Effect of Mo capping layers thickness on the perpendicular magnetic anisotropy in MgO/CoFeB based top magnetic tunnel junction structure*

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(Received 4 July 2016; revised manuscript received 10 August 2016; published online 30 September 2016)

A detailed study of the magnetic characterizations of the top structure MgO/CoFeB/Mo is presented. The samples show strong perpendicular magnetic anisotropy (PMA) when the thickness of CoFeB is 0.9 nm and 1.1 nm. The saturation magnetic moment and interface anisotropy constant are 1566 emu/cm^3 and 3.75 erg/cm^2, respectively. The magnetic dead layer (MDL) is about 0.23 nm in this system. Furthermore, strong capping layer thickness dependence is also observed. The strong PMA of 1.1 nm CoFeB only exists in a Mo cap layer thickness window of 1.2–2 nm. To maintain PMA, the metal layer could not be too thin or thick in these multilayers. The oxidation and diffusion of the metal capping layer should be respectively responsibility for the degradation of PMA in these thin or thick metal capping layer samples.

Keywords: perpendicular magnetic anisotropy, capping layer, effective magnetic anisotropy, magnetic tunnel junction

PACS: 78.67.Pt, 75.70.Cn, 75.70.Rf, 75.60.Nt **DOI:** 10.1088/1674-1056/25/11/117805

1. Introduction

Spin-transfer-torque magnetic random access memories (STT-MRAMs)[1] with perpendicular magnetic anisotropy (PMA) are promising for next generation memory devices[2,3] due to their advantages of low power consumption, large storage capacity, and non-volatility compared with the traditional storage.[4,5] It is shown that the PMA materials are critical to the STT-MRAMs. So far, a number of PMA materials have been discovered, such as rare-earth/transition metal ferromagnetic alloys,[6,7] $L1_0$(Fe,Co)Pt alloys,[8] [$Fe_{1-x}Co_x$/Pt] multilayers,[9] and CoFeB/MgO stacks.[10–13] However, due to low spin polarization, large damping and low tunneling magneto-resistance (TMR) ratio are two issues that need to be solved urgently. Since PMA is built at CoFeB/MgO interfaces, the thickness of CoFeB is limited to a narrow range for PMA.[14] The PMA in the CoFeB/MgO interface could be attributed to the hybridization between 3d orbital of transition mental and O-2p.[15] Moreover, capping layer materials play an important role in the formation of PMA in this MgO/CoFeB/capping layer multilayer system, and Ta is the most common electrode material to obtain PMA in this system.[1,2] It is found that the stack of CoFeB/MgO with Ru capping layer or buffer layer does not show PMA.[16] In addition, the electrode material may affect the thermal stability, annealing temperature, and magneto-resistance of this CoFeB/MgO system MTJs. For example, the PMA in Ta/CoFeB/MgO stack degrades seriously at the annealing temperature above 300 °C.[17,18]

Recently, Mo has been considered a promising element to replace Ta due to its high annealing stability, and the CoFeB/MgO magnetic tunnel junctions (MTJs) with Mo buffer layer show great PMA at the annealing temperature of about 400 °C.[19] Furthermore, the interfacial PMA is observed to increase with annealing over the studied temperature range in Mo/CoFeB/MgO MTJs. The post-annealed stability of MTJs could be enhanced by using Mo element. The high post-annealed stability of Mo/CoFeB/MgO stacks makes them compatible with advanced CMOS back-end processes.[20] Very recently, large TMR of 120%[21] and 162%[22] were obtained in the MTJ of Mo electrodes. However, the effects of Mo capping layer thickness on the PMA in Mo/CoFeB/MgO stacks have not been systematically investigated.[23,24]

In the study reported here, first, we fabricated MgO(2)/$CoFeB_t$/Mo(1.4) (unit in nm) multilayers by varying CoFeB thickness from 0.9 nm to 2.1 nm, strong PMA are shown when the thickness of CoFeB is 0.9 or 1.1 nm. Then we prepared MgO(2)/CoFeB(1.1)/Mo_t (unit in nm) by varying Mo thickness from 1 to 5 nm, showing that the Mo capping layer could not be too thin or too thick to maintain strong

*Project supported by the National Fundamental Research Program of China (Grant No. 2011CB921804) and Beijing Key Subject Foundation of Condensed Matter Physics, China (Grant No. 0114023).

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PMA.

2. Experimental procedure

Three series of multilayered stacks of Mo(5)/MgO(2)/CoFeB(0.9$\leq t_1 \leq$2.1)/Mo(1.4), Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1$\leq t_2 \leq$5), and Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1)/MoO_x(0.5)/Mo(0.5) (unit in nm) were fabricated at room temperature by DC/RF magnetron sputtering on the thermal oxidized Si substrates at an Ar working pressure of 2×10^{-3} Torr with a base pressure less than 5×10^{-7} Torr. To investigate the annealing effects, some samples were post annealed at temperatures (T_a) of 300 °C for 1 hours at a pressure of 5×10^{-6} Torr. The magnetic properties were systematically analyzed by utilizing alternating gradient magnetometer (AGM). The value of the effective magnetic anisotropy energy was calculated by the ordinary Suck–Smith–Thompson method, and the presence of magnetic dead layer (MDL) was taken into account for the precise thickness of the ferromagnetic layer.

3. Results and discussion

The perpendicular (red line, ⊥) and in-plane (blue line, ∥) *M–H* curves of the as-deposited Mo(5)/MgO(2)/CoFeB(1.1)/Mo(2) (unit in nm) and the same sample with post-annealing at 300 °C are shown in Fig. 1. The as-deposited sample shows strong in-plane magnetic anisotropy. However, after the annealing process, the magnetic easy axis changes from in-plane to perpendicular direction, which means that the post-annealing process plays a very important role in realizing the PMA of the sample. The post-annealing multilayer film has the large saturation magnetic compared to the as-deposited sample. The change of the magnetic easy axis of the sample could be due to the crystallization of CoFeB layers which was induced by the adjacent MgO layer and triggered by a decrease of boron concentration during the post annealing.[25]

Figure 2 shows the perpendicular and in-plane *M–H* curves of the annealing Mo(5)/MgO(2)/$CoFeB_t$/Mo(1.4) (unit in nm) stacks with different CoFeB ferromagnetic layer thicknesses ranging from 0.9 nm to 1.5 nm. It can be seen that the PMA property was shown when the thicknesses of CoFeB is 0.9 nm or 1.1 nm. This means that the thickness of CoFeB layer is crucial for the existence of the PMA. The magnetic easy axis turns into in-plane when the thickness of CoFeB ferromagnetic layer increases to a certain value. The saturation magnetic fields in the in-plane direction are about 5 kOe and 7 kOe for the samples with CoFeB thicknesses of 0.9 nm and 1.1 nm, respectively, which indicates that the PMA are strong in these two thin CoFeB samples. The results are in agreement with the Mo buffer layer stacks,[19] and the PMA is only observed in the thin CoFeB samples.

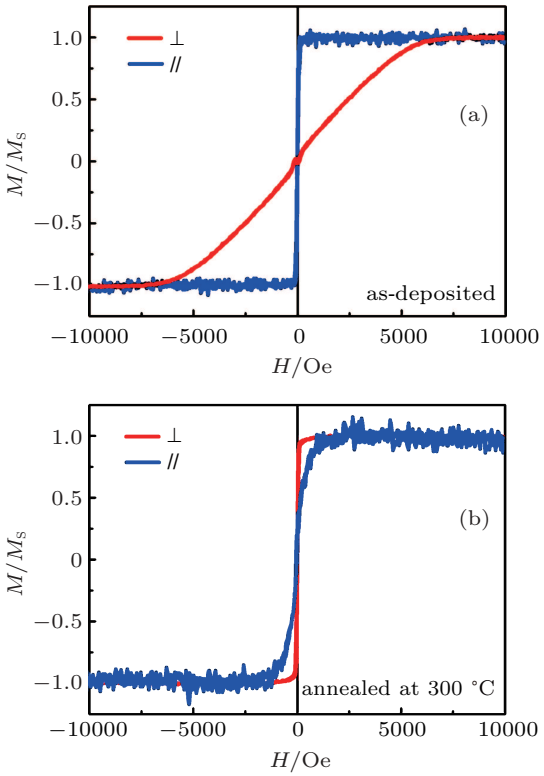


Fig. 1. (color online) Perpendicular (red line) and in-plane (blue line) *M–H* loops of Si/SiO_2/Mo(5)/MgO(2)/CoFeB(1.1)/Mo(2) (in nm) at (a) as-deposited and (b) post-annealed at 300 °C, respectively.

The m/A (area magnetization) and $K_{\rm eff}$ can be described by Eqs. (1) and (2),[26] where m/A, $t_{\rm CoFeB}$, $t_{\rm d}$, $K_{\rm eff}$, $M_{\rm s}$, and $H_{\rm k}$ represent the magnetic moment per unit area, nominal CoFeB thickness, the thickness of MDL, the effective magnetic anisotropy energy, the saturation magnetization, and saturation field, respectively. The positive (negative) value of $H_{\rm k}$ indicates that the magnetic easy axis of the sample is PMA (in-plane).

$$m/A = M_{\rm s}(t_{\rm CoFeB} - t_{\rm d}), \tag{1}$$

$$K_{\rm eff} = M_{\rm s}H_{\rm k}/2. \tag{2}$$

The m/A of the samples is based on a function of thickness of CoFeB layer. $M_{\rm s}$ is obtained from the slope and $t_{\rm d}$ is the intercept of the straight line at the axis of the CoFeB layer thickness. When the value of m/A decrease to zero, the axis of CoFeB has a positive intersection point, indicating that MDL was formed at the interface.[27] The magnetic moment per unit area versus nominal thickness of CoFeB in Mo(5)/MgO(2)/$CoFeB_t$/Mo(1.4) multilayer is shown in Fig. 3(a). The MDL thickness is 0.23 nm from the fitting line. The MDL of the top structure forms easier than that of the bottom structure.[28] The more active diffusion of Mo atom in the top structure boundary may be the main reason for this.[23] We can also obtain from Fig. 3(a) that $M_{\rm s}$ is about 1566 emu/cm^3, and the thickness of CoFeB is thinner than other capping layer to maintain PMA. The optimal thickness of the CoFeB layer with PMA could be decided by the temperature treatment and the stack structure or with varying Mo capping layer thickness.

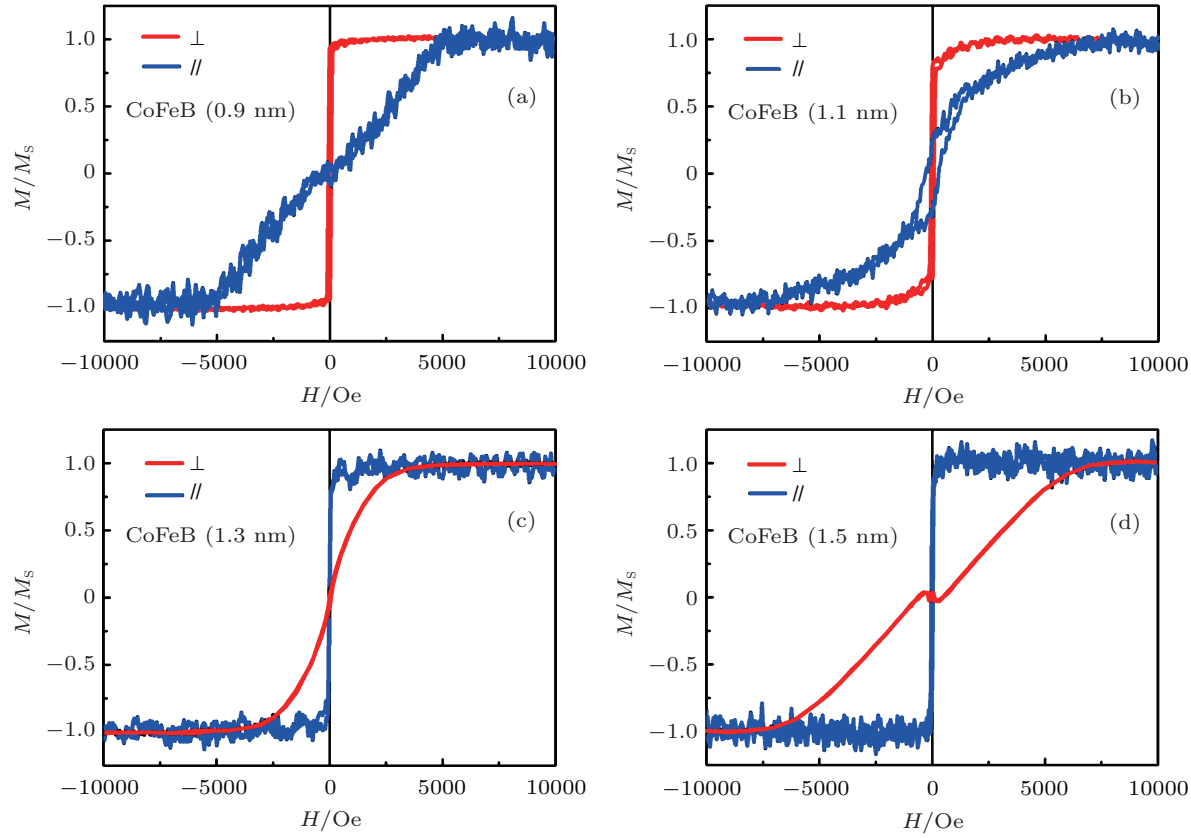


Fig. 2. (color online) Perpendicular (red line) and in-plane (blue line) M–H loops of Mo(5)/MgO(2)/CoFeB$_t$ ($0.9 \leq t \leq 1.5$)/Mo(1.4) (in nm) multilayer post-annealed at 300 °C. (a) $t = 0.9$, (b) $t = 1.1$, (c) $t = 1.3$, (d) $t = 1.5$.

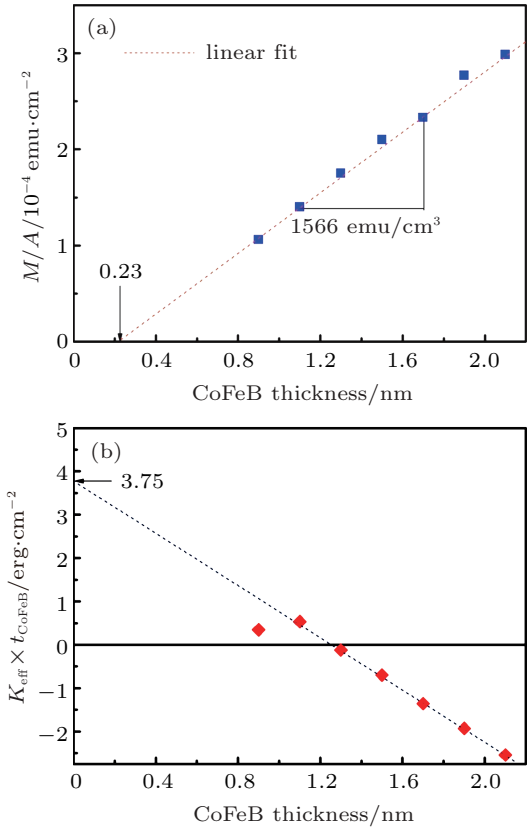


Fig. 3. (color online) (a) Magnetic moment per unit area versus nominal thickness of CoFeB in Mo(5)/MgO(2)/CoFeB$_t$/Mo(1.4) multilayer. (b) $K_{\rm eff} \times t$ versus the nominal thickness of the CoFeB in Mo(5)/MgO(2)/CoFeB$_t$/Mo(1.4) multilayer.

The effective anisotropy constant can be evaluated by Eq. (1) and also be gained by linear fitting of the following relation:

$$K_{\rm eff} = K_{\rm b} - 2\pi M_{\rm s}^2 + K_{\rm i}/t_{\rm CoFeB}, \tag{3}$$

where $K_{\rm b}$, $K_{\rm i}$, and $t_{\rm CoFeB}$ are the bulk anisotropy constant, interface anisotropy constant, and nominal thickness of CoFeB, respectively. The $K_{\rm eff} \times t_{\rm CoFeB}$ versus the nominal thickness of the CoFeB in Mo(5)/MgO(2)/CoFeB$_t$/Mo(1.4) multilayer is shown in Fig. 3(b). The $K_{\rm i}$ is obtained from the intercept of the vertical axis. The value of $K_{\rm i}$ is about 3.75 erg/cm^2 for the stacks of the Mo capping layer. The greater $K_{\rm i}$ value indicates that the interface diffusion is reduced under the Mo capping layer. The $K_{\rm eff} \times t_{\rm CoFeB}$ could be applied to lots of linear fitting, which is lower than the fitted value with thinner CoFeB thickness. This indicates that interface magnetic anisotropy cannot be regarded as a constant in this work, which plays a very important role in these samples with PMA, and it also relies on the thickness of CoFeB layer.[29]

Figure 4 shows perpendicular and in-plane M–H curves of annealed Mo(5)/MgO(2)/CoFeB(1.1)/Mo(t) (in nm) multilayer with varying capping thickness from 1 to 5 nm. All samples show PMA except the 1-nm-thick capping layer sample. The values of $M_{\rm r}/M_{\rm s}$ ($M_{\rm r}$ represents remnant magnetic) increase from about 0.8 to 1 with the increase of Mo capping

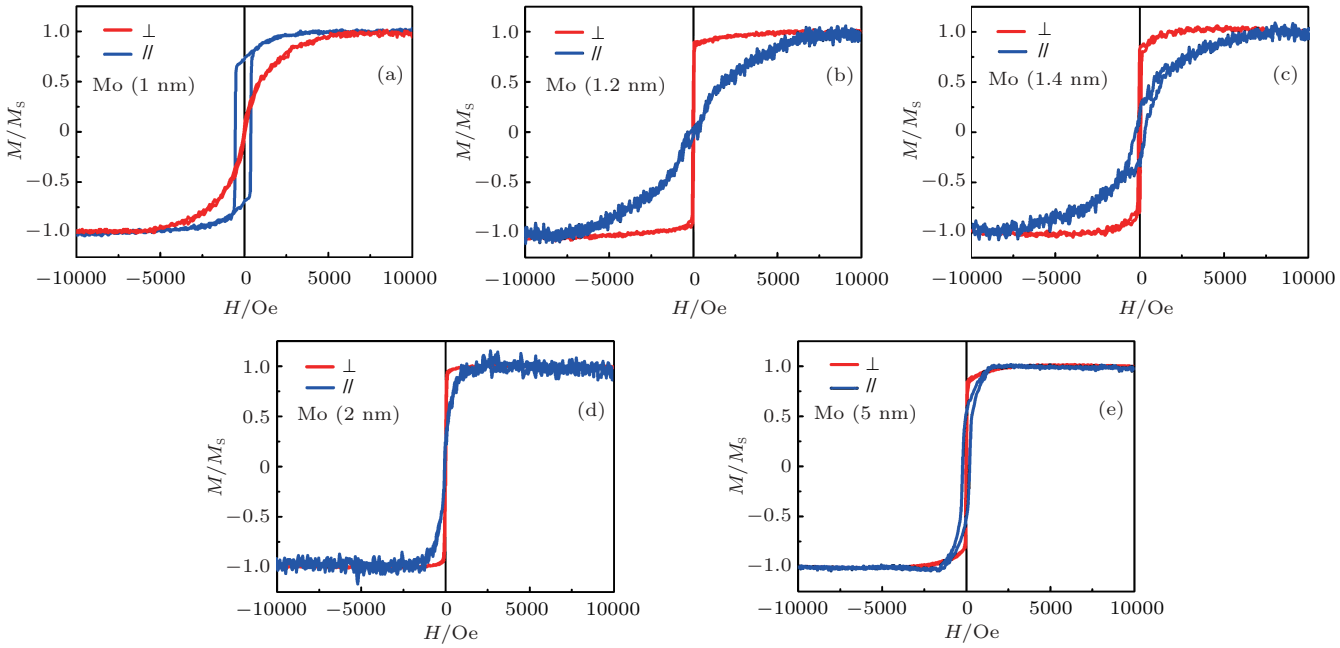


Fig. 4. (color online) Perpendicular (red line) and in-plane (blue line) *M*–*H* curves of annealed Mo(5)/MgO(2)/CoFeB(1.1)/Mo(t) (in nm) multilayer with capping thickness of (a) 1 nm, (b) 1.2 nm, (c) 1.4 nm, (d) 2 nm, (e) 5 nm.

layer thickness from 1.2 to 2 nm. The large in-plane direction saturation field indicates strong PMA in these thinner capping layer samples. Especially, the PMA of the sample with 2 nm Mo capping layer thickness is the strongest one. However, the M_r/M_s value decreases to about 0.8 by further increasing capping layer thickness to 5 nm, which illustrates the degradation of PMA.

Figure 5 shows K_{eff} and H_k versus Mo capping thickness in Mo(5)/MgO(2)/CoFeB(1.1)/Mo(t) (in nm) sample. K_{eff} shows the maximum value of about 5.25×10^6 erg/cm^3 when the Mo capping thickness is 1.2 nm. The value of K_{eff} decreases with the increase of Mo capping thickness, and decreases to about 8.60×10^5 erg/cm^3 or lower than this with the capping layer thickness above 2 nm. The diffusion of Mo atom toward to MgO/CoFeB interface and even to CoFeB layer may be the main reason for the degradation of PMA in these thicker capping layer samples. However, the thinner 1 nm Mo capping layer shows obvious in-plane magnetic anisotropy, and the corresponding K_{eff} value is negative, the oxidized Mo caplayer may be the main reason for the degradation of PMA in these thinner caplayer samples.[24] We will discuss this in detail later.

The change of K_{eff} is probably due to the variation of H_k value with increase of Mo capping layer thickness, since the thickness of CoFeB is 1.1 nm for all samples, and therefore the values of M_s for all samples are fixed. The maximum value of H_k is about 6700 Oe when the Mo capping thickness is 1.2 nm. The values of H_k decrease to about 1100 Oe with the increase Mo capping layer from 1.2 to 5 nm. Moreover, when the capping thickness is 1 nm, the sample shows clear in-plane magnetic anisotropy, and the H_k and K_{eff} are both negative.

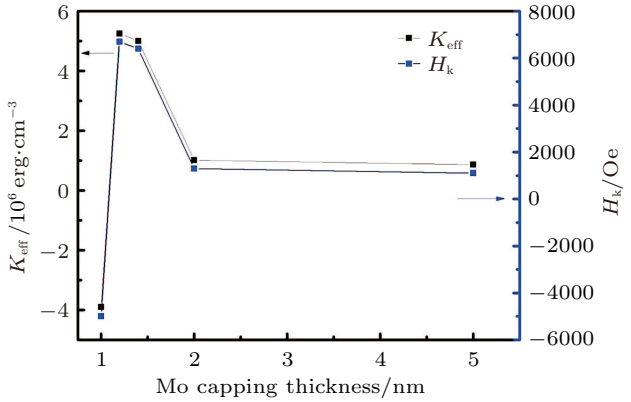


Fig. 5. (color online) K_{eff} and H_k versus Mo capping thickness in Mo(5)/MgO(2)/CoFeB(1.1)/Mo(t) (in nm) sample.

Actually, the results of Mo capping are similar to Ta and Nb samples in MgO/CoFeB based magnetic tunnel junction.[24] The origin of PMA in the CoFeB/MgO interface is related to the hybridization between 3d orbital of the transition mental and O-2p in MgO.[15] In addition, the CoFeB/metal interface also plays an important role for interface anisotropy. In the top structure, the PMA is very sensitive to the thickness of metal layer.[24] The main reason is plausible that the cap layer of Mo may be oxidized during the annealing due to the metal layer of the top structure is directly exposed to air, the surface of the samples may be oxidized,[30,31] especially for those thin capping layer samples. The oxidized surface layer may seriously reduce the effective thickness of metal layer in these thin capping layer samples.[32] As we all know, Ta has been reported as producing a good getter effect, and it may effectively absorb boron at a relatively lower annealing temperature,[24,33] and the diffusion of B atom de-

pends upon the thickness of the adjacent metal layer[34] in this case, Mo may replace boron with CoFeB and cause a deterioration of CoFeB at the CoFeB/Mo interface. Therefore, the deterioration of CoFeB at the CoFeB/Mo interface may be the main reason for the degradation of PMA in these thicker capping layer samples.

In order to further analysis the effect of Mo thickness on the PMA in MgO/CoFeB/Mo multilayer, we fabricated Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1)/MoO_x(0.5)/Mo(0.5) (unit in nm) multilayer, and the total thickness of capping layer is 2 nm. An ultrathin MoO_x was inserted between two thin Mo layers. On the one hand, it can protect the thin capping layer not to be oxidized; on the other hand, it can reduce the effect thickness of Mo. Figure 6 shows the perpendicular and in-plane M–H curves of Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1)/MoO_x(0.5)/Mo(0.5) (unit in nm) multilayer after annealed at 300 °C for 1 hour. The sample shows strong PMA, and the $K_{\rm eff}$ and $H_{\rm k}$ are 2.81×10^6 erg/cm^3 and 3600 Oe, respectively. The magnetic anisotropy changes from in-plane anisotropy to PMA compared with the results of thinner capping sample of Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1) (in nm). Therefore, the metal layer could not be too thin or thick in these multilayers to maintain PMA. The oxidation and diffusion of the metal capping layer should be respectively responsibility for the degradation of PMA in these thin or thick metal capping layer samples.

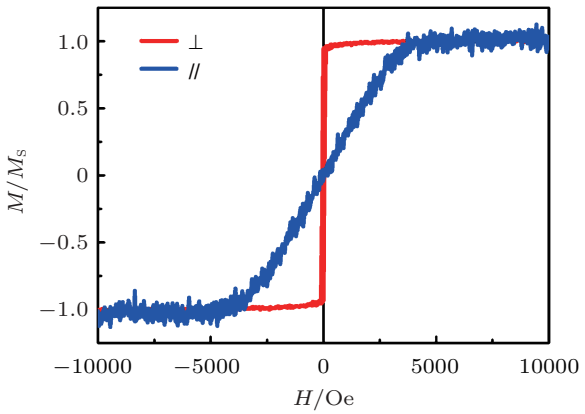


Fig. 6. (color online) Perpendicular (red line) and in-plane (blue line) M–H curves of Mo(5)/MgO(2)/CoFeB(1.1)/Mo(1)/MoO_x(0.5)/Mo(0.5) (in nm) multilayer after annealed at 300 °C for 1 hour.

4. Conclusions

In summary, the perpendicular magnetic anisotropy of a series of top MgO/CoFeB/Mo layers is studied. It is revealed that the PMAs of Mo/MgO/CoFeB/Mo stacks strongly depend on the thickness of the CoFeB layer. The samples show strong PMA only when the thickness of CoFeB is less than 1.1 nm. The dependence of the PMA on capping layer thickness is observed, and the strong PMA of 1.1 nm CoFeB only exists in a Mo cap layer thickness between 1.2 to 2 nm. This effect of Mo capping layer might be applied to tune the magnetic characteristics for future application in p-MTJs.

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