Monte Carlo Simulation for Magnetic Dynamic Process of Deformed Micro Magnetic Clusters

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Magnetic hysteresis and Barkhausen noise for deformed micro magnetic clusters were simulated by pseudo-nonequilibrial Monte Carlo method. The magnetic hysteresis curve showed a little dip around zero magnetic fields. Barkhausen noise on the dip was stronger than ordinal Barkhausen noise around coercive force. The result suggests a new measurement to reveal deformation of micro magnetic clusters.

***Index Terms*—Magnetic hysteresis modeling, magnetization processes, Monte Carlo method.**

I. Introduction

RECENTLY there have been many experimental reports for magnetic dynamic process and micro magnetic clusters such as quantum dots or nano-wires [1]–[9]. These studies will be available to realize high density magnetic memories or micro magnetic device. The deformation of these clusters, however, has not been considered sufficiently, although it affects the magnetic properties. In the near future, control of the deformation of micro magnetic clusters would be taken up as an important product process for keeping up the high magnetic properties.

We have studied magnetic dynamic process, such as hysteresis and Barkhausen noise using pseudo-nonequilibrial Monte Carlo (MC) method [10]–[15]. In this paper we will present the relation between deformation of magnetic cluster and magnetic properties.

II. Numerical Method

At first, a spin system composed of $31^2 = 961$ cells $(0 \leq \mathrm{x} \leq 30, 0 \leq \mathrm{y} \leq 30, \mathrm{Z} = 0)$ standing for a single square lattice was prepared as normal spin system. The lattice constant is 1 and this is regard as criterion of length. Next a deformed spin system was modeled on the normal spin system introducing loop dislocation as shown in Fig. 1. A simple Hamiltonian was used for the simulation as follows:

$$H = -\sum_{i,j} J_{ij} S_i S_j + B \sum_i S_i. \tag{1}$$

Here S_i denotes the spin state of ith cell, and J_{ij} stand for the effective exchange energy for ith and jth spins. B represents applied magnetic field. Here, we adopt the physical model of J_{ij} as a step function, namely

$$J_{ij} = \theta(1 - r_{ij}) = \begin{cases} 1(r_{ij} \leq 1) \\ 0(r_{ij} > 1) \end{cases} \tag{2}$$

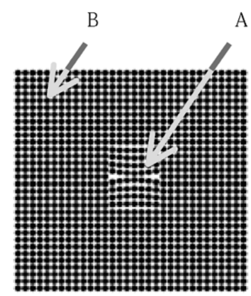

Fig. 1. Deformed spin system introducing loop dislocation [17]–[21].

where r_{ij} denotes the distance between ith and jth spins. Although the exchange energy of this model is supposed to be overestimated comparing with real magnetic materials, it will be allowed for the purpose to derive intrinsic effect of local deformation of crystal structure for dynamic magnetic process. For example, Europium Oxide (EuO), which is well known as typical magnetic semiconductor, has dominant exchange energy J_1 represented as exponential function of the distance between each site due to RKKY interaction, that is, the exchange interaction decreases rapidly as the distance increases. In the case that the lattice deformation becomes large, the distribution of J_1 could be regarded as a function similar to (2).

In general, MC method deals with thermal equilibrium state. Therefore usually MC steps are repeated until getting a stable state [16]-[22]. Here 1 MC step (MCS) means scanning up to the total cell number of times for the spin-flip process. But now we stopped the repeating before getting a stable state because of dealing with magnetic dynamic processes for BN. Under the constant magnetic field condition, the total spin is in an nonequlibrium state and going to an equilibrium state with progressing MC steps. The magnetic field slightly increases before achievement of the equilibrium state, then the total spin is kept under another nonequlibrium state again and proceeding to a new equilibrium state. The operation is renewed until achievement of final magnetic field. Because the change of the magnetic field is minute, it will be able to regard approximately that a series of steps is continuous process through an pseudo-nonequilibrium state. Here we introduce an assumption that magnetiza-

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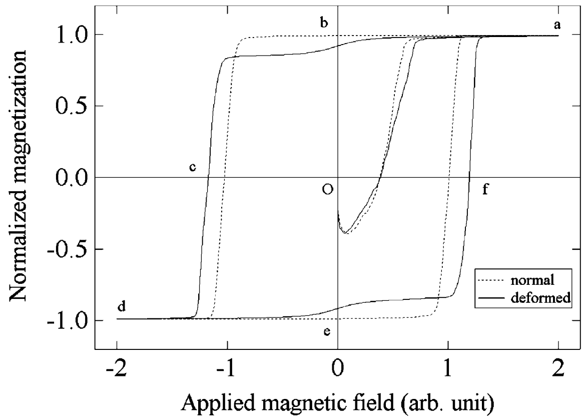

Fig. 2. M–H curve for the normal and deformed spin systems.

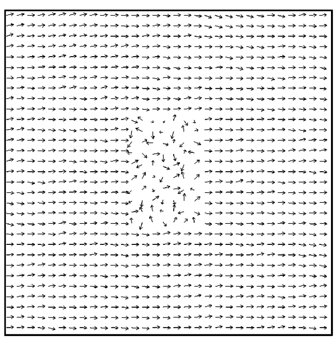

Fig. 3. Snapshot at "b" for deformed spin system.

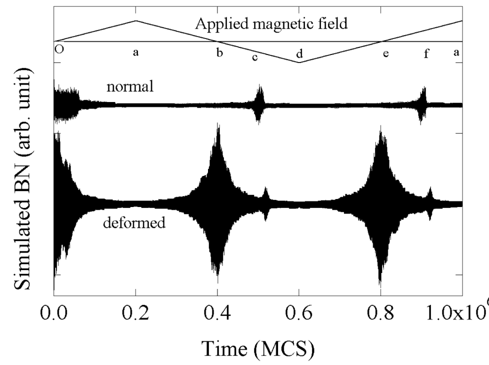

Fig. 4. Simulated BN for the normal and deformed spin systems. Time is represented using Monte Carlo step (MCS).

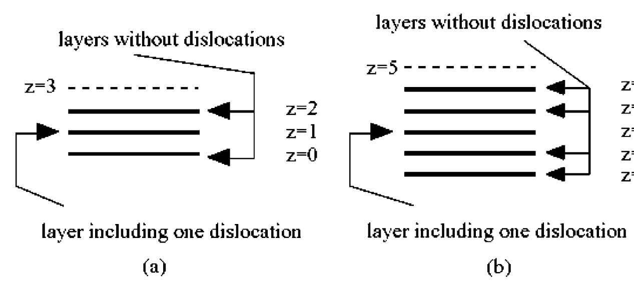

Fig. 5. Multilayer spin system intercalated layer including one dislocation. (a) 3 layers. (b) 5 layers.

tion intensity (M), namely the summation of total spin, of each Monte Carlo step can reflect the magnetic dynamic process on magnetic hysteresis. In this study, therefore we perform differential calculus $\mathrm{dM/d(MCS)}$ of the magnetic process for applied magnetic field and deal with the discrete components of $\mathrm{dM/d(MCS)}$ as simulated BN. Note that MCS on our simulation alternates time (t) on real system. For more details, see [12].

III. Results and Discussion

Fig. 2 shows the magnetic field dependence of magnetization (M–H curve) for the normal and deformed spin systems under applied magnetic field formed as triangle wave along the magnetic processes of $\mathrm{O} \rightarrow \mathrm{a} \rightarrow \mathrm{b} \rightarrow \mathrm{c} \rightarrow \mathrm{d} \rightarrow \mathrm{e} \rightarrow \mathrm{f} \rightarrow \mathrm{a}$. The M–H curve for the deformed spin system has dull shrinks around "b" and "e" which can not be seen for the normal spin system. Snapshot of spin configurations at "b," for the deformed spin system is shown in Fig. 3. It is clearly seen that many spins fluctuate around a loop dislocation. The exchange interaction J_{ij} as a step function would cause anisotropy of Hamiltonian for each spin differently in the area around the loop dislocation. The state may be regard as magnetic crystal introducing partially spin glass.

Simulated BN of the magnetic process of $\mathrm{O} \rightarrow \mathrm{a} \rightarrow \mathrm{b} \rightarrow \mathrm{c} \rightarrow \mathrm{d} \rightarrow \mathrm{e} \rightarrow \mathrm{f} \rightarrow \mathrm{a}$ are shown in Fig. 4 for the normal and deformed spin systems. The great discrepancy between the two spin systems is the existence of large BN around "b" for the deformed spin system. The lowering of the absolute value of the magnetization is not so much around "b" for even the deformed spin system, however, the peak of the BN at "b" for the deformed spin system is dominant over all.

For the real materials, such a deformed area is submerged in the system including plenty normal spin area. Then multilayer spin systems are also prepared as shown in Fig. 5. Fig. 5(a) shows 3 layers spin system which includes two normal layers $(\mathrm{z} = 0, 2)$ without any dislocation loops to be piled on the both sides of the layer $(\mathrm{z} = 1)$ including dislocation loops. Fig. 5(b) also shows 5 layers spin system composed of $\mathrm{z} = 0, 1, 3, 4$ layers without dislocations and $\mathrm{z} = 2$ layer with one dislocation. Notice that both multilayer spin systems have only one loop dislocation. The dips around zero magnetic fields on M–H curves decrease rapidly as increasing normal layers as shown in Fig. 6. For that reason the magnetization itself is not so sensitive for the local deformation in a magnetic cluster.

On the other hand there is a possibility that BN for the multilayer spin system is still sensitive for the existence of local disorder. Fig. 7 shows simulated BN for 3 layers and 5 layers spin systems in Fig. 5. The peak intensities of the anomalous BN corresponding to the dip is not so decrease for both multilayers.

Above discussion, simulated BN is dealt as the derivative of magnetization which is summation of each spin, in other words, the measurement of such a BN is performed as detecting the whole sample simultaneously using larger pick up coil than the sample. Considering the scale of the sample as a micro magnetic cluster, it seems reasonable. But now let's suppose to measure using a less detector than the sample or distribution of magnetic

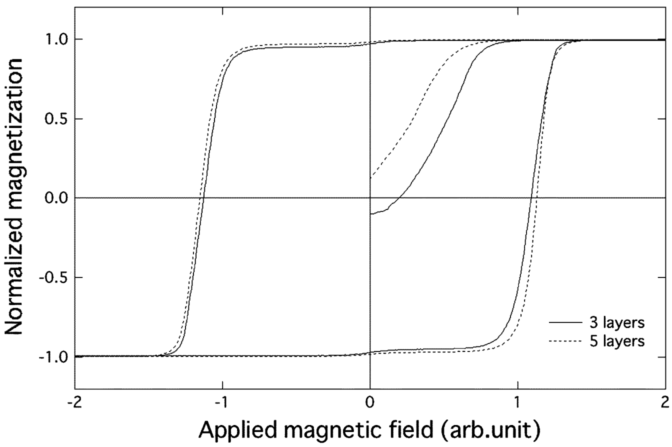

Fig. 6. M–H curve for 3 layers and 5 layers spin system in Fig. 5.

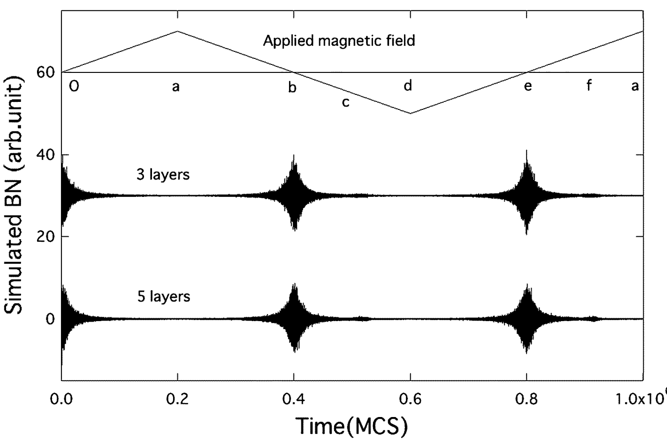

Fig. 7. Simulated BN for 3 layers and 5 layers spin system in Fig. 5.

field near the surface of the sample, which originated from magnetic moments of all spins. In general, a magnetic moment M produces a magnetic field H as the following equations:

$$H_r = \frac{M}{4\pi\mu_0}\frac{2\cos\theta}{r^3} \tag{3}$$

$$H_\theta = \frac{M}{4\pi\mu_0}\frac{\sin\theta}{r^3} \tag{4}$$

here r represents a distance between a magnetic dipole and a location for observation of magnetic field. The direction of r is at an angle of θ to the direction of magnetic dipole moment. M represents strength of magnetic dipole moment and μ_0 is permeability of vacuum, but now for simplicity $\mathrm{M}/4\pi\mu_0$ is set as 1. At a location for observation, the magnetic field H is composed as summation over the contribution from all magnetic dipoles, namely spins in our model. Of course such a magnetic field H depends upon the location for observation. Here 2 locations is chosen as A point and B point in Fig. 1, that is, the center of the layer plane $(\mathrm{x} = 15, \mathrm{y} = 15)$ and the location near a corner of the plane $(\mathrm{x} = 5, \mathrm{y} = 5)$ respectively. There are lift off distances of 1 from the surface plane in both cases. Then the location of height is set as $\mathrm{z} = 1$ for 1 layer spin system as shown in Fig. 1, $\mathrm{z} = 3$, and $\mathrm{z} = 5$ for 3 layers and 5 layers as shown in Fig. 5, respectively. When external magnetic field formed as triangle wave is applied for the spin systems, the discrete change

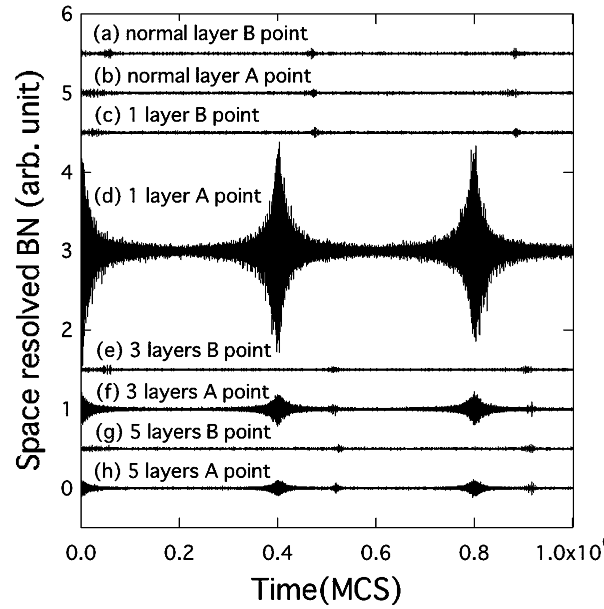

Fig. 8. Simulated space resolved BN for (a), (b) 1 layer normal spin system, (c), (d) 1 layer spin systems including one loop dislocation, (e), (f) 3 layers systems in Fig. 5 and (g), (h) 5 layer spin systems. A and B points show the area on surface in Fig. 1.

of H for time (or MCS) will give a kind of Barkhausen noise depending on the location. Then we call the Barkhausen noise simulated space resolved BN.

Fig. 8 shows the results of simulated space resolved BN for (a), (b) 1 layer without any dislocation and (c), (d) including one dislocation, (e), (f) 3 layers in Fig. 5(a) and (g), (h) 5 layers in Fig. 5(b). For a normal layer there is not much of difference of the space resolved BN between A point and B point as shown in Fig. 8(a) and (b). The result suggests the edge effect of the spin system can be neglect even B point because now the lift off distance is very small and the effect to H from farther spins is weak. On the other hand, for the 1 layer including one dislocation, there is a obvious difference between A point and B point. At A point, large anomalous BN is clearly seen in the magnetic field across the zero field as shown in Fig. 8(d). Notice that A point is just above the dislocation. But at B point of same spin system, there is no anomalous BN as same as a normal layer. The tendency remains for multilayers for Fig. 8(e) and (f), Fig. 8(g) and (h), although the peak intensity of anomalous BN becomes weakening as more layers due to increasing the distance of height between the dislocation and the observed location. The intensities of normal BNs around coercivity almost equal except for Fig. 8(d), probably owing that there are normal layers just below the location for observation.

IV. Conclusion

The above calculation results suggest high fluctuated and stressful state of spin system including local deformation. Our model for the simulation may include extreme over estimation, especially about the exchange interaction has sharp cut-off length. But the tendency will still remain in some degree for the real system. Then we may have a new measurement tool using BN for micro magnetic clusters to detect the deformation.

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