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The role of dipolar interactions for the magnetic properties of ferromagnetic nanoring

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ABSTRACT

We investigate numerically the effects of the dipolar interactions on magnetic properties in small ferromagnetic nanorings using a Monte Carlo technique. Our simulated results show that the strength of dipolar interaction in the magnetic nanoring has an important influence on the magnetization reversal processes and further the coercivity and the remanence. As the dipolar interaction increases, the transition of magnetization reversal processes from the onion-rotation state to the vortex state can occur, which results in an increase in coercivity and a decrease in remanence. On the other hand, it is found that the coercivity and the remanence depend more strongly on the strength of dipolar coupling for the relatively small size nanoring than for the large size nanoring in width. This can be attributed to the stable vortex state without core in smaller width nanoring in contrast to the metastable vortex state with core in larger width nanoring, induced by strong dipolar interactions. Additionally, the temperature dependence of coercivity and remanence in magnetic nanoring is also studied at a fixed dipolar interaction.

1. Introduction

Recently, a great number of studies have been actively conducted on the ferromagnetic nanorings driven by its potential application for magnetic random access memory [1–9]. In contrast to the circular magnetic disk where the transition from the vortex state to the single-domain state can occur below a threshold value of its radius owing to the high exchange energy of the vortex core, in the magnetic nanoring the vortex state can be stably retained on a similar size scale because of the absence of vortex core. Based on the stable vortex state, the magnetic nanoring is expected to be a suitable data storage element or logic element for applications of magnetic electronic devices [2].

The previous results have shown that the magnetic transition of nanorings occurs mainly via two types of processes, i.e., the onion state and the vortex state, depending on their sizes (thickness, diameter and width) [3,11], geometric shapes [12,13], and magnetic parameters [14]. In practices, which state dominates over the reversal processes is based on the consequences of competition between exchange energy, magnetostatic energy, magnetcrystalline anisotropy, and Zeeman energy. The exchange energy favors the parallel alignment of all spins while the magnetostatic energy favors magnetic closure structure with no stray field. Moreover, the long-range dipolar interaction is often ignored in theoretical studies of magnetic properties in bulk materials in view of its very small magnitude compared to the exchange interaction. For nanoscale materials, however, the dipolar interaction should be carefully treated as it may compete with short-range exchange energy due to its long-range character and position dependence. In the case of the small size nanoring, the dipolar interactions, as a primary source to the magnetostatic energy, should be included for the computation of the total energy.

In the present work, we carry out a systematical study of magnetic properties as a function of dipolar interactions in small ferromagnetic nanorings with the Monte Carlo method. It is found that the magnetic configurations and consequently the coercivity and remanence of magnetic nanoring depend on the dipolar interactions. As the dipolar interactions increase, the coercivity increases and the remanence decreases. We also study the dependence of the coercivity on temperature for different size nanorings in width at a fixed dipolar interaction.

2. Spin model and computational details

An individual magnetic nanoring of monolayer thickness is considered. As usual, the magnetic states of a nanoring can be determined by several competing energies: exchange energy, magnetostatic energy, Zeeman energy, and magnetocrystalline

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anisotropy. In this paper, we are mainly interested in the soft magnetic materials like the permalloy where the magnetocrystalline anisotropy is very weak compared to other energies, so the magnetocrystalline anisotropy can be safely neglected. Thus, the energy of the magnetic nanoring consists of three terms: the short-range exchange energy, the long-range dipolar interaction, which is a key source of magnetostatic energy, and Zeeman energy. The magnetic nanoring can then be described by the following Hamiltonian

$$\mathcal{H} = E_{ex} + E_{dip} + E_H \tag{1}$$

with

$$E_{ex} = -J\sum_{\langle ij\rangle} \vec{s}_i \cdot \vec{s}_j \tag{2}$$

$$E_{dip} = D\sum_{\{i,j\}} \left[\frac{\vec{s}_i \cdot \vec{s}_j}{|\vec{r}_{ij}|^3} - \frac{3(\vec{s}_i \cdot \vec{r}_{ij})(\vec{s}_j \cdot \vec{r}_{ij})}{|\vec{r}_{ij}|^5}\right] \tag{3}$$

$$E_H = -\vec{H}\sum_i \vec{s}_i, \tag{4}$$

where $\vec{s}_i(\vec{s}_j)$ is a three-dimensional unit vector, representing the spin at the site $i(j)$ in the lattice. The first term on the right-hand side of Eq. (1) denotes the exchange interactions with J being the exchange energy parameter and the sum running over all nearest neighboring spin pairs i and j. The second term represents the dipolar interactions where r_{ij} is the distance between spins s_i and s_j, $D=\mu_0 g\mu_B^2/4\pi d^3$ is dipolar coupling parameter with μ_0 the permeability of the vacuum, g Landé factor, μ_B the Bohr magneton and d the lattice constant, and the sum runs over all spin pairs i and j defining the vector $\vec{r}_{ij}$. The last term is Zeeman energy from the applied field H along the x direction. Note that here the spin $\vec{s}_i$ is normalized to unity, so that the field variable H as well as the exchange parameter and the dipolar parameter has units of energy. In the calculation, the magnetic field, dipolar interactions, and temperature are measured in units of exchange parameter J.

We investigate the thermal equilibrium magnetic properties of an individual magnetic nanoring using the Monte Carlo method based on the Metropolis algorithm and single-spin flip methods. The free boundary condition is used for all directions. In the MC simulation, the relaxation time of system is given in Monte Carlo step (MCS), which is not related to a real time interval. During a MCS, a spin on average is randomly chosen for reversal with a probability $\min[1,\exp(-\triangle E/k_BT)]$ in terms of Metropolis algorithm [15,16], where ΔE is the energy difference between new and current states, and k_B is the Boltzmann constant.

In our simulation, the dipolar interactions are computed accurately without any cutting. For calculating a complete hysteresis loop, 2×10^5 MCS per spin are used for computing average results after discarding 2×10^5 MCS per spin for acquiring a thermal equilibrium. The parameters used are taken to be $J=20$ meV fixed and $D=\gamma J=[0,0.4]J$ [17], where $\gamma=D/J$ describes the relative strength of the dipolar interaction to the exchange energy. The outer and inner radii of the magnetic nanoring are denoted as R_1 and R_2 in units of lattice constant, and thus its width can be approximately obtained by $w=R_1-R_2$. The external magnetic field is always applied in the x direction, and hence only the x-components of the magnetizations are presented in the following hysteresis loops.

3. Results and discussions

In Fig. 1, we show the hysteresis loops of the magnetic nanoring with the outer and inner radii $R_1=21$ and $R_2=17$ for different dipolar interactions. We take five γ values ranging from 0 to 0.4 based on the fact that the dipolar interaction is usually one or two orders of magnitude less than the exchange interaction. It can be seen that the coercivity increases and the remanence decreases with increasing γ values, i.e., the strength of dipolar interactions. This can be a consequence of a transition of magnetization reversal processes from the onion magnetic state to the vortex magnetic state as the dipolar interaction increases. Besides, we find that below $\gamma=0.04$, the shape of hysteresis loops changes only slightly with γ, but above this value, an obvious increase in coercivity and a decrease in remanence take place with γ increasing.

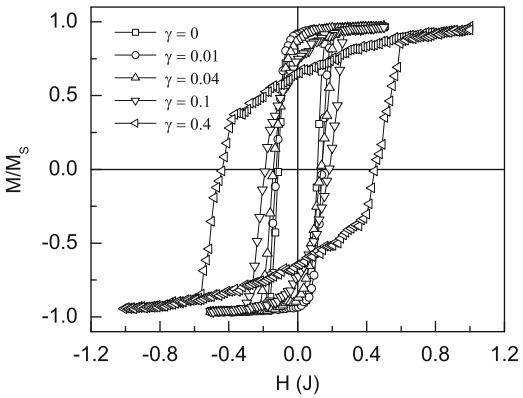

Fig. 1. The hysteresis loops of the magnetic nanoring (outer radius: $R_1=21$ and inner radius: $R_2=17$) for $\gamma=0,0.01,0.04,0.1,0.4$.

In order to gain a deep insight into magnetization reversal processes, we present magnetic configurations for the intermediate states of the above nanoring during reversal at two γ values 0.01 and 0.4, as shown in Fig. 2. In the case of $\gamma=0.01$, the nanoring's magnetic state is approximately a single-domain state at point A, and as the field is increased along the negative direction, several domain-walls appear at point B, and finally the magnetic state transforms to the single-domain state at point C, as shown in Fig. 2(a). For $\gamma=0.4$, i.e., the larger dipolar interaction, the magnetic transition occurs via the onion state at point D, and the vortex state at point E, and finally the onion state at point F, as shown in Fig. 2(b). Clearly, the large dipolar interaction gives rise to the vortex state, and then results in an increase in coercivity and a decrease in remanence. The magnetic transition processes at the large dipolar interaction are similar to those in experiments [3,11].

To have a completing understanding of the effects of dipolar interaction on the magnetic properties of the nanorings, we give a systematical investigation on the magnetic nanorings of various width with the outer radius $R_1=31$ fixed and variable inner radius $R_2=27$, 20, 11, 6, i.e., width $w=4$, 11, 20, 25. Shown in Fig. 3 are the coercivity and the remanence as a function of γ for the magnetic nanoring of different widths. For the case of $\gamma=0$ or very small γ values, there is no obvious difference from the coercivity and remanence of different nanorings. Above $\gamma=0.1$, the coercivity increases approximately linearly with γ by different slopes, depending on the width of magnetic nanoring (see Fig. 3(a)), and at the same time the remanence decreases with increasing γ values (see Fig. 3(b)). For a large dipolar interaction, the coercivity (remanence) of the small width nanoring is larger (smaller) than the large width nanoring. The different influences of dipolar interactions on magnetic properties are closely related to the magnetic transition processes of different nanorings.

Finally, we also study the temperature dependence of coercivity and remanence for magnetic nanorings with different