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In situ spin-wave Brillouin light scattering for the study of Co surfaces

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Abstract

We have developed an in situ spin-wave Brillouin light scattering system for the study of surface magnetism of magnetic thin films. The surface uniaxial anisotropy constant is determined for a bare surface of 10 monolayers (ML) of Co(0 0 0 1), indicating the in-plane anisotropy. With only 0.5 ML of Cu deposited on this Co(0 0 0 1) surface, the strong perpendicular anisotropy is immediately induced, which is followed by a weak peak at 1 ML of the Cu.

Keywords: Brillouin scattering; Anisotropy – surface; Anisotropy – perpendicular

Precise control of magnetic anisotropies in magnetic ultrathin films is necessary for applications of those films. Especially, the uniaxial perpendicular magnetic anisotropy (PMA) of Co(0 0 0 1) single-crystal films is important, since that anisotropy is rather strong and can be applied for sustaining ultrahigh density magnetic domains. In artificial film structures, such as ultrathin films and multilayers, the surface or interface anisotropy is a key factor for controlling the magnetic anisotropies because the effects of the surface or interface on the anisotropy become important. For the work reported here, we have used in situ Brillouin light scattering (BLS) to study the surface anisotropy of ultrathin Co(0 0 0 1) films, since the frequency of the spin-wave observable by BLS is very sensitive to the surface anisotropy in ultrathin films [1]. Previously, excellent in situ Brillouin study showed the determination of magnetic anisotropies and the effect of a Cu-overlayer on the surface anisotropy in Co(0 0 1)/Cu ultrathin films [2]. On the other hand, Engel et al. have demonstrated the non-monatomic dependence of PMA on the overlayer thickness for Co ultrathin films by means of a Kerr effect [3]. In this paper, we have developed an in situ BLS system in combination with our molecular beam epitaxy (MBE) for the study of surface magnetism of magnetic thin films under ultrahigh vacuum. We show the determination of a surface anisotropy constant of Co(0 0 0 1) and the effect of the deposition of ultrathin Cu on such anisotropy.

A RIBER 1000 MBE system was modified for the in situ BLS study. We added an ultrahigh vacuum chamber specially designed for the BLS observations with the pressure in the range of 10^{-10} Torr. A HF-cleaned Si(1 1 1) substrate was introduced to a growth chamber with the base pressure in the range of 10^{-11} Torr and annealed at 750° showing a (7×7) reconstructed surface. First, a Cu buffer layer with the thickness of 4 nm was deposited and followed by a 1 ML thick Au interlayer to get a high quality of a subsequent Co film. A single-crystal Co(0 0 0 1) film with the thickness of 10 ML was grown on it. Effusion cells were used for those films, including a high-temperature cell for the Co deposition. The film thickness was calibrated with an absolute accuracy of $\pm10\%$ using Rutherford back scattering spectroscopy. After the film deposition in the growth chamber, the sample was immediately transferred to the BLS chamber and a magnetic field was

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applied up to 2.4 kOe parallel to the film plane. The longitudinal-polarized laser light of a diode-pumped and frequency-doubled Nd:YAG laser with the wavelength of 532 nm and the output power of 200 mW was used for the excitation light source. A back scattering geometry was employed to collect the BLS from the sample surface, with the incidence angle of 45°. The applied field was normal to the polarization of the incident laser light. The *f*-number of a collecting lens outside the chamber for the back scattering was 2.0. Polarized-scattered light normal to the incident longitudinal mode was collected, which allowed us to detect only the scattering light due to the spin-waves. A tandem 6 pass (3 + 3) Fabry–Perot interferometer and a solid state detector with quantum efficiency of 44% and dark count of 2.2 cps was used for detection of the spin-wave spectrum. Accumulation time was 1.8 s/channel, which corresponded to about 30 min for one spectrum. A uniaxial PMA constant K_u was determined from the field dependence of the spin-wave frequency. Details of the calculation for the spin-wave frequency were described elsewhere [4].

Fig. 1 shows the spin-wave BLS spectra from the bare surface of Co(0 0 0 1) with various magnetic fields. As can be seen, high signal-to-noise ratios for each spin-wave spectrum can allow us to analyze the field dependence of the spin-wave frequency with sufficient accuracy. Fig. 2 shows spin-wave frequency as a function of external field. A solid line is the best fitted calculation result assuming in-plane magnetization and uniaxial PMA. We included effects of both the dipole and exchange fields in the calculation of spin-wave frequency, which are caused by a fluctuation of the magnetization due to the surface spin-wave observed by this light scattering method. From this fitting, we obtain the parameters, $g = 1.86$, $K_u = -4.6 \times 10^4\ \mathrm{J/m^3}$. Here, the negative value of K_u means in-plane anisotropy. Using our previous results [4] for this kind of ultrathin Co(0 0 0 1) film, we derive that the interface PMA constant $K_{u,\mathrm{Interface}}^{(\mathrm{Co/Au=1ML/Cu})}$ for the bottom interface of Co/Au(1 ML)/Cu is $-0.10\ \mathrm{mJ/m^2}$. The volume PMA constant $K_{u,\mathrm{Volume}}$ is $0.56\ \mathrm{MJ/m^3}$. With the values of the anisotropy constant, we can determine the upper surface PMA constant $K_{u,\mathrm{Surface}}^{(\mathrm{UHV/Co})}$, as follows:

$$K_{u,\mathrm{Surface}}^{(\mathrm{UHV/Co})} = K_u\, t_{\mathrm{Co}} - K_{u,\mathrm{Volume}}\, t_{\mathrm{Co}} - K_{u,\mathrm{Interface}}^{(\mathrm{Co/Au=1\ ML/Cu})} = -1.1\left(\mathrm{mJ/m^2}\right),$$

where t_{Co} is the thickness of Co. This result indicates that the surface PMA of a bare Co(0 0 0 1) is strong in-plane.

As it is well known, the Co(0 0 0 1) films stacked with several kinds of materials, such as, Pt, Pd, Cu, and Au, show strong interface PMA. Therefore, the effects of the deposition of ultrathin films on the surface of the bare Co(0 0 0 1) on the surface anisotropy should be examined from both viewpoints of the fundamental and application aspects. We deposited subsequently ultrathin Cu films on the Co(0 0 0 1) surface. The result is shown in Fig. 3. K_u is plotted as a function of Cu

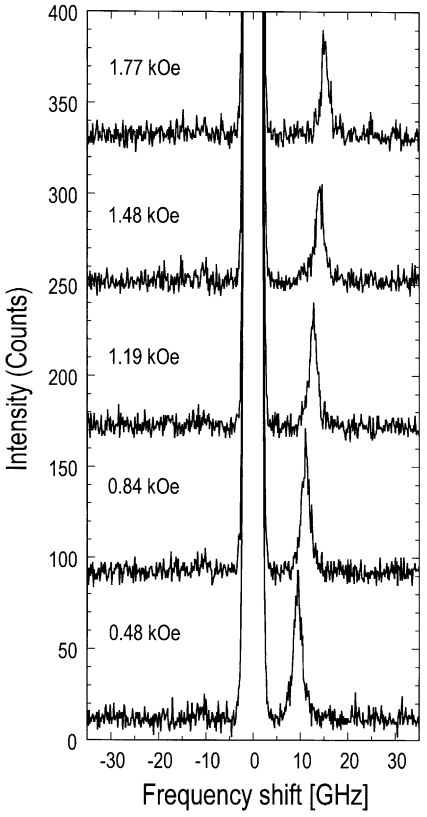

Fig. 1. In situ spin-wave BLS spectra with various fields, from the surface of 10 ML thick Co(0 0 0 1) film.

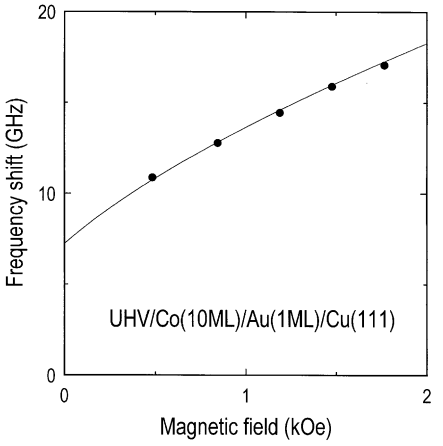

Fig. 2. Field dependence of the spin-wave frequency for the bare Co film. A solid line is the best fitted calculation.

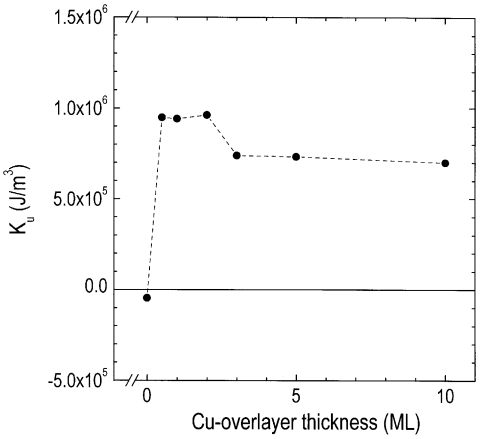

Fig. 3. Uniaxial anisotropy constant K_u as a function of Cu-overlayer thickness.

thickness, where the thickness of Cu was controlled by the deposition time. As can be seen, with only 0.5 ML of Cu deposited, strong PMA is induced. In addition to this, an intensity peak around 1 ML of Cu can be observed. For thicker Cu overlayers, the PMA remains almost constant. That steep increase in PMA with the coverage of Cu indicates that the interface PMA at the Cu/Co interface is generated with only 0.5 ML of Cu in ultrahigh vacuum. Also, the peak shows a modification of PMA due to the monatomic-scale coverage of Cu. Those experimental results suggest that the interface PMA of Cu/Co can be influenced by the steep change in the electronic structure of the Co surface, since the coverage as 0.5 ML is insufficient to explain such PMA with only simple Néel-type interface anisotropy. We have shown that the misfit strain of Co/Cu interface is rather small and thus does not affect significantly the interface PMA [4]. In addition to this, the lattice structure and the resultant volume PMA in Co with the Cu overlayer with the thickness of 3.0 nm are identical to those of the bulk single crystal. Finally, we comment about the sharpness of pronounced PMA peak around 1 ML thickness of Cu-overlayer, which has been previously reported using in situ Kerr hysteresis measurements [3]. In this study, the anisotropy constant was determined from the effective magnetic field acting on the long-wavelength spin-wave with the wavelength of 376 nm. Therefore, the spin-wave BLS can see the anisotropy fields averaged in several micrometers area in dimension. On the other hand, such Kerr-hysteresis measurement for the hard magnetization axis gives a sum of each magnetization orientation process. Further investigations for the microscopic aspects of the surface and interface anisotropies are needed.

We have used in situ spin-wave BLS, for determining a surface uniaxial anisotropy constant of Co(0 0 0 1) and the study of effects of ultrathin Cu-overlayers. As a result, the in-plane surface anisotropy of the Co surface is shown to change steeply to strong PMA with 0.5 ML coverage of Cu, which is followed by a weak intensity peak around 1 ML of Cu.

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