( \theta_H \) with \( z \). In Fig. 3a,b we report the MOKE-VM data for the polar \((M_z)\) and the longitudinal \((M_x)\) component of the magnetization, respectively. In the present experimental configuration we did not detect any transversal component \((M_y)\) in the whole investigated field range. In Fig. 3c, we show the field dependence of the calculated magnetization modulus \( M = \sqrt{M_x^2 + M_y^2} \), normalized to the saturation value \( M_{\text{sat}} \).

The different curves refer to different orientations of the applied magnetic field, with \( \theta_H \) ranging between \( 0^\circ \) and \( 20^\circ \). The perpendicular component \( M_z \) shows a remanence in zero field, the greater the lower is \( \theta_H \). Also the parallel component \( M_x \) is found to be nonzero in zero applied field; moreover, when the applied magnetic field is sufficiently high (\( |H| > 4 \) kOe), \( M_x \) is found to decrease with increasing \( H \) for \( \theta_H \leq 11^\circ \) and to increase for \( \theta_H = 20^\circ \). Therefore, these observations call for a canted ground state configuration in zero field with a canting angle \( \theta_0 \) comprised between \( 11^\circ \) and \( 20^\circ \). For the canted-field geometry of the MOKE-VM experiment one has (see Eq. (4) in the Appendix)

\[
\cos^2 \theta_0 = \frac{(H_{K_3^\parallel} + \frac{1}{2}H_{K_4^\parallel})/(H_{K_4^\parallel} + \frac{1}{2}H_{K_4^\perp})}{(H_{K_3^\parallel} + \frac{1}{2}H_{K_4^\parallel})/(H_{K_4^\parallel} + \frac{1}{2}H_{K_4^\perp})}.
\]

Hence, putting \( \theta_0 \approx 15^\circ \), we obtain \( H_{K_4^\perp} \approx 2.7 \) kOe. Concerning the magnetization modulus, we observe that it is always decreasing as the field is decreased, mainly owing to the the decrease of the \( M_z \) component. This is a strong evidence for a slightly canted ground state with a domain structure for the perpendicular component of the magnetization: \( \mathbf{M} = (M_z,0,\pm M_z) \).

\[\text{V. DISCUSSION}\]

Now, after having estimated all the Hamiltonian parameters which determine the frequency of the uniform mode (i.e. \( H_{K_3^\parallel} \approx 2.5 \) kOe, \( H_{K_4^\parallel} \approx 1 \) kOe and \( H_{K_4^\perp} \approx 2.7 \) kOe) we note that, using these values, the BLS data are well reproduced (see Fig. 2) only in a very high field region (\( H \gtrsim 10 \) kOe). In order to discuss the possible arising of instabilities\(,\) we need to generalize the calculation of the spin-wave frequency gap to a finite wavevector, \( \Omega_0(k_0) \). For doing that, we specialize to the in-plane easy axis direction \([110]\).

For long wavelength, the spin-wave acoustic mode (which is identified with the Damon-Eschbach mode in the Brillouin spectrum) of an ultrathin film with \( N \) planes takes the approximate form

\[
\Omega_0(k_\parallel) \approx \gamma \sqrt{A_1(k_\parallel) A_2(k_\parallel)}
\]

where the full expressions of \( A_1(k_0) \) and \( A_2(k_\parallel) \) are given in the Appendix. This expression is approximated in the sense that it is the generalization of the spin-wave dispersion relation of the monolayer\(,\) to the acoustic mode of an ultrathin film with \( N \) planes. Since \( A_1(k_0) \) is always strictly positive, the only reason for a field-induced instability at finite wavevector can be the vanishing of \( A_2(k_\parallel) = \alpha_0 - \alpha_1 (k_\parallel a) + \alpha_2 (k_\parallel a)^2 \) (where \( a \) is the square lattice constant and the \( \alpha_i \)'s are known functions of the physical parameters, see Eq. (A2) in the Appendix).

The minimum of \( A_2(k_\parallel) \) is obtained for \( k_\parallel a = k_\parallel^\text{(m)} a = \alpha_0 / (2\alpha_2) \) and we obtain \( A_2(k_\parallel^\text{(m)}) = \alpha_0 - \alpha_2^2 / (4\alpha_2) \): if
this quantity is negative, the spin wave frequency becomes pure imaginary, signaling the instability of the uniformly magnetized canted state. The instability appears when $A_2(k||) = 0$: this condition defines the values of the upper ($H^<_c$) and lower ($H^>_c$) critical fields. In the high field regime we find $H^<_c = H_c + \Delta H_c$ with $H_c = H_{K^2} + 4H_{K^4}$ and $\Delta H_c = (H_{dip}N)^2/(16f^2H_{ex})$, and $k^{(m)}_c = (H_{dip}N)/(4fH_{ex})$: the uniform ground state breaks into domains of size $\approx 1/k^{(m)}_c$.

The BLS data show the existence of two relevant fields: at $H \approx 9$ kOe experimental data start deviating from the theoretical spin wave frequency and at $H^* \approx 6$ kOe there is a clear change in their slope. The higher field is interpreted to signal the arising of a domain structure, which makes the experimental $\Omega_0$ deviate from the value predicted for a collinear in-plane phase: it is therefore identified as the field $H^<_c$. Instead, the change in the slope at a field $H^* \approx 6$ kOe should signal that a well defined domain structure is now established, whose size may strongly interfere with the light used in the BLS experiment.

We can sum up our interpretation as follows. At high fields we have an in-plane collinear phase and we start decreasing $H$. At $H = H^<_c \approx 9$ kOe, the collinear phase is unstable against the appearance of a domain structure: spins acquire a very small $z$ component that changes sign from a domain to a neighbouring domain. This instability corresponds to the vanishing of $A_2(k||)$ for a value $k^{(m)}_c$ which is just the inverse of the domain size. With further decreasing $H$, the domain structure becomes more and more defined and the domain size increases.

On the other side, the “lower” instability occurs for $H^<_c \approx H_c - \Delta H_c/2$. In our present interpretation, the quantity $\Delta H_c$ is taken as a free parameter and estimated, from the high field results, to be $\approx 6$ kOe. Consequently, since $H_c \approx 3$ kOe, the “lower” instability is expected to occur already for $H \approx 0$. We observe that such a conclusion about the instability of a collinear canted ground state is strongly supported by our MOKE-VM results in cantled field geometry: even a relatively high field $H \approx 4$ kOe applied nearly along the easy magnetization axis ($\theta_H = 11^\circ$ or $20^\circ$) is unable to give the saturation value of the magnetization modulus, see Fig. 3c.

In conclusion, new BLS measurements, performed upon increasing the in-plane field $H$, allowed to definitely exclude a metastable collinear state for epitaxial Cu/Ni/Cu/Si(001) films with thickness in the range (17-80)Å. This feature is confirmed by spin-wave calculations. The MOKE-VM data in cantled-field geometry suggested the presence of a domain structure where the magnetization is slightly canted ($\theta \approx 15^\circ$) with respect to the film normal. We are confident that our results can be useful to explain spin wave anomalies previously observed in other systems, such as Co/Au ultrathin films, as well as Co/Pd multilayers and Co/Au multilayers.

**APPENDIX A: SPIN-WAVE DISPERSION**

The spin-wave dispersion relation of the acoustic mode frequency of an fcc $N$-planes ultrathin film, described by Hamiltonian (1), is found to be, in the low wavevector limit

$$\Omega_0(k||) \approx \sqrt{A_1(k||) A_2(k||) - |\text{Im}B(k||)|^2} \quad (A1)$$

where

$$A_1(k||) = \left\{ H[\sin \theta \sin \theta_H \cos(\varphi - \varphi_H) + \cos \theta \cos \theta_H] + H_{K^{2a}} \cos^2 \theta - H_{K^{4a}} \cos^4 \theta + \frac{1}{4} H_{K^{4}} \sin^2 \theta[3 \cos^2 \theta - \cos 4\varphi(3 + \sin^2 \theta)] \right\}$$

$$+ \left\{ \frac{N}{2f} H_{dip} \sin^2(\varphi - \varphi_k) \right\} \cdot (k||a)$$

$$+ H_{ex} \cdot (k||a)^2 \quad (A2a)$$

$$A_2(k||) = \alpha_0 - \alpha_1 \cdot (k||a) + \alpha_2 \cdot (k||a)^2$$

$$= \left\{ H[\sin \theta \sin \theta_H \cos(\varphi - \varphi_H) + \cos \theta \cos \theta_H] + H_{K^{2a}} \cos^2 \theta - H_{K^{4a}} \cos^4 \theta(1 - 4 \sin^2 \theta) - \frac{1}{4} H_{K^{4}} \sin^2 \theta(1 - 4 \cos^2 \theta)(3 + \cos 4\varphi) \right\}$$

$$- \left\{ \frac{N}{2f} H_{dip} \sin^2 \theta - \cos^2 \theta \cos^2(\varphi - \varphi_k) \right\} \cdot (k||a)$$

$$+ H_{ex} \cdot (k||a)^2 \quad (A2b)$$

$$\text{Im}B(k||) = \left\{ - \frac{3}{4} H_{K^{4}} \sin^2 \theta \cos \theta \sin 4\varphi \right\}$$

$$- \left\{ \frac{N}{4f} H_{dip} \cos \theta \sin[2(\varphi - \varphi_k)] \right\} \cdot (k||a) \quad (A2c)$$

The expression for $\Omega_0(k||)$ is approximated in the sense that it is the generalization of the spin-wave dispersion relation of the monolayer [23], [24] to the case of an ultrathin film with $N$ planes. For the latter case, it represents the energy of the acoustic mode of the film, which is measured in a BLS experiment. We notice that the effect of the finite number of planes manifests itself as a prefactor $N$ in the terms containing $H_{dip}$ and linear in the wavevector $k||$. In the previous equations, $k||$ is the in-plane two-dimensional wavevector forming an angle $\varphi_k$ with the in-plane $x = [100]$ crystallographic axis; $a = a_0/\sqrt{2}$ is the constant of the square lattice on the (001) surface expressed in terms of $a_0$, the constant of the bulk fcc lattice; $\theta$ and $\varphi$ denote the polar coordinates of the magnetization taking $z$ (the normal to the film plane) as polar axis, while $\theta_H$ and $\varphi_H$ are the polar coordinates of the applied magnetic field. Dipolar sums were evaluated in the limit of small $k||$ using an
Ewald-type summation method. The dipolar field is \( H_{dp} = 4\pi M_0 c_1 \), where \( M_0 = 4\mu_B S/a_0^3 \) is the magnetization of the bulk fcc lattice and \( c_1 = f/\sqrt{2} \) is a thickness dependent coefficient. The other fields are defined in the text after Eqs. (A3a) and (A3b).

In the general case, the ground state configuration \((\theta, \varphi)\) is obtained solving the system

\[
\begin{align*}
[H_{K_4}^g + \frac{1}{4} H_{K_4}^\perp (3 + \cos 4\varphi)] \sin^3 \theta \cos \theta \\
-(H_{K_4}^g - H_{K_2}^\perp) \sin \theta \cos \theta \\
-H[(\cos \theta \sin \theta H \cos(\varphi - \varphi_H) - \sin \theta \cos \theta_H)] = 0 \quad (A3a)
\end{align*}
\]

\[
H \sin \theta_H (\varphi - \varphi_H) - \frac{1}{2} H_{K_4}^\perp \sin^3 \theta \sin 4\varphi = 0 \quad (A3b)
\]

When the external magnetic field is applied in plane along the easy direction \((\theta_H = \pi/2, \varphi_H = \pi/4)\), Eq. (A3b) is satisfied by \( \varphi = \pi/4 \), while Eq. (A3a) becomes

\[
\cos \theta [(H_{K_4}^g + \frac{1}{2} H_{K_4}^\perp) \sin^3 \theta \\
-(H_{K_4}^g - H_{K_2}^\perp) \sin \theta - H] = 0 \quad (A4)
\]

Hence, the zero-field canting angle reported in Eq. (B1) is obtained, provided that \( H_{K_4}^g > H_{K_2}^\perp \). Moreover we observe that, for \( \varphi = \varphi_H = \pi/4 \), \( \text{Im} B(\mathbf{k}_0) \) reduces to a term linear in \( H_{dp} \), and in the wavevector: thus its square can safely be neglected in Eq. (A1), so that Eq. (B1) is obtained. Finally, it is worth noticing that in the case of zero in-plane anisotropy, \( H_{K_4}^g = 0 \), one recovers for \( A_1(\mathbf{k}_0) \) and \( A_2(\mathbf{k}_0) \) the expressions previously found by Erickson and Mills.

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27. The field dependence below 2 kOe could not be studied because the central line overwhelms the inelastic spin-wave mode.
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29. \( N_{z4} \) depends on the aspect ratio \( r = L/t \) (\( L \) is the width of the stripes, \( t \) is the film thickness) and the ratio between the anisotropy field \( H_{K_4} \) and the dipolar field \( H_{dp} \); in the limit of a uniformly magnetized sample \( (r \rightarrow \infty) \) one has \( N_{z4} \rightarrow 1 \).
30. The canting of the magnetization vector in systems like Fe/Tb (see Ref. 18) has been observed using a Mössbauer technique, which does not require an applied field to probe magnetization.
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It is worthwhile noticing that in Co/Cu multilayers a direct visualization of the domain structure using magnetic force microscopy was possible.

FIG. 1. Brillouin light scattering spectra for several values of the external field $H$, applied in-plane along the [100] direction. The Ni film was 60 Å thick, and data were obtained using the backscattering configuration; see text for the experimental details.

FIG. 2. Brillouin light scattering data for the spin wave frequency $\Omega_0$ of a $t = 60$ Å-thick Ni film versus the intensity of a magnetic field $H$ applied along the in-plane easy axis [110], on increasing $H$ (solid squares) as well as on decreasing it (solid circles). The solid line is the spin wave frequency, calculated from Eq. (2) assuming a uniform in-plane magnetization. In the inset we compare the $\Omega_0(H)$ data measured for $H$ applied along the easy axis [110] (solid symbols) and for $H$ along the hard axis [100] (open symbols).

FIG. 3. Magneto-optic vector magnetometry data in a canted field geometry, showing the field dependence of: a) the polar ($M_z$) component of the magnetization, b) the longitudinal ($M_x$) component, c) the magnetization modulus $M = \sqrt{M_x^2 + M_z^2}$. All quantities are normalized to the saturation value $M_{sat}$. The field was applied at different angles ($\theta_H = 0^\circ, 5^\circ, 11^\circ, 20^\circ$) with the film normal, $z$. 
