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Perpendicular magnetization of CoFeB on single-crystal MgO

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CoFeB films deposited on single-crystal MgO(100) exhibit significantly reduced out-of-plane demagnetization fields after magnetic annealing in the film plane, resulting in perpendicular magnetization for a 15 Å CoFeB film. The perpendicular magnetic anisotropy can be enhanced further by inserting a thin Ru capping layer on top of CoFeB, resulting in perpendicular magnetization in even thicker CoFeB films. © *2011 American Institute of Physics*. [doi:10.1063/1.3592986]

I. INTRODUCTION

CoFeB deposited on MgO has been widely used to fabricate magnetic tunnel junctions (MTJs) for spin-transfer-torque magnetoresistive random access memory (STT-MRAM) and read heads for magnetic recording. This material combination has produced MTJs with high tunneling magnetoresistance (TMR) and low resistance-area (RA) product; however, it remains challenging to decrease the critical switching current density (J_c) for STT-MRAM applications without compromising thermal stability, determined by the energy barrier between the two preferred magnetization states, E_B. Optimizing J_c and E_B is crucial for developing STT-MRAM that can be competitive with conventional memories over a wide range of operating conditions.

Thin CoFeB films typically exhibit in-plane magnetization due to thin-film shape anisotropy. Because spin-transfer-torque (STT) switching involves oscillation of moments in out-of-plane directions, the thin-film demagnetization field ($4\pi M_s$) needs to be overcome during STT switching. Recently, it has been reported that Fe-rich CoFeB free layers may exhibit reduced J_c by introducing perpendicular magnetic anisotropy (PMA) that can cancel a substantial portion of the demagnetization field yielding an effective demagnetization field $4\pi M_{eff} = 4\pi M_s - H_{k\perp}$, where $H_{k\perp}$ is the uniaxial anisotropy field perpendicular to the film plane.[1] When $H_{k\perp}$ exceeds $4\pi M_s$, the CoFeB moments become perpendicular to the film plane. Ikeda *et al*. report that a 15-Å $Co_{20}Fe_{60}B_{20}$ film annealed in a perpendicular field exhibits perpendicular moments, and have demonstrated CoFeB-based perpendicular MTJs (pMTJs).[2] In general, pMTJs are more amenable to device scaling than in-plane MTJs.[3] Because CoFeB is an established material from a manufacturing standpoint, the possibility of using CoFeB to fabricate deeply scaled pMTJs has attracted considerable attention.[4]

Although the physical origin of perpendicular anisotropy in the CoFeB-MgO system is still ambiguous, it has been posited that interfacial anisotropy arising from the CoFeB-MgO interface is responsible.[2] In this paper, we investigate PMA in $Co_{20}Fe_{60}B_{20}$ films deposited on single-crystal MgO substrates in order to examine interfacial anisotropy. We first report that our $Co_{20}Fe_{60}B_{20}$ films exhibit strong PMA after magnetic annealing in the film plane, with sufficiently thin $Co_{20}Fe_{60}B_{20}$ films exhibiting perpendicular moments. In addition, we show that the PMA can be further enhanced by inserting a capping layer.

II. FILM DEPOSITION AND CHARACTERIZATION

$Co_{20}Fe_{60}B_{20}$(15–50 Å)/Ta(50 Å) films were deposited on single-crystal MgO(100) substrates by dc magnetron sputtering. The films were annealed at 300 °C for 2 h in a 1.5 T magnetic field in the film plane. In-plane and out-of-plane magnetization curves were measured by vibrating sample magnetometry (VSM). We extract a magnetic dead layer thickness of 4.1 Å for the annealed films by examining the saturated moment (M_s) as a function of nominal film thickness. M_s calculated using an effective magnetic volume accounting for the dead layer thickness was ~830 emu/cc and ~1130 emu/cc before and after magnetic annealing, respectively. The increase in M_s is due to crystallization of CoFeB during annealing.

III. RESULTS AND DISCUSSION

Figure 1(a) shows out-of-plane magnetization curves for a 15 Å CoFeB film capped with Ta before and after magnetic annealing. While the as-deposited film showed in-plane magnetization with a saturation field (H_{sat}) of ~4 kOe, the annealed film was perpendicularly magnetized as clearly seen in Fig. 1(b). H_{sat} of the annealed film obtained from the in-plane magnetization curve was ~1.5 kOe. The moments of films with thicker CoFeB remained in the plane even after magnetic annealing, exhibiting increasing H_{sat} with increasing CoFeB thickness. The dramatic change in CoFeB magnetization is due to strong interfacial anisotropy arising from the MgO-CoFeB interface. We speculate that during magnetic annealing, boron diffuses out primarily toward Ta,[5] resulting in a sharper CoFeB-MgO interface.

To quantify the effect of magnetic annealing on the interfacial anisotropy, the correlation between effective CoFeB thickness (t_{eff}) and effective magnetic anisotropy energy

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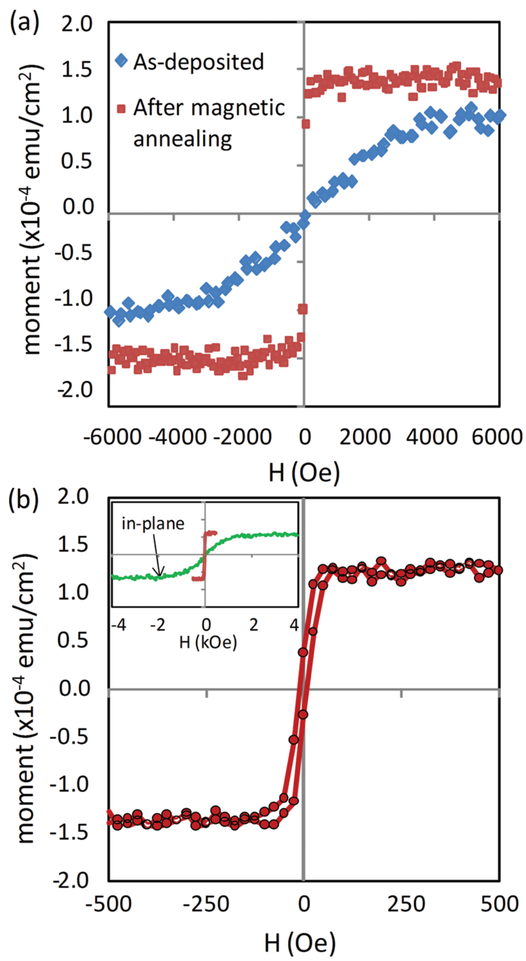

FIG. 1. (Color online) (a) Out-of-plane magnetization curves for a 15 Å CoFeB film before and after magnetic annealing (b) Out-of-plane magnetization curve for the annealed CoFeB film in a smaller field range. The corresponding in-plane magnetization curve is inset.

(K_{eff}) was examined before and after magnetic annealing. As shown in Fig. 2, both as-deposited and annealed films obey a phenomenological relation: $K_{eff} = K_v + K_i/t_{eff}$, where K_v and K_i represent the volume anisotropy and the interfacial anisotropy, respectively.[6] For the annealed films (red diamonds), the extracted K_v is 7.17×10^6 erg/cm^3, which is comparable to the expected thin-film shape anisotropy $2\pi M_s^2$, and K_i is 0.94 erg/cm^2. When the nominal CoFeB thickness is used instead of t_{eff}, as in Ref. 2, K_i becomes 1.33 erg/cm^2, which is comparable to the previously reported value obtained with RF-sputtered MgO.[2] It is noteworthy that we observe considerable interfacial anisotropy even in the as-deposited films, characterized by a K_i of 0.44 erg/cm^2 ($K_v = 5.59 \times 10^6$ erg/cm^3). Thus we find that magnetic annealing enhanced the interfacial anisotropy by a factor of $\sim$2.

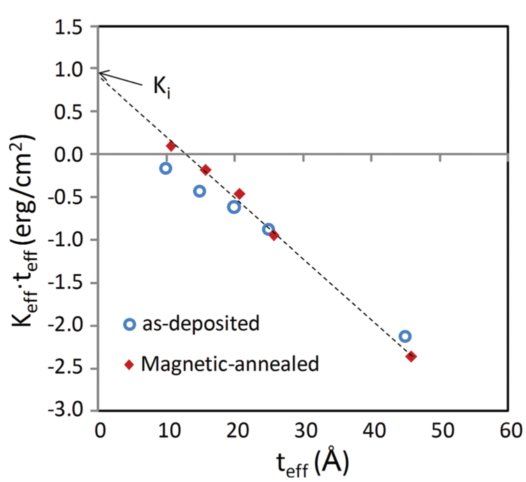

FIG. 2. (Color online) Magnetic anisotropy energy (K_{eff}) times the CoFeB thickness (t_{eff}) vs t_{CFB} for as-deposited and annealed CoFeB films.

Exploiting interfacial anisotropy in CoFeB-based pMTJs entails using very thin CoFeB layers. E_B is given by $H_k M_s V/2$ in the macrospin limit where H_k is the net uniaxial perpendicular anisotropy field and V is the free layer volume. Hence, K_i must be large enough to compensate for reduced free layer volumes in order to ensure an adequately large E_B for thermal stability. For instance, if the 15 Å CoFeB film shown in Fig. 1 were used as the free layer of a pMTJ, the expected E_B for a circular 40 nm diameter pMTJ cell would be only 30 $k_B T$ at 300 K. Enhanced K_i may be necessary for CoFeB-based pMTJs to be practical at future CMOS technology nodes. In addition, the damping constant (α) tends to increase as the CoFeB thickness decreases.[2] Since J_c is proportional to α, this may counter the benefits of CoFeB-based pMTJs. Enhanced PMA would enable perpendicular moments in comparatively thicker CoFeB, avoiding the increased damping seen in thinner films.

One path toward enhancing PMA is insertion of a capping layer to promote additional PMA at the top CoFeB surface. It has recently been shown that a Pd capping layer can induce strong PMA in Co-rich CoFeB.[7] Here, we demonstrate that thin Ru capping layers inserted between $Co_{20}Fe_{60}B_{20}$ and the Ta capping layer adds additional PMA, resulting in perpendicular moments in comparatively thicker CoFeB films. Figure 3(a) compares the out-of-plane magnetization curves for CoFeB(20 Å)/Ru(9 Å)/Ta with that of CoFeB(15 Å)/Ta. Capping a 20 Å CoFeB film with 9 Å Ru produced a perpendicularly magnetized film, with simultaneously enhanced squareness of the out-of-plane hysteresis, indicating the presence of stronger PMA ($H_k \sim 2$ kOe). The increased moment and anisotropy field suggest that we can achieve an enhanced E_B of $\sim$47 $k_B T$ for a circular 40 nm

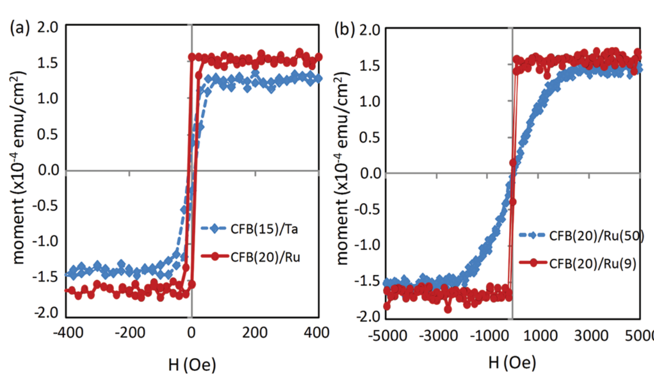

FIG. 3. (Color online) (a) Out-of-plane magnetization curves of CoFeB(15)/Ta and CoFeB(20)/Ru(9)/Ta films (thickness in Angstroms). (b) Out-of-plane magnetization curve of CoFeB(23)/Ru(9)/Ta. The corresponding in-plane magnetization curve is inset.

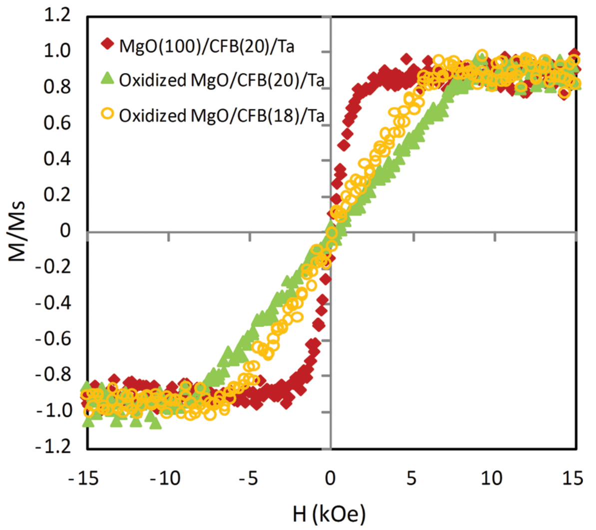

FIG. 4. (Color online) Out-of-plane magnetization curves of single-crystal MgO(100) substrate/CoFeB(20)/Ta and Si substrate/Ta buffer/oxidized MgO/CoFeB(18 or 20)/Ta

diameter pMTJ cell by inserting a thin Ru layer. On the other hand, a sample capped with 50 Å Ru did not exhibit strong PMA, displaying in-plane magnetization as shown in Fig. 3(b). Strain-induced anisotropy is one possible origin of this Ru thickness effect. It has been reported that the thicknesses of Ta and Ru capping layers on CoFeB/MgO/CoFeB can affect RA and TMR by inducing stress strain onto the MgO barrier.[8] Amorphous CoFeB has also been found to have a considerable saturation magnetostriction constant (~30 ppm) and external stress can modify the CoFeB in-plane anisotropy induced by magnetic annealing.[9]

While single-crystal MgO(100) and rf-sputtered MgO seem to induce comparable interfacial PMA, it is unknown whether MgO produced by Mg oxidation ("oxidized MgO") can also promote substantial interfacial PMA. In general, oxidized MgO has desirable properties (film uniformity, high throughput, etc.) for manufacturing MTJs with low RA ($< 10\ \Omega\ \mu m^2$).[10–12] Fig. 4 shows out-of-plane magnetization curves of single-crystal MgO(100)/$Co_{20}Fe_{60}B_{20}$(20 Å)/Ta and Si substrate/Ta buffer/oxidized MgO/$Co_{20}Fe_{60}B_{20}$(18 or 20 Å)/Ta. The oxidized MgO was prepared by metallic Mg deposition followed by natural flow oxidation of Mg. 20 Å CoFeB deposited on the oxidized MgO showed a much higher H_{sat} (~8 kOe), indicating substantially weaker interfacial PMA in comparison to single-crystal MgO(001). 18 Å CoFeB exhibited slightly reduced H_{sat} (~6 kOe) as expected. The oxidized MgO grown on the amorphous Ta buffer is expected to have poor crystallinity in comparison to rf-sputtered MgO,[12] which may affect the CoFeB crystallization at the MgO-CoFeB interface during magnetic annealing. We speculate that MgO crystallinity and crystallization of CoFeB at the MgO-CoFeB interface are critical to introducing strong interfacial PMA. In Ref. 12, Choi *et al*. show that the crystallinity of naturally-oxidized MgO can be enhanced by utilizing CoFeB/CoFe bi-layers as a crystallization template, demonstrating high TMR (253%) at an RA-product of 5.9 Ω-μm^2. The same material scheme may also increase interfacial PMA.

IV. CONCLUSION

In summary, we have demonstrated perpendicularly-magnetized CoFeB films deposited on single-crystal MgO(100) substrates. While as-deposited CoFeB films exhibit significant interfacial anisotropy, magnetic annealing in the film plane increases the interfacial anisotropy by a factor of ~2. We also find that the top interface of CoFeB films can be engineered to introduce additional PMA, allowing perpendicular moments in thicker CoFeB layers, embodying a promising means of enhancing the thermal stability of CoFeB-based perpendicular MTJs. While the origin of the interfacial anisotropies we observe is not yet fully understood, we believe that enhancing MgO crystallinity may improve interfacial anisotropy, thereby decreasing critical switching current densities in STT-MRAM devices.

ACKNOWLEDGMENTS

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