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Analytic treatment of the incomplete ferromagnetic domain-wall model for exchange bias ☆

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Abstract

The incomplete ferromagnetic domain-wall model we proposed recently is solved analytically. We derive the dependence of the exchange bias field (H_{EB}) on the different parameters that characterize the magnetic bilayer system. Excellent agreement with the numerical solutions is achieved. Moreover, the model yields a crossover from a t_F^{-1} dependence of H_{EB} for thin ferromagnetic films, to a $t_F^{-1.9}$ dependence for thick films, where t_F is the ferromagnetic film thickness. Our results are in agreement with experiment. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Exchange bias (EB) refers to the unidirectional anisotropy that develops in a system that has a ferromagnet (FM) and an antiferromagnet (AF) in atomic contact [1–4]. This anisotropy results from the exchange coupling, across the interface, after the system is cooled in a static external magnetic field H_{cf} from above the ordering Néel temperature T_N of the AF. The most telling signature of this unidirectional anisotropy is a shift in the magnetization loop center away from the zero-field axis. It is called negative (positive) EB when the shift is in the opposite (same) direction as the cooling field H_{cf}.

While the phenomenon is observed in a large variety of systems [1–4], it is thin films multilayers that it has found important in technological applications, as a domain stabilizer of magneto-resistive heads [5] and in spin-valve-based devices [6]. However, despite more than 40 years of research since EB was discovered [7], a complete understanding of the phenomenon and the underlying mechanisms has not been achieved to date.

The simplest theoretical models [7,8] assume a perfect, flat, *uncompensated* [9] AF interface. However, they yield EB fields H_{EB} two orders of magnitude larger than observed. In addition, they

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fail to explain biasing for a fully *compensated* AF interface, i.e. when the AF interface layer has an equal number of magnetic moments pointing in opposite directions[3]. To explain these discrepancies, several approximations in the models to describe the system have been used. These include different assumptions on the interface structure [9–11], and the formation of domains in the AF [12–19]. While these models are successful, in differing degrees, to explain most of the common phenomena related to negative EB, they fail to provide an understanding of some of the more recent experimental findings [20–26]. In particular, the transition from negative to positive EB [23], the asymmetric magnetization reversal [26] and the memory effect [27–29]. Not long ago, and in order to properly describe some of these experimental findings, a new model based on an incomplete ferromagnetic domain wall (FM-DW) was put forward [30]. In this model, the magnetization cycle is obtained by an exact-discrete-micromagnetic calculation and the values obtained for H_{EB} are in agreement with experiment [29,30]. In addition, both negative and positive H_{EB} values are obtained [32].

However, as always, an analytic solution is more powerful and convenient since it offers the possibility of studying diverse physical limits in a clear and simple way. In fact, the above-mentioned micromagnetic calculations and simulations [30–32] are rather lengthy and cumbersome to carry out. On the contrary, an analytic solution is both more direct in providing a proper physical picture and also easier to implement numerically. Thus, the main purpose of the present paper is to derive analytic expressions, in the framework of the incomplete FM-DW model, for H_{EB} as a function of the films exchange and anisotropy parameters, and of the cooling field H_{cf}.

The outline of this paper is as follows: after this introduction, the incomplete FM-DW model is described in Section 2, and solved analytically in Section 3. Finally, we draw conclusions in Section 4.

[3] For a detailed description of interface structure, in particular the definition of compensated and uncompensated interfaces, the reader is referred to Refs. [1,4].

2. FM-DW model

The model put forward by Kiwi et al. [30] assumes that the AF interface monolayer reconstructs into an almost rigid canted magnetic structure close to the Néel temperature T_N, which fully freezes when the AF bulk orders. Moreover, it remains frozen, in a metastable state, during the cycling of the external magnetic field, when performed for $H < H_{cf}$.

The total magnetic energy of the system is written as

$$E = -\sum_{\langle i \neq j \rangle}^{N} J_{ij}\ \vec{S}_i \cdot \vec{S}_j - \sum_{i=1}^{N} [K_i\ (\vec{S}_i \cdot \hat{e}_i)^2 + \mu_B g_i\ \vec{S}_i \cdot \vec{H}]\,. \tag{1}$$

The first term above represents the nearest neighbor exchange interaction, with constants $J_{ij} = J_F,\ J_{AF}$ and $J_{F/AF}$ for the FM and AF films, and for the interface, respectively. The second term is the uniaxial anisotropy, with the easy axis in the $\hat{e}_i$ direction (the FM anisotropy is ignored since it is very small). The last term in Eq. (1) is the Zeeman interaction with an external magnetic field $\vec{H}$, where g_i ($i = g_F$ and g_{AF}) denote the gyromagnetic ratios, and μ_B is the Bohr magneton.

As is the case for FeF_2 and MnF_2, let us assume that the crystal has a tetragonal-rutile structure, and that it is grown in the [1 1 0] direction. The two magnetic sublattices, present in the AF, are labelled as α and β. Due to symmetry considerations, we assume that the FM spins $\vec{S}_k$ are parallel within each layer of the FM film. Thus, $E = E_{AF} + E_{F/AF} + E_F$ can be written as

$$\begin{aligned} E_{AF} = &- J_{AF}\,[S\ \hat{e}_{AF} \cdot (\vec{S}^{(\alpha)} - \vec{S}^{(\beta)}) + 2\vec{S}^{(\alpha)} \cdot \vec{S}^{(\beta)}] \\ &- \tfrac{1}{2} K_{AF}\ [(\vec{S}^{(\alpha)} \cdot \hat{e}_{AF})^2\ +\ (\vec{S}^{(\beta)} \cdot \hat{e}_{AF})^2] \\ &- \tfrac{1}{2} \mu_B g_{AF}\ (\vec{S}^{(\alpha)} + \vec{S}^{(\beta)}) \cdot \vec{H}, \end{aligned} \tag{2}$$

$$E_{F/AF} = -J_{F/AF}\,(\vec{S}^{(\alpha)} + \vec{S}^{(\beta)}) \cdot \vec{S}_1, \tag{3}$$

$$E_F = -2J_F \sum_{k=1}^{N_F-1} \vec{S}_k \cdot \vec{S}_{k+1} - \mu_B g_F \sum_{k=1}^{N_F} \vec{S}_k \cdot \vec{H}, \tag{4}$$

where N_F is the number of FM monolayers. For a compensated AF interface, the bulk magnetic order of the FM and AF spins are perpendicular to each other [17], which implies that the AF easy direction $\hat{e}_{AF}$ is perpendicular to the direction of the applied magnetic field.

As mentioned above, during the cooling process, the AF interface layer is assumed to freeze into a canted spin configuration. To determine the canting angle θ_c, of this configuration, we have to recall that $T_C > T > T_N$ (where T_C is the FM Curie temperature). Thus, the configuration the system adopts is with all FM spins parallel to H_{cf} and the AF spins, with the exception of those at the AF interface [31,33], in the direction of AF easy axis. Consequently, for a single magnetic cell, the expression for the energy E, in Eq. (1), reduces to

$$E = 2|J_{AF}|[\cos(2\theta) - \sin\theta] - K_{AF}\sin^2\theta + (2|J_{F/AF}| - \mu_B g_{AF} H_{cf})\cos\theta\,, \tag{5}$$

where constant terms have been omitted and $\theta^{(\alpha)}$ ($\theta^{(\beta)}$) is the average angle between $\vec{S}^{(\alpha)}$ ($\vec{S}^{(\beta)}$) and the cooling field $\vec{H}_{cf}$. Moreover, we assume that $\theta^{(\alpha)} = -\theta^{(\beta)} = \theta$. The value of θ_c is obtained by minimizing Eq. (5) with respect to θ.

When the determination of the hysteresis loop is carried out, for $T < T_N$, the only non-constant terms which contribute are those related to the FM, since the AF interface is assumed to be frozen. This allows to write Eq. (1) as

$$\varepsilon = -\sum_{k=1}^{N_F-1}\cos(\theta_{k+1} - \theta_k) - h\sum_{k=1}^{N_F}\cos\theta_k - \kappa\cos\theta_1\,. \tag{6}$$

In the above equation, we introduced the following dimensionless quantities: $\varepsilon = E/2J_F$, the applied field $h = \frac{1}{2}g_F\mu_B H/J_F$, the effective interface coupling $\kappa = -(|J_{F/AF}|/J_F)\cos\theta_c$, and θ_k, which is the angle between the spins in the kth FM layer and the $\vec{H}_{cf}$ direction. $k = 1$ labels the FM interface layer. The sign of κ is the signature of EB ($\kappa > 0$ yields negative and $\kappa < 0$ positive EB) [33]. The magnetization curve, and therefore the H_{EB} value, is obtained by minimizing ε in Eq. (6).

3. Analytic results

An analytic expression for the canting angle θ_c can be obtained by writing $\theta = \pi/2 + \gamma$ and expanding θ, on the right-hand side of Eq. (5), to second order in γ. Thus, minimizing the energy with respect to γ one obtains

$$\theta_c = \frac{\pi}{2} + \frac{2\ |J_{F/AF}| - g_{AF}\mu_B H_{cf}}{10\ |J_{AF}| + 2K_{AF}}\,, \tag{7}$$

and consequently the effective interface coupling κ is given by

$$\kappa = \frac{|J_{F/AF}|}{J_F}\sin\left[\frac{2|J_{F/AF}| - g_{AF}\ \mu_B\ H_{cf}}{10|J_{AF}| + 2K_{AF}}\right]. \tag{8}$$

The numerator in Eq. (8) is smaller than the denominator, since $J_{F/AF} \approx J_{AF}$. Thus, for all physically accessible values of H_{cf}, the argument of $\sin(x)$ in Eq. (8) obeys $|x| < 1$. It is also apparent that the transition from negative to positive EB occurs for $H_{cf} = 2|J_{F/AF}|/g_{AF}\mu_B$. All of these features are displayed in Fig. 1, which illustrates the behavior of the canting angle, θ_c, versus H_{cf}. The angle $\theta_c = \cos^{-1}(-\kappa J_F/|J_{F/AF}|)$ plays a key role in our model [32], since it determines whether the EB field H_{EB} is positive ($\theta_c < 90°$) or negative

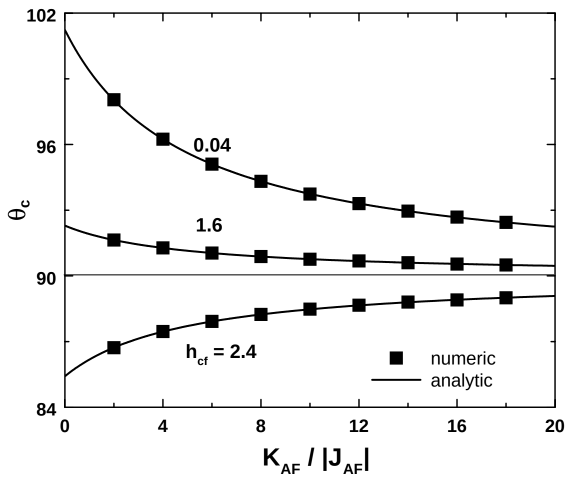

Fig. 1. The AF interface canting angle, θ_c, measured in degrees, versus the ratio of the AF parameters $K_{AF}/|J_{AF}|$, for three values of $h_{cf} = g_{AF}\mu_B H_{cf}/|J_{AF}|$. The squares represent the data calculated numerically and the solid lines are the corresponding analytical solutions. $\theta_c < 90°$ corresponds to positive and $\theta_c > 90°$ to negative EB. We adopted $J_{F/AF} = J_{AF}$.

($\theta_c > 90°$). In Fig. 1, we display the values of θ_c, obtained both numerically and analytically, versus the ratio of the AF parameters $K_{AF}/|J_{AF}|$, for weak ($h_{cf} = 0.04$), intermediate ($h_{cf} = 1.6$) and strong ($h_{cf} = 2.4$) cooling field intensities, where for convenience we have introduced the definition of the non-dimensional parameter $h_{cf} \equiv g_{AF}\mu_B H_{cf}/|J_{AF}|$. As in previous contributions [30–32], we adopted $J_{F/AF} = J_{AF}$. The solid lines are the analytic solutions, while the discrete points were obtained by solving numerically Eq. (5). The agreement between them is quite remarkable.

After cooling, when the hysteresis curve is obtained, we confirm that the angle between spins located in adjacent FM layers is small [31]. Thus we write $\theta_k = \theta_1 + (k-1)\delta$ into Eq. (6), where the angle θ_k depends on the intensity of the applied field, i.e. $\theta_k = \theta_k(H)$. It is also important to notice that when this applied field is strong enough to saturate the magnetization, the condition $\delta = 0$ has to be satisfied. This matter was discussed in detail, and illustrated in Fig. 4 of Ref. [31]. Moreover, it is justified by the solutions of Eq. (14) below. Keeping terms up to second order in δ in Eq. (16), yields

$$\varepsilon = (N_F - 1)\delta^2 - hN_F M(\theta_1, \delta) - \kappa\cos(\theta_1), \tag{9}$$

where $M(\theta_1, \delta)$, the normalized magnetization of the film, is given by

$$M(\theta_1, \delta) = \cos\theta_1 - (N_F - 1) \times \left[\tfrac{1}{2}\,\delta\,\sin\theta_1 - \tfrac{1}{12}\,(2N_F - 1)\delta^2\,\cos\theta_1\right]. \tag{10}$$

The equilibrium state is determined by equating to zero the partial derivatives of ε with respect to δ and θ_1

$$\frac{1}{2\,(N_F - 1)}\frac{\partial\varepsilon}{\partial\delta} = \delta + \frac{1}{4}\,h\,N_F\left[\sin\theta_1 - \frac{1}{3}(2\,N_F - 1)\,\delta\cos\theta_1\right] = 0, \tag{11}$$

$$\frac{\partial\varepsilon}{\partial\theta_1} = -h\,N_F\,\frac{\partial M(\theta_1, \delta)}{\partial\theta_1} + \kappa\sin\theta_1 = 0\ . \tag{12}$$

The dimensionless EB field, h_{EB}, is obtained from the intersection of the magnetization curve with the abscissa, i.e. when $M(\theta_1, \delta) = 0$, which reads as

$$\cos\theta_1 - (N_F - 1) \times \left[\tfrac{1}{2}\,\delta\sin\theta_1 - \tfrac{1}{12}(2N_F - 1)\delta^2\cos\theta_1\right] = 0\ . \tag{13}$$

δ can be eliminated solving Eq. (11) to obtain

$$\delta = \frac{3hN\sin\theta_1}{2hN^2\cos\theta_1 - hN\cos\theta_1 - 12}\ , \tag{14}$$

which implies that $\delta = 0$ for both $\theta_1 = 0$ and $\theta_1 = \pi$ (saturated magnetization), which justifies the assertion made before Eq. (9). By eliminating δ and θ_1 from Eqs. (11)–(13), a relation between h_{EB} versus κ and N_F is obtained. It reads as

$$h_{EB} = -\frac{x[\kappa x(2N_F - 1)(1 - x^2) + 24]}{N_F\,[x^2(N_F + 1) + 3(N_F - 1)]}\ , \tag{15}$$

where x satisfies the following polynomial equation:

$$\begin{aligned}&\kappa^2\left(20N_F^2 - 4N_F + 5 + \frac{4}{N_F - 1}\right)x^7 \\ &\quad - 2\kappa^2\left[(2N_F + 1)^2 + \left(\frac{2}{N_F - 1}\right)\right]x^5 \\ &\quad + 72\kappa\,(5N_F - 1)x^4 - 12\kappa^2 N_F \\ &\quad \times (N_F - 1)\,x^3 - 144\kappa\,(N_F + 1)\,x^2 \\ &\quad + 1728\,x - 216\kappa(N_F - 1) = 0\ .\end{aligned} \tag{16}$$

The solutions for x of Eq. (16) are antisymmetric (odd) with respect to κ, as shown in the x versus κ plot provided in Fig. 2, for several values of N_F. Eq. (15) implies that this also must be fulfilled by h_{EB} and the corresponding curves are plotted in Fig. 3. They show that, for large κ values, the EB field h_{EB} saturates. Since the variation of κ is due to the change of the cooling field H_{cf} intensity (see Eq. (8)), we find that the experimentally observed H_{EB} versus H_{cf} behavior is indeed obtained in this way [23,24].

In the weak interface coupling limit $|\kappa| < \kappa_0$, where $\kappa_0 = \sqrt{24/(N_F^2 - 1)}$, the expression for h_{EB} reduces to

$$h_{EB} = -\frac{\kappa}{N_F}\ , \tag{17}$$

and thus, in this limit, $h_{EB} \propto N_F^{-1}$.

The full solution for h_{EB}, obtained by substitution of the solutions of Eq. (16) into Eq. (15), is illustrated in Fig. 4. It is observed that in the

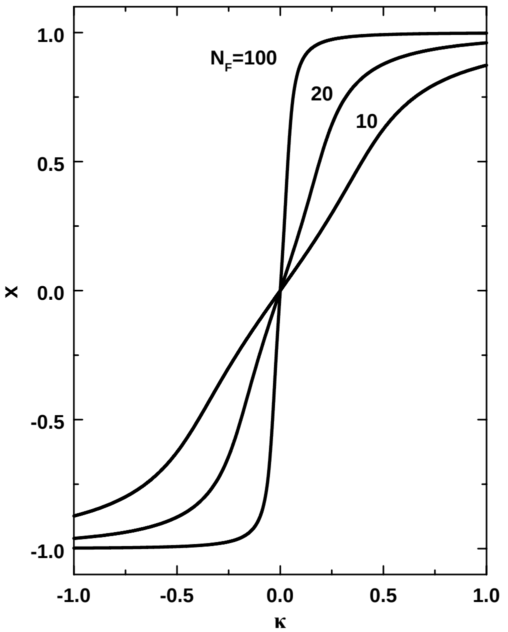

Fig. 2. Solutions of Eq. (16) for three FM film thickness (N_F) values.

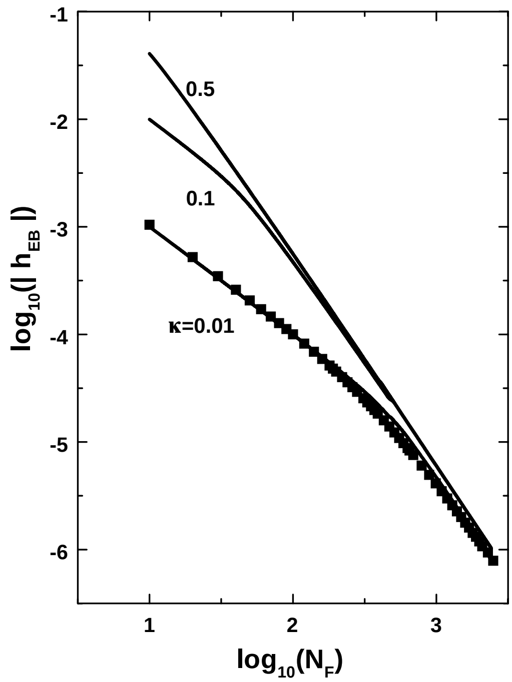

Fig. 4. h_{EB} dependence on FM layer thickness, N_F, for three values of the effective interface coupling strength κ. For $\kappa = 0.01$, the slope exhibits a crossover from -1, for thin films, to -1.9 around $N_F \sim 500$; this behavior is observed both for the analytic solution (full lines) as well as for the numeric results (full squares). For $\kappa = 0.5$, the slope is ≈ -1.9 over the whole range of N_F values.

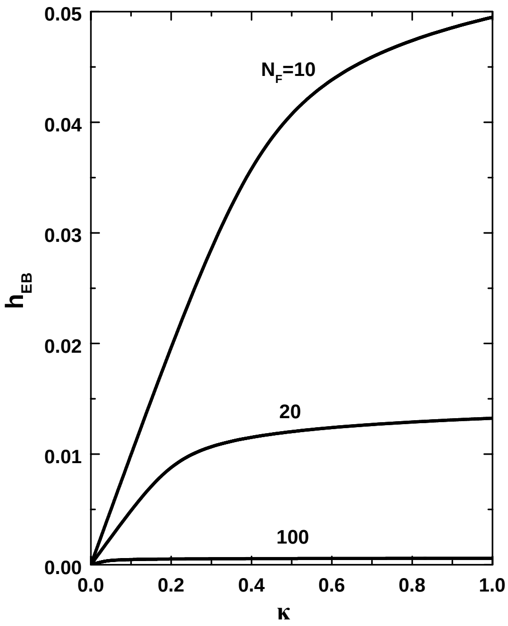

Fig. 3. EB field h_{EB} versus κ, for three values of the FM film thickness, N_F.

strong effective interface coupling region ($\kappa = 0.5$), the relation $h_{EB} \propto N_F^{-1.9}$ is obeyed. However, in the weak coupling limit $\kappa = 0.01$, which corresponds to the Fe/FeF_2 case [34], a more complex behavior is apparent. In fact, a crossover from an N_F^{-1} to an $N_F^{-1.9}$ dependence sets in around $N_F \sim 500$ monolayers, which corresponds to ~ 100 nm.

The above-described behavior is consistent with extensive experimental results listed in the review by Nogués and Schuller [1]. We just mention that the $h_{EB} \propto N_F^{-1}$ behavior was observed, among others, by Nogués et al. [34] in the Fe/FeF_2 system, for Fe films of up to 10 nm thick; by Chen et al. [35]; in Fe films of up to 10 nm grown on GaAs; by Jungblut et al. [36] in the $Ni_{80}Fe_{20}/Fe_{50}Mn_{50}$ system; by Fuke et al. [37] in the $Co_{90}Fe_{10}/IrMn$ system; and by Han et al. [38] in the NiFe/NiO system.

On the other hand, the h_{EB} dependence of thick FM films on the width of the FM slab was already investigated in 1965 by Goto et al. [39], who found that experimental observations, that they carried out, of the pitch of a domain wall in a soft FM in contact with a very hard one, could be understood on the basis of a continuum approximation treatment of the spatial variation of the magnetization in the FM. This procedure is quite appropriate, since the thickness of the Ni–Co films they investigated is $\sim 1\,\mu m$, i.e. much larger than the pertinent characteristic length, the domain wall width, which is $\sim 100\,nm$. Their model yields $H_{EB} \propto N_F^{-2}$, albeit with significant error bars.

It is possible to understand the above-described crossover invoking simple physical arguments. The magnetic spring that develops in a thin FM is dominated by the clamping of the magnetization, both at the interface and the topmost FM layer (which aligns with the externally applied magnetic field). On the contrary, in a thick FM slab, the pitch of the magnetization develops as in the bulk, that is, almost independent of the boundary conditions at the interface and free surface.

Thus, our treatment covers the whole range of interface coupling constant strength (κ) and FM thickness (N_F), yielding results in full agreement with experimental measurements. In addition, it unifies previous approaches into a single analytic framework.

4. Conclusions

In summary, we have obtained an analytic solution for the incomplete FM–DW model of the exchange bias phenomenon that we recently put forward [30–32]. The one additional approximation we use here consists in keeping only up to second-order terms in the magnetization angle between contiguous FM monolayers, which is a small parameter indeed. Moreover, when the approximate analytic results are compared with the values obtained by means of lengthy numerical computations, the agreement is quite remarkable.

In addition, several relevant physical conclusions for the EB phenomenon are derived by implementing our analytic treatment: (i) the effective interface coupling strongly depends on the exchange interaction across the AF–FM interface; (ii) H_{EB} is an odd function of the effective interface coupling; and (iii) a crossover from an N_F^{-1} dependence of H_{EB} for thin films, to an $N_F^{-1.9}$ dependence for FM films thicker than the domain wall width, is derived on the basis of our model. For the Fe/FeF_2 system, this corresponds to $N_F \sim 500$ monolayers.

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