Strain Mediated Control of Magnetic Anisotropy in Alternately Layered FeNi Thin Films

The $L1_0$-type FeNi multilayer has attracted attention as a candidate material for rare metal-free perpendicularly magnetized films for high-density recording media. To understand the fundamental magnetic properties, *in situ* observation of the growth process is important. In this study, we investigated the effect of the lattice strain on magnetic anisotropy of alternately layered FeNi ultrathin films by X-ray magnetic circular dichroism (XMCD) analysis, and showed that perpendicular magnetic anisotropy of Fe is enhanced when compressive strain in the in-plane direction is applied to the FeNi films.

The $L1_0$ ordered alloy, which consists of alternate stacking of two different atomic planes along the fcc [001] direction, is expected to exhibit uniaxial magnetic anisotropy in the c axis, [001]. Various efforts have been made to realize perpendicular magnetic anisotropy (PMA) in $L1_0$-type FeNi [1-3], however, it has not yet been achieved in the multilayered system. On the other hand, it is known that magnetic anisotropy is closely correlated with the surface/interface structure, strain, and so forth. Our previous *in situ* XMCD study revealed element-specific magnetic anisotropy energies (MAE) in FeNi thin films on a Cu(001) substrate [4], and indicated that PMA is enhanced in the case of Fe-terminated FeNi films, while that of Ni-terminated films is reduced.

In this article, we demonstrate from the XMCD study combined with reflection high-energy electron diffraction (RHEED) analysis that PMA is enhanced when compressive strain in the in-plane direction is applied to the Fe layer [5], and confirm that the magnetic anisotropy of FeNi is controlled by the lattice strain by changing the thickness of the Cu spacer layer on a NiCu/Cu(001) substrate [6].

All the experiments were performed *in situ* in an ultra-high vacuum chamber at the beamlines BL-7A and 16A of the Photon Factory. Figure 1 shows the ratio of orbital to spin magnetic moments, and MAE of the Fe and Ni layers in FeNi films grown on Ni/Cu(001) substrate, as functions of the in-plane lattice constant. Here, we call the nearest in-plane interatomic distance as the in-plane lattice constant, a_{in}. The results showed that the perpendicular component of the orbital magnetic moment increases and the in-plane component decreases as a_{in} gets smaller, suggesting that PMA is enhanced when compressive strain in the in-plane direction is applied. To confirm the enhancement of PMA in FeNi film itself, we used a non-magnetic Cu(t_{Cu}ML)/$Ni_{48}Cu_{52}$/Cu(001) substrate, where t_{Cu} indicates the thickness of the Cu spacer layer. The in-plane lattice constant was continuously modulated by changing t_{Cu}. 1 ML Fe and Ni layers were alternately grown starting with an Fe layer on the substrate, so that the effect of strain on the magnetic property of the FeNi layer could be investigated at the same time by using wedged-shaped substrates with various lattice constants. XMCD spectra were taken in total electron yield mode at room temperature. A pulsed magnetic field of 2 kOe was applied before each measurement. We first estimate a_{in} of Cu(t_{Cu}ML)/NiCu(124 ML)/Cu(001) as a function of t_{Cu}. a_{in} changes from 0.2536 to 0.2546 nm when t_{Cu} increases from 0 to 88 ML, while that of bare Cu(001) is reported to be 0.2550 nm.

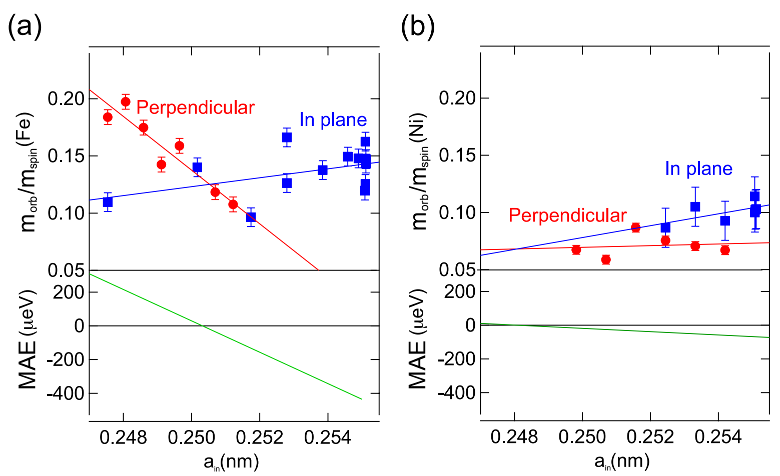

Figure 1: Ratios of orbital to spin magnetic moments in the perpendicular and in-plane directions, and MAE of sandwiched (a) Fe and (b) Ni layers as functions of in-plane lattice constant, a_{in}.

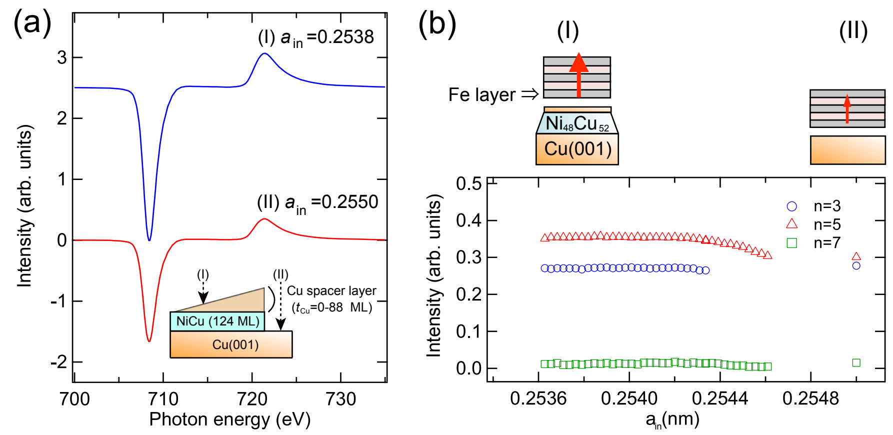

Figure 2: (a) Fe L-edge XMCD spectra for 5 ML FeNi films grown on regions (I) and (II). XMCD were measured at the normal incidence configuration. A cross-sectional view of the substrate is also shown. (b) XMCD intensity at Fe L_3 peak top for *n* ML FeNi films as a function of a_{in}. XMCD was measured at the normal incidence configuration.

Figure 2(a) shows Fe L-edge XMCD spectra for 5 ML FeNi films grown on regions (I) and (II). a_{in} estimated from RHEED analysis is also shown in the figure. In the present case, the FeNi films show perpendicular magnetization when they are grown on (I) and (II). The XMCD signal is larger for (I), which suggests that PMA is enhanced when the lattice constant of the substrate is smaller. To investigate the relation between the structure and magnetic anisotropy systematically, we plot the XMCD intensity at the Fe L_3 peak top for *n* ML FeNi films as a function of a_{in} in Fig. 2(b). The 5 ML FeNi film shows perpendicular magnetization in a wide region of a_{in} including (I) and (II), but larger XMCD intensity is observed at smaller a_{in}. This indicates that the compressive strain in the in-plane direction enhances PMA in FeNi films. This is contrary to the earlier result on Ni films, in which Ni thin films showed enhancement of PMA when tensile strain was applied in the in-plane direction [7]. It is reported from first-principles calculations for $L1_0$-type FeNi that only the Fe components of the orbital density of states exist at the Fermi level [8], and the Fe d_{x2-y2} and $d_{yz,zx}$ orbitals delocalize near the Fermi level by the compressive strain [9]. Indeed, we observed diffused magnetic moment in the XMCD spectra of Fe, which would be evidence of the delocalization [6]. We conjecture that such delocalization increases the perpendicular orbital magnetic moment, and leads to an enhancement of PMA, which cannot be realized in Ni thin films.

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BEAMLINES

BL-7A and BL-16A

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