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Initial Magnetization and Coercivity Mechanism in Amorphous Tb_xCo_{1-x} Thin Films with Perpendicular Anisotropy

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The coercivity mechanism in permanent magnets was analyzed according to the effects of domain nucleation and domain wall pinning. The coercivity mechanism of a TbCo thin film with high perpendicular magnetic anisotropy was considered in terms of the local inhomogeneity in the thin film. The initial magnetization curves of the TbCo thin films demonstrated domain wall pinning to be the main contributor to the coercivity mechanism than domain nucleation. Based on the coercivity model proposed by Kronmüller *et al.*, the inhomogeneity size acting as a domain wall pinning site was determined. Using the measured values of perpendicular anisotropy constant (K_u), saturation magnetization (M_s), and coercivity (H_c), the inhomogeneity size estimated in a TbCo thin film with high coercivity was approximately 9 nm.

Keywords : TbCo, perpendicular anisotropy, domain wall, nucleation

1. Introduction

Models of domain wall pinning and domain nucleation mechanisms are generally used to examine permanent magnets with high coercivities. The coercivity (H_c) of a permanent magnet is quite sensitive to microstructures, such as defects, polycrystalline grains and other phases. The magnetic properties and coercivity mechanism in perpendicular recording media was considered with relation to polycrystalline grains, phase segregation and intermixing between the multilayers [1, 2]. Kronmüller *et al.* developed a model for the coercivity mechanism based on the assumption that nanometer-scale inhomogeneity in permanent magnets may create domain nucleation and/or domain wall pinning. The model considered the effects of misaligned grains, local stray field and changes in the exchange constant and anisotropy constant [3]. The inhomogeneous region was defined as the region with different exchange and anisotropy constants from the homogeneous matrix region. In this model, the temperature dependence of H_c is described empirically by the following equation [3, 4]:

$$H_c(T) = \alpha(T)2K_1/M_s - N_{eff}M_s \quad (1)$$

where $\alpha(T)$ and N_{eff} are the microstructural parameters and averaged local effective demagnetization factor, respectively. When the microstructural parameters a and N_{eff} are determined quantitatively, the solution of this equation can be clear. A quantitative determination of the microstructural parameters was done based on experimental data. Using the model of the coercivity mechanism based on domain wall pinning proposed by Kronmüller, Suzuki estimated the size of the wall pinning sites in Co/Pt multilayers with high H_c and high squareness where the coercivity mechanism was due mainly to wall pinning rather than the nucleation process [5]. In this case, α at Eq. (1) is a parameter related with a microstructure that is determined by the coupling strength between the domain wall and domain wall pinning site. N_{eff} is a demagnetization factor, which is related to the size and type of the pinning site (magnetic or nonmagnetic). Using the model, the dependence of coercivity on an inhomogeneity size (r_o) can be predicted. With the size of r_o compared to the wall width, δ_B, the coercivity (H_c) is described as follows [5]:

$$H_c(T) = \kappa\,(r_o/\delta_B)(2K_u/M_s) - N_{eff}M_s \quad \text{for } r_o << \delta_B \quad (2)$$

$$H_c(T) = \kappa'\,(\delta_B/r_o)(2K_u/M_s) - N_{eff}M_s \quad \text{for } r_o >> \delta_B \quad (3)$$

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The constants, κ and κ' can be determined empirically from the values of the exchange coupling constants and the anisotropy constants in the matrix and inhomogeneous region. The size of the inhomogeneity, r_o, can be obtained from the slope of the linear fitting from Eq. (2) or (3).

Amorphous TbCo alloy thin films exhibit ferrimagnetic order due to anti-parallel exchange coupling between the rare-earth (RE) 4f and the transition-metal (TM) 3d electrons [6]. The structural disorder causes strong local anisotropy for the RE moments, which induces strong perpendicular magnetic anisotropy. The exchange coupling constant (A) and perpendicular anisotropy (K_u) depend strongly on the compositions of the TbCo thin films and temperature variations. For this reason, a coercivity mechanism was considered for amorphous TbCo thin films with perpendicular magnetic anisotropy under the assumption that the inhomogeneous region is caused mainly by local deviations in film composition.

2. Experiments

Amorphous Tb_xCo_{1-x} thin films were deposited on Si substrates by magnetron sputtering with a composite target. The base pressure was 2×10^{-7} Torr. Pre-sputtering was performed to remove any impurities from the target surface. Sputter deposition was carried out by controlling the Ar gas pressure and substrate to target distance. The film thickness was measured from the cross-sectional SEM images of the films. The composition of the Tb_xCo_{1-x} thin films was analyzed by energy dispersive x-ray spectroscopy (EDX). In the films deposited with a composite target, the Tb content changed from 20% to 32% with increasing sputter Ar gas pressure from 3 to 15 mTorr. Magnetic hysteresis loops and initial magnetization curves were measured using a vibrating sample magnetometer with a temperature controlling system. The magnetization and coercivity measurements were taken over the temperature range, −150 ~ 300°C.

3. Results and Discussion

Fig. 1 shows a strong perpendicular magnetic anisotropy of amorphous $Tb_{0.26}Co_{0.74}$ thin films. The amorphous Tb_xCo_{1-x} thin films in the Tb composition range of 20~32% exhibited rectangular hysteresis loops when the magnetic field was applied perpendicular to the film plane. On the other hand, the hysteresis loop measured with the film plane parallel to the applied field direction was not saturated, even at 13 kOe. The magnetic anisotropy constant can be obtained by measuring the anistropy field H_k using equation (4);

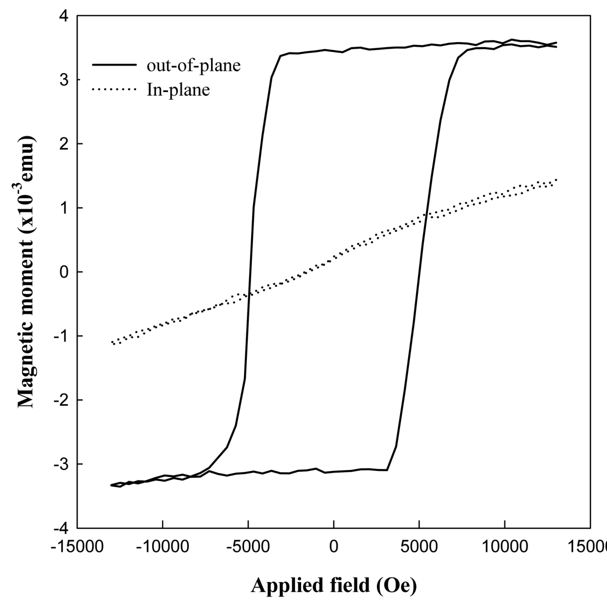

Fig. 1. Out-of-plane and in-plane magnetization hysteresis loops of amorphous $Tb_{0.26}Co_{0.74}$ thin films.

$$H_k = 2K_u/M_s \tag{4}$$

where K_u and M_s are the anisotropy constant and saturation magnetization, respectively. The uniaxial anisotropy field (H_k) of amorphous TbCo thin films was estimated by an extrapolation of the in-plane magnetization hysteresis loops to saturation magnetization, which was determined from the perpendicular magnetization hysteresis loops. The magnetic anisotropy constant (K_u) was calculated using Eq. (4). The K_u of amorphous TbCo thin films is strongly dependent on the Tb content in the films and temperature. The K_u of amorphous Tb_xCo_{1-x} thin films varied from 6×10^5 to 2×10^6 erg/cm^3 with the Tb content from 20 to 32% in the films at room temperature. Fig. 2 shows the temperature dependence of K_u in the $Tb_{0.26}Co_{0.74}$ film, which demonstrates that K_u decreases with temperature.

The saturation magnetization of heavy RE-TM alloys show that the ferrimagnetic order is determined by the strong RE-TM negative exchange interaction. The alloys have compensation points where the saturation magnetization and coercivity approaches zero and infinity, respectively. There are two types of compensation points in amorphous RE-TM alloys with negative exchange coupling between the RE and TM atoms. One is a compensation composition (x_{comp}, 28 atomic % of Tb), which is determined by the balance of the RE and TM moments with a change in composition. The other is a temperature compensation point (T_{comp}), which is determined by the balance of the RE and TM sublattice magnetization

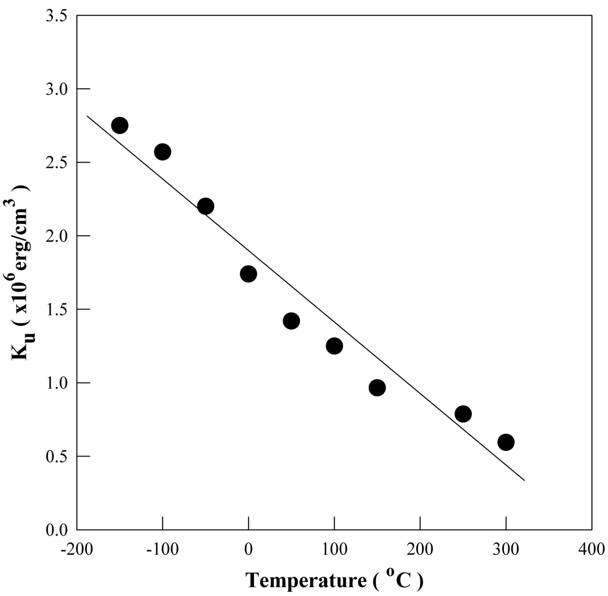

Fig. 2. Temperature dependence of perpendicular anisotropy, K_u, in amorphous $Tb_{0.26}Co_{0.74}$ thin films.

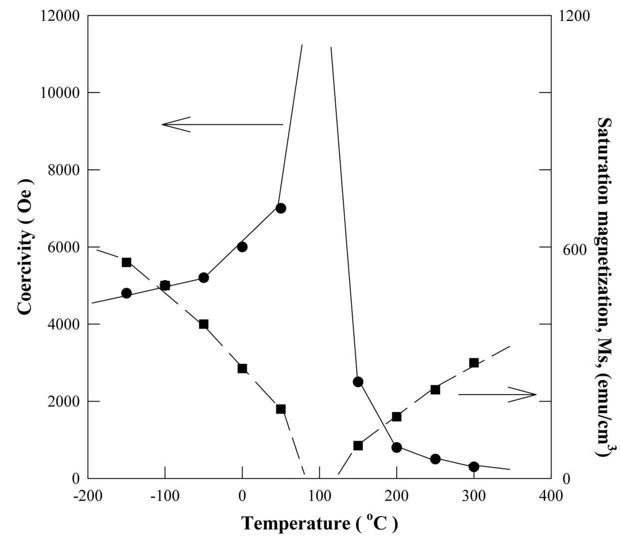

Fig. 3. Temperature dependence of saturation magnetization and coercivity in amorphous $Tb_{0.26}Co_{0.74}$ thin films, where the temperature compensation point (T_{comp}) is approximately 100 °C.

changes with temperature at a particular composition. The net magnetic moment with composition and the net magnetization with temperature in amorphous RE_xTM_{1-x} alloys can be described by the following [7]:

$$\mu_{net} = | \mu_{TM}(1-x) - \mu_{RE}x | \tag{5}$$

$$M_s^{net}(T) = | M_{TM}(T) - M_{RE}(T) | \tag{6}$$

where μ_{TM} and μ_{RE} are the TM and RE magnetic moments. $M_{TM}(T)$ and $M_{RE}(T)$ are the TM and RE sublattice magnetization with temperature. In Fig. 3, the temperature compensation point (T_{comp}) in the $Tb_{0.26}Co_{0.74}$ film appears at approximately 100°C, where the RE and TM moments are balanced, yielding $M_s^{net}(T_{comp}) = 0$ and $H_c(T_{comp}) =$ infinity.

The initial magnetization curves can provide important information on the magnetization reversal process. Fig. 4 shows the initial magnetization curves of demagnetized amorphous Tb_xCo_{1-x} thin films with different coercivities. The initial curves indicate that the magnetization reversal in these films proceeds by the domain wall pinning mechanisms. When an external field is applied, the domain whose magnetization vector is closest to the field direction grows at the expense of those less favorably oriented. Therefore, the process of magnetization is actually one of domain growth and displacement of the domain walls. Domain wall motion is prevented by the domain wall pinning sites at the initial stages of magnetization in demagnetized amorphous Tb_xCo_{1-x} thin films (Fig. 4). The nucleation process for complete magnetization reversal gradually takes place. Figs. 5 and 6 show a linear fit to

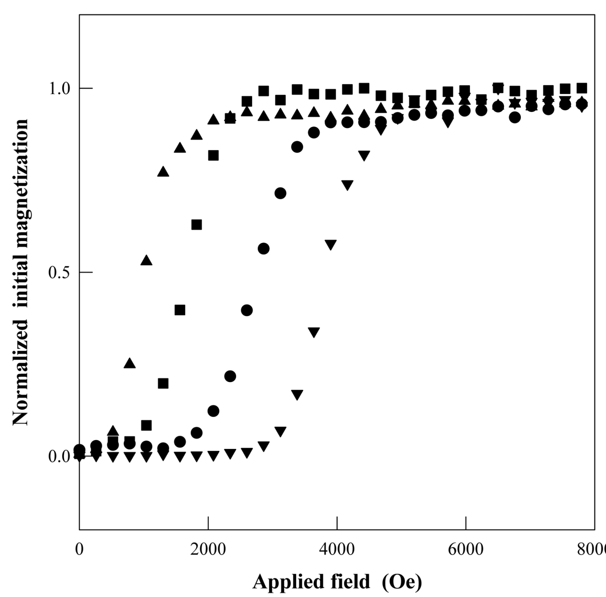

Fig. 4. Initial magnetization curves of the amorphous Tb_xCo_{1-x} thin films with different coercivities.

the experimental data of amorphous $Tb_{0.26}Co_{0.74}$ thin films to predict an inhomogeneity size (r_o), which was obtained from eqs. (2) and (3), respectively. The perpendicular anisotropy (K_u) and saturation magnetization (M_s) were obtained from the perpendicular and in-plane magnetization hysteresis loops at different temperatures. The Co-Co sublattice is the strongest exchange interaction in amorphous Co-based RE-TM alloy thin films [8]. Therefore, the exchange constant (A) was approximated based on the lattice spacing between the Co-Co sublattices to

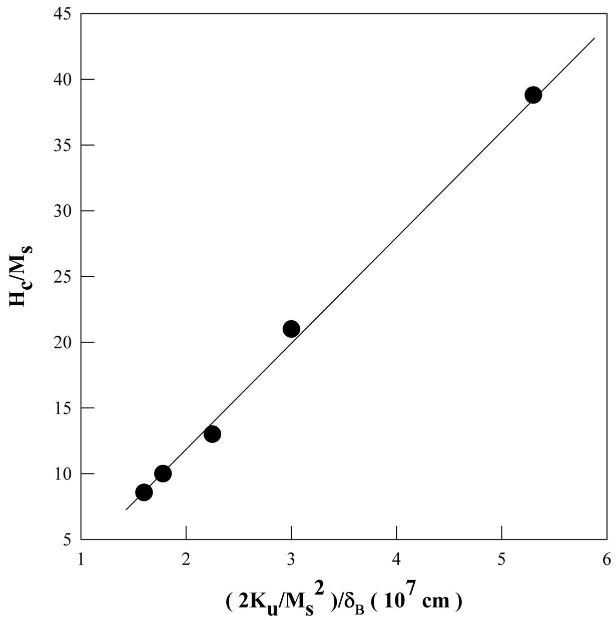

Fig. 5. Linear fit of the coercivity mechanism of amorphous $Tb_{0.26}Co_{0.74}$ thin film obtained from eq. (2).

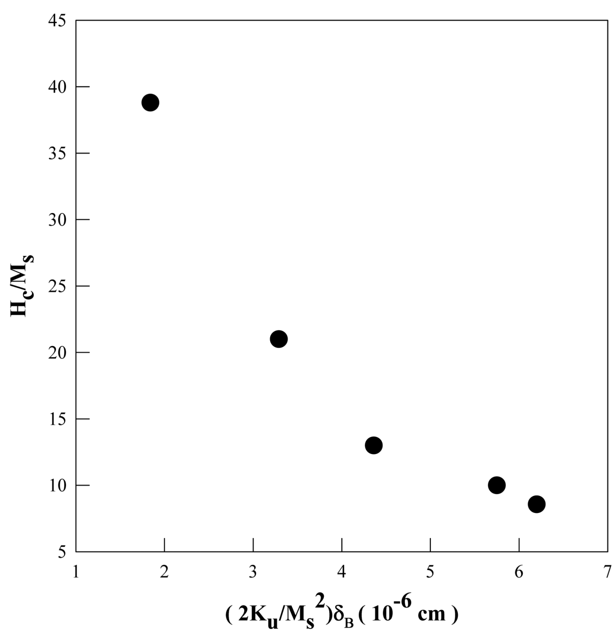

Fig. 6. A linear fit of the coercivity mechanism of amorphous $Tb_{0.26}Co_{0.74}$ thin films obtained from eq. (3).

obtain the domain wall width, $\delta_B=(A/K_u)^{1/2}$. Using the measured values of K_u (Fig. 2), M_s and H_c (Fig. 3), and the estimated exchange constant (A), 3.3 × 10^{-6} erg/cm, the inhomogeneity size in amorphous $Tb_{0.26}Co_{0.74}$ thin film was estimated using eq. (2) for the coercivity depending on r_o being smaller than the wall width δ_B. The κ value was determined based on the maximum and minimum values of A (Max.: 3.3 × 10^{-6} erg/cm, Min: 1.6 × 10^{-5} erg/cm) and Ku (Max.: 2 × 10^6 erg/cm, Min: 6 × 10^5 erg/cm) in the Tb composition range of 20~32% [3]. Using $\kappa = 1$, which means the inhomogeneous region is caused mainly by local deviations in film composition, eq. (2) for amorphous $Tb_{0.26}Co_{0.74}$ thin films was fitted linearly at temperatures below the temperature compensation point (T_{comp}), as shown in Fig. 5. The value of the inhomogeneity size (r_o) was determined from the slope of the linear fit. The size of the inhomogeneity (r_o) obtained from Fig. 5 was approximately 9 nm.

4. Conclusion

The domain wall pinning mechanism in amorphous Tb_xCo_{1-x} thin films with high perpendicular magnetic anisotropy was considered using the coercivity mechanism proposed by Kronmüller *et al.*. From the initial magnetization curves and a linear fit to a coercivity mechanism, it was shown that domain wall pinning was a main contributor to the high coercivity in amorphous TbCo thin films. Using the measured perpendicular magnetic anisotropy constant (K_u), saturation magnetization (M_s) and coercivity (H_c), the inhomogeneity size, which impedes domain wall motion in a TbCo thin film with high coercivity, was estimated to be approximately 9 nm.

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