Magnetic exchange coupling in (Dy,Tb)FeCo magneto-optical recording films

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The required bias field of a sperimagnetic film is governed by a finite exchange coupling coefficient (λ) mainly determined by the subnetwork coupling. From the study of a series of (Dy,Tb)FeCo films at compensation composition, it is found that λ is mainly determined by the concentration of the rare earth components. Moreover, the exchange integral between rare earth and transition metal subnetworks can be derived from λ so that the number of uncertain parameters for mean field modeling is reduced. Accordingly, the bias field required for magneto-optical recording is mainly proportional to λ that can be obtained quantitatively from either measurement and/or mean field modeling. © *1997 American Institute of Physics.* [S0021-8979(97)00806-2]

I. INTRODUCTION

Amorphous TbFeCo alloys are the primary media for magneto-optical (MO) recording because they possess the high coercivity and perpendicular anisotropy required for high density recording.[1] However, bias fields typically larger than 200 Oe, for single-layered TbFeCo media, can limit the potential for direct overwrite using magnetic field modulation. Therefore, reducing the bias field by techniques[2] or developing an alternative medium, which can record at a reasonably low bias field,[3–5] is essential if MO recording is to achieve a useful high data rate.

For MO recording, amorphous DyFeCo films possess higher sensitivities in both the switching field and the write power than TbFeCo films.[3–5] The recording characteristics of (Dy,Tb)FeCo films have been analyzed by mean field modeling, and found to depend on both the anisotropy dispersion of the rare earth (RE) constituents and the exchange integral between RE and transition metal (TM) subnetworks.[5] Measurements of the anisotropy energy constant, K_u, in sperimagnetic films, show apparent dips near the compensation composition (X_{comp}) and the compensation temperature (T_{comp}).[6,7] By considering the canting between RE and TM subnetworks,[6–8] the finite exchange coupling coefficient (λ) is found to be responsible for these apparent dips. The exchange coupling coefficient for TbFeCo films has already been studied qualitatively by Fu *et al.*[8] In this work, both quantitative measurements and mean field calculations of λ were performed to characterize the magnetic properties and the recording characteristics of (Dy,Tb)FeCo films.

II. EXPERIMENT

All the samples and disks of 100 nm $(\mathrm{Dy,Tb})_x(\mathrm{Fe}_y,\mathrm{Co}_{100-y})_{100-x}$ films, with $18 \leq x \leq 28$ and $70 \leq y \leq 90$, were deposited on glass and polycarbonate substrates, respectively, to study their magnetic properties and recording characteristics. The MO active layer was dc magnetron cosputtered from RE and FeCo-composite targets; its composition was determined by inductively coupled plasma—atomic emission spectrometry (ICP-AES). Two silicon nitride layers were deposited to protect the MO active layer by rf magnetron reactive sputtering. The saturation magnetization $M_s(T)$ of the samples was measured with a vibrating sample magnetometer (VSM). The temperature dependence of the coercivity H_c, the anisotropy field H_c^*, and the Kerr angle θ_K (measured with a Kerr loop tracer) were used to derive the compensation temperature, the Curie temperature (T_C), and the compensation composition. The bias field (H_b), CNR, and jitter were measured with a disk tester using light intensity modulation with a laser wavelength of 785 nm and an objective lens of NA=0.55.

The exchange coupling coefficient of (Dy,Tb)FeCo films can be derived experimentally from a plot of the in-plane magnetization ($M_\parallel$) versus the magnetic field (H) applied in the film plane, i.e., $\lambda = H/M_\parallel$, for samples at T_{comp}.[8] For the sake of simplicity, a set of (Dy,Tb)FeCo samples at X_{comp} were selected to measure λ at room temperature (RT). All samples were initially magnetically saturated along the film normal at a temperature different from T_{comp}. The measured λ of the MO layer is the inverse of slope of $M_\parallel(H)$ after subtracting a contribution from the diamagnetic substrate.

III. RESULTS AND DISCUSSION

A. Exchange coupling coefficient λ

The finite exchange coupling coefficient λ of a sperimagnetic film can be derived from the exchange coupling energy between RE and TM subnetwork magnetizations, given by[8]

$$\lambda = 2Z|\vartheta_{\text{RE-TM}}|\cos\langle \phi_{Ku}\rangle / N g_{\mathrm{RE}} g_{\mathrm{TM}} \mu_B^2, \tag{1}$$

(see Fig. 1) where Z is the average number of nearest neighbor atoms, $\vartheta_{\text{RE-TM}}$ is the exchange integral between RE and TM subnetworks, ϕ_{Ku} is the dispersion angle of the RE constituent,[9] $\langle \phi_{Ku}\rangle$ is the average angle of the distributed RE moments, N is the atomic density, g_{RE} and g_{TM} are the gyromagnetic factors, and μ_B is the Bohr magneton. The $\cos\langle \phi_{Ku}\rangle$ term is used for sperimagnetic materials because the exchange coupling energy depends on the average angle between RE and TM subnetworks. All these parameters can

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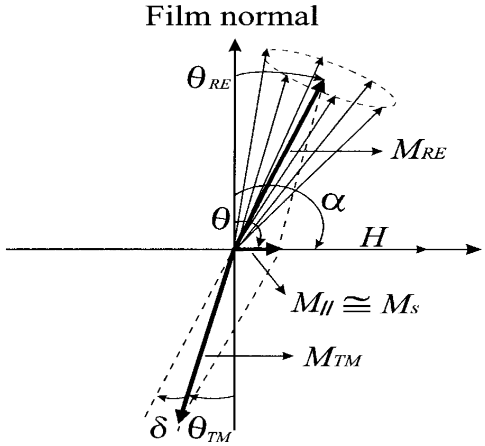

FIG. 1. Definition of exchange coupling coefficient λ of sperimagnetic materials. λ is given by $\lambda \cong H/M_s$.

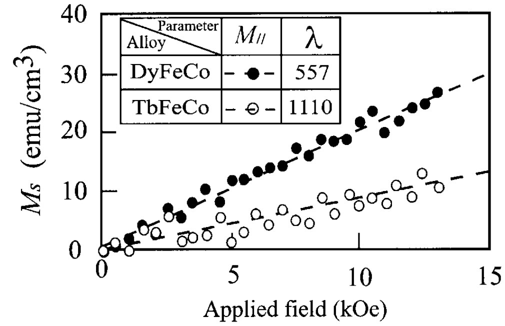

FIG. 2. Measured $M_\parallel$ vs H for $Dy_{23.7}(Fe_{87}Co_{13})_{76.3}$ and $Tb_{23.1}(Fe_{90}Co_{10})_{76.9}$, from which λ is derived. The dashed line is a linear fit to the data.

be obtained from a mean field analysis of the $M_s(T)$ data. Using the values of the relevant parameters listed in Table I, the mean-field-calculated λ is 571 for $Dy_{23.7}(Fe_{87}Co_{13})_{76.3}$, and 1115 for $Tb_{23.1}(Fe_{90}Co_{10})_{76.9}$. Since $|\vartheta_{\text{Dy-TM}}| < |\vartheta_{\text{Tb-TM}}|$ and $\langle \phi_{Ku}\rangle_{\text{Dy}}| > \langle \phi_{Ku}\rangle_{\text{Tb}}|$, the exchange interaction between Dy-TM moments is less than that between Tb-TM moments so that DyFeCo films are more anisotropically dispersive than TbFeCo films.

The magnetic and the MO properties of RE-TM films such as $M_s(T)$, $H_c(T)$, and $\theta_K(T)$, are dependent upon both T_C and T_{comp}. To assess the influence of the RE constituents on the properties of RE-TM films, the (Dy,Tb)FeCo films should have about the same T_C and T_{comp}. $Tb_{23.1}(Fe_{90}Co_{10})_{76.9}$ and $Dy_{23.7}(Fe_{87}Co_{13})_{76.3}$ films, with $T_C \approx 200$ °C and T_{comp}=RT, were chosen to derive λ. The measured values of λ are 557 for DyFeCo, and 1110 for TbFeCo (see Fig. 2). These measured λ are very close to the calculated values shown in Table I. Accordingly, λ can be determined from both measurement and mean field modeling.

B. Constituent dependence of λ

Achieving a data rate of several MBytes/s is still an issue in MO recording using magnetic field modulation direct overwrite. A reduction of the required H_b of MO media is feasible by carefully tailoring the magnetic properties. In a previous work,[5] we reported that the recording characteristics of (Dy,Tb)FeCo films are governed by $\vartheta_{\text{RE-TM}}$ and $\cos\langle\phi_{Ku}\rangle$ upon which λ is dependent. Thus, λ may be related to the required bias field of a sperimagnetic film. The dependence of λ, H_b, and $\Delta T_{\text{comp}}/\Delta\text{RE}$ on the RE components of (Dy,Tb)FeCo films with $T_C \cong 200$ °C and T_{comp} = RT are shown in Fig. 3, where $\Delta T_{\text{comp}}/\Delta\text{RE}$ is the slope of T_{comp} vs RE content. It can be seen that the λ, H_b, and $\Delta T_{\text{comp}}/\Delta\text{RE}$ curves are similar. The measured λ of the TbFeCo film is higher than that of the DyFeCo film by a factor of about 2 (1110 vs 557), as is the required bias field H_b (160 Oe vs 70 Oe). By increasing the Dy at.% in the RE content, $\Delta T_{\text{comp}}/\Delta\text{RE}$ is reduced from about 45 °C/at.% for TbFeCo films to 28 °C/at.% for DyFeCo films. Thus, all λ, H_b, and $\Delta T_{\text{comp}}/\Delta\text{RE}$ decrease with increasing Dy at.% in RE content. Furthermore, the required bias field of sperimagnetic films may also be influenced by T_C. Figure 4 shows the compositional dependence of λ, H_b, and T_C for a set of DyFeCo films with T_{comp}=RT but different T_C. It can be seen that λ increases very slightly with the Co content. Thus, following the above discussion, λ is mainly determined by the RE components, but slightly by the TM components; the higher λ, the higher H_b that is required for recording.

We now consider the correlation among λ, H_b, and $\Delta T_{\text{comp}}/\Delta\text{RE}$ in terms of the subnetwork exchange integrals including $\vartheta_{\text{RE-RE}}$, $\vartheta_{\text{RE-TM}}$, and $\vartheta_{\text{TM-TM}}$, which govern the

TABLE I. Parameters used to derive the exchange coupling coefficient λ of $Dy_{23.7}(Fe_{87}Co_{13})_{76.3}$ and $Tb_{23.1}(Fe_{90}Co_{10})_{76.9}$ films.

Parameter \ RE-TM	Dy	TM	Tb
g	1.33	2	1.5
$\langle\phi_{Ku}\rangle$	50°	0°	35°
$\vartheta_{\text{RE-TM}}$(erg)	-0.55×10^{-15}		-0.95×10^{-15}
Z		12	
N (atoms/cm^3)		6.5×10^{22}	
μ_B (emu)		9.27×10^{-21}	
λ	571		1115

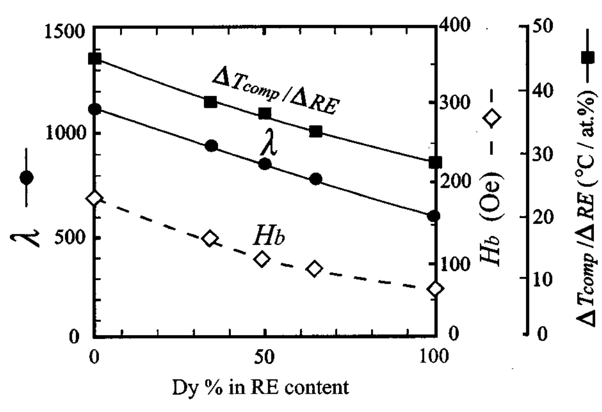

FIG. 3. λ, H_b, and $\Delta T_{\text{comp}}/\Delta\text{RE}$ as a function of Dy/RE in $(\text{Dy},\text{Tb})_x(\text{Fe}_y\text{Co}_{100-y})_{100-x}$ films of $T_C \approx 200$°C, $23 \leqslant x \leqslant 24$ and $87 \leqslant y \leqslant 90$. The solid and dashed curves are a mean-field-calculated fit and a quadratic fit, respectively, to the data.

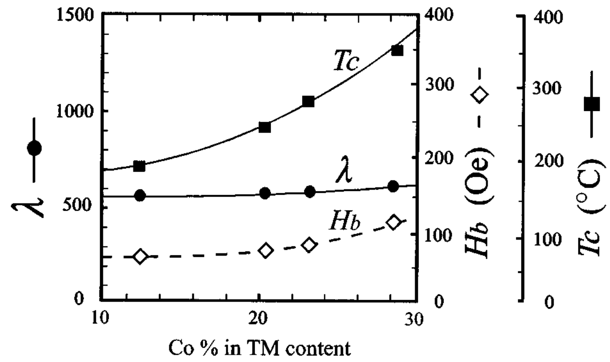

FIG. 4. λ, H_b, and T_C as a function of Co/TM in DyFeCo films. The solid and dashed curves are a mean-field-calculated fit and a quadratic fit, respectively, to the data.

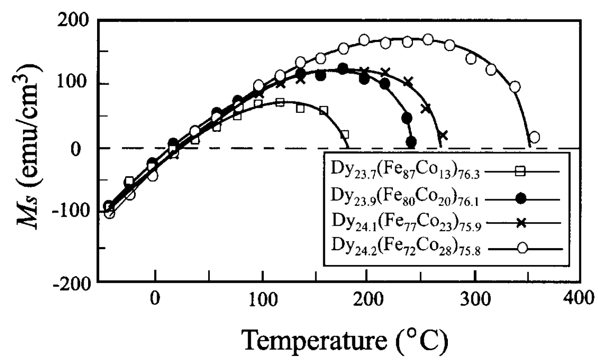

FIG. 6. Temperature dependence of M_s for $Dy_x(Fe_{100-y}Co_y)_{100-x}$ films with $70 \leqslant y \leqslant 90$. The solid curves are mean-field-calculated fits to the data.

RE, TM, and net magnetizations (M_{RE}, M_{TM}, and M_s). For a sperimagnetic film, $M_{RE}(T)$ and $M_{TM}(T)$ contribute oppositely to $M_s(T)$, and $|\vartheta_{RE\text{-}TM}|$ and $|\vartheta_{RE\text{-}RE}|$ are smaller than $|\vartheta_{TM\text{-}TM}|$.[10,11] Thus, the decreasing rate of the $M_{RE}(T)$ at T_{comp} is larger than that of the $M_{TM}(T)$, and usually dominates the decreasing rate of the net magnetization at T_{comp}, $(\partial M_s/\partial T|T_{comp})$. Since $\vartheta_{RE\text{-}TM}$ and $\vartheta_{RE\text{-}RE}$ are magnetically interrelated, $|\vartheta_{RE\text{-}TM}|$ is proportional to $|\vartheta_{RE\text{-}RE}|$.[10,11] The decreasing rate of $M_{RE}(T)$ and $M_s(T)$ are mainly determined by $\vartheta_{RE\text{-}TM}$. When the (Dy,Tb)FeCo films have about the same T_C and T_{comp}, a higher $|\vartheta_{RE\text{-}TM}|$ results in a lower decreasing rate of $M_{RE}(T)$ and a lower $|\partial M_s/\partial T|T_{comp}$. By the equation $\partial M_s/\partial T \cong [\Delta M_s/\Delta \text{RE(at.\%)}] \times [\Delta \text{RE(at.\%)}/\Delta T]$, $\Delta T_{comp}/\Delta \text{RE}$ is inversely proportional to $\partial M_s/\partial T|_{T_{comp}}$. Accordingly, the smaller λ or $|\vartheta_{RE\text{-}TM}|$ of a RE-TM film is, the smaller $\Delta T_{comp}/\Delta \text{RE}$ is. Moreover, it has been reported that the required H_b of a sperimagnetic film is proportional to $\Delta T_{comp}/\Delta \text{RE}$.[1,10] Therefore, H_b is mainly proportional to λ.

C. Mean field analyses with derived $\vartheta_{RE\text{-}TM}$

The mean field model is useful to analyze the magnetic properties of RE-TM films. However, the use of too many uncertain parameters in the analysis will complicate the curve fitting, and may result in errors. A generalized mean field model[11] which contains only five uncertain, constituent dependent parameters was used here. If the number of uncertain parameters can be reduced, good agreement between the experimental data and the mean field calculations can be achieved easily. By Eq. (1), $\vartheta_{RE\text{-}TM}$ is dependent upon λ. Following the discussion in Sec. III A, $\vartheta_{RE\text{-}TM}$ may be derived from a measured λ with the assistance of mean field modeling.

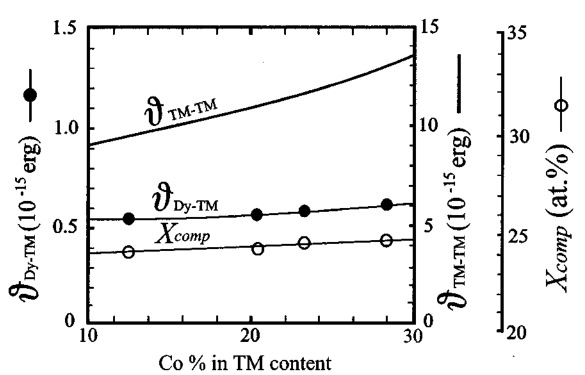

FIG. 5. $\vartheta_{Dy\text{-}TM}$, $\vartheta_{TM\text{-}TM}$, and X_{comp} as a function of Co/TM in DyFeCo films with $80 \leqslant y \leqslant 90$. The solid curves are mean-field-calculated fits to the data.

To assess the validity of the $\vartheta_{RE\text{-}TM}$ derived from the measured λ, the compositional dependence of $\vartheta_{Dy\text{-}TM}$, $\vartheta_{TM\text{-}TM}$, and X_{comp} for $Dy(Fe_yCo_{100-y})$ films with $70 \leqslant y \leqslant 90$ are shown in Fig. 5. The four $\vartheta_{Dy\text{-}TM}$ points are derived from the measured values of λ shown in Fig. 4. The X_{comp} data were determined from the Kerr loop measurements. Since the curve fitting exercise is not very sensitive to $\vartheta_{Dy\text{-}Dy}$, the value of $\vartheta_{Dy\text{-}Dy}$ is assumed to be 0.20×10^{-15} erg. The modeling leaves $\vartheta_{TM\text{-}TM}$ as an adjustable parameter to fit the $M_s(T)$ data. We find that not only the $M_s(T)$ data shown in Fig. 6 but also the experimental data already shown in Figs. 4 and 5 are fitted quite well by the mean-field-calculated results. Thus, the values of $\vartheta_{RE\text{-}TM}$ derived from the measured λ are suitable for mean field modeling.

Following the above discussion, we have now shown that λ, $\vartheta_{RE\text{-}TM}$, and H_b are all correlated. The required bias field H_b of sperimagnetic films is mainly proportional to the exchange coupling coefficient λ that can be obtained quantitatively from either measurement and/or mean field modeling. Moreover, the mean field calculations using values of $\vartheta_{RE\text{-}TM}$ derived from the measured λ can be reliable and meaningful. Thus, once a sperimagnetic system has been characterized in this way, it is possible to predict the fundamental characteristics of a thin film with a given composition, or to find the composition which has the desirable characteristics for a given application.

IV. CONCLUSION

Amorphous (Dy,Tb)FeCo films were fabricated to study their magnetic and recording characteristics. The results show that the magnetic properties of sperimagnetic films are governed by the exchange coupling coefficient λ that is primarily proportional to the subnetwork exchange interaction. Through both quantitative measurements and mean field calculations of λ, we have found that λ is mainly determined by the RE constituents; the higher λ, the higher the value of H_b that is required for MO recording. Moreover, the exchange integral $\vartheta_{\text{RE-TM}}$ derived from the measured values of λ is suitable for mean field modeling. Thus, the magnetic properties (including the required bias field) of a RE-TM thin films are easily determined, and may be further improved through a knowledge of λ and appropriate mean field modeling.

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[1] P. Hansen, C. Clausen, G. Much, M. Rosenkranz, and K. Witter, J. Appl. Phys. **66**, 756 (1989).
[2] S. Ohnuki, K. Shimazaki, N. Ohta, and H. Fujiwara, J. Magn. Soc. Jpn. **15** (Suppl. S1), 399 (1991).
[3] D. Raasch, IEEE Trans. Magn. **MAG-29**, 34 (1993).
[4] M. Tabata, Jpn. J. Appl. Phys. **33**, 5811 (1994).
[5] W. K. Hwang and H. P. D. Shieh, IEEE Trans. Magn. **MAG-31**, 3292 (1995).
[6] T. H. Wu, H. Fu, R. A. Hajjar, T. Suzuki, and M. Mansuripur, J. Appl. Phys. **73**, 1368 (1993).
[7] F. Hellman, Appl. Phys. Lett. **59**, 2757 (1991).
[8] H. Fu, T. H. Wu, and M. Mansuripur, Jpn. J. Appl. Phys. **33**, 2541 (1994).
[9] J. M. D. Coey, J. Appl. Phys. **49**, 1646 (1978).
[10] P. Hansen, S. Klahn, C. Clausen, G. Much, and K. Witter, J. Appl. Phys. **69**, 3194 (1991).
[11] M. Mansuripur and M. F. Ruane, IEEE Trans. Magn. **MAG-22**, 33 (1986).