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ABSTRACT
The perpendicular magnetic anisotropy (PMA) and perpendicular exchange bias (PEB) have been investigated in a CoPt/spacer/FeMn heterostructure by inserting Ta and Pt as spacer layers, respectively. First, we show that strong PMA can be obtained in (111)-oriented A1-CoPt single layer and CoPt/FeMn bilayer films on MgO (111) substrates. Then we demonstrate that the Ta and Pt spacer layers have largely different effects on the PMA and PEB of the CoPt/spacer/FeMn films. By increasing the thickness of the Ta spacer layer to 1 nm, the PMA and PEB drastically decrease. While, in the case of Pt, the PMA and PEB increase first, then slightly decrease. When the Pt spacer layer is 1 nm, a value of 85 Oe of the long-range PEB still can be obtained. The possible mechanisms were discussed to explain the different trends of PMA and PEB. Since Ta and Pt are the generally used materials in the spintronics, our study provides a piece of information for the control of the magnetic anisotropy and exchange bias in the current-induced magnetization switching of ferromagnet without external magnetic field.

Over the past decade, antiferromagnetic materials have attracted intensive studies due to their interesting magnetic properties and the potential applications in spintronics.1-7 Spintronic devices based on antiferromagnetic materials promise much faster switching speed and robustness against external magnetic fields.8,9 Moreover, the exchange bias (EB) generated in a ferromagnet (FM)/antiferromagnet (AFM) bilayer can be used to assist the current-induced magnetization switching.10 For the current induced magnetization switching in generally used nonmagnet (NM)/FM bilayer system, an in-plane external magnetic field collinear with the current is required, which is a critical problem for the practical applications.11-13 This problem can be well solved in a FM/AFM bilayer system. The EB between the FM and AFM layers can be utilized as an effective magnetic field, and the AFM layer can be used as an efficient spin-torque generator to manipulate the magnetization in the adjacent FM layer.14 As a result, efficient current-induced magnetization switching can be realized in the AFM/FM bilayer without external magnetic field. The EB between AFM and FM layers has been generally considered due to the interfacial magnetic exchange coupling at the FM/AFM interface.15,16 Thus, most studies on the FM/AFM magnetic coupling have been conducted by directly contacting the FM layer with the AFM layer.17-20 While, long-range EB across a spacer layer was also reported in the previous studies. Gökemeijer et al.14 reported that by inserting Ag, Au and Cu as spacer layers in the Ni81Fe19/spacer/CoO films, the EB can still be observed. They found that this long-range EB decays exponentially with the spacer thickness, and extends to as much as 5 nm. Lee et al.21 theoretically and experimentally studied the long-range EB in NiFe/Cu/NiO films. They observed oscillatory EB through the Cu spacer layer. Thomas et al.22 reported that by inserting Al, Ag, Au, Si, Pd, Ru and Ti as spacer layers in the Fe55Co45/spacer/Ir22Mn78 films, the EB decreases exponentially in most cases by increasing the thickness of the spacer layers. A nonmonotonic variation of perpendicular exchange bias was also observed in [Pt/Co]n/Pt/AFM (AFM= FeMn and IrMn) layers caused by difference in the initial activation energy barrier or Co magnetization orientation tuned by
Pt insertion,\textsuperscript{17,18} while PEB evolution in heterostructures with CoPt single layer (with Co/Pt ratio as 1), rather than multilayer has rarely been studied. Although the direct contact between FM and AFM layers is desired for the exchange coupling, in view of practical application, inserting a metallic nonmagnetic spacer layer is necessary to avoid the interface mixing between FM and AM layers, especially, the oxidation of the FM layer from the AFM oxide, and even effectively control the magnetic anisotropy of the FM layer by the spacer layer.\textsuperscript{9,20} This will greatly enhance the thermal stability and reliability of the devices involving FM/AFM heterostructures. Therefore, to study the long-range EB in such an FM/spacer/AFM system is important in the antiferromagnetic spintronics.

In this work, we study the perpendicular magnetic anisotropy (PMA) and perpendicular exchange bias (PEB) in a CoPt/spacer/FeMn heterostructure by inserting Ta and Pt spacer layers, respectively. First, we show that strong PMA can be obtained in a single A1-CoPt layer without assist of buffer or top layer. Then we demonstrate that the Ta and Pt spacer layers have different effects on the PMA and PEB in the CoPt/spacer/FeMn films. By increasing the thickness of the Ta spacer layer, PMA and PEB decrease drastically. While, for the case of Pt, PMA and PEB increase first, then decrease slightly. When Pt is 1 nm, the PEB with a value of 85 Oe can be obtained, which is much larger than that in the previous reports.\textsuperscript{14,15}

The films were deposited on MgO (111) single crystal substrates by dc magnetron sputtering. Before deposition, the substrates were cleaned in ultrasonic baths of acetone and ethanol and then thermally cleaned in vacuum by annealing at 585 °C. For the deposition, a CoPt layer was deposited on the substrate at 350 °C, and then other layers, including Ta, Pt spacer layers and antiferromagnetic FeMn layer, were deposited after cooling down the substrate to room temperature without breaking the vacuum. The base pressure in the chamber before deposition was better than 5 × 10⁻⁶ Pa, and the deposition pressure was 0.6 Pa. For the CoPt and FeMn deposition, composite Co-Pt and Fe-Mn targets were used, and pure argon gas was supplied during the sputtering. The thicknesses of the CoPt and FeMn layers were fixed as 3 nm and 8 nm, respectively. The thicknesses of the Ta and Pt spacer layers were varied from 0 to 1 nm.

Crystal structure of the films was characterized by x-ray diffraction (XRD) with Cu Kα irradiation. A vibrating sample magnetometer was used to measure the hysteresis loops along the in-plane and out-of-plane (perpendicular) direction of the films. For the field-cooling treatment, a 5 kOe magnetic field was applied during cooling down the samples from 230 °C to room temperature. Magnetic domain images of the films were taken by polar-magneto-optic Kerr microscopy. All the measurements were conducted at room temperature.

Figure 1(a) shows the XRD profiles of the CoPt single and CoPt/FeMn bilayer films on the MgO (111) substrates. For the 3 nm thick CoPt single layer film, only a CoPt (111) peak can be observed, indicating the epaxial growth between the CoPt and MgO substrate. No superlattice peaks of L1₁ and L1₀ CoPt ordered phase but the fundamental peak associated with A1 (111) were found in XRD profile at 2θ = 41.90°,\textsuperscript{21,22} indicating the absence of L1₁ and L1₀, and the formation of disordered fcc A1 CoPt phase. By depositing an 8 nm-thick antiferromagnetic FeMn layer on CoPt, a small FeMn (111) peak can be observed, indicating the epaxial growth between FeMn and CoPt. To investigate the magnetic properties of the films, we measured the M-H curves of the films. The CoPt single layer shows strong PMA as shown in Fig. 1(b). By depositing FeMn on CoPt, the PMA tends to be stronger (Fig. 1(c)). The strong PMA is contributed by the magnetoelastic anisotropy, which is induced by
the epitaxial strain between CoPt and MgO. Since the about 10% mismatch of the lattice constant between A1-CoPt (0.38 nm) and MgO (0.42 nm) results in a tensile stress in the CoPt layer, which favors PMA. The field cooling (FC) treatment was conducted by cooling down the CoPt/FeMn bilayer film from 230°C to room temperature. An external magnetic field along the out-of-plane direction of the film was applied during the FC treatment. As shown in Fig. 1(d), the M-H curves exhibit enlarged coercivity and loop shift, which are evidences for the magnetic coupling between the ferromagnetic CoPt and antiferromagnetic FeMn layers. The PEB is measured as about 90 Oe.

In the following, we investigate the effect of the spacer layers on the PEB of the films. Ta and Pt were inserted between CoPt and FeMn layers by varying the thicknesses from 0 to 1 nm, respectively. Figures 2(a) and 2(b) show the XRD profiles of the two series of samples. Both figures indicate that the insertion of the spacer layers has no obvious effect on the structure of (111) textured A1-CoPt layer. While, the spacer layers slightly hinder the epitaxial growth of FeMn, since the intensity of the FeMn (111) peak slightly decreases by increasing the thickness of the Ta or Pt spacer layer. The corresponding M-H curves are plotted in Figs. 2(c) and 2(d). Different from the effect on the structures, Ta and Pt have different effects on the magnetic properties of the films. By increasing Ta thickness, the PEB and PMA decrease drastically. On the other hand, by increasing Pt thickness, the PEB increases first, and then decreases slightly. All the CoPt/Pt/FeMn films have strong PMA. To quantitatively compare the difference of the effect between Ta and Pt, we calculated the effective magnetic anisotropy energy \( K_{\text{eff}} \) as shown in Fig. 3(a). \( K_{\text{eff}} \) decreases monotonically with the increase of the Ta thickness. While, by inserting a 0.25 nm thick Pt spacer layer, \( K_{\text{eff}} \) increases from \( 2.5 \times 10^6 \) erg/cm\(^3\) to \( 3.1 \times 10^6 \) erg/cm\(^3\), and then decreases to \( 2.4 \times 10^6 \) erg/cm\(^3\) by further increasing the Pt thickness to 1 nm. The remanence ratio also shows similar tendency for the insertion of Ta and Pt spacer layers, respectively (Fig. 3(b)). This result indicates that the Ta insertion weakens the PMA, but the strong PMA can be retained by the Pt insertion, which can even be enhanced with a proper thickness of the Pt spacer layer. Figure 3(c) and 3(d) exhibit the change of the PEB \( H_{\text{EB}} \) and perpendicular coercivity \( H_c \). By increasing the Ta thickness to 1 nm, \( H_{\text{EB}} \) decreases from 90 Oe to 45 Oe monotonously. While, in the case of Pt, a maximum value of \( H_{\text{EB}} = 130 \) Oe is obtained when Pt is 0.25 nm, which decreases to 85 Oe at 1 nm.

When depositing Ta on CoPt layer, interfacial roughness is an important factor to be considered. It has been shown that Ta layer is supposed to be discontinuous at 0.25 nm, leading the significant influence on the grain sizes and crystal structure of AFM layer,\(^{26}\) resulting in weakened PEB and PMA. Furthermore, the formation of dead layer is another important affecting factor. Interface reaction may take place and change the local electronic...
structure at the interface of Ta spacer layer and CoPt layer, giving rise to the formation of a magnetically dead layer.\(^{27}\) Moreover, as the thickness of the spacer layer increases, the magnetic coupling between CoPt and FeMn decreases. Therefore, the PMA and PEB decrease with increasing the Ta thickness. On the other hand, it has been reported that a thin Pt layer can prevent the formation of above-mentioned magnetically dead layer.\(^{21}\) The enhanced perpendicular Co orbital moment induced by the Pt 5d-Co 3d hybridization also favors the PMA.\(^{29}\) These factors enhance the PMA and PEB when Pt is 0.25 nm. By further increasing the Pt spacer layer thickness, the magnetic coupling between CoPt and FeMn weakens, which results in a decrease of the PMA and PEB.

We further used the polar-magneto-optic Kerr (PMOKE) microscopy to directly observe the magnetic domain structure of the films. The domains were imaged using magneto-optical Kerr effect microscopy at 300 K in the polar configuration, at which it is sensitive to out-of-plane magnetization.\(^{19}\) Domain images were obtained after perpendicular field cooling with 5 kOe external field, and the images were recorded without external field. Figure 4 shows the magnetic domain images after the FC treatment. By increasing the Ta thickness, the number of domains not set by the applied field largely increase. While for the case of Pt insertion, such domains only slightly increase. The evolution of the domain images is consistent with the M-H curves, which evidences the significant roles of the spacer layers to manipulate the PMA between CoPt and FeMn layers.

In summary, we have studied the magnetic properties in CoPt/FeMn films by inserting Ta and Pt spacer layers with different thicknesses. First, we show that strong PMA can be obtained by just directly depositing a single A1-CoPt layer film on the MgO (111) substrate. We further show that the Ta and Pt spacer layers have different effects on the PMA and PEB in the CoPt/spacer/FeMn films. The PMA and EB decrease by increasing the PMA and EB thickness to 1 nm. While, strong PMA and EB can be retained by increasing the Pt thickness to 1 nm, which can be even enhanced by inserting a 0.25 nm-thick Pt spacer layer.

REFERENCES

1. T. Jungwirth, X. Marti, P. Wadley, and J. Wunderlich, Nat. Nanotechnol. 11, 231 (2016).

2. V. Baltz, A. Manchon, M. Tsoi, T. Moriyama, T. Ono, and Y. Tserkovnyak, Rev. Mod. Phys. 90, 015005 (2018).

3. P. Wadley, B. Howells, J. Železný, C. Andrews, V. Hills, R. P. Campion, V. Novák, K. Olejník, F. Maccherozzi, S. Dhesi et al., Science 351, 587 (2016).

4. H. Yan, Z. Feng, S. Shang, X. Wang, Z. Hu, J. Wang, Z. Zhu, H. Wang, Z. Chen, H. Hua et al., Nat. Nanotechnol. 14, 131 (2019).

5. Y.-C. Lau, D. Betto, K. Roche, J. Coey, and P. Stamenov, Nat. Nanotechnol. 11, 758 (2016).

6. S. Fukami, C. Zhang, S. Dutta-Gupta, A. Kurenkov, and H. Ohno, Nat. Mater. 15, 535 (2016).

7. I. M. Miron, K. Garello, G. Gaudin, P.-J. Zermatten, M. V. Costache, S. Außerf, S. Bandiera, B. Rodmacq, A. Schuhl, and P. Gambardella, Nature 476, 186 (2011).

8. L. Liu, C.-F. Pai, Y. Li, H. Tseng, D. Ralph, and R. Buhrman, Science 336, 555 (2012).

9. J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. 192, 203 (1999).

10. H. Ohldag, A. Scholl, F. Notling, E. Arenholz, S. Maat, A. Young, M. Carey, and J. Stohr, Phys. Rev. Lett. 91, 017203 (2003).

11. A. Maitre, D. Ledue, and R. Patte, J. Magn. Magn. Mater. 324, 403 (2012).

12. C. Liu, C. Yu, H. Jiang, L. Shen, C. Alexander, and G. Mankey, J. Appl. Phys. 87, 6644 (2000).

13. Y. Tang, B. Roos, T. Mewes, S. O. Demokritov, B. Hillebrands, and Y. Wang, Appl. Phys. Lett. 75, 707 (1999).

14. N. Gökemeijer, T. Ambrose, and C. Chien, Phys. Rev. Lett. 79, 4270 (1997).

15. Y. J. Lee, C. R. Chang, T. M. Hong, C. Ho, and M.-T. Lin, J. Magn. Magn. Mater. 239, 57 (2002).

16. S. Thomas, A. J. Kellock, and S. S. Parkin, J. Appl. Phys. 87, 5061 (2000).

17. M. Czaplewicz, T. Stobięcki, and S. van Dijken, Phys. Rev. B 77, 024416 (2008).

18. L. Lechevallier, A. Zarefy, R. Lardé, H. Chiron, J.-M. Le Baltz, B. Rodmacq, and B. Dieny, Phys. Rev. B 79, 174434 (2009).

19. Y. J. Lee, C. R. Chang, T. M. Hong, C. Ho, and M.-T. Lin, J. Magn. Magn. Mater. 239, 57 (2002).

20. C.-F. Pai, M.-H. Nguyen, C. Belvin, L. H. Vilela-Leao, D. Ralph, and R. Buhrman, Appl. Phys. Lett. 104, 082407 (2014).

21. A. C. Sun and C. F. Huang, J. Appl. Phys. 113, 17C110 (2013).

22. C. Leroux et al., J. Phys. F: Metal Phys. 18, 2033 (1988).

23. A. C. Sun, J. Appl. Phys. 77, 174434 (2001).

24. P. Caserio, T. Harumoto, Y. Nakamura, and J. Shi, J. Appl. Phys. 125, 053904 (2019).

25. H. An, S. Takada, T. Sannomiya, S. Muraiishi, J. Shi, and Y. Nakamura, Appl. Phys. A 113, 31 (2013).

26. M. Ali, C. H. Marrows, and B. J. Hickey, Phys. Rev. B 77, 134401 (2008).

27. K.-i. Li, Z. Guo, G. Han, J. Qiu, and Y.-W. Wu, J. Appl. Phys. 93, 6614 (2003).

28. J. Chuang, L. Yang, and J. Minghua, Chinese J. Vac. Sci. Tech, S1 (2008).

29. N. Nakajima, T. Koide, T. Shidara, H. Miyairi, H. Fukutani, A. Fujimori, K. Ich, T. Katayama, M. Nyvlt, and Y. Suzuki, Phys. Rev. Lett. 81, 5229 (1998).

30. R. A. Khan, H. T. Nembach, M. Ali, M. Shaw, C. H. Marrows, and A. M. Thomas, Phys. Rev. B 98, 064413 (2018).