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Monte Carlo simulation for thermal assisted reversal process of micro-magnetic torus ring with bistable closure domain structure

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ABSTRACT

Monte Carlo simulations were performed for temperature dependences of closure domain parameter for a magnetic micro-torus ring cluster under magnetic field on limited temperature regions. Simulation results show that magnetic field on tiny limited temperature region can reverse magnetic closure domain structures when the magnetic field is applied at a threshold temperature corresponding to intensity of applied magnetic field. This is one of thermally assisted switching phenomena through a self-organization process. The results show the way to find non-wasteful pairs between intensity of magnetic field and temperature region for reversing closure domain structure by temperature dependence of the fluctuation of closure domain parameter. Monte Carlo method for this simulation is very valuable to optimize the design of thermally assisted switching devices.

1. Introduction

Recently, thermally assisted magnetic reversal processes are predicted to be used as the new recording technique for high-density magnetic memories with high magnetic anisotropy [1,2]. The basis of this technique is to magnetically record on high-density media when the coercivity, which has large value at lower temperature due to the high anisotropy, becomes weaken by increasing temperature e.g. using a focused laser beam. It is important to identify the most effective temperature range for recording, to most efficiently use the applied magnetic field energy, although such estimation seems insufficient for concrete needs. One of the reasons why simulations have not taken much the estimation issue up that to analyze the effect of temperature is slightly difficult to deal with, especially for LLG simulations that are popular in micro-magnetic analysis. On the other hand, Monte Carlo (MC) simulations would have a potential to solve such estimation problems concerned with temperature. This paper discusses the application of MC simulation for thermally assisted magnetic reversal processes, using micro-magnetic torus rings to illustrate the method.

Micro-magnetic torus rings have attracted a lot of attention from both experimental and theoretical research, because of the possibility of developing high-density storage devices [3,4]. The torus rings have bistable closure domain (CD) structures, clockwise (CW) or counterclockwise (CCW) directions. The direction of CD can be switched by rotational magnetic fields due to a linear current I penetrating the center of the ring as shown in Fig. 1(a). But the stable CD structure at low temperature requires a large magnetic field to reverse the direction because the process includes the generation of magnetic reversal nuclei. Difficulty with reversing the CD structure will be overcome by thermally assisted processes as shown above. We will show the easier reversal process by thermal assistance using Monte Carlo (MC) method and the suitable temperature range to apply magnetic field for producing a seed of a reverse vortex and for growing the rigid reverse CD structure through a cooling process without any disturbing.

2. Simulation method

A magnetic torus ring was prepared with a major radius $R=8$ and a minor radius $r=3$ as shown in Fig. 1(b). The ring is a cluster composed of 1764 spins standing for the single-cubic lattice with a lattice constant $L=1$. For the cluster, the simulation is performed using a MC method with an applied rotation magnetic field produced by the linear electric current I along z-axis to be set at the center of the ring. In this simulation, the following Hamiltonian is used;

$$H = H_J + H_D + H_B = -\sum_{\text{near}} J_{ij}\mathbf{S}_i\cdot\mathbf{S}_j + D\sum_{\text{all}}\left(\frac{\mathbf{S}_i\cdot\mathbf{S}_j}{|\mathbf{r}_{ij}|^3} - \frac{3}{|\mathbf{r}_{ij}|^5}(\mathbf{S}_i\cdot\mathbf{r}_{ij})(\mathbf{S}_j\cdot\mathbf{r}_{ij})\right) + B\sum_i \mathbf{S}_i\cdot \quad (1)$$

Each term of H_J, H_D and H_B represents the exchange interaction

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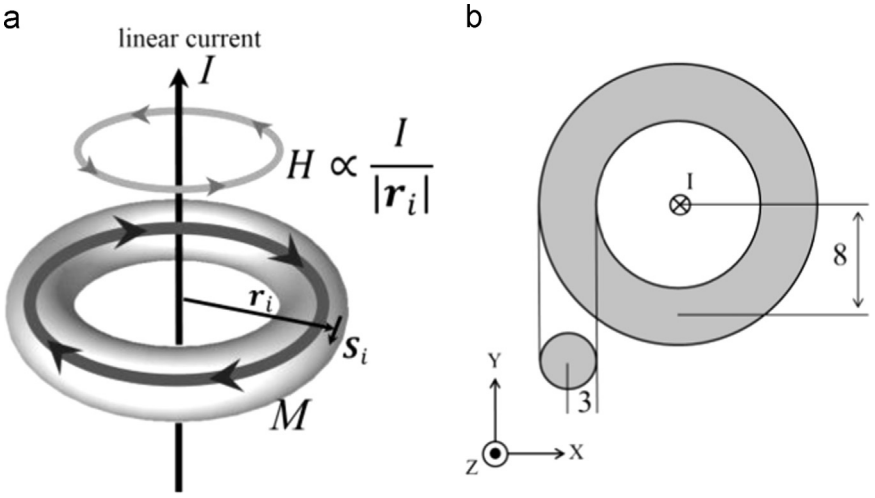

Fig. 1. (a) Schematic view for a magnetic torus ring and rotational magnetic field H due to linear electric current I and (b) diagram for torus ring cluster with a major radius of $R=8$ and a minor radius of $r=3$.

energy, magnetic dipole interaction energy and applied magnetic field energy (Zeemann energy), respectively. Here S_i denotes the magnetic moment of the magnetic site of the i-th cell and r_{ij} represents the vector between the i-th and j-th sites. In the first term H_J, J_{ij} stands for the exchange interaction energy constant for i-th and j-th sites. The exchange interaction works between nearest neighbor sites. In the second term H_D, D stands for the magnetic dipole interaction constant. The magnetic dipole interaction works on all magnetic sites because it is due to magnetic field interspersed in all space. In the third term of H_B, B represents applied rotational magnetic field along the circumference direction of the ring due to a supposed linear electric current I, namely B is in proportion to I/r_{spin}, here r_{spin} is the distance between the center of the ring and each of the spins. The changing of S_i on MC simulation progresses as spin-flips by Metropolis sampling [5–7]. The random sampling is iterated sufficiently with acceptance probability $e^{-\Delta E/k_BT}$ at constant temperature k_BT. Here, ΔE is the energy difference between the two state that calculated from Eq. (1). For same physical condition under cooling processes, the calculations are repeated until 100 times with different seeds of the random number series and the pair results with the same random series are used for comparing between different conditions.

In this simulation, the parameters were set as $J_{ij}=1.0$, $D=0.1$ and S_i was set as $|S_i|=1$. Temperature k_BT is scaled by the $J_{ij}=1.0$ as a unit of energy; k_BT/J. For details of MC methods for magnetic dynamic process, see the references [8,9].

3. Results and discussion

Fig. 2 shows the temperature dependence of the CD parameter M_ϕ without any magnetic fields; $I=0$. Here the CD parameter M_ϕ represents the degree of the CD state and that is set:

$$M_\varphi = \frac{1}{N}\sum_i \left(\frac{\mathbf{r}_{spin}}{|\mathbf{r}_{spin}|}\times S_i\right) \quad (2)$$

Here, N is the total magnetic site number [10]. Under the different random number series used for this MC calculation, the CD structures have a half probability for CCW direction; $M_\phi=+1$, and CW direction; $M_\phi=-1$ at the lowest temperature, respectively. The Currie temperature k_BT_C/J is around 1.5 as shown in Fig. 2.

Linear electric current I dependences of M_ϕ were calculated for different temperatures as shown in Fig. 3. The results show hysteresis curves with a coercivity of $I=\pm 20$ at lowest temperature

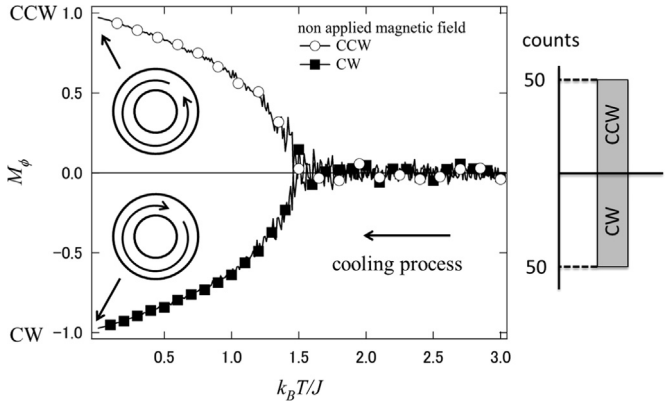

Fig. 2. Temperature dependence of CD parameter M_ϕ without any magnetic fields; $I=0$. For 100 times trial using different random number series, results show generating of 50 CCW state and of 50 CW state respectively.

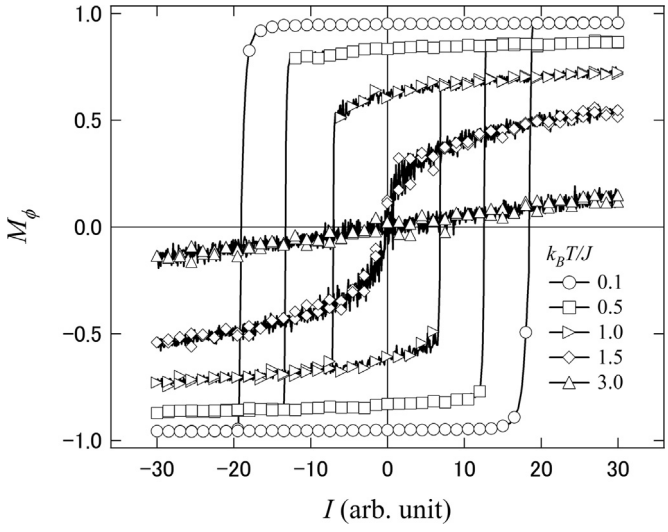

Fig. 3. Linear electric current dependence of M_ϕ for different temperatures; $k_BT/J=0.1$, 0.5, 1.0, 1.5 and 3.0.

$k_BT/J=0.1$. Hence the CD structure can not be reversed between the CCW and CW directions under a rotation magnetic field due to $|I|<20$ at the lowest temperature.

Next, the temperature dependences of M_ϕ were calculated