The effects of annealing temperature and heating rate on Ta/TbFeCo bilayers

Lin-Xiu Ye, Ramesh C. Bhatt, Ching-Ming Lee, Shih-Min Chang, and Te-ho Wu

Cite as: AIP Advances 9, 125316 (2019); https://doi.org/10.1063/1.5129098
Submitted: 27 September 2019. Accepted: 12 November 2019. Published Online: 20 December 2019

© 2019 Author(s).
The effects of annealing temperature and heating rate on Ta/TbFeCo bilayers

Cite as: AIP Advances 9, 125316 (2019); doi: 10.1063/1.5129098
Presented: 6 November 2019 • Submitted: 27 September 2019 • Accepted: 12 November 2019 • Published Online: 20 December 2019

Lin-Xiu Ye,1,2 Ramesh C. Bhatt,1,2 Ching-Ming Lee,1,2 Shih-Min Chang,1,2 and Te-ho Wu1,2,a)

AFFILIATIONS
1 Taiwan SPIN Research Center, National Yunlin University of Science and Technology, Douliou 64002, Taiwan
2 Graduate School of Materials Science, National Yunlin University of Science and Technology, Douliou 64002, Taiwan

Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.

A) Author to whom correspondence should be addressed: wuth@yuntech.edu.tw

ABSTRACT
Among various perpendicularly anisotropic magnetic materials, amorphous rare earth-transition metal RE-TM alloys have attracted much interest due to the advantages of tunable magnetic properties and suitable perpendicular magnetic anisotropy (PMA) strength. In this study, the magnetic properties of the Ta/TbFeCo/MgO structure with various Tb-contents are investigated under different annealing conditions like heating rate and annealing temperature. The samples were annealed at heating rate from 10 °C/min to 50 °C/min and holding time was varied from 10 min to 30 min with annealing temperatures ranging from 100 to 150 °C. We found that fast heating rate and low holding temperature help to improve PMA and significantly increase the saturation magnetization and squareness of the TbFeCo films.

I. INTRODUCTION
In recent years, spin orbit torque (SOT)1–2 stimulated wide interest due to its potential capabilities like energy efficient fast switching of magnetic random-access memory (MRAM). A typical SOT device structure utilizes a heavy metal (HM) attached at the top or bottom of the free layer (FL) of the magnetic tunnel junction (MTJ). A current with sufficient strength through the HM generates a spin current which can switch the magnetization of the FL in an MTJ. The most versatile HM materials used in the SOT structure are tantalum (Ta),3 tungsten (W),4 and platinum (Pt)5 due to their large spin Hall angle. A free layer using perpendicular magnetic anisotropy material is suitable for high-density applications because of the lower aspect ratio and better thermal stability. Among various magnetic materials with perpendicular magnetic anisotropy (PMA), rare earth-transition metal (RE-TM) alloys,6–7 thin film binary multilayers8–9 and L10 -FePt10 have been used as magnetic switching layers in perpendicularly magnetized MTJ fabrications.

In the RE-TM alloys, where RE element (Tb, Gd, etc.) and TM element (Co, Fe, etc.) sublattices are antiparallelly coupled, the net magnetic moment can be tuned easily by varying the RE-TM composition. At room temperature, pure Tb and FeCo thin films are paramagnetic and ferromagnetic (in-plane anisotropy), respectively. The TbFeCo alloy can be simply fabricated from the co-sputtering of the FeCo and Tb targets using an RF or DC magnetron sputtering at room temperature without any post-annealing processes. However, the bottom material and thickness of the magnetic layer affects the perpendicular magnetic anisotropy (PMA) of these films.11–13

The rapid thermal annealing (RTA) could keep TbFeCo as an amorphous structure. During RTA the annealing temperature and time can strongly affect the magnetic properties while maintaining the amorphous nature of the sample. In this study, the magnetic properties of the Ta/TbFeCo/MgO structure with various Tb-contents and are explored when subjected to different annealing conditions.

II. EXPERIMENTAL PROCEDURE
The samples of structure Ta(10 nm)/TbFeCo(10 nm)/MgO (4 nm) were deposited on Si substrates at room temperature. The TbFeCo and Ta thin films were deposited by DC magnetron sputtering, while the MgO layer was deposited using a radio-frequency reactive sputtering method. During the deposition, the base pressure was less than 3.0×10−7 Torr. Highly purified Ar gas was kept...
at a pressure as low as approximately $4.0-5.0 \times 10^{-4}$ Torr during sputtering in order to obtain a flat surface morphology. The Ar pressure during MgO deposition was 15 mTorr and the magnetron sputter power was 200 W. The MgO deposition rate was 0.02 nm/sec.

The Tb and Fe$_{80}$Co$_{20}$ targets were used to co-sputter the TbFeCo film. The DC sputter power of Fe$_{80}$Co$_{20}$ was fixed 135 Watt while the Tb power was varied from 40 to 100 Watt. The Ar pressure during magnetic layer deposition was 3 mTorr. The deposition rates of TbFe$_{80}$Co$_{20}$ was varied from 0.05 to 0.1 nm/sec. The samples were then annealed at different heating rates from 10 °C/min to 50 °C/min and holding time from 10 min to 30 min with temperatures ranging from 100 to 150 °C. The magnetic properties were measured using an alternating gradient magnetometer (AGM).

III. RESULTS AND DISCUSSIONS

The out-of-plane hysteresis loops for the Ta/TbFeCo/MgO structures with various annealing conditions of Tb 40 Watt and 85 Watt are shown in Fig. 1. Tb 40 watt and Tb 85 Watt correspond to a FeCo-rich and Tb-rich phase of TbFeCo, respectively. For the Tb 40-Watt case, the as-deposited TbFeCo film exhibits perpendicular magnetic anisotropy; however, there appears a kick in the magnetic hysteresis as shown in Fig. 1(a). Low heating rate (10 °C/min) and temperature (100 °C) with long holding time (30 min) induce good PMA with reduced saturation magnetization (Ms). After annealing at 100 °C, coercivity is reduced from 625 Oe (as-deposited) to 438 Oe. For 100 °C annealing temperature, both the coercivity and saturation magnetization improves with increasing the heating rate. It was observed that the long temperature holding time (30 min) could effectively increase the amount of perpendicular magnetization. However, the structure cannot withstand high-temperature annealing. An annealing temperature of only 150 °C causes a significant decrease in the amount of magnetization. Coercivity is reduced from 625 Oe for as-deposited to 420 Oe after 150 °C annealing with 10 min holding time. On extending the holding time the amount of magnetization is increased, however, still lower than the as-deposited state. Figure 1(b) shows the annealing results of Tb 85 Watt. Different from the FeCo-rich structure, it has the highest magnetization amount under the holding time of 40 minutes at annealing temperature 100 °C. At 150 °C annealing, although the coercivity decreases but the Ms and curve behavior are similar to as-deposited. Hence, it can be concluded that a high heating rate with suitable annealing temperature and holding time can effectively enhance PMA and Ms.

Figure 2 shows the relations of Ms (solid line) and Hc (dotted lines) with various Tb power for different holding time under 100 °C annealing temperature and heating rate 50 °C/min. From the trend profile, the compensation composition is estimated at around 72 Watt. For an as-deposited sample, the coercivity diverges symmetrically at the compensation point. After annealing for 10 minutes, the Ms is reduced substantially; however, coercivity is only mildly changed. On increasing annealing time to 30 minutes, Ms is greatly improved and the coercivity rises sharply near the compensation point. The value of Ms is about 3 to 5 times more than the as-deposited state.
Figure 3 shows the relations of Ms (solid line) and Hc (dotted lines) with Tb power for different holding time under 150 °C annealing temperature. Irrespective of the annealing time duration, Ms is greatly reduced. The Ms value for FeCo-rich structure is dropped more than the corresponding Tb-rich structure.

The coercivity increases with increasing the annealing time but remains lower than the as-deposited state. By comparing Fig. 2 and Fig. 3, we observed that the saturation magnetization is nearly the same when the annealing temperatures are 100 °C and 150 °C and Fig. 3, we observed that the saturation magnetization is nearly the same when the annealing temperatures are 100 °C and 150 °C with holding time 10 minutes. The effect of temperature increase after raising the temperature holding time is obvious. The annealing temperature of 150 °C is too high for this structure.

For both 100 °C and 150 °C annealing temperatures most of the samples in the experiment have good squareness after annealing. To further understand the effect of annealing parameters on the PMA of the Ta/TbFeCo/MgO, the anisotropy energy constant (Ku) for different annealing conditions are shown in Fig. 4. It shows that annealing at 150 °C will cause Ku to be lower than the as-deposited state. Ku values vary from 0.14 to 0.72 Merg/cm³. The Ku value is also very low when the temperature is maintained at 100 °C for 10 minutes. Ku values vary from 0.16 to 0.64 Merg/cm³. Annealing conditions at 100 °C for 30 minutes provides the largest anisotropy values. Although the coercivity is not significantly improved, the saturation magnetization and Ku are greatly improved. The Ku value after annealing is increased by at least 4 to 10 times relative to the as-deposited sample.

IV. CONCLUSIONS

In short, we fabricated Ta/TbFeCo (10 nm)/MgO structures with perpendicular magnetic anisotropy. We found that a rapid heating rate helps to increase TbFeCo magnetic anisotropy. The annealing temperature of 100 °C with a holding time of 30 minutes found to be the optimum annealing condition. For the Tb 40 Watt sample that the annealing enhanced the Ms value from 334 to 1529 emu/cm³, the coercivity from 677 Oe to 761 Oe, and the anisotropy Ku from 1.51 to 6.6 Merg/cm³. The study presents significant improvement in PMA of RE-TM alloy film by annealing.

ACKNOWLEDGMENTS

This work was supported by the National Science Council of Taiwan, Republic of China, under Contract No. NSC 107-2112-M-224-001-MY2 and the Feng-Tay foundation Taiwan ROC.

REFERENCES

1. G. Prebat, K. Jabeur, P. Vanhauwaert, G. Di Pendina, F. Oboril, R. Bishnoi, M. Ebrahimi, N. Lamard, O. Boule, R. Garelo, J. Langer, B. Ocker, M, C. Cyrille, P. Gambardella, M. Tahoori, and G. Gaudin, “Ultra-fast and high-reliability SOT-MRAM: From cache replacement to normally-off computing.” IEEE Trans. Mul. Comp. Sys. 2(1), 49–60 (2016).
2. J. E. Hirsch, “Spin Hall effect.” Phy. Rev. Let. 83(9), 1834–1837 (1999).
3. L. Liu, C.-F. Pai, Y. Li, H. W. Tseng, D. C. Ralph, and R. A. Buhrman, “Spin-torque switching with the giant spin Hall effect of tantalum,” Science 336, 555 (2012).
4. K.-U. Demasius, T. Phung, W. Zhang, B. P. Hughes, S.-H. Yang, A. Kellock, W. Han, A. Pushp, and S. S. P. Parkin,”Enhanced spin-orbit torque by oxygen incorporation in tungsten films,” Nature Communications 7, 10644 (2016).
5. V. Ostwal, A. Penumatcha, Yu-M. Hung, A. D. Kent, and J. Appenzeller, “Spin-orbit torque based magnetization switching in Pt/Cu/[Co/Ni] multilayer structures,” J. Appl. Phys. 122, 213905 (2017).
6. M. Nakayama, T. Kai, N. Shimomura, M. Amano, E. Kitagawa, T. Nagase, M. Yoshikawa, T. Kishi, S. Ikeya, and H. Yoda, “Spin transfer switching in TbCoFe/Cu/CoFeB/MgO magnetic tunnel junctions with perpendicular magnetic anisotropy,” J. Appl. Phys. 103, 07A710 (2008).
7. H. Ohnori, T. Hatori, and S. Nakagawa, “Perpendicular magnetic tunnel junction with tunneling magnetoresistance ratio of 64% using MgO(100)/barrier layer prepared at room temperature,” J. Appl. Phys. 103, 07A911 (2008).
8. D. Lim, S. Kim, and S. R. Lee, “Magnetoresistance behavior of a magnetic tunnel junction with perpendicularly magnetized Co/Pd multilayers,” J. Appl. Phys. 97, 10C902 (2005).
9. L. X. Ye, C.-M. Lee, J. W. Syu, Y. R. Wang, K. W. Lin, Y. H. Chang, and T.-h. Wu, “Effect of annealing and barrier thickness on MgO-based Co/Fe/MgO multilayered perpendicular magnetic tunnel junctions,” IEEE Trans. Magn. 44(11), 3601–3604 (2008).
10. M. Yoshikawa, E. Kitagawa, T. Nagase, T. Daibou, M. Nagamine, K. Nishiyama, T. Kishi, and H. Yoda, “Tunnel magnetoresistance over 100% in MgO-based...
magnetic tunnel junction films with perpendicular magnetic L1₀-FePt electrodes,”
IEEE Trans. Magn. 44(11), 2573–2576 (2008).
11P. Hansen, C. Clausen, G. Much, M. Rosenkranz, and K. Witter, "Magnetic and
magneto-optical properties of rare-earth transition-metal alloys containing Gd,
Tb, Fe, Co," J. Appl. Phys. 66, 756–767 (1989).

12L. Ertl, G. Endl, and H. Hoffmann, "Structure and magnetic properties of
sputtered Tb/Co multilayers," J. Magn. Magn Mater. 113, 227–237 (1992).
13C.-M. Lee, L.-X. Ye, J.-M. Lee, W.-L. Chen, C.-Y. Huang, G. Chern, and
T.-h. Wu, "Ultrathin (Gd, Tb)-FeCo films with perpendicular magnetic
anisotropy," IEEE Trans. on Magn. 45(10), 3808–3811 (2009).