Magnetic Compton Profiles of Co/Pd Multilayers

Metallic multilayers, such as Co/Pd, exhibit large positive uniaxial anisotropies when the magnetic layer thickness is reduced to a few monolayers [1]. The presence of perpendicular magnetic anisotropy in metallic multilayers has attracted much interest because of technological advances in high-density magnetic recording. In spite of many experimental and theoretical studies related to the understanding of magnetic anisotropy, the origin of perpendicular anisotropy in multilayered magnetic thin films has not yet been clarified. Theoretical investigations to clarify this have pointed out the importance of the anisotropy of wavefunctions [2].

A magnetic Compton profile (MCP), $J_{mag}(p_z)$, is expressed by a projection of a spin density map to the p_z axis in the momentum space. Here, p_z denotes the z component of the electron momentum $\boldsymbol{p}$ in the solid. Then the MCP probes the anisotropies of spin-dependent wavefunctions [3]. However, there are few MCP measurements of thin films. This is because scattering photons from the film substrates are rather strong in comparison with those from the films. Recently, we have suggested a novel and convenient technique for reducing background scattering from the substrates, in which the film sample is deposited on a thin substrate, such as polyethylene terephthalate (PET), and have succeeded in observing for the first time the anisotropy of magnetic Compton profiles in Pd/Co multilayers [4]. In this paper, we report on the anisotropies of MCPs in Co/Pd multilayers and discuss the anisotropy of wavefunctions and electronic structures.

Three multilayer films (Pd(x nm)/Co(0.8 nm), x = 0.8, 1.6, 4.0) were fabricated on PET film substrates of 4 μm thickness by RF sputtering. The total film thickness of the multilayers was adjusted to about 1 μm. The thin-film samples were folded 16 times to increase their effective thickness; the effective thicknesses of the films and the PET substrate were 16 μm and 64 μm, respectively.

The crystal structure was confirmed by $\theta - 2\theta$ X-ray diffraction measurement. The (111) texture of the fcc structure or the (0001) texture of the hcp structure was observed in the middle angle region. Satellite peaks, which were observed around the middle angle region, confirm the designed period of the multilayers. Magnetizations were measured in an out-of-plane configuration (applied fields were perpendicular to the sample surface) and an in-plane configuration (applied fields were parallel to the sample surface). The anisotropy energies, obtained from magnetization measurement, were –0.1 Merg/cc, 0.67 Merg/cc and 1.57 Merg/cc for the Pd(0.8 nm)/Co(0.8 nm) multilayer, Pd(1.6 nm)/Co(0.8 nm) multilayer and Pd(4.0 nm)/Co(0.8 nm) multilayer, respectively (a positive energy shows a perpendicular anisotropy).

MCPs were measured on the high-energy beamline **BL08W**. Figure 1 shows the experimental setup of the MCP measurements for the in-plane configuration and the out-of-plane configuration. The circularly polarized X-ray energy was selected to be 174 keV. The degree of circular polarization was about 0.76. The scattered X-rays were detected by a 10-segment Ge solid-state detector (SSD) with a scattering angle of 178 degrees. The SSD was installed at a distance of 1 m from the sample. The momentum resolution was 0.43 atomic units (a.u.). The applied magnetic field, which was supplied by a superconducting magnet, was ±2.5 T for magnetization saturation in both the in-plane and out-of-plane configurations. All the measurements were carried out under vacuum at room temperature.

Figure 2 shows MCPs of Pd(x nm)/Co(0.8 nm) multilayers in the in-plane configuration ((a), (b), (c)) and out-of-plane configuration ((d), (e), (f)). Changes in the MCP shapes are significant in the out-of-plane configuration, but not in the in-plane configuration. Figure 3 shows the anisotropies of the MCPs. The anisotropies depend on Pd thickness and are observed up to 2 a.u. Although spin magnetic moments have been reported for both Co 3d electrons and Pd 4d electrons [5], the anisotropies of the MCP are due to

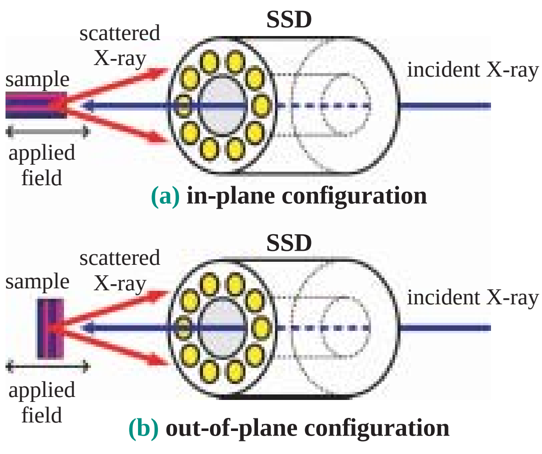

Fig. 1. Experimental setup of MCP measurements for in-plane configuration (applied fields are parallel to the sample surface) and out-of-plane configuration (applied fields are perpendicular to the sample surface).

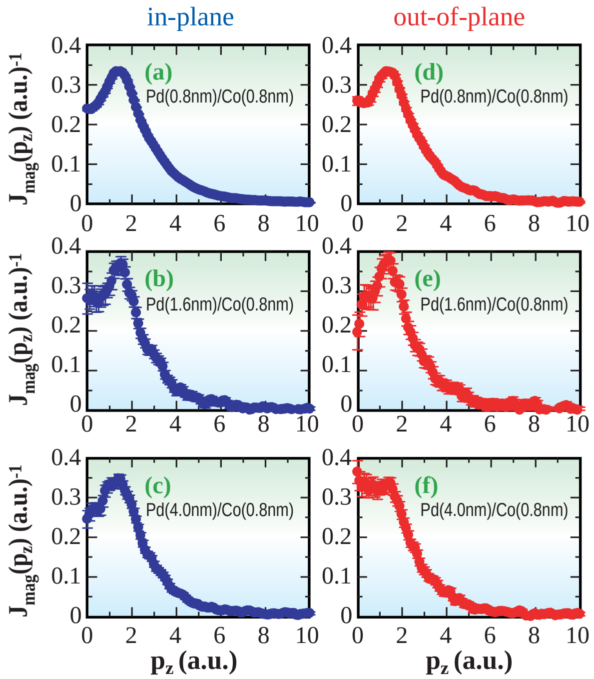

Fig. 2. Magnetic Compton profiles (MCPs) of Pd/Co multilayers in out-of-plane and in-plane configurations. MCPs are normalized to a unit area.

Co 3*d* electrons. This is because of the following two reasons. The first is the difference in momentum distribution between Co 3*d* electrons and Pd 4*d* electrons. Model MCPs of Co 3*d* and Pd 4*d* that assumed an atomic wavefunction with uniaxial crystal field symmetry show that the anisotropies are obtained up to 2 a.u. for Co 3*d* electrons but within 1 a.u. for Pd 4*d* electrons. This suggests that the observed experimental anisotropies reflect features of Co 3*d* anisotropies. The second is that Pd 4*d* spin moment contributions are small compared with the total magnetization [5]. This suggests a minor contribution of Pd 4*d* electrons to the anisotropies.

Fitting analyses using the model MCPs reproduce the experimental anisotropy as shown in Fig. 3 (yellow solid lines). The analyses give the population of each Co 3*d* state (|*m*| = 0, 1 and 2, *m*: magnetic quantum number) as summarized in Table 1. Electron density maps for each 3*d* state are shown in Fig. 4. Pd(0.8 nm)/Co(0.8 nm) with isotropic magnetization has an isotropic wavefunction. Pd(1.6 nm)/Co(0.8 nm), which has a weak perpendicular anisotropy, is dominated by |*m*| = 1 state. Pd(4.0 nm)/Co(0.8 nm), which has a strong perpendicular anisotropy, is dominated by |*m*| = 2 state.

These results shows that perpendicular anisotropy is dominated by both the |*m*| = 1 and |*m*| = 2 states.

Table 1. Populations of |*m*|=0, |*m*|=1 and |*m*|=2 states (*m*: magnetic quantum numbers) of Co 3*d* states in Pd/Co multilayers.

	|*m*| = 2	|*m*| = 1	|*m*| = 0
Pd 0.8 nm/ Co 0.8 nm	40%	40%	20%
Pd 1.6 nm/ Co 0.8 nm	30%	60%	10%
Pd 4.0 nm/ Co 0.8 nm	50%	20%	30%

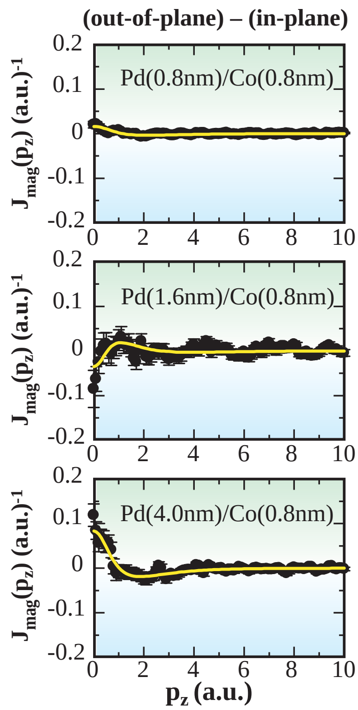

Fig. 3. Anisotropies of magnetic Compton profiles (MCPs) in Pd/Co multilayers. $\Delta J_{mag}(p_z)$ are obtained from differences in MCP between the in-plane and out-of-plane configurations.

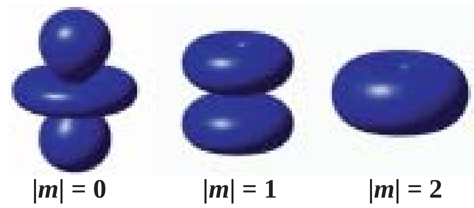

Fig. 4. Electron density maps of |*m*| = 0, |*m*| = 1 and |*m*| = 2 states (*m*: magnetic quantum numbers) of 3*d* states.

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