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Hysteresis behavior of Blume–Capel model on a cylindrical Ising nanotube

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ABSTRACT

We have investigated Blume–Capel model on a cylindrical Ising nanotube by using the effective field theory with correlations. Hysteresis loops, magnetic susceptibility and coercivities have been calculated numerically for ferromagnetic and antiferromagnetic cases. When interactions are low between the core and shell sites, double and triple hysteresis loops can be seen in the system for ferro- and antiferromagnetic interactions, respectively. The effect of temperature has been examined on hysteresis loops and dependencies of coercivity based on temperature are depicted.

1. Introduction

The fundamental concept of ferromagnetic materials is the occurrence of hysteresis due to appearance of the multiple free energy minima in the vicinity of first-order phase transition. Occupied state of a ferromagnetic material is one of these multiple states, stable or metastable, depending on its initial historical condition. The reversal external field (h) forces magnetization, m (h), to be the single-valued stable state until the field reaches large enough to suppress all metastable states. The closure field shapes the hysteresis loop. Ferromagnets have wide applications such as a "soft" ferromagnet in transformer core and a "hard" permanent magnets in hard disk, magnetic tape and motors depending on the extent of this hysteresis loop [1,2]. The further development of materials with hysteresis needs a deep understanding of their microscopic interactions and how these interactions influence their hysteresis phenomena [3].

Magnetic nanoparticles, nanodots or nanotube/nanowire, have been receiving considerable attention for recent years [4,5]. Furthermore, nano-particles have also both an important research tool in the areas of material science and diverse technological applications such as ferrofluids, permanent magnets [6], medical applications [7] and bio-technology [8,9]. An interesting magnetic nanoparticle system is that of core/shell structured nanoparticles in which the magnetic core is embedded in a non-magnetic, an antiferromagnetic, or a ferro/ferri-magnetic shell. These shells govern the core stabilization and surface functionality, wideness of coercivity [10,11]. For example, the thermal stability of ferromagnetic cobalt nanoparticles, coated with either a paramagnetic (Al_2O_3) or an antiferromagnetic matrix (CoO), has been investigated by virtue of its potential application in the ultrahigh-density magnetic recording. The magnetization curves of these substances are split under field-cooled and zero-field-cooled conditions; as a result, coercivity and superparamagnetic phases are observed in both matrices [12]. At the superparamagnetic state, even though the grains have magnetic moments, global magnetic order disappears below Curie temperature [13]. The effective couplings between the clusters increase with further decreasing temperature and it causes the system to become ferromagnetic single domain [14].

Ising model is a well-known and widely used pioneering theoretical model on the magnetic systems. The Ising model including a crystal-field or a single-ion anisotropy term was firstly introduced as a spin-1 Ising model and studied within the mean-field approximation by Capel [15] and independently by Blume [16], shortly Blume–Capel (BC) model. BC model has been studied with many techniques following decades and it is proved that it exhibits very interesting and rich critical phenomena. A hexagonal lattice of magnetic nanodots, consisting of metallic nanodots deposited onto non-magnetic insulator substrate, is studied using

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the differential operator technique with the approximated Van der Waerden identity by Bakuzis and Morais [17]. A ferromagnetic core/shell nanocube Ising model on a simple cubic lattice, assuming three different interactions among the core and the shell of the particles, has been studied by Zaim et al. [18]. They have examined the magnetic properties and hysteresis curves of single nanocube by using Monte–Carlo simulation. Kaneyoshi [19] has studied magnetizations of a nanoparticle on a concentric hexagonal ring described by the transverse Ising model. He has also investigated phase diagrams of a transverse Ising nanowire (nanotube) [20–23] by use of the effective field theory (EFT) with correlations. Recently, magnetic properties and the phase diagram of spin-1 Ising nanotube [24] and mixed spin Ising nanotube [25,26] are also extensively studied by EFT with correlations. As far as we know, the hysteresis behavior of Ising nanotube has not yet been investigated. The main purpose of this work is to understand how microscopic interactions affect hysteresis phenomena of cylindrical Ising nanotube.

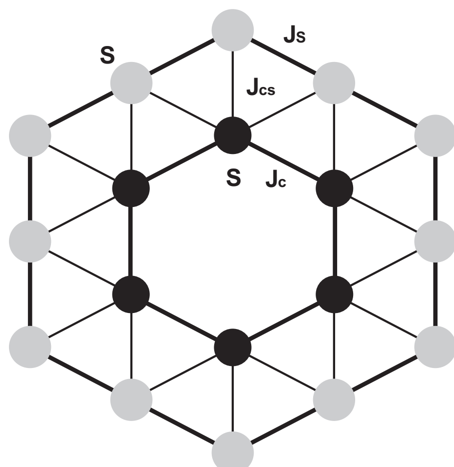

Fig. 1. Schematic representation of cylindrical nanotube. The gray and black circles indicate magnetic atoms at the surface and core shell, respectively. Two different classes of surface spins lead to specific form of Hamiltonian.

The outline of this paper is as follows: in Section 2, the model has been defined and a brief formulation of the cylindrical Ising nanotube within the theoretical framework of the EFT has been given. In the following section, the hysteresis loops and numerical results are given for both ferromagnetic and antiferromagnetic interactions between the shell and the core of Ising nanotube. Finally, the last section is devoted to concluding remarks.

2. Model and formulation

We have considered a cylindrical core/shell nanotube model, as shown in Fig. 1. A nanotube mainly consists of two parts, i.e., the core and the surface shells, and the core is surrounded by the surface shell. Each site on the lattice is occupied by an Ising spin. Moreover, each spin has connection to the two nearest-neighbor spins on the above and below sections along the cylinder, i.e., Fig. 1 is a two-dimensional projection of infinite cylindrical nano-tube. This ensures the thermodynamic limit.

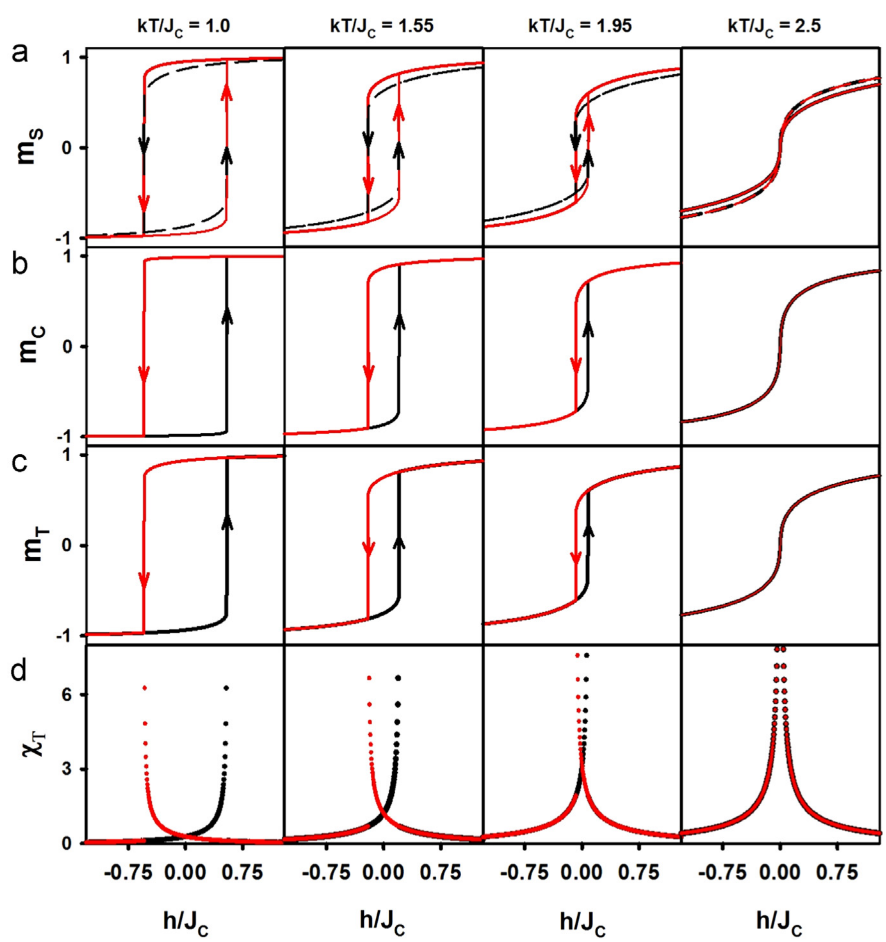

Fig. 2. (Color online) The variation of hysteresis loops and total susceptibility with reduced external field for $J_{cs}/J_c = 1.0$ and $D/J_c = -2.7$ at which the temperatures are given at top of the figures. The ascending and descending external field directions are represented by arrows on the each magnetization curve.