Tunable interface anisotropy in a Pt/$Co_{1-x}Fe_x$/Pt multilayer*

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Interfacial magnetic anisotropy in a Pt/$Co_{1-x}Fe_x$/Pt multilayer is tuned by doping iron atoms into the cobalt layer. The perpendicular magnetic anisotropy and out-of-plane coercivity are found to decrease with increasing x. For a specific x, the out-of-plane coercivity acquires a maximal value as a function of the thickness of the CoFe layer. At low temperature, the coercivity is enhanced. Small coercivity but reasonably large perpendicular magnetic anisotropy can be obtained by controlling the x and CoFe layer thickness.

Keywords: Pt/CoFe/Pt multilayers, perpendicular magnetic anisotropy, interfacial magnetic anisotropy

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1. Introduction

Magnetic thin films with perpendicular magnetic anisotropy (PMA) are of great interest because of their potential applications in magnetic–optical (MO) recording, high-density magnetic recording, and non-volatile memory.[1–4] Large PMA and out-of-plane coercivity H_C are often required in these applications. Recently, perpendicularly magnetized materials were incorporated into magnetic tunneling junction and spintronics devices as free layers.[5,6] In each of these magnetic sensing devices, a moderate magnetic anisotropy and small H_C are often required in order to reduce the switching field, leading to a high sensitivity. Accordingly, the fabrication of a CoFeB/MgO bilayer and its magnetic properties have been extensively studied in magnetic junction devices.[7,8] Moreover, $[Co/Pt]_n$ multilayers have prevailed because of the flexible preparation conditions compared with ordered alloys, e.g. SmCo and $L1_0$-FePt.[7,9,10] Very recently, much effort has been made to reduce the PMA and H_C by either magnetic alloy layers such as CoFe/Pt, or nonmagnetic spacer layers such as Pt-Fe.[11–14] Ding *et al.*[12] successfully adjusted the PMA of $[CoFe/Pt]_n$ multilayers by changing the CoFe and Pt layer thicknesses and the number of CoFe/Pt bilayers because the PMA is very sensitive to the thickness of the Co and Pt layers. Feng *et al.*[13] optimized the magnetic properties of the $[CoFe(0.2\ nm)/Pt(0.2\ nm)]_n$ multilayers by changing the thermal annealing conditions and bilayer number. In this paper, we address the optimization of the PMA and H_C of Pt/Co/Pt multilayers by doping iron atoms into the cobalt layer. By tuning the Fe concentration x in the cobalt layer, the PMA and H_C are reduced significantly.

2. Experiments

In this study, the Pt(20 nm bottom)/$Co_{1-x}Fe_x$ (=CoFe) (0–1.0 nm)/Pt(10-nm top) multilayers were prepared on 2 cm×5 cm silicon wafers with 2 nm natural oxide layers by a computer-controlled multi-source dc sputtering system at ambient temperature. Here, CoFe layers were deposited from the CoFe composite target, on which small iron pieces (99.99% pure) were placed on the Co target. The CoFe layer took a wedged thickness along the long edge of the substrate. The samples were then cut into 17 small pieces, and each can be treated as a uniform thickness. The base pressure was 2.0×10^{-5} Pa and the Ar working pressure was 0.68 Pa. The deposition rates were 0.2 nm/sec and 0.1 nm/sec for the Pt and CoFe, respectively. A set of single $Co_{1-x}Fe_x$ layers on Si were also prepared to measure the saturation magnetization. The film thickness and microstructure were characterized by X-ray reflectivity (XRR) and X-ray diffraction (XRD) at large angles. Energy dispersive spectrometer (EDS) analysis was employed to determine the compositions of the CoFe layers. The magnetic properties were measured by a vector vibrating sample magnetometer (VVSM) from LakeShore 7407 and the Versa-Lab system of Quantum Design.

3. Results and discussion

Figure 1(a) shows the typical XRR pattern of the Pt (20 nm)/CoFe (0.3 nm)/Pt (10 nm) multilayers with $x = 0.53$. From the reflection fringes, the thickness of the constituent layers from bottom to top are fitted to be 18.66 nm, 0.45 nm, and 9.81 nm, which are close to the designed values. Fig-

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ure 1(b) shows the XRD pattern of the same sample. The main peak located in $2\theta = 39.6^\circ$ corresponds to the fcc Pt (111) orientation. Due to the small thickness, the peak near $2\theta = 44.2^\circ$ corresponding to the fcc Co (111) orientation does not appear.[9]

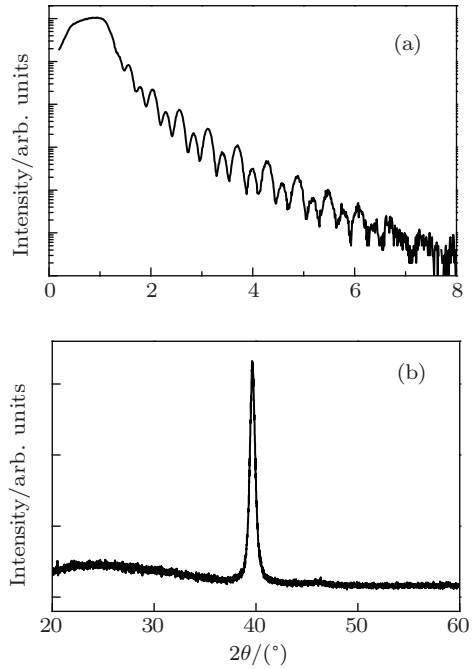


Fig. 1. Typical XRR (a) and XRD (b) of Pt (20 nm)/CoFe (0.3 nm)/Pt (10 nm) multilayer films with $x = 0.53$.

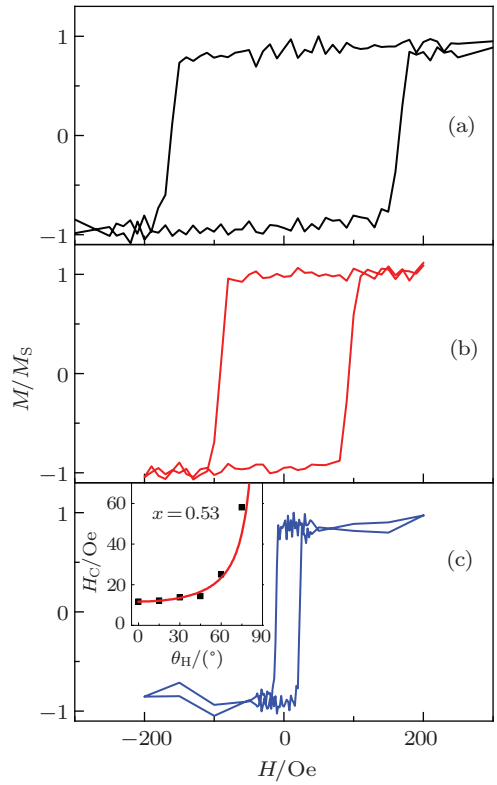


Fig. 2. (color online) Out-of-plane hysteresis loops of Pt(20 nm)/CoFe (0.3 nm)/Pt(10 nm) multilayers with $x = 0$ (a), 0.2 (b), and 0.53 (c). The inset shows the angular dependence of room-temperature H_c for $x = 0.53$. The solid lines refer to the fit results of $1/\cos(\theta_H)$, 1 Oe = 79.5775 A/m.

The out-of-plane hysteresis loops of the Pt (20 nm)/CoFe (0.3 nm)/Pt (10 nm) multilayers with $x = 0$, 0.2, and 0.53 are given in Fig. 2. It is indicated that the PMA is established with the magnetic easy axis perpendicular to the film plane in all three samples. We also study the magnetization reversal mechanism of the Pt/CoFe (0.3 nm)/Pt multilayer with $x = 0.53$. The room-temperature H_C is measured as a function of the θ_H angle between the external magnetic field and the normal direction of the film, as shown in the inset of Fig. 2(c). H_C increases with increasing θ_H and approximately obeys a proportional function of $1/\cos(\theta_H)$. Apparently, the magnetization reversal mechanism is accompanied by the pinned domain wall motion (DWM) and can be described by the Kondorsky model.[15,16] It is surprising that the magnetic easy axis still remains along the normal direction of the film even for $x = 0.53$, indicating a much higher surface magnetic anisotropy than reported before.[11,12]

Figures 3(a) and 3(b) show the x dependences of the H_C and in-plane saturation field H_S, which was taken as the in-plane anisotropy field.[12] H_C and H_S both decrease monotonically with Fe concentration. H_C decreases from 162 Oe at $x = 0$ to 8 Oe at $x = 0.53$. H_S decreases from 4517 Oe at $x = 0$ to 1750 Oe at $x = 0.53$. The PMA in the Co/Pt multilayers is believed to come from Co/Pt interface anisotropy and Co bulk anisotropy.[1] The total effective magnetic anisotropy energy is often defined as[10,17,18]

$$K_{\text{eff}} = K_{\text{U}} - 2\pi M_{\text{S}}^2 + 2K_{\text{S}}/t_{\text{CoFe}}, \tag{1}$$

where the first two terms on the right-hand side correspond to the magnetocrystalline anisotropy and the shape anisotropy of the bulk anisotropy, respectively, K_S is the interfacial anisotropy at the CoFe/Pt interface, M_S the saturation magnetization of the CoFe layer, and t_{CoFe} the CoFe thickness. As reported before, K_{eff} mainly comes from the interfacial anisotropy due to the lowered symmetry at the interface.[18]

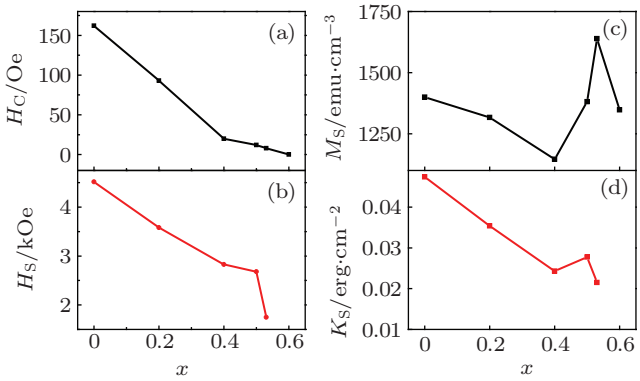


Fig. 3. (color online) Dependences of H_C (a), H_S (b), M_S (c), and K_S (d) on the Fe concentration in the Pt(20 nm)/CoFe (0.3 nm)/Pt(10 nm) multilayers, 1 erg = 10^{-7} J.

The in-plane saturation field and anisotropy field are both equal to $2K_S/M_S$.[19] In order to obtain the interfacial

anisotropy K_S, the saturation magnetization M_S is measured. Figures 3(c) and 3(d) show the x dependences of M_S and K_S in the Pt(20 nm)/CoFe(0.3 nm)/Pt(10 nm) multilayers, respectively. M_S is estimated from the measured magnetic moment of the 20-nm $Co_{1-x}Fe_x$ single film and reaches a maximal value of about 1600 emu/cm^3 at $x = 0.5$, which is consistent with the Slater–Pauling curve.[20] With x increasing, the K_S is found to decrease from 0.05 erg/cm^2 to 0.02 erg/cm^2 (1 erg=10^{-7} J). From formula (1), it is found that K_{eff} mainly comes from the competition between the demagnetization energy and the interfacial anisotropy K_S when K_U can be ignored in the polycrystalline film. By tuning x, the K_S and demagnetization energy are tuned, leading to a reduction in PMA.

The results in Fig. 2 can be ascribed to the x dependence of K_S. The randomly distributed Fe atoms in the Co matrix may have a strong effect on the orbital hybridization between the d electrons in Pt and the Co atoms at the Pt/Co interface, leading to the changing interfacial anisotropy.[11,21] With the further increase in the Fe content up to 60 at% in CoFe, the room-temperature hysteresis loop becomes considerably slanted, suggesting that the PMA is no longer large enough to overcome the shape anisotropy.

It is essential to investigate the Pt/CoFe/Pt multilayers with different values of CoFe layer thickness. The thickness dependence of H_C is shown in Fig. 4(a). All the samples are found to show similar variation trends. With increasing CoFe thickness, H_C first increases and then decreases after a maximal H_C. When $x = 0.4$, for instance, H_C reaches a maximal value of 60 Oe at a CoFe thickness of 0.27 nm. For a thinner CoFe layer, the interfacial anisotropy energy is not large enough to overcome the demagnetization energy because of the relative non-uniformity of film coverage.[17] For a thick CoFe layer, the out-of-plane H_C increases, indicating the increase in interfacial anisotropy energy, owing to the well established interface. After that, H_C is reduced, with the CoFe thickness further increasing because of the increasing effect of demagnetizing energy compared with the interfacial anisotropy energy.[9]

To further understand the H_C of the Pt/CoFe(0.3 nm)/Pt multilayer, hysteresis loops are measured at different temperatures from 380 K to 60 K. In the experiments, it is found that the hysteresis loops are squared at low temperatures and become slanted at high temperatures. The magnetization easy axis is aligned along the film normal direction at low temperatures and along the film plane at high temperatures. The crossover temperature decreases with increasing x. For example, it is equal to 350 K and 250 K for $x = 0.4$ and 0.6, respectively. Figure 4(b) shows that the values of H_C increase significantly as the temperature decreases for all samples with $x = 0.6$, 0.53, 0.4, 0.2, and 0. The H_C variation can be ascribed to the temperature dependence of the PMA and the magnetization reversal mechanism of the CoFe/Pt multilayers.[22,23]

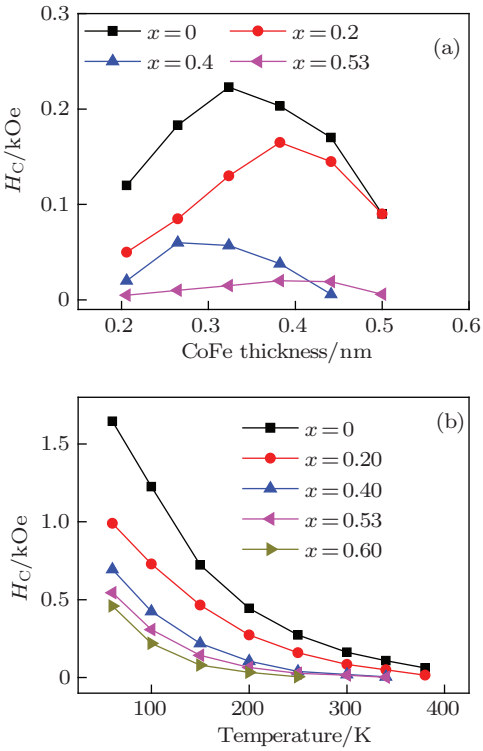


Fig. 4. (color online) Values of H_C versus CoFe thickness (a) and temperature (b) for the Pt(20 nm)/CoFe/Pt(10 nm) multilayers with various Fe concentrations.

4. Conclusion

In this paper, for Pt/CoFe/Pt multilayers with a specific CoFe layer thickness, the PMA and the out-of-plane H_C are found to decrease with increasing x, indicating the tuning effect of the Fe concentration x on interfacial anisotropy. Moreover, H_C is found to acquire a maximal value at a moderate thickness, and increases with decreasing temperature. For Pt/CoFe/Pt multilayers with $x = 0.53$ and 0.45 nm thick CoFe layers, a low H_C of about 10 Oe and a reasonably large PMA are obtained, which may facilitate the fabrication of spintronics devices.

References

[1] Johnson M T, Bloemen P J H, den Broeder F J A and de Vries J J 1996 *Rep. Prog. Phys.* **59** 1409
[2] Zheng M, Xu Y, Guo Z H and Wang Y J 1996 *Chin. Phys. Lett.* **13** 711
[3] Ma P P, Zheng W, Wang A L, Chen J C, Wang Y J, Li J and Chen L Y 1998 *Chin. Phys. Lett.* **15** 376
[4] Mizunuma K, Ikeda S, Park J H, Yamamoto H, Gan H, Miura K, Hasegawa H, Hayakawa J, Matsukura F and Ohno H 2009 *Appl. Phys. Lett.* **95** 232516
[5] Ikeda S, Miura K, Yamamoto H, Mizunuma K, Gan H D, Endo M, Kanai S, Hayakawa J, Matsukura F and Ohno H 2010 *Nat. Mater.* **9** 721
[6] Park J H, Park C, Jeong T, Moneck M T, Nufer N T and Zhu J G 2008 *J. Appl. Phys.* **103** 07A917
[7] Zeper W B, van Kesteren H W, Jacobs B A J, Spruit J H M and Carcia P F 1991 *J. Appl. Phys.* **70** 2264

[8] Fowley C, Decorde N, Oguz K, Rode K, Kurt H and Coey J M D 2010 *IEEE Trans. Magn.* **46** 2116
[9] Numata T, Kiriyama H, Inokuchi S and Sakurai Y 1988 *J. Appl. Phys.* **64** 5501
[10] Feng C, Mei X Z, Yang M Y, Li N, Jiang Y, Yu G H and Wang F M 2011 *J. Appl. Phys.* **109** 063918
[11] Lü Q L, Cai J W, He S L and Sun L 2011 *J. Magn. Magn. Mater.* **323** 465
[12] Ding Y F, Judy J H and Wang J P 2005 *J. Appl. Phys.* **97** 10J117
[13] Feng J F, Rode K, Ackland K, Stamenov P S, Venkatesan M and Coey J M D 2012 *J. Magn. Magn. Mater.* **324** 2298
[14] Zhang Z and Wigen P E 1991 *J. Appl. Phys.* **69** 5649
[15] Coffey K R, Thomson T and Thiele J U 2003 *J. Appl. Phys.* **93** 8471
[16] Kondorsky E 1940 *J. Phys. (Moscow)* **2** 161
[17] Kisielewski M, Maziewski A, Tekielak M, Ferré J, Lemerle S, Mathet V and Chappert C 2003 *J. Magn. Magn. Mater.* **260** 231
[18] Shan R, Gao T R and Zhou S M 2006 *J. Appl. Phys.* **99** 063907
[19] Kipgen L, Fulara H, Raju M and Chaudhary M 2012 *J. Magn. Magn. Mater.* **324** 3118
[20] Gallagher K, Johnson F, Kirkpatrick E M, Scott J H, Majetich S and McHenry M E 1996 *IEEE Trans. Magn.* **32** 4842
[21] Moulas G, Lehnert A, Rusponi S, Zabloudil J, Etz C, Ouazi S, Etzkorn M, Bencok P, Gambardella P, Weinberger P and Brune H 2008 *Phys. Rev. B* **78** 214424
[22] Bartolomé J, Figueroa A I, García L M, Bartolomé F, Ruiz L, González-Calbet J M, Petoff F, Deranlot C, Wilhelm F, Rogalev A and Brookes N 2012 *Low Temp. Phys.* **38** 1053
[23] Suzuki T, Notarys H, Dobbertin D, Lin C J, Weller D, Miller D and Gorman G 1992 *IEEE Trans. Magn.* **28** 2754