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Spin-reorientation transitions in magnetic multilayers with cubic anisotropy and biquadratic exchange

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Abstract

Theoretical investigations of phase transitions in magnetic multilayer structures are presented. We suppose that biquadratic and Heisenberg exchange energy between adjacent layers is of the same order of magnitude. Anisotropy energy is cubic. Our consideration is close to the Fe/Cr(0 0 1) superlattice. An investigation is given showing that two phases with noncollinear orientation of magnetization in adjacent layers can represent the ground state. In the case being considered external magnetic field aligned perpendicular to the layers direction induces a spin-reorientation transition. Other types of anisotropy are also discussed. © 1997 Elsevier Science B.V. All rights reserved.

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1. Introduction

Presently, exchange interaction of magnetic thin layers via a nonmagnetic spacer is widely discussed. The main term of this interaction has a Heisenberg form $J_1 \boldsymbol{n}_i \boldsymbol{n}_{i+1}$ where $\boldsymbol{n}_i$ is a unit vector in the direction of magnetization in the ith magnetic layer. By virtue of the fact that J_1 changes sign as spacer thickness increases [1–3] the presence of a biquadratic term [4–6] $J_2(\boldsymbol{n}_i \boldsymbol{n}_{i+1})^2$ holds much physical significance. Experimental observations of noncollinear orientation of magnetization in adjacent layers [5, 7] provide support for this view.

The Heisenberg exchange tends to align magnetization in adjacent layers parallel or antiparallel depending on the sign of J_1 being negative or positive. According to theoretical treatment and experimental observations J_2 is always positive. Thus biquadratic exchange tends to align magnetization of adjacent layers in perpendicular directions. The joint action of the Heisenberg and biquadratic exchange brings into existence phases with noncollinear orientation of the magnetization in neighboring layers.

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In the case being considered, in the zero anisotropy approximation, phase transitions in magnetic multilayers are studied in Ref. [8]. Nevertheless, results obtained in Ref. [8] have only a qualitative meaning. In the real multilayers of magnetic materials the anisotropy energy has at least the same order of magnitude as exchange energy. A uniaxial anisotropy in the plane of magnetic layers is taken into account in Ref. [9]. But this paper discusses only phase transitions under the action of an external field parallel to the magnetic layers.

The present paper is devoted to the theoretical investigation of the spin-reorientation transitions in fields perpendicular to the plane of the layers. We examine the case of cubic anisotropy. Our study revealed that there are two phases with non-collinear orientation in adjacent layers. A magnetic field gives rise to spin-reorientation transitions in a superlattice. The case under consideration is analogous to the Fe/Cr(0 0 1) superlattice structure.

2. Energy functional and phase diagram at zero field

Let us consider N magnetic layers mediated by $N-1$ spacer layers with antiferromagnetic interaction between adjacent layers. In the case of infinite layers, $N \gg 1$, or a spin-wave structure, $N = 2$, the energy functional has the form of a two-sublattice magnet. It differs from that of a classical antiferromagnet by the biquadratic exchange term. For the sake of definiteness, we take the z-axis perpendicular to the layers' plane and the x-axis along one of the two easy axes in the layers' plane.

The energy functional of such a system can be written as

$$F = \sum_{i=1}^{2} [k[(n_i^x n_i^y)^2 + (n_i^z n_i^y)^2 + (n_i^x n_i^z)^2] + \tfrac{1}{2}m\,(n_i^z)^2 - h(n_i^z)] + \tfrac{1}{2}J_1(\boldsymbol{n}_i\boldsymbol{n}_{i+1}) + \tfrac{1}{2}J_2(\boldsymbol{n}_i\boldsymbol{n}_{i+1})^2 . \quad (1)$$

Here J_1 is the Heisenberg exchange energy, J_2 the biquadratic exchange energy, k the energy of cubic anisotropy, h the Zeeman energy in external magnetic field, m the demagnetizing energy. All the energies are measured in the units of magnetic field.

It is convenient to change the variables from rectangular $\boldsymbol{n}_i$ to polar coordinates θ_i and φ_i, where θ_i measures the angle between z-axis and vector $\boldsymbol{n}_i$ and the azimuthal angle φ_i measures the angle between the $\boldsymbol{n}_i$ projection on the x–y plane and the x-axis. Thus the energy functional depends on four variables θ_1, φ_1, θ_2 and φ_2.

At zero external field a strong demagnetization field prevents any deviation of magnetization from the plane. Thus substituting in Eq. (1) $\theta_1 = \theta_2 = \pi/2$ we have

$$F = \tfrac{1}{2} J_1 \cos(\varphi_1 - \varphi_2) + \tfrac{1}{2} J_2 \cos^2(\varphi_1 - \varphi_2) + \tfrac{1}{4} k \sum_{i=1}^{2} \sin^2 2\varphi_i . \quad (2)$$

The energy functional, Eq. (2), has its minimum when the set of φ_1, φ_2 is equal to one of the four sets are presented in Table 1.

Minimum conditions and energy values for each set are displayed in Table 1 also. For definiteness sake it is assumed that linear exchange interaction between adjacent layers is antiferromagnetic (i.e.

Table 1
Properties of phases which minimize energy functional (2)

	Phase	Stability condition	Energy
I	$\varphi_1 = \varphi_2 = 0$	$2k > J_1 + 2J_2$	$(J_1 + J_2)/2$
II	$\varphi_1 = 0, \varphi_2 = \pi$	$2k + J_1 > 2J_2$	$(J_2 - J_1)/2$
II	$\varphi_1 = -\varphi_2 = \frac{1}{2}\arccos J_1/[2(k - J_2)]$	$\sqrt{2} < \lvert J_1/(J_2 - k)\rvert < 2$	$(J_1^2 - 4kJ_2 + 4k^2)/8(k - J_2)$
IV	$\varphi_1 = -\frac{1}{2}\pi - \varphi_2 = \frac{1}{2}\arcsin J_1/[2(k + J_2)]$	$\sqrt{2}(k + J_2) > J_1$	$-J_1^2/8(k + J_2)$

$J_1 > 0$). The case $J_1 < 0$ will be briefly discussed below. Then depending on k, J_1, J_2 only one of three phases (II, III, IV) can represent a global minimum of Eq. (2). Two of them are noncollinear. Fig. 1 shows the phase diagram in variables J_2/J_1 and k/J_1.

3. Field-induced spin-reorientation transitions

There is evidence that magnetization departs from the layers plane under the action of an external field directed in the perpendicular direction. As this takes place, the problem of energy functional [Eq. (1)] minimization becomes considerably more complex. It has not proved feasible to obtain an analytical solution of this problem in the general case. In actual conditions, an exchange field and anisotropy field are far less than the demagnetization field. For a superlattice Fe/Cr, as an example, anisotropy and exchange fields are less than or equal to 1 kOe and the demagnetization field on the order of 10–20 kOe. Then we can find from equations $\partial F/\partial\theta_1 = 0$ and $\partial F/\partial\theta_2 = 0$ to a good approximation

$$\theta_1 = \theta_2 = \arccos(h/m). \tag{3}$$

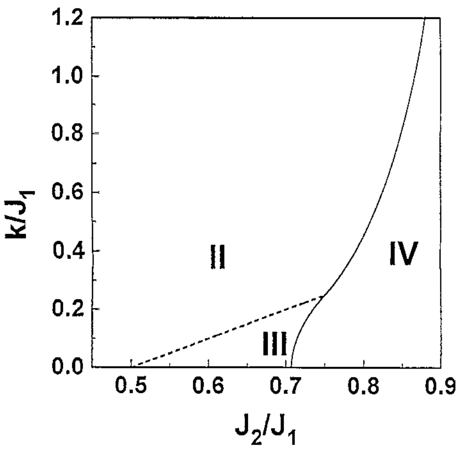

Fig. 1. Phase diagram in variables $k/2J_1$, $J_2/2J_1$. Roman numbering of phases are in agreement with Table 1. The solid line corresponds to the first order phase transitions and the dashed line corresponds to the second order phase transitions.

Substitution of these expressions into Eq. (1) gives an energy functional in the form of Eq. (2), where J_1, J_2, k are replaced by renormalized values

$$J_1(h) = \left(1 - \frac{h^2}{m^2}\right)\left(J_1 + J_2\frac{2h^2}{m^2}\right),$$

$$J_2(h) = \left(1 - \frac{h^2}{m^2}\right)^2, \qquad k(h) = k\left(1 - \frac{h^2}{m^2}\right)^2, \tag{4}$$

respectively. With this the equilibrium values of $\varphi_1(h)$ and $\varphi_2(h)$ can be defined using the expressions in Table 1, provided that instead of J_1, J_2, k the expressions in Eq. (4) are taken. As $h \to m$, $k(h)/J_1(h)$ and $J_2(h)/J_1(h)$ tend to zero. Then according to the data in Table 1 $|\varphi_1(h) - \varphi_2(h)| = \pi$ as $h = m$. If $\varphi_1(m)$ and $\varphi_2(m)$ differ from $\varphi_1(0)$, $\varphi_2(0)$ then the applied external magnetic field causes a spin-reorientation phase transition as h increases from 0 to m.

To take an example we consider the case when at zero field the phase IV is suited to the requirements of an energy functional minimization. In particular this is true for $J_2 \geqslant J_1$. In view of the fact that $k(h)/J_2(h) = \text{const.}$ (see Eq. (4)) we can easily calculate the critical fields of a spin-reorientation phase transition. If $3k > J_2$ then at $h = h_1$ occurs a first-order phase transition to the antiferromagnetic phase II where

$$h_1 = \frac{m}{\sqrt{8J_2(4J_2 + 3k)}}\,[8J_2(2J_2 - J_1) + k(4J_2 - J_1) - 4(J_1 + 2J_2)\sqrt{k(k + J_2)}\,]^{1/2}. \tag{5}$$

In the case of $3k < J_2$ transition to phase II occurs in two steps. Initially the first order phase transition from phase IV to phase III takes place at $h = h_2$ and thereupon the second order phase transition from phase III to phase II occurs at $h = h_3$. Expressions for h_2, h_3 are as follows:

$$h_2 = m\left[\frac{2(k^2 - J_2^2 - J_1J_2) + (J_1 + 2J_2)\sqrt{2(J_2^2 - k^2)}}{2(k^2 + J_2^2)}\right]^{1/2},$$

$$h_3 = m\left[\frac{2J_2 - 2k - J_1}{2(2J_2 - k)}\right]^{1/2}. \tag{6}$$

We take as our example a Fe/Cr(0 0 1) spin-valve structure with $J_2 = 90$ Oe, $k = 560$ Oe. Thus according to Eq. (1) we find that for $J_1 > 93$ Oe the ground state is antiferromagnetic. If $J_1 = 50$ Oe we have a spin-reorientation phase transition at $h = 0.4m$ from angle phase IV to antiferromagnetic phase II.

The main conclusion $|\varphi_1(h) - \varphi_2(h)| \to \pi$ as $h \to \pi$ remains unchanged for other types of anisotropy. This fact can be explained as follows. If the angle between $\boldsymbol{n}_i$ and $\boldsymbol{n}_{i+1}$ exceeds $\pi/2$ then Heisenberg exchange acts as the repulsive force and biquadratic exchange as the attractive force. Otherwise both of these forces act as repulsive. Thus if the deviation of magnetization from the basal plane exceeds $\pi/4$ then exchange forces tend to align the magnetization of adjacent layers so that the angle between the projection of magnetization in adjacent layers equals π. Our calculations for uniaxial anisotropy give support for this view.

The case of ferromagnetic Heisenberg exchange $J_1 < 0$ can be investigated in the same manner as the antiferromagnetic one. The expressions in Table 1 remain true. Consequently, one of the three phases (I, III, IV) can represent the global minimum of Eq. (2) for $J_1 < 0$. Here we do not present detailed considerations for this case but it is significant that the renormalized exchange constant $J_1(h)$ changes sign as h increases if $J_2 > |J_1|$.

In conclusion, the equilibrium distribution of magnetization in a magnetic superlattice has been investigated. Two of the three ground state phases at zero field are noncollinear. An external magnetic field aligned perpendicularly to the layers direction was demonstrated to induce reorientation transitions.

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References

[1] S.S.P. Parkin, N. More, K.P. Roche, Phys. Rev. Lett. 64 (1990) 2304.
[2] S.S.P. Parkin, Phys. Rev. Lett. 67 (1990) 3598.
[3] P. Bruno, Phys. Rev. B 52 (1995) 411.
[4] J. Slonczevski, Phys. Rev. Lett. 67 (1991) 3172.
[5] M. Rührig, M. Schäfer, A. Hubert, J.A. Wolf, S. Democritov, P. Grünberg, Phys. Stat. Sol. (a) 125 (1991) 635.
[6] R.P. Ericson, K.B. Hathaway, J.R. Cullen, Phys. Rev. B 47 (1993) 2626.
[7] C.D. Potter, R. Schad, P. Beliën et al., Phys. Rev. B 49 (1994) 16055.
[8] V.V. Ustinov, M.M. Kirillova, I.D. Lobov et al., 109 (1996) 477.
[9] N.S. Almeida, D.L. Mills, Phys. Rev. B 52 (1995) 13504.