The effect of heat inducing magnetic instabilities on dynamic hysteresis characteristics in Ising ultra-thin films

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Abstract. In this study, the magnetization and hysteresis of Ising ultra-thin-film were studied under the influence of both external magnetic field and thermal field (in a form of square pulses) using Monte Carlo simulation and Finite Element method. The results show that the steady magnetic hysteresis loops exist when the frequency of applied thermal field is integer multiple (*n* times) of the frequency of magnetic field. Two reflection symmetry types of the thermal and magnetic hysteresis, i.e. symmetric and asymmetric shapes, are evident. The symmetric magnetic hysteresis exists when *n* is even. On the other hand, the asymmetric hysteresis has two different coercivity values and exists when *n* is odd. Further, the thermal hysteresis results obtained can be used to predict when the maximum temperature is reached during the magnetic field cycle. Therefore, it is possible to establish how efficient is the applied thermal field can assist the magnetization reorientation. This could be useful for magnetic recording technology in the writing module in reducing the excessive heat usage.

1. Introduction

The high density magnetic recording media requires ferromagnetic materials with very high coercivity to maintain the magnetization direction against thermal noises to prevent unintentional changes to information stored in digital bits [1]. However, in some very high coercivity materials, the magnetic field generated by the writing head may be insufficient to change the magnetization in the bits. Therefore, to reduce too high coercivity, the technique called Heat Assisted Magnetic Recording (HAMR) has been introduced by applying thermal field (e.g. laser) to rise the temperature at the writing spot [2]. However, current laser heating technology limits the recording density to be about 3 Tb/in^2 due to the thermal diffusion of the media. The use of series of heating pulses showed some potentials to increase the recording density as it helps reducing the increase in temperature of the media. It was expected that the recording density could be up to 5 Tb/in^2 for the pulse-width being shorter than 200 ps. For instance, the density of 4.5 Tb/in^2 has been achievable in FePt recording media with 100 ps pulse laser generated from 2 GHz laser diode [3]. However, the dynamical responses of the magnetization, such as the hysteresis loop, are less investigated when both time variation magnetic and thermal perturbation are concurrently applied onto the magnetic system. Nevertheless, the knowledge of dynamical magnetic properties under the periodic magnetic field and series-pulse thermal heating can give some benefits to the design of the magnetic recording media. In this work, the perpendicular recording was considered and modelled to investigate the magnetization profiles under the application of magnetic field and thermal field (in square pulses). Ising model was used to represents infinite uniaxial anisotropy that causes very high coercivity and resembles to the perpendicular recording [4]. Monte Carlo simulation and Finite Element methods were used to determine both magnetic and temperature profiles. Both frequencies of the heat pulses and magnetic field were varied, and then the thermal/magnetic hysteresis loops were extracted and analyzed.

2. Materials and methods

In this study, the Ising spins positioning on square lattice was constructed to represent magnetic grains arraying in ultra-thin-film or monolayer structure. The ultra-thin-films were composed of 250×250 magnetic grains with 2 nm of diameter each. The initial temperature of the system was set to 300 K with the substrate being always held at 300 K during the simulation by assuming that it attaches to an ideal heat sink. For this study, the magnetic grain contains one Ising spin and then the dynamical evolution of magnetization under the influence of magnetic field and temperature was determined by Monte Carlo methods with Metropolis algorithm. The Ising spin Hamiltonian under the influence of external magnetic field takes the form

$$H = -J\sum_{\langle ij\rangle} s_i s_j - h\sum_i s_i, \tag{1}$$

where $s_i = \pm 1$ represents the spin up (+1) or spin down (–1) of the magnetic grain i^{th}, J_{ij} is the exchange interaction between spins s_i and s_j, the notation $<ij>$ considers only the interaction between the first nearest neighbour spins, and $h = h(t)$ is the magnetic field. The time evolution of the spin state was updated via the Metropolis probability [5]

$$p = \exp\left(-\Delta E_i / k_B T\right), \tag{2}$$

where ΔE_i is the energy difference associated to the update (spin flip) of spin s_i. The simulation time unit was defined as 1 mcs (Monte Carlo step per site), which is equal to N trial spin flips while N is the total number of spins in the model. For the unit conversion, the 1 mcs was set to the time step of $\Delta t = 10^{-12}$ sec (the FePt case) [6]. In this work, $J = 1$ was used as the energy unit, so unit of temperature and magnetic field becomes J/k_B and J, respectively. With apply thermal field (in a form of laser square pulses, the temperature becomes time-varying with magnitude governed by the heat transfer equation i.e. [7]

$$-\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right) + Q = \rho c \frac{\partial T}{\partial t}, \tag{3}$$

where q_x, q_y and q_z are the heat flowing rate, Q is heat source, ρ is mass density, and c is specific heat. In solving equation (3), Finite Element method (FEM) was considered by discretizing the domain of problem into many subdomains and the solution on each element depends with the specific boundary. With FePt parameters [8], the temperature profiles can be extracted and used in the simulation [8].

3. Results and discussion

Firstly, we investigated the dynamic of magnetization under the influence of sinusoidal magnetic field and square-pulse thermal field. The 2 GHz of sinusoidal magnetic field frequency was chosen as shown in figure 1 as the field period of 500 ps (or 500 mcs) is long enough in allowing spins to correspond with applied fields [6, 8]. Specifically, the magnetization has time to get saturated while the hysteresis is of broad shape. For the thermal field, the 4 GHz of thermal pulses was chosen as an example for presenting in figure 2(a). Next, both the sinusoidal magnetic field with 0.5 J magnitude and the thermal pulses with 10 mW power were applied to the spins system at temperature 300K. The applied magnetic field causes the magnetization to vary as a function of time, while the thermal field causes the time variation of temperature, resulting in thermal hysteresis (the temperature versus variation of the magnetic field) as shown in figure 2(b,c). The thermal hysteresis could be used to figure out how the temperature varies during magnetic field cycle. For instance, in figure 2(c), the highest temperature occurs when the magnetic field is maximum (or minimum) and the 300K temperature occurred at the zero magnetic field. This symmetric shape of thermal hysteresis describes the efficiency in heating pattern that synchronizes with the maximum magnetic field magnitude in assisting the spins reorientation. Then, the influence of heating cycle frequencies was studied using the thermal hysteresis. We found that the heating frequency can yield either symmetric or asymmetric steady thermal hysteresis (in term of reflection symmetry with $h = 0$ as the symmetry axis) via the relation $f = n/P$, $n = 1,2,3,\ldots$, where f is the heating frequency, P is the time period of applied magnetic field, and n is a positive integer. Therefore, the thermal hysteresis loops were further investigated for $n = 1, 2, 3, 4$, i.e. $f = 2, 4, 6$, and 8 GHz (for $P = 500$ ps), as shown in figure 3.

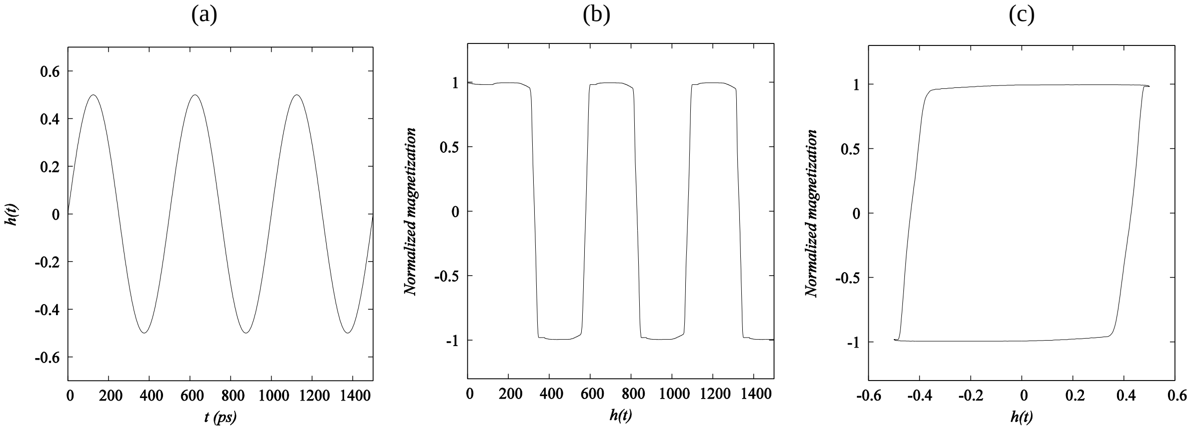

Figure 1. (a) The sinusoidal magnetic field with 0.5 J magnitude and 2 GHz frequency, (b) the magnetization variation as a function of time, and (c) the corresponding hysteresis loop.

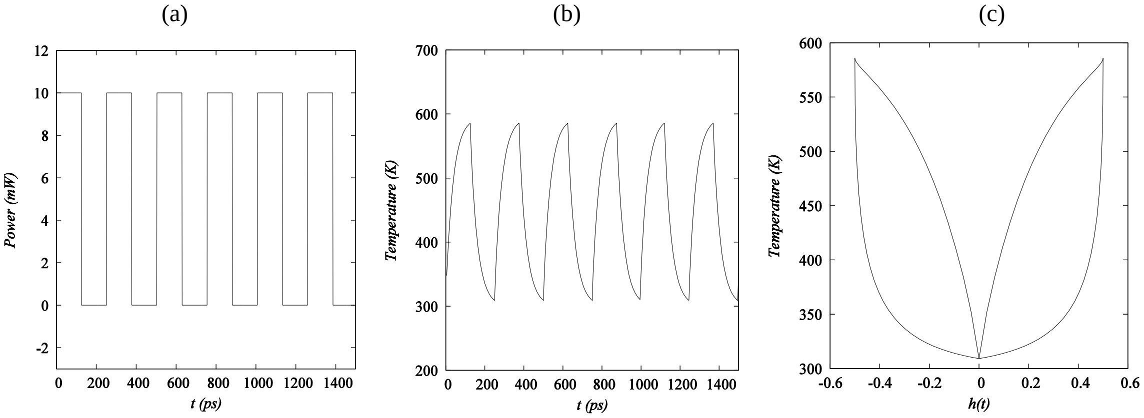

Figure 2. (a) The thermal pulses with 10 mW power and 4 GHz frequency, (b) the temperature variation as a function of time, and (c) the thermal hysteresis loop.

As seen, the results show that the thermal hysteresis loops are asymmetric when the integer n is odd number but are symmetric when n is even integer. The number of times that temperature becomes highest is equal to n times per one period of magnetic field, i.e. 4 times when $n = 4$. Further, for even n, the highest temperatures occur before the magnetic field reach to the maximum value and then decrease to 300K when the magnetic field is maximum. This suggested of heat assistance being inefficient in changing magnetization direction because the supplied heat does not synchronize with the magnetic field. For n being odd integer, the temperatures of the system are different even the applied magnetic field is the same on magnitude but on different direction, as both fields are not in phase. For instance, when $n = 3$, the highest temperature occurs two time on positive magnetic field and one time on negative magnetic field. In addition, the corresponding magnetic hysteresis loops for $n = 1$ to 4 were shown in figure 4. The magnetic hysteresis loops also present symmetric and asymmetric behaviour in accordance with their thermal hysteresis loops except $n = 1$, where the magnetization is robust against magnetic field switching due to the insufficient heat supplied and low magnetic field amplitude. Note that, the asymmetric magnetic hysteresis has two different coercivity because of different highest temperatures between positive and negative directions of the magnetic field. Nevertheless, with this investigation, the frequency of heating cycle that yields the symmetric or asymmetric magnetic hysteresis at specific magnetic field frequency can be predicted. These thermal hysteresis results can describe how effective is the heating cycle in assisting magnetic reorientation of the spins, which may be useful in the heat assisted magnetic recording technology.

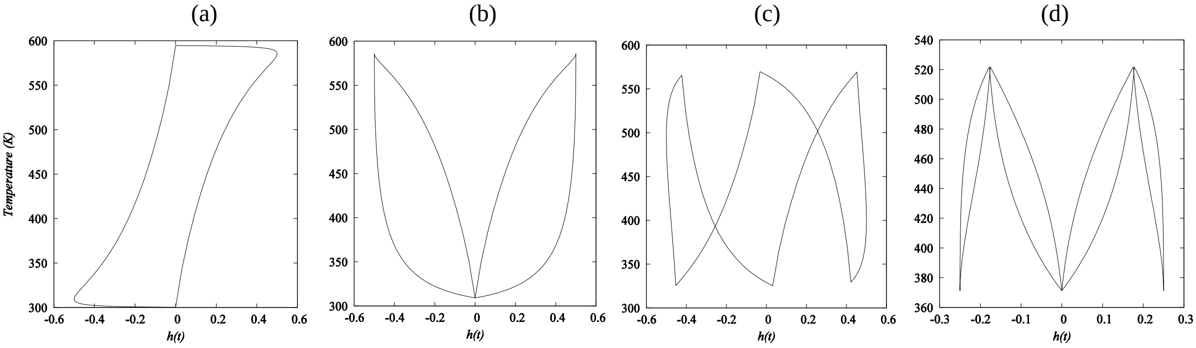

Figure 3. The thermal hysteresis for (a) $n = 1$, (b) $n = 2$, (c) $n = 3$, and (d) $n = 4$.

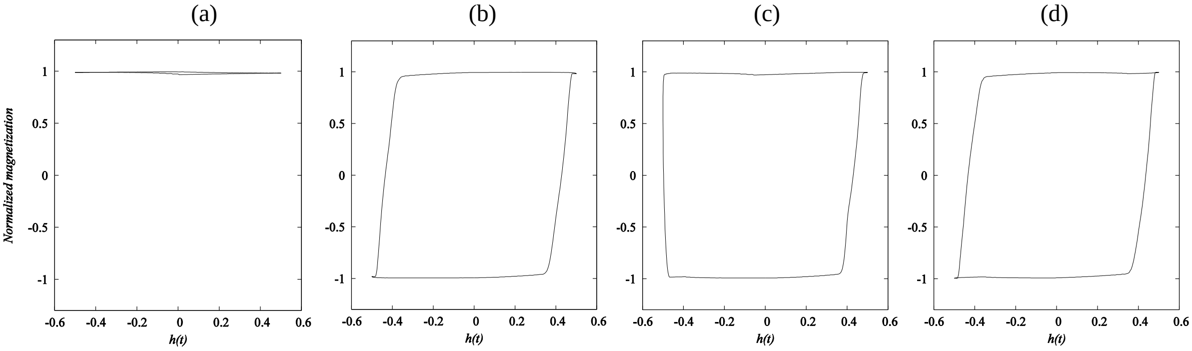

Figure 4. The corresponding magnetic hysteresis of thermal hysteresis in figure 3 for (a) $n = 1$, (b) $n = 2$, (c) $n = 3$, and (d) $n = 4$.

4. Conclusion

In this numerical study, the periodic heat that applies to the Ising film could assists the magnetization to be varied along the magnetic field. The magnetic hysteresis could be existed as symmetric of asymmetric shape depends on the frequency of heat pulse whether n was odd or even integer times the magnetic field frequency. The symmetric hysteresis could be existed only when n was even and yield magnetic hysteresis with one coercivity value. On the other hand, when n was odd integer the magnetic hysteresis is asymmetric, which have two different coercivity values. Moreover, the thermal hysteresis can be used to establish that how efficiently of the heating pulses can assists in changing of the magnetization direction.

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