Exchange bias for a ferromagnetic film coupled to a spin glass

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For a model system consisting of a ferromagnetic layer exchange coupled to a spin glass, extensive Monte Carlo simulations are performed. For the spin glass the standard short-range Gaussian model is used. Exchange bias is observed as a result of a frozen spin-glass state. The exchange bias fields are calculated for different temperatures, cooling fields, and thicknesses of the spin-glass layer and the training effect is investigated. A major result of our simulations is that the bias field decreases with increasing strength of the cooling field in qualitative agreement with recent experiments.

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I. INTRODUCTION

For a ferromagnet (FM) in contact with an antiferromagnet (AFM) a unidirectional anisotropy can occur which is called exchange bias (EB). Usually, EB is observed after cooling the entire system in an external magnetic field to low temperatures. Although this effect has been well known for many years[1,2] it is still the subject of intense research due to its use in magnetic sensor elements.

By now it is well established that the occurrence of EB is the result of an interfacial interaction between FM and AFM. EB is due to a net magnetization along the AFM interface which is exchange coupled to the FM, providing part of this magnetization is stable during field reversal. For compensated interfaces this requires a mechanism which breaks the symmetry between the different spin states in the AFM. Malozemoff[3–5] in his pioneering work argued that due to interface roughness stable domains in the AFM will occur for temperatures below the Néel temperature T_N carrying a small net magnetization at the FM/AFM interface. However, the formation of domain walls in the AFM only due to interface roughness is energetically unfavorable and therefore unlikely to occur.

In a series of papers[6–9] it was shown both experimentally and by Monte Carlo simulations that it is possible to strongly influence EB by replacing magnetic atoms by nonmagnetic ones or by defects (called *dilution* in the following) not at the FM/AFM interface, but rather throughout the volume part of the AFM. In this case the observed EB is primarily not due to disorder or defects at the interface. Rather, the full antiferromagnetic layer must be involved and it was argued that in these systems EB has its origin in a domain state (DS) in the volume part of the AFM which triggers the spin arrangement and the FM/AFM exchange interaction at the interface. This domain state carries magnetization since it develops during a cooling process in which the AFM is in contact with a saturated FM and eventually also exposed to a magnetic field. The formation of domains with increasing dilution leads to an increase in the excess magnetization in the AFM and thus to a strong increase in the EB. In a recent paper[10] it was shown that an inclusion of some additional roughness at the interface shifts the maximum of the bias field to lower dilution so that even a quantitative agreement between experiments and simulations can be achieved.

Already in this early work it was conjectured that disorder in the AFM is important for EB to occur but that the type of disorder is not that important and it was claimed that a FM layer coupled to a spin glass (SG) also would show EB.[6] Experimentally, this has been observed in many systems.[11–14] Computer simulations on this effect, however, have not been systematically explored until now. Very recently experiments on Co/CuMn bilayers, a canonical example of a spin-glass system, have revealed new and surprising results as, e.g., a change in the sign of the bias field when approaching the blocking temperature and a decrease in its absolute value when increasing the cooling field.[15] Initial results obtained from computer simulations reported in this work support the sign change of the bias field. However, there is still a need for a more extended theoretical study of FM/SG multilayer systems.

In the present work we report on extensive computer simulations for a FM monolayer exchange coupled to a SG. Although from an experimentalist's point of view it would be desirable to model the SG as a diluted system with some long-range exchange interaction we have chosen the standard short-range Gaussian model for the SG because the diluted model would require too much computer time for any realistic system size.

The system studied shows all the phenomena associated with exchange bias and a qualitative agreement with some of the results found experimentally[15] is achieved. A major result of our investigations is that with increasing cooling field the absolute value of the bias field decreases monotonically. This is in contrast to what is found usually for FM/AFM multilayers where the absolute value of the bias field increases with increasing strength of the cooling field providing the interface exchange is positive or the bias field changes sign for large cooling fields in the case of negative interface exchange, respectively. It is argued that the reason for this interesting behavior is the different role a homogeneous field plays in a FM/SG system as compared to conventional FM/AFM systems.

II. MODEL

The Monte Carlo simulations were performed on a model consisting of a FM monolayer exchange coupled to a spin glass consisting of typically six monolayers. Only in Sec. III C we vary the thickness of the SG film studying for a special set of parameters also the thickness dependence of EB. A simple cubic lattice is assumed for both the FM and the spin glass with the FM layer lying in the xy plane.

The FM is described by a classical Heisenberg model with exchange constant J_{FM}. The Heisenberg spins $\underline{S}_i$ are unit vectors with Cartesian components S_{ix}, S_{iy}, and S_{iz} where i denotes a site index. We introduce an easy axis in the FM (x axis, anisotropy energy $d_x=0.1J_{\mathrm{FM}}$) in order to obtain well defined hysteresis loops. The anisotropy constant d_x sets the Stoner-Wohlfarth limit of the coercive field, i.e., the low-temperature limit of the coercive field for the case of magnetization reversal by coherent rotation ($\mu B_c=2d_x$ in our units for a field parallel to the easy axis). The dipolar interaction is replaced by an additional anisotropy term (anisotropy constant $d_z=-0.1J_{\mathrm{FM}}$) which mimics the shape anisotropy. The precise value of d_z is not crucial since for any finite value of d_z the magnetization is preferentially in the xy plane.

For the spin-glass system we assume a large uniaxial anisotropy because it is known from conventional FM/AFM systems that this leads to large exchange bias.[9] The spin glass is therefore described by an Ising Hamiltonian where the easy axis is parallel to that of the FM. We further assume a nearest-neighbor interaction $J_{\mathrm{SG}}(i,j)$ between pairs of spins of the SG and an interaction $J_{\mathrm{SG,int}}(k)$ across the interface between an Ising spin at the SG interface layer and its neighbor in the FM layer both labeled with the same index k.

Thus the Hamiltonian of our system is given by

$$\begin{aligned}\mathcal{H} = &-J_{\mathrm{FM}}\sum_{\langle i,j\rangle} \underline{S}_i\cdot\underline{S}_j - \sum_i (d_z S_{iz}^2 + d_x S_{ix}^2 + \mu\underline{B}\cdot\underline{S}_i)\\ &-\sum_{\langle i,j\rangle} J_{\mathrm{SG}}(i,j)\sigma_i\sigma_j - \sum_i \mu B_z\sigma_i - \sum_k J_{\mathrm{SG,int}}(k)\sigma_k S_{kx}.\end{aligned} \tag{1}$$

The first line contains the energy contribution of the FM, the second line describes the SG, while the third line includes the coupling between FM and SG, where it is assumed that the Ising spins $\sigma_{\mathbf{i}}$ interact with the x component of the Heisenberg spins of the FM. An external magnetic field $\underline{B}$ is applied to the system and μ denotes the magnetic moment of the spins.

The exchange interaction in many spin-glass systems is of Rudermann-Kittel type, i.e., long-range and oscillating so that an average over a large number of randomly chosen exchange interactions vanishes. We simplify these interactions by describing the SG by the standard short-range Gaussian model[16] so that the quantities $J_{\mathrm{SG}}(i,j)$ are independent random variables having a Gaussian distribution with standard deviation J_{SG} and zero mean. They are fixed during the simulation (quenched disorder). In microscopic models for FM/AFM multilayers studied so far, it is usually assumed that the exchange across the interface is constant or has at least a finite average. However, FM/SG systems studied experimentally will have competing interface exchange interactions. Therefore, a natural choice for the interaction across the interface between SG and FM, $J_{\mathrm{SG,int}}(k)$, is also a random one for which we assume a Gaussian distribution with zero mean and the same standard deviation, J_{SG}, as in the bulk of the SG in order to reduce the number of free parameters. We set $J_{\mathrm{SG}}=J_{\mathrm{FM}}/2$ mainly in order to have a (nearly) saturated ferromagnetic layer in the relevant temperature region below the spin-glass freezing temperature which is of the order of J_{SG}.

The assumed random spin-glass-type interaction $J_{\mathrm{SG,int}}(k)$ across the interface is an important ingredient making the present model quite distinct from microscopic models for multilayers studied so far. This can best be understood when considering the cooling process during which the magnetization of the FM layer tends to saturate at low temperatures. Thus, as far as the Ising spins are concerned the last term in Eq. (1) acts like a *random field* on the SG interface layer for low temperatures. This term is responsible for EB and for an enhanced coercivity. The corresponding *interface exchange field* u_{SG} is defined by

$$u_{\mathrm{SG}} = \frac{1}{L^2}\sum_k \langle J_{\mathrm{SG,int}}(k)\sigma_k\rangle, \tag{2}$$

where the angular brackets denote thermal averages. For a (nearly) saturated FM layer this quantity is (proportional to) the interface energy which determines the switching of the magnetization. The interface exchange field u_{SG} plays a similar role as the interface magnetization of the AFM layer in conventional FM/AFM systems: indeed, both are proportional for constant exchange interaction across the interface.

From Eq. (2) follows a crucial difference as far as the role of the external fields is concerned, be it the eventually applied field during the initial cooling or the field for cycling the hysteresis loop. For conventional FM/AFM systems there is a homogeneous contribution to the effective fields acting on the AFM interface layer due to the saturated FM layer. The external fields add to these exchange fields, thereby directly influencing the interface magnetization, which causes EB and enhanced coercivity. For random exchange, however, the homogeneous part of this interface polarization cancels out and it is the local spin structure in the SG interface layer entering Eq. (2) which is responsible for these effects.

III. MONTE CARLO SIMULATIONS

The model explained above is simulated using Monte Carlo methods with a heat-bath algorithm and single-spin flip dynamics. The trial step for a spin update is a random choice of a spin vector for the Heisenberg model and—as usual—a spin flip for the Ising model.[17] We perform typically 600 000 Monte Carlo steps per spin (MCS) for a complete hysteresis loop (for one particular configuration of the Gaussian distributed exchange interactions).

Since we are not interested in any critical behavior of the model studied it is not necessary to perform a systematic finite-size analysis. Instead we use rather large systems of lateral extension $L\times L$ with $L=128$ in the xy plane—the film plane—with periodical boundary conditions within this plane and we checked by comparing with simulations of smaller systems that there are no relevant finite-size effects as long

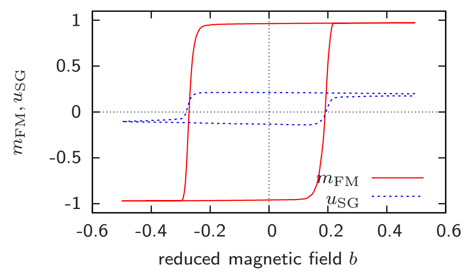

FIG. 1. (Color online) Typical hysteresis loop for temperature $t=0.1$. Shown is the FM magnetization as well as the interface exchange field. $b_{cool}=0.02$.

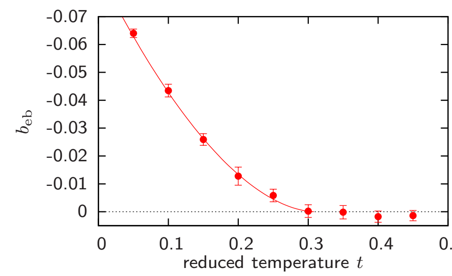

FIG. 2. (Color online) Bias field as a function of reduced temperature $t=k_B T/J_{FM}$. The line is a guide for the eyes.

as the system is not much smaller. In the following we will use reduced fields $b=\mu B/J_{FM}$ and temperatures $t=k_B T/J_{FM}$.

A. Hysteresis

In all our simulations the system is slowly cooled starting from an initial temperature $t=0.6$ down to the desired measuring temperature at which the hysteresis loops were monitored. We start with an FM initially magnetized along the (easy) x axis and a random spin configuration in the SG. The temperature t is reduced in small steps $\delta t=0.02$ and in each step 1000 MCS are performed. During cooling a very small magnetic field $b_{cool}=0.02$ parallel to the FM magnetization is applied in order to avoid a spontaneous magnetization reversal of the FM layer. We checked by comparing with simulations performed for other values of b_{cool} that such a small field has practically no effect on the SG. Only in Sec. III D the strength of the cooling field is varied systematically in order to study its influence on EB. For larger fields it is important to note that the cooling field also acts on the volume part of the SG.

When the desired final temperature is reached a magnetic field $\underline{b}=b_x\hat{\underline{x}}+b_y\hat{\underline{y}}$ is applied under a very small angle with respect to the easy axis, $b_y=\alpha b_x$ with slope $\alpha=0.02$, in order to define a certain path for the rotation of the magnetization during field reversal. The initial value of b_x is chosen to be 0.5, about twice the value of the switching field. The x component of the field, b_x, is then reduced in steps of $\delta b_x=0.004$ down to -0.5 and afterward raised again up to the initial value. This corresponds to one cycle of the hysteresis loop. At each field value during hysteresis 200 MCS were performed for thermalization followed by 1000 MCS for obtaining thermal averages of the relevant quantities. For a particular temperature $T=0.1$ we changed the number of Monte Carlo steps for obtaining these thermal averages from 1000 to 4000 in steps of 1000 and observed only a very small decrease in the bias field of about 5%. We believe that this gives evidence that we are in quasi-equilibrium during the hysteresis cycles. However, the following results for the thermal averages were all obtained using 1200 MCS per field value.

Typical hysteresis loops are depicted in Fig. 1. Shown is the magnetization of the FM layer,

$$m_{FM}=\frac{1}{L^2}\sum_i \langle S_{ix}\rangle,$$

as well as the exchange energy u_{SG}, Eq. (2), at reduced temperature $t=0.1$. The FM magnetization, m_{FM}, going from near saturation, $m_{FM}\approx 1$, to $m_{FM}\approx -1$, clearly shows EB. The corresponding EB field is determined from $b_{eb}=(b^+ + b^-)/2$, where b^+ and b^- are those fields of the hysteresis loop branches for increasing and decreasing field, where the easy axis component of the magnetization of the FM becomes zero. The corresponding coercive field is $b_c=(b^+ - b^-)/2$. Note that the Stoner-Wohlfarth limit for the coercive field is 0.2 in our reduced units.

The second quantity shown in Fig. 1 is the exchange energy, u_{SG}, experienced by the FM layer during a hysteresis cycle. This quantity corresponds to the magnetization in the AFM interface layer of conventional FM/AFM systems. Two features known from those systems are also observed here: (i) the upward shift of the exchange energy acting as an additional effective field on the FM resulting in EB and (ii) a training effect, i.e., the loop for the exchange energy is not closed.

There is, however, a very important difference as compared to conventional FM/AFM systems: u_{SG} is only weakly dependent on the applied magnetic field during hysteresis cycles (in field intervals where the FM layer is nearly saturated). This special feature is due to the random interface coupling. The applied field polarizes the SG interface layer which because of the random interface coupling has no big influence on u_{SG} in contrast to conventional FM/AFM systems where this additional field induced polarization of the interface layer adds up to the polarization due to the FM layer leading to an interface magnetization which has a significant dependence on the applied field.[6,7] Thus an applied field in FM/SG systems plays a different role than in FM/AFM multilayers studied so far. This will turn out to be important for the field cooling investigation in Sec. III D.

B. Temperature dependence and training

The temperature dependence of the EB field is shown in Fig. 2. Here, as described before, the system is slowly cooled from $t=0.6$ down to the desired measuring temperature at which the hysteresis loops were monitored and the fields b_{eb} and b_c were extracted. To reduce the statistical errors we averaged over ten different realizations of the disorder resulting in rather small error bars. The EB field decreases with temperature and goes to zero at a temperature of the order of the spin-glass freezing temperature.[16] In Ref. 15 a remarkable change in the sign of the bias field as function of temperature is found experimentally. Our simulations do not support this finding. Although the bias field is positive

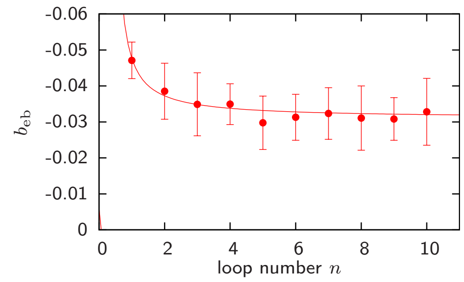

FIG. 3. (Color online) Dependence of the bias field on the number of consecutive hysteresis cycles. Reduced temperature $t=0.1$. The line is a guide for the eyes.

around $t=0.4$ the statistical fluctuations are too large for a definite conclusion. In any case, if such a sign change takes place around the onset of EB, only a tiny bias field much smaller than observed experimentally is compatible with our simulations. On the other hand, mean-field calculations of the energy of a long-range SG model reported in Ref. 15 support the experimental findings. The reason for this is not known to us. We leave this issue as an open problem for further research.

It is well known that it is very difficult to reach thermal equilibrium in a SG because of extremely slow relaxation processes. However, these questions concerning equilibration of the SG are not relevant in the present context since hysteresis phenomena are related to quasi-equilibrium states, i.e., related to states in which the system under consideration is trapped during the time of the experiment. Concerning simulations it is of course difficult to compare with experimental time scales but one can measure for instance the dependence of the bias field on the perpetual repetition of field cycles, the so-called training effect. Results are shown in Fig. 3 for a reduced temperature of $t=0.1$. The decrease in the bias field is about 30% going from the first cycle to the tenth, showing that the SG state is rather stable at this particular temperature.

C. Thickness dependence

We have studied the thickness dependence of EB for a SG/FM system with random interface coupling at a reduced temperature of $t=0.1$ and for a cooling field of $b_{cool}=0.02$. Our simulation results are shown in Fig. 4. The bias field b_{eb} increases rapidly with increasing number of SG layers and

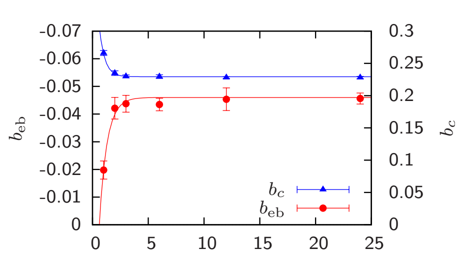

FIG. 4. (Color online) Exchange bias (lower curve) and coercivity (upper curve) versus number of SG layers. Reduced temperature $t=0.1$. The lines are guides for the eyes.

levels out at about three SG layers. To understand this behavior we consider first the case of only one SG layer. During cooling in the (negligible) field $b_{cool}=0.02$ a spin-glass state develops under the influence of the random field coming from the saturated FM layer. This SG state has a frozen component on the time scale of the simulations, i.e., a component which does not change during field cycling resulting in EB. With increasing number of SG layers this frozen component is strengthened thereby increasing the bias field b_{eb}. On the other hand, that part of the SG layer which due to the exchange interaction with the FM layer follows the field cycling contributes to the coercive field. It decreases with increasing number of SG layers thus leading to a decrease in the coercive field because of the above-mentioned increase in the frozen part. A strong increase in the absolute value of the bias field as function of SG thickness followed by a nearly thickness-independent value has also been observed experimentally.[15]

The second feature, a strong decrease in the coercive field followed by a thickness-independent value, is also in qualitative agreement with these experiments if only the data for not too small CuMn thicknesses are considered. But this is certainly justified, because we consider a *discrete* model having one SG monolayer as its minimum in contrast to the SG system studied experimentally. Those systems are highly diluted so that the number of magnetic ions interacting with the ferromagnetic sheet goes continuously to zero for decreasing thickness of the SG layer and becomes very small even for a rather thick SG layer. It is therefore not possible to compare our results with the experimental results for film thicknesses less than about 20 layers which contain about the same amount of magnetic ions as a spin-glass monolayer in our simulations.

D. Cooling field dependence

In conventional FM/AFM multilayer systems with a ferromagnetic interface exchange field the bias field will increase with increasing cooling field since the cooling field acting on the bulk of the AFM layer gives rise to an additional induced magnetization in the DS of the AFM.[7] The irreversible part of this magnetization then increases the EB field. For the case of antiferromagnetic interactions there is a competition between AFM magnetization contributions which are induced either by the positive cooling field or the negative exchange field stemming from the FM. This competitions leads to a change in sign of the EB field with increasing cooling field which is called positive bias.[7]

For the FM/SG multilayers with random interface interaction a different scenario applies. For this type of interaction an applied cooling field will lead to a certain polarization of the SG but because the exchange coupling to the FM layer is random with zero mean any homogeneous part will cancel. Our simulation results at reduced temperature $t=0.1$ are shown in Fig. 5.

A strong decrease in the bias field is observed with increasing cooling field in contrast to what is found usually in conventional FM/AFM systems. The reason for this behavior is the different role the external field plays in the system

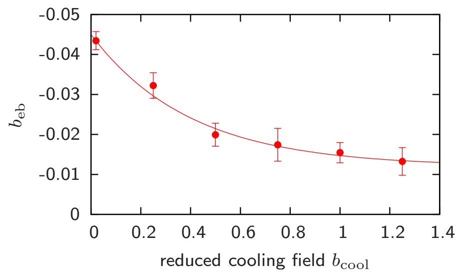

FIG. 5. (Color online) Exchange bias as function of cooling field b_{cool} at $t=0.1$. The line is a guide for the eyes.

studied. One effect of the external field is the polarization of the SG layers, but the homogeneous part of it does not contribute to the exchange field u_{SG}. On the other hand, the frozen states in the SG responsible for exchange bias are influenced by an external field but in a destructive way: a homogeneous external field is competing with the SG order which is of random nature. This leads to a weakening of the frozen states resulting in a decrease in the bias field. These results agree with unpublished experimental findings.[18] The coercive field, on the other hand, is slightly increasing with increasing cooling field (not shown) by about 3% in the field interval studied.

IV. CONCLUSIONS

In conclusion, we have shown with extensive Monte Carlo simulations that a FM layer coupled to a SG shows EB but with a variety of effects not observed in conventional FM/AFM multilayers. The most interesting result is a strong decrease in the absolute value of the bias field with increasing cooling field which is due to a weakening of the frozen SG state due to this field. One has to note that the rather strong external fields necessary to cycle the hysteresis loops also contribute to a certain weakening of the frozen SG state. These strong fields are needed since we consider in this paper only one ferromagnetic layer with a rather large uniaxial anisotropy energy following closely the setup of our earlier work[6] mainly in order to be able to compare both works. Experimentally, the ferromagnetic layer usually exceeds the thickness of the SG (or AFM) layer resulting in much weaker external fields needed for the hysteresis loops which in turn also have a much weaker influence on the frozen SG state. It would be interesting to study this behavior systematically. Work in this direction is in progress.

Another interesting result is the dependence of EB on the SG thickness. It becomes independent of the SG thickness after around three to four SG layers similar to the behavior of AM/AFM systems with a strong disorder in the AFM. This is easy to understand within the DS model for these systems according to which strong disorder leads to small domains which become insensitive to the AFM thickness. Because the SG is a strongly disordered system it is plausible that its interface structure also becomes rather insensitive to the thickness of the SG layer provided it is not too thin.

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