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Dependence of magnetic anisotropy on MgO thickness and buffer layer in $Co_{20}Fe_{60}B_{20}$-MgO structure

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We investigated the dependence of perpendicular magnetic anisotropy in CoFeB-MgO on the MgO layer thickness. Magnetization curves show that a clear perpendicular magnetic easy axis is obtainable in a 1.5-nm thick CoFeB layer by depositing MgO of more than three monolayers. We investigated anisotropy in CoFeB-MgO deposited on four different buffer layers. Results show that a counter interface of CoFeB-nonmagnetic metal affects the perpendicular anisotropy of CoFeB/MgO. © *2011 American Institute of Physics*. [doi:10.1063/1.3554204]

I. INTRODUCTION

Recently, fabrication of magnetic tunnel junctions (MTJs) with a perpendicular magnetic easy axis using the standard material combination of ferromagnetic CoFeB electrodes and MgO barrier layers has been demonstrated, with high tunnel magnetoresistance over 120%, high thermal stability at reduced dimensions, and low current density for current-induced magnetization switching.[1] This MTJ stack system is attractive for storage bits in magnetoresistive random access memory (MRAM) and nonvolatile logic-in-memory based on MTJs/CMOS hybrid circuits fabricated using this leading edge technology.[2–7] The origin of the perpendicular magnetic easy axis is related to CoFeB-MgO interfacial perpendicular magnetic anisotropy.[8–12] The perpendicular easy axis was observed for CoFeB with a thickness of less than about 1.5 nm, where the interfacial perpendicular magnetic anisotropy is more dominant than the in-plane easiness because of demagnetization.[1,12] We investigated the dependence of perpendicular magnetic anisotropy in CoFeB on MgO thickness to show the minimum thickness at which a MgO layer can produce a stable perpendicular magnetic anisotropy. Answering that question is important because MTJs with a thinner MgO barrier show a lower resistance area product and are suitable for current-induced magnetization switching. We also investigated the magnetic anisotropy in CoFeB/MgO on different buffer layers because the counter interface of CoFeB-nonmagnetic metal may play an additional role in obtaining perpendicular magnetic anisotropy in such a thin CoFeB layer.[13]

II. EXPERIMENTAL PROCEDURES

All samples were deposited using rf magnetron sputtering on a thermally oxidized Si (001) substrate. We prepared two sets of samples: set A for investigating the MgO thickness t_{MgO} dependence, and set B for the buffer dependence on perpendicular magnetic anisotropy. Samples in set A consisted of Ta(5)/MgO (t_{MgO})/$Co_{20}Fe_{60}B_{20}$(1.5)/Ta(5) (numbers are nominal thickness in nanometers) from the substrate side, where t_{MgO} was 0.4–1.6 nm. Samples in set B consisted of buffer/$Co_{20}Fe_{60}B_{20}$(1.0)/MgO(1.0)/Ta(5), where we adopted four different buffer layers: Ta(5)/Ru(10)/Ta(5), Ta(5)/Ru(10), Ru(10)/Ta(5), and Ta(5). Some samples were annealed in vacuum for an hour under a perpendicular magnetic field of 0.4 T at temperature $T_a = 300\,^\circ C$ for set A and $T_a = 200$–$350\,^\circ C$ for set B. Room temperature magnetization curves (*M–H* curves) were measured using a vibrating sample magnetometer, where the magnitude of magnetization *M* was determined from the nominal thickness of CoFeB.

III. RESULTS AND DISCUSSION

Figures 1(a) and 1(b) show the *M–H* curves under in-plane and out-of-plane magnetic fields for the samples (set A) with $t_{MgO} = 0.5$ and 1.2 nm after annealing at $T_a = 300\,^\circ C$, respectively. The results show that both samples have a perpendicular easy axis and that the strength of perpendicular anisotropy increases as t_{MgO} increases, indicating that the CoFeB-MgO interfacial perpendicular magnetic anisotropy is indeed the source of the observed perpendicular easy axis. The t_{MgO} dependence of the saturation magnetization M_S and effective magnetic anisotropy energy density *K* obtained from the *M–H* curves are shown in Figs. 1(c) and 1(d), respectively. The magnitudes of M_S and *K* saturate at 0.85 T and 1.5×10^5 J/m^3 for the sample with $t_{MgO} > 0.6$ nm, respectively. This result shows that three monolayers of MgO (0.63 nm) are needed for stabilization of the perpendicular easy axis originated from CoFeB-MgO interfacial perpendicular magnetic anisotropy. Samples with $t_{MgO} < 0.5$ nm show no detectable magnetic anisotropy with a superparamagnetic-like response. The mechanism of the disappearance

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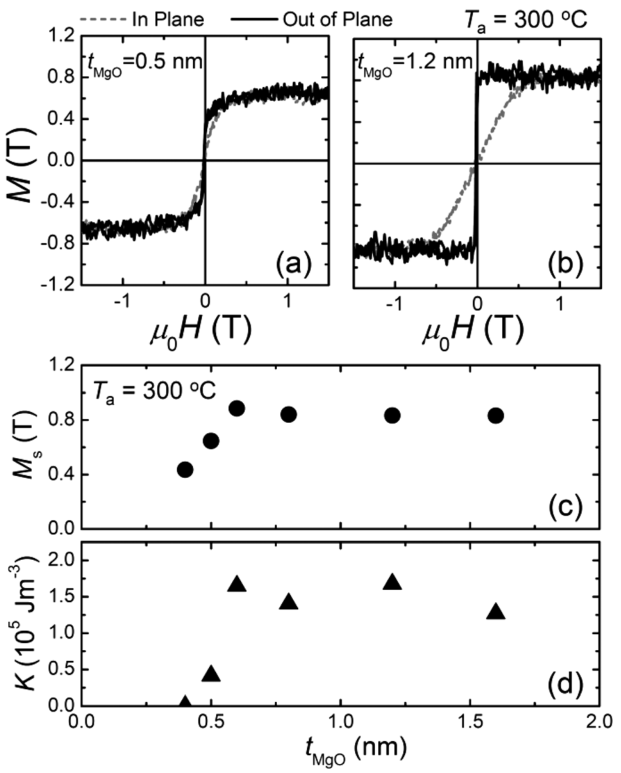

FIG. 1. Magnetization curves of 1.5-nm thick CoFeB deposited on MgO with thickness of (a) 0.5 and (b) 1.2 nm. MgO thickness dependence of (c) saturation magnetization and (d) effective magnetic anisotropy energy density.

of clear ferromagnetic state remains unclear, but it may be related to the structural dependent formation of magnetically dead layer at the CoFeB-Ta interface during deposition[14,15] or intermixing upon annealing, or the roughness of the underlayer on which CoFeB layer was deposited.

Hereinafter, we particularly examine the perpendicular magnetic anisotropy of CoFeB deposited on different buffer layers (set B). Before investigating perpendicular magnetic anisotropy, we first checked the degree of crystallization and surface morphologies of the buffer layers used for set B using a high-resolution transmission electron microscope (HRTEM) and an atomic force microscope (AFM), respectively. Figure 2(a) shows a cross-sectional HRTEM image of Ta(5)/Ru(10)/Ta(5) deposited on Si/SiO_2 substrate. The HRTEM image reveals that Ta on Ru layer and Ru layer itself have a polycrystalline structure with hcp or fct structure, whereas Ta on Si/SiO_2 substrate is amorphous. The surface morphologies are presented in Fig. 2(b) for Ta(5)/Ru(10), 2(c) for Ru(10)/Ta(5), and 2(d) for Ta(5). They showed no apparent difference; the root-mean-square of the surface roughness was about 0.11 nm. We then measured *M–H* curves of CoFeB(1)/MgO(1) deposited on these buffer layers. Figure 3 shows the *M–H* curves under in-plane and out-of-plane magnetic fields of as-deposited $Co_{20}Fe_{60}B_{20}$/MgO(1.0)/Ta(5) stacks with (a) Ta/Ru/Ta, (b) Ta/Ru, (c) Ru/Ta, and (d) Ta buffer layers. A clear perpendicular magnetic anisotropy is observed for all stacks. Magnetization curves for samples with Ta/Ru/Ta [Fig. 3(a)] and Ta [Fig. 3(d)] are the same within experimental error, indicating that the perpendicular magnetic anisotropy is not much dependent on the degree of crystallization in the buffer layers of crystal-

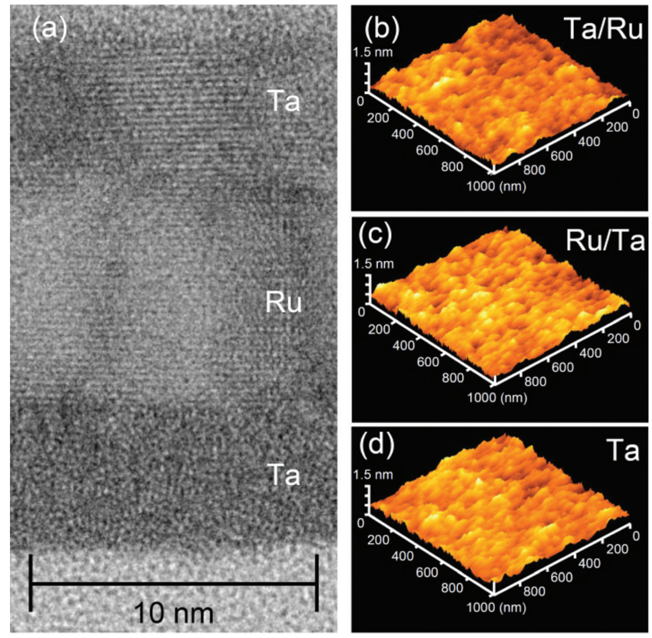

FIG. 2. (Color online) (a) Cross-sectional HRTEM image of Ta/Ru/Ta buffer on Si/SiO_2 substrate. AFM images of the surface of (b) Ta/Ru, (c) Ru/Ta, and (d) Ta.

line-Ta and amorphous-Ta. It is noteworthy that the strength of perpendicular magnetic anisotropy in CoFeB on Ta/Ru [Fig. 3(b)] is less than those with other buffer layers. The mechanism responsible for this reduced perpendicular

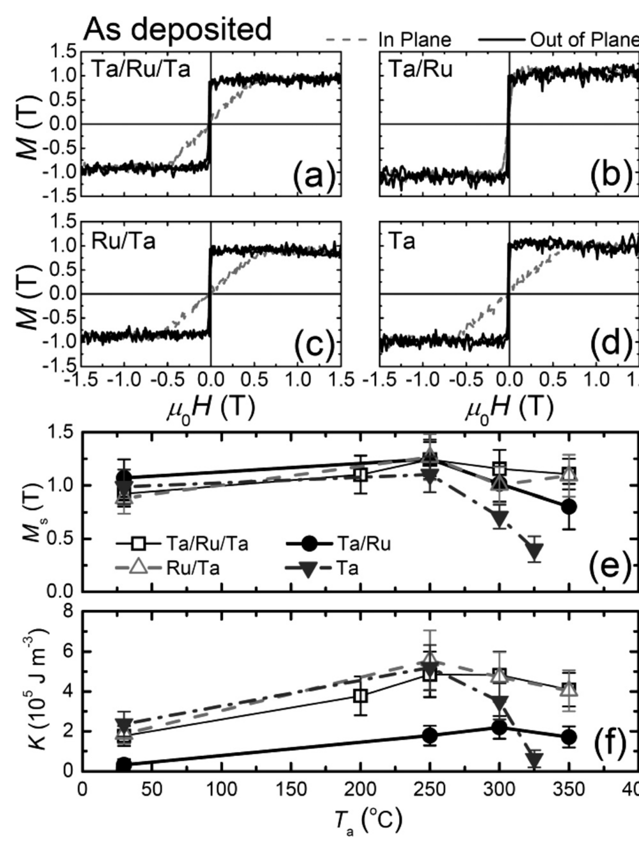

FIG. 3. Magnetization curves of CoFeB (1.0 nm)/MgO (1.0 nm) deposited on (a) Ta/Ru/Ta, (b) Ta/Ru, (c) Ru/Ta, and (d) Ta. Annealing temperature dependence of (e) saturation magnetization and (f) effective magnetic anisotropy energy density.

anisotropy in CoFeB on Ta/Ru may be related to the in-plane magnetic anisotropy induced by Ru/CoFeB.

Finally, Figs. 3(e) and 3(f) show results of our investigation of the annealing temperature dependence of M_S and K for set B. For all buffer layers except for the Ta/Ru one, the values of K are the same at $T_a \leq 250\,^\circ$C within experimental error. A clear difference starts to appear at $T_a > 250\,^\circ$C. The K for the Ta/Ru/Ta and Ru/Ta buffer layers reaches 4.8×10^5 J/m^3 at $T_a = 300\,^\circ$C. Although K decreases slightly at $250\,^\circ$C $\leq T_a \leq 350\,^\circ$C, K of 4.1×10^5 J/m^3 is comparable to the maximum value is maintained even after annealing at $T_a = 350\,^\circ$C, which is equivalent to the annealing temperature in a standard CMOS integrated process.[16,17] In contrast, the K for the Ta buffer decreases rapidly at T_a of more than $300\,^\circ$C. The increase of K with T_a could be attributed to the degree of the crystallization of CoFeB.[18] The decrease of K at higher T_a is probably attributable to the decrease of CoFeB thickness resulting from intermixing of CoFeB and buffer layer, as suggested from the decrease of M_S shown in Fig. 3(e). Moreover, the rapid decreases of M_S and K observed for CoFeB on Ta buffer layer suggest that the degree of intermixing depends on the degree of crystallization in the buffer layer because the Ta buffer layer on Si/SiO_2 substrate is amorphous, whereas the other buffers are polycrystalline. The value of K of the sample with Ta/Ru also increases concomitantly with increasing T_a at $T_a \leq 300\,^\circ$C. However, the magnitude of K is smaller than those with Ta/Ru/Ta, Ru/Ta, and Ta buffers at each T_a.

IV. CONCLUSIONS

In conclusion, the perpendicular easy axis in CoFeB-MgO structures originates from the interfacial perpendicular magnetic anisotropy at CoFeB-MgO interface, as confirmed by our investigation of the strength of perpendicular magnetic anisotropy as a function of MgO thickness. A clear perpendicular magnetic easy axis is obtainable in a 1.5-nm thick CoFeB layer by deposition of MgO of more than three monolayers. Results also show the influence of buffer layer on perpendicular magnetic anisotropy. The CoFeB/MgO deposited on Ru shows smaller perpendicular magnetic anisotropy than that on Ta, which indicates that a counter interface of CoFeB-nonmagnetic metal affects the perpendicular anisotropy induced by CoFeB-MgO. Furthermore, the degree of crystallization in the buffer layer is shown to be an important factor for obtaining high durability for annealing treatment through the study of the annealing temperature dependence of magnetic properties with various buffer layers.

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