August 2001

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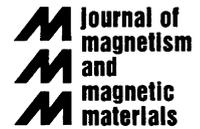
Exchange bias in a generalized Meiklejohn–Bean approach

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Abstract

A generalized Meiklejohn–Bean model is considered in order to derive an analytic expression for the dependence of the exchange bias field on the layer thickness involved in ferromagnetic/antiferromagnetic heterosystems, on the orientation of the applied magnetic field with respect to the magnetic easy axes and on the quenched magnetization M_{AF} of the antiferromagnetic pinning layer. While M_{AF} is a well-known feature of field-cooled dilute antiferromagnets, it seems to occur quite generally also in pure AF pinning substrates. The new analytic expressions are successfully compared with recent experimental results and Monte Carlo investigations. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

The Stoner–Wohlfarth model is a well-established phenomenological approach in order to describe coherent hysteretic magnetization reversal processes of single domain particles and magnetic thin films [1]. Although it does not take into account the influence of domain formation, its simplicity makes it a favorable first approach in order to interpret experimental data. E.g., it has been successfully applied in a phenomenological description of the exchange bias effect, which is observed in ferromagnetic (FM)/antiferromagnetic (AF) heterostructures. After field cooling of FM/AF layered heterosystems to below the AF Néel

temperature, the hysteresis loop of the FM film is shifted along the magnetic field axis by the exchange bias field $\mu_0 H_e$. This shift reflects the unidirectional anisotropy, which originates from the FM/AF coupling at the interface. The coupling has been introduced into a phenomenological free energy expression by Meiklejohn and Bean (MB) [2,3]. The bilinear exchange between the FM/AF interface magnetic moments gives rise to the unidirectional anisotropy energy.

In the limit of infinite anisotropy of the antiferromagnet, the MB model yields the simple, but powerful formula $\mu_0 H_e = -JS_{AF}S_F/(M_{FM}t_{FM})$ [2,3]. It exhibits the well-known dependencies of $\mu_0 H_e$ on the FM layer thickness t_{FM} [4], on the magnetization of the FM layer [5] and on the interface magnetic moments S_{AF} and S_F. No information about the origin of S_{AF} and S_{FM} is provided by the MB model. In

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addition, the coupling constant J enters the MB approach only as a phenomenological constant. A lot of theoretical work, which tackles the microscopic foundation of these parameters or develops alternative descriptions of the undirectional anisotropy, has been done [6]. Nevertheless, the simple MB formula already points out the necessity of net magnetic moments at the interface, not only on the FM, but also on the AF side in order to obtain finite exchange bias. Without exception this holds also in the case of so-called compensated AF surfaces, where $S_{AF} \neq 0$ requires deviations from the ideal AF order [7].

In the framework of the present analysis we point out the implications of the MB model on the $\mu_0 H_e$ vs. t_{AF} dependence which is, e.g., observed in experiments on NiFe/FeMn heterostructures [8] and in Monte Carlo studies on Ising systems of FM and diluted AF layers [9] exhibited in Figs. 1 and 2, respectively. It turns out, that both non-vanishing AF magnetization M_{AF} and a finite angle θ between the applied magnetic field and the magnetic easy axes tune the details of the t_{AF} dependencies. We exploit the full capability of the MB approach in analytic expressions and overcome restrictions due to partial solutions accounting either for θ [10,11] or t_{AF} [12] alone.
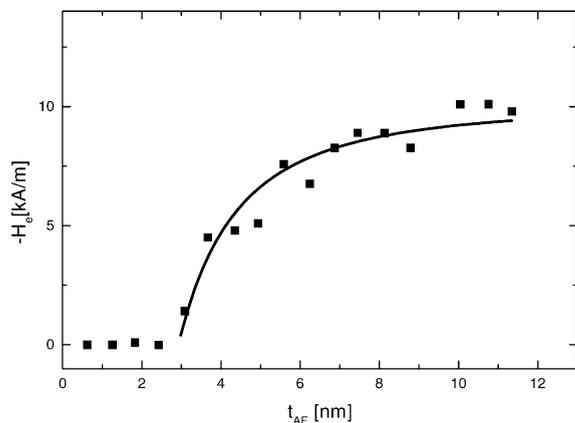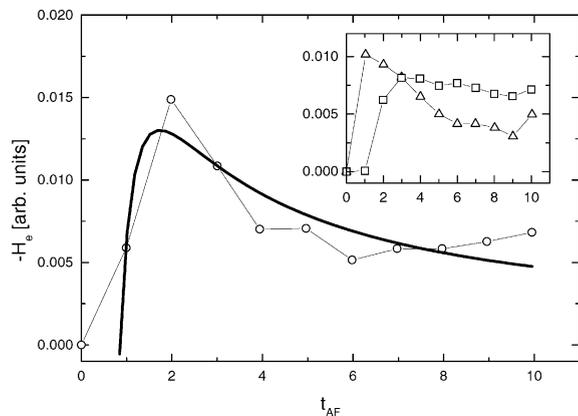

Fig. 2. Data from Monte Carlo simulations [9] of the exchange bias field as a function of the number of AF layer monolayers, t_{AF}, are shown for 40% (circles), 30% (triangles in the inset), and 60% (squares in the inset) quenched site dilution of the AF. The bold solid line is a best fit of Eq. (9) to the data at 40% dilution.

2. Model and analysis

We start from the free energy per unit area [2,3] completed by adding a Zeeman term involving M_{AF},

$$
\begin{aligned}
F = &- \mu_0 H M_{FM} t_{FM} \cos(\theta - \beta) \\
&- \mu_0 H M_{AF} t_{AF} \cos(\theta - \alpha) \\
&+ K_{FM} t_{FM} \sin^2 \beta \\
&+ K_{AF} t_{AF} \sin^2 \alpha - J S_{AF} S_{FM} \cos(\beta - \alpha). \quad (1)
\end{aligned}
$$

Here H is the applied magnetic field and $M_{FM/AF}$, $t_{FM/AF}$, $K_{FM/AF}$, $S_{FM/AF}$ are the absolute values of the magnetization, the layer thickness, the uniaxial anisotropy constant, and the interface magnetic moments of the FM/AF layer. The latter ones can be interpreted as macroscopic moments because the MB model assumes parallel orientation of all FM moments during the entire process of coherent rotation. Hence, the FM spins fulfill the condition $\underline{s}_i^{FM} = \underline{s}^{FM} \, \forall i$, and the interaction of the microscopic spins at the interface can be transformed into an interaction of the macroscopic interface moments according to $\sum_{i,j} \underline{s}_i^{FM} \underline{s}_j^{AF} \propto \underline{S}_{FM} \underline{S}_{AF}$. They are coupled via J, the exchange interaction constant. θ, β and α are the angles between H,

Fig. 1. Dependence, H_e vs. t_{AF}, of the exchange bias field in $Ni_{80}Fe_{20}$/FeMn [8]. The line shows the best fit of Eq. (7) to the data at $t_{AF} > 3$ nm.

M_{FM}, M_{AF} and the FM/AF anisotropy axis, which are aligned in parallel for simplicity (see Fig. 3).

The AF magnetization, M_{AF}, is generally assumed to be zero. This is reasonable in the case, where the sublattice magnetizations mutually compensate in the long-range AF ordered state. However, this is no longer the case in diamagnetically diluted AF systems. They are known to decay into a random-field-induced domain state with frozen excess magnetization when cooling to below T_N in an external magnetic field [13]. This mechanism seems to control the appearance of interface magnetization, $S_{AF} \neq 0$, at compensated AF surfaces and thus enables exchange bias [7,9]. On the other hand, also the excess bulk magnetization, $M_{AF} \neq 0$, of a quenched AF domain state may be important by virtue of the corresponding Zeeman energy term in Eq. (1). Surprisingly, metastable domain states can also be induced in non-diluted AF pinning layers. They are probably due to interface roughness [14–17] and give rise to both M_{AF} and excess susceptibility.
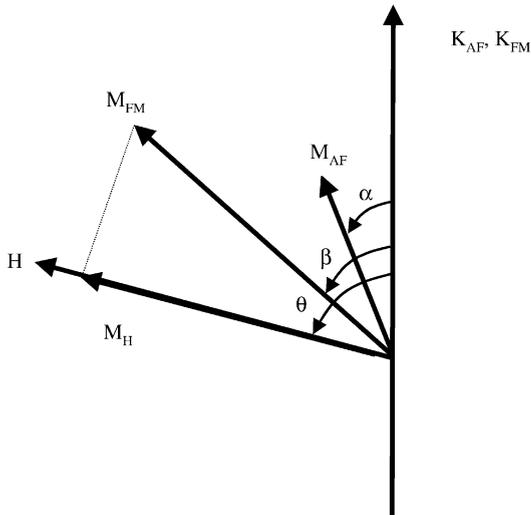

Fig. 3. Vector diagram involving the angles α, β, and θ related to the orientation of the net AF magnetization M_{AF}, the magnetization of the ferromagnet M_{FM} and the applied magnetic field H with respect to the easy axis of the antiferro- and ferromagnet designated by the corresponding anisotropy constants K_{AF} and K_{FM}, respectively. M_H indicates the projection of M_{FM} onto the field direction.

In the case of infinite anisotropy K_{AF}, the minimization of the free energy yields $\alpha = 0$. Hence, in the case of strong but finite anisotropy, a series expansion of Eq. (1) with respect to $\alpha = 0$ is reasonable. It reads

$$
\begin{aligned}
F \approx & -JS_{AF}S_{FM}\cos\beta - \mu_0 HM_{FM}t_{FM}\cos(\theta - \beta) \\
& - \mu_0 HM_{AF}t_{AF}\cos\theta + K_{FM}t_{FM}\sin^2\beta \\
& + \alpha\left(-JS_{AF}S_{FM}\sin\beta - \mu_0 HM_{AF}t_{AF}\sin\theta\right) \\
& + \alpha^2\left(K_{AF}t_{AF} + \tfrac{1}{2}JS_{AF}S_{FM}\cos\beta \right. \\
& \left. + \tfrac{1}{2}\mu_0 HM_{AF}t_{AF}\cos\theta\right).
\end{aligned}
\tag{2}
$$

This expression is minimized with respect to β and α, which is physically equivalent to the determination of the equilibrium angles β_{eq} and α_{eq} of vanishing torque. $\partial F/\partial\alpha = 0$ yields

$$
\begin{aligned}
& \alpha_{eq} \\
& = \frac{JS_{AF}S_{FM}\sin\beta + \mu_0 HM_{AF}t_{AF}\sin\theta}{2K_{AF}t_{AF} + JS_{AF}S_{FM}\cos\beta + \mu_0 HM_{AF}t_{AF}\cos\theta}
\end{aligned}
\tag{3}
$$

From $\partial F/\partial\beta = 0$ we determine the magnetic fields H_{c1} and H_{c2}. They fulfill the condition $M_H(H_{c1}) = M_H(H_{c2}) = 0$, where $M_H = M_{FM}\cos(\theta - \beta)$ is the magnetization component of M_{FM} pointing parallel to the applied magnetic field (see Fig. 3). M_H is the experimentally relevant FM magnetization component, which is measured by standard scalar magnetometry. In order to obtain explicit expressions for H_{c1} and H_{c2} we insert $\alpha = \alpha_{eq}$, $\beta_1(M_H = 0) = \theta - \pi/2$ and $\beta_2(M_H = 0) = \theta - 3\pi/2$ into $\partial F/\partial\beta = 0$. Expansion of $\partial F/\partial\beta$ to first order with respect to $M_{AF} \approx 0$ yields two corresponding linear equations in H, which provide H_{c1} and H_{c2}, respectively. The exchange bias field is then calculated according to

$$
H_e = (H_{c1} + H_{c2})/2.
\tag{4}
$$

Although the calculation is straightforward, the result is lengthy. In order to simplify the resulting expression, H_e is again expanded into a Taylor series with respect to $M_{AF} \approx 0$ and $1/K_{AF} \approx 0$ up to first and second order, respectively. The approximation of strong anisotropy, $1/K_{AF} \approx 0$, is consistent with the series expansion, Eq. (2). One

finally obtains

$$
\begin{aligned}
\mu_0 H_e = & -\frac{J S_{AF} S_{FM} \cos\theta}{M_{FM} t_{FM}} \\
& - \Bigg(\frac{J S_{AF} S_{FM} \cos\theta}{16 K_{AF}^2 M_{FM}^2 t_{AF}^2 t_{FM}^2} \\
& \times (-4 J K_{AF} M_{AF} S_{AF} S_{FM} t_{AF}^2 \\
& + J^2 M_{FM} S_{AF}^2 S_{FM}^2 t_{FM} \\
& + J K_{FM} M_{AF} S_{AF} S_{FM} t_{AF} t_{FM} - J S_{AF} S_{FM} \\
& \times (-4 J K_{AF} M_{AF} t_{AF}^2 + 3 J M_{FM} S_{AF} S_{FM} t_{FM} \\
& + 4 K_{FM} M_{AF} t_{AF} t_{FM}) \cos 2\theta \\
& + 3 J K_{FM} M_{AF} S_{AF} S_{FM} t_{AF} t_{FM} \cos 4\theta \Bigg).
\end{aligned}
$$
(5)

In the limit of infinite anisotropy K_{AF}, Eq. (5) yields the θ-dependent expression

$$
\mu_0 H_e = -\frac{J S_{AF} S_{FM} \cos\theta}{M_{FM} t_{FM}},
$$
(6)

which has already been derived in Ref. [10]. In particular, Eq. (6) provides, again, the basic MB expression in the case $\theta = 0$, which implies parallel orientation of the applied field with the easy axes.

The simplest possible t_{AF} dependence is derived from Eq. (5) in the limit $M_{AF} = 0$ and $\theta = 0$ and finite, but strong anisotropy K_{AF}. It reads

$$
\mu_0 H_e = -\frac{J S_{AF} S_{FM}}{M_{FM} t_{FM}} + \frac{J^3 S_{AF}^3 S_{FM}^3}{8 K_{AF}^2 M_{FM} t_{FM} t_{AF}^2}.
$$
(7)

Eq. (7) qualitatively explains the steep increase and the subsequent saturation of $|\mu_0 H_e|$ with increasing AF layer thickness. Such behavior is not described within the alternative random field approach of Malozemoff [14], but has been reported by various authors [8,18,19]. While Xi and White [18] introduced a more complicated ansatz involving a helical structure of the AF magnetic moments, it is the aim of this analysis to stress the capabilities of the MB model.

The existence of a critical AF layer thickness was already pointed out by MB. It can simply be motivated from Eq. (3) on applying the condition $\alpha_{eq} \ll \pi$, as required within the scope of validity of Eq. (2). In the limit $M_{AF} = 0$, Eq. (3) yields

$$
\alpha_{eq} = \frac{\sin\beta}{(2 K_{AF} t_{AF} / J S_{AF} S_{FM}) + \cos\beta}.
$$
(8)

In order to prevent the unphysical divergence of α_{eq} for any direction of M_{FM}, $0 \leqslant \beta \leqslant \pi$, the condition $|K_{AF} t_{AF}| > |J S_{AF} S_{FM}/2|$ has to be fulfilled and, hence, the existence of a critical AF layer thickness becomes obvious. Substitution of the conventional expression of the critical AF layer thickness [2,3] $t_{AF}^{cr} = |J S_{AF} S_{FM}/K_{AF}|$ yields $|\alpha_{eq}| < 1/\sqrt{3}$ for $0 \leqslant \beta \leqslant \pi$, which proves that in fact $\alpha_{eq} \ll \pi$ is fulfilled for $t_{AF} > t_{AF}^{cr}$.

Fig. 1 shows the best fit of Eq. (7) to the $\mu_0 H_e$ vs. t_{AF} data [8] of a $Ni_{80}Fe_{20}$ layer with thickness $t_{FM} = 6.5$ nm deposited on top of FeMn for $3 < t_{AF} < 12$ nm. The two-parameter fit yields $J S_{AF} S_{FM}/(M_{FM} t_{FM}) = 0.013$ T and $J^3 S_{AF}^3 S_{FM}^3 / (8 K_{AF}^2 M_{FM} t_{FM}) = 1.08 \times 10^{-19}$ T/m^2. With $t_{FM} = 6.5$ nm and $M_{FM}(Ni_{80}Fe_{20}) = 0.73$ MA/m [20], we obtain the coupling energy $|J S_{AF} S_{FM}| = 6 \times 10^{-5}$ J/m^2 and the AF anisotropy $K_{AF} = 7.3 \times 10^3$ J/m^3. The latter one is of the same order of magnitude as the K_{AF}-values obtained, e.g., by Mathieu et al. [21] from Brillouin light scattering investigations and by Parkin et al. [12] from torque measurements. The above expression of the critical thickness then yields $t_{AF}^{cr} = 8$ nm, which lies, however, 2.7 times above the steep increase of $\mu_0 H_e$ vs. t_{AF} shown in Fig. 1. Apparently, the situation can be improved by setting $t_{AF}^{cr} = J S_{AF} S_{FM}/2 K_{AF}$, which emerges as the lower bound of t_{AF} values fulfilling the condition $|K_{AF} t_{AF}| > |J S_{AF} S_{FM}/2|$. In that case, the remaining error is reduced to less than 34%. Note, however, that the inequality is only a necessary condition. It is not obvious, that its lower boundary can be identified with the critical thickness. This numerical discrepancy may originate from the strong simplifications, which underlay Eq. (7). One of them, the assumption $M_{AF} = 0$, will be discussed below.

Besides this numerical inconsistency (see above), the simple $1/t_{AF}^2$ dependence of Eq. (7) does not model any kind of a peak-like structure in the $|\mu_0 H_e|$ vs. t_{AF} dependence. This is, however, known from experiments, e.g., on $Ni_{80}Fe_{20}$/FeMn [8] or Fe_3O_4/CoO [22] bilayers as well as from

Monte Carlo simulations [9]. In accordance with these findings, Eq. (5) exhibits the possibility of a competing $1/t_{AF}$-term in the case of $M_{AF} > 0$ and $\theta \neq 0$. The latter condition is not obvious, however, closer inspection of Eq. (5) shows that the $1/t_{AF}$-terms cancel each other in the case $\theta = 0$. This is in full agreement with the results from Monte Carlo simulations on heterostructures of diluted antiferromagnets and FM layers [9]. As discussed above, the diluted antiferromagnet breaks into a random field domain state on cooling to below the Néel temperature in the presence of an applied magnetic field. These random field domains carry a frozen net magnetization M_{AF}. Within the framework of the MB approach, Eq. (5), this opens the possibility for a t_{AF} dependence of the type

$$\mu_0 H_e = a + \frac{b}{t_{AF}} + \frac{c}{t_{AF}^2}. \qquad (9)$$

Fig. 2 shows the result of a best fit of Eq. (9) to the Monte Carlo data of Ref. [9], which are obtained on a heterosystem with 40% of quenched dilution of the AF-sites (see Ref. [9] for details). The peak structure of $|\mu_0 H_e|$ vs. t_{AF} is qualitatively reproduced with fitting parameters $a = -9 \times 10^{-4}$, $b = -0.042$, and $c = 0.037$ involving units adapted to the Monte Carlo data. Moreover, the simulations show that the peak strongly decreases for 30% as well as 60% dilution. This is reasonable, because the maximum frozen AF moment is expected to be induced by the maximum random field. In accordance with the approximation $h_r \propto \sqrt{x(1-x)}$, the random field, h_r, maximizes at 50% dilution, $x = 0.5$ [23]. Obviously, both concentrations reduce the magnetic moment of the AF layer with respect to the case of 40% dilution. In agreement with the MB approach, Eq. (5), a reduction of M_{AF} gives rise to a reduced peak height. Hence, in accordance with the results of the Monte Carlo simulations our analysis suggests that apart from the random field enhanced AF interface magnetic moment S_{AF}, the magnetization of the subsequent AF layers strongly influences the $\mu_0 H_e$ vs. t_{AF} behavior.

3. Conclusion

We present analytic descriptions of the exchange bias field of FM/AF heterostructures based on a generalized Meiklejohn–Bean [2,3] ansatz of the free energy. They stress explicitly the dependencies on the thicknesses t_{FM} and t_{AF}, on the orientation angle θ of the anisotropy axes with respect to the external field and on the frozen magnetization of the antiferromagnet, M_{AF}. Within this framework, results from previous experimental investigations and simulations are successfully described. In particular M_{AF} turns out to be responsible for the observed peak structure in the H_e vs. t_{AF} dependence. While M_{AF} is a well-known feature of field-cooled dilute antiferromagnets, it seems to occur quite generally also in pure AF pinning substrates. This should be taken into account in future analytic investigations of the exchange bias which are beyond the MB approach.

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