Journal of Magnetism and Magnetic Materials 240 (2002) 386–388

journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Effects of perpendicular magnetic anisotropy on a large enhancement of elastic light scattering in ultrathin Co films

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Abstract

Effects of a perpendicular magnetic anisotropy (PMA) on a large enhancement of elastic light scattering (ELS) in ultrathin Co films have been studied, where the ELS intensity shows a maximum at a critical field (H_{crit}) between the in-plane and out-of-plane magnetization. We find that the maximum ELS intensity increases significantly with increasing Co thickness, where the strong PMA realizes H_{crit} in such thicker Co films.

Keywords: Brillouin scattering; Anisotropy – perpendicular

In ultrathin magnetic films with a strong perpendicular magnetic anisotropy (PMA), the magnetization will incline towards the out-of-plane of the film. The angle between the magnetization and the film plane is a function of the PMA, film thickness, saturation magnetization, and external field. Therefore, the transient behaviors of the magnetization become complicated, depending on the relations among those factors. The magnetization of the film with such large PMA starts to rotate towards the in-plane direction with a critical field (H_{crit}) by applying in-plane fields. Several interesting light scattering phenomena can be observed around H_{crit} such as, enhancements of the in-elastic spin-wave Brillouin light scattering (BLS) intensity [1] and the field-dependent spin-wave BLS line broadening [2]. Recently, we have reported a large enhancement of the intensity of polarized *elastic* light scattering (ELS) in ultrathin Au/Co/Au/Cu(1 1 1) films with a strong PMA [3,4]. In this paper, we report the effects of the PMA strength on such large enhancements of the ELS intensity in those films. For this purpose, the PMA strength was adjusted by the Au-interlayer thickness, since it depended on the Au thickness. In addition, the Co thickness was varied from 3 to 8 monolayers (ML).

Details of the sample preparation were described elsewhere [3]. A Cu-buffer layer was deposited on the 7×7-reconstructed Si substrate under ultrahigh vacuum at room temperature (RT) followed by an Au-interlayer. After this Au-interlayer, a Co film was deposited, followed by a 3.5 nm Au-overlayer. The light scattering measurements were performed at RT using a tandem $6(3+3)$-pass Fabry–Perot interferometer. A frequency-doubled and vertically polarized cw-Nd:YAG laser with a wavelength of 532 nm and an output power of 200 mW was used as an excitation light source. The back-scattered light with the polarization normal to that of the incidence light was detected. It should be noted that the reflected light from the film surface was not collected by this back-scattering configuration. An external magnetic field was applied parallel to the film surface and normal to the incident polarization.

First, we explain the equilibrium position of magnetization in a Co film with a strong PMA. Fig. 1 shows the in-plane field dependence of the magnetization direction in the 5 ML-thick Co film with a 1 ML-thick Au-interlayer. For the derivation of the magnetization direction, magnetic parameters including g-factor and

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PII: S0304-8853(01)00831-9

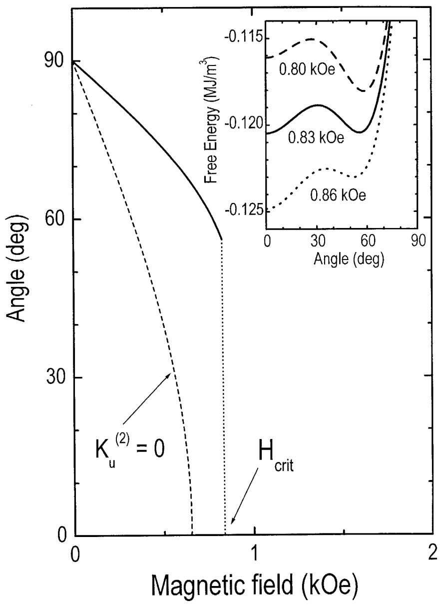

Fig. 1. A calculated angle of the magnetization direction with respect to the film plane as a function of in-plane field, in a 5 ML-thick Co film with a 1 ML-thick Au-interlayer. A critical field H_{crit} is determined from the potential minima in the system (inset, see text). Above this H_{crit}, the magnetization lies in the film plane (0°). A dashed line shows the field dependence of the angle calculated with $K_u^{(2)} = 0$ (J/m^3).

PMA constants were determined from the field dependence of the spin-wave BLS frequency. The calculation procedure was described elsewhere [3]. The equilibrium position of the magnetization was calculated from the angular differential of the free energy using such parameters. With uniaxial PMA, the in-plane direction of the magnetization is parallel to the external field. Therefore, the angle of the magnetization with respect to only the film plane is shown as a function of field. As can be seen, the second-order PMA constant $K_u^{(2)}$ affects the equilibrium position of the magnetization. As the in-plane field increases, the magnetization rotates towards the in-plane direction and is then discontinuously pulled into the film plane at H_{crit}. It is noticed that there are two potential minima in the angle dependence of the free energy of this system around H_{crit}, due to the $K_u^{(2)}$ contribution (inset). The angles corresponding to these potential minima are obtained from the above calculation and one is always 0° (in-plane direction). At H_{crit}, both potentials are equal, therefore, the magnetization direction changes discontinuously. The magnetization direction becomes unstable around this H_{crit}, since the potential barrier energy between those potential minima is lower than the thermal energy at the RT. As reported in the previous papers [3,4], significant enhancements of the ELS intensity were observed around this H_{crit}. We attributed this phenomenon to random fluctuations of the magnetization, since the light scattering due to

Table 1
Results of the 1st- and 2nd-order PMA constants $K_u^{(1)}$ and $K_u^{(2)}$, the critical field H_{crit}, and the maximum intensity of ELS, in Co films with various thicknesses of Au-interlayer[a]

Co-thickness (ML)	Au-thickness (ML)	$K_u^{(1)}$ (MJ/m^3)	$K_u^{(2)}$ (J/m^3)	H_{crit} (kG)	Max. intensity ($\times 10^5$ counts/s)
3	0	1.63	80.9	3.88	2.8
4	0	1.48	58.4	2.12	2.6
	1	1.51	33.6	2.47	2.4
5	1	1.36	43.5	0.83	12.1
	2	1.60	29.0	4.16	4.2
	3	1.67	29.0	5.08	2.6
6	1	1.26	—	—	—
	2	1.46	24.6	2.36	12.0
	3	1.49	46.2	2.67	9.9
	5	1.54	26.0	3.41	10.7
7	2	1.35	43.3	0.85	37.7
	3	1.40	46.2	1.51	35.7
	5	1.41	50.5	1.73	24.1
8	2	1.28	—	—	—
	3	1.33	—	0.57	49.0
	5	1.35	—	0.86	53.7

[a] Some samples show no H_{crit} and thus no ELS enhancements, since the PMA strength in such films is not enough to sustain the out-of-plane magnetization. Also, in some samples, $K_u^{(2)}$ cannot be determined (see text).

random fluctuations of the polarizability showed a spectrum peak with zero energy shift. As described above, the direction of magnetization becomes unstable at H_{crit} in addition to the instability in precession motion of the magnetization. Therefore, these instabilities should cause random fluctuations of the polarizability through the spin–orbit coupling.

Next, we examine the effects of the PMA strength on the enhancement of the ELS intensity. The PMA strength was solely changed by varying atomic-scale thicknesses of the Au-interlayer ranging from 0 to 5 ML. H_{crit} was determined by the competition between the PMA and the in-plane shape anisotropy depending on the Co thickness. The results are summarized in Table 1. As can be seen, the first-order PMA constant $K_u^{(1)}$ shows a monotonic increase with increasing Au-interlayer thickness. The magnitude of $K_u^{(2)}$ is much smaller than that of $K_u^{(1)}$. Therefore, H_{crit} is mainly affected by $K_u^{(1)}$. However, as described above, the $K_u^{(2)}$ contribution makes the magnetization rather unstable. It should be noted that some $K_u^{(2)}$ values for Co films with low H_{crit} could not be obtained by our BLS method, since the $K_u^{(2)}$ was derived from the field dependence of the spin-wave frequency below H_{crit} and the low H_{crit} like 0.5 kOe did not allow us to observe such field dependence of the spin wave. With the same thickness of Co, we observe that the maximum intensity of the ELS enhancement tends to increase with decreasing H_{crit}. The lower H_{crit} is originated from the weaker PMA in combination with the larger in-plane anisotropy. Therefore, the force sustaining the magnetization towards the perpendicular direction is weak. Such a situation can make the magnetization instabilities more significant.

Finally, we find the strong dependence of the ELS enhancement on the Co thickness. To clarify this, the Co-thickness dependence of the maximum intensity of the ELS is plotted in Fig. 2. As can be seen, the maximum intensity increases significantly with increasing Co thickness, with the fourth power law. This marked increase in the maximum ELS intensity is interpreted by the combination effect of the thicker Co films with the lower H_{crit}. In our experiment, the strong PMA obtained with thick Au-interlayers realizes H_{crit} even in these thick Co films like 8 ML. Therefore, we conclude that the maximum intensity in this ELS enhancement can be controlled by designing the PMA strength and the Co thickness.

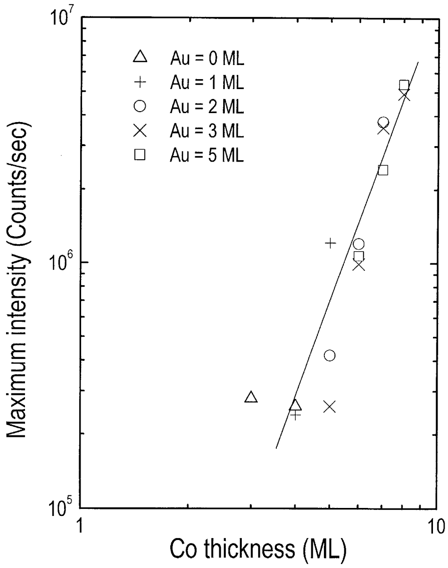

Fig. 2. The maximum intensity in the ELS enhancements as a function of Co thickness with various thicknesses of the Au-interlayer. A solid line shows the fourth power law.

In summary, effects of the PMA on large enhancements of the polarized ELS intensity in ultrathin Au/Co/Au/Cu(1 1 1) films have been examined by varying the Au-interlayer thickness. As a result, the ELS enhancement factor increases significantly with increasing Co thickness up to 8 ML as well as decreasing H_{crit}, where the strong PMA realizes H_{crit} even in thick Co films.

This research is partially supported by USDOE grant DE-FG02-93ER45488 and also by the CREST, the Japan Science and Technology Corporation.

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