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Micromagnetic properties of the Cu/Ni crossed-wedge film on Cu(0 0 1)

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Abstract

The micromagnetic properties of a Ni film in a Cu/Ni crossed-wedge on Cu(0 0 1) are investigated by a combination of photoelectron emission microscopy and X-ray magnetic circular dichroism. Two spin-reorientation transitions (SRT) from in-plane to perpendicular to the film plane and back to in-plane were observed with increasing Ni thickness. Whereas no clear Cu thickness dependence of the former SRT has been observed, the latter strongly depends on Cu thickness, and is shifted to thinner Ni thicknesses by increasing Cu overlayer thickness. Furthermore, the size and the shape of the ferromagnetic domain structure in the perpendicular magnetization region also depend on Cu thickness. The average domain size decreases with increasing Ni thickness near the second SRT line. It is observed for the first time that these domain structure changes also depend on Cu overlayer thickness.

Keywords: Electron microscopy; Magnetic measurements; Magnetic phenomena (cyclotron resonance, phase transitions, etc.); Copper; Nickel; Single crystal epitaxy; Magnetic films; Magnetic surfaces

1. Introduction

The easy axis of magnetization (EAM) of magnetic ultrathin films is determined by the competition among all contributions to the magnetic anisotropy energy: surface, interface, magneto-elastic, crystalline, and shape anisotropy (demagnetization energy) etc. Several epitaxially grown ultrathin films were reported to have the EAM oriented perpendicular to the film plane [1–8]. Among them, Ni/Cu(0 0 1) shows an unusual spin-reorientation transition (SRT). An SRT from in-plane to perpendicular to the film plane takes place at 11 atomic monolayers (ML) in Ni thickness, and returns to in-plane at around 50 ML [7–12,14]. The effect of a Co capping layer [13] or absorption of CO or H_2 [14] on the EAM of Ni films on Cu(0 0 1) were also reported. A Co overlayer strongly forces the magnetization of Ni films in the plane, even if it is less than 3 ML, because a Co film on Ni/Cu(0 0 1) has a strong in-plane magnetic anisotropy [13]. When a wedge-shaped Ni film is covered by 0.5 ML of CO and H_2, the first SRT line shifts to lower Ni

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thicknesses by about 3 and 4 ML [14], respectively. These measurements suggest the importance of the magneto-elastic and the interface anisotropy contributions to the EAM. In our measurements, in addition, a strong thickness dependence of the SRT of Cu/Ni bilayers on Cu(0 0 1) on the thickness of the Cu overlayer was observed.

Photoelectron emission microscopy (PEEM) [15] is a powerful method for the observation of the magnetic domain structure, especially when it is applied to wedge-shaped films. In this paper, 0–11 ML Cu/0–60 ML Ni bilayer crossed double-wedges were deposited on Cu(0 0 1). The absorption of circularly polarized synchrotron radiation leads to an element-selective magnetic contrast by using the technique of X-ray magnetic circular dichroism (XMCD). The magnetic orientation of the Ni film below the Cu layer is visualized. Thus the thickness dependence of the SRT on both Ni and Cu films can be measured. These observations shed light on the discussion of the origin of the SRT, such as the change of the magneto-elastic anisotropy energy or the interface anisotropy energy between Cu and Ni films.

The domain structure in the range of perpendicular magnetization between two SRT lines is another interesting issue. Stripe domain patterns in perpendicularly magnetized ultrathin films were reported [5,6,13], the average domain width of which decreases in the vicinity of the SRT. In our measurements, stripe domains of constant width were observed only underneath an 11 ML Cu film. A reduction in scale of this width with increasing Ni thickness was observed near the SRT line. The magnetic domain size was found to depend also on Cu overlayer thickness. It becomes smaller for increasing the Cu thickness.

2. Experimental

The experiments were carried out at beamline UE56-2 PGM2 [16] of BESSY II in Berlin, Germany. Circularly polarized X-rays were applied to the sample under an incidence angle, θ, of 60° to the surface normal (see Fig. 1(b)). PEEM was used to observe the SRT lines and the domain structures. The clean surface of a Cu(0 0 1) single crystal

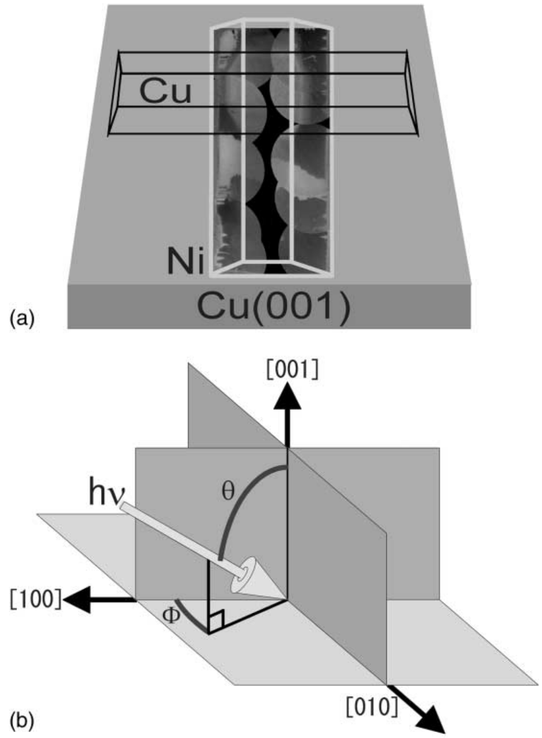

Fig. 1. (a) Schematic picture of the sample, consisting of a crossed double-wedges of Cu/Ni on Cu(0 0 1). Ni and Cu were grown epitaxially at room temperature with a rectangular slit (2×0.5 mm^2). It is placed 1 mm in front of the sample surface. There are four parts of crossed-wedge regions. PEEM images are superimposed (for detail see the text). (b) The crystal axis of the Cu(0 0 1) substrate is denoted to appreciate the incident angle of X-ray.

substrate was prepared by Ar^+ ion bombardment and annealing. Cleanliness was checked by Auger electron spectroscopy with the base pressure of below 5.0×10^{-10} mbar in the sample preparation chamber. Crossed double-wedge bilayers of Cu and Ni were epitaxially grown on the Cu(0 0 1) substrate at room temperature. The deposition rates of Ni and Cu were calibrated by medium-energy electron diffraction intensity oscillations. They were 48 s/ML for Ni and 250 s/ML for Cu. A rectangular slit (2.0×0.5 mm^2) was set at 1 mm in front of the Cu surface. During evaporation, the substrate and the slit were rotated together to make wedge-shaped films (see Fig. 1(a)). Rotation was from +10° to −10° about the axis parallel to the long side of the slit with a speed of 1.25° s^{-1}.

The photon energy was set to the maximum of the Ni L_3 absorption peak (853 eV) and the secondary electrons were detected by the PEEM. Local XMCD is deduced from the asymmetry between two PEEM images excited by positive (σ_+) and negative (σ_-) helicity. The asymmetry $(\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ is proportional to $\cos\alpha$, where α is the angle between the directions of the incident circularly polarized X-rays and the Ni film magnetization. To divide by $(\sigma_+ + \sigma_-)$ enables us to distinguish domains of different magnetization directions.

3. Results and discussion

The Ni magnetic domain pattern of the whole area of a Ni double-wedge film is shown superimposed to a sketch of the sample in Fig. 1(a). The light was incident to the sample with the azimuth angle, φ, of 27° to the [1 0 0] crystal axis of the Cu substrate (see Fig. 1(b)). The direction of magnetization is indicated by the gray scale, i.e., a direction parallel to the light incidence as white and an anti-parallel direction as black. The Cu double-wedge crossing horizontally can be identified from the octagonal white part shown in the upper part of this image.

Fig. 2 shows an enlarged view of the upper left part of Fig. 1(a). The magnetization direction can be determined by changing the azimuth angle. In this figure, the azimuth angle of the incoming X-rays was set to 196° to the [1 0 0] crystal axis, i.e., the sample was rotated 169° in the film plane with respect to Fig. 1(a). If the sample has a perpendicular magnetization direction, the gray scale contrast does not change after this rotation. On the other hand, the contrast reverses if the sample has an in-plane magnetization. The thicknesses of Cu and Ni are indicated at the left hand side and at the bottom of the figure, respectively. Arrows in the figure show the magnetization directions of domains. Two SRT lines, labeled B and D, are identified. These are marked by broken and solid white lines, respectively.

At room temperature, Ni films with a thickness above 8 ML begin to be ferromagnetic, which is denoted as A in Fig. 2. The area just above 8 ML

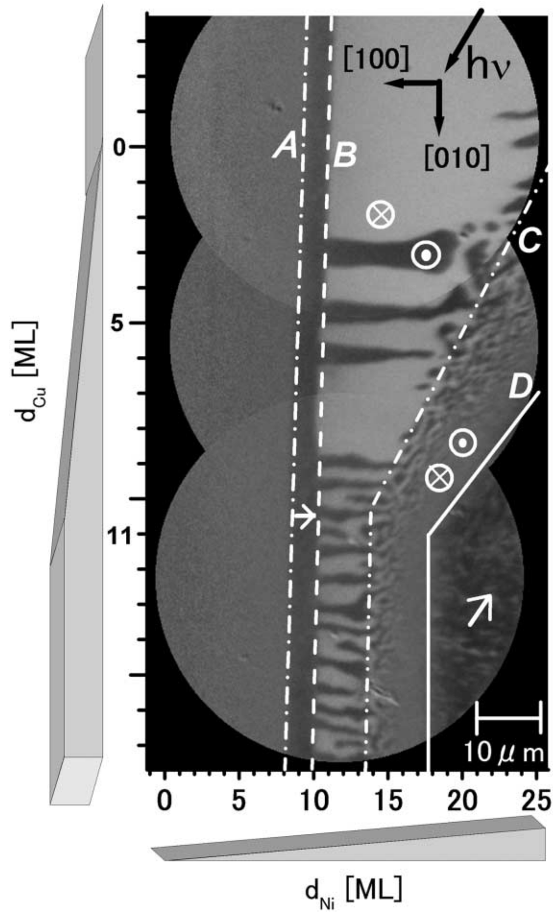

Fig. 2. Enlargement of the upper left part of Fig. 1. The thicknesses of Cu and Ni wedges are indicated at the left and the bottom of the image, respectively. The Ni film has an in-plane magnetization between lines A and B and as well as on the right-hand side of line D. Between lines B and D it has a perpendicular magnetization. Starting at line C the domain width is getting significantly smaller for increasing Ni thickness up to line D.

has in-plane magnetization. Then the magnetization changes from in-plane to perpendicular to the film plane at the SRT line B, at about 10 ML in Ni thickness. It was reported [7] that this SRT line B moves to thinner Ni thicknesses by about 1 ML under a Cu overlayer, but this could not be observed here clearly. Another SRT line denoted as D is present, at which the Ni magnetization orients back to in-plane for increasing Ni thickness. This SRT line shows a strong Cu overlayer thickness dependence. Underneath an 11 ML Cu overlayer the SRT line D is located at a Ni thickness of only 18 ML. In the region uncovered by Cu, however, the SRT D occurs at about 50 ML, in agreement with O'Brien et al. [7].

For Ni on Cu(0 0 1), the total anisotropy energy K_{eff} is usually expressed as

$$K_{\mathrm{eff}} = -2\pi M^2 + K_{\mathrm{ME}} + \frac{K_{\mathrm{I}} + K_{\mathrm{S}}}{d_{\mathrm{Ni}}}, \tag{1}$$

where $-2\pi M^2$ is the demagnetizing energy, and d_{Ni} the thickness of the Ni film. K_{ME}, K_{I} and K_{S} are the magneto-elastic, interface and surface anisotropy energies, respectively. The first and the third term of the right hand side of Eq. (1) are responsible for the in-plane EAM and have negative values, whereas the second term is positive, favoring out-of-plane magnetization. If K_{eff} is negative (positive), a Ni film has in-plane (perpendicular) magnetization [7,8].

In the case of Cu capped Ni/Cu(0 0 1), the third term in the right hand side of Eq. (1) would become $2K_{\mathrm{I}}/d$, if one assumes identical interfaces, as in the analysis by O'Brien et al. [7]. Since both interfaces, the one to the substrate and the one to the capped Cu, may not be identical, their magneto-elastic contributions to the anisotropy by the stress induced by the Cu may also be different. It has been reported that in Ni films on Cu(0 0 1) with a thickness of more than 13 ML the stress is released by the formation of misfit dislocations [7]. The influence of a Cu overlayer grown on a partially relaxed Ni film with locally differing lateral lattice constant on the film anisotropy may thus be different to that coming from the substrate/Ni interface. This could lead to different anisotropy contributions from these two interfaces. An epitaxially grown Cu overlayer will also induce a different stress in the Ni film on the top than on the bottom, which could lead to a different contribution to K_{ME}.

The interface anisotropy $K_{\mathrm{Cap-Ni}}$ between the Cu overlayer and the Ni film can be written as

$$K_{\mathrm{Cap-Ni}} = K_{\mathrm{S}} + \alpha(d_{\mathrm{Cu}}), \tag{2}$$

where $\alpha(d_{\mathrm{Cu}})$ is a function of d_{Cu}, which is zero when $d_{\mathrm{Cu}} = 0$. From this suggestion Eq. (1) will then be written as follows:

$$K_{\mathrm{eff}} = -2\pi M^2 + K_{\mathrm{ME}} + \frac{K_{\mathrm{Sub-Ni}} + K_{\mathrm{S}} + \alpha(d_{\mathrm{Cu}})}{d_{\mathrm{Ni}}}. \tag{3}$$

A more detailed study is required to determine the function $\alpha(d_{\mathrm{Cu}})$.

Another new discovery is that the magnetic domain structure of the Ni film between the two SRT lines B and D, i.e., in the perpendicular magnetization region, depends also on the Cu overlayer thickness. Fig. 3(a) is an enlargement of the domain pattern at constant Cu thickness of 11 ML. The stripe-shaped domains start from the SRT line B. Fig. 3(b) shows the number of domain walls in 50 μm at each Ni thickness. The Ni thickness is given at the horizontal axis in the same scale as that of Fig. 3(a). The solid line serves to guide the eye. The competition between the gain in magnetostatic demagnetizing energy by forming narrow stripe domains and the related energy cost in creating domain walls leads to an exponential increase in stripe domain density close to a SRT, at which the domain wall energy vanishes [6]. Interestingly in the present sample this is only observed at the second SRT (line D), not at the first SRT at 10 ML Ni thickness (line B). Kinetic barriers for the formation of smaller stripe domains in the course of film deposition could be responsible for the absence of stripe bifurcations at line B.

Fig. 3(a) and (b) show that the number of domains starts to increase significantly at around 14 ML Ni thickness by bifurcation of stripe domains. Above that thickness, which we will call the domain structure transition (DST) line in this paper, the domain width decreases with increasing Ni thickness until the SRT line D. The DST line is denoted as C (double-dotted line) in Fig. 2. Underneath the Cu plateau, the DST line is perpendicular to the Ni-slope direction. Underneath the Cu-wedge, however, it is interesting that the thickness of the Cu overlayer has a strong effect on the position of the DST, namely, the DST line C shifts to higher Ni thickness as the Cu overlayer gets thinner. The domain size is also controlled by the Cu overlayer thickness.

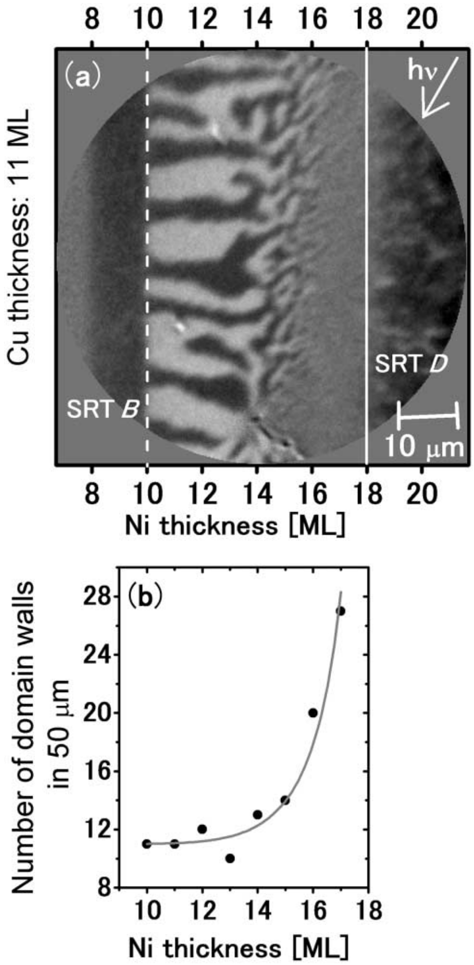

Fig. 3. (a) Enlargement of the region of the Cu plateau of Fig. 2 and (b) the number of domain walls in 50 μm as a function of Ni thickness. The Ni thickness is indicated in the horizontal axis for both (a) and (b) in the same scale. The vertical axis of (b) is the number of domain walls in 50 μm at each Ni thicknesses. The solid line in (b) serves as a guide to the eye. The density of domains increases significantly at around 14 ML Ni thickness.

4. Conclusion

Four different magnetization regions of the Ni film were investigated by using crossed-wedge Cu/Ni bilayers on Cu(0 0 1). Below 8 ML, the Ni film is non-ferromagnetic at room temperature. Increasing the Ni thickness, the Ni film is magnetized in-plane until at 10 ML, SRT B takes place, and the magnetization turns to out-of-plane. Another SRT D from perpendicular to in-plane to the film plane is also observed at higher Ni thicknesses. Underneath the Cu-wedge overlayer, the SRT line D shows a strong dependence on the Cu thickness. It shifts from 50 to 18 ML in Ni thickness when the thickness of the Cu overlayer increases from 0 to 11 ML. Furthermore, the scale down of stripe domain width in the perpendicularly magnetized region have been investigated with increasing Ni thickness. The dependence of the DST line on the thickness of the Cu overlayer is firstly observed.

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