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Angular-Dependent X-ray Magnetic Circular Dichroism in Perpendicularly Magnetized Co/Pd Multilayers

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CoPd is a candidate for the spintronics materials possessing perpendicular magnetic anisotropy (PMA) which can be utilized for the low power operation devices [1]. The 4*d* transition metal (TM) system of Pd is well recognized as the sustainable elements of 5*d* TM system in Pt toward the PMA materials combined with the magnetic 3*d* TMs. In order to understand the mechanism of PMA in CoPd, the contributions of orbital magnetic moments of each element have to be clarified explicitly. Bruno theoretically proposed the orbital moment anisotropy in TM multilayers as a second perturbation of spin-orbit interaction [2]. However, even in the strong spin-orbit coupled cases using 4*d* or 5*d* TMs, the applicability of this formula has been still debated [3].

We reveal the anisotropic orbital magnetic moments in Co/Pd multilayers using angular-dependent x-ray magnetic circular dichroism (XMCD) and their spectral analysis. The determination of anisotropic orbital moments in Co depending on the layer structures becomes important for the physics in orbital moment anisotropy. Our aim in this study is to discuss both orbital and spin moments of Co for PMA and in-plane anisotropy samples. Furthermore, we discuss the relationship between anisotropic orbital moments and PMA energy in Co/Pd multilayered system.

We prepared two kinds of samples of Co/Pd multilayered structures: Co (0.69 nm)/Pd (1.62 nm) for PMA and Co (1.03 nm)/Pd (1.62 nm) for in-plane anisotropy with stacking five periods on the Si substrates [4]. We performed XMCD experiments at BL-7A, Photon Factory, KEK. Total electron yield mode by directly detecting the sample current was adopted. A magnetic field of ±1.2 T was applied along the direction of the incident polarized soft x-ray with the geometry of normal incidence (NI) and grazing incident (GI) setup.

We observed clear XMCD signals in Co *L*-edges as shown in Fig. 1. Asymmetry between L_3 and L_2 becomes large in NI compared with that in GI case, which suggests that the large orbital magnetic moments are induced when the $H_{\mathbf{ext}}$ is perpendicular to the film plane. On the other hand, in case of in-plane sample, the differences in XMCD line shapes between NI and GI are small because the shape anisotropy in Co layers becomes dominant. Element-specific hysteresis curves at Co L_3 edge for both samples also reveal the PMA and in-plane magnetic properties as shown in the right panel. Furthermore, we confirmed Pd *M*-edge XMCD after the surface sputtering in other XMCD experiment.

Considering these results, we discuss the PMA in Co/Pd multilayers. The Co atoms possess large spin moments and the Pd atoms possess large spin-orbit interaction. The orbital moments in Co is enhanced through the proximity with Pd which induces the spin-orbit coupling. On the other hand, magnetic moments are induced in Pd through the proximity with Co. These collaborate at the interfaces, which enhances the PMA in Co/Pd multilayers. In case of thick Co, the shape anisotropy in Co governs the in-plane anisotropy. Therefore, we propose that the origin of the PMA in Co/Pd interface can be explained by the orbital moment transfer at the interface, which opens up new research fields of '*Spin-Orbitronics*'.

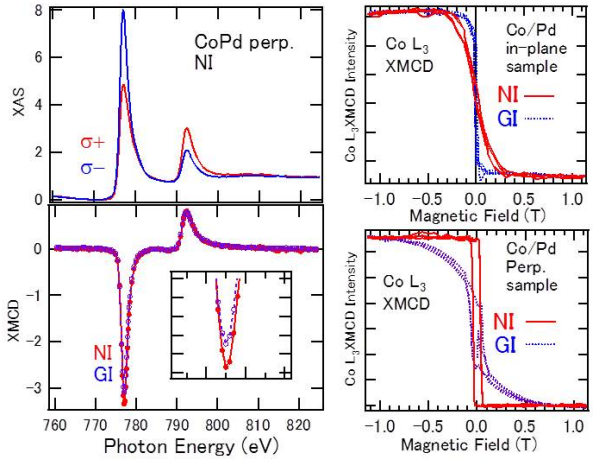

Fig. 1, XAS and XMCD of Co *L*-edge in perpendicularly magnetized Co (0.69 nm)/Pd (1.62 nm) multilayer. Inset shows the expanded view of L_3-edge XMCD. Element-specific hysteresis curves at Co L_3 edge for PMA and in-plane samples are also shown.

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