# Exchange coupling coefficient and domain wall mobility of (Dy,Tb)FeCo magneto-optical films

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The magnetic properties and recording characteristics of (Dy,Tb)FeCo films are dependent upon the anisotropy dispersion of rare earth constituents and the exchange integral between rare earth and transition metal sub networks. The exchange coupling coefficient λ and the domain wall mobility $\mu_{\text{eff}}$ are found to be interrelated by both measurements and calculations. The higher the λ or the lower the $\mu_{\text{eff}}$, the higher bias field that is required for magneto-optical recording. The temperature independent λ is demonstrated to be an important parameter in the assessment of magnetic properties and recording characteristics of sperimagnetic films. © *1997 American Institute of Physics.* [S0021-8979(97)02611-X]

## I. INTRODUCTION

Amorphous (Gd,Tb,Dy)FeCo alloys have been studied intensively for a number of years as erasable media for magneto-optical (MO) recording.[1–4] TbFeCo-based alloys are the primary materials because they possess the high coercivity and perpendicular anisotropy required for high density recording.[1] However, to switch the required bias field (Hb) of typically more than 200 Oe for TbFeCo media at several MHz is still an issue in direct overwrite using magnetic field modulation. Recently, DyFeCo films have been found to possess a higher switching field sensitivity than TbFeCo films.[2–4] It is therefore quite possible that DyFeCo-based films are more suitable for advanced MO recording media.

Magnetic properties and recording characteristics of sperimagnetic films are mainly determined by the exchange coupling coefficient λ,[5–7] which is governed by the sub network exchange interaction. The coefficient λ has been characterized by a set of (Dy,Tb)FeCo films at compensation composition ($X_{\text{comp}}$).[6,7] The experimental results showed that the required Hb of a (Dy,Tb)FeCo film is mainly proportional to its λ,[7] due to the fact that the exchange coupling energy is more important than the anisotropy energy at recording temperature.[1,2,8] From the measured λ, the exchange integral between rare earth (RE) and transition metal (TM) sub networks $\vartheta_{\text{RE-TM}}$, one of the most crucial parameters used in mean-field modeling, can be derived.[7] Thus, a generalized mean field model containing only four constituent dependent parameters is applicable to the performance analysis of a RE-TM film. In a previous work,[4] we reported that the required Hb of (Dy,Tb)FeCo films is mainly determined by domain wall mobility ($\mu_{\text{eff}}$): the higher the $\mu_{\text{eff}}$ of a RE-TM film is, the lower the Hb is required for recording. Since both λ and $\mu_{\text{eff}}$ are dependent upon both $\vartheta_{\text{RE-TM}}$ and the anisotropy dispersion of RE constituents $\cos\langle\phi_{Ku}\rangle$,[4,6,7] the common properties of λ and $\mu_{\text{eff}}$ will be discussed in this article. Great attention should be paid to calibration of the instrument used for the λ measurement, particularly when the compensation temperature ($T_{\text{comp}}$) of the test samples is different from room temperature (RT).

## II. EXPERIMENT

All the disks and samples in this study have been prepared and characterized in the same way as those investigated in the previous work.[7] The exchange coupling coefficient λ 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 their $T_{\text{comp}}$.[5] The test samples were initially magnetically saturated in the film normal direction at a temperature different from $T_{\text{comp}}$. The measured λ is obtained from the inverse of slope of $M_{\parallel}(H)$ for the MO active layer after subtracting the slope contributed by the substrate.

The accuracy of the measured λ is limited by the sensitivity and calibration of the vibrating sample magnetometer (VSM). The smallest detectable signal level of the VSM used is about $2.5\times10^{-5}$ emu. When the geometry of a thin film is about 100 nm (thickness)$\times$1 cm$^2$ (area), the accuracy of the measured magnetization is within $\pm$ 2 emu/cm$^3$. However, the temperature dependent parameters such as the magnetic susceptibility of the sample holder may affect the slope of $M_{\parallel}(H)$. The magnetic susceptibility of a diamagnetic sample holder decreases with increasing temperature. Overestimated (underestimated) λ will be obtained for TM-rich (RE-rich) samples with $T_{\text{comp}}<\text{RT}(T_{\text{comp}}>\text{RT})$, if the VSM is calibrated only at RT. Thus, great care should be taken to obtain λ at different temperatures.

The apparatus used for the measurements of domain wall velocity $\nu$ and mobility $\mu_{\text{eff}}$ is a static tester, composed mainly of a polarizing microscope and an electromagnet providing a magnetic field up to 6 kOe.[9] Domain wall mobility $\mu_{\text{eff}}$ is the derivative of the domain wall velocity $\nu$ with respect to the applied field. This method for the actual velocity/mobility measurements is only applicable to circular domains with diameters larger than 1 $\mu$m. Measurements of

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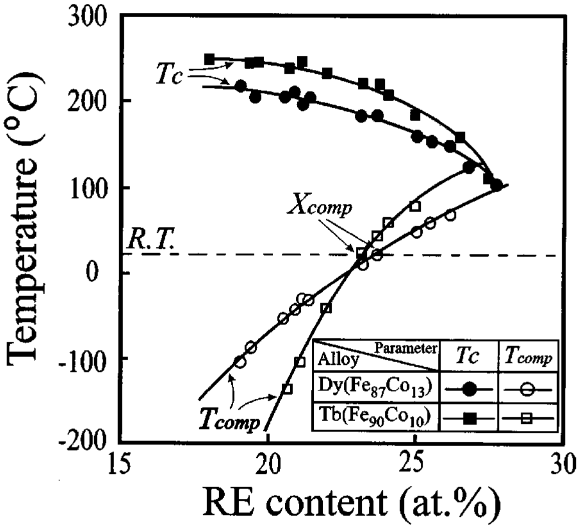

FIG. 1. $Tc$ and $T_{\mathrm{comp}}$ as functions of RE at % for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$, and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films with $18 \leqslant x \leqslant 28$. The solid curves are mean-field-calculated fits to the data.

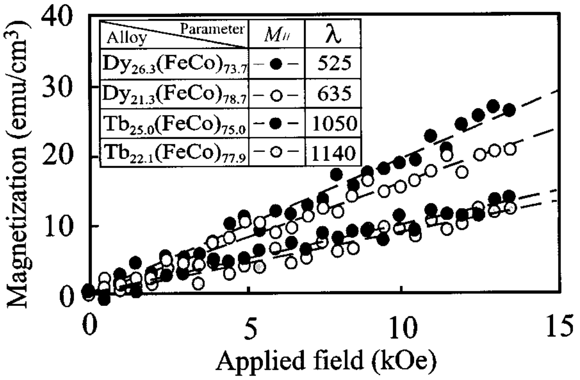

FIG. 3. Measured $M_{\|}$ vs $H$ for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films, from which λ is derived. The dashed lines are linear fits to the data.

sub-$\mu$m domains may result in $\nu$ and $\mu_{\mathrm{eff}}$ being underestimated.[10]

## III. RESULTS AND DISCUSSION

### A. Magnetic characteristics

The mean-field model is useful to analyze the magnetic properties such as $M_s(T)$, $Tc$, and $T_{\mathrm{comp}}$ of RE-TM films which play critical roles in the MO recording characteristics.[1,2,8] The generalized mean-field model containing only four constituent dependent parameters[7,8] is employed to fit the magnetic data of $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films with $18 \leqslant x \leqslant 28$. As shown in Fig. 1, the mean-field-calculated $Tc$ and $T_{\mathrm{comp}}$ are very close to the measured data. Derived from a mean-field analysis, the compositional dependence of $\vartheta_{\text{RE-TM}}$ and $\vartheta_{\text{TM-TM}}$, for the (Dy,Tb)FeCo films discussed in Fig. 1, are shown in Fig. 2. It can be seen that $|\vartheta_{\text{Tb-TM}}|$ is higher than $|\vartheta_{\text{Dy-TM}}|$ by a factor of about 2, meaning $\vartheta_{\text{RE-TM}}$ is mainly determined by the RE constituents, and the exchange interaction strength between Tb-TM sub networks is larger than that between Dy-TM sub networks. Since the exchange integrals are magnetically interrelated and the strong TM-TM interaction can enhance the RE-TM interaction slightly, both $\vartheta_{\text{RE-TM}}$ and $\vartheta_{\text{TM-TM}}$ are reduced with an increasing RE content. However, it has been reported that the magnetic properties and recording characteristics of sperimagnetic films are governed by the exchange integrals, which is mainly proportional to the sub network interaction.[7] Following the good fit shown in Fig. 1, derived values of $\vartheta_{\text{RE-TM}}$ and $\vartheta_{\text{TM-TM}}$, shown in Fig. 2, were used in the following mean-field analyses.

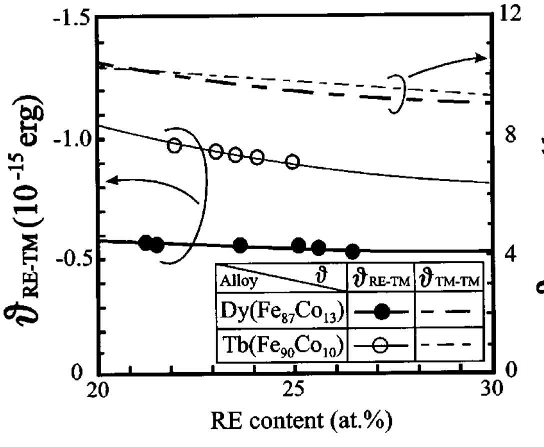

FIG. 2. Derived values of $\vartheta_{\text{RE-TM}}$ and $\vartheta_{\text{TM-TM}}$ as functions of RE at % for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films. All the curves are mean-field-calculated fits to the data. The $\vartheta_{\text{RE-TM}}$ data are derived from the measured λ in Fig. 4.

### B. Exchange coupling coefficient λ

In a previous work, we reported that the exchange integral between RE and TM sub networks $\vartheta_{\text{RE-TM}}$ can be obtained experimentally from the exchange coupling coefficient λ.[7] To characterize (Dy,Tb)FeCo films, λ can be derived from the exchange coupling energy between RE and TM sub networks, given by[5–7]

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

where $Z$ is the average number of nearest neighbor atoms, $\vartheta_{\text{RE-TM}}$ is the exchange integral between RE and TM sub networks, $\phi_{Ku}$ is the dispersion angle of the RE constituent, $\langle\phi_{Ku}\rangle$ is the average angle of the distributed RE moments, $N$ is the atomic density, $g_{\text{RE}}$ and $g_{\text{TM}}$ are the gyromagnetic factors, and $\mu_B$ is the Bohr magneton. From Eq. (1), λ is dependent upon $\vartheta_{\text{RE-TM}}$ and $\cos\langle\phi_{Ku}\rangle$,[6,7] but is independent of temperature.[5] Thus, λ can be obtained at any temperature.

The recording characteristics of RE-TM films depend not only on the RE constituents, but also on the RE/TM ratio. To derive λ from $M_{\|}(H)$, Fig. 3 plots the in-plane magnetization $M_{\|}$ versus the applied field $H$ for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films at their $T_{\mathrm{comp}}$. The measured $M_{\|}$ for a typical MO sample at a magnetic field of 13.5 kOe is about 10–30 emu/cm³, but the ± 2 emu/cm³ noise level may result in an error of 6%–20% in the slope of $M_{\|}(H)$. A linear fit is used here to suppress

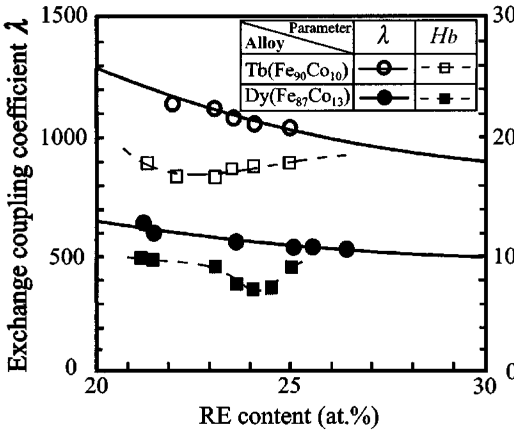

FIG. 4. The coefficient λ and bias field Hb as functions of RE at % for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films with $21 \leqslant x \leqslant 27$. The solid lines are mean-field-calculated fits to the data, dashed lines are used to connect data points. The Hb data were reported in Ref. 4.

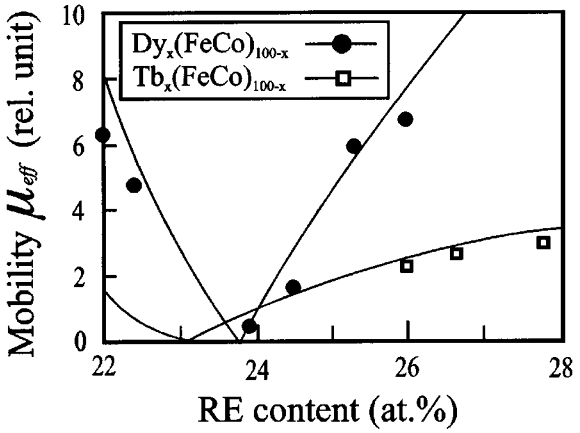

FIG. 5. Compositional dependence of $\mu_{\rm eff}$ for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films with $22 \leqslant x \leqslant 28$. The solid curves are mean-field-calculated fits to the data.

the random noise, achieving a more accurate measurement of λ. To perform a systematic characterization of λ, Fig. 4 shows the compositional dependence of λ for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films with $21 \leqslant x \leqslant 27$. It can be seen that the mean-field-calculated λ (solid curve) agrees well with the data. The exchange coupling coefficient λ of TbFeCo films is about twice that of DyFeCo films in this composition range, implying that λ is mainly determined by the RE constituents. However, at a given Fe to Co ratio, an increase in the RE to TM ratio lowers the TM-TM interaction (and therefore reduces $\vartheta_{\text{TM-TM}}$). Since the exchange integrals are magnetically interrelated, $\vartheta_{\text{RE-TM}}$ and $\vartheta_{\text{TM-TM}}$ (shown in Fig. 2) change with the same trend as λ (shown in Fig. 4). The terms $\vartheta_{\text{RE-TM}}$, $\vartheta_{\text{TM-TM}}$, and λ are decreased slightly with an increasing RE content. Moreover, the required Hb for the $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films, in the compositional range $22 < x < 25$ (shown in Fig. 4) is about twice that for the $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ films. Thus, the required Hb of the (Dy,Tb)FeCo films is mainly proportional to the exchange coupling coefficient λ. Since the $\vartheta_{\text{RE-TM}}$ data shown in Fig. 2 are derived from the measured λ shown in Fig. 4, sperimagnetic films can be characterized quantitatively by λ.

### C. Domain wall mobility $\mu_{\rm eff}$

Domain wall mobility $\mu_{\rm eff}$ is an important parameter in determining the recording characteristics of MO media. For a two sub network system of RE-TM alloys, $\mu_{\rm eff}$ is given by[11,12]

$$\mu_{\rm eff}=\frac{Ms}{M_{\rm RE}\alpha_{\rm RE}/\gamma_{\rm RE}+M_{\rm TM}\alpha_{\rm TM}/\gamma_{\rm TM}}\sqrt{\frac{A}{Ku}}$$

$$\propto\frac{1}{\alpha_{\rm RE}}\sqrt{\vartheta_{\text{RE-TM}}\cos\langle\phi_{Ku}\rangle/Ku}, \qquad (2)$$

where $M_{\rm RE}$ and $M_{\rm TM}$ are the magnetizations of the RE and TM sub networks, respectively, and $\alpha$ and $\gamma$ are the damping parameter and the gyromagnetic ratio of each sub network, respectively. As shown in Eqs. (1) and (2), both λ and $\mu_{\rm eff}$ are dependent upon both $\vartheta_{\text{RE-TM}}$ and $\cos\langle\phi_{Ku}\rangle$. There are some properties in common between λ and $\mu_{\rm eff}$.

It has been observed that the measured velocity (or mobility) of recorded domains is very dependent upon the measurement technique.[9,10] Here we estimate the relative values of $\mu_{\rm eff}(T)$ for $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films from the $\gamma_{\rm Dy}:\gamma_{\rm Tb}=8:9$ and $\alpha_{\rm Dy}:\alpha_{\rm Tb}=9:10$ that are used in the mean-field modeling. As shown in Fig. 5, the compositional dependent $\mu_{\rm eff}$ of $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ films at RT is larger than that of $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films by a factor of about 2, implying that recorded domains in DyFeCo films are more field sensitive than those in TbFeCo films.

In the previous work,[4] we found that the recording characteristics of (Dy,Tb)FeCo films were also influenced by domain wall motion. When the total force, $F_t^*(T)$, acting on the domain wall is larger than the coercive force, $2M_s(T)Hc'(T)$, during thermomagnetic recording, the domain wall velocity $v(T)$ is given by[10]

$$v(T)=\mu_{\rm eff}(T)[H-Hc'(T)],$$

$$\text{when } F_t^*(T)>2M_s(T)Hc'(T). \qquad (3)$$

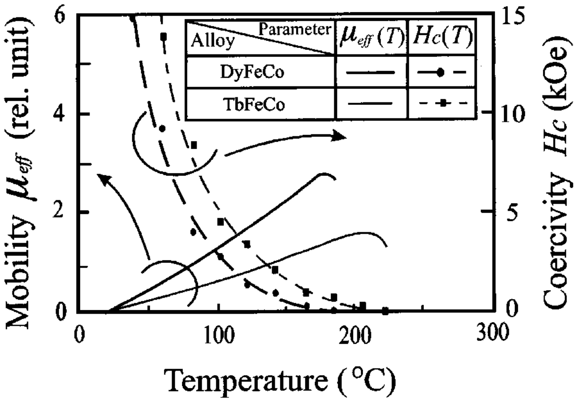

FIG. 6. The terms $\mu_{\rm eff}(T)$ and $Hc(T)$ of $\mathrm{Dy}_{23.7}(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{76.3}$ and $\mathrm{Tb}_{23.1}(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{76.9}$ films. The solid and dashed curves are mean-field-calculated and quadratic fits, respectively, to the data.

Here $Hc'(T)$ is the dynamic coercivity of the recorded domain that is not equal to, but still proportional to, the measured $Hc(T)$. Within the temperature range $(Tc - 40\,°\mathrm{C}) < T < Tc$ where the final domain size is determined, the $\mu_{\mathrm{eff}}(T)$ and $Hc(T)$ for $\mathrm{Dy}_{23.7}(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{76.3}$ are about two and one half of that for $\mathrm{Tb}_{23.1}(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{76.9}$, respectively (shown in Fig. 6). If the applied field for $\mathrm{Dy}_{23.7}(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{76.3}$ is 1/2 of that for $\mathrm{Tb}_{23.1}(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{76.9}$, then the domain wall velocities of both films will be about the same. Readout signal is proportional to mark size in optical recording. Thus, to reach the same domain size, DyFeCo films need an Hb of only about one half of that for TbFeCo films. Therefore, the parameter $\mu_{\mathrm{eff}}(T)$ can also be used like $\lambda$ to characterize the recording performance of (Dy,Tb)FeCo films.

Based on the above discussion, the magnetic properties and recording characteristics of (Dy,Tb)FeCo films can be assessed by both $\mu_{\mathrm{eff}}(T)$ and $\lambda$. The experimental results indicate that the higher the $\mu_{\mathrm{eff}}(T)$ or the lower the $\lambda$ of a sperimagnetic film, the lower the Hb that is required for MO recording. Furthermore, the temperature independent $\lambda$ is a good parameter to assess the magnetic properties and recording characteristics of sperimagnetic films. Therefore, both the magnetic and the MO performance of sperimagnetic films can be easily determined, and may be further improved by systematic characterization of exchange coupling coefficient $\lambda$.

## IV. CONCLUSION

Amorphous $\mathrm{Dy}_x(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{100-x}$ and $\mathrm{Tb}_x(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{100-x}$ films, with $18 \leqslant x \leqslant 28$, were fabricated to study their magnetic and recording characteristics. Both the exchange coupling coefficient ($\lambda$) and the domain wall mobility ($\mu_{\mathrm{eff}}$) were related to the anisotropy dispersion of the RE constituent, $\cos\langle\phi_{Ku}\rangle$, and the exchange integral between RE and TM sub networks, $\vartheta_{\text{RE-TM}}$. The experimental results have shown that the exchange coupling coefficient and the mobility of $\mathrm{Dy}_{23.7}(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{76.3}$ films are about one half and two times those of $\mathrm{Tb}_{23.1}(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{76.9}$ films, respectively. As a result, the required bias field Hb for $\mathrm{Dy}_{23.7}(\mathrm{Fe}_{87}\mathrm{Co}_{13})_{76.3}$ films is about one half of that for $\mathrm{Tb}_{23.1}(\mathrm{Fe}_{90}\mathrm{Co}_{10})_{76.9}$ films, implying that the higher $\mu_{\mathrm{eff}}(T)$ or the lower $\lambda$ of a RE-TM film, the lower Hb that is required for MO recording. Furthermore, the temperature independent $\lambda$ is a good parameter to assess the magnetic properties and recording characteristics of sperimagnetic films.

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[1] P. Hansen, C. Clausen, G. Much, M. Rosenkranz, and K. Witter, J. Appl. Phys. **66**, 756 (1989).
[2] P. Hansen, S. Klahn, C. Clausen, G. Much, and K. Witter, J. Appl. Phys. **69**, 3194 (1991).
[3] D. Raasch, IEEE Trans. Magn. **MAG-29**, 34 (1993).
[4] W. K. Hwang and H. P. D. Shieh, IEEE Trans. Magn. **MAG-31**, 3292 (1995).
[5] H. Fu, T. H. Wu, and M. Mansuripur, Jpn. J. Appl. Phys. **33**, 2541 (1994).
[6] W. K. Hwang, T. H. Wu, and H. P. D. Shieh, J. Magn. Soc. Jpn. **20S1**, 157 (1996).
[7] W. K. Hwang and H. P. D. Shieh, J. Appl. Phys. **81**, 2745 (1997).
[8] M. Mansuripur and M. F. Ruane, IEEE Trans. Magn. **MAG-22**, 33 (1986).
[9] H. P. D. Shieh and M. H. Kryder, IEEE Trans. Magn. **MAG-24**, 2464 (1988).
[10] M. Du, M. D. Schultz, and M. H. Kryder, Jpn. J. Appl. Phys. **32**, 5202 (1993).
[11] R. S. Weng and M. H. Kryder, IEEE Trans. Magn. **MAG-29**, 2177 (1993).
[12] R. Giles and M. Mansuripur, Comput. Phys. **5**, 204 (1991).