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Direct Measurement of Subnetwork Exchange Coupling Constant for Ferrimagnets

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We show that the subnetwork exchange coupling constant λ of ferrimagnetic films is equal to the slope of the plot of the magnetic field H applied in the film plane versus the in-plane magnetization $M_{/\!/}$ at compensation temperature $T_{\rm comp}$, i.e. $H=\lambda M_{/\!/}$ at $T_{\rm comp}$. This finding enables the direct measurement of λ for ferrimagnetic magneto-optical recording thin films, regardless of the complexity of the two-subnetwork problem. The experimental results are within the range predicted by the mean-field theory.

KEYWORDS: exchange coupling constant, canting of magnetic subnetworks, magneto-optical recording medium

Since Rinaldi and Pareti[1] showed that the exchange coupling between the magnetic rare-earth (RE) and transition-metal (TM) subnetworks is not so strong as to hold the two magnetizations strictly anti-parallel, it has been recognized that the subnetwork properties are more fundamental than the gross quantities in characterizing the ferrimagnetic RE-TM samples. The reason is that the small canting between the RE and TM subnetworks caused by the finite exchange coupling can significantly affect the validity of models based on a single subnetwork, especially in the vicinity of the compensation point. A particular interesting example is provided by the measurements of the intrinsic magnetic anisotropy energy constant K_u. As Sarkis and Callen first pointed out,[2] if one neglects the canting between RE and TM subnetworks and uses the single subnetwork Stoner-Wohlfarth model,[3] then the canting causes an apparent drop in K_u near compensation, and at the exact compensation point K_u drops to zero. This apparent behavior was also observed and discussed by other researchers.[4–6] In a recent work we showed that the apparent behavior of K_u depends on the technique used in the measurement.[7] For example, K_u measured by torque magnetometry shows a dip as found in refs. 2, 4, 5 and 6, but if K_u is measured by the extraordinary Hall effect, then K_u versus temperature or composition will show an apparent dip in the TM-rich side and an apparent peak in the RE-rich side.[7] It should be emphasized that these apparent dips and peaks in K_u are not physical: they appear simply because the small canting was neglected in the single subnetwork model (based on which K_u is defined and deduced), so that the consequences of the existing canting was improperly attributed to the decrease or increase of K_u. The energy required to change the magnetic spin orientation (i.e. the physical anisotropy energy) does not drop. In order to get rid of the non-physical behavior and correctly characterize the magnetic properties of the sample, one has to use the canting model[2] (i.e. a generalized version of the Stoner-Wohlfarth model with two subnetworks), which takes into account the individual directions of the RE and TM subnetworks. The purpose of the present paper is to describe a simple method by which one can measure the exchange coupling constant between the RE and TM subnetworks, which is a key parameter in the canting model. To our knowledge this is the first report on the direct measurement of this constant.

Let $M_{\rm R}$ and $M_{\rm T}$ be the respective RE and TM subnetwork magnetizations, and let $K_{\rm R}$ and $K_{\rm T}$ be the corresponding subnetwork anisotropy constants. For the RE-rich geometry (see Fig. 1), the total energy of the two-subnetwork system is written

$$\begin{aligned}E_{\rm tot}=&-H[M_{\rm R}\cos(\alpha-\theta_{\rm R})-M_{\rm T}\cos(\alpha-\theta_{\rm T})]\\&+[K_{\rm R}\sin^2\theta_{\rm R}+K_{\rm T}\sin^2\theta_{\rm T}]\\&+2\pi(M_{\rm R}\cos\theta_{\rm R}-M_{\rm T}\cos\theta_{\rm T})^2\\&-\lambda M_{\rm R}M_{\rm T}\cos(\theta_{\rm R}-\theta_{\rm T}),\end{aligned}\tag{1}$$

where H is the magnitude of the applied magnetic field; α, $\theta_{\rm R}$ and $\theta_{\rm T}$ describe the directions of the applied magnetic field and the subnetwork magnetizations (see Fig. 1). The first three terms in eq. (1) are the external, anisotropy and demagnetizing energy density. The last term $\lambda M_{\rm R}\cdot M_{\rm T}$ is the exchange coupling energy density between the RE and TM subnetworks and λ is the dimensionless (in cgs) exchange coupling constant. This constant characterizes the strength of canting and is the key parameter in the model. However, it is usually estimated based on the mean-field theory,[6,7] and has never been directly measured for magneto-optical recording media.

Let us first present the mean-field theory value for λ.

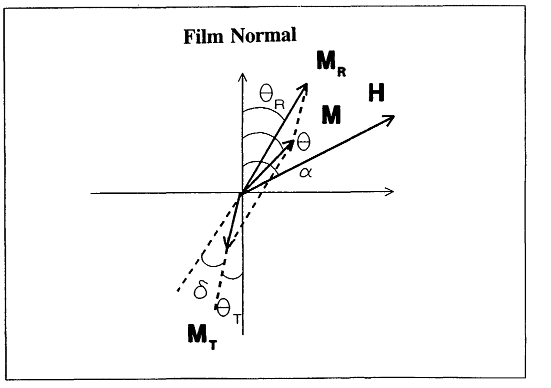

Fig. 1. Definitions of the field direction angle α, and orientation angles $\theta_{\rm R}$ and $\theta_{\rm T}$ for RE and TM subnetworks. δ is the small canting angle between the RE and TM subnetworks. M is the net magnetization vector and θ is its directional angle. This geometry applies for RE-rich case.

By calculating the exchange energy between RE and TM ions per unit volume, one can show that the dimensionless coupling constant λ is given by

$$\lambda=\frac{2(Z+1)|J_{\text{RE-TM}}|}{Ng_{\text{RE}}g_{\text{TM}}\mu_{\text{B}}^2}, \qquad (2)$$

where Z is the coordination number (average number of nearest neighbor atoms), $2J_{\text{RE-TM}}$ the exchange energy per RE-TM pair, N the total atomic number density, g_{RE} and g_{TM} the gyromagnetic factors, and μ_{B} ($=9.27\times10^{-21}$ emu) the Bohr magneton. The various numbers for a specific RE-TM material can be found in ref. 8. For $Tb_x(FeCo)_{1-x}$, we have $Z\simeq12$, $J_{\text{RE-TM}}\simeq-10^{-15}$ erg, $g_{\text{RE}}=1.5$, $g_{\text{TN}}\simeq2$. Thus, using $N=10^{23}$ cm^{-3}, we have $\lambda\simeq10^3$. An important property shown by eq. (2) is that λ is independent of temperature. This property allows us to measure λ at any particular temperature (*e.g.* at the compensation temperature T_{comp}) and still obtain the general result. The temperature dependence of exchange energy $\lambda M_{\text{R}}\cdot M_{\text{T}}$ is contained in M_{R} and M_{T}.

The solution for θ_{R} and θ_{T} of eq. (1) can be found by minimizing E_{tot} with respect to θ_{R} and θ_{T}. Since we will be interested in the case at compensation, where both θ_{R} and θ_{T} are very small (*e.g.* $<1°$), we can solve θ_{R} and θ_{T} analytically by neglecting $O(\theta_{\text{R}}^2)$ and $O(\theta_{\text{T}}^2)$ terms. The solution in the RE-rich case ($M_{\text{R}}\geq M_{\text{T}}$) can be written as follows:

$$\theta_{\text{R}}=\frac{H\sin\alpha\,(\lambda M_{\text{s}}+H_{\text{T}}-H\cos\alpha)}{\lambda(2K_{\text{R}}+2K_{\text{T}}-4\pi M_{\text{s}}^2+HM_{\text{s}}\cos\alpha)+(H_{\text{T}}-H\cos\alpha+4\pi M_{\text{s}})(H_{\text{R}}+H\cos\alpha-4\pi M_{\text{s}})}$$
$$\theta_{\text{T}}=\frac{H\sin\alpha\,(\lambda M_{\text{s}}-H_{\text{R}}-H\cos\alpha)}{\lambda(2K_{\text{R}}+2K_{\text{T}}-4\pi M_{\text{s}}^2+HM_{\text{s}}\cos\alpha)+(H_{\text{T}}-H\cos\alpha+4\pi M_{\text{s}})(H_{\text{R}}+H\cos\alpha-4\pi M_{\text{s}})} \qquad (3)$$

where we have used $H_{\text{R}}=2K_{\text{R}}/M_{\text{R}}$ and $H_{\text{T}}=2K_{\text{T}}/M_{\text{T}}$. Equation (3) is for $M_{\text{R}}>M_{\text{T}}$, but the solution for the case $M_{\text{R}}<M_{\text{T}}$ can be obtained simply by making the change $R\leftrightarrow T$ in the subscripts. Equation (3) contains actually four unknowns: λ, M_{R} or M_{T} (since $M_{\text{s}}=|M_{\text{R}}-M_{\text{T}}|$ can be measured by VSM), K_{R} and K_{T}; so it is usually a complicated problem to determine λ experimentally. However, eq. (3) simplifies drastically if we keep the sample at T_{comp} and apply an external field in the film plane. In this case $M_{\text{R}}=M_{\text{T}}(M_{\text{s}}=0)$ and $\alpha=90°$, and the total in-plane magnetization component $M_{/\!/}$ resulting from the canting between RE and TM is given by

$$M_{/\!/}=M_{\text{R}}\sin\theta_{\text{R}}-M_{\text{T}}\sin\theta_{\text{T}}\simeq\frac{H}{\lambda}\quad(\text{at } T=T_{\text{comp}}) \qquad (4)$$

In eq. (4) we have neglected a term $Q=2K_{\text{R}}K_{\text{T}}/[M_{\text{R}}M_{\text{T}}(K_{\text{R}}+K_{\text{T}})]$ in comparison with λ in the denominator. This is accurate ($Q=0$) in the case of $K_{\text{T}}=0$. For another extreme case of $K_{\text{T}}=K_{\text{R}}$, we have $Q=4K_{\text{R}}/M_{\text{R}}^2$. Consider a typical case of $K_{\text{R}}\simeq10^6$ erg cm^{-3} and $M_{\text{R}}\simeq10^3$ emu cm^{-3}, we find $Q=4$, which is still much smaller than $\lambda(\simeq10^3)$. Equation (4) shows that, if we measure $M_{/\!/}$ as a function of H at T_{comp} and plot H vs $M_{/\!/}$ (a straight line), then λ is precisely the slope. This simple relation enables us to measure λ directly.

We have measured two amorphous samples which are of interest for magneto-optical recording: $Tb_{21.4}(FeCo)_{78.6}$ and $Tb_{24.9}(FeCo)_{75.1}$. Both samples are 800 Å thick and are sputter-deposited on silicon substrates. The values of T_{comp} for these two samples are found to be -19°C and $+87$°C, respectively, by measuring the remanent magnetization versus temperature. For measurements of λ we kept the samples at their compensation temperature. The external field strength H was varied from 0 to 14 kOe along a fixed direction in the film plane ($\alpha=90°$). The in-plane magnetization component $M_{/\!/}$ was measured by VSM. Since the sample was kept at T_{comp}, the perpendicular magnetization component is of the second order [combinations of $O(\theta_{\text{R}}^2)$ and $O(\theta_{\text{T}}^2)$], which is much smaller than the first order in-plane component $M_{/\!/}$. This assures that the measured value for $M_{/\!/}$ is solely due to the canting of the subnetworks, but not due to the projection of the perpendicular component

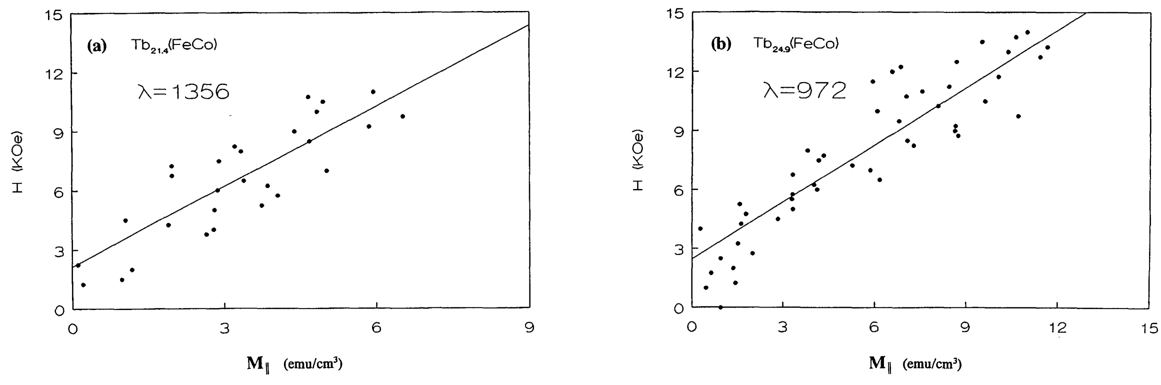

Fig. 2. The applied field strength H versus the measured in-plane magnetization $M_{/\!/}$. The slope of the average data points is equal to the exchange coupling constant λ. (a) $\lambda=1356$ for $Tb_{21.4}(FeCo)_{78.6}$. The data were measured at $T_{\text{comp}}=-19$°C. (b) $\lambda=972$ for $Tb_{24.9}(FeCo)_{75.1}$. The data were measured at $T_{\text{comp}}=+87$°C.

which may result from misalignment of the sample. In order to eliminate the magnetization of the silicon substrate induced by the external field, we first applied the field in the perpendicular direction (i.e. the film normal direction) and measured the perpendicular magnetization. Since the sample is at T_{comp}, these measured data give permeability of substrate. We then subtract the slope due to substrate in the corresponding in-plane measurement and found $M_{/\!/}$. This procedure of eliminating the induced magnetization can be applied to both diamagnetic and paramagnetic substrates.

The measured data for the two samples are presented in Figs. 2(a) and 2(b). Though the measured signal from the VSM is fluctuating, the trend that the average data of $M_{/\!/}$ increases linearly with increasing H is clearly observed. From the slope we found $\lambda=1356$ for $Tb_{21.4}(FeCo)_{78.6}$ and $\lambda=972$ for $Tb_{24.9}(FeCo)_{75.1}$. The two values are of the same order of magnitude as estimated by eq. (2).

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