Photon Factory Activity Report 2019 #37 (2020)

BL-16A/2016G066

Co thickness dependence of spin and orbital magnetic moments in W/Co/Pt heterostructures studied by x-ray magnetic circular dichroism

Zhendong Chi[1,*], Yong-Chang Lau[1,2], Goro Shibata[1], Shoya Sakamoto[1], Yosuke Nonaka[1], Keisuke Ikeda[1], Yuxuan Wan[1], Masahiro Suzuki[1], Masako Suzuki-Sakamaki[3], Kenta Amemiya[3], Masamitsu Hayashi[1,2] and Atsushi Fujimori[1]
[1]Department of Physics, The University of Tokyo, Bunkyo, Tokyo, 113-0033, Japan
[2]National Institute for Materials Science, Tsukuba, 305-0047, Japan
[3]Photon Factory, 1-1 Oho, Tsukuba, 305-0801, Japan

1 Introduction

Ultrathin film heterostructures that consist of a ferromagnetic metal (FM) and a non-magnetic heavy metal (HM) layer are attracting great interest because of novel phenomena that originate from strong spin-orbit coupling in bulk and at the interfaces originating from the HM. Efficient current-induced magnetization reversal and fast motion of magnetic domain walls in heterostructures with perpendicular magnetic anisotropy (PMA) in the FM layers have been observed and contributed to spin-orbit coupling-induced effects [1, 2]. To stabilize chiral magnetic structures, which are essential for magnetization switching and magnetic domain wall motion based on FM/HM heterostructures, strong Dzyaloshinskii-Moriya interaction (DMI) [3, 4] is necessary [5]. In order to develop systems with strong DMI, a deeper understanding of these phenomena, in particular at FM/HM interfaces, is required. The microscopic origin of interfacial DMI has been discussed in relation to the orbital moment anisotropy (OMA) [6] and magnetic dipole (m_T) [7] in the FM layer. In order to investigate the OMA of the FM in FM/HM heterostructures with different environments, here, we report the Co layer thickness dependence of spin and orbital magnetic moments of Co in W/Co/Pt heterostructures, which have in-plane magnetic anisotropy, studied by using x-ray magnetic circular dichroism (XMCD) spectroscopy.

2 Experiment

Co thin films sandwiched by W and Pt, 3 W/t_{Co} Co/1 Pt/1 Ru (the numbers denote the nominal thicknesses in nm, stack order from button to top) were grown on 10×10 mm^2 thermally oxidized Si substrates (SiO_2/Si) by magnetron sputtering at room temperature in a base pressure better than 5×10^{-7} Pa (See Fig. 1 for the detail of sample). The top Ru layer is used to protect the heterostructures from oxidization. The thicknesses of Co (t_{Co}) in the samples were changed from 0.6 to 1.19 nm. X-ray absorption spectroscopy (XAS) and XMCD measurements at the Co $L_{3,2}$ edges were performed using soft x rays at the helical undulator beamline BL-16A of Photon Factory, High Energy Accelerator Research Organization (KEK-PF). The spectra were measured in the total electron yield (TEY) mode. The measurements were performed at room temperature in an ultra-high vacuum (UHV) lower than 5×10^{-7} Pa. The magnitude of the external magnetic field (H_{ext}) was set as 5T and the field was applied parallel to the incident x rays in all the measurements (See Fig. 1). In order to obtain the out-of-plane (OP) and in-plane (IP) magnetization configurations, H_{ext} was applied to the sample with an incident angle, θ, of 90° and 30° to the sample surface, defined as out-of-plane and "in-plane" magnetic field.

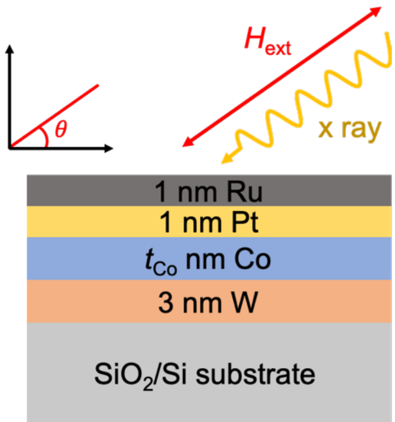

Fig. 1: Schematic figure of the sample stacking and the experimental set-up. t_{Co} is the thickness of the Co layer.

3 Results and Discussion

Figure 2 illustrates the XAS and XMCD spectra at the Co $L_{3,2}$ edge of the W/Co/Pt heterostructures measured under a magnetic field of 5 T. No obvious peak shift or spectral line-shape change is found in both the XAS and XMCD spectra, suggesting that there is no significant changes in the chemical state of Co, i.e., the oxidation of Co is negligibly small. The solid and dashed curves in Fig. 2 represent spectra measured when out-of-plane and "in-plane" magnetic field are applied, respectively. These results indicate that the magnetic moments of Co in the W/Co/Pt heterostructures are anisotropic.

The spin magnetic moments (m_{spin}) and m_T of Co atom are estimated using XMCD sum rules [8]. The out-of-plane and in-plane components of the magnetic moments are obtained from the integrated XAS/XMCD spectra measured under out-of-plane and "in-plane" magnetic fields, respectively. Here, m_{spin} is considered to be isotropic, but m_T possesses an angular dependence as $m_T(\theta) = -1/2\, m_T(1 - 3\sin^2\theta)$ [9]. The estimated values of m_{spin} and m_T of Co of the W/Co/Pt heterostructures are shown in Fig. 3 as a function of magnetization effective thickness (t_{eff}). t_{eff} is defined as $t_{eff} = t_{Co} - t_D$, where t_D is the magnetic dead layer thickness in W/Co/Pt and its value is obtained by using a vibrating sample magnetometer. Here, the magnetic moments are presented in units of Bohr magnetron per hole. m_{spin} decreases with decreasing t_{eff} from the bulk value (a dashed horizontal line). Such variation of m_{spin} with magnetic layer thickness has also been observed in similar systems [10]. m_T, which is considerably small than m_{spin}, represents the anisotropic spin-density distribution and its strength characterizes the anisotropy of the charge/spin distribution of the d orbitals. The value of m_T is positive, which means that the spin density distribution is expanded in the in-plane direction. Although it has been reported that m_T is related to the emergence of DMI [7], here it is below the accuracy limit and we cannot determine its dependence on t_{eff}.

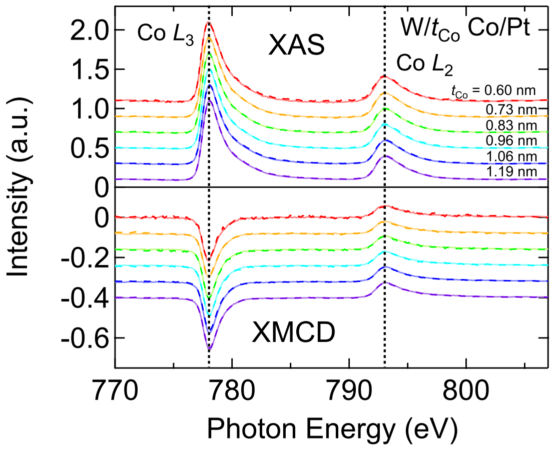

Fig. 2: XAS and XMCD spectra at the Co $L_{3,2}$ edges for the W/Co/Pt heterostructures with different Co thin thicknesses (t_{Co}). Spectra after background subtraction are shown. The spectra obtained under out-of-plane and “in-plane” magnetic field are plotted by solid and dashed curves, respectively.

The orbital magnetic moment (m_{orb}) of Co atom is also estimated using the XMCD sum rule [8]. The out-of-plane component of m_{orb}, $m_{orb}^{\perp}$, is estimated from the XAS and XMCD spectra measured under the out-of-plane magnetic field. The in-plane component, $m_{orb}^{\parallel}$, is obtained using the spectra measured under the out-of-plane and “in-plane” fields according to the relationship,

$$m_{orb}(\theta) = m_{orb}^{\perp}\sin^2\theta + m_{orb}^{\parallel}\cos^2\theta,$$

with θ is 30°. The t_{eff} dependence of m_{orb} is plotted in Fig. 4. Both of $m_{orb}^{\perp}$ and $m_{orb}^{\parallel}$ decrease with decreasing t_{eff} from the bulk value. We find the decrease of $m_{orb}^{\parallel}$ with t_{eff} is stronger than that of $m_{orb}^{\perp}$. The difference leads to the OMA which is shown by the black squares in Fig. 4, where one can see that the OMA of Co increases with decreasing t_{eff} and its slope changes abruptly at $t_{eff} \sim 0.9$ nm.

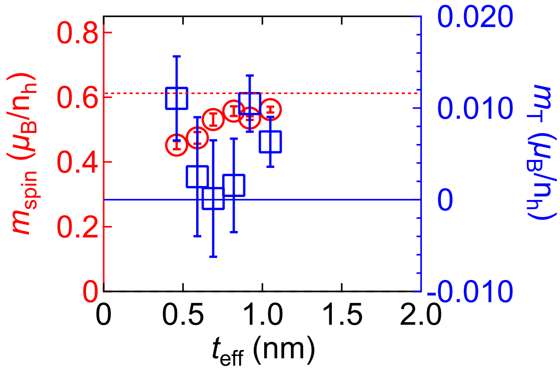

Fig. 3: Magnetization effective thickness (t_{eff}) dependence of spin magnetic moment (m_{spin}, red circles) and magnetic dipole (m_T, blue squares) in the W/Co/Pt heterostructures. The spin magnetic moment value of bulk hcp Co [10] is shown by a red horizontal line.

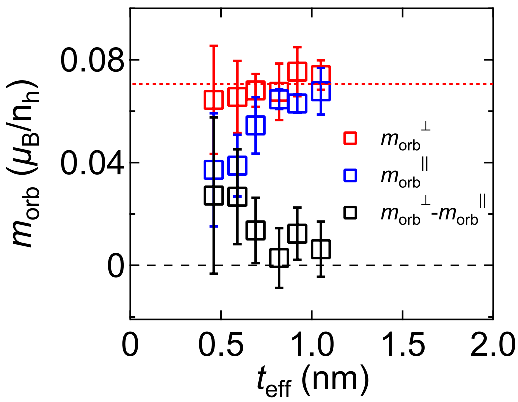

Fig. 4: Magnetization effective thickness (t_{eff}) dependence of the orbital magnetic moment (m_{orb}) for the different magnetization directions in the W/Co/Pt heterostructures. The orbital magnetic moment value of bulk hcp Co [10] is shown as the red dashed horizontal line.

Although all the samples have in-plane magnetic anisotropy, the positive OMA and m_T of Co indicates that the magnetocrystalline anisotropy (MCA) favors perpendicular magnetization based on the formulas driven by Bruno [12] and van der Lann [13]. We conclude that the origin of the in-plane magnetic anisotropy in our W/Co/Pt samples is attributed to the shape anisotropy energy exceeding the small MCA. The abrupt slope change of the OMA of Co at $t_{eff} \sim 0.9$ nm indicates the complicated interfacial environment in the W/Co/Pt heterostructures with ultrathin Co layer. The growth of hcp/fcc Co on β-phase (or amorphous) W results in the degradation of the (111) texture compared to the structures where Co is grown on fcc based materials (e.g. Pt and Ru). We suggest that such degradation contributes to intermixing at the W/Co interfaces. Furthermore, the interfacial DMI is a property which is sensitive to the interface condition. Therefore, we infer that such interfacial environment should result in the complicated behavior of DMI in the W/Co/Pt heterostructures.

References
[1] I. M. Miron *et al.*, *Nature* **476**, 189 (2011).
[2] I. M. Miron *et al.*, *Nat. Mater.* **10**, 419 (2011).
[3] I. E. Dzyaloshinskii, *JETP* **5(6)**, 1259 (1957).
[4] T. Moriya, *Phys. Rev.* **120**, 91 (1960).
[5] A. Thaville *et al.*, *Europhys. Lett.* **100**, 57002 (2012).
[6] K. Yamamoto *et al.*, *AIP Adv.* **7**, 056302 (2017).
[7] S. Kim *et al.*, *Nat. Commun.* **9**, 1648 (2018).
[8] C. T. Chen *et al.*, *Phys. Rev. Lett.* **75**, 152 (1995).
[9] R. Wu *et al.*, *Phys. Rev. Lett.* **70**, 694 (1994).
[10] J. M. D. Coey, *Magnetism and magnetic materials* (Cambridge, U.K., 2010).
[11] T. Ueno *et al.*, *Sci. Rep.* **5**, 14858 (2015).
[12] P. Bruno, *Phys. Rev. B* **39**, 865 (1989).
[13] G. van der Lann, *J. Phys.: Condens. Matter* **10**, 3239 (1998).

* z.chi@qspin.phys.s.u-tokyo.ac.jp