Magnetocrystalline anisotropy, Dzyaloshinskii-Moriya interaction, and orbital moment anisotropy in W/Co/Pt trilayers

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We have studied the Co layer thickness dependences of magnetocrystalline anisotropy (MCA), Dzyaloshinskii-Moriya interaction (DMI), and orbital moment anisotropy (OMA) in W/Co/Pt trilayers. We find the MCA favors magnetization along the film normal and monotonically increases with decreasing effective magnetic layer thickness ($t_{\text{eff}}$). The magnitude of the Dzyaloshinskii-Moriya interaction constant ($|D|$) increases with decreasing $t_{\text{eff}}$ until $t_{\text{eff}} \sim 1$ nm, below which $|D|$ decreases. MCA and $|D|$ scale with $1/t_{\text{eff}}$ for $t_{\text{eff}}$ larger than $\sim 1.0$ nm, indicating an interfacial origin. To clarify the cause of the $t_{\text{eff}}$ dependences of MCA and DMI, the OMA of Co in W/Co/Pt trilayers is studied using x-ray magnetic circular dichroism (XMCD). We find non-zero OMA when $t_{\text{eff}}$ is smaller than $\sim 0.8$ nm. The OMA increases with decreasing $t_{\text{eff}}$ at a rate that is larger than what is expected from the MCA and Bruno’s formula, indicating that other factors contribute to the MCA at small $t_{\text{eff}}$ to break the $1/t_{\text{eff}}$ scaling. The $t_{\text{eff}}$ dependence of the OMA also suggests that $|D|$ at $t_{\text{eff}}$ smaller than $\sim 1$ nm is independent of the OMA at the interface. We consider the growth of Co on W results in a strain that reduces the interfacial MCA and DMI at small $t_{\text{eff}}$, indicating the importance of lattice structure to control their properties.

I. INTRODUCTION

Ultrathin film heterostructures that consist of a ferromagnetic metal (FM) layer and a non-magnetic heavy metal (HM) layer are attracting great interest as phenomena that originate from the strong spin-orbit coupling of bulk and interface have been successively discovered. Efficient current-induced magnetization reversal [1] and fast motion of magnetic domain walls [2] in heterostructures with perpendicular magnetic anisotropy (PMA) in the FM layer have been observed and attributed to spin-orbit coupling-induced effects such as the spin Hall effect [3-4], the Rashba-Edelstein effect [5-6], and the Dzyaloshinskii-Moriya interaction (DMI) [9-10]. To stabilize chiral Néel domain walls [11-13] and skyrmions [14-15], which are essential for potential racetrack memory applications based on FM/HM heterostructures [16-18], strong DMI is necessary [19-21]. Solid understanding on these interfacial phenomena is essential to develop systems with PMA and strong DMI.

The microscopic origins of PMA and interfacial DMI have been discussed in relation to the orbital moment anisotropy (OMA) [22-23] and the magnetic dipole moment in the FM layer [24-25]. Theoretically, OMA should exist both in the FM and HM layers [26]. It is thus of high importance to identify the role the OMA (of FM and HM) plays in PMA and DMI.

Here, we study the correlation between magnetocrystalline anisotropy (MCA), DMI and OMA in W/Co/Pt trilayers. The Co layer thickness dependences of MCA and DMI in W/Co/Pt trilayers are studied using vibrating sample magnetometer (VSM) and Brillouin light scattering spectroscopy (BLS), respectively. The Co layer thickness dependences of the spin and orbital magnetic moments of Co in W/Co/Pt trilayers and the proximity-induced magnetization (PIM) in W and Pt in W/Co and Pt/Co bilayers are studied using soft- and hard-x-ray magnetic circular dichroism (XMCD), respectively. We find the MCA, DMI, and OMA of Co show different Co layer thickness dependences in W/Co/Pt trilayers.

II. EXPERIMENT

Co thin films sandwiched by W and Pt, i.e. 3 W/tCo Co/1 Pt/1 Ru (the numbers denote the nominal thicknesses in nm, stacking order from button to top) were grown on 10×10 mm$^2$ thermally oxidized Si substrates by magnetron sputtering at room temperature in a base pressure better than $5 \times 10^{-7}$ Pa. The top Ru layer is used to protect the trilayers from oxidation. The Co layer thickness ($t_{\text{Co}}$) was changed from $\sim 0.6$ to $\sim 1.7$ nm. The magnetic hysteresis loops of the samples were measured using a VSM at room temperature. The magnitude of DM exchange constant ($|D|$) was investigated by BLS [27]. X-ray absorption spectroscopy (XAS) and XMCD
measurements at the Co $L_{3,2}$ edges were performed using soft x ray at the helical undulator beamline BL-16A1 of Photon Factory, High Energy Accelerator Research Organization (KEK-PF). The spectra were measured in the total electron yield (TEY) mode, using right- ($\sigma+$) and left-hand ($\sigma-$) circularly-polarized x rays. The measurements were performed at room temperature in an ultra high vacuum (UHV) better than $5 \times 10^{-7}$ Pa. The magnitude of the magnetic field was set at 5 T and the field was applied parallel to the incident x rays in all measurements. The W and Pt $L_{3,2}$-edge XAS and XMCD measurements of 0.6 W/0.8 Co and 0.6 Pt/0.8 Co bilayers were conducted using hard x rays at BL39XU of SPring-8. The partial fluorescence yield (PFY) method and x-ray polarization switching were used in the acquisition of spectra. The measurements were performed at atmospheric pressure and at room temperature. A magnetic field of up to 2 T was applied during the measurement. In order to obtain the out-of-plane and in-plane components of the magnetic moments, magnetic field was applied to the sample along the film normal and 30° with respect to the sample surface, referred to out-of-plane and “in-plane” magnetic field hereafter.

III. RESULTS AND DISCUSSION

The magnetic properties of the trilayers are shown in Fig. 1. The $t_{Co}$ dependence of the magnetic moment is shown in Fig. 1(a). The moment scales with $t_{Co}$. A linear function is fitted to the data with larger weight on the films with larger $t_{Co}$. The slope and the horizontal axis intercept represents the magnetic dead layer thickness $t_{D}$. After considering the area of samples, we find $M_s \sim 1350 \pm 50$ emu-cm$^{-3}$ and $t_{D} \sim 0.14 \pm 0.05$ nm. The value of $M_s$ is close to that of bulk Co [38]. $t_{D}$ is typically negative when Co faces a Pt layer due to PIM [24, 33]. Positive $t_{D}$ indicates that the magnetic dead layer at the W/Co interface compensates the negative $t_{D}$. We infer that the true dead layer thickness at the W/Co interface is $0.2 \sim 0.3$ nm.

The effective magnetic anisotropy energy density, $K_{eff}$, is obtained by taking the integrated areal difference between the easy-axis and hard-axis magnetization hysteresis loops. With the effective magnetic layer thickness defined as $t_{eff} \equiv t_{Co} - t_{D}$, the product of $K_{eff}$ and $t_{eff}$, $K_{eff}t_{eff}$, is given by the following equation [30, 51]:

$$K_{eff}t_{eff} = K_1 + (K_B - 2\pi M_s^2)t_{eff},$$

where $K_B$ and $K_1$ represent the bulk and interfacial contributions to $K_{eff}$. The $2\pi M_s^2$ term represents the shape anisotropy energy density. $K_{eff}t_{eff}$ is plotted against $t_{eff}$ in Fig. 1(b). Negative $K_{eff}t_{eff}$ corresponds to the magnetic easy axis of the samples lying along the film plane. A linear function is fitted to the data with larger weight on the films with larger $t_{eff}$. The slope and the y-axis intercept of the linear function represent $(K_B - 2\pi M_s^2)$ and $K_1$, respectively. From the fitting, we obtain $K_B \sim (0.8 \pm 0.7) \times 10^6$ erg-cm$^{-3}$ and $K_1 \sim 0.6 \pm 0.1$ erg-cm$^{-2}$. $M_s$ is obtained from the fitting shown in Fig. 1(a). $K_1$ is smaller than that typically reported for structures which include Co/Pt interfaces [24, 30]. Note that the data show deviation from the linear fitting when $t_{eff}$ is smaller than $1$ nm.

MCA is obtained by excluding the contribution from the shape anisotropy in $K_{eff}$, defined as

$$MCA \equiv K_{eff} + 2\pi M_s^2 = \frac{K_1}{t_{eff}} + K_B.$$  

We plot the $t_{eff}$ and $1/t_{eff}$ dependences of the MCA in Fig. 2(a) and (b). MCA increases monotonically by decreasing $t_{eff}$. Positive MCA favors perpendicular magnetization. According to the values obtained from the linear fitting in Fig. 1(b), contribution from $K_1$ is considerably larger than that of $K_B$. We, therefore, expect the MCA to scale with $1/t_{eff}$. The calculated MCA using the parameters obtained from the fitting in Fig. 1(b) is shown by the red solid lines in Fig. 2. Although the MCA is proportional to $1/t_{eff}$ for $t_{eff} > 1$ nm, it clearly deviates from the scaling for $t_{eff} \lesssim 1$ nm.

The $t_{eff}$ dependence of the magnitude of the
is estimated using the XMCD sum rule \[34, 35\]:

\[ m_{\text{spin}}(b) = \text{fit to the data.} \]

spectroscopy (BLS) measurements. The solid lines in (a) and (b) show fit to the data.

Dzyaloshinskii-Moriya exchange constant \(|D|\) is plotted in Fig. 3(a). \(|D|\) increases with decreasing \(t_{\text{eff}}\) until \(t_{\text{eff}} \sim 1\) nm, below which it drops. A similar tendency has been observed in HM/FM systems \[22, 23\], which is not in accordance with the simple picture of interface-driven DMI. We plot the \(1/t_{\text{eff}}\) dependence of \(|D|\) in Fig. 3(b). The data are fitted using a linear function with a larger weight on the films with larger \(t_{\text{eff}}\): the results are shown by a red solid line in Fig. 3(b). The parameters obtained from the linear fitting in Fig. 3(b) are used to calculate the \(1/t_{\text{eff}}\) dependence of \(|D|\) in Fig. 3(a). The calculated results are shown by a red solid line in Fig. 3(a). The experimental data deviates from the linear fitting for \(t_{\text{eff}} < 1\) nm.

To identify the origin of the \(t_{\text{eff}}\) dependences of MCA and DMI in W/Co/Pt trilayers, the XAS and XMCD spectra of Co are studied. Fig. 4(a) illustrates the XAS and XMCD spectra at the Co L\(_{3,2}\) edges of the W/Co/Pt trilayers 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. 4(a) represent the spectra measured when out-of-plane and “in-plane” magnetic fields are applied, respectively. The integrated XMCD spectra, as displayed by the corresponding curves in Fig. 4(b), show clear differences under out-of-plane and “in-plane” field application. These results indicate that the magnetic moment of Co is anisotropic.

The effective spin magnetic moment \((m_{\text{eff}})\) of Co atom is estimated using the XMCD sum rule \[34, 35\]:

\[ m_{\text{eff}} = m_{\text{spin}} + \frac{7}{2} m_{T} \]

\[ = -\frac{2 \int_{L_{3,2}} \Delta \mu \, d\nu - 4 \int_{L_{3,2}} \Delta \mu \, d\nu}{\int_{L_{3,2}} \mu \, d\nu} n_{h}, \]

where \(\Delta \mu\) and \(\mu\) are the difference and sum of the XAS spectra obtained using right- and left-handed circularly polarized light, \(m_{\text{spin}}\) is the spin magnetic moment of Co atom, \(m_{T}\) is the magnetic dipole, \(n_{h}\) is the number of holes in the \(d\) band of the magnetic atom. Here, we present magnetic moments in units of Bohr magneton per hole. The out-of-plane and in-plane components of the magnetic moments are obtained from the integrated XAS/XMCD spectra measured under the out-of-plane and “in-plane” magnetic field, respectively. \(m_{\text{spin}}\) is considered to be isotropic, but \(m_{T}\) possesses an angular dependence: \(m_{T} = -\frac{1}{2} m_{T_{0}} (1 - 3 \sin^{2} \theta) \[36, 37\]. Here, \(m_{T_{0}}\) represents the out-of-plane component of \(m_{T}\) and \(\theta\) is the angle between the magnetization and the film plane.

The estimated values of \(m_{\text{spin}}\) and \(m_{T_{0}}\) are shown in Fig. 4(c) and (d) as a function of \(t_{\text{eff}}\), respectively. \(m_{\text{spin}}\) deviates from its bulk value, shown by a horizontal dashed line, and tends to decrease with decreasing \(t_{\text{eff}}\). Such variation of \(m_{\text{spin}}\) with magnetic layer thickness has also been observed in similar systems \[29\]. \(m_{\text{spin}}\) is fitted against \(t_{\text{Co}}\) using a relation: \(m_{\text{spin}} = (1 - t_{\text{D}}/t_{\text{Co}}) m_{\text{spin,active}}\), where \(m_{\text{spin,active}}\) is the active spin magnetic moment, to estimate the \(t_{\text{D}}\) in the Co layer. From the fitting, we obtain \(t_{\text{D}} \sim 0.20 \pm 0.03\) nm, which is consistent with our assumption on the true dead layer thickness at the W/Co interface. \(m_{T_{0}}\), which is considerably smaller than \(m_{\text{spin}}\), represents the anisotropic spin-density distribution and its strength characterizes the anisotropy of the charge/spin distribution of the \(d\) orbitals. The value of \(m_{T_{0}}\) is positive, which means that the spin density distribution is expanded in the in-plane direction and is consistent with the MCA favoring perpendicular magnetization. Although it has been reported that \(m_{T_{0}}\) is related to the emergence of PMA \[24\] and DMI \[25\], here its magnitude is considerably smaller than past report \[25\] and the accuracy is not high enough to determine whether \(m_{T_{0}}\) possesses any \(t_{\text{eff}}\) dependence.

The orbital magnetic moment \((m_{\text{orb}})\) of Co atom is estimated using the XMCD sum rule \[34, 35\]:

\[ m_{\text{orb}} = -\frac{4}{3} \int_{L_{3,2}} \frac{\Delta \mu \, d\nu}{\mu \, d\nu} n_{h}. \]  

The out-of-plane component of \(m_{\text{orb}}\), \(m_{\text{orb}}^{\perp}\), is estimated from the XAS and XMCD spectra measured under the out-of-plane magnetic field. The in-plane component, \(m_{\text{orb}}^{\parallel}\), is obtained using the spectra measured under the out-of-plane and “in-plane” fields according to the relationship,

\[ m_{\text{orb}}^{\parallel}(\theta) = m_{\text{orb}}^{\parallel} \sin^{2} \theta + m_{\text{orb}}^{\parallel} \cos^{2} \theta, \]

with \(\theta = 30^\circ\). The \(t_{\text{eff}}\) dependence of \(m_{\text{orb}}^{\parallel}\) is plotted in Fig. 4(c). Both \(m_{\text{orb}}^{\parallel}\) and \(m_{\text{orb}}^{\parallel}\) decrease with decreasing \(t_{\text{eff}}\) from their bulk value. We find the decrease of \(m_{\text{orb}}^{\parallel}\) with \(t_{\text{eff}}\) is stronger than that of \(m_{\text{orb}}^{\perp}\). This difference leads to the OMA of Co which is shown by black squares in Fig. 4(c). The normalized orbital magnetic moment
The XMCD signal is only found in the Pt/Co bilayer. These results indicate PIM exists at the Pt/Co interface but W do not possess any induced magnetic moment.

Here, we discuss the relationship between the MCA, DMI and the OMA of Co in W/Co/Pt trilayers. The $t_{\text{eff}}$ dependences of the three parameters are schematically illustrated in Fig. 4. MCA and $|D|$ scale with $1/t_{\text{eff}}$ for $t_{\text{eff}} \gtrsim 1$ nm, indicating an interfacial origin of the two properties. Bruno has proposed that the MCA and OMA are proportional to each other in FM monolayers. Both MCA and the OMA of Co indeed increase with decreasing $t_{\text{eff}}$ is smaller than $\sim 0.8$ nm. However, the OMA tends to increase more rapidly with decreasing
tion to derive the scaling reported in Ref. [23]. The magnitude of $m_T$ found in this system is considerably smaller than that reported in Ref. [25] and, therefore, its contribution to DMI, if any, is also likely small. We thus infer that the DMI is more sensitive to strain effect or the (111) texture of Co. Theoretical studies [43, 44] have indicated that the crystal structure at the HM/FM interface influences the strength of DMI dramatically. In the present case, strain and texture of the Co layer near the W/Co interface may significantly degrade $|D|$ for $t_{\text{eff}} \lesssim 1$ nm. With increasing Co thickness, such effects are then mitigated by the Co/Pt interface that favors the (111) texture.

IV. SUMMARY

In summary, we have studied the effective magnetic layer thickness ($t_{\text{eff}}$) dependences of magnetocrystalline anisotropy (MCA), Dzyaloshinskii-Moriya interaction (DMI), and orbital moment anisotropy (OMA) in W/Co/Pt trilayers. For $t_{\text{eff}}$ larger than $\sim 1$ nm, MCA and DMI scale with $1/t_{\text{eff}}$, indicating an interfacial origin. Whereas MCA continues to increase with decreasing $t_{\text{eff}}$, DMI tends to decrease when $t_{\text{eff}}$ is smaller than $\sim 1$ nm. The OMA of Co deduced from x-ray magnetic circular dichroism (XMCD) measurements is almost zero (below the detection limit) when $t_{\text{eff}}$ is larger than $\sim 0.8$ nm, below which the OMA of Co increases with decreasing $t_{\text{eff}}$. The rate at which the OMA of Co increases with decreasing $t_{\text{eff}}$ is larger than what is predicted from the MCA using Bruno’s formula. The reduction of DMI with decreasing $t_{\text{eff}}$ for films with $t_{\text{eff}} \lesssim 1$ nm, despite the presence of OMA, suggests that other factors contribute to the DMI in this thickness range. We infer that the strain in the Co layer induced by the W underlayer significantly weakens the DMI and, to a lesser extent, the MCA.

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[1] I. M. Miron, K. Garello, G. Gaudin, P. J. Zermatten, M. V. Costache, S. Auffret, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Nature 476, 189 (2011).
[2] I. M. Miron, T. Moore, H. Szombolyis, L. D. Buda, Prejbeanu, S. Auffret, B. Rodmacq, S. Pizzini, J. Vogel, M. Bonm, A. Schuhl, and G. Gaudin, Nat. Mat. 10, 419 (2011).
[3] M. I. Dyakonov and V. I. Perel, Jett Papers-Ussr 13, 467 (1971).
[4] J. E. Hirsch, Phys. Rev. Lett. 83, 1834 (1999).
[5] J. Sinova, S. O. Valenzuela, J. Wunderlich, C. H. Back, and T. Jungwirth, Rev. Mod. Phys. 87, 1213 (2015).
[6] L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, Science 336, 555 (2011).
[7] Y. A. Bychkov and E. I. Rashba, Jetp Lett. 39, 78 (1984).
[8] V. M. Edelstein, Solid State Communications 73, 233 (1990).
[9] I. E. Dzyaloshinskii, JETP 5, 1259 (1957).
[10] T. Moriya, Phys. Rev. 120, 91 (1963).
[11] M. Bode, M. Heide, K. von Bergmann, P. Ferriani, S. Heinze, G. Bihlmayer, A. Kubetzka, O. Pietzsch, S. Blügel, and R. Wiesendanger, Nature 447, 190 (2007).
[12] M. Heide, G. Bihlmayer, and S. Blügel, Phys. Rev. B 78, 140403 (2008).
[13] S. Emori, U. Bauer, S.-M. Ahn, E. Martinez, and G. S. D. Beach, Nat. Mater. 12, 611 (2013).
[14] B. B. S. Mühlbauer, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böi, Science 323, 915 (2009).
[15] X. Z. Yu, Y. Onose, N. Kanazawa, J. H. Park, J. H. Han, Y. Matsui, N. Nagaosa, and Y. Tokura, Nature 465, 901 (2010).
[16] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science 320, 190 (2008).
[17] M. Hayashi, L. Thomas, R. Moriya, C. Rettner, and S. S. P. Parkin, Science 320, 209 (2008).
[18] A. Fert, V. Cros, and J. Sampaio, Nat. Nanotech. 8, 152 (2013).
[19] A. Thiaville, S. Rohart, É. Jué, V. Cros, and A. Fert, Europhys. Lett. 100, 5 (2012).
[20] S. Tacchi, R. E. Troncoso, M. Ahlberg, G. Gubbiotti, M. Madami, J. Åkerman, and P. Landeros, Phys. Rev. Lett. 118, 147201 (2017).
[21] X. Ma, G. Yu, S. A. Razavi, S. S. Sasaki, X. Li, K. Hao, S. H. Tolbert, K. L. Wang, and X. Li, Phys. Rev. Lett. 119, 027202 (2017).
[22] P. Bruno, Phys. Rev. B 39, 865 (1989).
[23] K. Yamamoto, A.-M. Pradipto, K. Nawa, T. Akiyama, T. Ito, T. Ono, and K. Nakamura, AIP Adv. 7, 056302 (2017).
[24] G. van der Lann, J. Phys.: Condens. Matter 10, 3239 (1998).
[25] S. Kim, K. Ueda, G. Go, P.-H. Jang, K.-J. Lee, A. Belabbes, A. Manchon, M. Suzuki, Y. Kotani, T. Nakamura, K. Nakamura, T. Koyama, D. Chiba, K. Yamada, D.-H. Kim, T. Moriyama, K.-J. Kim, and T. Ono, Nat. Commun. 9, 1648 (2018).
[26] I. V. Solovyev, P. H. Dederichs, and I. Mertig, Phys. Rev. B 52, 13419 (1995).
[27] K. Di, V. L. Zhang, H. S. Lim, S. C. Ng, M. H. Kuok, J. Yu, J. Yoon, X. Qiu, and H. Yang, Phys. Rev. Lett. 114, 047201 (2015).
[28] J. M. D. Coey, Magnetism and magnetic materials (Cambridge, U.K., 2010).
[29] T. Ueno, J. Sinha, N. Inami, Y. Takeichi, S. Mitani, K. Ono, and M. Hayashi, Sci. Rep. 5, 14858 (2015).
[30] Y.-C. Lau, Z. Chi, T. Taniguchi, M. Kagawachi, G. Shibata, N. Kawamura, M. Suzuki, S. Fukami, A. Fujimori, H. Ohno, and M. Hayashi, Phys. Rev. Mater. 3, 104419 (2019).
[31] J. Sinha, M. Hayashi, A. J. Kellock, S. Fukami, M. Yamanoouchi, H. Sato, S. Ikeda, S. Mitani, S.-H. Yang, S. S. P. Parkin, and H. Ohno, Appl. Phys. Lett. 102, 242405 (2013).
[32] J. Cho, N.-H. Kim, S. Lee, J.-S. Kim, R. Lavrijsen, A. Solignac, Y. Yin, D.-S. Han, N. J. van Hoof, H. J. Swagten, B. Koopmans, and C.-Y. You, Nat. Commun. 6, 7635 (2015).
[33] M. Belmeguenai, M. S. Gabor, Y. Roussigné, T. P. Jr., R. B. Mos, A. Stashkevich, S. M. Chérif, and C. Tsuhan, Phys. Rev. B 97, 054425 (2018).
[34] B. T. Thole, P. Carra, F. Sette, and G. van der Laan, Phys. Rev. Lett. 68, 1943 (1992).
[35] P. Carra, B. T. Thole, M. Altarelli, and X. Wang, Phys. Rev. Lett. 70, 694 (1993).
[36] R. Wu and A. J. Freeman, Phys. Rev. Lett. 73, 99 (1994).
[37] J. Stöhr, J. Magn. Magn. Mater. 200, 470 (1999).
[38] M. T. Johnson, P. J. H. Bloemen, F. J. A. den Broeder, and J. J. de Vries, Rep. Prog. Phys. 59, 1409 (1996).
[39] Y.-C. Lau, P. Sheng, S. Mitani, D. Chiba, and M. Hayashi, Appl. Phys. Lett. 110, 022405 (2017).
[40] S. Miwa, M. Suzuki, M. Tsujikawa, K. Matsuda, T. Nozaki, K. Tanaka, T. Tsukahara, K. Nawaoka, M. Goto, Y. Kotani, T. Ohkubo, F. Bonell, E. Tamura, K. Hono, T. Nakamura, M. Shirai, S. Yuasa, and Y. Suzuki, Nat. Commun. 8, 15848 (2017).
[41] K. Ikeda, T. Seki, G. Shibata, T. Kadono, K. Ishigami, Y. Takahashi, M. Horio, S. Sakamoto, Y. Nonaka, M. Sakamaki, K. Amemiya, N. Kawamura, M. Suzuki, Y. Takahashi, and A. Fujimori, Appl. Phys. Lett. 111, 142402 (2017).
[42] G. Shibata, M. Kitamura, M. Minohara, K. Yoshimatsu, T. Kadono, K. Ishigami, T. Hanano, Y. Takahashi,
S. Sakamoto, Y. Nonaka, K. Ikeda, Z. Chi, M. Furuse, S. Fuchino, M. Okano, J. i. Fujimori, A. Uchida, K. Watanabe, H. Fujihira, S. Fujihira, A. Tanaka, H. Kumigashira, T. Koide, and A. Fujimori, npj Quan. Mat. 3, 3 (2018).

[43] H. Yang, A. Thiaville, S. Rohart, A. Fert, and M. Chshiev, Phys. Rev. Lett. 115, 267210 (2015).

[44] A. Hrabec, N. A. Porter, A. Wells, M. J. Benitez, G. Burnell, S. McVitie, D. McGrouther, T. A. Moore, and C. H. Marrows, Phys. Rev. B 90, 020402 (2014).