Center of mass method for exchange bias measurements

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Exchange bias measurement techniques are tested using an Ising model for exchange-coupled bilayer structures. In the presence of hysteresis loop asymmetry, the conventional exchange bias characterization method of measuring the sum of the coercive fields is found to be rather inaccurate if compared to the interface coupling energy. An alternative method based on the analysis of entire hysteresis loops is proposed, tested, and found to be substantially more robust. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2359431]

Exchange bias is the shift of hysteresis loops that is commonly observed in ferromagnetic/antiferromagnetic bilayer structures upon field cooling below the Neel temperature of the antiferromagnetic material.[1] Traditionally, this effect is quantified by a single field, called the exchange bias field, which is determined as the sum of the coercive fields. Such a *two-point* (TP) measurement is well justified for symmetric hysteresis loops, where all points on the loop can be viewed as shifted by the same amount. Then indeed, the value of the bias field determined from any two complementary points on the loop would be equivalent to the measurement based on the coercivities. However, many exchange bias systems do not only show a field shift, but they also exhibit asymmetric hysteresis loops.[2] In this case, the bias field determined from any TP measurement is no longer unique, but will be different for different complementary points on the hysteresis loop. More fundamentally, any single field measure is insufficient to describe the complexity of such exchange bias systems, even though different measures can lead to different levels of reliability. Thus, two questions arise, which will be the topic of this letter: (i) How reliable is the conventional TP measurement using the coercive fields? (ii) Is there a more robust way of quantifying exchange bias?

To study the above questions, we have devised a microscopic model of exchange bias systems that allows not only the simulation of hysteresis loops but also enables an independent determination of the exchange bias effect by means of the directional dependence of the interface energy, i.e., the origin of exchange bias. This will allow for a consistency check of hysteresis-loop-based exchange bias measurements, which are the most widely used experimental tools. As we will see, if the loops are asymmetric, the TP method no longer relates to the coupling energy unambiguously. We therefore propose a different method of general applicability, called the "center of mass" method, which yields very accurate results for loops of arbitrary shape. Another alternative to or generalization of the TP method was recently proposed.[3] This particular method, however, relied on symmetric hysteresis loops and therefore did not address reliability issues related to loop asymmetry.

The model for our calculations is based on recent experimental work on exchange bias in all-ferromagnetic systems.[4] Here, the ferromagnet/antiferromagnet structure of conventional exchange bias systems is replaced by two ferromagnetic layers, soft layer (SL) and hard layer (HL) ferromagnets, which are antiferromagnetically coupled by a thin Ru layer.[4] The model structure is shown schematically in Fig. 1, with SL and HL being described as two two-dimensional Ising models. The large separation of the switching field distributions for the SL and HL [Fig. 1(b)] allows tuning of the SL exchange bias simply by presetting the magnetization state of the HL.[4–6] The magnetization states of the SL and HL grains, denoted, respectively, as s_i^s and s_j^h, are ±1 and oriented within the film plane along the external magnetic field direction. Due to the simplicity of this model, the exchange bias is well defined as the mean value of locally varying bias fields at the interface separating the two Ising-like layers, a value that will be used as the reference point. While the large switching fields of the HL grains will be modeled by elementary rectangular hysteresis loops with symmetric thresholds $\pm\alpha_i^h$, the much smaller intrinsic switching fields of the SL grains [Fig. 1(b)] will be set $\alpha_i^s=0$ for simplicity. Randomness of the magnetic anisotropy in the HL is taken into account by assuming a Gaussian distribution of

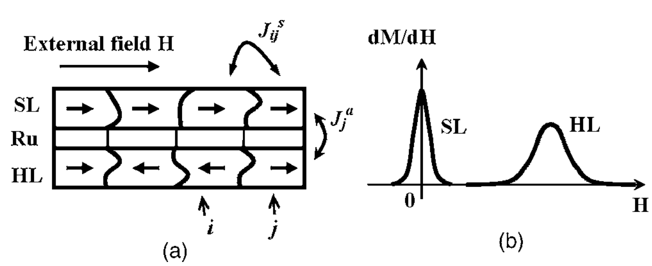

FIG. 1. (a) Schematic of the bilayer system used as an exchange bias model here. (b) Switching field distribution of the bilayer system, which shows clearly separated switching for the SL and the HL.

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α_i^h with a mean value $H_c=1$ and a variance σ_{hc}. We furthermore assume an interlayer exchange coupling strength J_i^a to couple adjacent grains s_i^s and s_i^h. Hereby, J_i^a is a locally random variable following a distribution $\eta(J_i^a)$. The model also encompasses a ferromagnetic intergranular exchange interaction J_{ij}^s in between neighboring grains s_i^s and s_j^s within the SL. The local field governing the flipping of the SL grain at lattice site i can then be written as

$$H_i^s = \sum_j J_{ij}^s s_j^s + J_i^a s_i^h + H, \tag{1}$$

where the first sum describes the contribution from the exchange interaction between immediately neighboring grains s_j^s, the second term expresses the local effective bias field, $h_i = J_i^a s_i^h$, acting on the SL grain s_i^s due to the coupling to the adjacent HL grain s_i^h, and H is the external magnetic field. Analogously, the HL flipping field is given as

$$H_i^h = J_i^a s_i^s + H. \tag{2}$$

To reduce the number of free parameters in the model, direct interactions between HL grains have been ignored here. Finally, the definition of our model is completed by assuming a field-driven dynamics, in which the HL and SL evolve through single grain flips upon changing the external field according to

$$s_i^x(n+1) = \begin{cases} 1 \text{ if } & H_i^x \geqslant \alpha_i^x \\ -1 \text{ if } & H_i^x \leqslant -\alpha_i^x \\ s_i^x(n) & \text{otherwise,} \end{cases} \tag{3}$$

with $x \equiv h$ and s for the HL and SL grains, respectively, and n being the sequence step. The system is always given enough time to settle into a stable state before the external field is allowed to change further.

Note that Eq. (1) essentially resembles a random field Ising model,[7] in which each grain (spin) is subjected to a local random field. In the present case, these random fields are defined by the local biases h_i and their probability distribution $\rho(h_i)$, which depends on the magnetization state of the HL. Thus, $\rho(h_i)$ is the quantity that governs the SL exchange bias effect. Its dependence on the HL magnetization M_{HL} can be expressed as

$$\rho(h_i) = P(s_i^h = +1)\,\eta(J_i^a) + P(s_i^h = -1)\,\eta(-J_i^a). \tag{4}$$

The functions $P(s_i^h = \pm 1)$ define probabilities of HL grain s_i^h being in either +1 or −1 state. While $\eta(J_i^a)$ is fixed, the functions $P(s_i^h = \pm 1)$ depend on the HL magnetization, and consequently on the external field history.

Although the detailed SL exchange bias behavior depends on the entire distribution ρ, we can define within our model a single field description, H_{ex}, corresponding to the mean of ρ, i.e.,

$$H_{\text{ex}} = \int x\rho(x)dx = N^{-1}\sum_i J_i^a s_i^h. \tag{5}$$

with N being the number of HL or SL grains in the system. This exchange bias field H_{ex}, which represents the mean-field value contribution to the interface energy, will be further used as a reference point for comparing different exchange bias measurement techniques based on SL hysteresis loops.

In general, Eqs. (1)–(3) produce SL hysteresis loops $M_{\text{SL}}(H)$, which are asymmetric in addition to being shifted, similar to experimental observations. Figure 2 shows three such examples together with the corresponding distribution functions $\rho(h_i)$, calculated for three different HL magnetization states. In all cases shown in Fig. 2 we assumed the distribution η to be Gaussian with a mean value $J^a = -0.1$ and variance $\sigma_a = 0.08$. In Figs. 2(a) and 2(b), the HL is in a demagnetized state with equal numbers of grains being positive and negative (i.e., $M_{\text{HL}}=0$). The expression (4) yields $P(s_i^h=+1)=P(s_i^h=-1)=1/2$, and the distribution ρ is therefore always symmetric with zero mean, independently of the choice of $\eta(J_i^a)$. As a result, the average bias acting on the SL vanishes and the associated SL loop is not shifted. Figures 2(e) and 2(f) show the situation when the HL is fully saturated with all grains being positively magnetized (i.e., $M_{\text{HL}}=1$). Equation (4) yields $\rho(h_i)=\eta(J_i^a)$. Thus, the average bias field is equal to $J^a M_{\text{HL}} = -0.1$, resulting in a corresponding positive shift of the SL loop. Figures 2(c) and 2(d), obtained for $M_{\text{HL}}=0.7$, show an asymmetric SL loop caused by an asymmetric distribution ρ. According to Eq. (4), such behavior is expected whenever the probabilities describing the state of interfacial magnetic moments are not equal. Thus, we have verified that our simple model is indeed able to produce hysteresis loops with a varying degree of asymmetry.

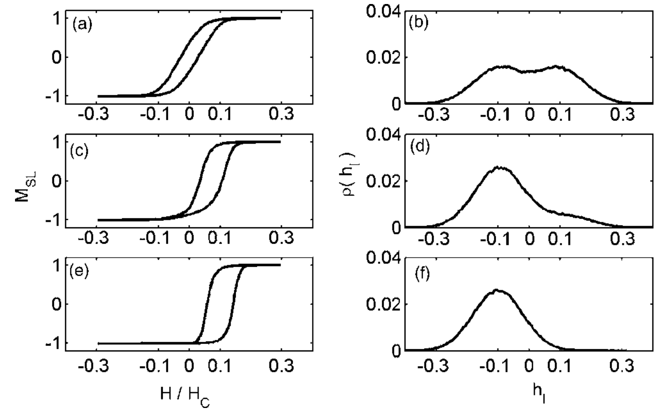

FIG. 2. Calculated SL hysteresis loops (left) and corresponding local bias field distributions (right) for three different magnetization states of the HL. [(a) and (b)] $M_{\text{HL}}=0.0$, [(c) and (d)] $M_{\text{HL}}=0.7$ and [(e) and (f)] $M_{\text{HL}}=1.0$. Simulation parameters: $J^s=0.04$, $J^a=-0.1$, lattice size=100×100 grains, $\sigma_{hc}=0.3$, and $\sigma_a=0.08$.

Having developed a model with well defined exchange bias and the ability to produce asymmetric hysteresis loops, we can now analyze relation between the loop asymmetry and the deviations between the conventional TP measurement, called here H_{bt}, and the mean field H_{ex} calculated from Eq. (5). The starting point is the observation that since H_{bt} is determined by averaging over the coercive fields of the hysteresis loops, it is related to the median and not to the mean of the bias field distribution ρ. The equality $H_{\text{bt}}=-H_{\text{ex}}$ thus holds for symmetric loops (and symmetric distributions), but if the loops are asymmetric (nonsymmetric distributions), the field H_{bt} is no longer expected to correspond to the mean bias. Such behavior has indeed been confirmed by the results of our simulations shown in Fig. 3(a). The data were obtained for different M_{HL} by gradually increasing the set field starting from a demagnetized HL.[6] The deviation between H_{bt} and H_{ex} is as much as 20% for this specific example, but can be worse for particularly sensitive cases. We also find that this deviation is strongly correlated with the asymmetry of the biased hysteresis loops as can be seen from a compari-

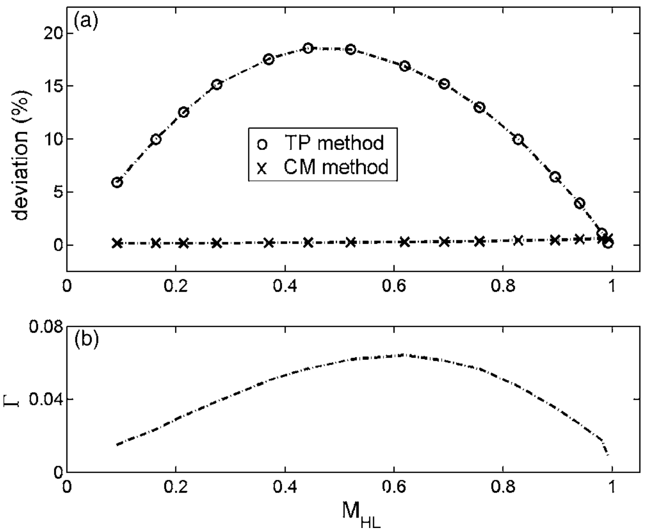

FIG. 3. (a) Comparison of the two-point (TP) measurement error with the center of mass (c.m.) measurement error as a function of the HL magnetization. (b) Corresponding SL loop asymmetry coefficient Γ (Ref. 8). Simulations parameters: $J^s=0.01$, $J^a=-0.1$, lattice size=100×100 grains, $\sigma_{hc}=0.3$, and $\sigma_a=0.08$.

son between Figs. 3(a) and 3(b), in which the asymmetry values are displayed for the same set of simulations.[8] Thus, in systems with considerable loop asymmetry, the exchange bias determined using the two-point method indeed significantly deviates from the mean bias H_{ex}.

In the following, we describe a different method, based on determining the mean bias H_{ex} directly from hysteresis loop measurements. For this let us first assume that there are no interactions in the SL. Setting $J^s_{ij}=0$ in Eq. (1) will eliminate the grain-to-grain interaction term responsible for all hysteretic effects in the SL. Both the increasing and decreasing branches of the $M_{SL}(H)$ curve then merge, and their dependence on external field H can be expressed simply as

$$M_{SL}(H) = -1 + 2\int_{-H}^{\infty} \rho(x)dx. \tag{6}$$

Differentiating Eq. (6) with respect to H yields $dM_{SL}=2\rho(-H)dH$, which after inserting to Eq. (5) gives

$$H_{ex} = -\frac{1}{2}\int_{-1}^{+1} H(M_{SL})dM_{SL}. \tag{7}$$

Relation (7) allows us to determine the mean of the bias field distribution ρ from the magnetization curve by a simple integration of its inverse over the magnetization axis. In the presence of hysteresis, Eq. (7) is now applied to both the ascending and the descending hysteresis loop branches, for clarity denoted respectively as $H_\uparrow(M)$ and $H_\downarrow(M)$,

$$H_{c.m.\uparrow,\downarrow} = -\frac{1}{2}\int_{-1}^{+1} H_{\uparrow,\downarrow}(M_{SL})dM_{SL}. \tag{8}$$

Then, the bias effect is calculated as an average,

$$H_{c.m.} = \frac{1}{2}(H_{c.m.\uparrow} + H_{c.m.\downarrow}). \tag{9}$$

The method (8) and (9) will be called *center of mass* (c.m.) method, since it is designed to measure the mean of the effective bias field distribution ρ, i.e., its center of mass. As shown in Fig. 3, the method yields excellent agreement with the mean bias, even for asymmetric hysteresis loops and even in the presence of SL hysteresis, where Eq. (7) does not apply anymore. As intragranular interactions increase, the squareness of hysteresis loop increases[6,9] and the loop asymmetry decreases. We observed in our simulations that while the deviation of the TP improves, the deviation of the c.m. from the mean bias never exceeds 3%. At very strong interaction strengths, relative to the variance of the distribution $\rho(h_i)$, both methods give comparable results. This behavior is expected, since as the interaction strength between the SL grains increases, the magnetic correlation length becomes considerably larger than the grain size. The SL magnetization then no longer follows the variation of the interfacial exchange coupling locally, but rather the average over the correlation length.[9] Consequently, the sensitivity of the SL reversal on the fine details of the probability function $\rho(h_i)$ diminishes and both TP and c.m. methods become comparable.

In summary, we have shown by means of a simple microscopic exchange bias model that the conventional TP method of exchange bias measurement can yield an ambiguous description of the bias effect if the observed hysteresis loops are asymmetric. We furthermore propose a new measurement scheme, the center of mass method, and demonstrate that it takes loop asymmetry into account. Although our model resembles all ferromagnetic exchange bias structures, we believe that our findings are representative for all exchange bias systems because in all cases the exchange bias and its effect on the SL hysteresis loop are caused by a stable HL magnetization that is not reversed during the measurements. Recent experiments by Binek *et al.* have furthermore highlighted the similarity between the different types of exchange bias systems by demonstrating a training effect in all ferromagnetic samples.[10] Moreover, since the microscopic origin of the effective bias field distribution has not been essential in developing the center of mass method, we believe that this method is also applicable to epitaxial samples where magnetization reversal takes place via domain nucleation, and where domains of variable size replace the grains used in our analysis. Finally, the new method does not require any further data acquisition as it relies on conventional hysteresis loops only, i.e., exactly the same set of data that are presently measured for the TP method.

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