Angular dependence of the exchange bias obtained from magnetization and ferromagnetic resonance measurements in exchange-coupled bilayers

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Theoretical calculations of the angular dependence of the exchange bias field in ferromagnetic/antiferromagnetic bilayers were carried out in the framework of a model assuming the formation of a planar domain wall at the antiferromagnetic side of the interface with the reversal of the ferromagnetic orientation. The calculations were performed for various exchange interaction field strengths and for both cases of ferromagnetic and antiferromagnetic coupling. Analytical expression for the angular dependence of the ferromagnetic resonance field was obtained as well. It was shown that the exchange bias field variations derived from ferromagnetic resonance and hysteresis loop measurements become very close for strong interactions only. These field shifts, due to the different magnetization processes involved in the corresponding measurements, are different physical entities and, in general, must give different values.

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I. INTRODUCTION

The phenomenon of exchanged anisotropy[1] refers to the exchange interactions at the interface between ferromagnetic (FM) and antiferromagnetic (AF) materials. It is characterized by several experimental observations, the most well known being the shift of the magnetization curve away from the zero field axis. Although it has found important technological application in magnetoresistive heads biasing[2] and spin valve structures,[3] up to now there exists no basic, generally applicable, predictive theory or model,[4–6] the reason being the inherent complexity in a structural combination that leads to competing interactions. The models proposed in the literature have attained different degrees of agreement with existing experimental results. Models which, similar to the one of Mauri *et al.*,[7] include the existence of AF domain wall in exchange coupled systems, account quantitatively for the 10^{-2} reduction of the exchange field from the ideal interface model case,[7–11] as well as for accumulative memory effects of the thermal and field history of real FM/AF bilayers.[12] Miltényi *et al.*[13] have shown both by experiments and by numerical simulations that for some systems diluting the AF layer in the volume part away from the FM/AF interface leads to formation of volume domains in the AF which could significantly enhance the exchange bias.

An interesting feature of the exchange biased bilayers is the fact that different experimental techniques may yield different values for the shift field H_{eb}. Recently, Xi *et al.*,[14] based on the model of Mauri *et al.*, investigated theoretically the irreversible and reversible measurements of exchange anisotropy. They derived expressions relating H_{eb} measured by various techniques with the interface coupling field H_E, and the effective domain wall field H_W, for external field applied along the exchange bias direction, and concluded that different techniques must give different H_{eb} values. Geshev[15] derived analytical expressions for H_{eb}, coercivity H_c, and effective anisotropy field in the framework of the same model. He showed that hysteresis loop and ferromagnetic resonance (FMR) measurements in such systems should not give different values for the exchange coupling for the cases of very weak and very strong interfacial coupling as the analytical expressions for H_{eb} from magnetization measurements H_{eb}^{MAG}, coincide with the ones from FMR measurements H_{eb}^{FMR}. The difference between the shift field values, estimated experimentally by ac susceptibility and through hysteresis loop measurements, has been explained as well. An attempt to reconcile the data obtained with three different techniques, namely magneto-optical Kerr effect magnetometry, Brillouin light scattering (BLS), and FMR, was reported by Fermin *et al.*[16]

Measurements of the dependences of H_{eb} and H_c on the angle ϕ_H that the applied field H, makes with the easy axis of the FM layer are very informative and provide an independent test for the validity of the existing theoretical models. The choice of the model used is of decisive importance for the interpretation of data obtained via experimental techniques such as FMR, BLS, or ac susceptibility. Recently, the angular dependences of H_{eb} and H_c have been explored experimentally and/or by model calculations.[16–22] For several real systems, it has been obtained that $H_{eb}(\phi_H)$ and $H_c(\phi_H)$ were not simple sinusoidal functions as initially expected.[1] Thus, revealing the angular dependence of the exchange coupling is of crucial importance in understanding its nature.

In the present work, theoretical calculations of the angular dependence of H_{eb}^{MAG}, the FMR resonance field H_R, and H_{eb}^{FMR} were carried out based on the model of Mauri *et al.*[7] for both ferromagnetic and antiferromagnetic coupling. The question of whether the exchange bias variations obtained through the above two techniques should coincide is discussed.

II. MODEL

Let us consider two coupled magnetic layers, denoted as A and B, with magnetizations M_A and M_B, and thicknesses t_A and t_B, respectively. A generic form of the total free energy of the system per unit area can be written as

$$E = t_\mathrm{A}E_\mathrm{A} + t_\mathrm{B}E_\mathrm{B} + E_{\mathrm{int}}. \tag{1}$$

The energies E_A and E_B could include, for each layer, the Zeeman, anisotropy, domain wall, and demagnetizing terms; E_{int} corresponds to the interlayer interactions. The static equilibrium directions of the magnetization vectors of the two layers, assuming that each of them rotates coherently, can be calculated from Eq. (1) by finding the polar (θ_A and θ_B) and azimuthal (ϕ_A and ϕ_B) angles of M_A and M_B in the spherical coordinate system for which E is at minimum. The projections of $\mathbf{M}_A$ and $\mathbf{M}_B$ along the field direction will give the layers' magnetizations.

When this exchange-coupled bilayer is located in applied static magnetic field, the magnetization of each layer, if perturbed from its equilibrium orientation, will precess around its equilibrium direction. Following Smit and Beljers,[23] the roots of the determinant of the 4×4 matrix

$$\begin{bmatrix} E_{\theta_A\theta_A} & E_{\theta_A\phi_A}+iz_A & E_{\theta_A\theta_B} & E_{\theta_A\phi_B} \\ E_{\theta_A\phi_A}-iz_A & E_{\phi_A\phi_A} & E_{\theta_B\phi_A} & E_{\phi_A\phi_B} \\ E_{\theta_A\theta_B} & E_{\theta_B\phi_A} & E_{\theta_B\theta_B} & E_{\theta_B\phi_B}+iz_B \\ E_{\theta_A\phi_B} & E_{\phi_A\phi_B} & E_{\theta_B\phi_B}-iz_B & E_{\phi_B\phi_B} \end{bmatrix}$$

will give the dispersion relation of the exchange-coupled bilayer system, i.e., a fourth-order equation in ω (the angular frequency of precession) with at most two meaningful solutions at any given dc field. Here E_{ij}'s denote the second derivatives with respect to the equilibrium angles θ and ϕ of the energy given in Eq. (1), $z_A=(\omega/\gamma_A)t_AM_A\sin\theta_A$, $z_B=(\omega/\gamma_B)t_BM_B\sin\theta_B$, and γ_A and γ_B are the gyromagnetic ratios of the two layers.

In the following, a bilayer whose behavior can be described in the framework of the model proposed by Mauri *et al.*,[7] has been considered. It applies to a system formed by an infinitely thick AF layer and a FM layer (layer A) with thickness t_A. The FM spins rotate coherently, and a domain wall can form at the AF side of the interface. t_A is much smaller than the thickness of the domain wall. Both films are assumed to have uniaxial anisotropy, and the FM easy magnetization axis is chosen to coincide with the AF one. The energy of the system per unit area can be phenomenologically written as

$$E=[2\pi(\mathbf{M}_A\cdot\hat{\mathbf{n}})^2-\mathbf{H}\cdot\mathbf{M}_A-K_A(\mathbf{M}_A\cdot\hat{\mathbf{u}}/M_A)^2]t_A - \sigma_W\mathbf{M}_B\cdot\hat{\mathbf{u}}/M_B-J_E\mathbf{M}_A\cdot\mathbf{M}_B/(M_AM_B). \quad (2)$$

The first term contains the demagnetizing, the Zeeman, and the FM anisotropy energies, respectively, with K_A the uniaxial anisotropy constant; the last two terms refer to the domain wall energy of the AF and the bilinear exchange anisotropy with J_E being the interfacial coupling constant. $J_E>0$ and $J_E<0$ correspond to ferromagnetic and antiferromagnetic couplings, respectively. σ_W is the energy per unit surface of a 90° domain wall in the AF. The unit vectors $\hat{\mathbf{u}}$ and $\hat{\mathbf{n}}$ represent the uniaxial anisotropy direction (along the x axis) and the normal to the film surface direction (i.e., the z axis), respectively. Note that there are no terms in this energy expression corresponding to the second term in Eq. (1). However, due to the domain wall energy term in Eq. (2), the dispersion relation depends on the second derivatives of E in respect to θ_B and ϕ_B as well, so one cannot use the standard resonance relation[23] $(\omega/\gamma)^2=(E_{\theta_A\theta_A}E_{\phi_A\phi_A}-E^2_{\theta_A\phi_A})/(t_AM_A\sin\theta_A)^2$. Thus, in the framework of the present model H_{eb}^{MAG} and H_R (and subsequently H_{eb}^{FMR}) are strongly influenced by the AF magnetization. The latter is found to change during the field variation (see, e.g., Fig. 2 in the work of Mauri *et al.*[7] and Fig. 4 in the Geshev's work[15]). The domain wall formation and motion in the AF is crucial for the existence of exchange bias also for the systems investigated in the work of Miltényi *et al.*[13]

III. RESULTS AND DISCUSSION

In the present study, the dc magnetic field is applied in the film's plane and its azimuthal angle ϕ_H was varied from 0 to 2π. The dispersion relation we obtained for this case ($\gamma=\gamma_A$, $\theta_H=\theta_A=\theta_B=\pi/2$) is

$$\frac{\omega^2}{\gamma^2}=[H\cos(\phi_A-\phi_H)+H_U\cos^2\phi_A+4\pi M_A+H_1^{eff}] \times[H\cos(\phi_A-\phi_H)+H_U\cos2\phi_A+H_2^{eff}], \quad (3)$$

where

$$H_1^{eff}=\frac{H_W\cos\phi_B\cos(\phi_A-\phi_B)-H_E\sin^2(\phi_A-\phi_B)}{(H_W/H_E)\cos\phi_B+\cos(\phi_A-\phi_B)},$$

$$H_2^{eff}=\frac{H_W\cos\phi_B\cos(\phi_A-\phi_B)}{(H_W/H_E)\cos\phi_B+\cos(\phi_A-\phi_B)}.$$

Here $H_U=2K_A/M_A$ is the FM anisotropy field, $H_E=J_E/(t_AM_A)$ the exchange coupling field, and $H_W=\sigma_W/(t_AM_A)$ is the domain wall effective field. Equation (3) must be taken at the equilibrium positions of M_A and M_B. The in-plane angular dependence of H_R can be derived from the above equations, i.e.,

$$H_R=\left[H_U(1-3\cos^2\phi_A)-4\pi M_A-H_1^{eff}-H_2^{eff} + \sqrt{(H_U\sin^2\phi_A+4\pi M_A+H_1^{eff}-H_2^{eff})^2+4\frac{\omega^2}{\gamma^2}}\right] \Big/ 2\cos(\phi_A-\phi_H). \quad (4)$$

The equilibrium magnetization directions were found using the minimization procedure used in our previous works.[15,24] In the hysteresis loop calculations, the field step was 0.02 Oe, the initial step for the angles $\theta_{i,j}$ and $\phi_{i,j}$ was 10^{-3} rad, and the angles corresponding to the energy minimum were determined to an accuracy of 10^{-16} rad. The other parameters used were $\omega/\gamma=3000$ Oe, $M_A=780$ emu/cm^3, $H_U=20$ and 200 Oe, $H_W=100$ Oe, and H_E was varied from 0.5 to 900 Oe.

The resulting H_R vs ϕ_H variations are shown in Fig. 1. For $H_E=0$, the resonance field variation is very close to pure $\cos2\phi_H$ behavior. When increasing H_E, there are significant

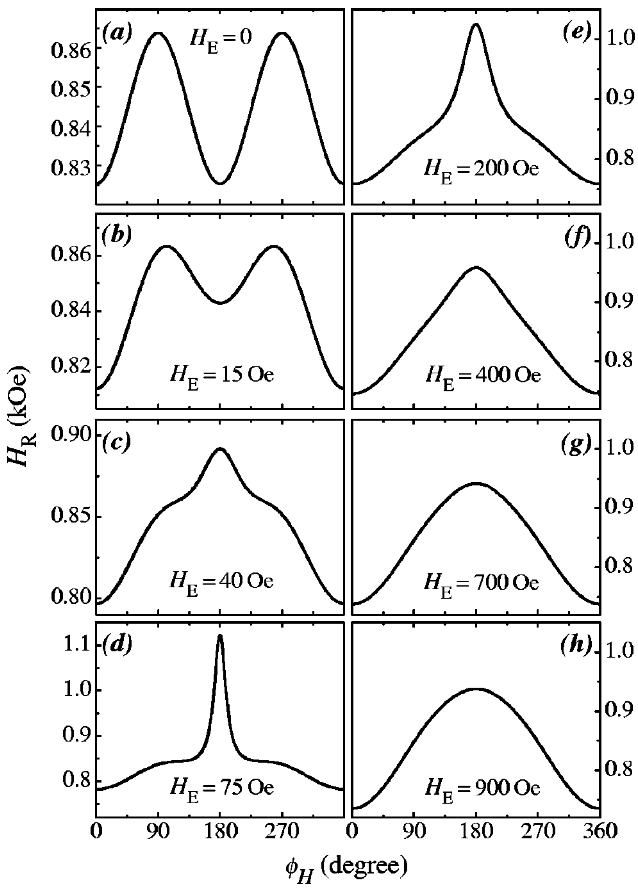

FIG. 1. Angular dependence of the resonance field for $\omega/\gamma = 3000$ Oe, $M_A = 780$ emu/cm^3, $H_U = 20$ Oe, $H_W = 100$ Oe, and $H_E = 0$, 15, 40, 75, 200, 400, 700, and 900 Oe.

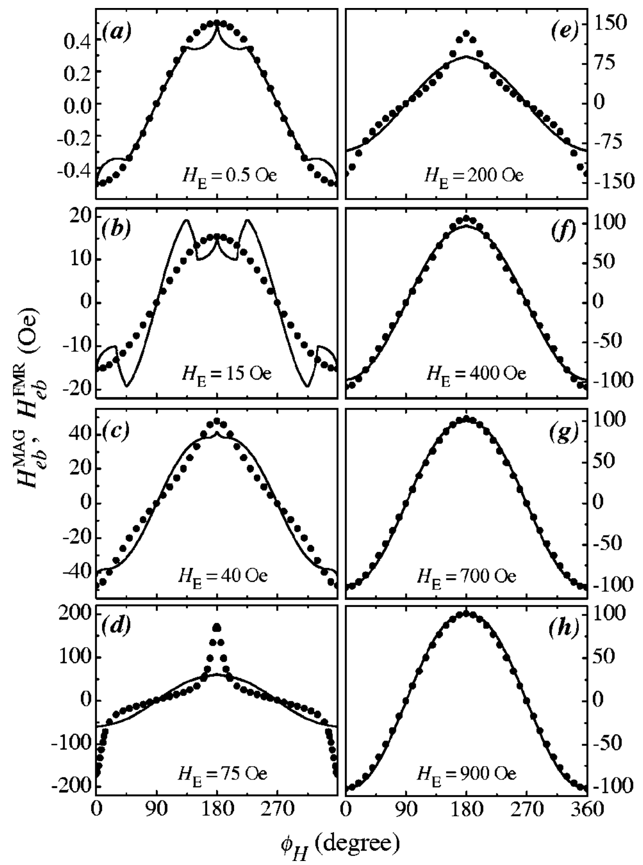

FIG. 2. Angular variation of H_{eb}^{MAG} (curves) and H_{eb}^{FMR} (symbols) for $H_E > 0$ with the same parameters used to obtain the data in Fig. 1. Only in (a) $H_E = 0.5$ Oe was used instead of $H_E = 0$.

changes in the shape of the curves, the most pronounced being the increase of $H_R(\pi)$, which reaches infinity value at $H_E = H_W$. Further increase of H_E results in a gradual decrease of $H_R(\pi)$, and the angular variation becomes closer to pure cosine behavior. If $H_E \geqslant H_W$, there is one more term in the H_R variation compared to the one for $H_E = 0$, i.e., $-H_W \cos\phi_H$; in the case into consideration ($H_W = 5H_U$) this $\cos\phi_H$ term is dominant. A gradual decrease of $H_R(0)$ is observed when increasing H_E starting from zero, which equals $H_E H_W/(H_E + H_W)$ for each H_E, and is asymptotically equal to H_W when $H_E \to \infty$. An increase of H_U only restricts the possible $H_R(\phi_H)$ and $H_{eb}(\phi_H)$ variation types. For example, for $H_U = 200$ Oe, the $H_U \cos 2\phi_H$ term is dominant in the H_R expression, and the plots (not shown) corresponding to very strong interactions are similar to the ones represented in Figs. 1(b) and 2(b).

For **H** along the exchange bias direction, H_{eb}^{FMR} is defined as[25,26] $\frac{1}{2}[H_R(0) - H_R(\pi)]$. With the help of Eq. (4) one readily obtains the result of Xi *et al.*[14]

$$H_{eb}^{\mathrm{FMR}}(\pi)_{H_E > H_W} = \frac{H_W H_E^2}{H_E^2 - H_W^2},$$

$$H_{eb}^{\mathrm{FMR}}(\pi)_{H_E < H_W} = \frac{H_E H_W^2}{H_W^2 - H_E^2}.$$

It is worth noting that the above expressions are derived here without using the restriction imposed in Ref. 13, i.e., $4\pi M_A$ much larger than the resonance field. Actually, they are valid for any demagnetizing energy and frequency values.

When $H_E = 0$, $H_R(\phi_H) = H_R(\pi + \phi_H)$, see Fig. 1(a). Thus, one can define $H_{eb}^{\mathrm{FMR}}(\phi_H)$,

$$H_{eb}^{\mathrm{FMR}}(\phi_H) = \frac{1}{2}[H_R(\phi_H) - H_R(\pi + \phi_H)] \tag{5}$$

as the exchange bias field obtained from FMR measurements when $H_E \neq 0$. Using the above expression, H_{eb}^{FMR}'s versus ϕ_H are obtained from the $H_R(\phi_H)$ dependences given in Fig. 1. They are shown in Fig. 2 along with the corresponding angular variations of H_{eb}^{MAG} derived from the hysteresis loops calculations. The curves in Fig. 2(a) are calculated for $H_E = 0.5$ Oe instead of $H_E = 0$. It is clearly seen that both H_{eb}^{MAG} and H_{eb}^{FMR} exhibit unidirectional symmetry, $H_{eb}(\phi_H) = H_{eb}(-\phi_H) = -H_{eb}(\pi \pm \phi_H)$ for all H_E values, whereas the coercivity (not plotted in the figure) shows uniaxial symmetry, $H_c(\phi_H) = H_c(-\phi_H) = H_c(\pi \pm \phi_H)$, as expected.

These curves show strong dependence on the exchange coupling field strength. The field shifts are far from being simple $\cos\phi_H$ dependences for all H_E, contrary to what is expected by Wu *et al.*[27] For very weak interactions [Fig.

2(a)], the curves practically coincide in a broad ϕ_H range. For slightly stronger interactions, the $H_{eb}^{MAG}(\phi_H)$ are characterized by the largest values not at $\phi_H=0$ or π as commonly believed, but at other angles, near $\pm\pi/4$ for $H_E=15$ Oe, for example. Such curves have been experimentally measured for a NiFe/CoO bilayer,[17] NiFe/Au/CoO trilayers,[18] and NiFe/CrMnPt bilayers.[22] The H_{eb}^{FMR} versus ϕ_H curves, on the other hand, show the largest variations for H_E/H_W values close to unity and, as a consequence, the two field shifts show rather different variations. For high H_E/H_W values, however, the angular dependences become very close, as can be seen in Figs. 2(f)–2(h). Variations of this type have been experimentally observed in exchange-biased Permalloy layers.[16,19,27] Note that for this case (i.e., relatively strong interactions) $H_{eb}(0)\approx H_W$, whereas for weak interactions $H_{eb}(0)\approx H_E$ [Figs. 2(a)–2(c)].

Our results demonstrate that H_{eb}^{MAG} and H_{eb}^{FMR}, in general, must give different values. That is because perturbative measurements (like FMR), rather than reversing the magnetization, move it only a small amount during the measurement, i.e., different magnetization processes are involved in the hysteresis loop and FMR measurements. Although both H_{eb}^{MAG} and H_{eb}^{FMR} shifts are caused by the same interlayer interactions, they are different physical entities, which is clearly seen from the frequency dependence of H_R [Eq. (4)]. As a consequence, H_{eb}^{FMR} depends on ω as well, contrary to H_{eb}^{MAG}. We verified this frequency dependence of H_{eb}^{FMR} by calculating its angular variations for $\omega/\gamma=9$ kOe. Small (however notable) differences were observed between these field shifts and those for $\omega/\gamma=3$ kOe, especially for $H_E\approx H_W$. H_{eb}^{MAG} and H_{eb}^{FMR} fields only coincide (exactly) when **H** is applied along the easy axis direction for the cases of very weak ($C<1$ and $H_E<H_W$) and very strong ($C\geqslant -1$ and $H_E>H_W$) interactions[15], where $C=(H_EH_W)^2/[H_U(H_W-H_E)^3]$.

H_R vs ϕ_H variations have also been calculated for the case of antiferromagnetic exchange interaction, i.e., $H_E<0$. It turned out that

$$H_R(\phi_H)_{H_E<0}=H_R(\pi+\phi_H)_{H_E>0}, \tag{6}$$

which relation can be easily understood by interpreting $H_E<0$ as a field that "couples ferromagnetically" $\mathbf{M}_A$ with a vector $-\mathbf{M}_B$. This, however, is actually the case of positive H_E and H direction given by $\pi+\phi_H$, thus explaining the above relation.

The angular dependences of H_{eb}^{MAG} and H_{eb}^{FMR} for negative H_E have been calculated as well. The only difference between these data and those for $H_E>0$ is the opposite sign of both field shifts for negative H_E, as compared with the ones for positive H_E.

IV. SUMMARY

In this article, we have determined the angular dependence of the exchange bias derived from magnetization and FMR measurements in exchange-coupled bilayers whose behavior can be described in the framework of a model assuming the formation of a planar domain wall at the AF side of the interface. We have concluded that these field shifts, due to the different magnetization processes involved in the corresponding measurements, are different physical entities and, in general, must give different values. They become very close for high exchange interaction field strength only.

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