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ISING MODEL FOR EXCHANGE BIAS IN FERROMAGNETIC/ANTIFERROMAGNETIC BILAYERS

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We propose a Random Anisotropy Ising Model (RAIM) to describe exchange bias in a ferromagnetic(F)/antiferromagnetic(AF) system. The F and AF spins are arranged in a square lattice permitting to control the interface between the two layers. The AF film is quenched and exhibit negative exchange interactions, while interactions in the F film are positives. An anisotropy term is introduced in both layers. The influence of the AF spin arrangement at the interface on exchange bias field is analyzed for compensated, uncompensated or rough interfaces.

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1. Introduction

Exchange bias (EB) was observed for the first time almost 50 years ago by Meiklejohn and Bean [1] on a system of oxidized Co particles. After this system was field cooled from a temperature greater than the CoO Néel temperature, a unidirectional anisotropy appeared in the samples, inducing the "shift" of the hysteresis loop on the field axis. This shift is called exchange bias field (H_{eb}). If we note with H_- and H_+ the switching fields, H_{eb} is calculated as: $H_{eb} = \left(H_- + H_+\right)/2$. Nowadays, exchange bias is receiving a great deal of interest, mainly because of its use as a pinning force in spin valves [2] or tunnel junctions [3].

Most of the EB systems are the ferromagnetic(F)/antiferromagnetic(AF) bilayers, (see reference [4] for a review of EB). In all the analyzed layers it was observed that H_{eb} varies roughly inversely proportional with the thickness of the F layer. With the increase of the AF layer thickness, H_{eb} generally increases, to stabilize at a constant value. The interfacial properties, such as the spin configuration, the roughness, or the impurities, are crucial for the exchange bias value. Unfortunately, it's difficult to control and to analyze the quality of the F/AF interface, so that controversial results are often presented in the literature [4].

Several models of this phenomenon have been proposed until now, describing more or less generally the specific features of the exchange coupled systems (for a review see [5]). The initial models are more qualitative, explaining the unidirectional anisotropy as the result of the exchange interactions between the F and the AF spins at the interface. A flat and homogenous interface is generally supposed. Other models verify the role of the AF spin configuration on exchange bias, the main discussed feature being the compensated versus uncompensated AF interface. A compensated interface has a zero surface magnetization, because the two AF sublattices are equally present at the interface. If the AF spin arrangement induces a non-zero interfacial magnetization, the interface is considered uncompensated.

More recent micromagnetic models take into account roughness and defects at the interface, such as the model proposed by Schulthess and Butler [6], or that proposed by Kiwi [5]. Stiles and McMichael [7] do not focus on atomic scale but use a polycrystalline AF interface. The domain state model [8] starts from a diluted antiferromagnet to introduce a domain structure in the AF.

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2. Model

We propose a Random Anisotropy Ising Model (RAIM) to describe exchange bias in a F/AF system. The model is in fact an improved variant of the $T = 0$ random-field Ising model presented in [9]. By difference with the initial model, where interfacial spins are chosen randomly, in this model the F and AF spins are arranged in a square lattice so that we can have a better control of the interface between the two layers (Fig. 1) (☐ positive AF moments, ☒ negative AF moments, ○ positive F moments).

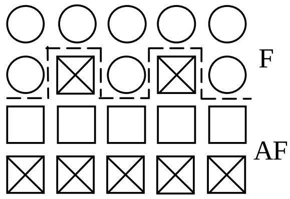


Fig. 1. The F/AF spin structure.

The AF has two perfectly compensated antiferromagnetic sublattices and the F one has ferromagnetically coupled spins. The spins from the two different layers are coupled by interlayer exchange interaction. The system Hamiltonian is taken as:

$$\mathrm{H} = \mathrm{H}_{AF} + \mathrm{H}_F + \mathrm{H}_C \tag{1}$$

where H_{AF}, H_F, and H_C are, respectively, the interaction energies in the AF layer, in the F layer and the interfacial coupling between the F and AF spins, all assumed to be Ising like to simplify the calculations. The Hamiltonian of the AF system is:

$$\mathrm{H}_{AF} = -\frac{1}{2} J_{AF} \sum_{i=1}^{N_{AF}} \sum_{j=1}^{N_n^{AF}} \sigma_i \sigma_j - H_{AF}^{anis} \sum_{i=1}^{N_{AF}} \sigma_i - H \sum_{i=1}^{N_{AF}} \sigma_i \tag{2}$$

where σ_i represents the spins on the AF at site i interacting with the nearest neighbors through an exchange constant $J_{AF} < 0$, N_n^{AF} meaning the number of nearest neighbor AF spins, N_{AF} the number of AF spins in the system, H_{AF}^{anis} the local uniaxial anisotropy in the AF and H the external field.

The Hamiltonian for the F layer is calculated after:

$$\mathrm{H}_F = -\frac{1}{2} J_F \sum_{i=1}^{N_F} \sum_{j=1}^{N_n^F} S_i S_j - \sum_{i=1}^{N_F} H_{Fi}^{anis} S_i - H \sum_{i=1}^{N_F} S_i - \sum_{i=1}^{N_F} h_i S_i \tag{3}$$

where S_i represents the spins on the F layer at site i interacting with the N_n^F nearest neighbor spins through the exchange constant J_F, N_F represents the total number of F spins, H_{Fi}^{anis} is the local uniaxial field in the F layer, considered to be distributed after a Gaussian probability density. The disorder present in any ferromagnetic system is introduced in the model through the Gaussian distributed random fields h_i.

The interlayer exchange interaction energy is:

$$\mathrm{H}_C = -J_C \sum_{i=1}^{N_C} S_i \sigma_i \tag{4}$$

where J_C is the coupling exchange constant and N_C is the number of spins at the interface. Roughness is introduced in the model by randomly changing a certain number of interfacial F spins with the corresponding AF spins.

3. Results

We have used a rectangular lattice with a side representing the interface (kept constant with 10.000 spins) and the other the thickness of the F/AF bilayer (with variable number n_F of the F lattices). The F and the AF exchange constants have been taken $J_F = -J_{AF} = 1$. Positive interfacial interactions have been considered, choosing the coupling constant value $J_C = J_F$. The AF spin structure has been quenched imposing a high anisotropy constant, $H_{AF}^{anis} = 10 J_F$. The anisotropies in the F layer are Gaussian distributed with the mean value $H_F^{anis} = 1$ and the standard deviation $\sigma_{anis} = 1$. The Gaussian distribution of the random fields h_i has zero mean value and the standard deviation $\sigma_h = 1$. The magnetic field is expressed in terms of J_F.

We have studied the dynamics of the system at zero temperature by changing the external field H in small steps. After each field step, one compares the value of the effective local field $h_i^{eff} = J_F \sum_{j=1}^{N_n^F} S_j + H + h_i$ of each spin, with that of the local anisotropy field, H_{Fi}^{anis}. If $\left|h_i^{eff}\right| > \left|H_{Fi}^{anis}\right|$ then the spin is unstable and it flips [10].

The model was used to simulate the hysteresis loops for different types of F/AF interfaces. EB is obtained only for uncompensated AF interfaces, as indicated in Fig. 2.

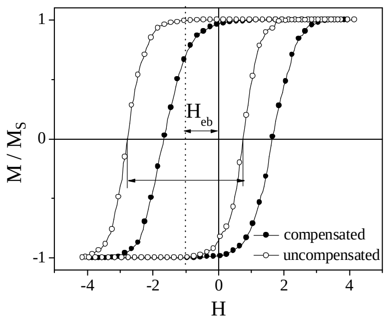


Fig. 2. Hysteresis cycles for two samples with compensated and uncompensated AF interfaces. EB is obtained only in the sample having uncompensated AF spins at the interface.

If roughness is introduced in the samples having a compensated AF structure, a certain number of uncompensated AF spins appears at the interface, generating EB. When only one AF sublattice forms the interface, roughness decreases the total number of interfacial uncompensated AF spins and H_{eb} value decreases (Fig. 3(a)). As presented in Fig. 3(b), the decrease of EB is associated with the increase of H_c. This variation of H_c with the roughness was experimentally observed in the NiO/NiFe bilayers [11] but no evident influence of the roughness upon H_{eb} was experimentally obtained in the same system. In other systems, the decrease of H_{eb} at the increase of the roughness was reported [4].

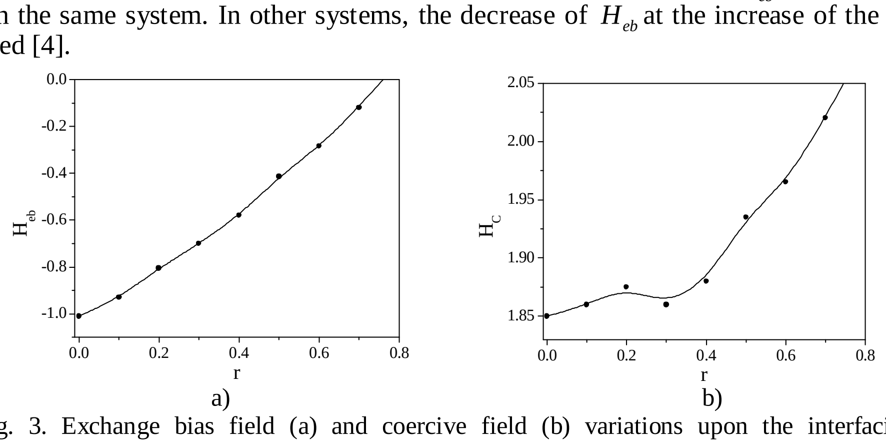
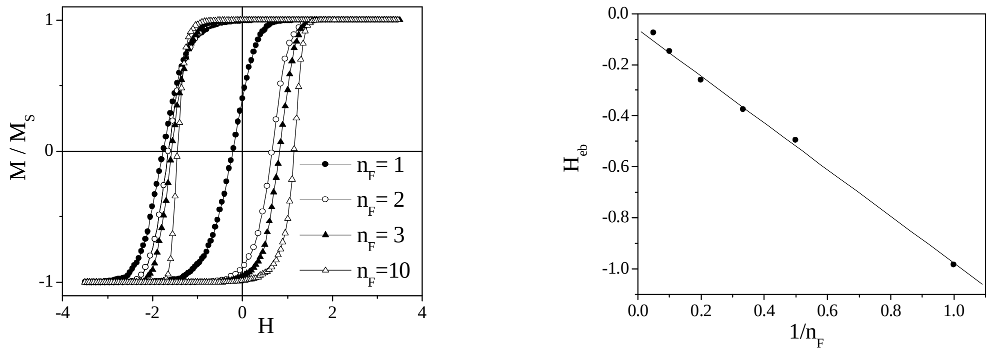


Fig. 3. Exchange bias field (a) and coercive field (b) variations upon the interfacial roughness, *r*, for a sample having an uncompensated AF interface. The roughness *r* is calculated as the fraction of replaced F spins reported to the total number of F spins at the interface.

The change of the hysteresis loop shift with the thickness of the F layer is presented in Fig. 4(a). The thickness of the layer is modified by changing the number n_F of the F spin lattices. As indicated in Fig. 4(b) the expected inverse proportional dependence of H_{eb} upon n_F is obtained.



a) b)

Fig. 4. a) Hysteresis loops simulated for systems with different number n_F of F lattices. b) H_{eb} variation upon n_F .

4. Conclusions

A Random Anisotropy Ising Model was introduced to describe EB in F/AF bilayers. With this model we obtained EB for the uncompensated AF interfaces and we reproduced the experimental inverse proportional dependence of H_{eb} with the F layer thickness. Roughness at the interface is easy to introduce in order to simulate realistic samples.

In a further paper we shall analyze more complex magnetic properties of EB systems using the First Order Reversal Curves.

Acknowledgments

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