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$MgAl_2O_4$ capping effects on the magnetic properties of TbFeCo films

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ABSTRACT

We investigate $MgAl_2O_4$ (MAO) capping effects on the magnetic properties of TbFeCo films. Compared with TbFeCo films, a shift of compensation point to lower temperatures together with significantly reduced saturation magnetization is found in the case of MAO capping. An antiferromagnetic exchange coupling is observed in TbFeCo/MAO structures. This can be well explained by a double layer model with opposite phases. An exchange energy density of ~ 0.5 erg/cm^2 is obtained, which is comparable but lower than that of TbFeCo bilayers with opposite phases. Our findings may be useful for developing ultrathin TbFeCo/MAO heterostructure-based spintronic devices.

1. Introduction

Heavy rare-earth transition metal (HRE-TM) alloys have received increasing attention for the spintronic applications due to perpendicular magnetic anisotropy (PMA) [1,2]. In the alloys, the moments of the 4f RE and 3d TM sublattices are antiferromagnetically coupled, which allows faster magnetization dynamics as compared to that of ferromagnets [3]. Accordingly, there is magnetization compensation point Tcomp, where the moments of RE and TM sublattices compensate. The film may be either RE-rich or TM-rich, depending on the Tcomp. The Tcomp can be tuned by film composition, and it has been recently revealed that the interfacial region can cause thickness dependent Tcomp [4–7].

TbFeCo film possesses strong PMA and sufficiently large coercivity, which may be used as the reference in magnetic tunnel junction (MTJ). It has been known that the interfaces of HRE-TM alloy with adjacent layers have significant impact on magnetic properties of the alloy films [8,9]. The deposition of MgO barrier on TbFeCo film has been studied for the applications of MgO-based MTJs [10]. In this work, capping effects of $MgAl_2O_4$ (MAO) on magnetic properties of TbFeCo films are investigated, as MAO is currently a promising tunneling barrier for MTJs [11]. Our results show MAO capping can cause lower Tcomp and even a large antiferromagnetic exchange coupling (AFC). Our findings are useful in developing ultrathin TbFeCo/MAO-based spintronic devices.

2. Experimental details

TbFeCo and TbFeCo/MAO structure with 5 nm Pt buffer and Ta capping were deposited on Si (1 0 0) substrates pre-coated with 5 nm Ta by magnetron sputtering with a base pressure of less than 6.0×10^{-6} Pa. A composite target consisting of FeCo alloy disk and Tb chips was designed for TbFeCo growth. The sputtering rate of TbFeCo was calibrated to be 0.5 nm/s. TbFeCo thickness is varied from 4.5 to 72 nm and MAO capping is adjusted from 0.5 to 4 nm. The film thickness was checked by the cross-sectional view under a field-emission scanning electron microscope (FE-SEM, Sigma 300 VP) and composition was measured by an energy dispersive spectroscopy (EDS) accessory. Magneto-optical Kerr effect (MOKE) loops were measured in polar geometry using a He-Ne laser. Magnetic properties were characterized using a vibrating sample magnetometer (VSM, Microsense EZ7).

3. Result and discussion

M−H loops of a 72-nm-thick TbFeCo film is presented in Fig. 1a. The saturation magnetization *Ms* is determined to be ~ 109 emu/cm^3. The effective PMA constant K_{eff} is estimated to be ~ 5.7×10^5 erg/cm^3 from the area between the in-plane and out-of-plane M−H loops [12]. This is a typical order in magnitude for TbFeCo films with similar thickness [13]. The polarization of the MOKE loop, shown in Fig. 1b, is opposite to the corresponding M−H loop, indicating the film is Tb-rich. This will be confirmed later. The cross-sectional view of the 72 nm film for reference

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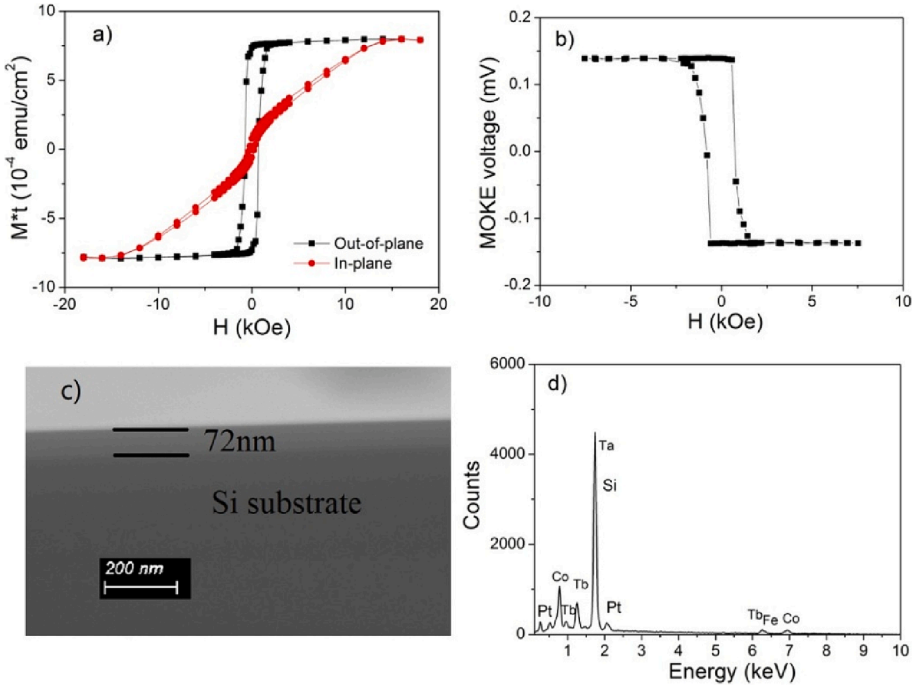

Fig. 1. A) in-plane and out-of-plane magnetization and b) moke loops of a TbFeCo film. c) Cross-sectional view and d) EDX spectrum of the film.

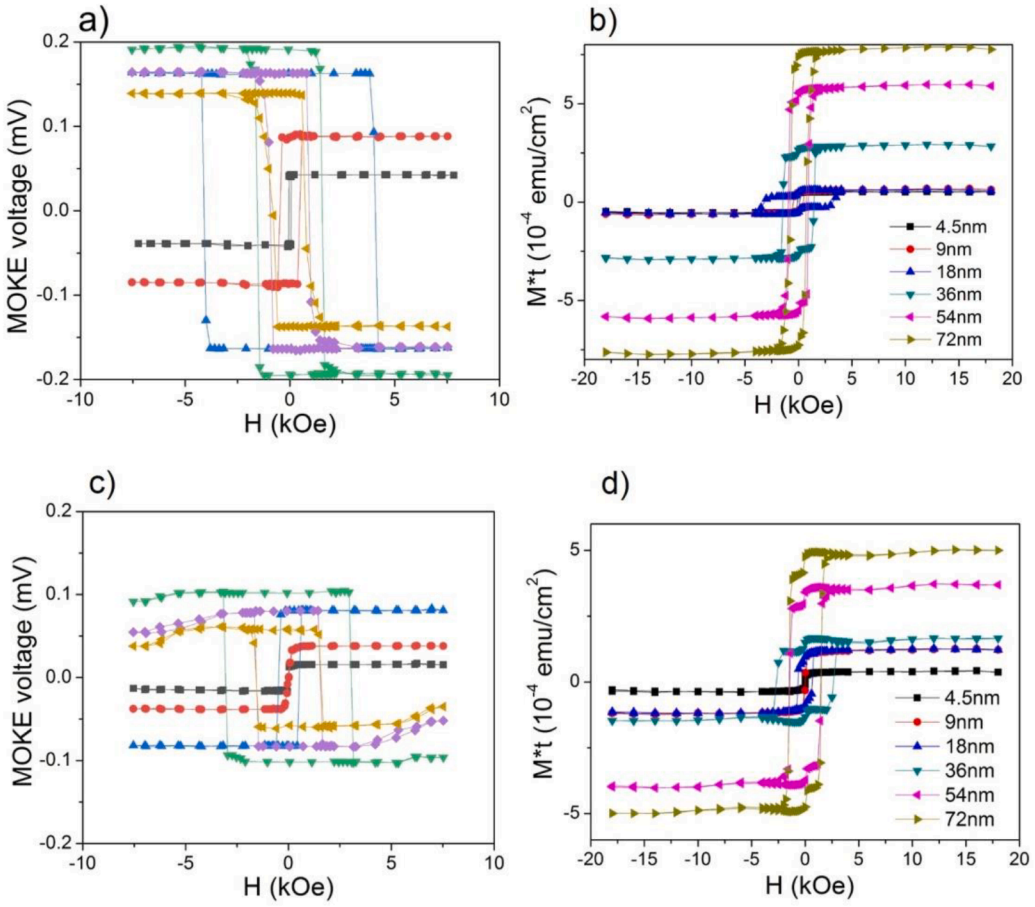

Fig. 2. A) moke and b) out-of-plane m-H loops of TbFeCo films with varying thickness ranged from 4.5 to 72 nm. c) and d) are corresponding measurements on TbFeCo/MAO(2.5 nm) stacks.

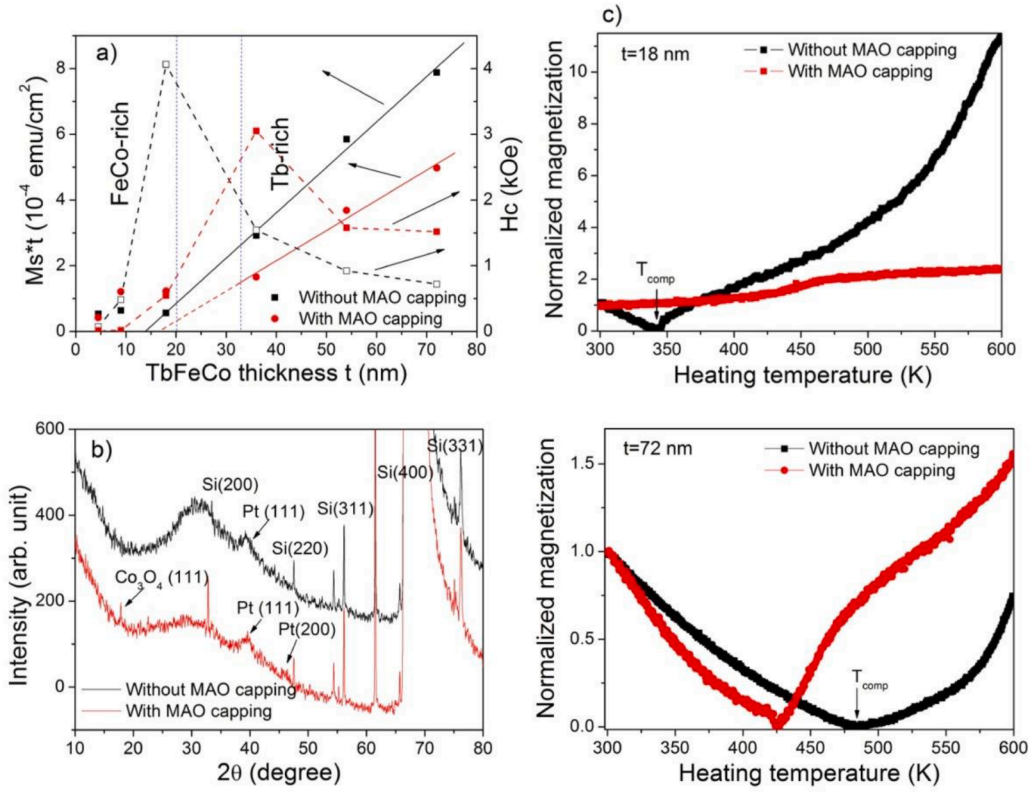

Fig. 3. A) plots of saturation magnetization per unit area (ms*t) and Hc against TbFeCo thickness. b) XRD patterns. c) Thermomagnetic curves of TbFeCo films with/without 2.5 nm MAO capping.

is shown in Fig. 1c. The EDS spectrum is presented in Fig. 1d. The Tb concentration is determined to be ~ 34 at.%, confirming the film is indeed rich in Tb. For 35 nm thick film the surface roughness was previously determined to be ~ 0.2 nm, showing sputtered amorphous TbFeCo films are quite smooth [14].

Fig. 2a and 2b show MOKE and out-of-plane M−H loops of TbFeCo films with varying thickness, respectively. MOKE loops with full remanence confirm all the films are perpendicularly magnetized. The magnetic configuration changes from Tb-rich to FeCo-rich phase when film thickness reduces to 9 nm. The reverse of MOKE loop for 9 nm TbFeCo film indicates a shift of Tcomp to lower temperature, which will be confirmed later. This thickness dependence of magnetic properties was often observed in ferrimagnetic RE-TM films with thickness less than tens of nanometers. This was revealed to be contribution of interface region in the films [4]. MOKE and M−H loops of the TbFeCo/MAO(2.5 nm) structures are plotted in Fig. 2c and 2d, respectively. The magnetic configuration changes from Tb-rich to FeCo-rich phase when the TbFeCo thickness decreases to 18 nm. It indicates that the Tcomp of the TbFeCo film with MAO capping is lower than that without capping. Please note here a twist part around zero field is witnessed in M−H loops of thick TbFeCo films, which may be attributed to soft FeCo-rich phases with in-plane anisotropy [15].

Fig. 3a plots Ms × t and Hc against TbFeCo thickness, respectively. For the TbFeCo films, the effective Ms is determined to be 138 ± 6 emu/cm^3 from the slope of the linear fitting of thickness dependent Ms × t. The compensation thickness is obtained from the intercept of the linear fitting with the horizontal axis. At this thickness of ~ 14 nm the net magnetization is zero. The 18-nm-thick film exhibits the lowest Ms and the largest Hc, showing the film is close to the compensation region. In contrast, for the TbFeCo films with MAO capping Ms of 92 ± 12 emu/cm^3 and larger compensation thickness of ~ 16.6 nm are obtained from the fitting.

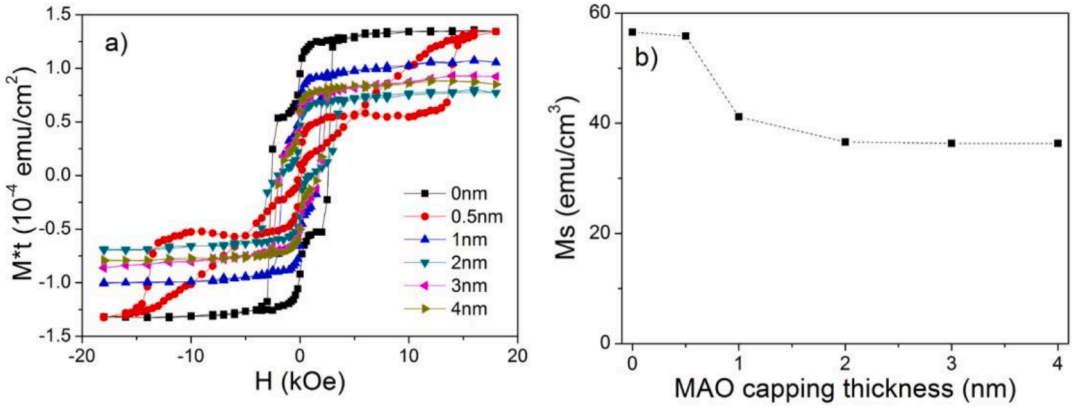

Fig. 4. A) out-of-plane m-H loops of the TbFeCo(24 nm)/MAO structures with varying MAO thickness. b) Capping thickness dependent Ms.

XRD patterns of the TbFeCo films with and without MAO capping are presented in Fig. 3b. Except Pt and Si peaks, no peak from the TbFeCo is detected, showing amorphous nature. With capping a Co_3O_4 (1 1 1) peak can be recognized, showing occurrence of serious oxidation. Thermomagnetic measurements are plotted in Fig. 3c. For the 18 nm thick TbFeCo film the Tcomp is determined to be ~ 432 K and reduces to below RT in the case of MAO capping. The Tcomp of the 72 nm TbFeCo film is measured to be ~ 484 K and falls to ~ 425 K with MAO capping. The films with Tcomp above RT exhibit Tb-rich, in good agreement with the polarization of the MOKE loops in Fig. 1. A obvious reduction in Tcomp is witnessed in the case of MAO capping.

Fig. 4a presents out-of-plane M−H loops of TbFeCo(24 nm)/MAO structures with varying MAO thickness. In the case of 0.5 nm capping separate switching is observed, showing AFC. This can be explained by a bilayer model with one partially oxidized layer with Tcomp below and the other part of Tcomp above RT [16]. At negative saturation all the magnetization are aligned along the field direction and an interlayer domain wall (DW) forms. With decreasing the field the first switching of the softer part happens with the annihilation of the DW at H= ~ −14 kOe, where the reduced field cannot stabilize the DW. The exchange energy density σ can be estimated by the equation $\sigma = H_b M_s \times t$, where $M_s t$ are the saturation magnetization per unit area of the switched part [17]. The exchange bias H_b is the difference between the switching field H and Hc of the switched part. Here, the Hc of the switched part is considered to be almost equal to that of film, i.e., ~2 kOe. The σ is estimated to be ~ 0.5 erg/cm^2 using H_b = ~13 kOe and $M_s t$=~4 × 10^{-5} emu/cm^2, which is comparable but lower than that in TbFeCo bilayer with opposite phases [18]. With further increasing the field towards positive direction, the reversal of harder part happens and all the net magnetization are parallel with the formation of DW again. Please note here no sharp switching is observed during the second reversal, which can be ascribed to no clear boundary between two parts. It is worth mentioning that a minor signal is witnessed at high fields in the MOKE loops for thick samples in Fig. 2b. This can also be explained by a interfacial layer with different compositional gradient formed at the TbFeCo/MAO interface. A monotonic decrease in Ms is observed with increasing capping thickness, plotted in Fig. 4b. This mainly comes from the oxidation effect, as revealed by XRD measurements.

4. Conclusion

In short, significant effects of MAO capping on the magnetic properties of TbFeCo films are reported. Both lower Tcomp and significantly reduced saturation magnetization are found in TbFeCo films with capping. Particularly, an AFC is witnessed in the TbFeCo/MAO structure. Our findings may be used in developing ultrathin TbFeCo/MAO heterostructure-based spintronic devices.

CRediT authorship contribution statement

Ke Wang: Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zhenxiao Nie:** Investigation, Data curation. **Shangqian Wang:** Investigation, Data curation. **Jian Liu:** Investigation. **Jiangwei Cao:** Resources. **Daniel Wamwangi:** Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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