Magnetic properties of multilayers based on anisotropic Heisenberg films with dipolar long-range interaction

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Abstract. The Monte Carlo simulation of the critical behavior of multilayer structures based on anisotropic Heisenberg mode are presented. The non-equilibrium critical relaxation of structures consisting of two magnetic layers with dipolar interlayer interaction is studied. The investigation of non-equilibrium critical behavior of multilayer structure which correspond to the nanoscale superlattice Co/Cr demonstrates that the aging effects can be observed in a wider temperature range than for bulk magnetic systems.

Magnetic order in the multilayers is complex due to a strong influence of the shape and the magnetocrystalline anisotropies of the sample. It is well known now the fundamental role of competing interactions in the emerging features of low-dimensional systems. Among a wide number of numerical and theoretical investigations on equilibrium and dynamical properties of several model Hamiltonian of low-dimensional magnets, Heisenberg-like models are one of the most widely used to approach real magnetic materials [1].

This study includes the Monte Carlo simulation of the critical behavior of multilayers based on anisotropic Heisenberg films with dipolar interaction. Competition between short-range exchange interaction, uniaxial anisotropy and long-range dipolar interaction results in appearance of different domain structures and in occurrence of the phase transitions.

Magnetic film is constructed as a spin lattice with Heisenberg Hamiltonian

\[ H = -J \sum_{i,j} [S_i S_j - \Delta(N) S_i^z S_j^z] - A \sum_i S_i^z - h \sum_i S_i + D \sum_{i \neq j} \left( \frac{S_i S_j}{r_{ij}^3} - 3 \frac{(S_i r_{ij})(S_j r_{ij})}{r_{ij}^5} \right), \]  

where \( S_i \) is a three-dimensional spin in the lattice cite \( i \), \( J \) is exchange constant, \( A \) characterizes uniaxial anisotropy in out-of-plane direction, \( h \) is applied magnetic field, \( D \) characterizes the strength of dipolar interaction and \( r_{ij} = r_i - r_j \) is the distance between cites \( i \) and \( j \).

Anisotropy parameter \( \Delta \) characterizes the amount of anisotropy: \( \Delta = 0 \) corresponds to the isotropic Heisenberg case, \( \Delta = 1 \) – the case of XY-model. Microscopic nature of anisotropy in films of Fe, Co, Ni and it’s dependence from film thicknesses \( N \) is determined by influence of crystalline field of substrate surface, magnetic single-ion anisotropy and dipole-dipole interaction of magnetic moments of atoms in film and their concurrence [2].

We measured the magnetization the total magnetization \( m = m_1 + m_2 \) and the staggered magnetization \( m = m_1 - m_2 \), where \( m_1, m_2 \) are magnetizations of adjacent magnetic layers. The modeling of the trilayer structure consisting of two ferromagnetic films with dipolar interlayer interaction separated by nonmagnetic metal film demonstrates the effective antiferromagnetic character of this interaction. The simulations were carried out for layers with...
Figure 1. Temperature dependencies of the adjacent layer magnetization \( m_{i,z} \) (left), ”staggered” \( m_{\text{stg}} \) and total \( m \) magnetization (right) of multilayer structure with dipole interaction. The temperature is measured in units \( J/k_b \).

Figure 2. Ageing effects in non-equilibrium relaxation of multilayers from high-temperature initial state for \( h = 0 \) (left) and 0.07 (right).

sizes \( L \times L \times N \) with the use of periodic and free boundary conditions for the in-plane and out-plane directions, respectively. \( N \) is the thickness of ferromagnetic layers. The Metropolis algorithm was used for Monte Carlo simulations. Magnetic properties are calculated for this system with \( A = 0.1J \), \( D = 0.01J \), \( \Delta = 0 \) (Figure 1). Dipolar interaction is resulted in antiparallel orientations of adjacent ferromagnetic layers.

In investigations of influence of the initial states on characteristics of non-equilibrium critical behaviour we computed the magnetization

\[ m(t) = \left\langle \frac{1}{NL^2} \sum_{i=1}^{NL^2} S_i(t) \right\rangle, \quad (2) \]

and the time-dependent autocorrelation function

\[ C(t, t_w) = \left\langle \frac{1}{NL^2} \sum_{i=1}^{NL^2} S_i(t)S_i(t_w) \right\rangle - m(t)m(t_w), \quad (3) \]

The time variable \( t_w \) characterizes the age of a sample and is called waiting time. Autocorrelation function in nonequilibrium processes depend not only on the difference \( t - t_w \) but also on each time variable individually at \( t - t_w \) and \( t_w \) much smaller than the relaxation time of the system \( t_{\text{rel}} \). The non-equilibrium evolution starts when the system after initial preparation is placed to the thermostat with \( T = T_c \). At the waiting time \( t_w \), we have begun to measure two-time correlation function within the \( 1 \ll t, t_w \ll t_{\text{rel}} \) range. The aging of a system
Figure 3. Aging effects of $C(t, t_w)$ for evolution from different initial states $m_{stg}^0 = 0$, $m_{stg}^0 = 1$ (left) and scaling "collaps" of $F(t/t_w) = t_w^{\beta/\nu z} C(t, t_w)$ for initial state $m_{stg}^0 = 0$ (right)

is manifested in slowing down relaxation processes with the time passing from the preparation of a sample. The trilayer structure with dipolar interaction demonstrates the aging effects (Figure 2). The presence of external magnetic field $h$ leads to increasing of relaxational processes.

The features of non-equilibrium critical dynamics [3] can be considered as basis for understanding and interpretation of the experimental data obtained for Co/Cr [4]. The next values of modelling parameters $\Delta(N = 3) = 0.7$, $A = 0$, $D = 0$ and $J_1 \approx 4 \times 10^{-21} J$ are used for the multilayer structure, which correspond to the nanoscale superlattice [Co(0.6 nm)/Cr(0.78 nm)] [4]. The investigation of the magnetization relaxation in the multilayer superlattice has revealed the magnetic aging phenomena (Figure 3.left). The realization of dynamical scaling which demonstrated in Figure 3 gives the possibility to determine the critical exponent $\beta/\nu z = 0.159$.

The nanoscale periodicity creates in these magnetic multilayer structures mesoscopic spatial magnetic correlations with slow relaxation dynamics when quenching of the system into a non-equilibrium state is realized. In comparison with bulk magnetic systems where the slow dynamics and aging phenomenon are displayed close to critical point, the magnetic superlattices, structured on the nanoscale, give possibility to increase relaxation time due to the increasing in the characteristic spin-spin correlation length. The aging can be observed in the multilayer structures in a wider temperature range $T < T_c = 249.6 K$ than for bulk magnetic systems.

Therefore we have studied the magnetic properties of the trilayer structure consisting of two ferromagnetic films separated by nonmagnetic metal film. It were considered long-range dipolar interlayer interaction or RKKI interaction, which lead to the effective antiferromagnetic interaction for specified thickness of nonmagnetic layer. The study of aging effects in multilayered structures shows that these effects brightly appear in non-equilibrium relaxation from initial states.

Acknowledgments
This work was supported by Grant No. MD-6024.2016.2 of Russian Federation President and by Project of the Ministry of Education and Science of the Russian Federation. The simulations were supported by the Supercomputing Center of Lomonosov Moscow State University, Moscow and Saint Petersburg Joint Supercomputer Center of the Russian Academy of Sciences.

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