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Orbital moment anisotropy in Co-heavy metal heterostructures studied by x-ray magnetic circular dichroism

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1 Introduction

Fast domain wall (DW) motion controlled by electrical current in ferromagnet (FM)/5d heavy metal (HM) heterostructures with perpendicular magnetic anisotropy (PMA) may be a promising playground for realizing novel spintronics devices, such as current-controlled and low energy-consumption magnetic memory devices. Dzyaloshinskii-Moriya interaction (DMI) [1, 2] is considered to play an essential role in stabilizing Néel type DWs at the interface of FM/HM heterostructures [3]. Such Néel type DW can be moved by electric current induced spin orbit torque [4-6]. However, the origin of such interfacial DMI is still unclear, becoming a large obstacle to design practical devices. Although micromagnetics or perturbation theory introduces the DMI term to predict spin texture of FM/HM interfaces and try to understand the origin of DMI in these systems, the observation of non-trivial thickness-dependent interfacial DMI [7] suggests that the mechanism behind it is much more complicated.

It has been proposed that the microscopic origin of the interfacial DMI may be attributed to anisotropies of the orbital magnetic moment and magnetic dipole moment of the ferromagnetic metal [8,9]. However, it has been theoretically found that both the FM and HM elements in FM/HM heterostructures will have orbital magnetic moment anisotropy (OMA) [10], which may be closely correlated with the strength and sign of the DMI. In order to investigate the relationship between the DMI strength and the OMA of FM in FM/HM systems, we have studied the spin and orbital magnetic moments of Co in different HM/Co/HM sandwich heterostructures by x-ray magnetic circular dichroism (XMCD) spectroscopy. We have found that the magnitude of the OMA of Co indeed has an HM dependence similar to that of the DMI strength estimated from the DW motion velocity under a pinning magnetic field [11]. This gives a direct experimental evidence for the correlation between the OMA of Co and the DMI strength.

2 Experiment

Co ultrathin films sandwiched by different HMs, Sub./1Ta/3Pt/*t*Co/1Pt/1Ru and Sub./1Ta/3W/0.6Co/1Pt/1Ru (the numbers denote the nominal thicknesses in nm), together with a reference Sub./1Ta/3Cu/0.6Co/1Cu/1Ru sample, were grown on 10×10 mm^2 thermally oxidized Si substrates by the magnetron sputtering method at room temperature. The thicknesses of Co (t) in the Sub./1Ta/3Pt/*t*Co/1Pt/1Ru samples were 0.6, 1, 1.5 and 3 (nm). X-ray absorption spectroscopy (XAS) and XMCD measurements were performed at the helical undulator beamline BL-16A1 of KEK-PF. The spectra were measured in the total electron yield (TEY) mode, as a relatively surface sensitive measurement mode. All the measurements were performed at room temperature in an vacuum of ~5×10^{-9} Torr. The magnitude of the magnetic field was set to 5 T and it is applied parallel to the incident x-ray in all the measurements. The angle between the magnetic field and the sample surface was set to 30^o for the in-plane magnetization configuration.

3 Results and Discussion

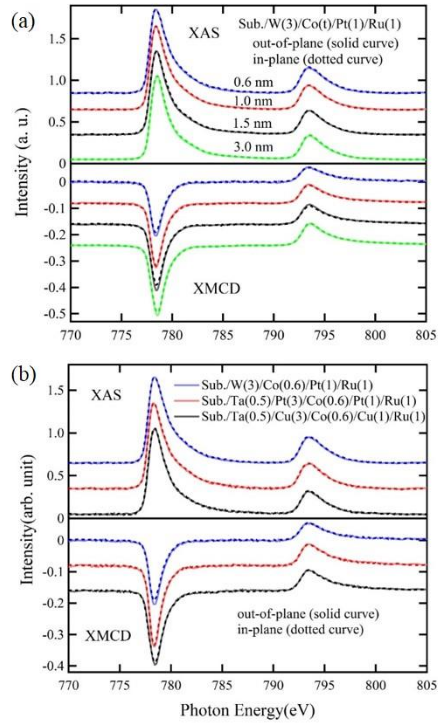

Fig. 1: Co $L_{2,3}$-edge XAS and XMCD spectra of (a) 3W/*t*Co/1Pt samples with different Co thin thicknesses and (b) 0.6Co sandwiched by different elements.

Figure 1 illustrates the XAS and XMCD spectra at the Co $L_{2,3}$ edges in different sandwich heterostructures. The spectral line shapes of all the samples are similar to that of metallic Co, suggesting that Co is protected from oxidation

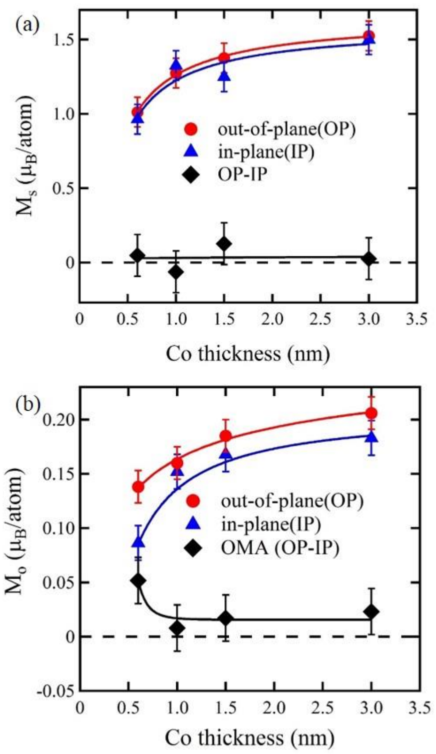

Fig. 2: Spin (a) and orbital magnetic moments (b) of Co in the 3W/*t*Co/1Pt heterostructures with different Co thicknesses.

by the Ru cap well. From these spectra, we have estimated the spin and orbital magnetic moments of Co by using the XMCD sum rules [12]. Here the hole number of Co has been assumed to be 2.45 [13]. For the in-plane magnetization configuration in our experiments, the directions of the magnetic field is different from the sample surface. Therefore, the in-plane orbital magnetic moment should be corrected by using $m = m_{\perp}\sin^2\theta + m_{\parallel}\cos^2\theta$ (here θ is 30°), where $m_{\perp}$ is the out-of-plane magnetic moment and can be obtained from the sum rules directly. Fig. 2(a) and 2(b) show the Co-thickness dependencies of the effective spin and orbital magnetic moments, respectively, for the W/Co/Pt heterostructures. Both the effective spin and orbital magnetic moments are enhanced with increasing Co thickness, which agrees with the previous result of CoFeB/HM heterostructures [14]. The anisotropy of the effective spin magnetic moment is almost zero for all the thicknesses, suggesting that Co is magnetically saturated under external magnetic field of 5 T. However, the OMA of Co reduces with increasing Co thickness. When the Co layer thickness exceeds around 1 nm, the OMA becomes very small and does not depend on the thickness.

In order to see the element dependence of the OMA, we have estimated the magnetic moments of the heterostructures with Co thickness of 0.6 nm, which is expected to show the largest OMA among all the thicknesses studied. The effective spin and orbital magnetic moments of 0.6 nm-thick Co in different HM/Co

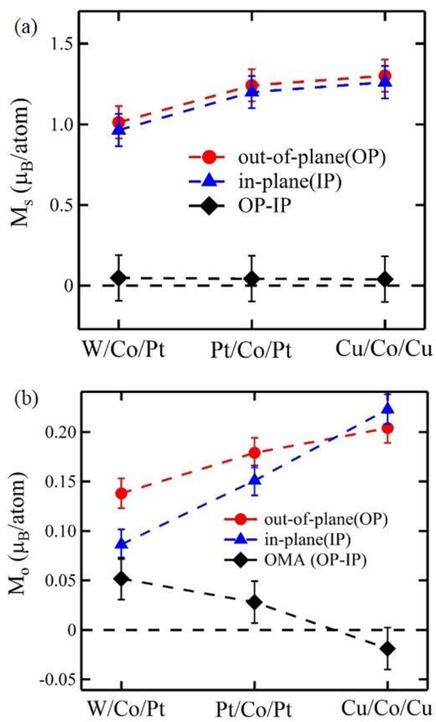

Fig. 3: Spin (a) and orbital magnetic moments (b) of Co sandwiched with different elements.

/HM heterostructures are shown in Figs. 3(a) and 3(b), respectively. As a reference, the data for the Cu/Co/Cu heterostructure is also plotted, which is considered that there should be almost no DMI at the Cu/Co interface due to the weak spin-orbit interaction (SOI) of Cu. The absolute value of the effective spin moment of Co in W/Co/Pt is smaller than those in the Pt/Co/Pt and Cu/Co/Cu samples. This may be attributed to a magnetic dead layer formed at the Co/W interface [15]. The anisotropy of the spin magnetic moment is almost zero for all the heterostructures, suggesting that Co is magnetically statured for both the out-of-plane and in-plane magnetization configurations. It is interesting to find that the OMA of Co shows a strong correlation with the HM elements. Although the absolute value of the orbital moments in W/Co/Pt is the smallest, the OMA is the largest in all the three systems. For Pt/Co/Pt, the OMA of Co is smaller than that of W/Co/Pt. For Cu/Co/Cu, Co has almost no anisotropy of orbital magnetic moments.

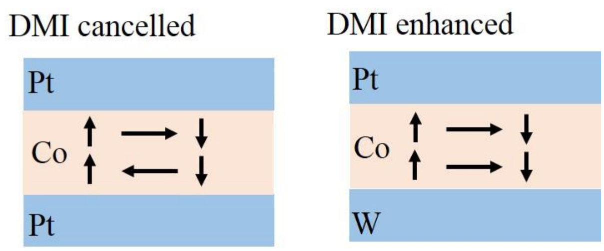

Fig. 4: DMI enhancement and cancellation in asymmetric and symmetric HM/Co/HM sandwich structures.

The correlation between the OMA of Co and the DMI can be understood as follows. As illustrated in Fig. 4, there are two Co/HM interfaces in the sandwich heterostructures, and the spin chirality of Co is determined by the strength and sign of the DMI at both the interfaces. When Co is sandwiched by HMs of the same element, the chiral magnetic structure induced by the DMI will be cancelled out, making the DMI to be zero as a whole. However, if the upper and lower interfaces have the opposite signs of DMI, it should be enhanced as a whole. It has been reported that the signs of the DMI for Co/Pt and Co/W are opposite [16,17]. Therefore, the DMI of W/Co/Pt should be the largest among the heterostructures studied. The small but finite OMA in the Pt/Co/Pt heterostructure may be attributed to the difference in the thicknesses of overlayer and underlayer Pt, which results in the breaking of the inversion symmetry. As mentioned above, there should be no DMI in Cu/Co/Cu due to the weak SOI of Cu. Thus, we conclude that the OMA of Co in HM/Co/HM has the same HM dependence as the DMI strength. Our results may give a new understanding of microscopic origin of interfacial DMI.

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