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Unique magnetic properties of an Ising nanowire with a spin glass like disorder at the surface

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ABSTRACT

The phase diagram and magnetizations in an Ising nanowire based on the core–shell concept are examined by using the effective-field theory with correlations. The nanowire is constructed from the ferromagnetic core and the spin glass like disordered surface shell. The effects of surface disorder and interlayer coupling between the core and the shell on the magnetic properties are examined. We have found a lot of novel phenomena in them.

1. Introduction

Currently, magnetic nanomaterials, such as nanoparticles, nanofilms, nanowires, nanotubes and so on, have been attracted considerable attention experimentally and theoretically, because of not only their academic interest, but also their technological applications. When the size of a magnetic material decreases to a nanometer scale, the magnetic and electronic properties become different from bulk counterparts. The physics of these effects governs the nanomagnetism of a material and points to the new way of finding important possible applications. In these nanosystems, surface effects particularly give the distinct contributions to the magnetic properties, since a large fraction of the atoms in them exist at the surface. They become more important when reducing the size of the materials. For nanoparticles, it is generally assumed experimentally and theoretically that the core–shell model is well satisfied, where the core often takes a ferromagnetic (or antiferromagnetic) spin configuration, while the shell at the surface shows a spin glass like disordered configuration [1,2]. For these nanosystems, hysteresis loops which are important for the manufacture of magnetic recording media are normally examined experimentally and theoretically. For nano-scaled thin films, furthermore, the thickness dependence of transition temperature, the temperature dependence of magnetization and the critical exponent β in ultra-thin films have been obtained experimentally by the use of some elaborate experimental techniques [3–5]. The magnetic nanowires and nanotubes have been synthesized by a wide variety of techniques and they are also applied to nanotechnology [6].

In order to understand the magnetic behaviors of nano-scaled systems, various model systems consisting of the core–shell structures have been examined by using various theoretical techniques. Mean field theory (MFA), effective field theory with correlations (EFT) and Monte Carlo simulation (MC) are the most commonly used theoretical methods for obtaining the magnetic properties of these nanosystems. The EFT [7,8] corresponds to the Zernike approximation [9] and it is believed to give more exact results than those of the MFA. The recent works for nanosystems [10,11] prove that the results obtained from the EFT have the same topology as those obtained from the MC, while the results obtained from the MC are smaller than those of the EFT. For instance, a variety of magnetic properties in a cylindrical Ising (or transverse Ising) nanowire (or nanotube) have been examined by the use of the EFT [12]. In these works, the effects of site dilution at the surface on them have been discussed. The effects of the random magnetic field distributions on the phase diagrams of the Ising nanowire have been also discussed within the EFT [13,14]. As far as we know, however, there is not any work in which the magnetic properties of a cylindrical Ising nanowire with a spin glass like disorder at the surface are examined.

In the recent works [15], the remarkable influences of interlayer coupling J_1 between the surface (shell) and the core (inner layers) on the magnetic properties in the ultra-thin Ising films with site and bond dilutions at the surfaces have been clarified by

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the use of the EFT. In particular, when the value of r ($r = J_1/J$, where J is the inner layer coupling) is taken as a very small or a very large value, some interesting phenomena have been found in the magnetic properties of the systems with thickness L (from $L=3$ to $L=10$), such as the appearance of a broad maximum in the variation of transition temperature (T_C) as a function of r for the site dilution, while such a phenomenon has not been obtained for the bond dilution. In [16], the possibility of reentrant phenomena in the transverse Ising nanowire which is free from disorder induced frustration has been discussed by the use of the EFT. Traditionally, the reentrant phenomena have been found in a variety of disordered magnetic systems experimentally and theoretically [17,18], especially spin glass systems in which the effects of frustration due to the change of sign in exchange interactions play an important ingredient. A ferromagnet in a random field also exhibits the reentrant phenomena, which is equivalent to the Ising antiferromagnet with randomly quenched exchange interactions in a uniform field [19]. Free from these disorder induced frustration, the reentrant phenomena of another type have been found in decorated Ising spin systems [20–22].

The aim of this work is, within the theoretical framework of the EFT, to investigate the phase diagram and the magnetizations in the cylindrical core–shell Ising nanowire with a spin glass like disorder at the surface. The effects of disorder at the surface and the core–shell coupling J_1 on the magnetic properties are examined carefully. In Section 2, the model and formulation are given. In Section 3, the phase diagrams and the thermal variations of magnetizations are examined. We find many characteristic phenomena in them, such as the two types of reentrant phenomena induced by the frustration due to the spin glass like disorder at the surface. Section 4 includes the conclusions.

2. Formulation

The schematic representation of a cylindrical nanowire with a spin glass like disordered spin configuration at the surface is depicted in Fig. 1. It is consisted of the surface shell (gray circles) and the core (black circles). The each site in the figure is occupied by a Ising spin. The each spin is connected to the two nearest neighbor spins on the above and the below sections. The surface shell is coupled to the next shell in the core with an exchange interaction J_1.

The Hamiltonian of the two systems is given by

$$H = -\sum_{(ij)} J_{ij}\mu_i\mu_j - J\sum_{(mn)} \mu_m\mu_n - J_1\sum_{(im)} \mu_i\mu_m \tag{1}$$

where μ_i is the Ising spin operator with $\mu_i = \pm 1$. The J_{ij} in the first term is the exchange interaction between two nearest-neighbor magnetic atoms at the surface shell. It is assumed to be randomly distributed according to the probability distribution function

$$P(J_{ij}) = (1/2)\left[\delta(J_{ij} - J_S) + \delta(J_{ij} + J_S)\right], \tag{2}$$

in order to realize the spin glass like disorder in the surface shell, when the value of J_1 is zero. The J_S is often defined as

$$J_S = J(1 + \Delta_S), \tag{3}$$

in order to clarify the effects of surface on the physical properties in the system. The J in the second term of (1) is the exchange interaction in the core.

Let us at first define the total magnetization m_T per site in the nanowire as follows:

$$m_T = (1/19)[12m_S + 6m_B + m_C], \tag{4}$$

with

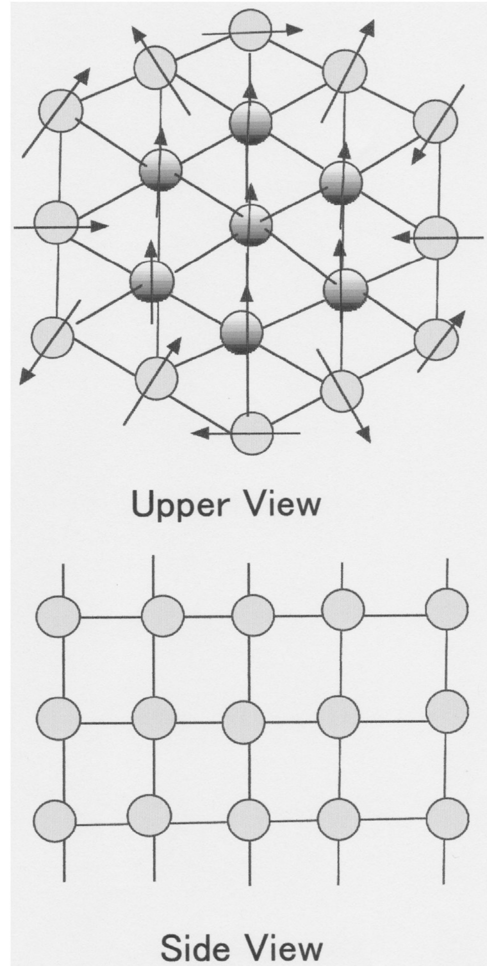

Fig. 1. Schematic representations of a cylindrical nanowire with a spin glass like disorder at the surface. The gray circles represent magnetic atoms at the surface shell. The black circles are magnetic atoms constituting the core. The lines connecting the gray and black circles represent the nearest-neighbor exchange interactions (J_S, J_1 and J). The arrows represent the spin directions.

$$m_S = (1/2)(m_{S1} + m_{S2}), \tag{5}$$

where m_S is the averaged magnetization per site at the surface shell.

For the nanowire depicted in Fig. 1, there exit two magnetizations ($m_{S1} = \left\langle\left\langle \mu_i \right\rangle\right\rangle_r$ and $m_{S2} = \left\langle\left\langle \mu_j \right\rangle\right\rangle_r$ where $\langle\langle A\rangle\rangle_r$ represents the random bond average of A) on the surface shell and the two magnetizations m_B and m_C ($m_\alpha = \langle\mu_m\rangle$ where α=B or C) in the core. Within the framework of the EFT, they can be given by

$$m_{S1} = \left[\left\langle \cosh\left(J_{ij}D\right)\right\rangle_r + m_{S1}\left\langle \sinh\left(J_{ij}D\right)\right\rangle_r\right]^2 \left[\left\langle \cosh\left(J_{ij}D\right)\right\rangle_r + m_{S2}\left\langle \sinh\left(J_{ij}D\right)\right\rangle_r\right]^2 [\cosh(B) + m_B\sinh(B)]f(x)|_{x=0} \tag{6}$$

$$m_{S2} = \left[\left\langle \cosh\left(J_{ij}D\right)\right\rangle_r + m_{S2}\left\langle \sinh\left(J_{ij}D\right)\right\rangle_r\right]^2 \left[\left\langle \cosh\left(J_{ij}D\right)\right\rangle_r + m_{S1}\langle \sinh\left(J_{ij}D\rangle_r\right)\right]^2 [\cosh(B) + m_B\sinh(B)]^2 f(x)|_{x=0} \tag{7}$$