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Exchange-bias systems with compensated interfaces

Miguel Kiwi,[a] José Mejía-López,[b] Ruben D. Portugal,[c] and Ricardo Ramírez
Facultad de Física, Pontificia Universidad Católica, Santiago 22, Chile

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When a ferromagnetic metal (F) is in contact with an antiferromagnet (AF), often a shift of the hysteresis loop away from its normal, symmetric position around $H=0$, to $H_E \neq 0$ does occur. This phenomenon is known as exchange bias (EB). We put forward an analytic model, for compensated AF interfaces, based on the AF interface freezing into a metastable canted spin configuration. The EB energy is reversibly stored in a spring-like magnet, or incomplete domain wall, in the F slab. Our theory yields the right values of H_E and its F thickness dependence $H_E \propto t_F^{-1}$. It also predicts the F layer by layer magnetization profile.
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When a ferromagnet (F) that is in contact with an antiferromagnet (AF) is field cooled in a field H_{cf}, through the AF's Néel temperature T_N, a unidirectional anisotropy may be created, resulting in a hysteresis loop shifted by H_E along the field axis. H_E is the exchange-biasing field. Exchange anisotropy was discovered more than 40 years ago by Meiklejohn and Bean.[1] However, in spite of the revived interest, it has lately awakened[2] and the technological applications that exchange bias (EB) has, a full understanding of the phenomenon is not yet available. We present and investigate a model[3] that yields the right values of H_E and its F thickness t_F dependence $H_E \propto t_F^{-1}$. It also predicts the F layer by layer magnetization profile.

Since its discovery, EB has been characterized as an interface-governed phenomenon. As early as 1962 Bean and Jacobs[4] established that for the Co/CoO system H_E is independent of the AF thickness t_{AF}, as long as $t_{\mathrm{AF}} > 2$ nm, while for Fe/FeF_2 and Fe/MnF_2 no variation of H_E as function of t_{AF} has been reported. Several EB theories were advanced,[5–10] with varying degree of success. Early models,[5,6] which yield much too large values of H_E, assume a domain wall (DW) in the AF. Koon suggested[7] that the F/AF interface structure is the one sketched in Fig. 1, with the F magnetic order orthogonal to the bulk AF easy axis. This was confirmed experimentally[11] for Fe/FeF_2 and also for the Fe_3O_4/CoO systems.[12] Recent experimental neutron reflectometry[13,14] and reversible anisotropic magnetoresistance[15] results confirmed the presence of a DW in the F slab. Another important experimental information[15] is that $H_E \propto t_F^{-1}$.

Our analytic model[3] is based on the assumption that the AF-compensated interface monolayer freezes, as the system temperature is lowered towards the Néel temperature T_N, into a canted magnetic structure which becomes rigid when the AF bulk orders. Moreover, the AF interface remains frozen, in this metastable state, throughout external magnetic-field cycling performed for $|H| < H_{\mathrm{cf}}$, and in the course of temperature cycling above T_N. The former agrees with the memory effect detected by Chien *et al.*,[16] who also observed the temperature cycling feature. The observation of the freezing of the AF magnetic structure was reported by Ball *et al.*[13] These experimental findings imply that the EB information is stored by the interface, since neither the ordered F nor the disordered AF above the Néel temperature can retain the sample magnetization history. In addition, Camley, Carriço, and Stamps[17] reported calculations showing that surface effects in FeF_2 do not extend beyond two monolayers. As a consequence, the energy is mainly stored in an incomplete domain wall (IDW) in the F slab, and our model allows us to evaluate the F thickness dependence of H_E and to predict the detailed magnetic structure of the IDW.

Using this model, we derive an expression for the energy per unit interface area ϵ, which reads

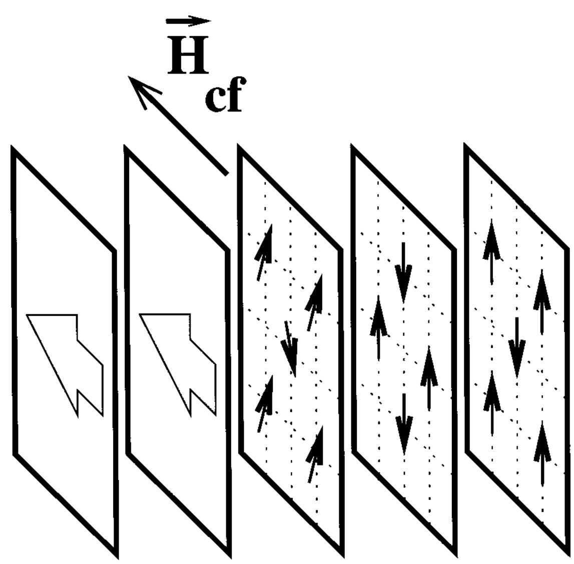

FIG. 1. Zero-applied-field spin configuration of the AF interface monolayer and the two F and AF monolayers closest to the interface. The canting angle θ_c is measured relative to the cooling field $\mathbf{H}_{\mathrm{cf}}$, applied parallel to the $(\bar{1}10)$ AF crystal direction.

[a]Electronic mail: mkiwi@puc.cl
[b]Permanent address: Facultad de Ciencias, Escuela Superior Politécnica de Chimborazo, Riobamba, Ecuador.
[c]PEDECIBA–Física Graduate Fellowship, Universidad de la República, Montevideo, Uruguay.

$$\epsilon = -h\sum_{k=1}^{N} \cos\theta_k - \sum_{k=1}^{N-1} \cos(\theta_{k+1}-\theta_k) - \kappa\cos\theta_1 - D\sum_{k=1}^{N} \cos^2\theta_k . \quad (1)$$

Above, we introduced the dimensionless applied field $h = \mu_B g H/2J_F < 10^{-3}$, where μ_B is the Bohr magneton, g the gyromagnetic ratio, and H the applied field. $D = K_F/2J_F < 10^{-5}$, where J and K denote the exchange and anisotropy parameters, respectively. $\kappa = -(|J_{F/AF}|/J_F)\cos\theta_c$ is the effective interface coupling and θ_c is the AF interface canting angle, which depends on the AF parameters (J_{AF} and K_{AF}) and on H_{cf}. We differentiate ϵ with respect to θ_j, equate to zero to minimize the energy, and thus obtain the set of nonlinear equations to be solved for $\{\theta_k\}$

$$h\sin\theta_j - (1-\delta_{j,N})\sin(\theta_{j+1}-\theta_j) + \delta_{j,1}\kappa\sin\theta_1 + (1-\delta_{j,1})\sin(\theta_j-\theta_{j-1}) + 2D\sin\theta_j\cos\theta_j = 0, \quad (2)$$

where $\delta_{i,j}$ is the Kronecker symbol. Below, we apply this model to two well-documented systems: Fe/FeF_2 and Fe/MnF_2. They have in common a very small AF-DW width (of the order of monolayers), and a well-characterized, controlled, and simple F/AF interface structure.[2] Our computations are carried out for the *compensated* (110) AF interface. A crucial feature to be stressed is the fact that, consistent with our assumption on the freezing of the AF interface layer, in these systems only this layer canting angle differs significantly from the F and AF magnetic bulk. Results for the magnetization vector angle θ_k, of the kth layer relative to the cooling field direction, are given in Table I. The condition required for negative EB ($H_E<0$) is that the minimum energy configuration corresponds to a net interface magnetization component opposite to H_{cf}, or equivalently, $\theta_c = \theta_{k=-1} > 90°$, as illustrated in Fig. 1. On the other hand, $\theta_c < 90°$, which materializes for large cooling fields, implies positive EB. Thus, it is $\theta_c \neq 90°$ that provides the symmetry breaking necessary to generate EB.

In Fig. 2 we display the M vs H plots we computed for a 13 nm Fe slab in contact with the (110)-compensated face of FeF_2 and MnF_2. The following parameter values, all of them obtained from experiment,[11] were used: $J_F = +16$ meV and $K_F = 0$; $J_{AF} = -1.2$ meV, $K_{AF} = 2.5$ meV/spin for Fe/FeF_2; and $J_{AF} = -1.3$ meV, $K_{AF} = 0.12$ meV/spin for MnF_2. The only unknown is the F/AF interfacial exchange parameter $J_{F/AF}$. The values $J_{F/AF} = -1.2$ and -0.35 meV fit the experimental results $H_E = -436$ and -50 Oe of Fe/FeF_2 and Fe/MnF_2, respectively. While the value of $J_{F/AF}$ for Fe/FeF_2 is the same as the AF bulk value, for Fe/MnF_2 it is smaller.

TABLE I. Magnetization vector angle θ_k, relative to the direction of the cooling field $\mathbf{H}_{cf}$, for the five layers $k = -3, -2, -1, 1$, and 2 of Fig. 1 ($H_{cf} = 2000$ Oe).

Layer	θ_k (Fe/FeF_2)	θ_k (Fe/MnF_2)
$F(k=2)$	0.17°	0.04°
$F(k=1)$	0.85°	0.26°
AF$(k=-1)$	98.16°	93.04°
AF$(k=-2)$	88.91°	89.41°
AF$(k=-3)$	90.07°	90.03°

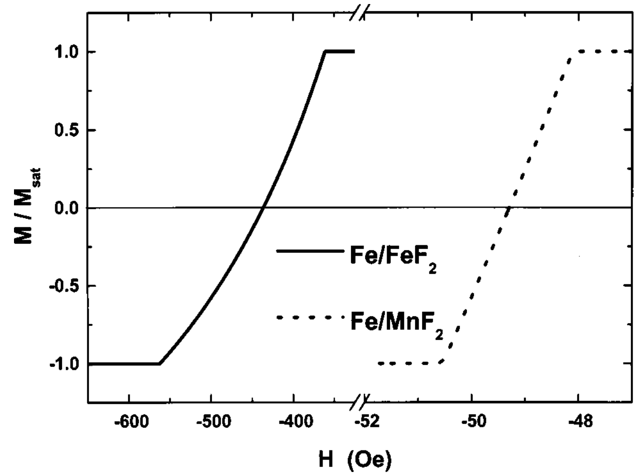

FIG. 2. Magnetization M vs applied field H for Fe/FeF_2 and Fe/MnF_2. The values of $J_{F/AF}$ are -1.2 and -0.35 meV for FeF_2 and MnF_2, respectively.

This is not altogether unexpected as was pointed out by Hasegawa and Herman,[18] and more recently for the specific case of Fe/MnF_2 by Leighton *et al.*,[19] when they explored the variation of J in the vicinity of an interface and its relation with EB. We also remark that since a single interface domain is assumed in our model the hysteresis loops are reversible, but not quite symmetric, which reflects the fact that the $H\to+\infty$ and $H\to-\infty$ states are not mirror images of each other, a crucial point to obtain EB. This asymmetry is more pronounced the larger the value of $J_{F/AF}$.

As already mentioned, another relevant feature of EB systems is the F thickness t_F dependence of H_E. Our calculations show conclusively that $H_E \propto t_F^{-1}$ over a wide range of values, as illustrated in Fig. 3, in agreement with experimental observations.[2,5,15,20]

Layer-by-layer magnetization profiles have recently been obtained with ever-increasing detail by several authors,[13,14] thus providing a challenging test ground for EB models. In Fig. 4, we plot the magnetization angle relative to the cooling field $\mathbf{H}_{cf}$ vs H, for a 13 nm Fe slab ($1 \leqslant k \leqslant 65$) in contact with FeF_2. First, we observe that the onset of the magnetization reversal is rather abrupt, both for increasing and decreasing H. It is also interesting to notice that the difference between the magnetization orientation of the F

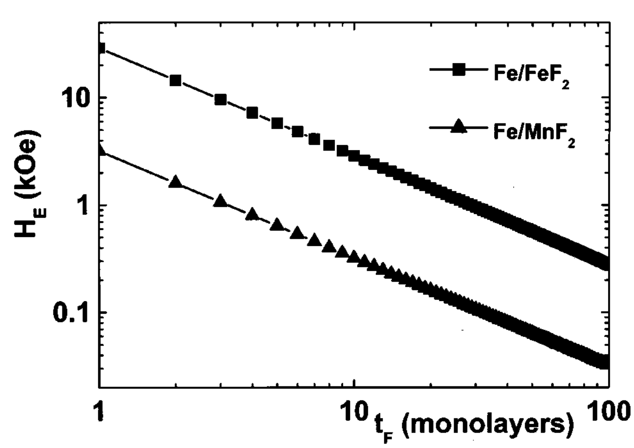

FIG. 3. Fe layer thickness t_F dependence of H_E. The computations yield $H_E \propto t_F^{-1.0112\pm0.0009}$ for Fe/FeF_2 and $H_E \propto t_F^{-0.9995\pm0.0005}$ for Fe/MnF_2.

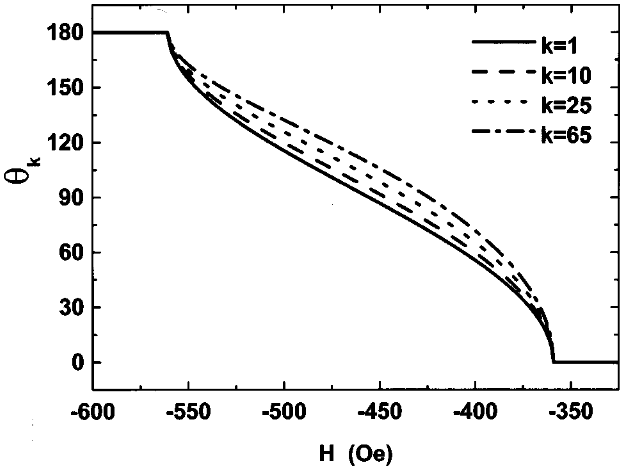

FIG. 4. Magnetization angle θ_k of the kth Fe layer with the cooling field $\mathbf{H}_{cf}$ vs applied field H.

interface layer ($k=1$) and the ''free'' layer ($k=65$) reaches its largest value for $\theta_k \approx 90°$. On the other hand, it is apparent that the twist of the magnetic spring, or IDW, is always less than 20°. The small amount of energy stored in the IDW is a relevant feature to understand the magnitude of H_E, as well as its overestimate by the early theories.[5,6]

In conclusion, on the basis of a theoretical model which is consistent with the available experimental information (in particular, the magnitude of H_E and its F slab thickness dependence $H_E \propto t_F^{-1}$), we have been able to derive magnetization profiles of the IDW that stores the EB energy. These profiles can be contrasted with neutron reflectometry[14] and reversible anisotropic magnetoresistance[15] experiments, which do provide a challenging testing ground for EB models.

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