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Exchange bias mechanism in FM/FM/AF spin valve systems in the presence of random unidirectional anisotropy field at the AF interface: The role played by the interface roughness due to randomness

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ABSTRACT

We propose an atomistic model and present Monte Carlo simulation results regarding the influence of FM/AF interface structure on the hysteresis mechanism and exchange bias behavior for a spin valve type FM/FM/AF magnetic junction. We simulate perfectly flat and roughened interface structures both with uncompensated interfacial AF moments. In order to simulate rough interface effect, we introduce the concept of random exchange anisotropy field induced at the interface, and acting on the interface AF spins. Our results yield that different types of the random field distributions of anisotropy field may lead to different behavior of exchange bias.

1. Introduction

The exchange bias (EB) effect, namely the prominent hysteresis loop shift observed in the magnetic systems composed of ferromagnetic (FM)/antiferromagnetic (AF) sandwiches has attracted considerable amount of interest since its discovery [1,2]. The reason is due to the fact that fabrication of several spintronic devices such as reading heads of magnetic hard disks, magnetic field sensors, permanent magnets and magnetoresistive devices rely on the EB effect. Indeed, using this effect, it is possible to beat superparamagnetism (SP) in magnetic recording devices [3,4]. Although the effect was primarily introduced approximately six decades ago, the physical mechanism behind this phenomenon remained unsolved until present day. Recently, there have been several important attempts to explain EB effect. Formerly, Malozemoff [5] considered the roughened interface model based on the formation of domain walls in AF volume due to interface roughness. In this model, it was suggested that in contrast to the flat compensated interfaces, upon introduction of rough interface structure at the FM/AF interface region, uncompensated AF interface spins may originate which may be responsible for the origination of non zero bias field. Based on this model, Schulthess et al. [6] showed that interfacial defects cause a unidirectional anisotropy which leads to EB which cannot be observed in systems with flat interfaces. Almeida et al. [7] proposed a microscopic model for a FM/AF bilayer exhibiting interface roughness. Due to this roughness, a random magnetic field configuration originates at the interface which results in EB. On the other front, Moritz and colleagues [8] argued for FM/AF bilayers that in the presence of roughness, both exchange bias field H_{EB} and coercivity H_C are weaker than those found for the perfect interface case.

From another point of view, Nowak and coworkers introduced the domain state model [9–12] which suggests the dilution of AF volume part. According to the results obtained within the framework of this model, it was found that the bias field H_{EB} increases upon increasing the dilution, it passes through a maximum for a certain dilution rate, then disappears due to the loss of lattice periodicity after exceeding the site percolation threshold. This model is also verified by another research group for EB effect in metallic antiferromagnets [13,14]. Most of the previous works suggest the presence of uncompensated interface AF moments as a requirement to be fulfilled in a magnetic system for the observation of EB behavior [15]. However, it was also reported that some systems with compensated interface spin configuration may also exhibit non zero EB field [16].

The physical origins of unidirectional anisotropy and EB phenomenology in magnetic bilayer and multilayer systems have been investigated in detail [17–22]. Besides, through the agency of recent experimental techniques, it is now possible to realize experimentally several fine particle systems such as magnetic nanoparticles. In this regard, EB properties of core-shell structured magnetic

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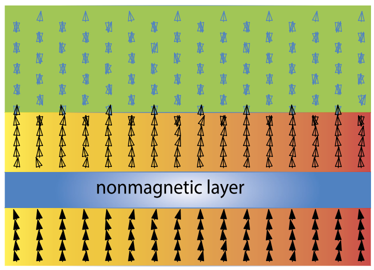

Fig. 1. Schematic representation of 2D cross-section of modeled spin valve system composed of FM/FM/AF sandwich. Free FM layer (bottom) is isolated from pinned FM layer (middle) by a non-magnetic substrate. The top AF layer is in magnetic contact with pinned FM layer via an interface exchange coupling J_{IF}.

nanoparticles have been intensely investigated from both experimental approaches and simulational tools [23–26]. The main difference between these aforementioned magnetic structures is that the magnetic nanoparticles in a spherical geometry exhibit natural roughness due to the different number of interface exchange coupling per interface spin which is defined for the spins located at the core/ shell boundary. However, magnetic multilayers in forms of magnetic thin films or spin valve systems which are composed of FM/FM/AF junctions may exhibit either flat or roughened interfaces.

It can be deduced from these works that the FM/AF interface plays a significant role on the EB properties of magnetic multilayers and nanoparticles, and the physical properties of such systems have been widely investigated [28–34]. The common, and one of the most important conclusions of these works is that the unidirectional anisotropy observed in EB systems may be a direct consequence of interfacial uncompensated spins. In this regard, in order to clarify the effect of interfacial roughness on the EB properties, we have performed detailed atomistic simulations for spin valve systems, and proposed a model where the unidirectional anisotropy at the interface region introduced by Ref. [35] is simulated according to the random field model introduced by Imry and Ma [36]. The plan of this letter can be summarized as follows: In Section 2, we present our model. Section 3 is devoted for numerical results, and finally Section 4 contains our conclusions.

2. Model and formulation

Conventionally, a spin valve system consists of a free ferromagnetic layer and a pinned ferromagnetic layer which are separated by a non magnetic spacer layer. Pinned FM layer is in a direct contact with an AF pinning layer whereas free FM and pinned FM layers do not interact with each other due to the presence of non magnetic spacer. We assume that the spacer has a monolayer thick, and it is fully site diluted, and hence we have no magnetic interaction between free and pinned FM layers (see Fig. 1). At this point, we note that our main point of interest in the present work is focused on the magnetic properties of pinned and AF layers, and particularly on their interface structure. However, in order to compare the behavior of free and pinned layers during the cooling process, we will give some results in the following discussions (cf. see Fig. 2c and related discussions).

For the present system, we consider a stacked magnetic multilayer in FM/FM/AF structure as shown in Fig. 1, and define the following Hamiltonian

$$\mathcal{H} = -J_{FM}\Big(\sum_{<i,j>}\mathbf{S}_i.\mathbf{S}_j + \sum_{<k,l>}\mathbf{S}_k.\mathbf{S}_l\Big) - J_{AF}\sum_{<m,n>}\mathbf{S}_m.\mathbf{S}_n$$
$$-J_{IF}\sum_{<i,m>}\mathbf{S}_i.\mathbf{S}_m - D_1\Big(\sum_i (S_i^x)^2 + \sum_k (S_k^x)^2\Big)$$
$$-D_2\sum_m (S_m^x)^2 - \sum_{i'}\mathbf{h}.\mathbf{S}_{i'}, \quad (1)$$

where the exchange interactions are considered for the nearest neighbor spin couples whereas the remaining summations are carried over all lattice sites. We assume that a classical Heisenberg spin vector with magnitude $|\mathbf{S}_i| = \sqrt{(S_i^x)^2 + (S_i^y)^2 + (S_i^z)^2}$ resides on each node of a simple cubic lattice with lattice parameter $a = 1$ (in arbitrary units). In Eq. (1), J_{FM} denotes the exchange coupling between spins located in free and pinned ferromagnetic multilayers, whereas J_{AF} denotes the AF exchange coupling between antiferromagnetic spins (see Fig. 1). At the interface region where pinned FM spins interact with AF spins, we define an exchange coupling J_{IF}. We set $J_{FM} = 1.0$ and scaled other interactions and temperature in our calculations in terms of J_{FM}. In order to observe EB, AF Néel temperature should be lower than the FM Curie temperature. Hence we set $J_{AF} = -0.1J_{FM}$. Besides, for simplicity we assume $J_{IF} = J_{FM}$. In order to set an easy axis for the magnetization direction, we introduce the single ion anisotropies for the FM and AF layers which are given by D_1 and D_2, respectively. For simplicity, we assume that single ion anisotropy constants for free and pinned FM regions are equal to each other. In order to have zero demagnetizing field effect (i.e. in order to reduce the influence of magnetostatic interactions on the system), in-plane magnetization direction is provided by considering uniaxial anisotropy constants as $D_1 = 0.1J_{FM}$, $D_2 = 1.0J_{FM}$ along the x axis of the film plane. Finally, in order to provide a certain orientation direction for the film magnetization during the cooling process, we consider a Zeeman energy term as the last term in Eq. (1) where $\mathbf{h} = (h, 0, 0)\hat{\mathbf{n}}$.

For each physical layers (i.e. for those of free FM, pinned FM, and AF layers) we define a certain thickness. Namely, the thickness along the z axis direction for free FM layer is L_{free} which is separated from pinned FM layer of thickness L_{pinned}. The thickness of nonmagnetic layer which separates free FM and pinned FM layers is L_{nm} and it is assumed to have monolayer thickness. Finally, the AF layer thickness is given by L_{AF}. Hence, the total thickness of the system is

$$L_z = L_{free} + L_{nm} + L_{pinned} + L_{AF}. \quad (2)$$

Following the results of our recent work [27], we set $L_{free} = L_{pinned} = L_{AF} = 3$ monolayers thick.

In order to investigate the EB properties of the present system, we use the Monte Carlo simulation method based on the improved Metropolis algorithm [37]. For this aim, starting by a high temperature configuration which corresponds to a temperature well above the Curie temperature T_C of ferromagnetic layers such as $T = 3.1J_{FM}/k_B$, the system has been cooled down to a low temperature configuration which is well below the Néel temperature of the AF part under the presence of a cooling magnetic field $\mathbf{h}_{fc}$. The cooled spin configuration obtained after this field cooling process is used as the staring configuration of the decreasing branch of the hysteresis measurement at which the magnetic field is swept from $+\mathbf{h}$ to $-\mathbf{h}$. Once the decreasing field semi-cycle has been completed, the last spin configuration of the process has been recorded and it has been used as the starting configuration for the increasing field branch where the magnetic field cycle is performed from $-\mathbf{h}$ to $+\mathbf{h}$. Bias field value is estimated from obtained hysteresis loop pattern using the relation $H_{EB} = (H_C^+ + H_C^-)/2$ where $H_C^\pm$ represents the coercive fields of increasing and decreasing branches. During the whole process, 2×10^4 Monte Carlo steps (MCSs) (at each temperature for cooling, and at each magnetic field for hysteresis) have been considered whereas the first 50 % of them were discarded for thermalization. Periodic and free boundary con-

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