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Influence of capping layers on CoFeB anisotropy and damping

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Magnetic behavior of CoFeB at various thicknesses ranging from 2 nm to 8 nm capped with different materials, such as MgO, Ta, Ru, and V have been studied. The films were sputter-deposited and subsequently characterized by magnetometry and broadband ferromagnetic resonance (FMR). There are magnetically dead layers at the interface observed with Ru and Ta capping layers, while MgO and V have almost no effect on the magnetization of the CoFeB. As the ferromagnetic layer is made thinner, the effective magnetization decreases, indicating an interfacial perpendicular anisotropy. Particularly in the case of MgO, V/Ru, and V/Ta capping layers, interfacial perpendicular anisotropy is induced in CoFeB, and the Gilbert damping parameter is also reduced. The origin of this perpendicular magnetic anisotropy (PMA) is understood to be caused by the interface anisotropy between the free layer and the capping layer. The effect of post-deposition annealing and CoFeB thickness on the anisotropy and damping of V/Ta capped samples are reported. Doping CoFeB with vanadium (V) greatly reduced the $4\pi M_s$ and $4\pi M_{eff}$ values, resulting in an effective increase in the PMA. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4749412]

I. INTRODUCTION

Magnetic tunnel junctions with spin transfer torque have attracted much interest recently in the field of nonvolatile memory devices. The concept of "spin transfer" was proposed independently by Slonczewski *et al.*[1] and Berger *et al.*[2] Spin transfer torque switched memory (STT-RAM) is attractive because of high thermal stability, nonvolatility, energy-efficiency in writing, low switching current for incorporating with CMOS transistors for a reliable memory device.[3,4] STT-RAM gained popularity over MRAM because of its potential to have lower switching currents. At very small device scales, the spin-polarized current can transfer its spin angular momentum to the magnetic element, thus providing reliable switching at low currents. Achieving low switching current density ($\sim$2 MA/cm^2) with high thermal stability at dimensions of about 25 nm is a great challenge. Theoretically, a giant MR ratio is expected only in epitaxial MTJ's such as FeCo (001)/MgO (001)/FeCo (001) with coherent tunneling of highly spin polarized electrons.[5–7] A strong fourfold symmetry at the barrier/ferromagnetic layer interface is essential to produce a giant TMR effect. However, giant TMR effect was also observed when the MgO barrier layer is sandwiched between amorphous CoFeB electrodes.[8,9]

The MR ratio is also sensitive to the cap layer deposited on the top CoFeB electrode layer. Studies on boron diffusion into the capping layers and induced interfacial perpendicular anisotropies have also been reported.[10–14] The interest in the effect of capping on the free layer originated from reports[15] that cap layers influence the crystallization of the CoFeB free layer through diffusion of the B into the cap, as well as induce a perpendicular magnetic anisotropy in the free layer.[16,17] Different cap layers affect in different ways the diffusion of the B from the free layer. Various reports detail investigation of the crystallization of CoFeB, B diffusion into capping layers, and induced interfacial perpendicular anisotropy.[16,17]

We have investigated the effect of different capping layers on the effective magnetization (H_{eff}) of the CoFeB free layer. To this end, we have studied the perpendicular anisotropy in the CoFeB free layer, which is induced by interface anisotropy between the CoFeB and different cap layers. This induced perpendicular anisotropy acts opposite to the demagnetizing fields, which tend to keep the magnetization in the plane of the film, thereby decreasing the critical current density for switching. This is an alternative exciting approach to fully perpendicular MTJ's using multilayers, $L1_0$ materials, or amorphous RE-TM materials, for which it is much more difficult to achieve high TMR ratios than for in-plane devices.[18]

II. EXPERIMENTS

Depositions were carried out on an SFI Shamrock sputter deposition system at a base pressure of 8×10^{-8} Torr with deposition powers ranging from 250 to 450 W. Deposition pressures were held at 2 mTorr. Two different compositions of CoFeB, $Co_{40}Fe_{40}B_{20}$ (A), and $Co_{31.5}Fe_{58.5}B_{10}$ (B) were investigated. Initially, four different thicknesses of the above-mentioned two compositions of CoFeB ranging from 2 nm to 8 nm of the form $Si/SiO_2/Ta_5/MgO_2/CoFeB_{(x)}$/cap layer/Ta were deposited with Ta, Ru, MgO, MgO/Ru, and V capping layers. All layers were capped with Ta to prevent oxidation of the CoFeB. The samples were characterized for their magnetic properties using a Princeton Scientific alternating gradient magnetometer (AGM) and a Quantum Design SQUID magnetometer. The damping parameter α and effective magnetization were measured with the help of an in-house-built fully automated broadband low temperature ferromagnetic resonance (FMR) setup.

III. RESULTS AND DISCUSSIONS

A. Effective magnetization

Ferromagnetic resonance was performed on all the samples with the magnetic field applied in the plane of the sample. Values for the effective magnetization $4\pi M_{eff}$ values are obtained by fitting frequency vs. applied field data to the Kittel formula,[19] which can be determined by solving the LLG equation in the low precession angle limit. The solution with respect to in-plane and perpendicular external field is given by

$$\omega = \gamma\sqrt{(H_{res} + H_k)(H_{res} + H_k + 4\pi M_{eff})},$$

where γ is the magneto-mechanical ratio for an electron spin and ω is the resonance frequency. From Fig. 1, it is observed that as the thickness of the CoFeB increases from 2 to 8 nm the $4\pi M_{eff}$ increases. The decrease in the Meff value with thinner CoFeB can be attributed to the surface anisotropy effect between CoFeB and the cap layer, which tends to pull the CoFeB perpendicular.

B. Damping parameter

The Gilbert damping parameter α is obtained by fitting the measured frequency dependence of the linewidth ΔH to the following formula:[20]

$$\Delta H = \Delta H_0 + \frac{2}{\sqrt{3}}\frac{\alpha}{\gamma}\omega.$$

As the thickness of CoFeB decreases, the damping parameter α increases. While the inhomogeneous contribution to the linewidth can be an important factor to determine the overall loss we found that for all samples investigated here ΔH_0 was less than 100 Oe.

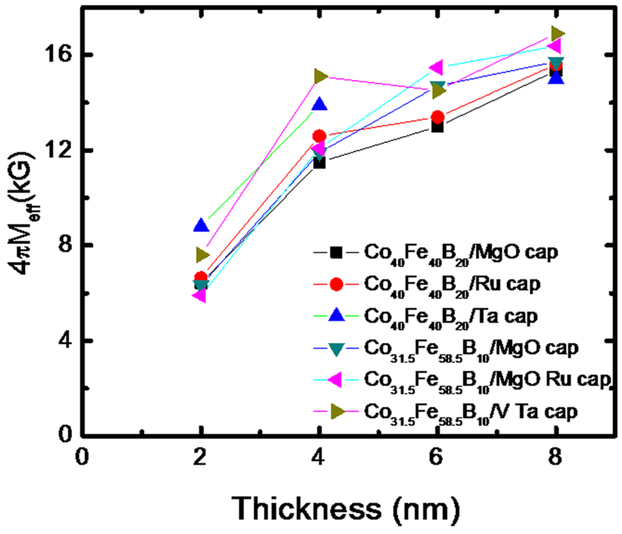

FIG. 1. $4\pi M_{eff}$ values for various t_{CoFeB} for various caps.

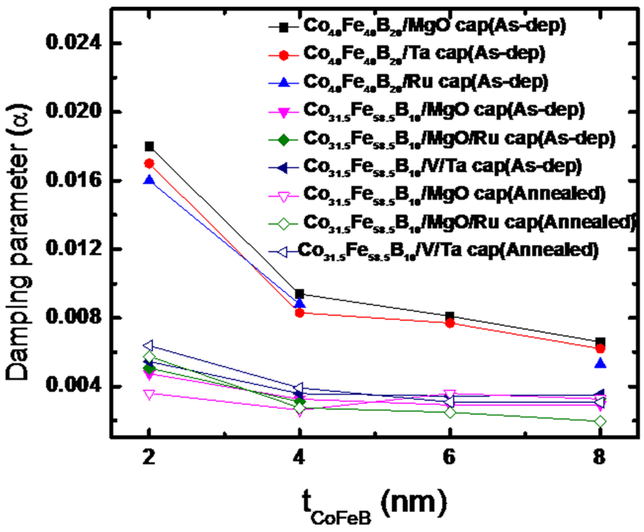

FIG. 2. Damping parameter (α) values as a function of t_{CoFeB} for different capping layers.

Fig. 2 indicates that damping did not vary much between different cap layers. The damping of $Co_{31.5}Fe_{58.5}B_{10}$ (B) is generally found to be much lower than that of $Co_{40}Fe_{40}B_{20}$ (A). $Co_{31.5}Fe_{58.5}B_{10}$ (B) has Gilbert damping values as low as 0.0035, close to other low damping materials such as CoFeGe with 30% Ge,[21] $Fe_{73}V_{27}$,[22] and the Heusler NiMnSb.[23]

C. Magnetic "dead" layer

In order to determine the extent of a magnetically "dead" layer in these samples, M_st vs. t data are plotted as shown in Fig. 3. The intercept with the thickness axis of a straight line through the experimental data gives the "dead" layer thickness, whereas the slope gives the saturation magnetization of the film. The "dead" layer of $Co_{40}Fe_{40}B_{20}$ (A) with MgO cap is 0.1 nm, Ru cap is 0.4 nm, and Ta cap is 0.7 nm. For $Co_{31.5}Fe_{58.5}B_{10}$ (B), the deadlayer for the MgO, MgO/Ru cap is about 0.2–0.4 nm. The V capping layer yields an anomalous positive intercept as-deposited, which may be

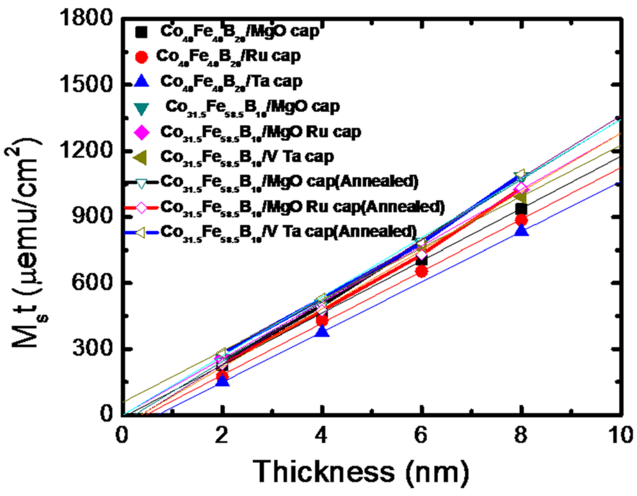

FIG. 3. M_st values for various t_{CoFeB} for various caps.

caused by measurement error. However, after annealing, the behavior of this capping layer is very similar to that of MgO.

D. K_ut and k_s determination

The perpendicular anisotropy K_u[24–26] can be determined by

$$4\pi M_{eff} = 4\pi M_S - H_{K\perp},$$

where the perpendicular anisotropy field is $H_{K\perp} = \frac{2k_s}{M_S t}$.

Thus, $4\pi M_{eff} = 4\pi M_S - H_{K\perp} = 4\pi M_S - \frac{2k_s}{M_S t}$. k_s are the total surface anisotropy energy per unit area of a magnetic layer, and it includes contribution from both interfaces.

Based on these expressions, we can write

$$K_u t = K_v t + k_s,$$

where K_ut, the effective magnetic anisotropy, is a sum of volume and surface contributions and $K_v t = K_b t - 2\pi M_s{}^2 t$. But, with our M_s and M_{eff} values, the K_ut will be obtained using

$$K_u t = \frac{1}{2} * M_{seff} * M_s t,$$

and from the plot of K_ut versus M_st, k_s values are easily gained from the intercept.

Fig. 4 shows a summary of results on the as-deposited samples of the two compositions of CoFeB (A and B) with MgO, Ru, and Ta caps. It is evident from the DL plot that Ta sputtered on top of CoFeB does significant damage to surface as deposited, but does not otherwise degrade the magnetization. Even the as deposited MgO on both CoFeB (A and B) interfaces induces a large surface anisotropy, which is three times larger than for Ta cap. Whereas Ru as deposited results in surface anisotropy, which is two times than that of Ta, however, is known to damage TMR.

Fig. 5 shows a summary of results on as-dep and annealed samples of CoFeB (B). For $Co_{31.5}Fe_{58.5}B_{10}$ (B), the MgO, MgO/Ru, and V caps all gave $k_s = 1.6$ erg/cm^2 (as dep) and 2–2.5 erg/cm^2 (annealed) closely followed by the V cap. For $Co_{40}Fe_{40}B_{20}$ (A), ks for the MgO cap is slightly smaller than for $Co_{31.5}Fe_{58.5}B_{10}$ (B), Ru is ~1 erg/cm^2, and Ta is 0.5 erg/cm^2. In all the above discussed caps $\frac{k_s}{2}$ is calculated and the effective single-interface contribution is understood that the V and MgO caps are the best caps in inducing surface anisotropy.

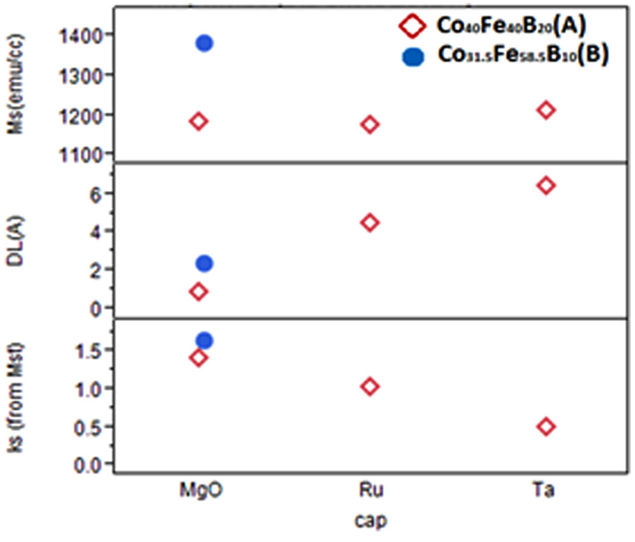

FIG. 4. Comparison of M_s, deadlayer (DL), and k_s values of as-deposited samples of CoFeB (A and B).

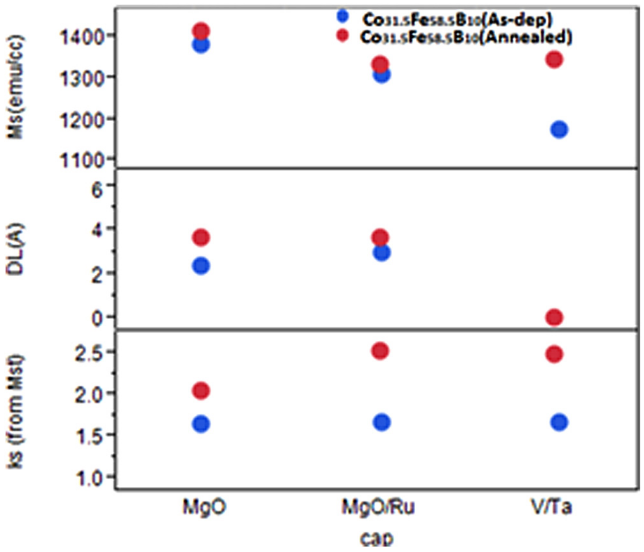

FIG. 5. Comparison of M_s, deadlayer (DL), and k_s values of as-deposited and annealed samples of CoFeB (B).

E. Effect of annealing on perpendicular magnetic anisotropy

Perpendicular magnetic anisotropy (PMA) is defined as

$$PMA\% = \left(\frac{4\pi M_s - 4\pi M_{eff}}{4\pi M_s}\right) \times 100.$$

Samples with 2 nm CoFeB thickness with various caps have been annealed under three conditions: 220 °C and 350 °C anneal in a furnace annealer for 1 and 2 h, respectively, and 450 °C *in-situ* rapid thermal anneal for 5 min.

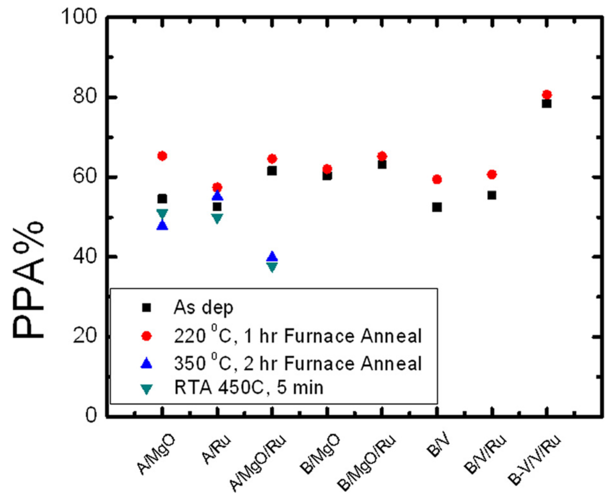

FIG. 6. Effect of annealing on PMA% vs. t_{CoFeB} of 2 nm with different caps.

From Fig. 5, it is evident that CoFeB with Ru capping has consistent PMA% at all the annealing conditions, whereas with MgO and other capping materials, there is greater sensitivity to annealing conditions (Fig. 6). This indicates that the interdiffusion of cap materials is temperature dependent. Most vanadium capped samples showed a significant increase in PMA with annealing.

IV. CONCLUSIONS

In summary, free layer engineering and thorough characterization of its properties are critical for STT-RAM design. We investigated an exciting new scheme for increasing thermal stability (Δ) and reducing critical current(I_c). Induced interfacial perpendicular anisotropy was successfully induced in CoFeB using four different capping layers. High interfacial anisotropy coupled with low α (as-deposited and after annealing) with a V/Ta capping layer has been found.

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[1] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1–L7 (1996).
[2] L. Berger, Phys. Rev. B **54**, 9353–9358 (1996).
[3] T. Kawahara *et al.*, ISSCC Dig. Tech. Papers **2007**, 480.
[4] T. Kishi, H. Yoda, T. Kai, T. Nagase, E. Kitagawa, M. Yoshikawa, K. Nishiyama, T. Daibou, M. Nagamine, M. Amano, S. Takahashi, M. Nakayama, N. Shimomura, H. Aikawa, S. Ikegawa, S. Yuasa, K. Yakushiji, H. Kubota, A. Fukushima, M. Oogane, T. Miyazaki, and K. Ando, IEDM Tech. Dig. **2008**, 309.
[5] W. H. Butler, X.-G. Zhang, T. C. Schulthess, and J. M. MacLaren, Phys. Rev. B **63**, 054416 (2001).
[6] J. Mathon and A. Umersky, Phys. Rev. B **63**, 220403 (2001).
[7] X.-G. Zhang and W. H. Butler, Phys. Rev. B **70**, 172407 (2004).
[8] D. Wang, D. Norman, C. Daughton, J. M. Qian, and Z. Fink: IEEE Trans. Magn. **40**, 2269 (2004).
[9] K. Tsunekawa, Y. Nagamine, and H. Maehara, in 9th Joint MMM/Intermag Conference, BD-02.
[10] D. D. Djayaprawira, K. Tsunekawa, M. Nagai, H. Maehara, S. Yamagata, N. Watanabe, S. Yuasa, Y. Suzuki, and K. Ando, Appl. Phys. Lett. **86**, 092502 (2005).
[11] J. Hayakawa, S. Ikeda, F. Matsukura, H. Takahashi, and H. Ohno, Jpn. J. Appl. Phys., Part 2 **44**, L587 (2005).
[12] T. Miyajima, T. Ibusuki, S. Umehara, M. Sato, S. Eguchi, M. Tsukada, and Y. Kataoka, Appl. Phys. Lett. **94**, 122501 (2009).
[13] K. Tsunekawa, D. D. Djayaprawira, M. Nagai, H. Maehara, S. Yamagata, and N. Watanabe, in *Digests of the IEEE International Magnetics Conference, INTERMAG* (IEEE, New York, 2005), HP-08.
[14] T. Ibusuki, T. Miyajima, S. Umehara, S. Eguchi, and M. Sato, Appl. Phys., Lett. **94**, 062509 (2009).
[15] E. Chen, D. Apalkov, Z. Diao, A. Driskill-Smith, D. Druist, D. Lottis, V. Nikitin, X. Tang, S. Watts, S. Wang, S. A. Wolf, A. W. Ghosh, J.W. Lu, S. J. Poon, M. Stan, W. H. Butler, S. Gupta, C. K. A. Mewes, Tim Mewes, and P. B. Visscher, IEEE Trans. Magn. **46**, 1 (2010).
[16] S. M. Watts, X. Tang, Z. Diao, D. Apalkov, D. Druist, E. Chen, V. Nikitin, in 11th Joint MMM-Intermag Conference, Washington, DC (2010), Digest FV-11.
[17] D. Worledge, D. Abraham, S. Brown, M. Gaidis, G. Hu, C. Long, J. Nowak, E. O'Sullivan, R. Robertazzi, J. Sun, P. Trouilloud, in 11th Joint MMM-Intermag Conference, Washington, DC (2010), Digest HB-10.
[18] Z. R. Tadisina, A. Natarajarathinam, B. D. Clark, A. L. Highsmith, T. Mewes, S. Gupta, E. Chen, and S. Wang, J. Appl. Phys. **107**, 09C703 (2010).
[19] C. Kittel, Phys. Rev. **73**, 155–161 (1948).
[20] B. Heinrich, J. F. Cochran, and R. Hasegawa, J. Appl. Phys. **57**, 3690, (1985).
[21] H. Lee, Y.-H. A. Wang, C. K. A. Mewes, W. H. Butler, T. Mewes, S. Maat, B. York, M. J. Carey, and J. R. Childress, Appl. Phys. Lett. **95**, 082502 (2009).
[22] C. Scheck, L. Cheng, I. Barsukov, Z. Frait, and W. E. Bailey, Phys. Rev. Lett. **98**, 117601 (2007).
[23] B. Heinrich, G. Wolterdorf, R. Urban, O. Mosendz, G. Schmidt, P. Bach, L. Molenkamp, and E. Rozenberg, J. Appl. Phys. **95**, 7462 (2004).
[24] H. Meng, W. H. Lum, R. Sbiaa, S. Y. H. Lua, and H. K. Tan, J. Appl. Phys. **110**, 033904-(1-4) (2011).
[25] K. Lee, J. J. Sapan, S. H. Kang, and Eric E. Fullerton, J. Appl. Phys. **109**, 123910-(1-3) (2011).
[26] S. Ikeda, K. Miura, H. Yamamoto, K. Mizunuma, H. D. Gan, M. Endo, S. Kanai, J. Hayakawa, F. Matsukura, and H. Ohno, Nature Mater. **9**(9), 721–724 (2010).