Symmetry of wavefunction in perpendicular magnetic anisotropy films

Recent high-density magnetic storage has been made possible by perpendicular magnetic recording (PMR) techniques. The first application of PMR to hard disk drives was achieved in Dec. 2005 [1]. PMR can achieve 5-10 times higher recording density than the previous conventional magnetic recording. The key material for PMR is a film with perpendicular magnetic anisotropy (PMA), which has a large positive magnetic anisotropy energy perpendicular to the film plane.

Metallic multilayers, such as Co/Pd and Co/Pt, exhibit large PMA energies when their magnetic layer thickness is reduced to a few monolayers [2-5]. In spite of many experimental and theoretical studies toward the understanding of magnetic anisotropy, the origin of PMA in multilayered magnetic thin films remains to be clarified.

Previous theoretical investigations [6,7] have shown the following. The orbital hybridization between Co-3*d* and Pd-4*d* (Pt-5*d*) at the interface increases the population of symmetric Co-3*d* states with $|m|=2$. Here, *m* denotes the magnetic quantum number. The angular momentum induced by the increased number of $|m|=2$ states gives enhanced orbital magnetic moments perpendicular to the film plane. The enhanced orbital magnetic moments perpendicular to the film plane induce PMA. X-ray circular magnetic dichroism (XMCD) experiments have shown the presence of enhanced Co *3d* orbital magnetic moments perpendicular to the film plane at the Co/Pd (or Pt) interface [8,9]. However, the contributions of the $|m|=2$ symmetry to PMA have not yet been confirmed experimentally.

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 momentum space. Here, p_z denotes the z component of the electron momentum $\boldsymbol{p}$ in a solid. Because the symmetries of a wavefunction are the same in real space and momentum space, the symmetry of the spin-dependent wavefunction can be determined if MCPs are observed from different directions [10].

Recently, we have applied MCPs to the analysis of Co/Pd and Co/Pd multilayers to directly observe the $|m|=2$ symmetry of Co 3*d* states in multilayers with PMA. In this paper, we report the symmetry of the wavefunction in multilayers with PMA [11].

Five multilayer films (Co(0.8 nm)/Pd(*x* nm), x = 0.8, 1.6, 4.0, Co(0.8 nm)/Pt(*x* nm) *x* = 0.8, 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, and the effective thicknesses of the films and 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 was observed in the intermediate-angle region. Satellite peaks, which were observed around the intermediate-angle region, confirm the designed period of the multilayers. The lattice constant obtained from the peak position of (111) has a linear relation with the thickness fraction of the Co layer.

Magnetization was 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). Figure 1 shows the lattice constants and PMA energies. The present results reproduce those of previous studies [2-5]. Magnetic anisotropy changes from in plane magnetic anisotropy to PMA at a lattice constant of more than 0.372 nm.

MCPs were measured at the high-energy beamline **BL08W**. The circularly polarized X-ray energy was set to be 174 keV. The degree of circular polarization was about 0.76. The scattered X-rays were detected by a 10-segmented Ge solid-state detector (SSD) with a scattering angle of 178° that was installed 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.

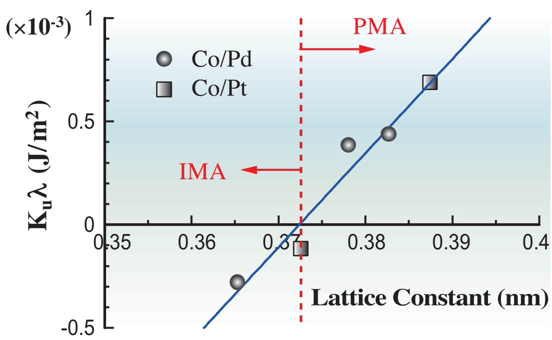

Fig. 1. Perpendicular magnetic anisotropy (PMA) energy density per bilayer against the lattice constants of fcc Co/Pd and Co/Pt multilayers. The blue solid line denotes a least squares fitting result as a visual guide. The red vertical dashed line denotes the boundary of PMA and in-plane magnetic anisotropy (IMA).

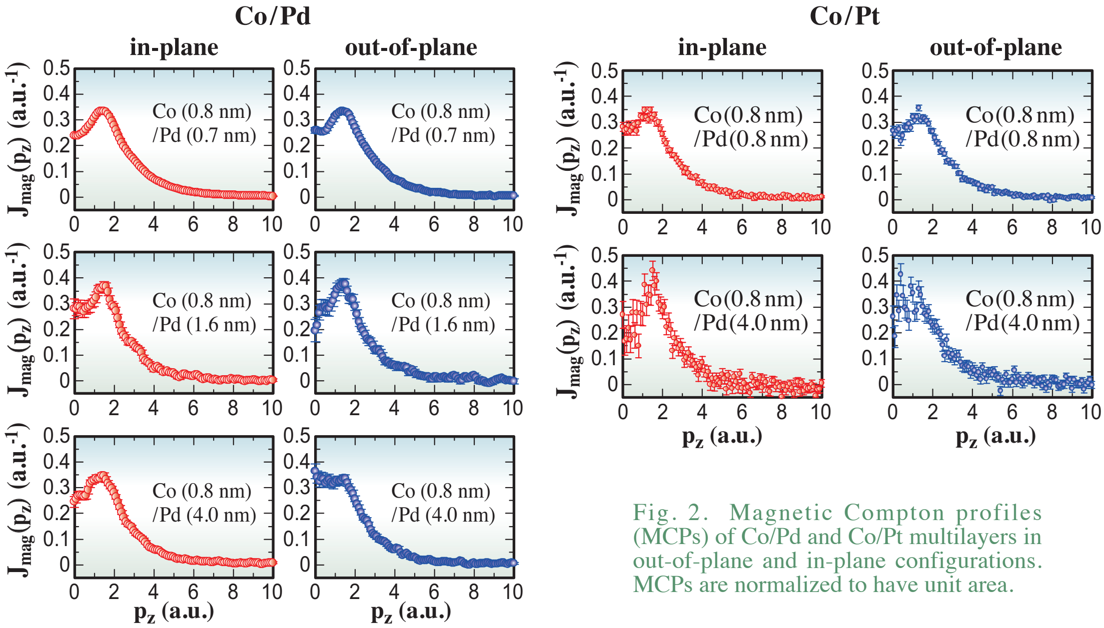

Fig. 2. Magnetic Compton profiles (MCPs) of Co/Pd and Co/Pt multilayers in out-of-plane and in-plane configurations. MCPs are normalized to have unit area.

Figure 2 shows the MCPs of the (Co(0.8 nm)/Pd(*x* nm) and (Co(0.8 nm)/Pt(*x* nm) multilayers with the in-plane and out-of-plane configurations. Differences in the MCP between the in-plane and out-of-plane configurations, which we call the anisotropies of the MCP, are observed for the Co/Pd and Co/Pt multilayers within the momentum region 2 a.u. The anisotropies depend on the Pd and Pt thickness, *x*. This dependence originates from the changes in the populations of |*m*| = 0, 1, and 2 states, and hence from the change in the symmetry of the wavefunctions. Then the MCPs are decomposed using the model calculation, and the populations of |*m*|=0, 1, and 2 states are obtained.

Figure 3 shows the lattice constants and populations of |*m*|=0, 1, and 2 states. |*m*|=2 states dominate above 0.380 nm. This indicates that |*m*|=2 states contribute to PMA. |*m*|=1 states dominate between 0.372 nm and 0.380 nm. This indicates that |*m*|=1 states also contribute to PMA on the boundary region.

In conclusion, the lattice constants change the PMA energy and the symmetry of the wavefunction. The contributions of the |*m*|=2 symmetry to PMA are confirmed experimentally. The contributions of the |*m*|=1 symmetry to PMA are also experimentally observed for the first time.

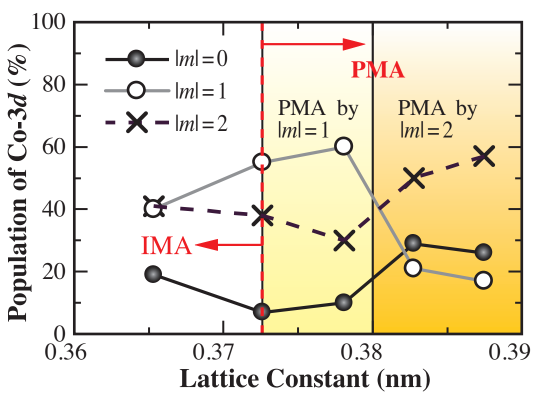

Fig. 3. Population of |*m*|=0, 1, and 2 states in the spin-projected Co 3*d* electrons against the lattice constants of fcc Co/Pd and Co/Pt multilayers. The red vertical dashed line denotes boundary of PMA and in-plane magnetic anisotropy (IMA).

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