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The rotational anisotropies in the ferromagnetism/antiferromagnetism 1/ antiferromagnetism 2 exchange bias structures*

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The rotational anisotropies in the exchange bias structures of ferromagnetism/antiferromagnetism 1/antiferromagnetism 2 are studied in this paper. Based on the model, in which the antiferromagnetism is treated with an Ising mean field theory and the rotational anisotropy is assumed to be related to the field created by the moment induced on the antiferromagnetic layer next to the ferromagnetic layer, we can explain why in experiments for ferromagnetism (FM)/antiferromagntism 1 (AFM1)/antiferromagnetism 2 (AFM2) systems the thickness-dependent rotational anisotropy value is non-monotonic, i.e. it reaches a minimum for this system at a specific thickness of the first antiferromagnetic layer and exhibits oscillatory behaviour. In addition, we find that the temperature-dependent rotational anisotropy value is in good agreement with the experimental result.

Keywords: FM/AFM1/AFM2 trilayer, rotational anisotropy, exchange coupling
PACC: 7530G, 7550R, 7570C

1. Introduction

Ferromagnetic (FM)/antiferromagnetic (AFM) bilayered systems are known to exhibit a lot of remarkable phenomena including exchange bias and increased coercivity,[1] training effects,[2] rotational hysteresis at high fields,[2] and rotational anisotropy.[3,4] Up to now, there has been an extensive literature dealing with the above phenomena, and a large number of references can be found in recent publications.[5−17] However, a satisfactory understanding of the above phenomena has not yet been achieved. In this article, we investigate the rotational anisotropy in the exchange bias structures consisting of one ferromagnet and two antiferromagnets, i.e. FM/AFM1/AFM2 structures. After the notation of Prosen, Holmen, and Gran,[3] rotational anisotropy is the anisotropy whose easy axis can be rotated by applying a high magnetic field. The rotatable anisotropy differs from the conventional anisotropy in thin film. The latter anisotropy is called the magnetic annealing anisotropy, in which the easy axis can be rotated only by heating or cooling in a magnetic field. Although it has been shown that the conventional easy axis can also be rotated at room temperature, it requires orders of magnitude more time than it does to remove the rotatable anisotropy. Experiments show that the rotational anisotropy always occurs in the biased ferromagnetic layer, and it decreases with temperature increasing. Recently, in FM/AFM1/AFM2 trilayer the experiment finds that the thickness-dependent rotational anisotropy value is non-monotonic for the first AFM thickness when the second AFM thickness is fixed, i.e. it can reach a minimum for this system at a specific thickness of the first AFM layer and exhibits oscillatory behaviour.[18] In this paper we present a reasonable model of FM/AFM1/AFM2 trilayer in which the interface with the FM layer is compensated while the interface between the two AFM layers is compensated on the AFM1 side and uncompensated on the AFM2 side. By using the mean field theory and assuming that the rotational anisotropy is proportional to the field created by the moment induced on the antiferromagnetic layer next to the ferromagnetic layer, we

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can explain why in experiments for FM/AFM1/AFM2 systems the rotational anisotropy value can reach a minimum at a specific thickness of AFM1 layer and decrease with the increase of temperature. Particularly, the rotational anisotropy value can reach zero at a specific exchange coupling between two AFM layers.

The rest of this paper is organized as follows. Section 2 is devoted to the basic model and the general formulas for resonance field and rotational anisotropy field in the FM/AFM1/AFM2 trilayer system. The relevant numerical results of and discussion about rotational anisotropy are presented in Section 3. Finally, a brief conclusion is given in Section 4.

2. Model

We consider an FM/AFM1/AFM2 trilayer system, in which the FM layer has one monolayer only while the first and the second AFM layers have $N_{1\mathrm{AF}}$ and $N_{2\mathrm{AF}}$ monolayers, respectively. The monolayered spin configuration for the FM/AFM/AFM trilayer is illustrated schematically in Fig.1.

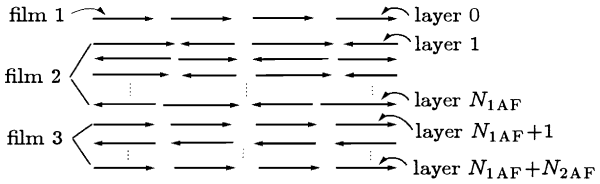


Fig.1. Configuration of FM/AFM1/AFM2 trilayer with the arrows representing the magnetization of each monolayer.

Here the only nearest-neighbour exchange coupling is considered because the next-nearest-neighbour exchange is generally extremely weak. We describe the FM/AFM1/AFM2 trilayer system in terms of isotropic spin Hamiltonian as

$$\begin{aligned} H =& - J'_{\mathrm{IF}} \sum_{<i,j>} S_{i\mathrm{FM}} S_{j1\mathrm{AF}} + J'_{1\mathrm{AF}} \sum_{<i,j>} S_{i1\mathrm{AF}} S_{j1\mathrm{AF}} \\ & - J'_{\mathrm{int}} \sum_{<i,j>} S_{i1\mathrm{AF}} S_{j2\mathrm{AF}} \\ & + J'_{2\mathrm{AF}} \sum_{<i,j>} S_{i2\mathrm{AF}} S_{j2\mathrm{AF}}, \end{aligned} \tag{1}$$

where J'_{IF} and J'_{int} are the interfacial exchange coupling constants between the FM layer and the first AFM layer and between the first and the second AFM layer, respectively. $J'_{1\mathrm{AF}}$ and $J'_{2\mathrm{AF}}$ are the nearest-neighbour exchange interaction constants in the body of the first and second AFM films, respectively. $S_{i\mathrm{FM}}$, $S_{i1\mathrm{AF}}$ and $S_{i2\mathrm{AF}}$ are the spin operators at the i site in the FM, the first and second AFM films, respectively. To be clear, we consider the sublattice separately for AFM layer, defining 'a' lattice as $a\hat{x}$ and 'b' lattice as $-b\hat{x}$ with x-axial unit vector $\hat{x}$. Thus

$$\begin{aligned} H =& - J_{\mathrm{IF}} \sum_{j} S_{\mathrm{FM}} a_{j1\mathrm{AF}} + J_{\mathrm{IF}} \sum_{j} S_{\mathrm{FM}} b_{j1\mathrm{AF}} \\ & - J_{1\mathrm{AF}} \sum_{<i,j>} a_{i1\mathrm{AF}} b_{j1\mathrm{AF}} \\ & - J_{\mathrm{int}} \sum_{<i,j>} a_{i1\mathrm{AF}} a_{j2\mathrm{AF}} + J_{\mathrm{int}} \sum_{<i,j>} b_{i1\mathrm{AF}} a_{j2\mathrm{AF}} \\ & - J_{2\mathrm{AF}} \sum_{<i,j>} a_{i2\mathrm{AF}} b_{j2\mathrm{AF}} \\ & - J_{2\mathrm{AF}} \sum_{<i,j>} a_{i2\mathrm{AF}} a_{j2\mathrm{AF}} \\ & - J_{2\mathrm{AF}} \sum_{<i,j>} b_{i2\mathrm{AF}} b_{j2\mathrm{AF}}, \end{aligned} \tag{2}$$

where J_{IF}, J_{int}, $J_{1\mathrm{AF}}$, and $J_{2\mathrm{AF}}$ are the average values of exchange coupling in the corresponding layers. We define $m_j^+ = (a_j + b_j)/2$, and $m_j = (a_j - b_j)/2$ for the first AFM film, and $m_j^+ = (a_j + b_{j+1})/2$, and $m_j = (a_j - b_{j+1})/2$ for the second film, and denote the label number of monolayer of AFM film by j. Based on the mean field spin calculation, for the first AFM film we can have

$$\begin{aligned} m_1^+ =& 0.5 \tanh \beta(4J_{1\mathrm{AF}} m_1^+ + J_{1\mathrm{AF}} m_2^+ + J_{\mathrm{IF}} s_{\mathrm{FM}}) \\ & + 0.5 \tanh \beta(4J_{1\mathrm{AF}} m_1^+ + J_{1\mathrm{AF}} m_2^+), \end{aligned} \tag{3}$$

$$\begin{aligned} m_1 =& - 0.5 \frac{\beta(4J_{1\mathrm{AF}} m_1 + J_{1\mathrm{AF}} m_2)}{\cosh^2 \beta(4J_{1\mathrm{AF}} m_1^+ + J_{1\mathrm{AF}} m_2^+ + J_{\mathrm{IF}} s_{\mathrm{FM}})} \\ & + 0.5 \frac{\beta(J_{\mathrm{IF}} s_{\mathrm{FM}} - 4J_{1\mathrm{AF}} m_1 - J_{1\mathrm{AF}} m_2)}{\cosh^2 \beta(4J_{1\mathrm{AF}} m_1^+ + J_{1\mathrm{AF}} m_2^+)}. \end{aligned} \tag{4}$$

If $j = N_{1\mathrm{AF}} = 1$ then

$$\begin{aligned} m_1^+ =& 0.5 \tanh \beta(4J_{1\mathrm{AF}} m_1^+ + J_{\mathrm{int}} m_2^+ + J_{\mathrm{IF}} s_{\mathrm{FM}}) \\ & + 0.5 \tanh \beta(4J_{1\mathrm{AF}} m_1^+), \end{aligned} \tag{5}$$

$$\begin{aligned} m_1 =& - 0.5 \frac{\beta(4J_{1\mathrm{AF}} m_1 + J_{\mathrm{int}} m_2)}{\cosh^2 \beta(4J_{1\mathrm{AF}} m_1^+ + J_{\mathrm{int}} m_2^+ + J_{\mathrm{IF}} s_{\mathrm{FM}})} \\ & + 0.5 \frac{\beta(J_{\mathrm{IF}} s_{\mathrm{FM}} - 4J_{1\mathrm{AF}} m_1 + J_{\mathrm{int}}(m_2^+ + m_2))}{\cosh^2 \beta(4J_{1\mathrm{AF}} m_1^+)}. \end{aligned} \tag{6}$$

But

$$m_2^+ = \tanh\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+ + J_{1\mathrm{AF}}m_3^+), \tag{7}$$

$$m_2 = -\frac{\beta(J_{1\mathrm{AF}}m_1 + 4J_{1\mathrm{AF}}m_2 + J_{1\mathrm{AF}}m_3)}{\cosh^2\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+ + J_{1\mathrm{AF}}m_3^+)}. \tag{8}$$

If $j = N_{1\mathrm{AF}} = 2$, then

$$\begin{aligned} m_2^+ =& 0.5\tanh\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+ + J_{\mathrm{int}}m_3^+) \\ &+ 0.5\tanh\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+), \end{aligned} \tag{9}$$

$$\begin{aligned} m_2 =& -0.5\frac{\beta(J_{1\mathrm{AF}}m_1 + 4J_{1\mathrm{AF}}m_2 - J_{\mathrm{int}}m_3)}{\cosh^2\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+ + J_{\mathrm{int}}m_3^+)} \\ &+ 0.5\frac{\beta(-J_{\mathrm{AF}}m_1 - 4J_{1\mathrm{AF}}m_2 + J_{\mathrm{int}}(m_3^+ + m_3))}{\cosh^2\beta(J_{1\mathrm{AF}}m_1^+ + 4J_{1\mathrm{AF}}m_2^+)}, \end{aligned} \tag{10}$$

otherwise

$$m_j^+ = \tanh\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+ + J_{1\mathrm{AF}}m_{j+1}^+), \tag{11}$$

$$m_j = -\frac{\beta(J_{1\mathrm{AF}}m_{j-1} + 4J_{1\mathrm{AF}}m_j + J_{1\mathrm{AF}}m_{j+1})}{\cosh^2\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+ + J_{1\mathrm{AF}}m_{j+1}^+)}. \tag{12}$$

If $j = N_{1\mathrm{AF}}$, then

$$\begin{aligned} m_j^+ =& 0.5\tanh\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+ + J_{\mathrm{int}}m_{j+1}^+) \\ &+ 0.5\tanh\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+), \end{aligned} \tag{13}$$

$$\begin{aligned} m_j =& -0.5\frac{\beta(J_{1\mathrm{AF}}m_{j-1} + 4J_{1\mathrm{AF}}m_j - J_{\mathrm{int}}m_{j+1})}{\cosh^2\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+ + J_{\mathrm{int}}m_{j+1}^+)} \\ &+ 0.5\frac{\beta(-J_{1\mathrm{AF}}m_{j-1} - 4J_{1\mathrm{AF}}m_j + J_{\mathrm{int}}(m_{j+1}^+ + m_{j+1}))}{\cosh^2\beta(J_{1\mathrm{AF}}m_{j-1}^+ + 4J_{1\mathrm{AF}}m_j^+)}. \end{aligned} \tag{14}$$

Similarly, for the second AFM film we can have

$$\begin{aligned} m_j^+ =& 0.5\tanh\beta(J_{2\mathrm{AF}}m_{j-2}^+ + 5J_{2\mathrm{AF}}m_j^+) \\ &+ 0.5\tanh\beta(5J_{2\mathrm{AF}}m_j^+ + J_{2\mathrm{AF}}m_{j+2}^+), \end{aligned} \tag{15}$$

$$\begin{aligned} m_j =& -0.5\frac{\beta(J_{2\mathrm{AF}}m_{j-2} - 3J_{2\mathrm{AF}}m_j)}{\cosh^2\beta(J_{2\mathrm{AF}}m_{j-2}^+ + 5J_{2\mathrm{AF}}m_j^+)} \\ &+ 0.5\frac{\beta(3J_{2\mathrm{AF}}m_j - J_{2\mathrm{AF}}m_{j+2})}{\cosh^2\beta(5J_{2\mathrm{AF}}m_j^+ + J_{2\mathrm{AF}}m_{j+2}^+)}. \end{aligned} \tag{16}$$

If $j = N_{1\mathrm{AF}} + 1$, then

$$\begin{aligned} m_j^+ =& 0.5\tanh\beta(5J_{2\mathrm{AF}}m_j^+) \\ &+ 0.5\tanh\beta(J_{2\mathrm{AF}}m_j^+ + J_{2\mathrm{AF}}m_{j+2}^+), \end{aligned} \tag{17}$$

$$\begin{aligned} m_j =& 0.5\frac{\beta(J_{\mathrm{int}}m_{j-1} + 3J_{2\mathrm{AF}}m_j)}{\cosh^2\beta(5J_{2\mathrm{AF}}m_j^+)} \\ &+ 0.5\frac{\beta(3J_{2\mathrm{AF}}m_j - J_{2\mathrm{AF}}m_{j+2})}{\cosh^2\beta(5J_{2\mathrm{AF}}m_j^+ + J_{2\mathrm{AF}}m_{j+2}^+)}, \end{aligned} \tag{18}$$

where $\beta = 1/(k_{\mathrm{B}}T)$, s_{FM} is the magnetization of FM film per unit area. In spherical coordinates, the total energy per unit area for the trilayer system in the presence of a magnetic field can be given by

$$\begin{aligned} E_{\mathrm{T}} =& (K_\perp - 2\pi M_{\mathrm{s}}^2)\sin^2\phi_{\mathrm{FM}} \\ &+ \frac{K_{||}}{4}(\sin^2 2\phi_{\mathrm{FM}} + \sin^4\phi_{\mathrm{FM}}\cos^2 2\theta_{\mathrm{FM}}) \\ &+ K_{\mathrm{u}}\sin^2\phi_{\mathrm{FM}}\sin^2\theta_{\mathrm{FM}} \\ &- J_{\mathrm{int}}m_1M_{\mathrm{s}}\sin\phi_{\mathrm{FM}}\cos\theta_{\mathrm{FM}} \\ &- HM_{\mathrm{s}}\sin\phi_{\mathrm{FM}}\cos(\theta_{\mathrm{H}} - \theta_{\mathrm{FM}}). \end{aligned} \tag{19}$$

The first term on the right-hand side of the above expression is the effective demagnetizing energy, where $2\pi M_{\mathrm{s}}^2$ is the out-of-plane demagnetization factor and $K_\perp$ a uniaxial anisotropy in the direction normal to the film plane. M_{s} is the magnitude of s_{FM}. The second and third terms are the fourfold and uniaxial anisotropy energy with anisotropy constants $K_{||}$ and

$K_{\rm u}$, respectively. The fourth term is the exchange coupling in the interface between the FM and the first AFM films. The last term is a Zeeman energy. The uniaxial anisotropy axis is oriented in the x-direction. The magnetic field is assumed to be applied in the $x-y$ plane with an angle $\theta_{\rm H}$ to the x-axis; the angles $\phi_{\rm FM}$ and $\theta_{\rm FM}$ are the polar angle to the z-axis and the azimuthal angle to the x-axis for the FM moment, respectively.

According to the theory presented by Smith and Beljers,[19] the resonance field can be determined from $E_{\rm T}$ as

$$\left(\frac{\omega}{\gamma}\right)^2 = \frac{1}{M_{\rm s}^2 \sin^2\phi_{\rm FM}}\left[\frac{\partial^2 E_{\rm T}}{\partial^2\phi_{\rm FM}}\frac{\partial^2 E_{\rm T}}{\partial^2\theta_{\rm FM}} - \left(\frac{\partial^2 E_{\rm T}}{\partial\phi_{\rm FM}\partial\theta_{\rm FM}}\right)^2\right]. \tag{20}$$

Here ω is the microwave driving frequency, and γ the gyromagnetic ratio.

According to Eq.(20), we can have the resonance field for the FM/AFM1/AFM2 trilayer system in a high field applied as follows:

$$\begin{aligned} H_{\rm res} = &\left\{\left[2\pi M_{\rm eff} + \frac{H_{||}}{8}(3-5\cos 4\theta_{\rm H}) + \frac{H_{\rm u}}{4}(1+3\cos 2\theta_{\rm H})\right]^2 + \left(\frac{\omega}{\gamma}\right)^2\right. \\ &\left. + \left[4\pi M_{\rm eff} + \frac{H_{||}}{4}(3-\cos 4\theta_{\rm FM}) + \frac{H_{\rm u}}{2}(1+\cos 2\theta_{\rm FM})\right](H_{||}\cos 4\theta_{\rm H} - H_{\rm u}\cos 2\theta_{\rm H})\right\}^{1/2} \\ &- 2\pi M_{\rm eff} + \frac{H_{||}}{8}(5\cos 4\theta_{\rm H} - 3) - \frac{H_{\rm u}}{4}(1+3\cos 2\theta_{\rm H}) + H_{\rm int}\cos\theta_{\rm H} - H_{\rm rot}. \end{aligned} \tag{21}$$

On the other hand, for the singular FM layer system we have

$$\begin{aligned} H_{\rm res} = &\left\{\left[2\pi M_{\rm eff} + \frac{H_{||}}{8}(3-5\cos 4\theta_{\rm H}) + \frac{H_{\rm u}}{4}(1+3\cos 2\theta_{\rm H})\right]^2 + \left(\frac{\omega}{\gamma}\right)^2\right. \\ &\left. + \left[4\pi M_{\rm eff} + \frac{H_{||}}{4}(3-\cos 4\theta_{\rm FM}) + \frac{H_{\rm u}}{2}(1+\cos 2\theta_{\rm FM})\right](H_{||}\cos 4\theta_{\rm H} - H_{\rm u}\cos 2\theta_{\rm H})\right\}^{1/2} \\ &- 2\pi M_{\rm eff} + \frac{H_{||}}{8}(5\cos 4\theta_{\rm H} - 3) - \frac{H_{\rm u}}{4}(1+3\cos 2\theta_{\rm H}), \end{aligned} \tag{22}$$

where $4\pi M_{\rm eff} = 4\pi M_{\rm s} - 2K_{\perp}/M_{\rm s}$, $H_{||} = 2K_{||}/M_{\rm s}$, $H_{\rm u} = 2K_{\rm u}/M_{\rm s}$ and $H_{\rm int} = J_{\rm int}m_1$ called the exchange coupling field. The parameter m_1 is determined by expressions(3)–(18) self-consistently. $H_{\rm res}$ and $H_{\rm rot}$ are called the resonance and rotational anisotropy field, respectively. According to Ref.[20], by comparing the expression (21) with the expression (22) we can obtain the rotational anisotropy field.

3. Discussion and results

For the FM/AFM1/AFM2 trilayer system, for simplicity we assume that the FM layer is isotropic in calculation below. Experimentally it was found that the rotational anisotropy value oscillates with the thickness $N_{\rm 1AF}$ of the first AFM film when the second AFM film is fixed.[18] Based on our above model we can have similar results as shown in Fig.2; with the increase of the thickness of the first AFM film the rotational anisotropy of the system first decreases and then increases , showing the oscillatory behaviour. The corresponding temperature-dependent rotational anisotropy value is shown in Fig.3, which is in agreement with the experimental result.[18] However the behaviour of the dependence of the rotational anisotropy upon thickness of the first AFM film distinctly depends on $J_{\rm 1AF}/J_{\rm 2AF}$. With the increase of $J_{\rm 1AF}/J_{\rm 2AF}$, the oscillatory behaviour will evanesce as shown in Fig.4. Figures 4 and 5 both show the rotational anisotropy field decreasing with the increase of the first AFM thickness and the temperature. We find that the results in Fig.4 significantly differ from those in Fig.2 while the trends of curves in Figs.3 and 5 are similar to each other.

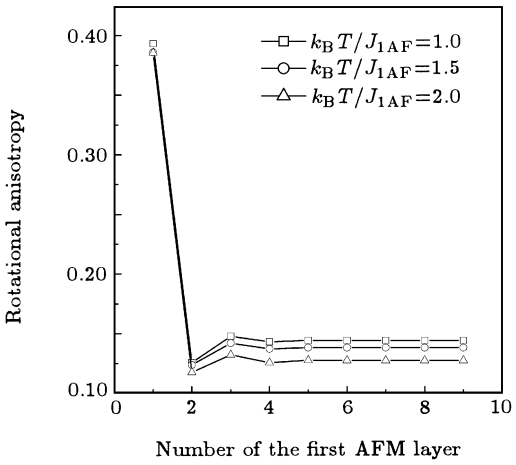


Fig.2. The rotational anisotropy $H_{\rm rot}$ vs thickness $N_{1\rm AF}$ of the first AFM film of the system, where $J_{\rm IF}$=1.8, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=2.0, $J_{\rm int}$=1.5, rotational anisotropy is in arbitrary units (the same below).

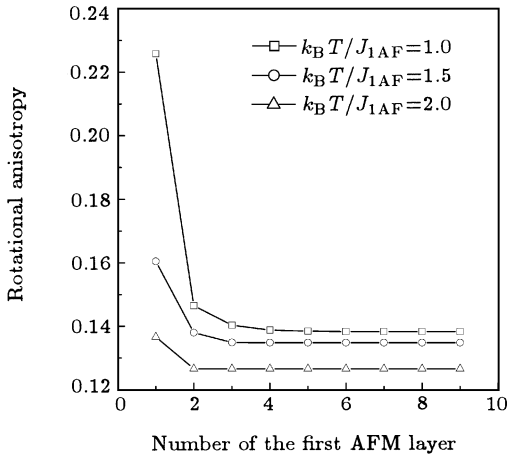


Fig.4. The rotational anisotropy $H_{\rm rot}$ vs thickness of the first AFM film of the system, where $J_{\rm IF}$=3.0, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=0.34, $J_{\rm int}$=0.58.

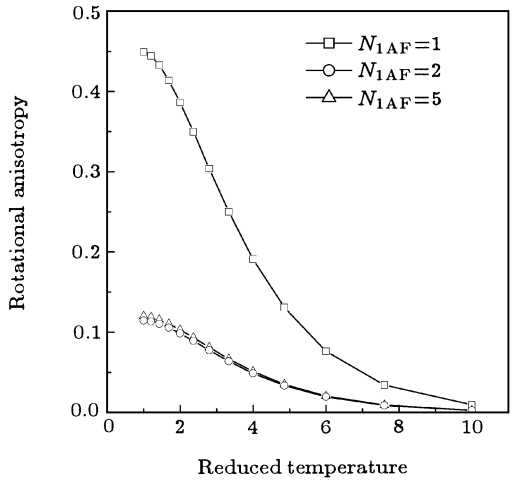


Fig.3. The rotational anisotropy $H_{\rm rot}$ vs the temperature ($k_{\rm B}T/J_{1\rm AF}$) of the system, where $J_{\rm IF}$=1.8, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=2.0, $J_{\rm int}$=1.5, here temperature is in arbitrary units (as below).

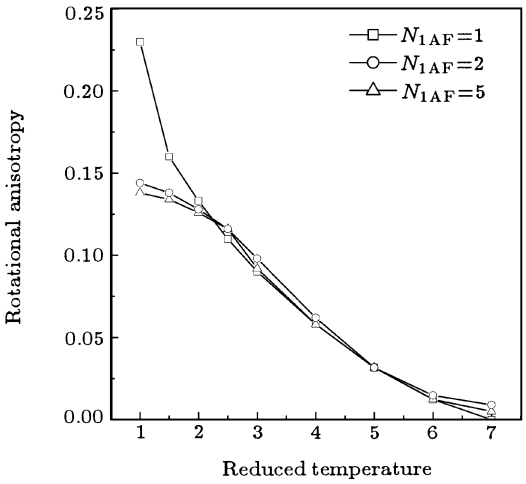


Fig.5. The rotational anisotropy $H_{\rm rot}$ vs the temperature ($k_{\rm B}T/J_{1\rm AF}$) of the system, where $J_{\rm IF}$=3.0, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=0.34, $J_{\rm int}$=0.58.

In order to understand why in experiments for ferromagnet (FM) / antiferromagnet 1 (AFM1) / antiferromagnet 2 (AFM2) systems the thickness-dependent rotational anisotropy value is non-monotonic,i.e.it reaches a minimum for this system at a specific thickness of the first antiferromagnetic layer and exhibits oscillatory behaviour, we calculate the net magnetization in the interface between the FM film and the first AFM layer and each monolayer's magnetization in the AFM film. We find that, in a limited thickness range for the first AFM film, the net magnetization in the interface between the FM film and the first AFM layer has a similar behaviour to the above, namely the rotational anisotropy varies with the increase of the thickness of the first AFM film due to the fact that monolayer's magnetic configuration is frustrated by competing between the interface FM coupling between FM and AFM films and the inner AFM coupling in the AFM film. In this case, for the monolayer in AFM film, the arrangement of site magnetization cannot completely meet the demand of antiferromagnetic matching between the nearest-neighbour sites, which will bring about the net magnetization for the compensated AFM monolayer. The net magnetization of each monolayer in the AFM film is shown in Fig.6, which depends on the competing between the inter-

face FM coupling between the FM and AFM films and the inner AFM coupling in the AFM film. It is seen from Fig.6 that the net magnetization of each monolayer in the first AFM film can increase or decrease even its direction is parallel or antiparallel to the x-direction, which is dependent upon the thickness of the first AFM film influencing the coupling strength of the inner AFM and the magnetic parameters of the system varying with the coupling strength of the interface FM, although the net magnetizations of the first and last monolayers in the interfaces between the FM layer and the first AFM film and between the first and the second AFM films always direct to the positive x-direction. Thus the net magnetization in the interface between the FM film and the first AFM layer will increase or decrease with the thickness of the first AFM film and the magnetic parameters of the system varying. As a result, the behaviour of the rotational anisotropy strongly depends on the coupling strengths between the FM layer and the AFM layer and between the first AFM layer and the second AFM layer. On the other hand, with temperature increasing the antiferromagnetic spin configuration becomes nonstatic and changes, which results in the rotational anisotropy decreasing with temperature increasing. Particularly, we find that the increasing of $J_{\rm int}$can cause the rotational anisotropy to reach zero in dip position as shown in Fig.7. Further calculation shows that the rotational anisotropy decreases linearly with the increase of $J_{\rm int}$

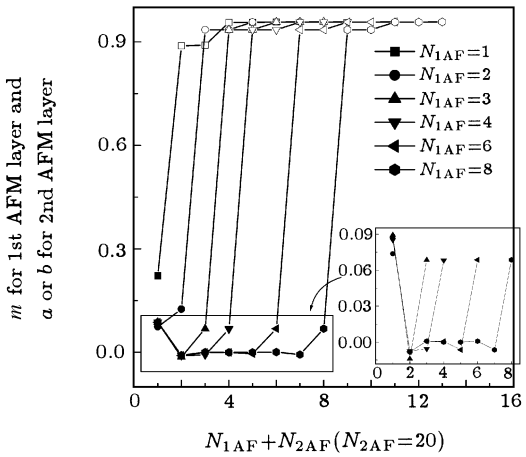


Fig.6. The calculated monolayer's net magnetization in the first AFM films (denoted by m with solid symbolic lines) and the second AFM film (the figure shows only monolayer magnetization from 1 to 5 for the second AFM layer denoted by a or b by open symbolic lines), where $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=2.0, $J_{\rm IF}$=1.8, $J_{\rm int}$=1.5, $k_{\rm B}T/J_{1\rm AF}$=3.0, magnetization is in arbitrary units.

as shown in Fig.8. In addition, when the next-nearest-neighbour exchange couplings are considered, the rotational anisotropy distinctly increases. Meanwhile the oscillatory behaviour of the thickness-dependent rotational anisotropy may become prominent but the rotational anisotropy more quickly decreases with temperature increasing.

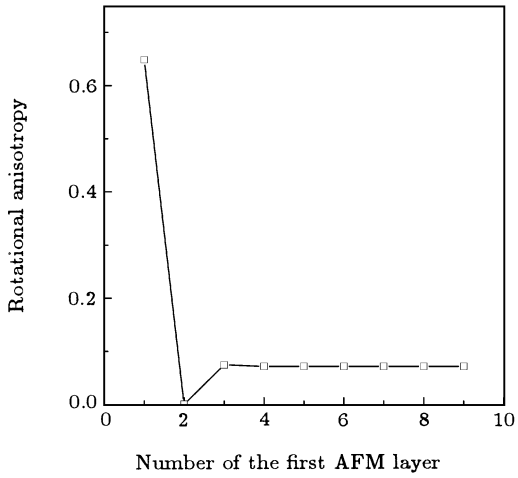


Fig.7. The rotational anisotropy $H_{\rm rot}$ vs thickness of the first AFM film of the system, where $J_{\rm IF}$=2.0, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=2.0, $J_{\rm int}$=5.5.

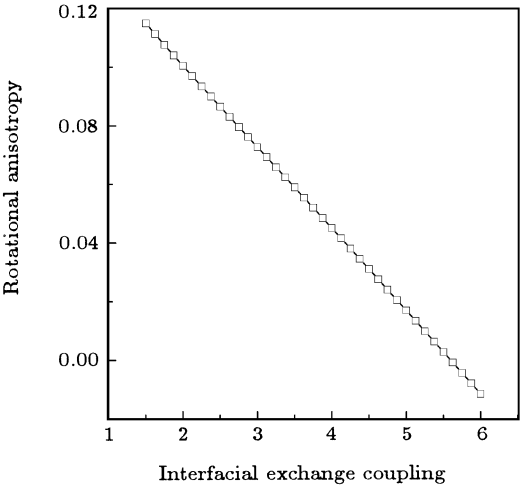


Fig.8. The rotational anisotropy $H_{\rm rot}$ vs interfacial exchange coupling of the system, where $J_{\rm IF}$=2.0, $J_{1\rm AF}$=1.0, $J_{2\rm AF}$=2.0, $N_{1\rm AF}$=2, $N_{2\rm AF}$=20, $k_{\rm B}T/J_{1\rm AF}$=4.0.

4. Conclusions

Based on our model, the thickness-dependent rotational anisotropy exhibits a dip and oscillatory behaviour. The reason for that is that the frustration of the magnetization in the AFM layer happens because of a sort of compensation created by competition between coupling to the ferromagnet and coupling to the

second antiferromagnet. On the other hand, the rotational anisotropy decreases with the increase of the temperature, which is due to the fact that the antiferromagnetic spin configuration is changed. The calculation also shows that the behaviour of dependence of rotational anisotropy upon the first AFM thickness in the FM/AFM1/AFM2 system closely depends on the interfacial exchange coupling and is related to the nonstatic antiferromagnetic spin configurations, which are determined by the AFM atomic level structure and their spin favour.

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