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Asymmetric Bubble Expansion in Pt/Co/MgO Layers with Dzyaloshinskii–Moriya Interaction

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Magnetic skyrmions are particle-like spin structures of topological origin found in several magnetic materials, making them a promising candidate for current-driven memory devices. However, for applications, it is important to understand the origin of the large mass of skyrmions that affects strongly their trajectory during the propagation. Here we investigate the strength of the Dzyaloshinsky–Moriya interaction at the ferromagnetic/heavy metal interface. Our measurements are carried out by the method based on asymmetric bubble expansion. Magneto-optical Kerr effect studies are performed on two different samples of asymmetric Pt/Co/MgO with different MgO thickness, where a larger Dzyaloshinsky–Moriya interaction can be expected.

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PACS/topics: magnetic domain wall, skyrmions, thin magnetic layers

1. Introduction

Magnetization dynamics in thin films [1, 2] and wires had generated a lot of interest recently due to high applicability [3–5] and potential impact on spintronic devices. In particular, magnetic skyrmions are topological structures that can be stabilized in thin magnetic films [6, 7]. It has been shown theoretically [8, 9] and experimentally [10, 11] that single skyrmions can be excited by magnetic fields or electric current. Depending on the excitation, mainly a breathing mode, where the size of the skyrmion changes periodically, and a translational mode, where the skyrmion behaves like a composite particle, are stimulated. The latter one makes the skyrmion a promising candidate for applications in novel memory and logic devices [12], due to the rich dynamics and high predicted efficiency of spin orbit torque. Simulations and experimental observations of the translation of a skyrmion quasi particle have shown that it behaves like a massive charged particle in a magnetic field following a hypocyclodic trajectory. From this trajectory, it can be determined that the quasi particle has a sizable mass, which is larger than in other magnetic structures [10]. For an application of the skyrmion, it is important to understand the origin of the large mass since the mass strongly affects the trajectory of the skyrmion [13]. One reason for the large mass can be the breathing mode of the skyrmion. Finally, for chiral skyrmion, the magnetic configuration of the skyrmion is strongly affected by the Dzyaloshinsky–Moriya interaction (DMI) that is antisymmetric exchange interaction favouring non-collinear orientation of neighbouring spins [14, 15]. The DMI is expected to have a large influence on the mass, and therefore on the dynamics of the skyrmion [15].

In this paper, we address both thin film preparation and quantification of DMI at the heavy metal/ ferromagnetic interface by the method based on asymmetric bubble expansion, originally proposed in [16] and later used in [17, 18]. The measurements are carried out on two different Pt/Co/MgO samples with asymmetric interface and different MgO layer thicknesses.

2. Experiment

The multilayers have been prepared by room temperature DC sputtering at small pressures of 10^{-6} mbar on thermally oxidized Si substrates with a 5 nm thick Ta buffer layer.

We started from a stack of Pt (4 nm)/Co (0.6–1 nm) /MgO (0.45 nm) wedge samples and observed the out of plane (OOP) magnetic anisotropy with magnetic bubbles at Co thickness of 0.85 nm that we finally used for our samples. The film exhibits a perpendicular anisotropy, as shown by the square out of plane hysteresis loops presented in Fig. 1.

The coercive field of about 15 mT in Pt/Co/MgO drops to about 14 mT as soon as the top 0.65 nm MgO surface is substituted by 0.42 nm thick MgO layer. The out of plane (OOP) anisotropy was measured by the vibrating sample magnetometry technique in an in-plane field configuration. The anisotropy field is about 0.1 T for all the films, which demonstrates that the anisotropy comes mostly from the bottom Pt/Co interface.

The asymmetric bubble expansion has been observed by Evico-Zeiss magneto-optical Kerr effect (MOKE) microscopy [19]. Contrary to the previous attempts [20], asymmetry in bubble expansion was not achieved by tilted magnet in our case, but we used the system of

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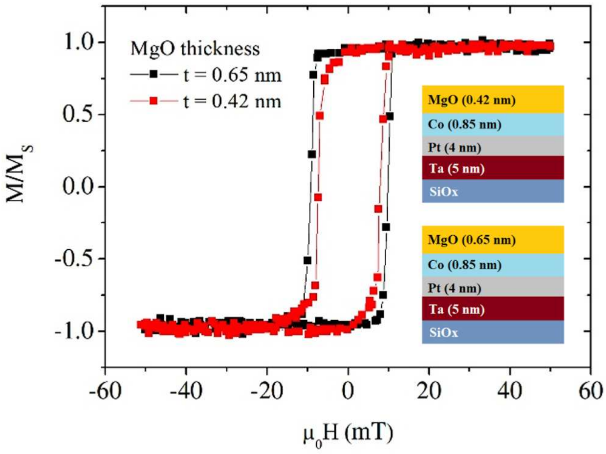

Fig. 1. Hysteresis loops with a perpendicular magnetic field show perpendicular magnetic anisotropy (PMA) in both studied samples.

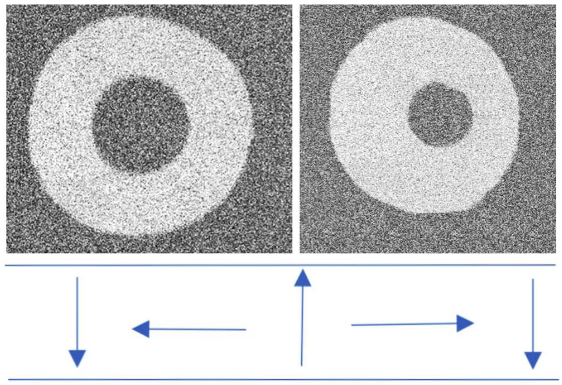

Fig. 2. Domain wall expansion in Pt/Co/MgO sample. The top left image shows asymmetric bubble expansion in OOP field. The top right image shows the bubble expansion with magnetic field applied in-plane of the sample. The bottom image shows a schematic profile of a spin structure of a bubble with Néel domain wall.

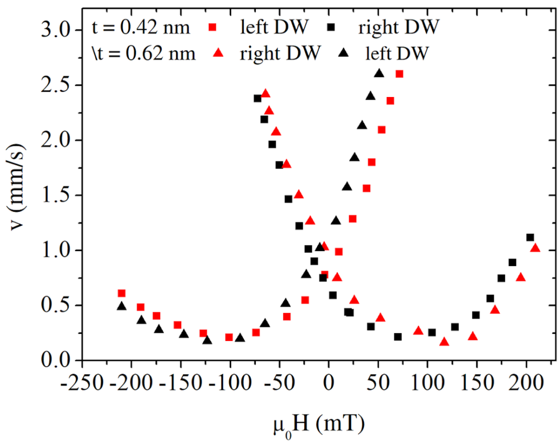

Fig. 3. The domain wall velocity as a function of the in-plane magnetic field.

two coils. The in-plane magnetic field was applied by commercial Evico-Zeiss water-cooled quadruple magnet and the out-of-plane component of the magnetic field was generated by simple hand-made coil. KEPCO amplifier controlled by commercial Kerr-Lab software has supplied both coils.

3. Results and discussion

A typical shape of magnetic bubble in Pt/Co/MgO sample is shown in Fig. 2. When the OOP magnetic field is applied to the sample, the boundaries of a bubble expand symmetrically because of magnetostatic (Zeeman) contribution to the overall energy. OOP magnetic field oriented in the same (opposite) direction as magnetization of bubble generates a torque that pushes the domain wall outwards (inwards) from the bubble. It has been shown previously that Pt/Co/MgO thin films contain domain walls with the Néel structures with a transient magnetization oriented in the plane of a sample. Hence, the OOP magnetic field does not break the radial symmetry of a bubble.

The effect of an in-plane (IP) magnetic field applied during bubble expansion is shown in Fig. 2. In each case, the background image was taken before asymmetric expansion. The in-plane magnetic field was set to a constant value 10 mT–100 mT, and the pulse of OOP field with the duration of 100 ms–4 s was used to expand the bubble. The shape of a bubble was imaged by MOKE microscope and the whole procedure was repeated as a function of applied IP magnetic fields. As seen in Fig. 2, the bubble expands asymmetrically with respect to the in-plane fields. The bubble edges oriented along IP fields propagates with different speed, while the bubble boundaries perpendicular to the direction of IP fields moved with the same velocities. The observed effect was previously attributed to the presence of DMI in thin films that in combination with an external field either assists or hinders domain wall motion. The minimum of the domain wall velocity corresponds to the effective DMI value [14].

As can be seen in Fig. 3, for Pt/Co/MgO layer with MgO thickness of 0.42 nm, the effective value of DMI is estimated to be about 90 mT. Higher thickness of MgO layer in the second sample ($t = 0.62$ nm) results in higher DMI value of around 130 mT. Therefore, variations of a top MgO layer thickness seem to be strong enough to influence the interfacial DMI. The effect could be used to manipulate the dynamic properties of skyrmions through their effective mass.

4. Conclusions

Here, we measure strength of the Dzyaloshinskii–Moriya interaction in two thin Pt/Co/MgO layers differing by the thickness of a top MgO layer. The measurements are carried out by MOKE method based on asymmetric bubble expansion. It is shown that application of the in-plane field leads to a more pronounced displacement of a domain wall boundary in sample with higher thickness of MgO layer. The observed mechanism could be used for precise engineering of the Dzyaloshinskii–Moriya interaction, that strongly affects dynamical properties of skyrmions.

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References

[1] H. Stoll, M. Noske, M. Weigand, et al., *Frontiers Phys.* **3**, 26 (2015).

[2] K. Richter, A. Krone, M.A. Mawass, B. Kruger, M. Weigand, H. Stoll, G. Schütz, M. Kläui, *Phys. Rev. B* **94**, 024435 (2016).

[3] H. Pacaiova, M. Oravec, M. Šmelko, P. Lipovský, F. Forraj, *J. Electr. Eng.* **69**, 493 (2018).

[4] K. Semrad, P. Lipovsky, J. Cernan, M. Jurcovic, *Proced. Eng.* **96**, 428 (2014).

[5] M. Šmelko, M. Spodniak, K. Semrad, P. Tulipan, P. Lipovský, V. Moucha, in: *Proc. XIII Int. Sci. Conf. — New Trends in Aviation Development (NTAD), Kosice (Slovakia)*, 2018, p. 128.

[6] S. Heinze, N. Romming, C. Hanneken, M. Menzel, J.E. Bickel, B. Wolter, K. von Bergmann, A. Kubetzka, R. Wiesendanger, *Nature Phys.* **7**, 713 (2011).

[7] N. Romming, Ch. Hanneken, M. Menzel, J.E. Bickel, B. Wolter, K. von Bergmann, A. Kubetzka, R. Wiesendanger, *Science* **341**, 636 (2013).

[8] C. Moutafis, S. Komineas, J.A.C. Bland, *Phys. Rev. B* **79**, 224429 (2009).

[9] I. Makfudz, B. Krüger, O. Tchernyshyov, *Phys. Rev. Lett.* **109**, 217201 (2012).

[10] S. Woo, K. Litzius, B. Krüger et al., *Nature Mater.* **15**, 501 (2016).

[11] K. Litzius, I. Lemesh, B. Krüger et al., *Nature Phys.* **13**, 170 (2017).

[12] A. Fert, V. Cros, J. Sampaio, *Nature Nanotechnol.* **8**, 152 (2013).

[13] K.W. Moon, B.S. Chun, W. Kim, Z.Q. Qiu, Ch. Hwang, *Phys. Rev. B* **89**, 064413 (2013).

[14] I. Dzyaloshinsky, *J. Phys. Chem. Solids* **4**, 241 (1958).

[15] T. Moriya, *Phys. Rev.* **120**, 91 (1960).

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

[17] A. Cao, X. Zhang, B. Koopmans, S. Peng, Y. Zhang, Z. Wang, S. Yan, H. Yang, W. Zhao, *Nanoscale* **10**, 12062 (2018).

[18] R. Lavrijsen, D.M.F. Hartmann, A. van den Brink, Y. Yin, B. Barcones, R.A. Duine, M.A. Verheijen, H.J.M. Swagten, B. Koopmans, *Phys. Rev. B* **91**, 104414 (2015).

[19] J. McCord, *J. Phys. D Appl. Phys.* **48**, 333001 (2015).

[20] W. Koshibae, N. Nagaosa, *Sci. Rep.* **9**, 5111 (2019).