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The phase diagrams of a ferromagnetic thin film in a random magnetic field

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ABSTRACT

In this paper, the magnetic properties and the phase diagrams of a ferromagnetic thin film with a thickness N in a random magnetic field (RMF) are investigated by using the Monte Carlo simulation technique based on the Metropolis algorithm. The effects of the RMF and the surface exchange interaction on the critical behavior are studied. A variety of multicritical points such as tricritical points, isolated critical points, and triple points are obtained. It is also found that the double reentrant phenomenon can appear for appropriate values of the system parameters.

1. Introduction

The random field Ising model (RFIM) has been studied extensively both theoretically and experimentally [1–3], because it helps simulate many interesting but complicated problems. One of interesting phenomena in the RFIM is the occurrence of a tricritical behavior. The impact of the temperature dependence of anisotropy field, the Curie temperature, etc. of the thin film is studied in many potential technological applications as Heat Assisted Magnetic Recording [4–7]. Also, Dzyaloshinskii–Moryia interaction of the thin film attained interest due to its possible applications in spintronic field [8,9]. From the experimental side, the interest comes from the fact that RMF can be found in a variety of distinct scenarios [10–12], for example the RFIM can be realized by dilute anisotropic antiferromagnetic in a uniform external magnetic field. In addition, standard experimental realization of the RFIM is the diluted Ising antiferromagnet in the presence of a uniform field [13,14], such as $Fe_xZn_{1-x}F_2$ and $Fe_xMg_{1-x}Cl_2$ [15,16]. In particular, the Ising antiferromagnet compound $Fe_xMg_{1-x}Cl_2$ behaves like a spin glass phase for $x < 0.55$, and is considered as a typical RFIM for higher magnetic concentration. In the RFIM regime this compound presents a very curious behavior: one finds a first-order transition turning into a continuous one due to a change in the random fields [17].

From the theoretical side, Hadjiagapiou [18,19] has examined the RFIM with an asymmetric bimodal or trimodal probability distribution by using the mean-field approximation. He has observed that the systems exhibit the reentrant phenomenon, the first- and second-order phase transition joined by one or two tricritical points. The behavior of the RFIM on a honeycomb lattice has been studied and discussed in Refs. [20,21] by using the effective field theory (EFT). No tricritical behavior was observed for this system. Using the effective field theory with probability distribution technique, Magoussi et al. [22] have studied the effect of the trimodal RMF on the magnetic properties of a spin-1 Ising nanotube. They have remarked that the phase diagram presents tricritical point and reentrant or double reentrant phenomenon. More recently, Monte Carlo simulation has been used to examine the phase diagrams of a spin-1 cylindrical nanowire in the presence of the RMF [23]. Akinci [24] has investigated the influence of the randomly distributed magnetic field on the phase diagrams of an Ising nanowire. Interesting results have been found, such as reentrant behavior and first-order phase transitions. Some interest has been directed to the understanding of more complicated systems in the presence of a RMF, i.e. the semi-infinite Ising model [25], the site-diluted Ising model [26,27], the amorphous Ising ferromagnets [28] and the nanocrystalline ferromagnets [29]. It has

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been shown that in these systems, many interesting phenomena such as, the existence of the tricritical point and the reentrance behavior can be found. Furthermore, Bupathy et al. [30] have studied the ground state (GS) morphologies of the RFIM on simple cubic (SC), body-centered cubic (BCC) and face-centered cubic (FCC) within a computationally efficient graph cut method. They have obtained the exact GS of the RFIM on three isometric lattices: SC, BCC and FCC. Akinci et al. used EFT to obtain phase diagrams for the RFIM with different random-field distributions on SC, BCC and FCC lattices [31]. They also provided estimates of the critical disorder $\triangle_c$ for these lattices. In another work, Koiller et al. studied interface properties in the $d = 2$ RFIM on square, triangular and honeycomb lattices [32]. An important consequence of quenched disorder is pinning and roughening of interfaces. These are characterized by a roughness exponent α and are self-affine with a fractal dimension $d_f = d - \alpha$. Koiller et al. observed a transition from faceted to fractal interfaces with increasing disorder. This transition was first order for the honeycomb lattice but second order for the square and triangular lattices. Moreover, recently phase transition properties of RFIM with symmetric double [33] and triple [34] Gaussian random fields distribution have also been studied by means of a replica method and a rich variety of phase diagrams have been presented.

Many theoretical and experimental works [35–37] in the area of magnetic thin films have been stimulated by technological progresses. In particular, modern high vacuum techniques, such as the epitaxial growth techniques, allow to fabricate very thin magnetic films of controllable thickness [38,39] that may show a number of interesting phenomena not observed in bulk materials. However, the interesting results for these systems are the dependence of the critical behavior on the thickness. It was found experimentally, that the Curie temperature and the average magnetic moment per atom increase with the thickness [40,41]. More interesting properties may be expected by taking the effect of the surfaces. Since the free surface breaks the translational symmetry, much interest has been devoted in order to investigate critical phenomena at surfaces [42,43]. Several authors [44–46] have studied the critical behavior of the ferromagnetic Ising thin film with different thicknesses. With varying the ratio of the surface interaction to the bulk one, they have found a special point at which the transition temperature becomes independent of the film thickness. Jiang et al. [47] have studied the magnetic and the thermodynamic properties of a nanoscale multilayer ferrimagnetic films within the effective-field theory with correlations. It is observed that the phase diagrams show two compensation points in a certain surface parameter range. The dynamic phase transitions characteristics in ferromagnetic thin-films have been studied in Ref. [48]. It is noticed that the system represents a crossover behavior in between ordinary to extraordinary transition in the presence of surface exchange enhancement. The effect of magnetic dipole interaction in ultrathin ferromagnetic films has been examined by Draaisma et al. [49]. It is shown that the anisotropy resulting from the dipole–dipole interaction can be interpreted as a surface and a volume anisotropy which depend on the crystalline structure and orientation of the film, but are independent of the thickness of the film. By applying the Monte Carlo simulation on the thin Ising film with perfect and non-perfect surfaces, Zaim et al. [50] found that the critical effective exponent has its maximal value at the surface and it decreases to reach its smallest value in the inner layers.

Taking into account all the above studies, it has been noticed that, the effect of a RMF on the phase diagrams of an Ising thin film with spin-1/2 atoms have not been investigated by using Monte Carlo simulation. On the other hand, as far as we know less attention has been paid to the critical behavior of the Ising thin film in the presence of a RMF in the literature. Therefore, the aim of this work, is to investigate the influences of the surface exchange interaction and the RMF on the phase diagrams of a spin-1/2 Ising thin film using Monte Carlo simulation.

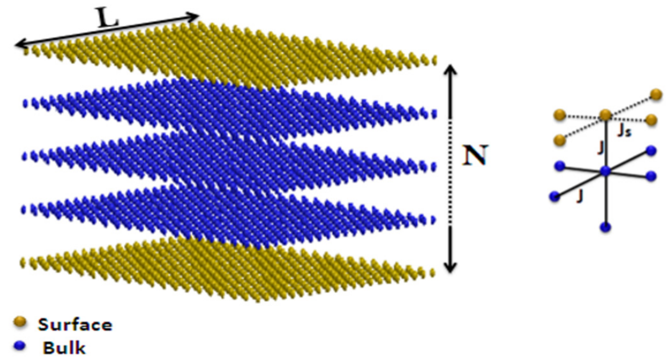

Fig. 1. Schematic representation of a thin film system in a simple cubic lattice.

The organization of this work is as follows: In Section 2, we give the formalism and Monte Carlo simulation. In Section 3, we present the results and discussions, while section 4 is devoted to a brief conclusion.

2. Model and Monte Carlo simulation

We have considered a ferromagnetic thin film with a thickness N (Fig. 1). In the Monte Carlo simulation based on the Metropolis algorithm [51,52], we apply periodic boundary conditions in the x, y directions and the free boundary conditions in the z direction. Namely, a spin in the bulk part of the system has always six nearest neighbors whereas a spin in the surface has five nearest neighbor spins. The Hamiltonian describing our model can be written as:

$$\mathcal{H} = -\sum_{\langle ij \rangle} J_{ij}\sigma_i^z\sigma_j^z - \sum_i h_i\sigma_i^z \tag{1}$$

σ_i^z is the spin-1/2 operator taking the values $\sigma_i^z = \pm 1$, J_{ij} is the exchange interaction between two nearest neighbor magnetic atoms. J_{ij} takes the value J_s in the surfaces ($z = 1$, $z = N$) and the value J otherwise. h_i is the RMF acting on σ_i^z, distributed according to a bimodal distribution law given by:

$$P(h_i) = \frac{1}{2}[\delta(h_i - h) + \delta(h_i + h)] \tag{2}$$

where δ stands for the delta function.This distribution distributes to magnetic field h half of the lattice sites and $-h$ the remaining half of the lattice sites randomly.

The simulations are carried out for simple cubic film containing $L \times L \times N$ spins with the distances between network nodes are about $a = 0.3$ nm. $L \times L$ represents the number of sites in each layer of the film and N (the real thickness is equal to $0.3\ \text{nm} \times (N - 1)$) is the number of layers in the film or its thickness. Results are reported for systems of size $L = 70$ (which means a size L about 69×0.3 nm) and for different thicknesses. A number of additional simulations were performed for $L = 80$ and 100, but no significant differences were found from the results presented here. We can test the equilibration of the system by monitoring the magnetization as a function of the Monte Carlo (MC) steps for $L = 70$. We have found that the steady states are easily achieved near the transition temperature after 10^4 MC steps. Thus, at each temperature, typically between 3×10^4 and 5×10^4 Monte Carlo steps were used for computing averages of thermodynamic quantities. The error bars were calculated with a Jackknife method [53] by taking all the measurements and grouping them in ten blocks.