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The structure dependence of exchange bias in ferromagnetic/antiferromagnetic bilayers*

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The structure dependence of exchange bias in ferromagnetic/antiferromagnetic (FM/AF) bilayers has been investigated in detail by extending Slonczewski's 'proximity magnetism' idea. Here three important parameters are discussed for FM/AF bilayers, i.e. interfacial bilinear exchange coupling J_1, interfacial biquadratic (spin-flop) exchange coupling J_2 and antiferromagnetic layer thickness $t_{\rm AF}$. The results show that both the occurrence and the variety of the exchange bias strongly depend on the above parameters. More importantly, the small spin-flop exchange coupling may result in an exchange bias without the interfacial bilinear exchange coupling. However, in general, the spin-flop exchange coupling cannot result in the exchange bias. The corresponding critical parameters in which the exchange bias will occur or approach saturation are also presented.

Keywords: FM/AF bilayers, exchange coupling, exchange bias
PACC: 7570, 7540M, 7530E, 7550R

1. Introduction

Since the first observation of exchange coupling between a ferromagnet (FM) in atomic contact with antiferromagnet (AF) almost half a century ago,[1] this issue has triggered an enormous number of studies experimental[2−7] and theoretical.[8−13] As a result of interfacial exchange coupling, the hysteresis loop of an FM in contact with an AF is shifted in an applied magnetic field, with respect to that of an isolated FM film by an amount termed the exchange field He. The effect is of great practical value, for it is critical for the operation of high-density recording heads based on giant magnetoresistance (GMR), as well as for magnetic random access memories (MRAM).[14,15] Despite numerous efforts that have been made, a satisfactory understanding of the FM/AF exchange bias is not yet available.

Up to now, many experimental and theoretical results have all shown that the exchange bias He is an interfacial effect, which is closely related to some structural parameters in the FM/AF,[4,16] such as FM/AF interface roughness denoted with interfacial bilinear exchange coupling J_1 and interfacial biquadratic (spin-flop) exchange coupling J_2, antiferromagnetic layer thickness $t_{\rm AF}$, etc. Xi and White[16] have presented the AF thickness dependence of the exchange bias by describing the reversible and irreversible behaviours of the AF in a simple FM/AF model without J_2. However, due to the frustration of spin configurations at the interface, the interfacial FM moments tend to align themselves perpendicular to AF easy axis. Experimentally, there have existed several systems exhibiting biquadratic coupling at the interface between FM and AF layers.[4,17] In recent years, some investigations on the role of the 'spin-flop' coupling in FM/AF have been carried out, which has been theoretically discussed first by Koon[18] and later by Schulthess and Butler,[19] but their results on whether the 'spin-flop' coupling leads to exchange bias are contrary to each other. More recently, Hu *et al* [20] have concluded that He is mainly determined by J_1, but J_2 may lower the exchange bias by establishing a phenomenological model. In their model the interface exchange coupling includes both J_1 and J_2, but the short-range exchange coupling in bulk of AF is ignored. In reality, the AF has a finite thickness in the FM/AF, thus the AF inner exchange coupling should

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be taken into account.[21] From the above, though some structure parameter dependencies of exchange bias in FM/AF bilayers have been studied separately, neither the interface exchange coupling J_1, J_2 and AF thickness dependence of exchange bias nor the corresponding critical parameters determining the occurrence and the saturation of exchange bias have been presented.

Recently, we have investigated the behaviour of an FM/AF bilayer by taking into account both the short-range AF inner exchange coupling and the interfacial exchange coupling including bilinear and biquadratic terms.[13] According to our model, we can describe the four possible phases for the AF magnetization, which are determined by J_1, J_2 and $t_{\rm AF}$. The origins of the exchange bias (He) and the enhanced coercivity (Hc) each have been explained. It shows that only in the reversible recovering phase can the FM/AF interfacial exchange coupling result in the exchange bias. The results also show that there is a critical biquadratic coupling constant $J_{2\rm crit}$, under which the FM/AF bilayer system has exchange bias, otherwise, the exchange bias is eliminated. Specially, only can small J_2 result in positive exchange bias without J_1, which, however, cannot lead to the exchange bias. The structure dependence of He and corresponding critical parameters are presented in this article.

The rest of this paper is organized as follows. Section 2 is devoted to the theoretical model and the general formulas. The relevant numerical results and discussion about structure dependence of the exchange bias are presented in Section 3. Finally, a brief conclusion is given in Section 4.

2. Model

We first describe the geometrical arrangement and magnetic configuration for an exchange-coupled AF/FM bilayer model. An early theoretical study has shown that there is no helical structure along the thickness direction in a thin enough FM layer exchange coupled with an AF layer.[22] Parkin *et al* [23] have observed a uniform magnetization distribution throughout the thickness of a 40 nm $Ni_{80}Fe_{20}$ layer coupled with a $Fe_{50}Mn_{50}$ layer. Therefore, we assume that the FM moments rotate uniformly in the presence of an applied field. In our model, uniaxial magnetocrystalline anisotropy is assumed for the AF layer to have a thickness of $t_{\rm AF}$, while bilinear and biquadratic

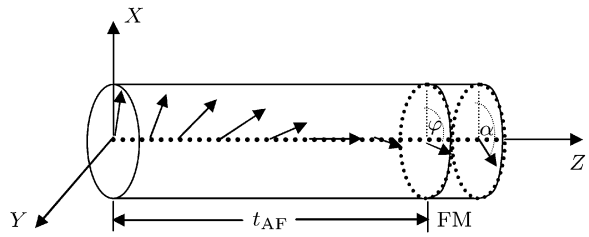


Fig.1. Schematic representation of the helical structure of AF moments with right end exchange coupled with FM. The angles are indicated in text.

couplings at the interface are taken into account. Figure 1 shows the magnetic moment configuration for an AF/FM bilayer film that lies in the $x-y$ plane with the z axis normal to the layer plane. The arrow at right end represents the magnetization $M_{\rm FM}$ for the FM, which rotates away from the AF easy axis, the x axis, through an angle of α. The series of arrows inside the AF represent the moments of one sublattice. Owing to the interface exchange coupling and AF inner exchange coupling, a twisting of the AF moments along the thickness direction is expected if the FM magnetization is rotated. Thus the energy including the volume energy of the AF layer and the interfacial exchange coupling energies can be written in a continuum form as

$$\begin{aligned} E_{\rm sw} = \int_0^{t_{\rm AF}} \left[A_{\rm AF} \left(\frac{{\rm d}\varphi}{{\rm d}z} \right)^2 + K_{\rm AF} \sin^2 \varphi \right] {\rm d}z \\ - J_1 \cos(\varphi - \alpha) \mid_{z=t_{\rm AF}} \\ + J_2 \cos^2(\varphi - \alpha) \mid_{z=t_{\rm AF}} , \end{aligned} \tag{1}$$

where $A_{\rm AF}$ and $K_{\rm AF}$ are exchange coupling constant and uniaxial anisotropy constant of the AF layer with a finite thickness of $t_{\rm AF}$, respectively. The moments of the AF layer at the interface are exchange coupled with the FM layers by both bilinear exchange coupling constant J_1 and biquadratic exchange coupling constant J_2. The FM magnetization $M_{\rm FM}$ is assumed to make an angle α with the AF easy axis. The direction of the AF moments varies spatially with z as described by $\varphi(z)$. Using the variational method to minimize the total energy, the AF moment structure is given by the differential equation for $\varphi(z)$ as follows:

$$2A_{\rm AF} \left(\frac{{\rm d}^2\varphi}{{\rm d}z^2} \right) - K_{\rm AF} \sin(2\varphi) = 0, \tag{2}$$

with the boundary conditions

$$\left(\frac{{\rm d}\varphi}{{\rm d}z} \right) \mid_{z=0} = 0$$

and

$$\left(\frac{\mathrm{d}\varphi}{\mathrm{d}z}\right)\Big|_{z=t_{\mathrm{AF}}} = \frac{J_1}{2A_{\mathrm{AF}}}\sin(\varphi-\alpha) - \frac{J_2}{2A_{\mathrm{AF}}}\sin 2(\varphi-\alpha). \quad (3)$$

In our case, the finite AF layer has moments at one end coupled with M_{FM} and moments at the other end freely rotating. To perform the numerical calculation, we transform Eqs.(2) and (3) into discrete forms in steps of $10^{-3}\delta_{\mathrm{w}}$, where $\delta_{\mathrm{w}} = \sqrt{A_{\mathrm{AF}}/K_{\mathrm{AF}}}$. Our results are independent of step size in this regime. In the following section, we present our numerical results for the AF thickness normalized by characteristic domain wall length δ_{w} and energy E_{SW}, and interfacial coupling constants normalized by the domain wall energy parameter $\sigma_{\mathrm{w}} = 2\sqrt{A_{\mathrm{AF}}K_{\mathrm{AF}}}$. Our previous investigation[13] turns out that this system shows four different behaviour, such as reversible recovering behaviour, irreversible half-rotating behaviour, irreversible reversing and irreversible half-reversing behaviour, depending strongly on interfacial bilinear coupling, interfacial biquadratic coupling and the AF thickness. In only the reversible recovering case the exchange coupling between FM and AF can just result in the exchange bias, otherwise, there is no exchange bias for the other cases. Our present aims are both to construct magnetic phase diagrams in terms of AF thickness t_{AF}, interfacial bilinear coupling J_1 and interfacial biquadratic coupling J_2 and to investigate the comprehensive dependences of exchange bias for the above three parameters.

3. Results and discussion

Here we assume that $J_1 < \sigma_{\mathrm{w}}$, for which the reversible transitions of the AF moments may take place, and an exchange bias may exist. Otherwise, the exchange coupling results in a nonbiased hysteresis loop in the exchange biased bilayer. According to a large number of numerical calculations, we can construct magnetic phase diagrams in terms of AF thickness t_{AF}, interfacial bilinear coupling J_1 and interfacial biquadratic coupling J_2 as shown in Fig.2.

There is a dimensional surface, under which the reversible transitions of the AF moments can take place, and the exchange coupling between FM and AF can just result in the exchange bias, otherwise, the irreversible half-rotating behaviour of the AF moments can take place, and there are no exchange bias. In other words, for a certain set of AF thickness t_{AF} and interfacial bilinear coupling J_1, there always exists a critical biquadratic coupling constant, $J_{2\mathrm{crit}}$, only below which can the exchange bias appear. The value of critical $J_{2\mathrm{crit}}$ is determined by both bilinear coupling J_1 and AF thickness t_{AF}, which largely increases with the increase of bilinear coupling J_1, but smoothly decreases with AF thickness t_{AF}. From Fig.2, we can conclude that critical biquadratic coupling constant $J_{2\mathrm{crit}}$ is mainly determined by bilinear coupling J_1, but some modifications come from AF thickness t_{AF}. Therefore, occurrence dependence of the exchange bias will be a comprehensive effect of bilinear coupling J_1, biquadratic coupling J_2 and AF thickness t_{AF}. In reality, the interface is complicated by defects and roughness, and most of AF films are polycrystalline, thus interfacial exchange couplings J_1 and J_2 will be hardly modified by the interface morphology, which would explain why the experimental results on the exchange bias are hardly consistent with each other. However, it is considerably significant that one can choose the FM and AFM layers with suitable magnetic parameters, such as J_1, J_2, and t_{AF} in the design of exchange biased bilayers. Specifically, for the case of J_1=0, when the AF film must be very thin and the interfacial biquadratic coupling must be small enough, the faint positive exchange bias appears, otherwise, there are no exchange bias in the system, which can explain the disagreement between Koon and Schulthess[18,19] on whether the interfacial biquadratic coupling leads to exchange bias.

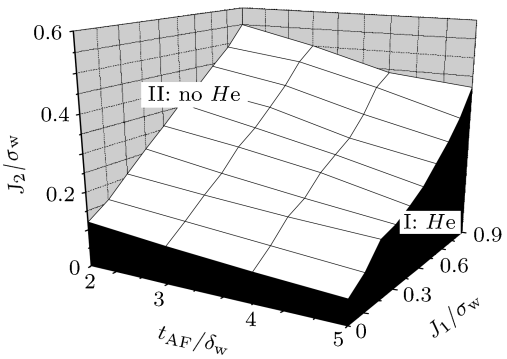


Fig.2. Magnetic phase diagrams in terms of t_{AF}, J_1 and J_2 for an AF/FM bilayer. The dimensional surface separates the nonzero He region I from zero He region II.

For a bilayer system in phase I, a reversible recovering behaviour of the AF moments occurs, leading to a nonzero value of the exchange bias, He, which is obtained as a magnitude of an applied field (Ha) at which M_{FM} becomes perpendicular to the easy axis,

corresponding to M=0 in a hysteresis loop measurement. Therefore, He is given as

$$He = Ha|_{M=0} = \left(\frac{1}{M_{\rm FM}t_{\rm FM}}\right)\left(\frac{{\rm d}E_{\rm SW}}{{\rm d}\alpha}\right)|_{\alpha=\pi/2}, \quad (4)$$

where $t_{\rm FM}$ is the FM layer thickness. The dependencies of the exchange bias on structure parameters, including interfacial J_1, J_2 and AF thickness $t_{\rm AF}$, are shown in Fig.3.

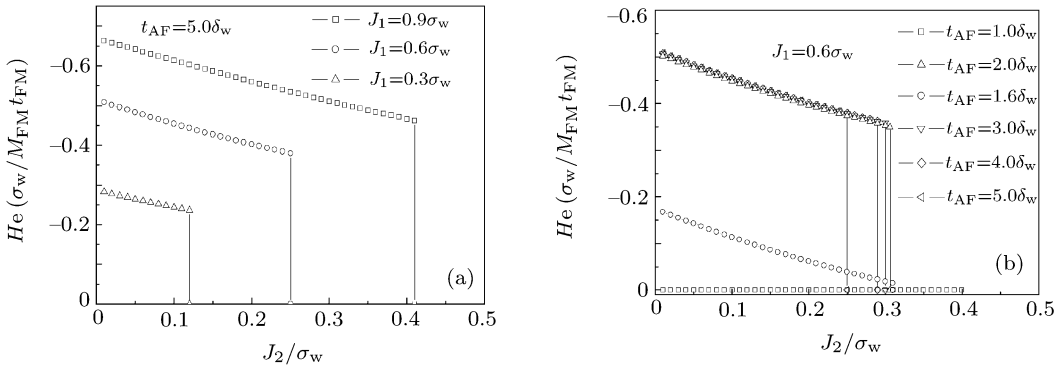


Fig.3. The dependencies of He on interfacial biquadratic coupling J_2 in cases of $t_{\rm AF} = 5.0\delta_{\rm w}$ (a) and $J_1 = 0.6\sigma_{\rm w}$ (b).

According to our example in Fig.3(a) with $t_{\rm AF} = 5.0\delta_{\rm w}$ which is much larger than the critical thickness ($t_{\rm AFcrit}$) determining the occurrence of He, He decreases slightly with the increase of biquadratic coupling J_2 for a given bilinear coupling J_1, but it can be enhanced distinctly by increasing bilinear coupling J_1. As a result, the bilinear and biquadratic couplings are two competitive factors for controlling the value of He, moreover, the exchange bias is determined mainly by the bilinear coupling, whereas the biquadratic coupling may lower or eliminate the exchange bias. This result is in good agreement with the former investigations.[20] In addition, for any bilinear coupling J_1, there exists a corresponding critical biquadratic coupling $J_{2\rm crit}$, above which the exchange bias vanishes abruptly. Form Fig.3(a), we obverse that critical value $J_{2\rm crit}$ increases with the increase of bilinear coupling J_1, which accords with the observed behaviour in Fig.2. As an example, for the $J_1 = 0.6\sigma_{\rm w}$ case in Fig.3(b), there is no exchange bias when $t_{\rm AF} = 1.0\delta_{\rm w}$, which must be less than the critical thickness, $t_{\rm AFcrit}$, mentioned above. He increases rapidly with the increase of AF thickness, approaching a saturated value. The same as the previous experimental and theoretical conclusions on the AF thickness dependence of the exchange bias, our calculations show that an FM/AF bilayer with $t_{\rm AF} < t_{\rm crit}$ results in a nonbiased hysteresis loop, but He approaches rapidly a saturated value with $t_{\rm AF}$ increasing. Furthermore, critical biquadratic coupling $J_{2\rm crit}$ determining the occurrence of He can be improved by reducing AF thickness $t_{\rm AF}$, but the improvement-extent of $J_{2\rm crit}$ decreases with $t_{\rm AF}$ decreasing. According to the above analyses, in order to obtain a bigger He, firstly, we should ensure that thickness $t_{\rm AF}$ is large enough, secondly, we may improve bilinear coupling J_1 or reduce biquadratic coupling J_2. Of course, these three parameters must satisfy the condition of the occurrence of He shown in Fig.2.

4. Summary

We have studied the structure dependence of exchange bias in FM/AF bilayer systems in detail. We find that for a certain set of AF thickness $t_{\rm AF}$ and interfacial bilinear coupling J_1, there always exists a critical biquadratic coupling constant, $J_{2\rm crit}$, only below which can the exchange bias appear. In addition, we conclude that the saturated value of He in an FM/AF bilayer with the thick enough AF increases markedly with bilinear coupling J_1, but slowly decreases with biquadratic coupling J_2, moreover, when $J_2 > J_{2\rm crit}$, He vanishes abruptly. The corresponding critical parameters in which the exchange bias will occur or approach saturation have been also presented. Particularly, J_2 can lead to a positive He without J_1, which is in agreement with the result of Koon,[18] generally, J_2 can weaken or eliminate He and enhance Hc greatly.

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