

Control of exchange bias by diluting the antiferromagnetic layer

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The domain state model for exchange bias is used for an investigation of recent experiments where the magnitude and direction of the exchange bias was controlled by He ion irradiation of an FeNi/FeMn sample. The defects in the sample which result from the irradiation are modeled as diluting the antiferromagnet (AFM) after the initial cooling procedure. This late dilution, carried out in presence of a field leads to a rearrangement of the original domain structure of the AFM resulting in an enhancement or reduction in the bias field.

When a ferromagnet (FM) is in contact with an antiferromagnet (AFM) a shift of the hysteresis loop along the magnetic field axis can occur which is called exchange bias (EB).¹ Usually, this shift is observed after cooling the entire system in an external magnetic field below the Néel temperature T_N of the AFM (for a review over the variety of experimental facts see Ref. 2). Miltényi *et al.*³ showed that it is possible to strongly influence EB in Co/CoO bilayers by diluting the antiferromagnetic CoO layer, i.e., by inserting non-magnetic substitutions ($\text{Co}_{1-x}\text{Mg}_x\text{O}$) or defects (Co_{1-y}O) not at the FM/AFM interface, but rather throughout the volume part of the AFM. In the same letter it was shown that a corresponding theoretical model investigated by Monte Carlo simulations shows a behavior very similar to the experimental results. It was argued that EB has its origin in a domain state in the volume part of the AFM which triggers the spin arrangement and the FM/AFM exchange interaction at the interface. Later it was shown that a variety of experimental facts associated with exchange bias can be explained within this domain state model.⁴⁻⁶ The importance of defects for the EB effect was confirmed by experiments on $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2/\text{Co}$ bilayers.⁷ Further support for the relevance of domains in EB systems was given by a direct spectroscopic observation of AFM domains.^{8,9}

In recent experiments^{10,11} it was shown that it is possible to modify EB by means of irradiating an FeNi/FeMn system by He ions in presence of a magnetic field. Depending on the dose of the irradiation and the magnetic field present at the time of irradiation, it was possible to manipulate both the magnitude and even the direction of the EB field. The sample was cooled below the Néel temperature in a cooling field of $B_{\text{prep}} = 500$ Oe to give an initial EB field of $B_{\text{EB}}^i = -190$ Oe. Then the sample was irradiated with He ions in presence of a magnetic field of approximately 1 kOe which was either parallel (B_p) or antiparallel (B_{ap}) to the initial field B_{prep} . The measurements showed that in the first case

the EB effect can be even stronger after the irradiation depending on its dose. The EB field first increased with the dose of irradiation up to a certain value beyond which it decreased, eventually decaying to zero. In the second case where the irradiation was carried out in presence of an antiparallel field the EB field first decreased with increasing dose, then changed its sign, and later once again vanished completely.

The domain state model³ for EB provides the framework for understanding the experimental facts. The model consists of one monolayer of FM and t monolayers of diluted AFM (see Ref. 12 for details). We have used $t=3$ for the results presented in this article. The FM is exchange coupled to the topmost layer of the AFM. The Hamiltonian of the classical Heisenberg system is given by

$$\begin{aligned} \mathcal{H} = & -J_{\text{FM}} \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - \sum_i (d_z S_{iz}^2 + d_x S_{ix}^2 + \mathbf{S}_i \cdot \mathbf{B}) \\ & - J_{\text{AFM}} \sum_{\langle i,j \rangle} \epsilon_i \epsilon_j \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j - \sum_i \epsilon_i (k_z \sigma_{iz}^2 + \boldsymbol{\sigma}_i \cdot \mathbf{B}) \\ & - J_{\text{INT}} \sum_{\langle i,j \rangle} \epsilon_j \mathbf{S}_i \cdot \boldsymbol{\sigma}_j, \end{aligned}$$

where \mathbf{S}_i denote normalized spins at sites of the FM monolayer and $\boldsymbol{\sigma}_i$ denote normalized spins at site of the AFM. The first line of the Hamiltonian describes the energy of the FM with the z axis as its easy axis (anisotropy constant $d_z = 0.1J_{\text{FM}} > 0$) and the x axis as its hard axis (anisotropy constant $d_x = -0.1J_{\text{FM}} < 0$). The resulting in-plane anisotropy keeps the FM preferentially in the y - z plane. The second line is the contribution from the AFM also having its easy axis along z ($k_z = J_{\text{FM}} > 0$). The AFM is diluted, i.e., a fraction p of sites is left without a magnetic moment ($\epsilon_i = 0$) while the other sites carry a moment ($\epsilon_i = 1$). The last term describes the interaction of the FM with the interface AFM monolayer. We consider nearest neighbor interactions on a simple cubic lattice with exchange constants J_{FM} and J_{AFM} for the FM and the AFM, respectively, while J_{INT}

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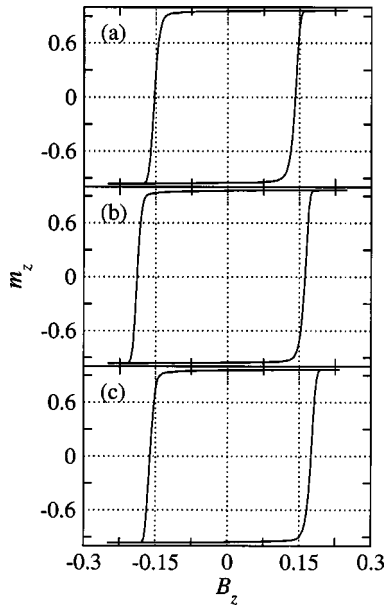


FIG. 1. Typical hysteresis loops after: (a) initial dilution ($p_i = 0.1$), (b) later dilution ($p_i = 0.45$) under parallel field and (c) later dilution under antiparallel field

stands for the exchange constant between FM and AFM. In our simulations we set $J_{\text{FM}} = -2J_{\text{AFM}} = 2J_{\text{INT}}$ (see Refs. 5 and 12 for a detailed discussion of the parameters of the model).

The basic idea behind the domain state model is that during the initial cooling procedure domains are formed in the diluted AFM under the influence of the external field and the additional exchange field of the FM (see e.g., Refs. 13 and 14 for reviews on diluted AFMs). Since the number of impurities in one sublattice of the AFM is in general not equal to that of the other sublattice within a domain, these domains carry a remanent magnetization following the so-called Imry–Ma argument which was originally proposed for random-field system.¹⁵ Furthermore the defects stabilize these domains by reducing the domain wall energy. This pinning effect—influence by thickness and the anisotropy of the AFM—provides the stability of the domains which is necessary to produce a bias field that acts on the FM during its hysteresis.

The defects which are caused experimentally by the He ion irradiation of the FeNi/FeMn samples are modeled by replacing magnetic atoms within the AFM by nonmagnetic impurities. Since we focus in the following on the understanding of the AFM we leave the FM undisturbed. However, in the experiment even the FM will be affected by the irradiation which may lead to additional effects beyond the purposes of our present investigation. Since a minimum dilution of the AFM is required in the framework of our model in order to form domains and, hence, produce an EB we consider now a two stage dilution process for the AFM: starting with an initial dilution p_i of the AFM the system is cooled below T_N in presence of an external magnetic field $B_{\text{prep}} = 0.25J_{\text{FM}}$ along the easy axis. The EB field obtained at this stage is called the initial bias field B_{EB}^i . Now the system is further diluted by an amount p_l keeping the temperature

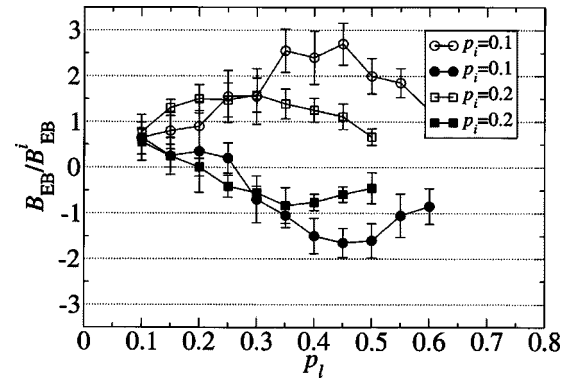


FIG. 2. Normalized EB field as a function of p_l for $p_i = 0.1$ (circle) and $p_i = 0.2$ (square). The open symbols correspond to late dilution with parallel field and the solid symbols are for late dilution with antiparallel field

fixed. After this second, additional dilution we let the system relax in presence of a field which could be either parallel (B_p) or antiparallel (B_{ap}) to B_{prep} so that the domains will rearrange. In our model this late dilution process corresponds to the ion irradiation and p_l to its dose. The EB field B_{EB} is now calculated for the final dilution $p = p_i + p_l$ of the AFM. For the calculations presented in the following we have used $B_p = -B_{\text{ap}} = 0.5J_{\text{FM}}$.

Typical hysteresis loops after the initial and later dilution are shown in Fig. 1. Clearly we observe an enhanced EB effect for the later dilution in a parallel field whereas the EB field is reversed for the later dilution in an antiparallel field. The influence of the later dilution on the EB depends on the amount of late dilution as well as the initial dilution.

Figure 2 shows how the EB field after the late dilution (normalized to its initial value) changes with the amount of late dilution p_l . For both values of initial dilution, $p_i = 0.1$ and $p_i = 0.2$, the data of the EB field show qualitatively the same behavior. For late dilution with parallel field there is at first an increase of EB with p_l up to a maximum value beyond which it starts decreasing again, obviously decaying to zero. In contrast to this for late dilution with antiparallel field the EB effect decreases with increasing p_l even changing its sign. For still larger dilution one finds an increase back towards zero. The peak value of the EB after later dilution in parallel field is attained at nearly the same value as the dip of the EB field after diluting in B_{ap} . All these findings are in agreement with the experimental results.^{10,11}

The key for the understanding of these effects is the behavior of the AFM. During the initial cooling procedure domains are formed in the AFM which carry a remanent interface magnetization.^{5,12} The direction of this remanent magnetization is parallel to the cooling field B_{prep} and also parallel to the effective exchange field which was provided by the FM since in our simulations the interface coupling is positive. Size and stability of the domains which are formed depend strongly on the initial dilution p_i besides other parameters like, e.g., the layer thickness of the AFM.⁴ The variation of the EB field on dilution was investigated in a former publication.⁵ Here, we have chosen the value of p_i in such a way that upon further dilution the remanent interface magnetization of the AFM domains can still increase thereby

leading to a stronger EB effect. Hence, the effect of the later dilution in presence of a parallel field is to reinforce the domains further enhancing the remanence. However, beyond a certain dilution when the impurities destroy the structure of the AFM the EB field must decrease.

On the other hand, if the later dilution is carried out in a sufficiently strong antiparallel field it opposes the initial remanence of the AFM domains. The domain structure of the AFM is rearranged and the resulting domains carry a remanent interface magnetization in the opposite direction as compared to the original one after the initial cooling procedure. This leads to the reversal of the EB field. However, the EB decreases with increasing p_i up to a minimum value, beyond which the remanence vanishes as in the parallel case since the impurities destroy the structure of the AFM. Consequently, as before the EB effect must vanish for a strong dilution. If the initial dilution is already high the domains have less chance to rearrange themselves upon further dilution. This explains why the peak is stronger for $p_i=0.1$ and why it is shifted towards higher values of p_l as compared to the peak corresponding to $p_i=0.2$.

To summarize, recent experiments^{10,11} which showed that EB can be modified by means of ion irradiating, i.e., by inducing defects in the bulk of the AFM underlines the importance of defects for the understanding of EB. The domain state model for EB in which the ion irradiation is modeled as a second dilution of the AFM after the initial cooling procedure explains the experimental facts in terms of domain re-

arrangements caused by diluting the system within an applied field

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¹W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956).

²J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999).

³P. Miltényi, M. Gierlings, J. Keller, B. Beschoten, G. Güntherodt, U. Nowak, and K. D. Usadel, Phys. Rev. Lett. **84**, 4224 (2000).

⁴U. Nowak, A. Misra, and K. D. Usadel, J. Appl. Phys. **89**, 7269 (2001).

⁵U. Nowak, K. D. Usadel, P. Miltényi, J. Keller, B. Beschoten, and G. Güntherodt, Phys. Rev. B **66**, 14430 (2002).

⁶J. Keller, P. Miltényi, B. Beschoten, G. Güntherodt, U. Nowak, and K. D. Usadel, Phys. Rev. B **66**, 14431 (2002).

⁷H. T. Shi, D. Lederman, and E. E. C. Fullerton, J. Appl. Phys. **91**, 7763 (2002).

⁸F. Nolting *et al.*, Nature (London) **405**, 767 (2000).

⁹H. Ohldag, A. Scholl, F. Nolting, S. Anders, F. U. Hillebrecht, and J. Stöhr, Phys. Rev. Lett. **86**, 2878 (2001).

¹⁰T. Mewes, R. Lopusnik, J. Fassbender, B. Hillebrands, M. Jung, D. Engel, A. Ehresmann, and H. Schmoranz, Appl. Phys. Lett. **76**, 1057 (2000).

¹¹A. Mougin, T. Mewes, M. Jung, D. Engel, A. Ehresmann, H. Schmoranz, J. Fassbender, and B. Hillebrands, Phys. Rev. B **63**, 60409 (2001).

¹²U. Nowak, A. Misra, and K. D. Usadel, J. Magn. Magn. Mater. **240**, 243 (2002).

¹³W. Kleemann, Int. J. Mod. Phys. B **7**, 2469 (1993).

¹⁴D. P. Belanger, in *Spin Glasses and Random Fields*, edited by A. P. Young (World Scientific Singapore, 1998).

¹⁵Y. Imry and S. Ma, Phys. Rev. Lett. **35**, 1399 (1975).