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Spin configurations in the absence of an external magnetic field in a magnetic bilayer with in-plane cubic or uniaxial anisotropies

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Abstract

The spin configurations in the absence of an external magnetic field have been systematically investigated for a magnetic bilayer system consisting of two ferromagnetic layers separated by a non-magnetic layer with interlayer exchange coupling. Based on a phenomenological model, the conditions for the existence of collinear and non-collinear spin structures were derived for three kinds of magnetic bilayers with different combinations of in-plane cubic and uniaxial anisotropies for the two ferromagnetic layers. The phase diagrams of the spin configurations at zero field were drawn, taking into account the lowest-order anisotropy parameters of both the ferromagnetic layers. The values of the canting angle have been derived analytically and then numerically plotted. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The ultrathin films, multilayers and superlattices have attracted extensive attention over the last decade on both experimental and theoretical aspects [1–5]. By growth techniques such as molecular beam epitaxy (MBE), an extraordinarily high quality of thin magnetic films and layered system can be obtained with nearly perfect crystals and layered structures. Film thickness may reach a few or even one atomic layer. It is natural, that such a high quality of the new magnetic systems results in the discovery of many static magnetic properties which contain valuable information about the intrinsic magnetism of layered structures. One feature of these layer structures is the well-known oscillatory interlayer exchange coupling between the adjacent ferromagnetic layers through the non-magnetic layer [6,7]. Several mechanisms have been proposed for this oscillation, including the dipolar and

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Ruderman–Kittel–Kasuya–Yosida (RKKY) interactions as well as the quantum well [8–10]. The strength of the interlayer coupling is quite weak as compared with that of the intersublattice exchange in bulk materials. But the ratio of interlayer exchange energy to anisotropy energy lies in the range 10^{-2}–10^{2}. Therefore, the competition between the exchange energy and the anisotropy energy also exists in the layer structures, which plays an important role in determining the spin arrangements.

Dieny et al. [11,12] have phenomenologically studied the magnetic behaviour of magnetic bilayer systems of cubic and uniaxial in-plane anisotropies with assumed antiferromagnetic coupling between adjacent identical ferromagnetic layers. What would happen if the magnetic bilayer consists of two distinct ferromagnetic layers, which possess different magnetizations and anisotropies? This work extends the magnetic bilayer system to a general case, and systematically investigates the spin configurations in the absence of an external magnetic field for this bilayer system, which is dependent on the competition between the strengths of the exchange coupling and the anisotropies. Moreover, the phase diagrams for different spin configurations have been drawn out for three kinds of magnetic bilayers with different combinations of in-plane cubic and uniaxial anisotropies. This method has even been successfully used in our previous work on the two-sublattice system [13,14].

2. Model

The magnetic bilayer system to be studied in what follows can be defined by the free-energy expression

$$E = JM_{\mathrm{A}}M_{\mathrm{B}}\cos\alpha + E_{\mathrm{A}}(\theta_{\mathrm{A}}) + E_{\mathrm{B}}(\theta_{\mathrm{B}}), \tag{1}$$

where J represents the interlayer exchange coupling between two ferromagnetic layers. A positive value of J favours antiparallel alignment (ferrimagnetic coupling), whereas a negative J favours a parallel one (ferromagnetic coupling). M_{A} and M_{B} denote the magnitude of the magnetization of layers A and B, respectively. It is postulated that each ferromagnetic layer is single-domain and single crystal and that the easy axes of magnetization of both layers are parallel to each other. Moreover, it is assumed that strong shape and/or negative perpendicular anisotropy confines the magnetic moments of both layers to the film planes. Fig. 1 schematically represents the configuration of this magnetic bilayer model. The assumptions correspond to the situation in magnetic bilayer with (0 0 1)-type growth. α is the angle between the moments of the two layers. E_{A} and E_{B} are the anisotropy energies of the layers A and B, respectively. The anisotropy energy is set by $K_1\cos^2\theta\sin^2\theta$ for the cubic case and $K_u\sin^2\theta$ for the uniaxial case with θ the angle of the magnetization of each layer with respect to the easy direction. If we use a convention allowing for negative values of θ_{A} and θ_{B}, then θ_{B} can be substituted by $\theta_{\mathrm{A}} + \alpha$, so the model can be studied in terms of only two independent variables, θ_{A} and α.

The equilibrium state is found by minimizing Eq. (1) with respect to the angles θ_{A} and α. Detecting the minima of Eq. (1) involves the first and second partial derivatives of the free energy with respect to the angles θ_{A} and α:

$$\frac{\partial E}{\partial \theta_{\mathrm{A}}} = 0, \tag{2}$$

$$\frac{\partial E}{\partial \alpha} = 0, \tag{3}$$

$$\Delta = \frac{\partial^2 E}{\partial \theta_{\mathrm{A}}^2}\frac{\partial^2 E}{\partial \alpha^2} - \left(\frac{\partial^2 E}{\partial \theta_{\mathrm{A}}\partial \alpha}\right)^2 > 0, \tag{4}$$

$$\frac{\partial^2 E}{\partial \theta_{\mathrm{A}}^2} > 0. \tag{5}$$

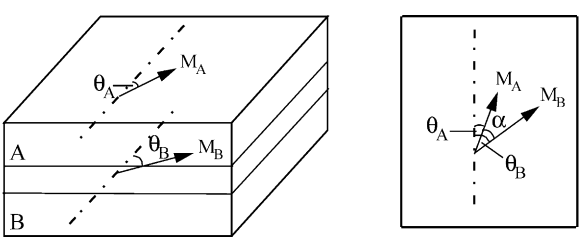

Fig. 1. Model of a magnetic bilayer system consisting of two ferromagnetic layers A and B, separated by an interlayer. On the right side is the vertical view, and the dashed lines are the easy axes of magnetization.

The solutions of Eqs. (2) and (3) satisfying the inequalities (4) and (5) correspond to the local minima of the free energy. We shall choose the one corresponding to the lowest minima of the free energy to determine the resulting moment orientations.

3. Spin configurations

In this section, we investigate the possible stable spin configurations of the magnetic bilayer model in three cases which correspond to the possible combinations of the cubic and uniaxial anisotropies for each layer. In each case, only the lowest-order term of the anisotropy energies is taken into account.

3.1. Two cubic in-plane anisotropies

First, we consider the case where both the layers have cubic in-plane anisotropy. Eq. (1) can be rewritten as follows:

$$E = JM_AM_B\cos\alpha + K_{1A}\cos^2\theta_A\sin^2\theta_A + K_{1B}\cos^2(\theta_A+\alpha)\sin^2(\theta_A+\alpha). \quad (6)$$

For simplicity, the relative magnitude of the interlayer exchange and the anisotropy energies and the ratio of the two anisotropy energies are defined as x and y, respectively:

$$x = \frac{JM_AM_B}{K_{1A}}, \quad y = \frac{K_{1B}}{K_{1A}}. \quad (7)$$

Making a convenience of this notation, Eqs. (2) and (3) and inequalities (4) and (5) can be expanded and reduced to

$$\sin 4\theta_A + y\sin 4(\theta_A+\alpha) = 0, \quad (8)$$

$$-2x\sin\alpha + y\sin 4(\theta_A+\alpha) = 0, \quad (9)$$

$$\Delta = 2K_{1A}^2[-x\cos\alpha\cos 4\theta_A + y(2\cos 4\theta_A - x\cos\alpha)\cos 4(\theta_A+\alpha)] > 0, \quad (10)$$

$$\frac{\partial^2 E}{\partial\theta_A^2} = 2K_{1A}[\cos 4\theta_A + y\cos 4(\theta_A+\alpha)] > 0. \quad (11)$$

A collinear spin configuration will always satisfy Eqs. (7) and (8), because for $\alpha = 0, \pi$ and $\theta_A = 0, \pi/4, \pi/2, 3\pi/4$, every term in both equations vanishes. To investigate whether such solutions indeed correspond to energy minima one has to turn to the criterion $\Delta > 0$ and $\partial^2E/\partial\theta_A^2 > 0$, which ensures the existence of a minimum. If under certain conditions, multiple solutions satisfy the criterion, the one corresponding to the lowest energy minimum will be effective. Therefore, provided $K_{1A} > 0$, combining inequalities (10) and (11) for $\alpha = 0, \pi$ and $\theta_A = 0, \pi/4, \pi/2, 3\pi/4$ gives collinear configurations in four regions.

I. For $\alpha = 0$, $\theta_A = 0, \pi/2$:
$y > -1$ and $x < 0$ and $x < 2y/(1+y)$;
II. For $\alpha = 0$, $\theta_A = \pi/4, 3\pi/4$:
$y < -1$ and $x < -2y/(1+y)$;
III. For $\alpha = \pi$, $\theta_A = 0, \pi/2$:
$y > -1$ and $x > 0$ and $x > -2y/(1+y)$;
IV. For $\alpha = \pi$, $\theta_A = \pi/4, 3\pi/4$:
$y < -1$ and $x > 2y/(1+y)$.

In the case of $K_{1A} < 0$, we can also observe these four regions, but the collinear configurations in them are interchanged symmetrically about the origin. In Fig. 2 these results are summarized, four curves and the positive y-axis separate the four regions. In each case, there are always two different spin configurations as the consequence of the biaxial symmetry of the cubic anisotropy. The central part of the phase diagram delineated by the borderlines of the collinear regions undoubtedly represents non-collinear spin arrangements where one shall be only interested in the value of the canting angle α. In order to reveal the dependence of the canting angle on x and y, one has to solve Eqs. (8) and (9). To get the solutions of Eqs. (8) and (9), we first subtract Eq. (9) from Eq. (8) to obtain

$$\sin 4\theta_A + 2x\sin\alpha = 0 \quad (12)$$

and use this result to eliminate θ_A from Eq. (9), and remove the common term $\sin\alpha$ ($\sin\alpha \neq 0$) to obtain

$$x[1 + y(1 - 2\sin^2 2\alpha)] = 2y\cos\alpha\sqrt{(1-4x^2\sin^2\alpha)(1-\sin^2 2\alpha)}. \quad (13)$$

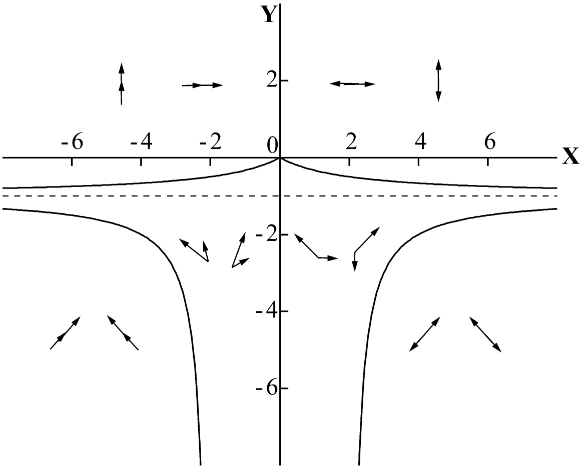

Fig. 2. Phase diagrams of the different spin configurations of a magnetic bilayer in the absence of an external field ($K_{1A} > 0$). Both the layers take the cubic in-plane anisotropy. Only the lowest-order anisotropy constants of the two layers are taken into account. The definition of the axes x and y is in Eq. (7).

After performing further manipulations, one can get a cubic equation in terms of cos 2α:

$$-2y^2\cos^3 2\alpha + 2y(2x^2 - y)\cos^2 2\alpha + x^2(1-y)^2 = 0. \tag{14}$$

This cubic equation determines the value of the canting angle in the region for non-collinear spin configurations. The required root must be a real, not complex, so it is very difficult to find the true root from the three roots of this cubic equation [15]. But we can numerically determine the value of the canting angle from Eq. (14). The dependence of the canting angle α on x and y is represented in Fig. 3. It is worth noting that there is a gap of ($\pi/4$, $3\pi/4$) (for $x = 0$) for the canting angle. The reason shall also be attributed to the biaxial symmetry of the cubic anisotropy, which can force the canting angle to lie in the range of $0 - \pi/4$ (or $3\pi/4 - \pi$) in order to diminish the interlayer exchange coupling energy.

3.2. One uniaxial, the other cubic

In this subsection, we let one layer take the uniaxial in-plane anisotropy, the other the cubic

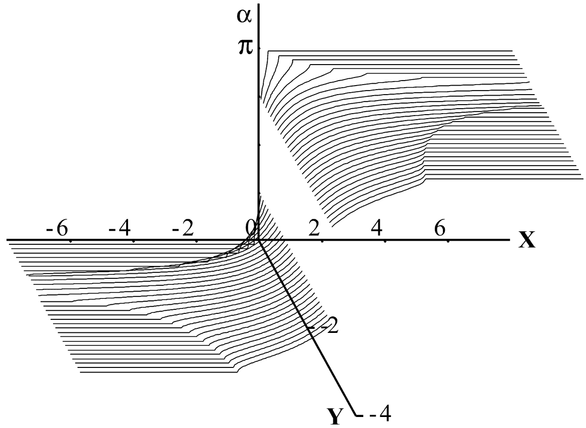

Fig. 3. Dependence of the canting angle α on the values of x and y, which are defined in Eq. (7). Both the layers have the cubic in-plane anisotropy ($K_{1A} > 0$).

one, which results in the following free energy expression:

$$E = JM_A M_B \cos\alpha + K_{uA}\sin^2\theta_A + K_{1B}\cos^2(\theta_A + \alpha)\sin^2(\theta_A + \alpha). \tag{15}$$

Accordingly, the definitions of x and y are changed into

$$x = \frac{JM_A M_B}{K_{uA}}, \quad y = \frac{K_{1B}}{K_{uA}}. \tag{16}$$

Eqs. (2) and (3) and inequalities (4) and (5) should be expanded and reduced to

$$2\sin 2\theta_A + y\sin 4(\theta_A + \alpha) = 0, \tag{17}$$

$$-2x\sin\alpha + y\sin 4(\theta_A + \alpha) = 0, \tag{18}$$

$$\Delta = 2K_{uA}^2[-x\cos\alpha\cos 2\theta_A + y(2\cos 2\theta_A - x\cos\alpha)\cos 4(\theta_A + \alpha)] > 0, \tag{19}$$

$$\frac{\partial^2 E}{\partial\theta_A^2} = 2K_{uA}[\cos 2\theta_A + y\cos 4(\theta_A + \alpha)] > 0. \tag{20}$$

For $\alpha = 0$, π and $\theta = 0$, $\pi/2$, the solutions of Eqs. (17) and (18), combining inequalities (19) and (20) would lead to four possible collinear configurations.

I. For $\alpha = 0$, $\theta_A = 0$:
$K_{uA} > 0$ and $y > -1$ and $x < 0$ and $x < 2y/(1+y)$;

II. For $\alpha = 0$, $\theta_A = \pi/2$:
$K_{uA} < 0$ and $y < 1$ and $x > 0$ and $x > 2y/(1-y)$;

III. For $\alpha = \pi$, $\theta_A = 0$:
$K_{uA} > 0$ and $y > -1$ and $x > 0$ and $x > -2y/(1+y)$;

IV. For $\alpha = \pi$, $\theta_A = \pi/2$:
$K_{uA} < 0$ and $y < 1$ and $x < 0$ and $x < 2y/(y-1)$.

These results are displayed in Figs. 4 and 5 for $K_{uA} > 0$ and $K_{uA} < 0$, respectively. The existence of the collinear structures are very sensitive to the sign of the anisotropy coefficient of layer A. Moreover, the boundaries between collinear and non-collinear configurations are different in Figs. 4 and 5. According to the procedure described in the above subsection, we can obtain a six-order equation in terms of the cosine of the canting angle:

$$16y^2\cos^6\alpha - 16x^3y\cos^5\alpha - 16y^2\cos^4\alpha + 8xy(3x^2-1)\cos^3\alpha + y^2(4-x^4)\cos^2\alpha + 4xy(1-2x^2)\cos\alpha + x^2(x^2y^2-y^2+1) = 0. \quad (21)$$

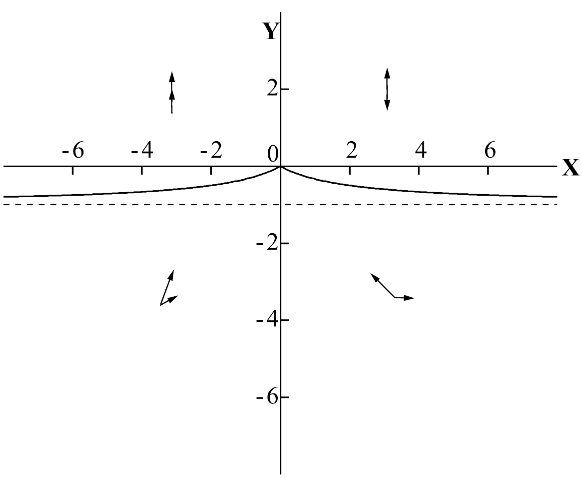

Fig. 4. Phase diagrams of the different spin configurations of a magnetic bilayer in the absence of an external field ($K_{uA} > 0$). One layer takes the uniaxial in-plane anisotropy, the other cubic one. Only the lowest-order anisotropy constants of the two layers are taken into account. The definition of the axes x and y is in Eq. (16).

Fig. 6 shows the dependence of the canting angle α on x and y in the case of $K_{uA} > 0$, which is numerically derived from Eq. (21). The gap of $(\pi/4, 3\pi/4)$ for the canting angle results from the cubic

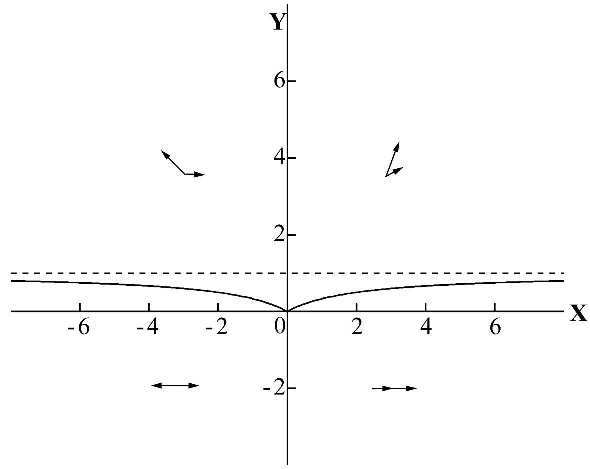

Fig. 5. Phase diagrams of the different spin configurations of a magnetic bilayer in the absence of an external field ($K_{uA} < 0$). One layer takes the uniaxial in-plane anisotropy, the other cubic one. Only the lowest-order anisotropy constants of the two layers are taken into account. The definition of the axes x and y is in Eq. (16).

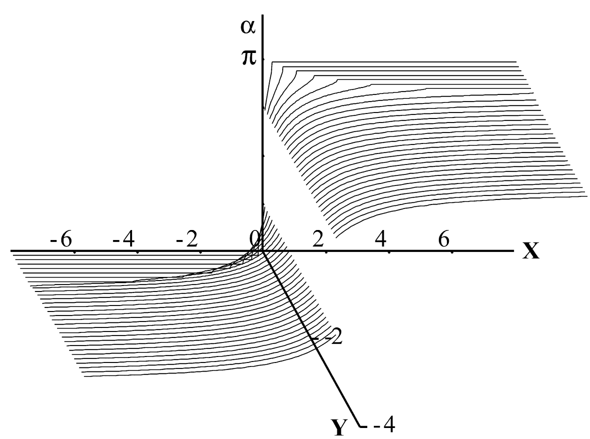

Fig. 6. Dependence of the canting angle α on the values of x and y, which are defined in Eq. (16). One layer takes the uniaxial in-plane anisotropy ($K_{uA} > 0$), the other cubic one.

anisotropy of layer B. For $K_{uA} < 0$, the dependence of the canting angle α on x and y has a feature similar to that for $K_{uA} > 0$, however, corresponding to Fig. 5. It is a central symmetry of Fig. 6 with respect to the origin.

3.3. Two uniaxial in-plane anisotropies

This case in a magnetic bilayer system is very similar to that in a two-sublattice system, when only the second-order anisotropy constants of the two sublattices are taken into account. Substituting the c-axis and the intersublattice molecular-field coefficient n_{AB} in Ref. [13] with the a-axis and the interlayer exchange coupling J will enable the result obtained in Ref. [13] to be applicable in this subsection. Figs. 1 and 2 in Ref. [13] showed the phase diagram of the different spin configurations and the dependence of the canting angle α on the values of x and y, respectively. The phase diagram resembles that obtained in Section 3.1, but in each region there is only one possible spin arrangement. This is due to the difference in symmetry between the cubic and uniaxial anisotropies, which also leads to the disappearance of the gap of the canting angle in the region of non-collinear configurations.

4. Summary

We have systematically studied the spin configurations in the absence of an external magnetic field in a highly idealized bilayered model consisting of two ferromagnetic layers of uniaxial or cubic anisotropies intervening by a non-magnetic layer. The results obtained indicate that the model can describe a wealth of possible relative spin arrangements between the two ferromagnetic layers. The competitions between three energies, the exchange coupling energy and the two anisotropy energies, result in collinear or non-collinear configurations. The symmetry of the anisotropy determines the character of the spin arrangement in the layer structures.

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