Exchange bias: Dependence on the properties of the ferromagnetic interface layer

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The effect of interface magnetic dilution on exchange bias is studied with extensive Monte Carlo simulations for a model system consisting of a ferromagnetic layer exchange coupled to a diluted antiferromagnet. The dependence of the exchange bias fields on properties of the *ferromagnetic* interface layer are identified with particular emphasis on magnetic dilution and bond distribution effects across the interface. It is shown that some dilution of the ferromagnetic interface layer can lead to an increase in the bias field magnitude, even though the net exchange interaction across the interface is reduced.

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I. INTRODUCTION

A unidirectional anisotropy can appear in a ferromagnet (FM) in contact with an antiferromagnet (AFM) after cooling the entire system to low temperatures. This effect is called exchange bias (EB). Although EB is well known since many years[1,2] it is still the subject of intense research due to its use in magnetic sensor elements.[3]

By now it is well established that the occurrence of EB is the result of an interfacial interaction between the 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[4–6] in his pioneering work argued that this symmetry breaking will occur because for temperatures below the Néel temperature T_N stable domains in the AFM will be formed due to interface roughness. However, the formation of domain walls in the AFM only due to interface roughness requires strong exchange fields with the FM layer and strong external fields to provide the energy necessary to break the AFM bonds along the domain wall.

In a series of papers[7–10] it was shown, 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) 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 whole 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 in turn to a strong increase in the EB. In a recent paper[11] it was shown that an inclusion of some additional roughness at the interface shifts the maximum of the bias field to lower dilution resulting in a better agreement between experiments and simulations. Note that in the limit of vanishing bulk dilution the model investigated numerically in Ref. 11 coincides with the model of Malozemoff[4–6] and it was found that EB indeed can appear only due to interface roughness supporting qualitatively the earlier ideas of Malozemoff.

Already in this early work it was conjectured that disorder in the AFM is important for EB to occur, although the type of disorder should not be important. It was claimed, for example, that a FM layer coupled to a spin glass would also show EB.[7] Experimentally, this has been observed in many systems.[12–16] Very recently we were able to confirm this by computer simulations.[17]

Experimentally, there is recently much interest in tuning exchange bias by introducing defects at or close to the FM/AFM interface. These defects can consist of magnetic atoms of various kinds or of nonmagnetic atoms.[18–20] Unfortunately, a detailed microscopic defect structure at the interface is not available. A complication is that introduction of magnetic or nonmagnetic defects can introduce too wide a variety of new parameters. In the interest of providing meaningful results that are not strongly dependent on fine details of the defects, we simulate in the present paper only certain aspects of the problem by choosing a highly restricted set of free parameters.

The aspect we want to concentrate on is the question of how two types of disorder at the AFM/FM interface affects EB. We consider site dilution and bond dilution. In the first case magnetic atoms in the FM interface layer are removed while in the second case exchange couplings across the AFM/FM interface are replaced by those of different strength. This is expected to capture in a simple way relevant aspects of the *dusting* of the interface with nonmagnetic and magnetic impurities, respectively, studied experimentally in Refs. 18 and 19. Note that it is important to keep the other parameters, in particular, those of the AFM layer, constant in order to better trace back the sources of possible changes in EB. Therefore, throughout this paper the concentration of magnetic sites in the AFM is chosen to be 0.5. This concentration was found to lead to an appreciable bias field and to small domains in the AFM.[8] These domains appear on a broad distribution of length scales with domain walls preferentially perpendicular to the AFM layer. Note also that in computer simulations within the frame work of the DS model typically one ferromagnetic monolayer without dilu-

tion is considered so far. In Ref. 11 a rough interface is modeled with an intermixed AFM interface composed of different magnetic ions in contact with a ferromagnetic monolayer. As explained below, this is a different case from that studied in the present paper.

II. MODEL

The Monte Carlo simulations were performed on a model consisting of a FM layer exchange coupled to an AFM layer (usually comprising four AFM monolayers). A simple cubic lattice is assumed for both the FM and the AFM layer which are 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 $d_x=0.05J_{\mathrm{FM}}$) 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 ($\mu B_{Stoner}=2d_x$ in our units for a field parallel to the easy axis). The dipole 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 very crucial since for any finite value of d_z the magnetization is preferentially in the xy plane.

For the AFM we assume a large uniaxial anisotropy because it is known that this leads to large exchange bias.[10] The AFM 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 $J_{\mathrm{AFM}}(i,j)$ between pairs of spins of the AFM and an interaction $J_{\mathrm{INT}}(k)$ across the interface between an Ising spin at the AFM 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

$$\mathcal{H}=-J_{\mathrm{FM}}\sum_{\langle i,j\rangle}\underline{S}_i\cdot\underline{S}_j-\sum_i\left(d_zS_{iz}^2+d_xS_{ix}^2+\mu_i\underline{B}\cdot\underline{S}_i\right)$$
$$-\sum_{\langle i,j\rangle}J_{\mathrm{AFM}}(i,j)\sigma_i\sigma_j-\sum_i\mu_iB_x\sigma_i-\sum_k J_{\mathrm{INT}}(k)\sigma_kS_{kx}. \tag{1}$$

The first line contains the energy contribution of the FM, the second line describes the AFM while the third line includes the coupling between FM and AFM, 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_i denotes the magnetic moment.

The exchange interaction across the interface between AFM and FM is denoted by $J_{\mathrm{INT}}(k)$ and will be specified in the following. We set $J_{\mathrm{AFM}}=-J_{\mathrm{FM}}/2$ throughout the paper mainly in order to have a (nearly) saturated ferromagnetic layer in the relevant temperature region below the AFM ordering temperature.

The systems considered are magnetically diluted. This means that only a certain fraction of lattice sites are occupied with spins. The sums in Eq. (1) run only over these occupied sites. The concentration of magnetic sites in the AFM which consists always of four monolayers is chosen to be $c_{\mathrm{AFM}}=0.5$ throughout the paper. This concentration leads to an appreciable bias field[10] and to small domains. The FM layer is assumed to consist of a bilayer where sites in the outer ferromagnetic monolayer are magnetically filled while the concentration of magnetic sites at the ferromagnetic interface layer is set to c_{FM}. Additionally, we consider a disorder of the bonds across the FM/AFM interface.

We consider quenched random disorder such that each site is either empty or filled with a site-independent probability or, in the case of bond disorder, the strength of each bond across the interface is chosen from a bond-independent probability distribution. For each particular disorder configuration, thermodynamic quantities are calculated and, if not otherwise stated, an average is taken over six independent configurations.

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 spin flip for the Ising model and a random choice of a spin vector for the Heisenberg model. To increase the acceptance rate in the simulations the choice of this spin vector is restricted to a cone around the spin to be updated. We perform typically 250 000 Monte Carlo steps per spin (MCS) for a complete hysteresis loop (for one particular configuration of the defects).

We use systems of lateral extension $L\times L$ with $L=128$ in the xy plane (the film plane) with periodic boundary conditions in the plane. Comparison with simulations of smaller systems confirmed that there are no relevant finite-size effects as long as the system is not much smaller than $L=128$. Note that this relatively small size provides reliable results because the large dilution of the AFM layer forces the creation of small domains in the AFM. All spins are assumed to have the same magnetic moment μ. In the following we will use reduced fields $b=\mu B/J_{\mathrm{FM}}$ and reduced temperatures $t=k_{\mathrm{B}}T/J_{\mathrm{FM}}$.

A. Hysteresis

In all our simulations the system is slowly cooled starting from an initial temperature $t=1.75$ 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 AFM. The temperature t is reduced in small steps $\delta t=0.002$ and in each step 100 MCS are performed.

When the desired final temperature is reached a magnetic field $\underline{b}=b_x\underline{\hat{x}}+b_y\underline{\hat{y}}$ is applied under a very small angle with respect to the easy axis, $b_y=\alpha b_x$ with slope $\alpha=0.1$, 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 0.2, about twice the value of the switching field. The x component of the field, b_x, is then reduced in steps of $\delta b_x=0.0005$ down to -0.2 and afterwards raised again up to the

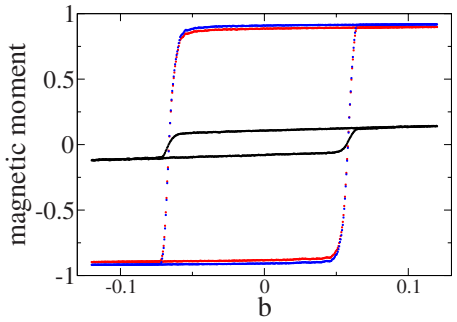

FIG. 1. (Color online) Typical hysteresis loops for temperature $t=0.35$. Shown is the reduced magnetic moment per spin of the AFM interface layer (smallest moment at $b=0.12$) and that of the two FM monolayers. Loops are truncated at $|b|=0.12$.

initial value. This corresponds to one cycle of the hysteresis loop.

Typical hysteresis loops are depicted in Fig. 1. Shown is the averaged layer resolved magnetic moment per spin, $\overline{\langle S_{ix}\rangle}$, for the two FM monolayers and that for the AFM interface layer, $\overline{\langle \sigma_i\rangle}$. Here, the brackets denote a thermal average while the bar denotes a spatial average over all spins within the layer considered.

Site dilution is considered here and the concentration of magnetic sites in the FM interface layer is $c_{\mathrm{FM}}=0.7$. Figure 1 shows that the averaged magnetic moment per spin of this layer is only slightly smaller than that of the other FM layer for low temperatures. For increasing temperatures simulations show that the interface moment is reduced considerable as compared to that of the other FM layer due to spatial disorder and thermal effects.

The FM hysteresis loops display a shift along the field axis to negative fields identified as exchange bias. The corresponding field is determined from $b_{\mathrm{eb}}=(b^{+}+b^{-})/2$, where b^{+} and b^{-} are those fields of the hysteresis loop branches for increasing and decreasing field, where the easy axis component of the magnetic moment becomes zero. In principle, one could define these fields b^{+} and b^{-} for each layer separately. In the following, however, b^{+} and b^{-} refer always to those fields where the x component of the total averaged moment of the FM layer becomes zero. The corresponding coercive field is $b_c=(b^{+}-b^{-})/2$.

B. Site dilution

The dependence of the EB field of a FM bilayer on the dilution of the FM interface layer is studied in detail for a reduced temperature of $t=0.05$. Our simulation results for systems cooled in an applied field $b_{\mathrm{cool}}=2.0$ are shown in Fig. 2. Going from $c_{\mathrm{FM}}=1.0$ to lower concentration of magnetic ions the absolute value of the bias first increases rapidly with increasing number of defects in the FM interface layer and reaches a maximum around $c_{\mathrm{FM}}=0.4$. For $c_{\mathrm{FM}}\to 0$, on the other hand, there is only one FM monolayer remaining which is decoupled from the AFM layer so that the bias goes to zero.

This observed increase in $|b_{eb}|$ for small dilution is remarkable because a dilution of the FM interface layer weakens the interface exchange interaction. Contrary to what might be expected, this weakening obviously does not lead to a decrease in $|b_{eb}|$. As will be discussed in detail below we understand this interesting behavior as a result of better adjustment of the domains in the AFM layer to the diluted FM interface layer as compared to the undiluted case (for not too large dilution), an argument put forward already in Ref. 19.

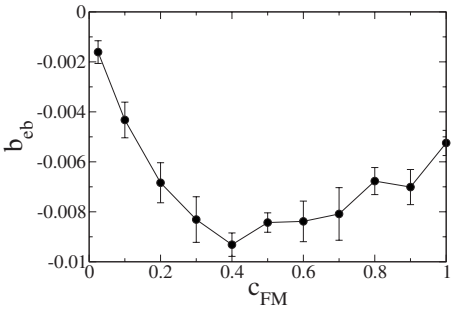

FIG. 2. Exchange bias versus concentration c_{FM} of magnetic ions in the FM interface layer at reduced temperature $t=0.05$ for a FM bilayer. The line is a guide to the eyes.

An initial increase in $|b_{eb}|$ with increasing number of defects has also been observed experimentally[18] in perpendicular exchange bias systems where it is claimed that the addition of a Pt spacer layer induces a better collinear alignment of the spins in the FM layer out of the plane. In Ref. 19, on the other hand, this effect is also observed again with a Pt layer for the case that the magnetization for both layers is parallel to the film similar to the situation in the present investigation. Note, however, that for other nonmagnetic impurities such an increase seems to be very small or even absent although the decay of the bias is very slow for a small number of defects.[19,20] A possible explanation is that already without dusting with nonmagnetic impurities the FM interface layer contains defects so that further dusting is less effective and primarily only weakens the exchange interaction at the interface.

For a deeper understanding of this unexpected behavior of the bias when diluting the FM interface layer we analyzed in more detail the magnetization behavior at the interface. The number of ferromagnetic bonds across the interface connecting a FM spin with an Ising spin is, on average, $0.5c_{\mathrm{FM}}$ for a dilution $c_{\mathrm{AFM}}=0.5$ of the AFM. Consider now a weakly diluted FM interface layer. If the domain state which is established during field cooling is only slightly dependent on c_{FM} we would expect frozen magnetizations in the AFM interface layer and correspondingly a bias field proportional to the number of bonds across the interface, i.e., proportional to c_{FM}, and inversely proportional to $(1+c_{\mathrm{FM}})$ because the reduced number of spins in the FM. This, however, is not observed in the simulations so that the assumption of a dilution independent domain state must be abandoned. On the contrary a strong dependence of the spin structure on c_{FM} during cooling must take place.

A simple argument for understanding this behavior can be constructed as follows. Consider an undiluted FM in contact with a diluted AFM. The region of the FM/AFM interface covering a domain in the AFM can take three possible configurations: (1) the FM is in contact with a preferentially

magnetized AFM, (2) the FM is in contact with an unfavorably magnetized AFM, and (3) the FM is in contact with a zero magnetized AFM. Using + and − to denote the orientation of spins, we represent these three configurations schematically as

(1):

+ + + + + F

+ − + − + AF,

(2):

+ + + + + F

− + − + − AF,

(3):

+ + + + F

+ − + − AF.

Defining f as the fraction of favorably oriented F/AF domains, u as the fraction of unfavorably oriented F/AF domains, and n as the fraction of neutral aligned domains, we require $1=f+u+n$. Furthermore, we assume that the f and u domains are frozen such that upon field cooling, the u domains do not turn into f domains. Now suppose that holes are introduced into the ferromagnet so that the ferromagnet concentration is c_{FM}. Next, under the assumption that c_{FM} is not too large, we might say that a hole in f does not on average affect the f domains. Likewise, if c is not too large, a hole in u does not on average affect u.

However, a hole in an n domain does change an n into either an f or a u domain. After field cooling, then if the resulting u domains can reverse to become f domains, one sees an increase in bias. This can be written as $b_{eb}=c[f-u+n(1-c)]=c(1-2u)-nc^2$ This gives a maximum bias at a value determined by n for some $c_{\mathrm{FM}}<0.5$.

Computer simulations support these qualitative arguments. To show this we measured along the hysteresis path the averaged magnetic moment of those spins in the AFM interface layer which are connected to a neighboring FM spin. To be more specific after cooling the system in a field $b_{\mathrm{cool}}=2.0$ down to a temperature of $t=0.05$ as described above a field $b_{max}=0.2$ is applied which is the starting field for the descending branch of the hysteresis loop. At this starting field 20 000 MC steps are performed for equilibration of the system. At this applied field, the averaged moment of AFM interface spins connected to FM spins is calculated, where the average is taken over 300 MCS in order to reduce thermal fluctuations. The averaged moment per connected AFM interface spin at this field is denoted by m_1.

After completion of the descending branch we similarly determined the magnetic moment m_2 at $-b_{max}$, and again after completion of the ascending branch of the loop we determined the moment m_3 at b_{max}. These quantities are shown in Fig. 3 as functions of c_{FM}. The interesting point is the rather strong increase especially of $|m_1|$ with decreasing c_{FM}

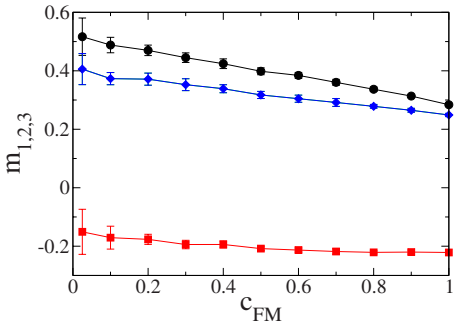

FIG. 3. (Color online) AFM interface moment m_1 (circles), m_2 (squares), and m_3 (diamonds) as explained in the text versus concentration c_{FM} of magnetic ions in the FM interface layer at reduced temperature $t=0.05$ for a FM bilayer.

This means that the domain state established upon cooling is significantly changed by diluting the FM interface layer: the magnetization of the connected AFM interface spins is increased due to a better adjustment of the AFM interface layer to the diluted FM layer.

The principle at work is analogous to how two rough surfaces can establish a contact which one another that is stronger than what would occur if one surface were perfectly flat. As a result there will be large differences in the friction associated with rough-rough and rough-smooth surfaces. In our magnetic case, the bias field is the analog to friction. Note that after completion of the first hysteresis cycle the magnetic moment at b_{max}, m_3, is slightly reduced as compared to m_1, the magnetization at the beginning of the loop, a phenomenon called training.

The quantities m_1+m_2 and m_2+m_3 are identified as the frozen parts of the AFM interface magnetization for the descending and the ascending branch, respectively, of the hysteresis loop, being at the origin of exchange bias.[7] Indeed, the bias field can be estimated from these shifts.

Consider first the descending branch of the hysteresis loop. The upward shift of the connected part of the magnetic moment of the AFM interface layer results in an exchange energy $\frac{1}{2}(m_1+m_2)ZJ_{\mathrm{INT}}$ leading to a shift of the hysteresis loop along the b axis of

$$\delta b = -\frac{1}{2}J_{\mathrm{INT}}(m_1+m_2)\frac{Z}{(L^2+N_{\mathrm{INT}})}, \tag{2}$$

where Z is the number of connected sites across the interface and N_{INT} the number of spins in the FM interface layer.

A similar shift can be calculated for the ascending branch of the loop by replacing m_1 by m_3.

These two shifts contribute to the bias field. Averaging their contribution leads to the following estimate of the bias field

$$\tilde{b}_{eb} = \frac{1}{4}J_{\mathrm{INT}}(m_1+2m_2+m_3)\frac{Z}{(L^2+N_{\mathrm{INT}})}. \tag{3}$$

This quantity is shown in Fig. 4 together with the bias field calculated in the usual way from the hysteresis loop. The agreement between the two approaches for calculating the bias field is fair in view of the fact that the calculation of the

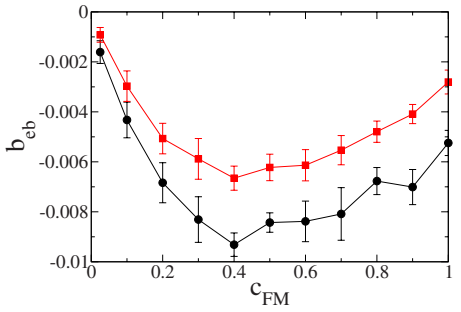

FIG. 4. (Color online) Exchange bias fields versus concentration c_{FM} of magnetic ions in the FM interface layer at reduced temperature $t=0.05$ for a FM bilayer as calculated from the switching fields along the hysteresis paths (circles, black) and from the magnetization shifts (squares, red), respectively. The lines are a guide to the eyes.

bias field using the magnetization shifts neglects those parts of the AFM spins which follow the field during hysteresis. These fields are important in the precise determination of the switching fields b_- and b_+ as was discussed in Ref. 21.

Note that in sufficiently large systems we have $N_{\mathrm{INT}}=c_{\mathrm{FM}}L^2$ and $Z=0.5c_{\mathrm{FM}}L^2$ (0.5 for the dilution of the AFM) so that

$$\tilde{b}_{eb}=-\frac{1}{4}J_{\mathrm{INT}}(m_1+2m_2+m3)\frac{c_{\mathrm{FM}}}{(1+c_{\mathrm{FM}})} \tag{4}$$

recovering the proportionality of b_{eb} to $c_{\mathrm{FM}}/(1+c_{\mathrm{FM}})$ and identifying the nonmonotonous behavior of b_{eb} as due to the strong dependence of the moments m_i on c_{FM}.

The coercive field shown in Fig. 5 decreases with increasing number of defects and goes through a minimum at a low concentration of magnetic sites of about $c_{\mathrm{FM}}=0.3$. This initial decrease agrees with experimental results in Ref. 19 but it is in disagreement with Ref. 18 where it is found that the coercive field more or less follows the absolute value of the bias field. Possibly this disagreement is due to the different spin structure in the two systems.

C. Bond disorder

The inclusion of magnetic impurities at the interface gives rise to a strong increase in the absolute value of the bias

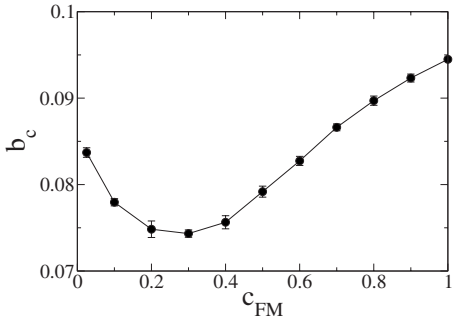

FIG. 5. Coercive field versus concentration c_{FM} of magnetic ions in the FM interface layer at reduced temperature $t=0.05$ for a FM bilayer. The line is a guide to the eyes.

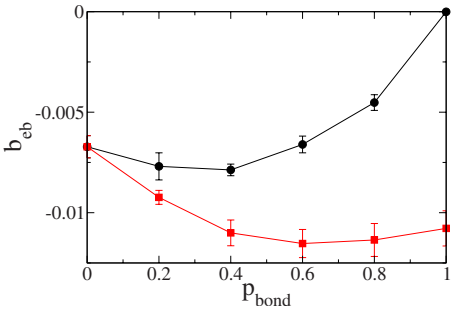

FIG. 6. (Color online) Exchange bias versus concentration p_{bond} of bonds across the AFM/FM interface with exchange interaction put to zero (circles) or enlarged by a factor of 2 (squares) at reduced temperature $t=0.05$ for a FM bilayer. The line is a guide to the eyes.

field.[19] In these experiments different kinds of magnetic impurities where placed at the FM/AFM interface. To model this in a simple way we consider a FM bilayer and vary the size of exchange bonds across the AFM/FM interface, keeping the other parameters fixed. The temperature is chosen to be $t=0.05$ and the systems are cooled in zero field.

The bias field as function of the concentration of bonds which have been modified, p_{bond}, is shown in Fig. 6 for two cases. Either the exchange interaction of these bonds is set to zero (bond dilution) or it is enlarged by a factor of 2. In the first case we again observe an increase in $|b_{eb}|$ with increasing dilution p_{bond} with a maximum around $p_{\mathrm{bond}}=0.4$. This corresponds exactly to the behavior found for site dilution. For $p_{\mathrm{bond}}\to 1$, on the other hand, there is only one FM monolayer left which is decoupled from the AFM layer so that the bias goes to zero.

In the second case an even stronger increase in $|b_{eb}|$ for small strength dilution p_{bond} is observed which levels out at around $p_{\mathrm{bond}}=0.5$. This behavior is similar to what has been found experimentally (see Fig. 3 in Ref. 19). The decrease in b_{eb} observed in this work for large values of the impurity layer thickness can be understood as due to the inverse dependence of bias on the large nominal ferromagnetic layer thickness.

For $p_{\mathrm{bond}}\to 1$, the bias is nearly twice as large as for $p_{\mathrm{bond}}\to 0$. In both of these limits there is no disorder in the bonds at the interface. In this case the bias $|b_{eb}|$ is proportional to J_{INT} and the frozen magnetization at the AFM interface as explained in detail in Ref. 21. If the latter is not affected too much by the strength of the bonds across the interface (within certain limits, of course) a proportionality to J_{INT} is expected.

The coercive field as function of p_{bond} is shown in Fig. 7. General speaking the effect of bond dilution on the coercive field is by far not as large as site dilution, see Fig. 5. The reason is that site dilution in the FM interface layer introduces strong disorder in this layer while a dilution in the bonds across the interface essentially only decouples the FM bilayer from the AFM layer: spins in the FM interface layer remain connected to five FM neighbors resulting in a (nearly) saturated FM layer at low temperatures so that a coercive field close to the Stoner value, $b_{Stoner}=0.1$, is expected. If, on the other hand, the exchange interaction across the interface is enhanced, the coercive field will increase

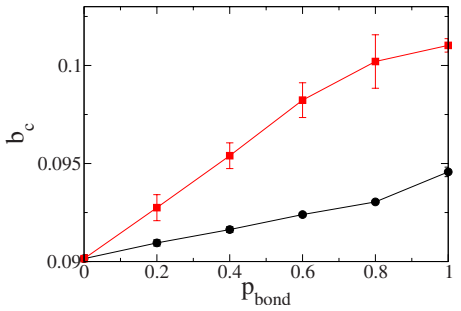

FIG. 7. (Color online) Coercivity versus concentration p_{bond} of bonds across the AFM/FM interface with exchange interaction put to zero (circles) or enlarged by a factor of 2 (squares) at reduced temperature $t=0.05$ for a FM bilayer. The line is a guide to the eyes.

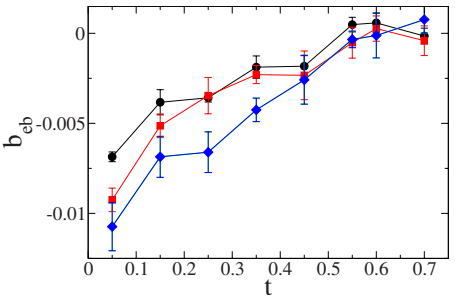

FIG. 8. (Color online) Bias field as a function of reduced temperature $t=k_BT/J_{\text{FM}}$ for a FM bilayer with $c_{\text{FM}}=1.0$ (circles), a FM bilayer with $c_{\text{FM}}=0.7$ (squares), and an undiluted monolayer (diamonds). The line is a guide to the eyes.

because an increased number of spins in the AFM layer will be reversed during hysteresis cycles.

D. Temperature dependence

The temperature dependence of the EB field is shown in Fig. 8 for three different site disorders and zero-field cooling. Circles show the bias field for a FM layer consisting of two undiluted monolayers, squares show the bias field if the FM interface layer is diluted, $c_{\text{FM}}=0.7$, while diamonds show the bias field if only one undiluted FM monolayer is present.

The absolute value of the EB field decreases with temperature and goes to zero at the blocking temperature (the temperature of the onset of EB). The blocking temperature is roughly the same for all three cases showing that it is a parameter mainly dependent on the properties of the AFM layer.

A second feature is worth mentioning: an increase in the dilution of the FM interface layer increases the absolute value of the bias field over the whole temperature region. We explain this as again an example of how domains in the AFM layer optimize to the diluted FM more effectively than in the undiluted case. Note that this increase only takes place for small dilutions (see Fig. 2).

Since EB is an interface effect it is expected that at low temperatures the bias field is reduced by a factor of 2 if the number of FM layers is doubled (providing there is no disorder in the FM layer present). This is indeed observed in our simulations. At a reduced temperature of $t=0.05$ the bias for the FM monolayer is about 0.011 while that of an undiluted FM bilayer turns out to be about 0.0068. They do not differ exactly by a factor of 2 because temperature effects reduce the magnetic order more severely in a monolayer as compared to a bilayer. The proportionality of the bias to the inverse of the number of FM monolayers is expected to be valid only for a given AFM layer, a situation different from that encountered in Ref. 11 where the bias was found to be independent of the number of FM monolayers.

The observed increase in the bias field for a diluted FM interface layer is in accordance with the argument that the bias should be proportional to the inverse of the nominal FM layer thickness. However, it is expected (and seen in our simulations) that this argument breaks down for increasing temperatures. The reason is that temperature reduces the magnetic order in the FM layer and this reduction is stronger in the magnetic monolayer as compared to a bilayer.

IV. CONCLUSIONS

While the importance of disorder in the AFM layer exchange coupled to a FM layer is well understood within the framework of the DS model, less is known about the influence of disorder in the FM layer on exchange bias and coercivity. By varying the properties of the FM interface layer of a FM bilayer exchange coupled to a diluted AFM layer we have shown with extensive Monte Carlo simulations that disorder in the FM layer also can have a significant influence on the properties of an EB system. We have shown, in particular, that both a (small) magnetic dilution of the FM interface layer and a bond dilution at the AFM/FM interface can *increase* the absolute value of the bias field significantly. Furthermore we have shown that a distribution of exchange interactions across the AFM/FM interface also gives rise to a remarkable increase of the bias, partly because of disorder effects, and partly because of larger exchange interactions. The observed initial increase in $|b_{eb}|$ is due to an easier adjustment of the domains in the AFM layer to the spins in a slightly diluted FM interface layer as discussed before.

In the present paper a simple model for the AFM/FM interface is studied. It would be desirable to have more microscopic information about the interface structure and the properties of the defects to set up a more realistic model for simulations. Without this we are restricted to only point out certain trends within our model.

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