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Dynamic phase diagrams of a cylindrical Ising nanowire in the presence of a time dependent magnetic field

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ABSTRACT

The dynamic phase diagrams of a cylindrical Ising nanowire in the presence of a time dependent magnetic field are obtained by using the effective-field theory with correlations based on the Glauber-type stochastic dynamics. According to the values of interaction parameters, a number of interesting properties have been found in the dynamic phase diagrams, such as many dynamic critical points (tricritical point, double critical end point, critical end point, zero temperature critical point, multicritical point, tetracritical point, and triple point) as well as reentrant phenomena.

1. Introduction

Recently, magnetic nanostructured materials have been subject of intensive interest due to their technological such as sensors, optics, spin electronics, thermoelectronic devices, molecular imaging devices, high density magnetic recorders, etc. [1–5] and biomedical applications, such as magnetic resonance imaging, drug delivery, cell and tissue targeting or hyperthermia [6–12].

On the other hand, the dynamic phase transition (DPT) temperature has attracted much attention in recent years, both theoretically (see [13–20] and references therein) and experimentally (see [21–27] and references therein). Especially, in pure Ising ferromagnet driven by oscillating magnetic field, became an interesting field of modern research in nonequilibrium statistical physics. Furthermore, the DPT presents new challenges and there is a strong motivation for analyzing it. Moreover, DPT of the spin-1/2 Ising model with periodic external magnetic field has been studied by means of mean-field theory (MFT) [28–32] and Monte Carlo simulations (MCS) [33–37], and there are also some works for higher spins [38,39] or mixed spin Ising systems [40,41], as well as the other variants of the model such as the transverse kinetic Ising model [42] based on the MFT.

While the DPT of the Ising model with periodic external magnetic field have been studied within the above theoretical methods [28–42] in nonequilibrium statistical physics, as far as we know, the DPT temperatures of the magnetic nanostructured materials have not been investigated in detail. Leite and Figueirredo [43] studied some dynamic behavior of the antiferromagnetic small particles within the MFT based on the the Glauber-type stochastic dynamics [44] and also MCS. Yüksel et al. [45] analyzed the nonequilibrium phase transition properties by means of the MCS. Keskin et al. used the spin-1 Ising systems to study the dynamical aspects of a cylindrical Ising nanotube [46,47] and nanowire [48] within the effective-field theory with correlations based on the Glauber-type stochastic dynamics (DEFT). They also presented the dynamic phase diagrams for only the cylindrical spin-1/2 Ising nanotube [47]. Moreover, Deviren et al. [49] studied the DPT temperatures of a cylindrical Ising nanowire. They examined the temperature dependence of the dynamic magnetizations for the shell and core, the dynamic total magnetization, the hysteresis loop areas, the dynamic correlations and the compensation behaviors. They are also found that the system strongly affected by the surface situations and five different types of compensation behaviors in the Néel classification nomenclature as well as reentrant behavior. However, in this study, they have not been studied on the dynamic phase diagrams and phases in the system.

Therefore, the aim of this paper is to investigate the dynamic phase diagrams of the cylindrical Ising nanowire in an oscillating magnetic field within the DEFT.

The paper is organized as follows. In Section II, we define the model and give briefly the formulation of the cylindrical spin-1/2 Ising nanowire by using the DEFT. In Section III, we present the numerical results and discussions. Finally, Section IV contains the summary and conclusions.

2. Model and formulation

We consider a cylindrical Ising nanowire, the schematic representation as depicted in Fig. 1 in which the wire consists of the

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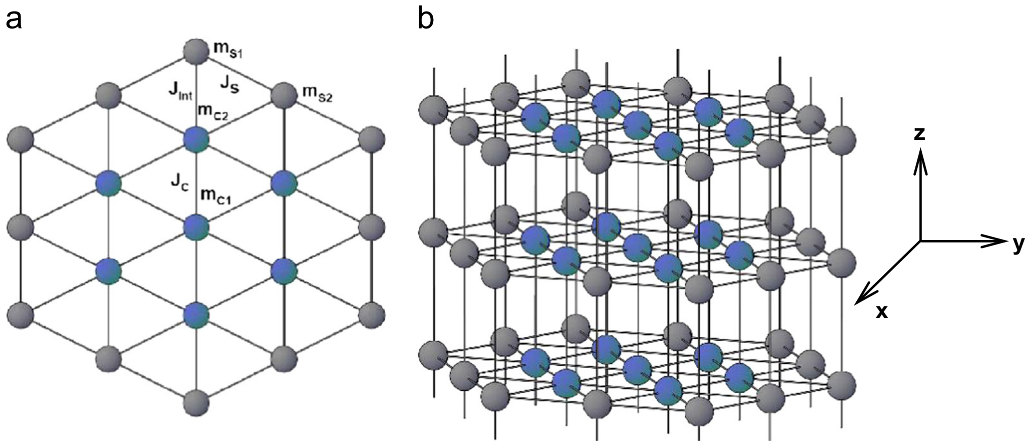

Fig. 1. Schematic representations of a cylindrical nanowire: (a) cross-section and (b) three-dimensional. The gray and blue circles indicate spin-1/2 Ising particles at the surface shell and core, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

surface shell and core, and each site is occupied by a spin-1/2 Ising particle on figure. Here, Fig. 1(a) shows as two dimensional (2D) which it is difficult to see the interactions between layers. Moreover, we also presented the schematic representation of a cylindrical nanowire in three dimensional (3D) in Fig. 1(c). Each spin is connected to the two nearest-neighbor spins on the above and below sections along the cylinder with an exchange interaction. So the Hamiltonian of the system can be expressed as

$$H - J_S \sum_{\langle ij \rangle} S_i S_j - J_C \sum_{\langle mn \rangle} S_m S_n - J_{Int} \sum_{\langle im \rangle} S_i S_m - h(t)\left(\sum_{\langle i \rangle} S_i + \sum_{\langle m \rangle} S_m \right), \quad (1)$$

where J_S, J_C and J_{Int} are the exchange interaction parameters between the two nearest-neighbor magnetic particles at the shell surface, core and between shell and core, respectively. Moreover, J_c and J_s are also interactions parameters between layers. Spin S_i takes the values $\pm 1/2$ at each site i of a cylindrical Ising nanowire system and the indexes $\langle ij \rangle$, $\langle mn \rangle$ and $\langle im \rangle$ denote the summations over all pairs of neighboring spins at the shell surface, core and between shell and core, respectively. The surface exchange interaction, namely J_S and coupling parameter, namely r, are often defined as $J_S = J_C(1+\Delta_S)$ and $r = J_{Int}/J_C$, respectively, in order to clarify the effects of surface on the physical properties in the nanosystem [13–15]. $h(t)$ is a time-dependent external oscillating magnetic field and is given by

$$h(t) = h_0 \sin(wt), \quad (2)$$

where h_0 and $w = 2\pi\nu$ are the amplitude and the angular frequency of the oscillating field, respectively. The system is in contact with an isothermal heat bath at absolute temperature T_A.

Kaneyoshi and co-workers [50] has described the EFT with correlations, which is a more advanced method dealing with Ising systems than the mean-field theory (MFT). Within the framework of the EFT with correlations, one can easily find the magnetizations m_{S1}, m_{S2}, m_{C1} and m_{C2} as coupled equations, for the cylindrical Ising nanowire system as follows:

$$m_{s1} = [\cosh(J_S\nabla) + m_{s1} \sinh(J_S\nabla)]^2 [\cosh(J_S\nabla) + m_{s2} \sinh(J_S\nabla)]^2$$
$$[\cosh(J_{Int}\nabla) + m_{C2} \sinh(J_{Int}\nabla)]^2 f(x+h)|_{x=0}, \quad (3)$$

$$m_{s2} = [\cosh(J_S\nabla) + m_{s2} \sinh(J_S\nabla)]^2 [\cosh(J_S\nabla) + m_{s1} \sinh(J_S\nabla)]^2$$
$$[\cosh(J_{Int}\nabla) + m_{C2} \sinh(J_{Int}\nabla)] f(x+h)|_{x=0}, \quad (4)$$

$$m_{C1} = [\cosh(J_C\nabla) + m_{C1} \sinh(J_C\nabla)]^2 [\cosh(J_C\nabla)$$
$$+ m_{C2} \sinh(J_C\nabla)]^6 f(x+h)|_{x=0}, \quad (5)$$

$$m_{C2} = [\cosh(J_C\nabla) + m_{C2} \sinh(J_C\nabla)]^4 [\cosh(J_C\nabla) + m_{C1} \sinh(J_C\nabla)]$$
$$[\cosh(J_{Int}\nabla) + m_{s1} \sinh(J_{Int}\nabla)]^2 [\cosh(J_{Int}\nabla)$$
$$+ m_{s2} \sinh(J_{Int}\nabla)] f(x+h)|_{x=0}, \quad (6)$$

where $\nabla = \partial/\partial x$ is a differential operator. The functions $f(x+h)$ are defined by

$$f(x+h) = \tanh(\beta(x+h)), \quad (7)$$

where $\beta = 1/k_B T_A$, T_A is the absolute temperature and k_B is the Boltzman factor.

In this point, we can obtain the set of the dynamical effective-field equations by means of the Glauber-type stochastic dynamics. We employ the Glauber transition rates, which the system evolves according to the Glauber-type stochastic process at a rate of $1/\tau$ transitions per unit time. Hence, the frequency of spin flipping, f, is $1/\tau$.

$$\tau \frac{dm_{S1}}{dt} = f(m_{S1}, m_{S2}, m_{C2}), \quad (8a)$$

$$\tau \frac{dm_{S2}}{dt} = g(m_{S1}, m_{S2}, m_{C2}), \quad (8b)$$

$$\tau \frac{dm_{C1}}{dt} = h(m_{C1}, m_{C2}), \quad (8c)$$

$$\tau \frac{dm_{C2}}{dt} = k(m_{S1}, m_{S2}, m_{C1}, m_{C2}), \quad (8d)$$

the explicit formulation of dynamic magnetizations are given in Ref. [49].

3. Numerical results and discussions

In this section, we investigate behavior of time variations of average order parameters to find phases in this system. Then, we calculated phase diagrams in the different planes, namely the (T, h), (r, T) and (Δ_S, T) planes. We have fixed $J_C = 1.0$ and $k_B = 1.0$ throughout of the paper.