Thickness Dependence of Magnetic Hysteresis of Ising Films in Nano-thickness Range

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ABSTRACT

The hysteresis properties of the Ising films in nano-thickness range under the influence of the oscillating magnetic field are investigated via mean–field analysis by solving its equation of motion with the fourth order Runge Kutta method. From the results, the hysteresis properties are found to strongly depend on thickness and the field frequency. The hysteresis area, remanence and coercivity are found to rise with increasing film thickness due to an increase of magnetic interaction. Furthermore, with increasing field frequency, the hysteresis area and remanence are found to increase at low frequencies but decrease at high frequencies regions respectively. Nevertheless, the coercivity increases at all considered frequencies. This is caused by the phase lag between magnetization and external field becomes higher with increasing frequency and the system cannot respond promptly to the oscillating field especially at high frequencies.

Key words: Nanostructure, Magnetic hysteresis, Mean–field, Ising model

INTRODUCTION

In recent years, the magnetic films in nano-thickness range has been investigated in order to increase a real density of magnetic recording media (Cheng et al., 2004) as to search for higher storage capacities at lower costs. In this paper the Ising model is used to study the behavior of magnetic systems since both theoretical (Bander and Mills, 1988) and experimental (Elmers et al., 1994) investigations show that the magnetic thin-film behavior in the nano-thickness is an Ising-like. Moreover, this model is also found useful in understanding hysteresis properties (Acharyya, 2004).

From literatures, hysteresis area has been investigated as a function of frequency in recent decades since it represents energy dissipation in one cycle of the domain reversal. It is assumed that kinetic behavior of domain reversal is frequency dependent like hysteresis area. An understanding about this will help technologists to design and improve magnetic devices. Acharyya (1997) studied that hysteresis properties in dynamic ferromagnetic and dynamic paramagnetic phase by both Monte Carlo and mean field analysis. Furthermore, evidence of the dynamic phase transition in ultrathin Co films on a Cu(001) surface (Jiang et al., 1995) and ferroic system (Kleemann et al., 2005) were found experimentally. However, those studies do not consider the effect of an increase films-thickness on the hysteresis properties even it is know that the critical temperature increases with increasing thicknesses and this strongly alters the hysteresis properties. For instance, the hysteresis may change from dynamic paramagnetic phase to dynamic ferromagnetic phase when a material has higher critical temperature.

Therefore, this is a point of doubt what will happen to the dynamic phase transition boundary and hysteresis properties when frequency of the field and thickness are varied. To meet the answer, dynamic phase transition diagram and frequency dispersion of hysteresis properties were investigated in details using Ising model and mean field method. To outline, the hysteresis behavior of the Ising model was extracted from the mean-field equation of motion. Then, the dynamic phase boundaries were drawn to search for a suitable set of field condition which yields symmetric hysteresis loop. Next, with varying the films thicknesses and the field frequencies, the hysteresis properties under the effect of these varying parameters were reported. This is followed by discussion and conclusion which summarizes prominent finding from the study.

MATERIALS AND METHODS

In this study, magnetic system consisting of magnetic spins arranged in a reduced structure (thin-films) at nano-thickness range (less than 20 layers) under an oscillating external field was studied using Ising model. Each Ising spin consists of two different states, e.g.+1 or –1. The Ising Hamiltonian takes a form of

$$H = -J \sum_{\langle jk \rangle nn} s_j s_k - h(t) \sum_j s_j \quad , \tag{1}$$

where the spin $s_j = \pm 1$ and $h(t) = h_0 \sin(\omega t)$. h_0 and ω are amplitude and frequency of the external time (t) dependent magnetic field, respectively. Since the spin sj is dimensionless, the exchange interaction J is a unit of energy, so the field $h(t)$ has a unit of J and the unit of temperature T is J/k_B. The sum $\langle jk \rangle$ takes only on the first nearest neighbor spins.

To extract the magnetic information from Eq. (1), mean field analysis was carried out where, in this picture, all spins were replaced with an average spin where fluctuation is discarded. The mean field equation of motion for the magnetization (the average spin $m(t)$) is given by (Suzuki and Kubo, 1968)

$$\tau \frac{dm(t)}{dt} = -m(t) + \tanh \beta \langle E \rangle \quad , \tag{2}$$

where $\tau = 1$ is defined a unit of time, $\beta = 1/k_B T$, and $\langle E \rangle = h + z_{nn}$ Jm is the local field which has the same value overall the system. znn denotes the coordination number. In films structure, z_{nn} equals to $z_0 + z_1$ where z_0 is number of nearest neighbors to a lattice point in the same layer and z_1 is number of nearest neighbors in one of the adjacent layers. For example z_{nn} for square lattice, simple cubic, body centered cubic and face centered cubic are 4, 6, 8 and 12 respectively. Besides, the mean field equations of motion for the magnetization on the ith layer of the films was given by

$$\tau \frac{dm_i(t)}{dt} = -m_i(t) + \tanh \beta \left\langle E_i \right\rangle , \tag{3}$$

with the local field

$$\left\langle E_i \right\rangle = h_0 \sin(\omega t) + z_0 m_i + z_1 m_{i+1}(1-\delta_{i,l}) + z_1 m_{i-1}(1-\delta_{i,1}) \ . \tag{4}$$

where i = 1,…l is the layer index.

In order to obtain magnetization as a function of time, mean field equation Eq. (2) was solved using the fourth order Runge Kutta method with the initial for all layers and the time step $dt = P/1000$ where P is period of oscillating external field. So, there are 1000 data for evaluating hysteresis properties in each loop. With increasing more data points, the result accuracy is not significantly different. Next, the average magnetization of the films was calculated from $\bar{m} = \sum_i m_i / l$ as well as the hysteresis loop area

$$A = \int \bar{m} dh \tag{5}$$

was calculated via Trapezoidal summation technique. In addition, remanence (mr) and coercivity (hc) were also measured. Next, the dynamic order parameter

$$Q = \frac{1}{P} \int^{P} \bar{m}(t) dt \tag{6}$$

which represents the time average magnetization over a full oscillating field period was calculated. This is since it separates the dynamic ferromagnetic phase ($Q \neq 0$) from paramagnetic phase ($Q = 0$) so the dynamic phase boundary can be defined by calculating Q (Acharyya, 1997).

RESULTS AND DISCUSSION

From the results, the dynamic phase transition boundary of two dimensional (2D) magnetic systems on the field amplitude (h_0) and temperature (T) plane was extracted where the boundary was found to be frequency dependent as shown in Figure 1(a). This boundary separates dynamic ferromagnetic phase ($Q \neq 0$) from dynamic paramagnetic phase ($Q = 0$). In the dynamic ferromagnetic phase, the hysteresis is an asymmetric type, but change to symmetric type for dynamic paramagnetic phase as seen in Figure 2(a) and 2(b) in order. Furthermore, for all considered frequencies ω in Figure 1(a), as $h_0 \rightarrow 0$, the dynamic phase transition occurs at $T = Tc = 4$ J/kB . This is since when external field is absent, the magnetic system below Tc is in ferromagnetic phase and one above Tc is in paramagnetic phase. As $h_0 < 4\,J$ and $T < T_{tp}$ or $T < T_c$ and $h_0 < h_{0tp}$ (where T_{tp} and h_{0tp} are T and h_0 on the dynamic transition boundary), the system is in dynamic ferromagnetic phase in agreement with previous result from Monte Carlo simulation (Jang and Grims, 2001).

As $T \rightarrow 0$, the dynamic phase transition takes place at $h_0 = 4\,J$ for all frequencies. This is also in accordance with the previous mean field results (Tome and Oliveira, 1990; Zhu et al., 2004), the interaction between external field and spin has more influence to the system when $h_0 > 4\,J$. The energy supplied by external field is greater than spin-spin interaction, so the spin prefers to follow external field to reduce the energy of the system.

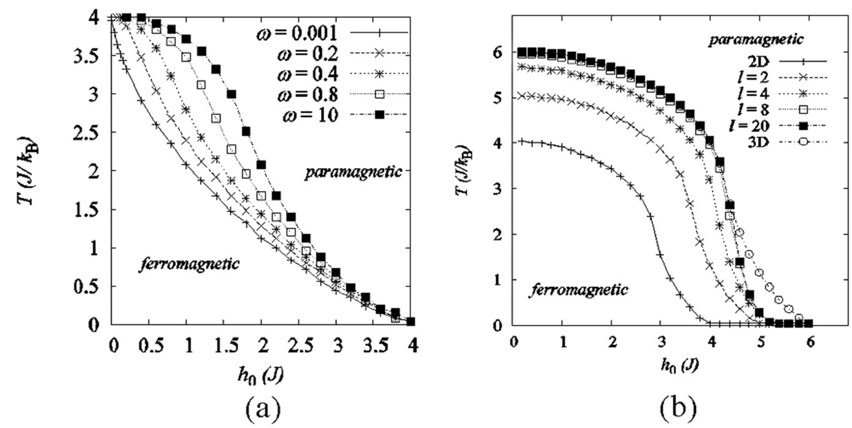


Figure 1. Diagram of dynamic phase transition boundaries on the field amplitude (h_0) and temperature (T) plane with varying frequencies for 2D system (a), and with varying thicknesses from 2D to 3D at $\omega = 10\ \tau^{-1}$(b).

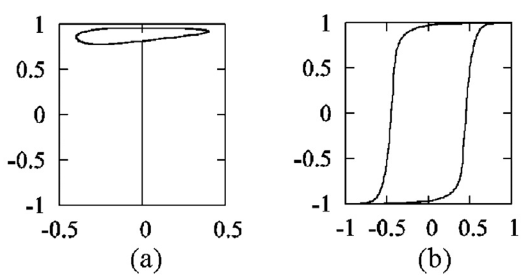
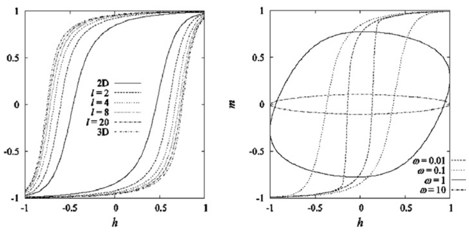


Figure 2. The 2D hysteresis loop which (a) shows asymmetric loops at $\omega = 0.5\ \tau^{-1}$, $T = 2\ J/\ k_B$ and $h_0 = 1.6\ J$, and (b) shows symmetric loops at $\omega = 0.05\ \tau^{-1}$, $T = 2\ J/\ k_B$ and $h_0 = 3\ J$.

On the other hand, with increasing the film thickness from 2D to the bulk 3D, the phase boundaries at a particular frequency (e.g. at $\omega = 10\ \tau^{-1}$) tend to move upwards as seen in Figure 1(b). This is due to the critical temperature and the interaction among spins increase with increasing thickness of the films. Moreover, Figure 1(b) shows critical temperature of each l-layered system at $h_0 \rightarrow 0$ in agreement with Monte Carlo results (Laosiritaworn et al., 2004).



(a) (b)

Figure 3. The hysteresis loops for (a) various thicknesses at $\omega = 0.5\ \tau^{-1}$, $T = 3.2\ J/k_B$ and $h_0 = 5$ J, and for (b) various field frequencies at $T = 3.2\ J/k_B$ and $h_0 = 5\ J$.

In general, the hysteresis loop with symmetric shape is most of use in applications, therefore only symmetric hysteresis loops are considered in this study. Figure 3(a) shows an example of thickness dependence of symmetric hysteresis loop. The shapes of all hysteresis loops at this frequency look similar but become broader with increasing film thicknesses from 2D to 3D. The shape-variation of magnetic hysteresis occurs due to each spin has more neighboring sites resulting in higher spin-spin interaction and larger critical temperature when thickness increases. Therefore, hc increases because the system requires more external field to reverse magnetization. In a same way, m_r gets larger for thicker films since spin-spin interaction increases.

Moreover, the shapes of hysteresis loops as various field frequencies are also shown in Figure 3(b). It takes a thin loop, expands into a broad-square shape with increasing frequencies and finally becomes a horizontal loop. This is due to the phase lag between magnetization and external field gets larger with increasing frequencies so the hysteresis loop expands with increasing frequencies. Furthermore, at a very high frequency, the system cannot respond promptly to the quickly oscillating field so loop is very narrow (Rao et al., 1990). In addition, the hysteresis properties i.e. hysteresis area, remanence and coercivity are also found to be a function of frequency. In Figure 4(a), the hysteresis area increases at low frequency and then decreases at high frequency. Being evident, at a particular frequency, the area is larger for thicker films. The reason is due to the effect of frequency on the phase–lag as the same as previously explained for the hysteresis shape-variation.

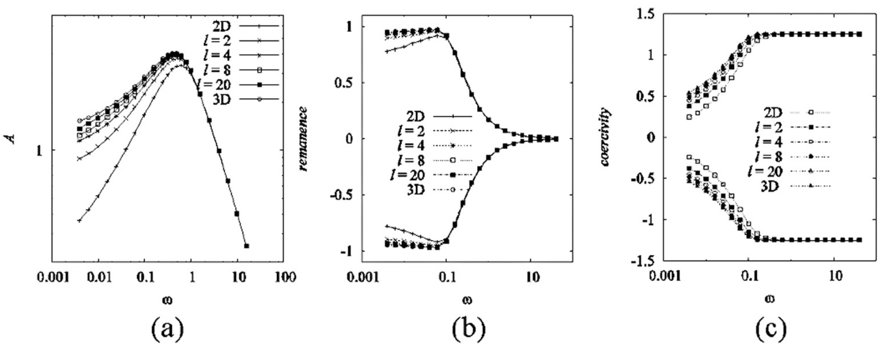


Figure 4. (a) The hysteresis area, (b) The hysteresis remanence and (c) The hysteresis coercivity as a function of a field frequency ω for various films thicknesses from 2D to 3D at $T = 3.2\ J/k_B$ and $h_0 = 5\ J$.

In addition, the hysteresis remanence and coercivity as a function of field frequency for various film thicknesses were also extracted and shown in Figures 4(b) and 4(c). From Figure 4(b), remanence increases with increasing frequency and reaches a maximum magnitude close to 1 and then decreases. This is also seen from Figure 3(b). Nevertheless, the remanence in low frequency region is higher than those in high frequency region. From Figure 4(c), coercivity increases with increasing frequency. The main reason for change of remanence and coercivity at low frequency region is that the field period is high so the spins have more time in following the field which leads to small phase lag and hence hysteresis is very thin vertical loop. Therefore, the system requires small coercivity for magnetization reversal. On the other hand, as $\omega \rightarrow \infty$ there is less time to reverse magnetization. Hence, remanence for symmetric hysteresis is very small close to zero and large coercivity is required. In the same way as hysteresis area, remanence and coercivity concern with thickness of magnetic films. The thicker films the more external energy is required to flip magnetization, so the coercivity rises as increasing the thickness. For remanence, due to the higher exchange interaction the remanence increases as increasing the thickness.

CONCLUSION

The hysteresis properties of Ising model in an oscillating field was studied using mean field calculation. The dynamic phase transition boundary on the amplitude and temperature plane were fined and found to depend on field frequency and thickness of films. From this phase boundary diagram, it was found that the magnetic system can cross the boundary by varying thickness of thin-film, field amplitude, frequencies or temperature. In addition, hysteresis properties such as hysteresis area, remanence and coercivity are thickness and frequency dependence. An increase in field frequency affects the shape of the hysteresis as it raises hysteresis area, remanence and coercivity in low frequency region but decreases hysteresis area and remanence in high frequency. On the contrary, an increase in thickness of magnetic films from 2D to 3D does not significantly affect the shape of hysteresis loop but increases hysteresis area, remanence and coercivity for all considered frequencies. From this work, thickness dependence of magnetic hysteresis in an oscillating external field was revealed by investigating hysteresis properties.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Thailand Research Fund (TRF), Commission on Higher Education (CHE) and the Graduate School of Chiang Mai University for financial supports.

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