In Situ Observation of Magnetic Anisotropy Energy of Alternately Layered FeNi Thin Films*

Masako Sakamaki[†] and Kenta Amemiya

Photon Factory and Condensed Matter Research Center, Institute of Materials Structure Science,
High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan

(Received 13 January 2012; Accepted 24 March 2012; Published 14 April 2012)

Magnetic anisotropy of alternately layered FeNi thin films grown on Ni(3–21 ML)/Cu(001) is investigated by means of the X-ray magnetic circular dichroism (XMCD). Perpendicular magnetic anisotropy is observed when the substrate Ni is thicker than 15 and 20 ML for 4 and 6 ML FeNi films, respectively, while in-plane magnetic anisotropy appears at the thinner substrate Ni region. By comparing with the magnetic phase diagram calculated from the magnetic anisotropy energies, which are obtained by the XMCD study [M. Sakamaki and K. Amemiya, Appl. Phys. Express 4, 073002 (2011)], we show that the phase boundary of the present samples shifts so as to prefer the in-plane magnetic anisotropy. This might be caused by the structural relaxation in the substrate Ni. [DOI: 10.1380/ejsnt.2012.97]

Keywords: X-ray absorption spectroscopy; Reflection high-energy electron diffraction; Metal-metal magnetic thin film structures

I. INTRODUCTION

The $L1_0$ type FeNi multilayer has attracted much attention as one of the candidate materials for rare metal-free perpendicularly magnetized films. The $L1_0$ ordered structure consists of alternate stacking of two different atomic planes along the fcc [001] direction. Some efforts have been made to realize the perpendicular magnetic anisotropy (PMA) by using alternate monatomic layer deposition on fcc (001) substrates [1–3]. Although they investigated the magnetic properties of the multilayer after the deposition of the whole film, an *in-situ* analysis at each growth process is also important for understanding the fundamental magnetic properties. Our recent X-ray magnetic circular dichroism (XMCD) study revealed the magnetic anisotropy energies (MAEs) of buried Fe and Ni layers as well as surface and remaining inner layers, and the total MAE simulated from the result showed qualitatively good agreement with the magneto-optic Kerr effect measurement [4]. However, it is also necessary to investigate the structure of the films at the same time. In the present study, we applied *in-situ* XMCD to alternately layered FeNi thin films systematically varying the thicknesses of the FeNi and the substrate Ni layers. Since the lattice constant of Ni grown on a Cu(001) single crystal depends on the Ni layer thickness [5, 6], one can control the structure of the FeNi and Ni films. Our result shows that PMA is observed when the substrate Ni is thicker than 15 and 20 ML for 4 and 6 ML FeNi films, respectively, while in-plane magnetic anisotropy appears at the thinner substrate Ni region. By comparing with the magnetic phase diagram calculated from MAEs, we show that the phase boundary of the present samples shifts so as to prefer the in-plane magnetic anisotropy. We discuss the origin of the MAE with regard to the structural information as well.

FIG. 1: RHEED images of (a) Ni(10 ML)/Cu(001) and (b) 4 ML FeNi film grown on Ni(10 ML)/Cu(001).

II. EXPERIMENTAL

All the experiments were performed *in situ* in an ultra high vacuum chamber with a base pressure of $\sim 9 \times 10^{-8}$ Pa at the beamlines BL-7A [7] and 16A [8] of the Photon Factory, Japan. A Cu(001) single crystal was cleaned by repeated cycles of Ar^+ sputtering at 1.5 keV and subsequent annealing at ~ 900 K. Fe and Ni layers were then grown at room temperature by the electron bombardment evaporation of Fe and Ni rods. The structure of the films were checked *in situ* by reflection high-energy electron diffraction (RHEED). The growth rate of the film was determined by monitoring the oscillatory intensity of the RHEED spot. 1 ML Fe and 1 ML Ni layers were alternately grown on a wedged-shaped Ni(3–21 ML)/Cu(001) substrate.

XMCD spectra were measured at room temperature by using the circularly polarized X rays. The sample was mounted with $[1\bar{1}0]$ lying in the horizontal plane, which is the magnetic easy axis of the in-plane magnetized films. A pulsed magnetic field of ~ 500 Oe, which is parallel to the incident X-ray beam, was applied for 1 s before each measurement. The normal and grazing X-ray incidence angle geometries were adopted, denoted as NI and GI, respectively. The angle between $[1\bar{1}0]$ and the X-ray beam was 30° at GI. We applied the depth-resolved XMCD technique at the Fe and Ni L edges, in which the spectra were measured at different probing depths [9–12]. The probing depth corresponds to the effective escape depth of the electrons, λ_e , which depends on the detection angle, θ_d .

*This paper was presented at the 6th International Symposium on Surface Science –Towards Nano, Bio and Green Innovation–, Tower Hall Funabori, Tokyo, Japan, December 11–15, 2011.

[†]Corresponding author: masako.sakamaki@kek.jp

FIG. 2: (a) Fe and (b) Ni *L*-edge XMCD spectra for 4 ML FeNi films grown on Ni(*x* ML)/Cu(001) taken in the partial electron yield mode with $\lambda_e=0.7$ nm. The films at $x=8$ and 20 ML show in-plane and perpendicular magnetization, respectively.

FIG. 3: Magnetic phase diagram as a function of FeNi layer thickness n and substrate Ni thickness x . Broken line shows the phase boundary between in-plane (open circle) and perpendicular (filled circle) magnetic anisotropy, calculated from the MAEs obtained by the XMCD study [4].

The partial electron yield mode with a retarding voltage of 500 V was adopted. λ_e was experimentally estimated at each θ_d from the thickness dependence of the edge-jump intensity of the films [9].

III. RESULTS AND DISCUSSION

Figure 1 displays RHEED images of Ni(10 ML)/Cu(001) and 4 ML FeNi film grown on Ni(10 ML)/Cu(001) taken at an electron energy of 12.5 kV. A bright spot is the direct beam from the electron gun and three streaks were observed along the incident electron beam direction $[1\bar{1}0]$. All the samples showed almost the same pattern, which suggests that Fe and Ni grow epitaxially on the Cu(001) substrate. Fine lines in the images are due to scratches on the phosphor screen, which are not essential. The lattice constant of fcc Ni is 2.5%

smaller than that of fcc Cu. Ni film is known to grow pseudomorphically on Cu(001) and this growth mode continues up to a critical thickness, d_c . d_c is reported to be ~ 13 ML, from which the film begins to relax as misfit dislocations form [5]. The whole magnetic anisotropy can be described as the sum of shape, magnetoelastic, surface and interface anisotropies, anisotropies due to roughness at the interface, and so on. Strain relaxation reduces the magnetoelastic anisotropy energy, and the magnetization direction changes to in-plane in the case of the Ni/Cu(001) thin film, because the magnetoelastic anisotropy energy of the Ni/Cu(001) film is positive under the tensile strain [5]. On the other hand, by capping with Fe, some change of the anisotropy in the Ni layer is also expected because of altering the surface and interface anisotropies. We therefore investigate magnetic anisotropy as changing the substrate Ni and FeNi layer thicknesses.

Figure 2 shows Fe and Ni *L*-edge XMCD spectra for 4 ML FeNi films grown on Ni(*x* ML)/Cu(001) taken in the partial electron yield mode with $\lambda_e=0.7$ nm. The films at $x=8$ and 20 ML show in-plane and perpendicular magnetization, respectively. That is, the film at $x=8$ shows a Ni *L*-edge XMCD signal only at GI, while at $x=20$, a significant XMCD signal is found at NI. We here do not discuss the detailed XMCD analysis but discuss the thickness dependence of magnetic anisotropy.

Figure 3 shows magnetic phase diagram as a function of FeNi layer thickness n and substrate Ni thickness x . Perpendicular magnetic anisotropy was observed when the substrate Ni is thicker than 15 and 20 ML for 4 and 6 ML FeNi films, respectively. In-plane magnetic anisotropy was observed at the thinner substrate Ni region. Ni films on Cu(001) are known to show the spin reorientation transition (SRT) from in-plane to perpendicular directions at the thickness between 7 and 11 ML [5, 13]. The SRT critical thickness of the substrate Ni becomes larger as increasing n . This result is well understood by phenomenological MAE model [14], i.e. the shape anisotropy becomes dominant as increasing the film thickness. To further investigate the origin of the magnetic anisotropy, we calculated

the magnetic phase boundary from the element-specific MAEs obtained by the previous XMCD study [4] as shown in Fig 3. Compared to the calculation, the boundaries of both 4 and 6 ML FeNi films lie in the thicker substrate Ni region, indicating that the films favor in-plane magnetization. Because the calculation does not consider the structural change in Ni and Fe layers, and the boundary exists near the critical thickness d_c for the relaxation of the strain, we assume this is due to the structural relaxation in the substrate Ni. Detailed structural investigation, as well as the analyses for the thickness dependent MAEs, is now underway.

IV. CONCLUSION

In conclusion, we investigated the magnetic anisotropy of alternately layered FeNi thin films grown on Ni(3–21 ML)/Cu(001) by means of XMCD. PMA is observed when

the substrate Ni is thicker than 15 and 20 ML for 4 and 6 ML FeNi films, respectively, while in-plane magnetic anisotropy appears at the thinner substrate Ni region. By comparing with the magnetic phase diagram calculated from MAEs, which are obtained by the XMCD study [4], the phase boundary of the present samples was found to shift so as to prefer the in-plane magnetic anisotropy. This might be caused by the structural relaxation in the substrate Ni.

Acknowledgments

The present work has been performed under the approval of the Photon Factory Program Advisory Committee (No. 2010S2-001). The authors are grateful for the financial support of the Quantum Beam Technology Program from the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

-
- [1] T. Shima, M. Okamura, S. Mitani, and K. Takanashi, *J. Magn. Magn. Mater.* **310**, 2213 (2007).
 - [2] M. Mizuguchi, S. Sekiya, and K. Takanashi, *J. Appl. Phys.* **107**, 09A716 (2010).
 - [3] T. Kojima, M. Mizuguchi, and K. Takanashi, *J. Phys.: Conf. Ser.* **266**, 012119 (2011).
 - [4] M. Sakamaki and K. Amemiya, *Appl. Phys. Express* **4**, 073002 (2011).
 - [5] W. L. O'Brien, T. Droubay, and B. P. Tonner, *Phys. Rev. B* **54**, 9297 (1996).
 - [6] J. W. Matthews and J. L. Crawford, *Thin Solid Films* **5**, 187 (1970).
 - [7] K. Amemiya, H. Kondoh, T. Yokoyama, and T. Ohta, *J. Electron Spectrosc. Relat. Phenom.* **124**, 151 (2002).
 - [8] K. Amemiya, A. Toyoshima, T. Kikuchi, T. Kosuge, K. Nigorikawa, R. Sumii, and K. Ito, *AIP Conf. Proc.* **1234**, 295 (2010).
 - [9] K. Amemiya, S. Kitagawa, D. Matsumura, T. Yokoyama, and T. Ohta, *J. Phys. Condens. Matter* **15** S561, (2003).
 - [10] K. Amemiya, S. Kitagawa, D. Matsumura, T. Ohta, and T. Yokoyama, *Appl. Phys. Lett.* **84**, 936 (2004).
 - [11] K. Amemiya and M. Sakamaki, *Appl. Phys. Lett.* **98**, 012501 (2011).
 - [12] K. Amemiya, E. Sakai, D. Matsumura, H. Abe, T. Ohta, and T. Yokoyama, *Phys. Rev. B* **71**, 214420 (2005).
 - [13] B. Schulz and K. Baberschke, *Phys. Rev. B* **50**, 13467 (1994).
 - [14] L. Néel, *J. Phys. Radium* **15**, 225 (1954).