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Bilayer Magnetic Structures with Dipolar Interaction

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Computer simulation of bilayer structures with dipolar interlayer interaction was performed. Equilibrium properties were considered for systems with various thicknesses of magnetic layers and distances between the layers. Non-equilibrium behavior was simulated for high- and low-temperature initial states.

Keywords: bilayer structures, dipolar interaction.

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Introduction

Thin magnetic films and multilayer structures are objects of intensive study due to their promising applications in memory devices [1], magnetic field sensors [2], and other electronic and spintronic devices. Multilayer structures consist of alternating magnetic and non-magnetic layers. Properties of the structures significantly vary with thicknesses and the number of magnetic and non-magnetic layers. Theoretical study of interactions responsible for these variations can be carried out by a computer simulation. Interaction between magnetic layers separated by non-magnetic material should have a long-range character. This work deals with Monte Carlo simulation of a structure with two magnetic layers and dipolar interlayer interaction.

1. The model of bilayer magnetic structure with dipolar interaction

A magnetic layer of the structure presents a set of spins situated in sites of a simple cubic lattice with linear size L in X- and Y-directions and $N < L$ in Z-direction. N characterizes a thickness of the magnetic layer. The system Hamiltonian $H = H_1 + H_2 + H_{12}$. Hamiltonians of the first and the second magnetic layers ($H_{\alpha=1,2}$) and Hamiltonian H_{12} determining interaction between the layers have the following form

$$H_{\alpha} = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - A \sum_i S_{i,z}^2, \quad H_{12} = D \sum_{ij} \left(\frac{\mathbf{S}_i \cdot \mathbf{S}_j}{r_{ij}^3} - 3 \frac{(\mathbf{S}_i \cdot \mathbf{r}_{ij})(\mathbf{S}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5} \right),$$

where \mathbf{S}_i is a spin (a unit vector in a three-dimensional space). The first term in H_{α} corresponds to the exchange interaction, $\langle \dots \rangle$ denotes that the summation is conducted only for nearest neighbouring spins. The second term corresponds to uniaxial anisotropy with an axis parallel to

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Z-direction, or perpendicular to the layer surface. Hamiltonian H_{12} has a form of dipolar interaction. Summation is conducted for all pairs of spins with one spin belonging to the first magnetic layer and the other to the second layer. The distance between magnetic layers S corresponds to a thickness of non-magnetic intermediate layer in a real structure. The Hamiltonian parameters were set to be: $A = 0.10J$, $D = 0.01J$.

2. Equilibrium behaviour of bilayer structures

The basic characteristics of the system are the total magnetization $m = \frac{1}{N_s} (\mathbf{M}_1 + \mathbf{M}_2)$, and the staggered magnetization $m_{stg} = \frac{1}{N_s} (\mathbf{M}_1 - \mathbf{M}_2)$, where $N_s = 2L \times L \times N$ is the number of spins in all magnetic layers, and \mathbf{M}_1 , \mathbf{M}_2 are magnetic moments of the first and the second layers, which equal to a vector sum of all spins in the corresponding magnetic layer.

Hamiltonian H_α describes a ferromagnetic anisotropic film, with all spins parallel to Z-direction in the ground state. Dipolar interaction leads antiparallel orientation of magnetic moments of the layers to be energetically preferable at low temperatures. In this case the staggered magnetization tends to unity and the total magnetization to zero at low temperatures. Temperature transition in such ordered state is demonstrated in Fig. 1(a). The transition temperature increases with the thickness of the magnetic layers, as it does in thin ferromagnetic films. Increasing of distance between the magnetic layers leads to weakening of interaction between them. As a result there is an increase of the number of tests with the system appearing in a metastable state with magnetic moments of both layers being parallel. This is responsible for increasing of the total magnetization and decreasing of the staggered magnetization with S at the same low temperature, which can be seen in Fig. 1(b).

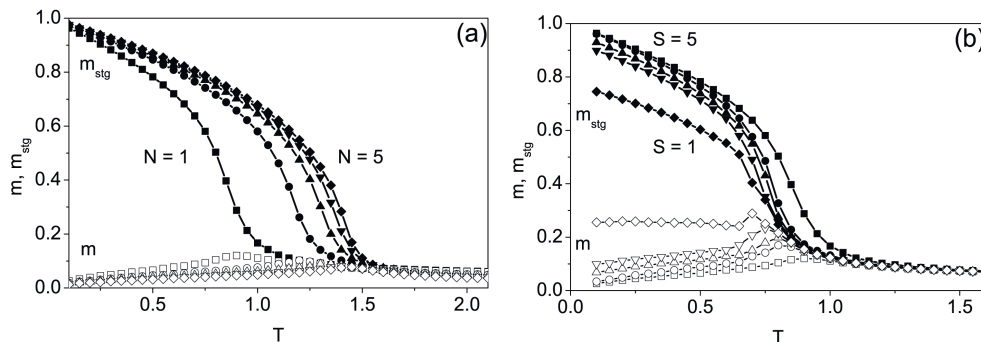


Fig. 1. Temperature dependence of the total m and the staggered m_{stg} magnetization for systems with linear size $L = 16$ (a) with different thicknesses of the magnetic layers N and the distance between the layers $S = 1$, (b) for systems with $N = 1$ and different S

3. Non-equilibrium behaviour of bilayer structures

Investigation of non-equilibrium behaviour of bilayer structures was based on time dependence of the autocorrelation function

$$C(t, t_w) = \left\langle \frac{1}{N_s} \sum_{i=1}^{N_s} \mathbf{S}_i(t) \mathbf{S}_i(t_w) \right\rangle - \left\langle \frac{1}{N_s} M(t) \right\rangle \left\langle \frac{1}{N_s} M(t_w) \right\rangle,$$

where t_w is a waiting time. The system with linear size $L = 64$, thickness of the magnetic layers $N = 1$ and the distance between the layers $S = 1$ was considered.

Non-equilibrium behaviour of the system significantly depends on the initial state. Simulation was carried out for the high- and low-temperature initial states. In the case of the high-temperature initial state spins have random orientations, the initial total magnetization $m^0 \ll 1$, and the initial staggered magnetization $m_{stg}^0 \ll 1$. In the case of the low-temperature initial state spins in the first layer are aligned in a positive direction of Z-axis and spins of the second layer are aligned in a negative direction, and $m^0 = 0$, $m_{stg}^0 = 1$. Fig. 2 shows time dependence of the autocorrelation function for different waiting times at the temperature $T = 0.9$. The autocorrelation function relaxation process slows down with the waiting time for the high-temperature initial state and accelerates for the low-temperature initial state.

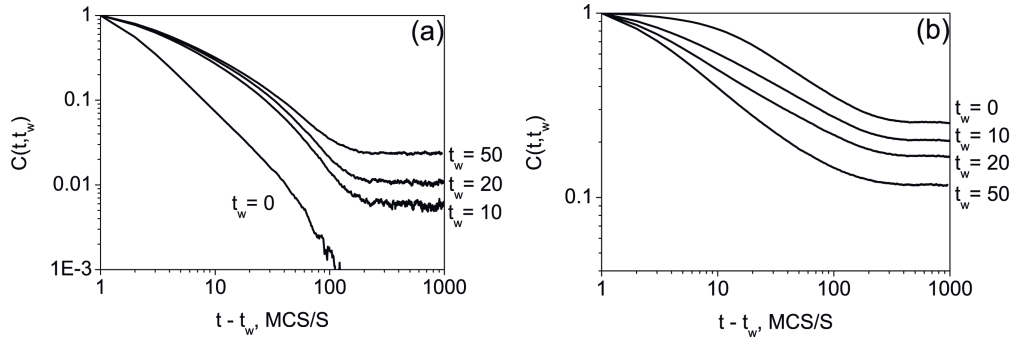


Fig. 2. Time dependence of the autocorrelation function $C(t, t_w)$ for different waiting times t_w for (a) high- and (b) low-temperature initial state

For the case with the waiting time $t_w = 50$ MCS/S (Monte Carlo steps per spin) simulation was carried out with changing of the temperature during the relaxation process. Simulation starts at the temperature $T = 0.9$, at the time $t = t_w$ the temperature is changed by $\Delta T = 0.2$ and at the time $t = 2t_w$ it is returned to its initial value. The results of simulation are shown in Fig. 3. One can see that when the temperature is changed the autocorrelation function deviates

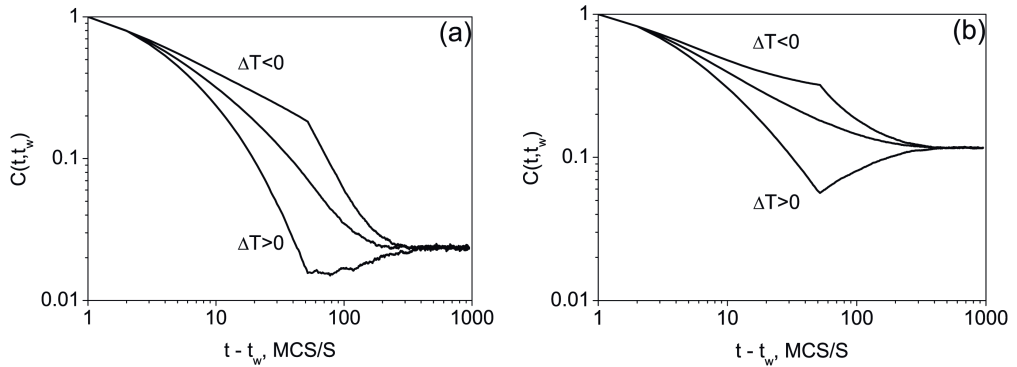


Fig. 3. Time dependence of the autocorrelation function $C(t, t_w)$ for the waiting time $t_w = 50$ MCS/S for (a) high- and (b) low-temperature initial state. Simulation is conducted at $T = 0.9$, at the time $t = t_w$ the temperature is decreased ($\Delta T = -0.2$) or increased ($\Delta T = 0.2$), at the time $t = 2t_w$ the temperature is returned to the initial value. Central curves denote the behaviour at the constant temperature.

from the behaviour at the constant temperature (central curves) upward when the temperature is decreased, and downward when the temperature is increased. When the temperature is returned to the initial value the autocorrelation function behaviour also returns to the initial one. This demonstrates that the system has a memory about the initial state.

Conclusions

Simulation of bilayer magnetic structures with dipolar interaction has revealed such phenomena as a transition to the low-temperature ordered state with antiparallel orientation of magnetic moments of the layers, effects of slowing down or accelerating of the autocorrelation function with the waiting time and memory effects.

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Двухслойные магнитные структуры с диполь-дипольным взаимодействием

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В работе проведено моделирование двухслойной структуры с диполь-дипольным межслоевым взаимодействием. Рассмотрено влияние толщины магнитных слоев и расстояния между слоями на равновесные характеристики структуры. Проведено моделирование неравновесного поведения структуры при старте из начальных высоко- и низкотемпературного состояний.

Ключевые слова: двухслойные магнитные структуры, диполь-дипольное взаимодействие.