ELSEVIER

Journal of Magnetism and Magnetic Materials 234 (2001) 584–595

Journal of magnetism and magnetic materials

www.elsevier.com/locate/jmmm

Topical review

Exchange bias theory

Miguel Kiwi*

Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago de Chile 6904411, Chile

Received 8 March 2001; received in revised form 1 June 2001

Abstract

Research on the exchange bias (EB) phenomenon has witnessed a flurry of activity during recent years, which stems from its use in magnetic sensors and as stabilizers in magnetic reading heads. EB was discovered in 1956 but it attracted only limited attention until these applications, closely related to giant magnetoresistance, were developed during the last decade. In this review, I initially give a short introduction, listing the most salient experimental results and what is required from an EB theory. Next, I indicate some of the obstacles in the road towards a satisfactory understanding of the phenomenon. The main body of the text reviews and critically discusses the activity that has flourished, mainly during the last 5 years, in the theoretical front. Finally, an evaluation of the progress made, and a critical assessment as to where we stand nowadays along the road to a satisfactory theory, is presented. © 2001 Elsevier Science B.V. All rights reserved.

PACS: 75.70.i; 75.60.Ej; 75.70.Cn; 75.60.Ch; 75.30.Gw

Keywords: Exchange bias; Magnetic multilayers; Interfaces; Nanostructures; Magnetic devices

1. Introduction

A complete theoretical understanding of the exchange bias (EB) phenomenon has posed a formidable challenge to condensed matter theorists for over four decades. The challenge emanates from several sources: the intrinsic interest of EB, the many supplementary physical phenomena that are involved and the important technological applications that have been developed recently. EB was discovered almost half a century ago, by Meiklejohn and Bean [1], and its characteristic signature is the shift of the center of magnetic hysteresis loop from its normal position at $H = 0$ to $H_E \neq 0$. It occurs in a large variety of systems [2] which are composed by an antiferromagnet (AF) that is in atomic contact with a ferromagnet (F) if the sample is grown, or after the system is cooled, below the respective Néel and Curie temperatures T_N and T_C, in an external cooling field H_{cf}. Examples of the type of systems where EB has been observed are clusters or small particles, F films deposited on single crystal or polycrystalline AFs and F/AF thin films bilayers, and spin glasses. A comprehensive review, which emphasizes experimental results and provides an up-to-date list of relevant publications, was recently published by Nogués and Schuller [2]. While I will not ignore

*Corresponding author. Tel.: +56-2-354-4476; fax: +56-2-553-6468.

E-mail address: mkiwi@puc.cl (M. Kiwi).

0304-8853/01/$ - see front matter © 2001 Elsevier Science B.V. All rights reserved.
PII: S0304-8853(01)00421-8

experimental observations, I refer the interested reader to Ref. [2] for extensive and detailed information. Other reviews have also been published, which discuss both theory and experiment, by Berkowitz and Takano [3] and very recently a paper by Stamps [4] includes novel results.

Defining the direction of the cooling field H_{cf} as positive, in general the EB shift is towards negative fields, i.e. $H_E < 0$; however, recently, Nogués et al. [5] found that samples exposed to large cooling fields ($H_{cf} \sim 1$ T) can exhibit positive EB, i.e. $H_E > 0$.

Several supplementary remarkable features are associated with EB, in addition to the symmetry breaking related to the appearance of the *unidirectional* anisotropy that brings about $H_E \neq 0$. Among them is the existence of a blocking temperature T_B above which EB vanishes. While usually $T_B \approx T_N$ (e.g. F slabs grown on the (1 1 1) face of NiO [6]) T_B can be considerably lower than the Néel temperature (e.g. AFs obtained through oxidation of permalloy [7,8]). Another remarkable feature of EB is the training effect, i.e. the dependence of H_E on the number of measurements n, with the value of H_E decreasing as n increases [7–9], which constitutes a hint that the interface actually is in metastable equilibrium. More recently, an important additional feature was discovered: the memory effect, which consists of the fact that the system keeps a memory of the temperature at which it was field-cooled [10–15]. The latter is closely related to the freezing of the AF magnetic structure reported by Ball et al. [15]. Still, another characteristic associated with many EB systems, observed when $T < T_B$ and which appears to have a magnetic origin [16,17], is a large increase of the coercivity.

As emphasized in the comprehensive review by Nogués and Schuller [2], the EB phenomenon has recently received renewed attention due to its important technological applications. However, and in spite of this renewed interest, a full understanding of EB has not yet emerged. In this review, I briefly mention some of the major experimental results that have been obtained over the years, but my attention is focused on the present status of the theoretical understanding of the phenomenon. The dynamic pace with which the field has developed, especially during the last 5 years, precludes me from mentioning every relevant contribution that has been accomplished recently; I can only ask the unjustly ignored authors for their indulgence.

Historically, the phenomenon was first observed in fine Co particles covered by CoO [1]; this case forms a part of the family of systems of small particles coated by their native oxide (like Ni/NiO [18] and Fe/Fe_3O_4 [19]) or by their nitride (like Co/CoN [20] and Fe/Fe_2N [21,23]). However, I will concentrate on the most widely studied group, namely EB materials in the form of thin film bilayers. There are several reasons for this preference: (i) experimentally these systems allow the best possible control and characterization of the interface [2,22,23]; (ii) most of the actual devices based on EB properties are fabricated in this form [24–26]; and, (iii) these systems are the most convenient to carry out the investigation of specific properties, such as the role of interface structure [27], interface magnetic coupling direction [28–30], cooling field intensity dependence [5,31], EB enhancement [22], coercivity enhancement [16,17], and the deviations from inversion symmetry of the hysteresis loop [32], among others. All the preceding items are relevant when trying to develop a proper theoretical description and understanding of EB.

An additional relevant characteristic of the interface is best defined at this stage: the important distinction between compensated and uncompensated AF interface layers. In the former, the net total magnetic moment of the AF interface layer vanishes, since the vector addition of the spins that belong to each of the two AF magnetic sublattices, pointing in opposite directions, cancels out. Conversely, in an uncompensated AF magnetic face all spins point in the same direction and the layer has a net magnetic moment. These definitions become quite relevant when I examine the early theories that were put forward to describe the interface properties of an F/AF system.

It is now appropriate to formulate precisely what I mean by a proper theoretical description and understanding of EB. The list of requirements that I define below certainly is neither unique nor all one could wish for, but constitutes the minimal

knowledge a theorist would like to have for oneself and to supply an experimentalist with. However, this minimum is still far in the horizon of accomplished achievements. My restricted list reads as follows: (1) first and foremost, to set down a mechanism, *free of ad hoc assumptions on the interface structure*, that yields the genuine reason for unidirectional anisotropy; (2) to derive values for the magnitude of the exchange anisotropy field H_E and the coercivity H_c, as functions of the temperature T and the cooling field H_{cf}; (3) to understand why compensated interfaces yield values of H_E larger, or at least as large, as uncompensated interfaces; (4) to understand the highly nontrivial relation between interface roughness and EB; (5) to explain the memory effect and how it is related to the blocking temperature; (6) to explain the training effect; and, (7) to understand the origin of the inversion asymmetry that is often observed in the shape of the shifted hysteresis loop.

This review is organized as follows: after this Introduction, in Section 2, I describe the main obstacle, that is, the knowledge of the interface atomic and magnetic structure. Next, in Section 3, I describe and classify a set of different theoretical approaches that have been put forward. Finally, in Section 4, an evaluation of the present state of affairs is given and conclusions are drawn.

2. Interface structure: a hard nut to crack

The most relevant unknown element in the development of a satisfactory understanding, and thus of a comprehensive theory of EB, are the unknown features of the interface structure. On the one hand, the systems which exhibit EB are many and varied [2]: thin films, single crystal AF with metallic coating, polycrystalline and amorphous ferromagnets in contact with ordered and disordered AF oxides and salts. On the other hand, the interface, even in the most ordered case of two single crystals in close contact, can have large lattice parameter mismatches, strains and defects. In addition, the magnetic structure in the vicinity of the interface is not necessarily identical to the bulk magnetic ordering [33].

However, most generally, the exact atomic arrangement in the vicinity of the interface is either unknown or, at best, only quite uncertain. Both crystallographic and magnetic relaxation and reconstruction might develop at both sides of the interface and, to complicate matters even further, these features are very rarely amenable to precise experimental probing [34].

The above obstacles are compounded by the complexity of the magnetic structure, with many equivalent easy axes directions that are often present. All in all this implies significant difficulties when trying to formulate a sound theory. However, if one persists in trying to achieve progress in developing a healthy theory of the EB phenomenon, it is necessary to assume or postulate a definite single crystal and magnetic interface structure, which quite certainly will not be completely accurate nor will it incorporate all the subtle intricacies of even the simplest systems [34].

Thus, it comes as no surprise that practically all the theories which have been put forward [35–50] at some point make a crucial assumption about the interface crystallographic and magnetic structure. For the time being, I will put aside the issue of the spatial atomic rearrangements (reconstruction) in the vicinity of the interface and concentrate my interest on the magnetic configuration of that region. Apart from the trivial collinear interfacial magnetic structure shown in Fig. 1 there are many alternative structures, two of which are illustrated in Fig. 2. They will prove relevant to analyze the latest EB theoretical models.

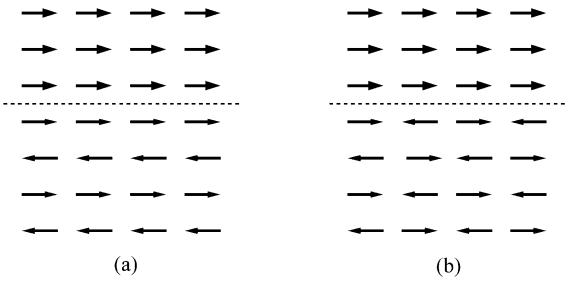

Fig. 1. Magnetically collinear interface configuration. (a) Ferromagnetic coupling across the interface: $J_{F/AF} > 0$; and (b) AF coupling: $J_{F/AF} < 0$.

3. Theoretical models

In classifying and describing the attempts to develop a proper EB theory, after a brief outline of earlier models, I will focus attention on relatively recent work (publications after 1995). Earlier models have in common the assumption of ground state collinear magnetic structures on the F and AF sides of the interface. However, the actual interface structure is much richer and quite complex, as was briefly described and discussed in Section 2. At this point, and to help the reader with a schematic outline of the present status of EB theories, I provide a sketchy route map of what will be explained below. Table 1 focuses on the main characteristics and results of the various models that have been put forward.

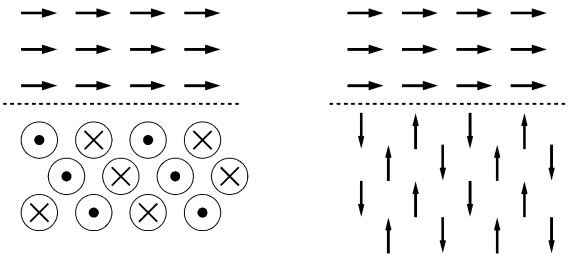

Fig. 2. Two examples of possible noncollinear interface configurations.

Inspection of the "route map" immediately points out an important feature: all the reviewed theories are based on simple models, mainly the Ising and Heisenberg Hamiltonians. However, how well these models describe actual interfaces, in particular the metallic ones, is a debatable issue which was recently tested, using first

Table 1

Theory	Main features	Interface magnetic structure	Main result
Early work [51]	Coherent F and AF magnetization rotation	Uncompensated AF interface layer, $\vec{m}_F \parallel \vec{m}_{AF}$ ($\vec{m}$: bulk magnetization)	H_E much larger than observed experimentally
Néel's model [35,36]	Continuum approximation	Uncompensated AF interface layer; $\vec{m}_F \parallel \vec{m}_{AF}$	Domain wall in the AF, requires large width of the F slab
Early random interface models [38–40]	Random defects create random fields	Uncompensated AF interface layer, $\vec{m}_F \parallel \vec{m}_{AF}$	Reasonable H_E values which depend on defect concentration
AF domain wall models [37]	F interface coupling; thin F film	Uncompensated AF interface layer, $\vec{m}_F \parallel \vec{m}_{AF}$	Reasonable H_E values
Orthogonal F and AF magnetization model [41]	Canting of the AF interface spins	Compensated AF interface layer, $\vec{m}_F \perp \vec{m}_{AF}$	Realistic interface magnetic structure
Generalized random interface models [42,43,49,50]	Rough interface; dipolar interaction is incorporated	AF interface compensated on average, $\vec{m}_F \perp \vec{m}_{AF}$ and $\vec{m}_F \parallel \vec{m}_{AF}$ are investigated	Reasonable H_E values; finite coercivity, dependent on interface defect concentration
Frozen interface model [45–47]	Spin glass like AF canted interface layer	Compensated AF interface; $\vec{m}_F \perp \vec{m}_{AF}$	Reasonable H_E values; one adjustable parameter
Local pinning field variation [44]	Full domain magnetization as basic element	Fluctuating easy axis directions of interface domains	Reasonable values of H_E; finite coercivity, several adjustable parameters

principles spin-density total energy methods, by Kurz et al. [52].

While most of the theories that fit into one of the categories defined in the "route map" are incompatible with those classified in the rest of the categories, the significant influence of Néel's contribution [35,36] on all works subsequent to his is quite apparent. In his analysis he analytically implemented the continuum approximation with several additional assumptions, but many of the later papers, even those which based their calculations on discrete treatments took, with more or less care as to their applicability, his results for granted. Another important and interesting milestone is the work by Koon [41], which pointed out the importance of relative orthogonal directions of the F and AF magnetizations; while the model by itself does not yield EB it strongly influenced later works [42–50].

I now proceed to explore and analyze in detail the theories roughly classified in the "route map".

3.1. Early work

The first attempt to develop an intuitive model for EB seems to be due to Meiklejohn [51]. He assumed coherent rotation of the magnetizations F and the AF, and wrote for ε, the energy per unit interface area, the following expression:

$$\varepsilon = -HM_{\mathrm{F}}t_{\mathrm{F}}\cos(\theta-\beta)+K_{\mathrm{F}}t_{\mathrm{F}}\sin^2(\beta) + K_{\mathrm{AF}}t_{\mathrm{AF}}\sin^2(\alpha)-J_{\mathrm{F/AF}}\cos(\beta-\alpha)\ , \qquad (3.1)$$

where H is the applied magnetic field, M_{F} the F saturation magnetization, t_{f} (t_{AF}) the thickness of the F (AF) slab, K_{F} (K_{AF}) the bulk anisotropy of the F (AF) and $J_{\mathrm{F/AF}}$ the interfacial exchange constant. The angles are defined as follows: α is the angle formed by $\vec{M}_{\mathrm{AF}}$ and the AF anisotropy axis, β is the angle formed by $\vec{M}_{\mathrm{F}}$ and the F anisotropy axis and θ is the angle between $\vec{H}$ and the F anisotropy axis. Neglecting the F anisotropy, which in general is considerably smaller than K_{AF}, and minimizing with respect to α and β, the hysteresis loop shift that Meiklejohn [51] obtained is

$$H_{\mathrm{E}}=\frac{J_{\mathrm{F/AF}}}{a^2M_{\mathrm{F}}t_{\mathrm{F}}}\ , \qquad (3.2)$$

where a is the lattice parameter. The order of magnitude of H_{E} that results depends on the unknown parameter $J_{\mathrm{F/AF}}$, a feature common to all of the theoretical models developed in the EB context. Assuming that, $J_{\mathrm{F}}\geqslant J_{\mathrm{F/AF}}\geqslant J_{\mathrm{AF}}$ the resulting value for H_{E} is orders of magnitude larger than that of the experimentally observed one [51]. This overestimate is a feature shared by many of the earlier models [35,51].

It is interesting to point out that, if one adopts these earlier models as a guide for an intuitive picture, one is to expect: (i) negative exchange bias ($H_{\mathrm{E}}<0$); (ii) the uncompensated interfaces that should display the largest magnitudes of $|H_{\mathrm{E}}|$; and (iii) the roughness of a compensated interface which should increase $|H_{\mathrm{E}}|$. Even a cursory inspection of the experimental results [2] shows that **none** of these expectations is fulfilled.

3.2. The ground breaking contribution of Néel

Ten years after the discovery of EB, Néel [35] formulated a model that applied to a system which consists of a weakly anisotropic uncompensated AF interface layer (see Fig. 1) ferromagnetically coupled across the interface to an F slab. He assumed that the magnetization $\vec{m}_i$ of layer i, both in the F and in the AF, is uniform within the layer and parallel to the interface. Adopting the lattice parameter $=1$ as the unit of length, the condition for $\vec{m}_i$ to be in equilibrium is

$$JS^2\ [\sin\tfrac{1}{2}(\theta_{i+1}-\theta_i)+\sin\tfrac{1}{2}(\theta_{i-1}-\theta_i)] - 2K\sin\theta_i=0\ , \qquad (3.3)$$

where $\frac{1}{2}\theta_i$ is the angle between $\vec{m}_i$ and the easy magnetization axis, and J and K were defined by Eq. (3.1). In the continuum approximation, the above set of difference equations becomes the following differential equation:

$$JS^2\frac{\mathrm{d}^2\theta}{\mathrm{d}i^2}-4K\sin\theta=0\ . \qquad (3.4)$$

Solving the above equation for specific values of J and K, with the assumption of uniaxial anisotropy, Néel was able to derive the magnetization profile. Under appropriate conditions, domains develop both in the F and in the AF, but the continuum approximation requires a minimum

width of the F and AF slabs to be valid; for example, a ferromagnetic iron slab in excess of 1000 Å is needed. Thus, while the Néel model is an important milestone, its application to the better characterized and well-controlled thin film EB systems developed recently is quite restricted and has to be implemented with due caution.

3.3. Early random interface model

Twenty years after Néel's publication Malozemoff [38], in 1987, proposed a model of exchange anisotropy based on the assumption of rough F/AF compensated and uncompensated interfaces, as illustrated in Fig. 3. Random interface roughness gives rise to a random magnetic field that acts on the interface spins, yielding unidirectional anisotropy. The latter causes the asymmetric offset of the hysteresis loop. This way it is possible to reconcile the experimental data with theory, reducing by two orders of magnitude the overestimate derived using Eq. (3.2). The expression given in Ref. [38], for the shift H_E of the hysteresis loop, is

$$H_E = \frac{2}{M_F t_F}\sqrt{\frac{J_{AF}K_{AF}}{a}}\,, \tag{3.5}$$

where I use the same notation as in Eq. (3.2). The reduction factor of the original estimate (ignoring the differences between the various exchange and anisotropy constants) is $2a/\sqrt{J/aK}$, which corresponds to the ratio of twice the lattice parameter a divided by the F domain wall [53] width d_w, since $d_w \sim \sqrt{J/aK}$. The role played by the ratio a/d_w underscores the fact that the characteristic length scale of this problem is d_w. A refinement of the above ideas, put forward in the same paper [38], reduces the ratio still further by allowing the formation of AF domain walls in the vicinity of the interface (the estimate for d_w is assumed to hold both for the F and AF).

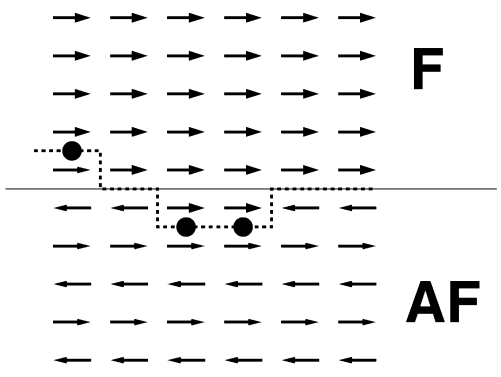

Fig. 3. AF rough interface with frustrated interactions marked by full dots. The dashed line marks the boundary between the F and the AF.

In spite of its success in obtaining a reasonable estimate for H_E, this model has a severe drawback: it crucially depends on a defect concentration at the interface which is not consistent with experiments, as will be discussed in detail further in this review. However, it was recently reexamined and extended by Schulthess and Butler [42,43], as mentioned below in Section 3.6.

3.4. AF domain wall models

Shortly after Malozemoff's proposal an alternative suggestion was advanced by Mauri et al. [37] (while usually referred as "the Mauri model", it is coauthored by Mauri, Siegmann, Bagus and Kay). The main assumptions made are: (i) F interface coupling across a perfect flat interface; (ii) parallel magnetization of the F and AF sublattices in the absence of an external field; (iii) an F slab thickness t_F much smaller than the F domain wall width; and (iv) a domain wall (DW) that develops inside the AF, which has the effect of imposing an upper limit on the exchange coupling energy, such that it reaches significantly smaller values than those given by Eq. (3.2). Assumptions (i), (ii) and (iv) are debatable; first, AF interface coupling is not only possible but most likely in several cases. In fact, Nogués et al. [54] have experimentally confirmed that AF interface coupling is necessary to observe positive exchange bias. Moreover, it does not provide clues to understand how compensated interfaces can yield values of H_E as large as, or even larger than, uncompensated ones [2]. Furthermore, in the magnetic ground state configuration, the F magnetic moments are orthogonal to the bulk AF easy axis (as pointed out by Koon [41] and confirmed experimentally by Moran et al. [28] and Ijiri et al.

[29]). Finally, for a DW to develop in the AF, the anisotropy constant K_{AF} has to be quite small; otherwise it is energetically favorable for the DW to form in the F side, as inferred experimentally in Refs. [15,32,55–58] and argued theoretically in Refs. [45–47].

3.5. Orthogonal F and AF magnetic lattices

In 1997, Koon [41] tackled the problem of explaining EB in thin films with compensated F/AF interfaces by means of a micromagnetic calculation. His main result was to establish, on the basis of a Heisenberg model, that the ground state configuration corresponds to *perpendicular* orientation of the bulk F moments relative to the AF magnetic easy axes direction, as illustrated in Fig. 4. Moreover, Koon also showed that the magnetic moments in the AF interface layer exhibit canting; in fact, the minimum energy is achieved with the AF spins adopting a relatively small canting angle ($\theta < 10^\circ$) relative to the AF bulk easy axis, with a component opposite to the cooling field direction.

While the work of Koon is relevant in establishing the right interface magnetic structure unfortunately, as properly pointed out by Schulthess and Butler [42], it fails to yield EB. In other words, the canted interface magnetic structure by itself is not sufficient to generate EB, i.e. to produce the required *unidirectional* anisotropy and the consequent shifted hysteresis loops with $H_E \neq 0$.

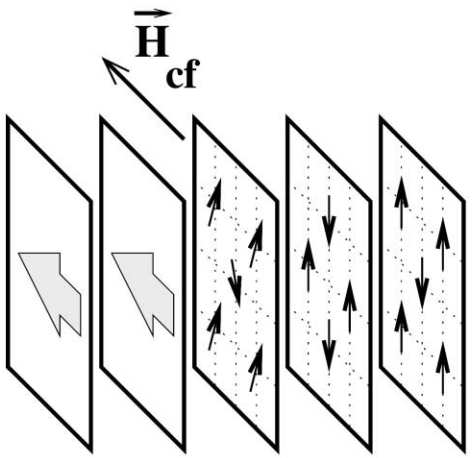

Fig. 4. Illustration of the perpendicular F and AF magnetic interface configuration, with spin canting in the first AF layer.

3.6. Random interface field models

Schulthess and Butler [42,43] showed that Malozemoff's random interface field and Koon's orthogonal magnetic arrangement, rather than being in conflict, could be combined to provide an explanation of EB. In their model they added to the usual exchange, Zeeman and anisotropy energies, the dipolar interaction term E_D

$$E_D = \sum_{i \neq j} \frac{[\vec{\mu}_i \cdot \vec{\mu}_j - 3(\vec{\mu}_i \cdot \hat{n}_{ij})(\vec{\mu}_j \cdot \hat{n}_{ij})]}{|\vec{R}_i - \vec{R}_j|^3}, \tag{3.6}$$

where $\{\mu_i\}$ is the magnetic moment configuration and $\hat{n}_{ij}$ is a unit vector parallel to $\vec{R}_i - \vec{R}_j$. Magnetic properties were obtained using a classical micromagnetic approach [59–61], solving the Landau–Lifshitz equations of motion, including a Gilbert–Kelley damping term, in order to attain stable or metastable equilibrium.

As already mentioned, when the above model is applied to the Koon orthogonal interface configuration, illustrated in Fig. 4, for flat interfaces the coupling that results does not yield unidirectional anisotropy, but rather irreversible magnetization curves with finite coercivity. The irreversibility appears as a bifurcation in the solution of the equation of motion. Thus, additional elements are required to generate exchange bias. Following the spirit of Malozemoff's model, in Refs. [42,43] surface defects were introduced by assuming a 4×4 2D interface unit cell, with one interfacial F site occupied by an AF magnetic moment. This way values of H_E, and of the coercivity H_c, of comparable magnitude to experimental observation [48] for the CoO/F system (F : Co and permalloy) are obtained, when exchange and anisotropy parameters of reasonable magnitude, and a canting angle of 10°, are adopted. Of course there is a caveat: the model hinges qualitatively on the assumption of a rough interface, and the quantitative results depend on the nature and concentration of the interface defects that are incorporated.

In this context it is pertinent to stress that the relation between surface roughness and EB is quite complex experimentally, and far from being understood theoretically. Experimentally, Moran et al. [62] already established in 1995 that interface disorder *increases* H_E in the permalloy/CoO system. Very recently Leighton et al. [16] reported an even more surprising result: that as a function of interface roughness both the coercivity H_c and H_E can manifest quite unexpected behaviors. For example, in the Fe/FeF_2 system the rougher the interface the larger the H_E, but the opposite occurs in the very similar Fe/MnF_2 system. Moreover, Fe/MnF_2 exhibits large changes of both H_E and H_c, as a function of the cooling field strength H_{cf}, when the interface is smooth, but hardly a significant variation when it is rough.

Also Zhang et al. [49] theoretically investigated the coercivity of EB systems induced by random fields at the F/AF interface. They incorporated domain walls on the F side of the interface and derived the correct order of magnitude and temperature dependence of the coercivity ($H_c \propto T^{-3/2}$). Still another random field model was investigated by Dimitrov et al. [50], starting from the assumption of an interface exchange interaction between F and AF magnetic moments $\vec{\mathbf{m}}_F$ and $\vec{\mathbf{m}}_{AF}$, respectively, given by

$$\varepsilon = J_1 \vec{\mathbf{m}}_F \cdot \vec{\mathbf{m}}_{AF} + J_2 (\vec{\mathbf{m}}_F \cdot \vec{\mathbf{m}}_{AF})^2 \ , \tag{3.7}$$

where J_1 and J_2 are the normal and biquadratic [63] exchange constants. J_1 favors parallel or antiparallel alignment, while J_2 favors orthogonal (spin flop like) F/AF coupling. Summing over all the interactions the above expression leads to the following form for the total energy:

$$E = C_1 + C_2 J_1 \cos\theta + C_3 J_2 \sin^2\theta, \tag{3.8}$$

where θ is the angle formed by the easy axes of the F and AF and the C_k's are coefficients which cannot be calculated without detailed interface information. Using an educated guess for the pertinent parameters several qualitatively correct conclusions were obtained from this model.

3.7. The frozen interface model

Recently, Kiwi et al. [45–47] put forward an EB model which applies to a large variety of systems where the anisotropy of the AF is relatively large, and thus the energy cost of creating a domain wall in the AF quite considerable. In particular, Fe/FeF_2 and Fe/MnF_2 were adopted as prototypes, since there is an extensive experimental information on them, they have precisely characterized interfaces, a rather simple crystal and interface structure, and large H_E values [2,5,16,27,30]. Attention was focused on the (1 1 0) *compensated* AF crystal face, which exhibits the largest EB. The zero applied field interface spin configuration is described by the illustrative cartoon provided as Fig. 4. This spin configuration is a consequence of the fact that the two characteristic length scales in the problem (the F and AF domain wall widths, d_w^F and d_w^{AF}, respectively) are very different [44]. While $d_w^{Fe} \sim 100$ nm, d_w^{AF} amounts to just a few monolayers due to the large FeF_2 anisotropy, which is consistent with results by Carrico et al. [64].

As in all models an assumption is made: that the first AF interface layer freezes into the canted spin configuration it adopts close to T_N. Since $t < d_w^F$, where t is the thickness of the F slab, a discrete treatment is in order. Analytically,

$$\mathscr{H} = \mathscr{H}_{AF} + \mathscr{H}_{F/AF} + \mathscr{H}_F \ , \tag{3.9}$$

where $\mathscr{H}_{AF}$, $\mathscr{H}_{F/AF}$ and $\mathscr{H}_F$ describe the AF substrate, interface coupling and the F slab, respectively. For the single magnetic cell, partially represented in Fig. 4, these terms can be written as

$$\begin{aligned}\mathscr{H}_{AF} = & -J_{AF}\ [S\,\hat{e}_{AF}\cdot(\vec{S}^{(\alpha)} - \vec{S}^{(\beta)}) + 2\vec{S}^{(\alpha)}\cdot\vec{S}^{(\beta)}\ ] \\ & -\tfrac{1}{2}K_{AF}\ [\ (\vec{S}^{(\alpha)}\cdot\hat{e}_{AF})^2\ +\ (\vec{S}^{(\beta)}\cdot\hat{e}_{AF})^2\ ] \\ & -\tfrac{1}{2}\mu_B g\ (\vec{S}^{(\alpha)} + \vec{S}^{(\beta)})\cdot\vec{H},\end{aligned} \tag{3.10}$$

$$\mathscr{H}_{F/AF} = -J_{F/AF}\ (\vec{S}^{(\alpha)} + \vec{S}^{(\beta)})\cdot\vec{S}_1, \tag{3.11}$$

$$\begin{aligned}\mathscr{H}_F = & -2J_F \sum_{k=1}^{N-1} \vec{S}_k\cdot\vec{S}_{k+1} - \sum_{k=1}^{N}\left[\frac{K_F}{H^2}\ (\vec{S}_k\cdot\vec{H})^2\right. \\ & \left. +\mu_B g\ \vec{S}_k\cdot\vec{H}\right],\end{aligned} \tag{3.12}$$

where $S = |\vec{S}|$ and N is the number of F layers. μ_B and g denote the Bohr magneton and the Fe gyromagnetic ratio, respectively, while $\vec{H}$ is the external applied magnetic field. J_μ denotes the Heisenberg exchange parameter and K_μ the uniaxial anisotropy. In Eq. (3.10), the unit vector $\hat{e}_{AF}$ defines the AF uniaxial anisotropy direction, $\vec{S}^{(\alpha)}$ and $\vec{S}^{(\beta)}$ which are canted spin vectors in the AF interface, belonging to the α- and β-AF sublattices. The vectors $\vec{S}_k$ are the spin vectors of the kth F layer, with $k = 1$ that labels the F interface, $1 \leqslant k \leqslant N$, where the value $N = 65$ was adopted for the total number of F layers. For Fe this corresponds to $t_F \approx 13$ nm, where t_F denotes the width of the F slab.

Labeling $\theta^{(\alpha)}$ ($\theta^{(\beta)}$) as the average angle between $\vec{S}^{(\alpha)}(\vec{S}^{(\beta)})$ and the cooling field $\vec{H}_{cf}$ and assuming that $\theta^{(\alpha)} = -\theta^{(\beta)}$, the set of nonlinear equations to be solved for $\{\theta_k\}$ is

$$h\sin\theta_j - (1-\delta_{j,N})\sin(\theta_{j+1}-\theta_j) + \delta_{j,1}\ \kappa\sin\theta_1 + (1-\delta_{j,1})\sin(\theta_j-\theta_{j-1}) + 2D\sin\theta_j\cos\theta_j = 0\ , \tag{3.13}$$

where $\delta_{i,j}$ is the Kronecker symbol, $h = \mu_B g H/2J_F < 10^{-3}$, μ_B is the Bohr magneton, $D = K_F/2J_F < 10^{-5}$, κ is the effective interface coupling, and J and K denote the exchange and anisotropy parameters, respectively.

This set of equations can be solved using Camley's method [65,66] and by simulated annealing [67]. Both yield the same values of H_E which, using a single adjustable parameter, the interface coupling constant $J_{F/AF}$, agree with experiment [45]. Moreover, the calculations show that $H_E \propto t_F^{-1}$, as long as the F thickness $t_F < d_w^F$. The energy is reversibly stored in an incomplete domain wall, or magnetic structure [68], in the F slab. The magnetic structure of this incomplete domain wall in the F has a twist smaller than 20°, and is qualitatively compatible with the neutron scattering experiment results obtained by Ball et al. [15].

However, the strongest experimental support for the above picture was obtained by very recent experiments. Nolting et al. [69] established that the alignment of the spins in individual F domains close to the interface is determined, domain by domain, by the spin direction in the underlying AF. Even more detailed support is provided by the scanning electron microscopy imaging experiments of Matsuyama et al. [70]. They investigated Fe domains deposited on the fully compensated (0 0 1) face of NiO and observed that the Fe spin polarization of each domain is roughly perpendicular to an easy axis of the NiO. Moreover, they also infer that the NiO interface spins cant in relation to the Fe spins.

The model by Kiwi et al. also allows for a simple explanation of positive exchange bias [47], which is in fairly good agreement with the experiment. The positive exchange bias problem had been addressed previously by Hong [71], on the basis of a spin wave theory put forward by Suhl and Schuller [72]. In the latter approach [72], the mechanism that generates EB is, to the best of my knowledge, the only one that does not introduce ad hoc assumptions about the interface structure, since the coupling is a consequence of the emission and reabsorption, by a ferromagnetic spin, of virtual AF spin waves across the interface. According to Hong [71], a strong cooling field polarizes the AF spins in the opposite direction to the low field cooled ones, which results in $H_E > 0$.

3.8. Local pinning field variation

Stiles and McMichael [44] adopted a conceptually different approach. Rather than focusing their attention on the interaction of individual atoms, or magnetic moments, they constructed their theory using polycrystalline interface AF grains, with stable magnetic order, as building blocks. They assume that the interface AF magnetic grains, which in the absence of the F slab can order themselves in many different quasi-degenerate arrangements, choose a particular stable energy configuration when in contact with the F. Due to the weakness of the Zeeman term, this interface magnetic configuration is stable and retains a "memory" of the initial F direction, i.e. the direction of the F magnetization when AF order sets in. Moreover, they suggest that due to the polycrystalline nature of the system under scrutiny, even for uncompensated AF interfaces, there is a substantial compensation of the

magnetic moments due to the fluctuating easy axis direction of each individual grain. Thus, in this model [44], a fraction of uncompensated spins at the interface drives the unidirectional anisotropy.

The starting point of the calculation is to consider a single domain AF grain. The energy of each grain that is coupled to the F is given by

$$\frac{E}{Na^2} = \frac{-J_{\text{net}}}{a^2}[\hat{\mathbf{M}}_{\text{FM}} \cdot \hat{\mathbf{m}}(0)] + \frac{J_{sf}}{a^2}[\hat{\mathbf{M}}_{\text{FM}} \cdot \hat{\mathbf{m}}(0)]^2 + \frac{1}{2}\sigma[1 - \hat{\mathbf{m}}(0) \cdot (\pm\hat{\mathbf{u}})], \tag{3.14}$$

where a is the lattice constant and $\hat{\mathbf{M}}_{\text{FM}}$, $\hat{\mathbf{m}}(0)$ and $\pm\hat{\mathbf{u}}$ establish the F magnetization, net AF sublattice magnetization and the two easy uniaxial anisotropy directions, respectively. J_{net} is the average coupling energy to the net moment of the AF grain, J_{sf} is the spin flop energy and σ is the energy of a 180° domain wall in the AF. Thus, there is a competition between parallel alignment described by J_{net} and perpendicular, spin flop-like, alignment induced by J_{sf}. The formal similarity between Eqs. (3.14) and (3.7) is quite obvious; however, it has to be stressed that the latter deals with single magnetic moments while the former applies to AF interface grains. Moreover, the possibility of a domain wall forming in the AF is additionally incorporated and described by the term proportional to σ.

On the basis of the above outlined model they calculate the relevant physical properties of the system, i.e. the magnitude of the unidirectional anisotropy and the hysteretic effects that induce coercivity, as well as the consequences for field rotational torque and ferromagnetic resonance measurements. This is done for a variety of parameter values, both ignoring and including spin flop-like coupling.

While a satisfactory description is thus achieved, several assumptions have to be made, in addition to those outlined above in relation to the justification of Eq. (3.14). To lock the interface spin configuration, partial domain walls are required to wind up in the AF. Moreover, it is postulated that for some AF grains a critical winding angle exists which, if exceeded, leads to instability of the AF order. This way the AF grains can either support a particular AF order or they can switch between two possible states; the former is associated with reversible, and the latter with hysteretic, behavior.

4. Summary and discussion

The challenge posed by the EB phenomenon has generated the vigorous activity described in the preceding sections. It is apparent that the effort to probe the EB phenomenon experimentally, and to understand it theoretically, has truly flourished during the last few years. As is often the case, the simple systems, that are more amenable to be grasped by theory (e.g. atomically ordered epitaxially grown bilayers), are less relevant for technological applications, since polycrystalline thin film multilayers are the ones routinely employed in actual devices. However, the insight derived from the understanding of simple systems may well prove transferable to more complex cases.

As discussed in Section 2, at present, the major obstacle in the path to a full understanding of EB is the knowledge of the crystallographic and magnetic structure in the vicinity of the F/AF interface. Thus, interface sensitive experimental probes, like the recently published work of Nolting et al. [69] and Matsuyama et al. [70], as well as the grazing angle neutron scattering experiments by Ball et al. [15] and Fitzsimmons et al. [32], provide important clues to improving our understanding of the phenomenon.

Besides the above uncertainties, theorists also have to deal properly with the intrinsically complex and subtle mechanisms involved in EB. For example, it took more than four decades from the discovery of EB by Meiklejohn and Bean [1] to the realization by Koon [41] that the F bulk magnetization is orthogonal to the AF sublattice magnetic moments. To order zero (perfectly ordered magnetic and crystal bulk structures all the way up to the interface) the collinear and orthogonal configurations require the same energy. In other words, the energy cost of the collinear configuration (one half of the interface magnetic moments that are frustrated) is the same as for perpendicular ordering (all the interface moments that are half-frustrated). It is only when

canting in the vicinity of the interface is incorporated in the calculation that the perpendicular ordering proves to be more favorable. Thus, the contribution by Koon is important, in spite of the fact that the model [41] fails to yield $H_E \neq 0$. It is worth mentioning that the orthogonal configuration was confirmed experimentally by Moran et al. [28] and Ijiri et al. [29].

In addition, as outlined in Section 1, there are many systems that exhibit EB and it is quite likely that no single theory will be able to properly fit and describe all of them. In fact, it might well be that each, or at least some, of the assumptions advanced on the interface structure apply to different classes of systems. The relative strength of the anisotropy parameters K_F, $K_{F/AF}$ and K_{AF} is also an important physical quantity in determining which theory is applicable to which system.

Thus, at this point it seems adequate to make a critical evaluation of where we stand, in terms of the list of requirements specified in Section 1, for a sound theory of EB. I will go through them point by point: (1) as far as the essential issue of establishing a mechanism *free of ad hoc assumptions on the interface structure* that yields unidirectional anisotropy, it is clear that there is a long way to go before that goal is achieved; (2) based on the several models put forward for the crystallographic and magnetic structure of the interface, reasonable values of H_E and H_c have been obtained. Also, the dependence of H_E on H_{cf} has been derived, but is less than the temperature dependence of these quantities [35–40,42–50]; (3) on the basis of the orthogonal interface spin arrangement, the rationale for the large H_E values that compensated AF interfaces exhibit are now on reasonably firm ground [42–47]; (4–7) on the contrary, the relation between interface roughness and EB remains a mystery to theory, as well as the memory effect and its relation to the blocking temperature, the training effect and the asymmetry of the hysteresis loop.

In conclusion, the abundant new experimental information and the refined theories put forward during the last 5 years have allowed investigators to make significant headway in the description, understanding and technological use of the exchange bias phenomenon, but it is equally clear that many important issues remain open.

Acknowledgements

I thank Professors Ivan K. Schuller, David Lederman and Josep Nogués for their valuable suggestions and the critical reading of the manuscript. Stimulating discussions with José Mejía-López, Ruben Portugal and Ricardo Ramírez are gratefully acknowledged. This work was supported by the Fondo Nacional de Investigaciones Científicas y Tecnológicas (FONDECYT, Chile) under Grant # 8990005.

References

[1] W.P. Meiklejohn, C.P. Bean, Phys. Rev. 102 (1956) 1413.
[2] J. Nogués, I. K. Schuller, J. Magn. Magn. Mater. 192 (1999) 203 and references therein.
[3] A.E. Berkowitz, K. Takano, J. Magn. Magn. Mater. 200 (1999) 552 and references therein.
[4] R.L. Stamps, J. Phys. D: Appl. Phys. 33 (2000) R247 and references therein.
[5] J. Nogués, D. Lederman, T.J. Moran, I.K. Schuller, Phys. Rev. Lett. 76 (1996) 4624.
[6] J.X. Shen, M.T. Kief, J. Appl. Phys. 79 (1996) 5008.
[7] E. Fulcomer, S.H. Charp, J. Appl. Phys. 53 (1972) 184.
[8] E. Fulcomer, S.H. Charp, J. Appl. Phys. 43 (1972).
[9] C. Tsang, K. Lee, J. Appl. Phys. 53 (1982) 2605.
[10] T. Ambrose, R.L. Sommer, C.L. Chien, Phys. Rev. B 56 (1997) 83.
[11] S.M. Chou, K. Liu, C.L. Chien, Phys. Rev. B 58 (1998) R14717.
[12] X.W. Wu, C.L. Chien, Phys. Rev. Lett. 2795 (1998) 2795.
[13] N.J. Gökemeijer, C.L. Chien, J. Appl. Phys. 85 (1999) 5516.
[14] N.J. Gökemeijer, J.W. Cai, C.L. Chien, Phys. Rev. B 60 (1999) 3033.
[15] A.R. Ball, A.J.G. Leenaers, P.J. van der Zaag, K.A. Shaw, B. Singer, D.M. Lind, H. Fredrikze, M.T. Rekveldt, Appl. Phys. Lett. 69 (1996) 1489.
[16] C. Leighton, J. Nogués, B.J. Jönsson-Åkerman, I.K. Schuller, Phys. Rev. Lett. 84 (2000) 3466.
[17] C. Hou, H. Fujiwara, K. Zhang, Appl. Phys. Lett. 76 (2000) 3974 and references therein.
[18] Y.D. Yao, Y.Y. Chen, M.F. Tai, D.H. Wang, H.M. Lin, Mater. Sci. Eng. A 217–218 (1996) 281.
[19] V. Papaefthymiou, A. Kostikas, A. Simopulos, D. Niarchos, S. Gangopadhyay, G.C. Hadjipanayis, C.M. Sorensen, K.J. Klabunde, J. Appl. Phys. 67 (1990) 4487.

[20] H.M. Lin, C.M. Hsu, Y.D. Yao, Y.Y. Chen, T.T. Kuan, F.A. Kuan, F.A Yang, C.Y. Tung, Nanostruct. Mater. 6 (1995) 977.
[21] C.M. Hsu, H.M. Lin, K.R. Tsai, J. Appl. Phys. 76 (1994) 4793.
[22] J. Nogués, D. Lederman, T.J. Moran, I.K. Schuller, K.V. Rao, Appl. Phys. Lett. 68 (1996) 3186.
[23] R. Jungblut, R. Coehoorn, M.T. Johnson, J. van de Stegge, A. Reinders, J. Appl. Phys. 75 (1994) 6659.
[24] B. Dieny, V.S. Speriosu, S. Metin, S.S.P. Parkin, B.A. Gurney, P. Baumgart, D.R. Wilhoit, J. Appl. Phys. 69 (1991) 4774.
[25] B. Dieny, V.S. Speriosu, S.S.P. Parkin, B.A. Gurney, D.R. Wilhoit, D. Mauri, Phys. Rev. B 43 (1991) 1297.
[26] B. Dieny, A. Granovsky, A. Vedyaev, N. Ryzhanova, C. Comache, L.C. Pereira, J. Magn. Magn. Mater. 151 (1995) 378.
[27] J. Nogués, T.J. Moran, D. Lederman, I.K. Schuller, Phys. Rev. B 59 (1999) 6984.
[28] T.J. Moran, J. Nogués, D. Lederman, I.K. Schuller, Appl. Phys. Lett. 72 (1998) 617.
[29] Y. Ijiri, J.A. Borchers, R.W. Erwin, S.H. Lee, P.J. van der Zaag, R.M. Wolf, Phys. Rev. Lett. 80 (608) 1998.
[30] J. Nogués, L. Morellon, C. Leighton, M.R. Ibarra, I.K. Schuller, Phys. Rev. B 61 (2000) R6455.
[31] C. Leighton, J. Nogués, H. Suhl, I.K. Schuller, Phys. Rev. B 60 (1999) 12 837.
[32] M.R. Fitzsimmons, P. Yashar, C. Leighton, I.K. Schuller, J. Nogués, C.F. Majkrzak, J.A. Dura, Phys. Rev. Lett. 84 (2000) 3986.
[33] D. Lederman, J. Nogués, I.K. Schuller, Phys. Rev. B 56 (1997) 2332.
[34] G. Charlton, P.B. Howes, C.A. Muryn, H. Raza, N. Jones, J.S.G. Taylor, C. Norris, R. McGrath, D. Norman, T.S. Turner, G. Thornton, Phys. Rev. B 61 (2000) 16 117.
[35] L. Néel, Ann. Phys. Paris 2 (1967) 61.
[36] N. Kurti (Ed.), Selected Works of Louis Néel, Gordon Breach, New York, 1988, includes an english translation of the preceding reference.
[37] D. Mauri, H.C. Siegmann, P.S. Bagus, E. Kay, J. Appl. Phys. 62 (1987) 3047.
[38] A.P. Malozemoff, Phys. Rev. B 35 (1987) 3679.
[39] A.P. Malozemoff, Phys. Rev. B 37 (1988) 7673.
[40] A.P. Malozemoff, J. Appl. Phys. 63 (1988) 3874.
[41] N. C. Koon, Phys. Rev. Lett. 78 (1997) 4865.
[42] T.C. Schulthess, W.H. Butler, Phys. Rev. Lett. 81 (1998) 4516.
[43] T.C. Schulthess, W.H. Butler, J. Appl. Phys. 85 (1999) 5510.
[44] M.D. Stiles, R.D. McMichael, Phys. Rev. B 59 (1999) 3722.
[45] M. Kiwi, J. Mejía-López, R.D. Portugal, R. Ramírez, Europhys. Lett. 48 (1999) 573.
[46] M. Kiwi, J. Mejía-López, R.D. Portugal, R. Ramírez, Appl. Phys. Lett. 75 (1999) 3995.
[47] M. Kiwi, J. Mejía-López, R.D. Portugal, R. Ramírez, Solid State Comm. 116 (2000) 315.
[48] K. Takano, R.H. Kodama, A.E. Berkowitz, W. Cao, G. Thomas, Phys. Rev. Lett. 79 (1997) 1130.
[49] S. Zhang, D. Dimitrov, G.C. Hadjipanayis, J.W. Cai, C.L. Chien, J. Magn. Magn. Mater. 198–199 (1999) 468.
[50] D.V. Dimitrov, S. Zhang, J.Q. Xiao, G.C. Hadjipanayis, C. Prados, Phys. Rev B 58 (1998) 12 090.
[51] W.P. Meiklejohn, J. Appl. Phys. 33 (1962) 1328.
[52] P. Kurz, G. Bihlmayer, K. Hirai, S. Blügel, Phys. Rev. Lett. 86 (2001) 1106.
[53] C. Kittel, Introduction to Solid State Physics, 6th Edition, Wiley, New York, 1986.
[54] J. Nogués, C. Leighton, I.K. Schuller, Phys. Rev. B 61 (2000) 1315.
[55] B.H. Miller, E.D. Dahlberg, Appl. Phys. Lett. 69 (1996) 3932.
[56] V. Strom, B.J. Jonsson, K.V. Rao, E.D. Dahlberg, J. Appl. Phys. 81 (1997) 5003.
[57] E.D. Dahlberg, B. Miller, B. Hill, B.J. Jönsson, V. Ström, K.V. Rao, J. Nogués, I.K. Schuller, J. Appl. Phys. 83 (1998) 6893.
[58] E.E. Fullerton, J.S. Jiang, M. Grimsditch, C.H. Sowers, S.D. Bader, Phys. Rev. B 58 (1998) 12 193.
[59] A.E. LaBonte, J.S. Kouvel, J. Appl. Phys. 40 (1969) 2450.
[60] J. William, F. Brown, Micromagnetics, Robert E. Krieger Publ. Co., Huntington, New York, 1978.
[61] A. Aharoni, Introduction to the Theory of Ferromagnetism, Oxford Science Publications, Oxford, England, 1996, and references therein.
[62] T.J. Moran, J.M. Gallego, I.K. Schuller, J. Appl. Phys. 78 (1995) 1887.
[63] J.C. Slonczewski, Phys. Rev. Lett. 67 (1991) 3172.
[64] A.S. Carrico, R.E. Camley, R.L. Stamps, Phys. Rev. B 50 (1994) 13 453.
[65] R.E. Camley, Phys. Rev. B 35 (1987) 3608.
[66] R.E. Camley, D.R. Tilley, Phys. Rev. B 37 (1988) 3413.
[67] S. Kirkpatrick, C.D. Gelatt, M.P. Vechi, Science 220 (1983) 671.
[68] E.E. Fullerton, J.S. Jiang, C.H. Sowers, J.E. Pearson, S.D. Bader, Appl. Phys. Lett. 72 (1998) 380.
[69] F. Nolting, A. Scholl, J. Stöhr, J.W. Seo, J. Fompeyrine, H. Siegwart, J.-P. Locquet, S. Anders, J. Lüning, E.E. Fullerton, M.F. Toney, M.R. Scheinfein, et al., Nature 405 (2000) 767.
[70] H. Matsuyama, C. Hanigoya, K. Koike, Phys. Rev. Lett. 85 (2000) 646.
[71] T.M. Hong, Phys. Rev. B 58 (1998) 97.
[72] H. Suhl, I.K. Schuller, Phys. Rev. B 58 (1998) 258.