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Thermal stability of magnetic characteristics in $Tb_{40}(FeCoV)_{60}$ films

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ABSTRACT

Films with a composition of $Tb_{40}(FeCoV)_{60}$ were fabricated by dc magnetron cosputtering from a multiple target arrangement at different substrate temperatures. The samples before and after annealing have been investigated by magnetic force microscope, vibrating sample magnetometer and other testing means for their structure and performance. With the increase of substrate temperature (T_s), out-of-plane coercivity decreases to a minimal value at $T_s = 150\,^{\circ}C$ and then increases rapidly while saturation magnetization reaches their highest value at a moderate substrate temperature of 150 °C. A homogenous high-contract stripe domain and a low-contrast island domain are obtained for the samples prepared at 150 °C and at 250 °C, respectively. High substrate temperature stabilizes the films against subsequent annealing which tends to eliminate the anisotropy. The coercivity decreases with increasing annealing temperature (T_A), but which shows hardly relaxation until the T_A reaches the original T_s. The easy direction of magnetization can be turned from perpendicular to in-plane direction at high annealing temperatures which increase with substrate temperature.

1. Introduction

Rare-earth transition metal (RE-TM) Tb–Fe (Co) amorphous alloys in film form are regarded as promising candidates for a suitable material in electromechanical transducing devices [1,2]. A large effort has been made to fabricate TbFe (Co) films with reduced coercivity and controlled orientation of easy axis by many methods such as e-beam co-evaporation and magnetron sputtering [3–6]. Among them, magnetron sputtering is a simple and practical method, which produces both perpendicular magnetic anisotropy and a large coercive field in amorphous Tb_xFe_{100-x} ($x = 25–45$) films [7–9]. These properties play an important role in practical applications, and they are sensitive to the process parameters such as sputtering pressure [10], substrate temperature [3] and annealing temperature [11]. The investigation of microstructure in TbFeCo films has been reported as a function of working argon pressure [12] and oblique incidence angle [13,14]. Yet, few attempts have been made to correlate the micro/magnetic structural changes of sputtered TbFeCo films as a function of temperature. In this work, we studied the micro/magnetic structure and magnetic characteristics of $Tb_{40}(FeCoV)_{60}$ films prepared at different substrate temperatures. Increasing substrate temperature stabilizes magnetic properties while annealing makes these films magnetically soft, and underlying mechanism is discussed.

2. Experimental

Films of $Tb_{40}(FeCoV)_{60}$ were deposited on polished monocrystalline Si (0 0 1) substrates by dc magnetron cosputtering from a multiple target arrangement with a pure Tb target and an alloy $Fe_{49}Co_{49}V_2$ target (America: Hiperco50, Russia: 50 KΦ, China: 1J22, curie temperature $T_c \approx 980\,^{\circ}C$ and saturation flux density $B_s \approx 2.4$ Tesla (T)). The base pressure and working argon pressure in vacuum chamber were 3.0×10^{-4} Pa and 0.6 Pa, respectively. The substrate temperature (T_s) controlled by a heater installed behind substrate holder varied from room temperature (RT) to 300 °C. The samples were annealed at temperatures (T_A) from 50 °C to 450 °C for 1 h in a vacuum of 2.0×10^{-4} Pa. The film thickness measured mechanically using a stylus profiler was about 120 nm without any coating. Structural properties were characterized by X-ray diffraction (XRD) with Cu K_{α} radiation. The magnetic domain structures were explored by magnetic force microscope (MFM). The microstructure investigations were performed using a field emission scan electron microscope (FEM). The magnetic measurements were carried out on a vibrating sample magnetometer (VSM) at room temperature.

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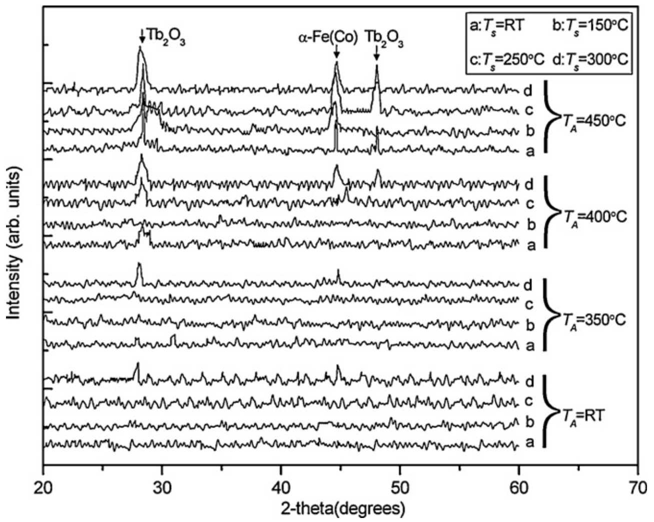

Fig. 1. XRD patterns of the $Tb_{40}(FeCoV)_{60}$ film prepared at different T_s and T_A.

3. Results and discussion

Fig. 1 shows the crystal structure of the samples prepared at different substrate temperatures and annealing temperatures. No XRD peak is found for the samples prepared at T_s below 300 °C and/or annealed at T_A below 400 °C indicating that these samples are amorphous. The weak peaks of Tb oxides and α-(Fe,Co) in the films either prepared or annealed at higher temperature are possibly due to the slight surface oxidation.

The normalized magnetic hysteresis loops measured with applied magnetic field in the film-normal directions are presented in Fig. 2(a) for the $Tb_{40}(FeCoV)_{60}$ films prepared at different substrate temperatures. The longitudinal magnetic measurement can serve as a direct determination of the perpendicular magnetization component. One can observe that a rectangular magnetic hysteresis loop is obtained at T_s = 150 °C while the hysteresis parallelograms become more oblique at other substrate temperatures. Fig. 2(b) shows the substrate temperature dependence of saturation magnetization and coercivity. Saturation magnetization increases and then decreases with increasing substrate temperature, a maximum of 291 kA/m is obtained at T_s = 150 °C. With the increase of substrate temperature, the coercivity decreases to a minimum of 22 mT at 150 °C and it rapidly increases, reaches a maximum at 250 °C and finally decreases at 300 °C. When T_s is higher than 250 °C, the in-plane component of easy axis appears in the films.

Based on the analysis of surface two-level-systems shown schematically in the inset of Fig. 2(b) [15], the reorientation of local structural units formed at the growth surface requires thermal activation over an energy barrier E_b, and the success rate n_2 for the reorientation is proportional to the anisotropy A, is then given by

$$A = A_0 \int_0^{\infty} D(E_b) \left[1 - \exp\left\{ -\tau\nu \exp\left(-\frac{E_b}{kT_s} \right) \right\} \right] dE_b \qquad (1)$$

where ν, T_s, τ, and $n_2 = 1 - \exp[-\tau\nu \exp(-E_b/kT_s)]$ are the attempt frequency, the substrate temperature, the time to deposit one monolayer, and the final occupancy of state 2, respectively. These units are initially randomly oriented into state 1 shown in the inset of Fig. 2(b), but can lower the surface free energy by reorienting into energetically favorable configurations marked as state 2. The increase in substrate temperature can enhance atomic rearrangements by increasing thermal activation energy and thus facilitates the formation and reorientation of local structural units (or adatom clusters). Hence, the fractional occupancy of state 2, n_2 described by Eq. (1), increases with increasing substrate temperature, resulting in a strong anisotropy. These results are consistent with those obtained from domain structures explored using MFM, as shown in Fig. 3. It exhibits distinct interlacement of bright and dark regions deriving from stripe domains with alternating perpendicular magnetization component. For film with a relatively lower perpendicular anisotropy (T_s = RT, Fig. 3(a)), a similar domain structure with a weak signal is found [16,17]. The weak contrast maybe due to the disturbance of domain structure by the stray field of the MFM tips. For film (T_s = 300 °C, Fig. 3(f)), the contrast is very weak due to the lack of the perpendicular anisotropy. In Fig. 3(c), the two kinds of stripes are found to have very high contract and almost equal areas, indicating a stronger perpendicular magnetic anisotropy (PMA) for the sample prepared at 150 °C than at other temperatures. In addition, the reorientation minimizes surface energy by maximizing coordination, causing the final structure to contain less defect and free volume. It has been found that the coercivity is limited by domain wall pinning which is controlled by the defects [3,18]. Therefore, the decrease in defects at high substrate temperature makes domain wall easier to move. Consequently, with increasing substrate temperature up to 150 °C, the improvement in homogeneity and densification would lead to the decrease of coercivity and the increase of saturation magnetization. Of course, the saturation magnetization may also be concerned

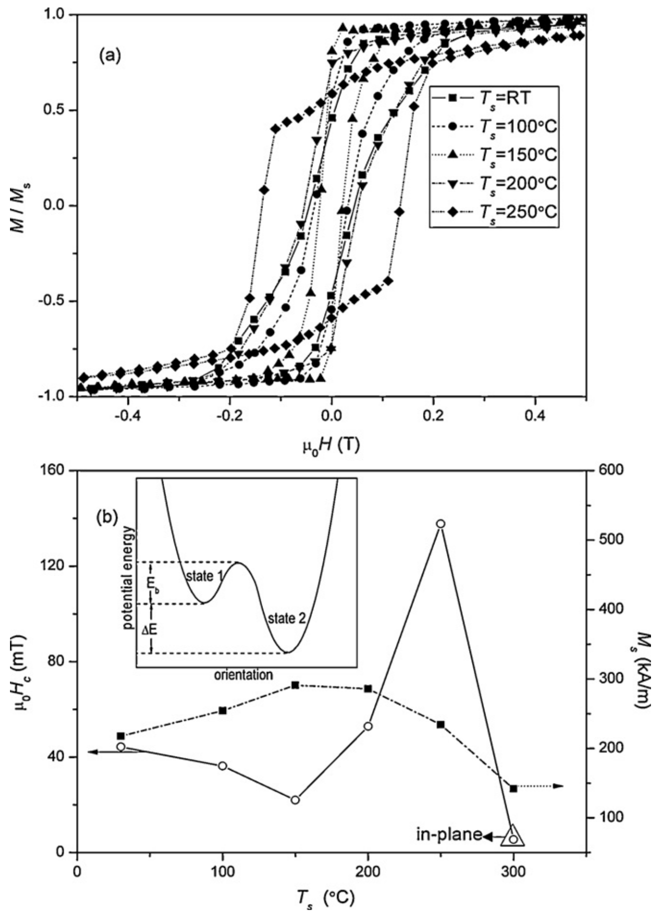

Fig. 2. (a) Out-of-plane hysteresis loops of the $Tb_{40}(FeCoV)_{60}$ films. (b) Coercivity $\mu_0 H_c$ and saturation magnetization M_s versus substrate temperature. Insert: two-level analysis of surface states during growth. State 1: Initial, randomly-oriented configuration. State 2: Oriented configuration maximizing coordination of surface atoms.