Estimation of Exchange Coupling Distribution in All-Ferromagnetic Bilayers

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Methodology for identification of interfacial exchange coupling distribution in all-ferromagnetic bilayers is proposed. The method is simple and requires only a basic set of hysteretic loop measurements as input data.

***Index Terms*—All-ferromagnetic bilayers, antiferromagnetic coupling, exchange bias.**

I. Introduction

ALL-FERROMAGNETIC bilayer structures, formed by antiferromagnetically coupling soft and hard ferromagnetic materials (AFC), are important in magnetic recording [1] and very convenient for studying the physics of exchange bias [2], [3]. The exchange bias effect in these structures can be tuned reversibly through the applied field history, without the thermal preprocessing required in the conventional antiferromagnetic-ferromagnetic compound structures [4]. To model the full observed complexity of this tuning process, it is necessary to account for the dispersion of interlayer exchange coupling [5]–[8]. The question naturally arises: Can such a coupling distribution be estimated from experimentally measured hysteresis loops?

A technique for estimation of interlayer exchange coupling distribution has recently been proposed using a model system of the AFC [9]. The model viewed the hard layer (HL) as a collection of independent magnetic grains represented by elementary hysteresis loops. All interactions between the HL grains were ignored, and hysteresis loops of grains were assumed symmetric. In the present paper, we generalize the original model by disposing of any assumptions regarding the nature of interactions within the HL layer. It is demonstrated that the developed identification method does not require any parameter fitting and is based on relatively easily obtainable set of experimental data.

II. Experimental Data Set for Identification

We first define the measurement data set required for identification of exchange coupling distribution. The soft layer (SL) and hard magnetic materials composing the AFC media are designed to have different ranges of switching fields [2], [3]. The training effects in the AFC materials we consider are small [10] and can be ignored. Thus it is possible to control the magnetic states of the two layers independently. While the state of the HL can be changed only at high external fields which fully saturate SL, the SL reversal takes place at much smaller fields insufficient to change the state of the HL. However, due to the presence of antiferromagnetic coupling between the layers, the change of the HL state results in a shift of the SL loop from the coordinate origin. As shown in Fig. 1(A), the position of the SL loop along the vertical axis is measured in the units of magnetization and is a direct measure of the HL remanent magnetization M_{r}. On the other hand, the bias field H_{b} (the horizontal shift, of the SL loop) is measured in the field units and is a measure of the exchange bias.

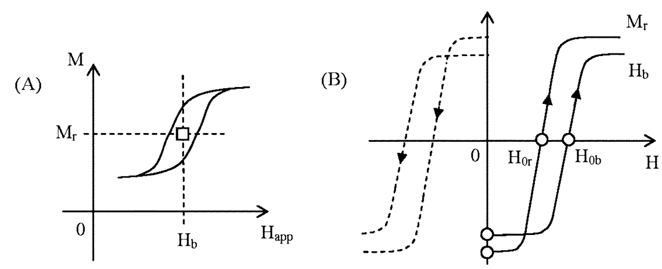

Fig. 1. (A) Schematics of the SL hysteresis loop. Vertical shift is a measure of the HL remanent magnetization M_{r} and horizontal shift is a measure of the exchange bias field H_{b}. (B) illustration of the typical M_{r} and H_{b} versus HL preset field H dependence obtained for increasing (solid line) and decreasing (dashed line) H starting, respectively, from negative and positive HL saturation. In (B), the saturation values are $M_{\mathrm{r}} = \pm 1$ and $H_{\mathrm{b}} = \pm H_{\mathrm{b}}^{\max}$. The preset field value $H_{0\mathrm{r}}$ corresponds to $M_{\mathrm{r}} = 0$, while $H_{0\mathrm{b}}$ corresponds to $H_{\mathrm{b}} = 0$.

Thus, an arbitrary HL magnetization state can be preset at high magnetic fields H in a first (bias setting) step and both quantities, $M_{\mathrm{r}}(H)$ and $H_b(H)$, can subsequently be obtained from the SL loop measurement at low fields H_{app} [2], [3]. The identification method to be discussed is based on the specific experimental data set generated by 1) setting the HL to a full negative saturation, 2) increasing the preset field to a value H, 3) reducing the H to zero and 4) recording the SL loop by applying a small field $|H_{\mathrm{app}}| \ll H$, sufficient to magnetize the SL only. $M_{\mathrm{r}}(H)$ and $H_{\mathrm{b}}(H)$ values are obtained from this SL loop. The steps 1–4 are then repeated while incrementing H towards positive HL saturation. Typical $M_{\mathrm{r}}(H)$ and $H_{\mathrm{b}}(H)$ responses obtained by this process are illustrated schematically in the Fig. 1(B) (solid line). Slopes of the curves, i.e., the derivatives dM_{r}/dH and dH_{b}/dH, will be denoted respectively by χ_{r} and χ_{b}. It will be demonstrated below that these slopes together with the saturation value of the bias field $H_{\mathrm{b}}^{\max}$ and the preset fields $H_{0\mathrm{r}}$ and $H_{0\mathrm{b}}$, such that $M_{\mathrm{r}}(H_{0\mathrm{r}}) = 0$ and $H_{\mathrm{b}}(H_{0\mathrm{b}}) = 0$ respectively, are the data required to find the variance of the exchange bias.

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III. Model of the HL Distribution and Exchange Bias in AFC

In this section, our goal is to relate the remanent HL magnetization $M_{\rm r}$ and the bias field $H_{\rm b}$ with the statistical properties of the exchange coupling.

1) HL Magnetization $M_{\rm r}$: Since in the conventional AFC design both, SL and HL, are sufficiently thin, we assume that their magnetizations do not vary with thickness. The HL magnetization reversal is, in general, a complex history dependent process even in the absence of coupling to the SL. It will be sufficient here to consider only monotone preset field H variations starting from initially fully saturated HL (note that due to the AFC design, no switching in the HL occurs until H reaches zero). For such processes, the magnetization switching due to individual HL grains can be represented by a simple threshold function

$$S(H-y)=\begin{cases}1, & H\geqslant y\\ -1, & H<y\end{cases}. \tag{1}$$

The grain switching thresholds are represented by the random variable y in (1) characterized by a probability density function $\nu(y)$. Normalization of $\nu(y)$ is guaranteed by normalizing the HL saturation to unity.

The locally varying exchange coupling between SL and HL is described here by a random variable x with density $\rho(x)$, which we want to find using measurements. Below we consider only the case of positively saturated SL. The case of negatively saturated SL is symmetric and does not contribute any additional information for finding $\rho(x)$. We assume that the presence of the exchange coupling x results in the additional local bias field x acting on the HL grains during the HL presetting stage. The switching of the HL grains influenced by the coupling can therefore be described by the threshold function $S(H-y-x)$. Then, since the variables x and y are statistically independent, the HL magnetization can be calculated as the expected value of the grain-switching function as follows:

$$M_r(H)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}S(H-x-y)\rho(x)\nu(y)dxdy \tag{2}$$

which, after the substitution $z=x+y$, gives

$$M_r(H)=-1+2\int_{-\infty}^{H}\mu_r(z)dz \tag{3a}$$

where

$$\mu_r(z)=\int_{-\infty}^{+\infty}\rho(x)\nu(z-x)dx \tag{3b}$$

can be interpreted as the probability density of the HL switching events occurring at the threshold z. Equation (3) demonstrates that increasing H starting from the negative saturation values with $M_{\rm r}=-1$ towards $M_{\rm r}=+1$ produces the increasing HL magnetization branch illustrated in Fig. 1(B). No switching in the HL occurs until $H>0$, when the SL becomes and remains positively magnetized during HL presetting.

2) Exchange Bias $H_{\rm b}$: Similar reasoning can be applied for calculation of exchange bias field as a function of presetting field H, i.e., the function $H_{\rm b}(H)$. Due to the reciprocity, HL grains also produce a bias field on the SL grains, which is proportional to x and to the HL grain magnetization. Since the magnetization of the HL grains is described by function $S(H-x-y)$, the local bias field is $xS(H-x-y)$, and its expected value (i.e., average bias on the SL) is given by

$$H_b(H)=\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}xS(H-x-y)\rho(x)\nu(y)dxdy. \tag{4}$$

Using the substitution $z=x+y$, the expression (4) can be re-written as

$$H_b(H)=-H_b^{\max}+2\int_{-\infty}^{H}\mu_b(z)dz \tag{5}$$

where

$$\mu_b(z)=\int_{-\infty}^{+\infty}x\rho(x)\nu(z-x)dx \tag{6a}$$

and

$$H_b^{\max}=\int_{-\infty}^{\infty}\mu_b(z)dz \tag{6b}$$

is the maximum observable bias field. The solid line in Fig. 1(B) shows a typical dependence $H_b(H)$ for increasing H. We also note that the (4) can be viewed as a mean-field approximation of the interface energy in AFC structures [5].

IV. Identification of Exchange Coupling Distribution

The models of the HL magnetization (2–3) and of the exchange bias (4–6) will now be used to derive exchange coupling distribution identification method. Differentiating (3) and (5) with respect to H yields

$$\chi_i(H)=2\mu_i(H) \tag{7}$$

where $i=r,b$ and $\chi_{\rm r}={\rm d}M_{\rm r}/{\rm d}H$ and $\chi_{\rm b}={\rm d}H_{\rm b}/{\rm d}H$. After taking the Fourier transforms (FT) of both (7) we obtain

$$\tilde{\chi}_i(\omega)={\rm FT}\{\chi_i(H)\}=2\tilde{\mu}_i(\omega). \tag{8}$$

Since the functions $\mu_{\rm r}(z)$ and $\mu_b(z)$ are convolutions, their FTs are products $\tilde{\mu}_r(\omega)=\tilde{\rho}(\omega)\tilde{\nu}(\omega)$ and $\tilde{\mu}_b(\omega)=j(d\tilde{\rho}(\omega)/d\omega)\tilde{\nu}(\omega)$. In the last expression we used the property of FTs that, if $\tilde{\rho}(\omega)$ denotes the FT of $\rho(x)$, then $jd\tilde{\rho}(\omega)/d\omega$ is the transform of $x\rho(x)$. Functions $\tilde{\mu}_r(\omega)$ and $\tilde{\mu}_b(\omega)$ are thus related as

$$\tilde{\mu}_b(\omega)=j\frac{1}{\tilde{\rho}(\omega)}\frac{d\tilde{\rho}(\omega)}{d\omega}\tilde{\mu}_r(\omega). \tag{9}$$

Multiplying both sides of (9) by 2 and using (8) gives

$$\tilde{\chi}_b(\omega)=j\frac{1}{\tilde{\rho}(\omega)}\frac{d\tilde{\rho}(\omega)}{d\omega}\tilde{\chi}_r(\omega) \tag{10}$$

which can be rearranged into the first-order differential equation

$$\frac{d\tilde{\rho}(\omega)}{d\omega}=-j\frac{\tilde{\chi}_b(\omega)}{\tilde{\chi}_r(\omega)}\tilde{\rho}(\omega) \tag{11}$$

with solution readily found to be

$$\tilde{\rho}(\omega)=\exp\left[-j\int_0^{\omega}\tilde{\chi}_b(\lambda)\tilde{\chi}_r^{-1}(\lambda)d\lambda\right]. \tag{12}$$

Note that using 0 as the lower limit of integration in the formula (12) ensures correct normalization of the distribution $\rho(x)$.

Thus, we could obtain the entire exchange bias distribution from (12) given the knowledge of $\chi_{\rm r}$ and $\chi_{\rm b}$. In many situations, however, we are interested only in the mean and the variance of the distribution $\rho(x)$.

1) The mean of $\rho(x)$ equals

$$\begin{aligned}\langle x\rangle &= \int_{-\infty}^{+\infty} x\rho(x)dx = \mathrm{FT}\{x\rho(x)\}|_{\omega=0}\\ &= j\frac{d\tilde{\rho}(\omega)}{d\omega}\bigg|_{\omega=0} = \frac{\tilde{\chi}_b(0)}{\tilde{\chi}_r(0)}\tilde{\rho}(0) \end{aligned} \tag{13}$$

after using (11) to obtain the last equality. Since $\tilde{\rho}(0)=1$, and since $\tilde{\chi}_r(0)=2$ and $\tilde{\chi}_b(0)=2H_b^{\max}$ [see (8)], the expression (13) reduces to

$$\langle x\rangle = H_b^{\max}. \tag{14}$$

Thus, assuming saturation values of $M_{\rm r}$ normalized to ± 1, the mean of the exchange coupling distribution equals to the saturation values of the $H_{\rm b}(H)$ curve [Fig. 1(B)]. This result is entirely expected.

2) The variance of $\rho(x)$ is determined by first calculating the second moment of the distribution

$$\begin{aligned}\langle x^2\rangle &= \int_{-\infty}^{+\infty} x^2\rho(x)dx = \mathrm{FT}\{x^2\rho(x)\}|_{\omega=0} - \frac{d^2\tilde{\rho}(\omega)}{d\omega^2}\bigg|_{\omega=0}\\ &= j\,\frac{d}{d\omega}\frac{\tilde{\chi}_b(\omega)}{\tilde{\chi}_r(\omega)}\bigg|_{\omega=0} + (H_b^{\max})^2 \end{aligned} \tag{15}$$

after using the expressions (11) and (14) and the normalization condition $\tilde{\rho}(0)=1$, to obtain the last equality. The variance of $\rho(x)$ follows from (14) and (15)

$$\sigma^2 = \langle x^2\rangle - \langle x\rangle^2 = j\,\frac{d}{d\omega}\frac{\tilde{\chi}_b(\omega)}{\tilde{\chi}_r(\omega)}\bigg|_{\omega=0}. \tag{16}$$

To simplify the expression (16), we define new shifted functions $\chi_{\rm rs}(H)=\chi_{\rm r}(H-H_{\rm 0r})$ and $\chi_{\rm bs}(H)=\chi_{\rm b}(H-H_{\rm 0b})$ [the preset fields $H_{\rm 0r}$ and $H_{\rm 0b}$ are defined in Fig. 1(B)]. Their FTs are related to $\tilde{\chi}_i(\omega)$ as $\tilde{\chi}_i(\omega)=\tilde{\chi}_{is}(\omega)\exp(-j\omega H_{0i})$, which after using in (16) give

$$\sigma^2 = j\frac{d}{d\omega}\left[\frac{\tilde{\chi}_{\rm bs}(\omega)}{\tilde{\chi}_{\rm rs}(\omega)}\exp(-j\omega\Delta H_0)\right]_{\omega=0} \tag{17}$$

with $\Delta H_0 = |H_{0r}-H_{0b}|$. Differentiating (17) at $\omega=0$ yields

$$\sigma^2 = j\frac{d}{d\omega}\left[\frac{\tilde{\chi}_{\rm bs}(\omega)}{\tilde{\chi}_{\rm rs}(\omega)}\right]_{\omega=0} + \Delta H_0\frac{\tilde{\chi}_{\rm bs}(0)}{\tilde{\chi}_{\rm rs}(0)}. \tag{18}$$

If both, $\chi_{\rm rs}(H)$ and $\chi_{\rm bs}(H)$ are even functions (i.e., if the $M_{\rm r}(H)$ and $H_{\rm b}(H)$ branches are symmetric around the points $H_{\rm 0r}$ and $H_{\rm 0b}$), which is often a good approximation [3], then the first term in (18) reduces to zero. Moreover, since the relations $\tilde{\chi}_{\rm rs}(0)=2$ and $\tilde{\chi}_{\rm bs}(0)=2H_b^{\max}$ hold, (18) can be rewritten as

$$\sigma^2 \approx \Delta H_0 H_b^{\max} = |H_{0r}-H_{0b}|H_b^{\max}. \tag{19}$$

Thus, the variance of the coupling distribution ρ is proportional to its mean, with the proportionality constant equal to the difference $|H_{\rm 0r}-H_{\rm 0b}|$.

V. Results and Conclusion

In summary, the proposed identification method is based on the knowledge of the fields $H_{\rm 0r}, H_{\rm 0b}$ and $H_{\rm b}^{\max}$ obtained from the experimental $M_{\rm r}(H)$ and $H_{\rm b}(H)$ dependences. These functions are measured using a standard protocol [2], [3], which has been reviewed here in Section II and Fig. 1. According to the developed model, the mean value of the coupling distribution equals to $H_{\rm b}^{\max}$ (14), while its variance is proportional to $H_{\rm b}^{\max}$ and depends also on the difference $H_{\rm 0r}-H_{\rm 0b}$ (19). We applied this approach to the recently published measurements performed on CoPtCrB-CoCr bilayer structure [3], where $H_{\rm b}^{\max}\sim 370$ Oe, $H_{\rm 0r}\sim 3730$ Oe and $H_{0b}\sim 3780$ Oe, yielding 370 Oe for the mean and 138 Oe for the variance of the coupling distribution.

Remarkably, the developed identification method is insensitive to assumptions on the nature of magnetization switching within the HL. In this paper the only assumptions were that the exchange bias on the SL can be modeled by a mean value of the bias field (4) and that the effect of the SL on the HL magnetization process is to simply delay the switching of HL grains. The accuracy of the method could not be tested at the present time, mainly due to the unavailability of any experimental or computational reference data. However, since the assumptions made are reasonable for typical AFC structures [2], [3], [5], [9], we believe that this method yields realistic estimates.

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