4-5 Tb/in² heat assisted magnetic recording by short pulse laser heating

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Due to poor thermal performance of media, it is difficult for the heat assisted magnetic recording (HAMR) to achieve densities greater than 3 Tb/in² for continuous wave laser heating. Short pulse laser heating is an attractive approach to improve the thermal response of media. In this paper, the recording performances of HAMR using short pulse laser heating are studied by dynamic micromagnetic simulations solving Landau-Lifshitz-Bloch equation. The results show that the magnetic damping constant of media, $\alpha$ and the applied magnetic field, $H$, exhibit significant effects on recording quality at pulse width of 100ps. From analyses of the relationships among readout signal and noise ratio, recorded track width, $\alpha$ and $H$, the required parameter setting for various recording densities are obtained. It is indicated that with a transducer tip size of 15 nm and heating laser pulse width of 100ps, the recording density greater than 4 Tb/in² is achievable for FePt recording media.

Index Terms—Heat-assisted magnetic recording, near field optical transducer, magnetic recording media, thermal response of media, short pulse laser, micromagnetic simulation.

I. INTRODUCTION

Heat assisted magnetic recording (HAMR) is the most promising technology for the next generation of magnetic recording. However, there are many challenges to be met[1-3]. Systematic recording simulations on recording density potentials with a transducer tip size of 10nm or heat source size of 10nm have been carried out and the recording density of less than 3 Tb/in² was achieved [3,4]. Both studies showed that the relatively large thermal spot size is the key limiting factor for the recording density increase. With continuous wave (CW) laser heating, the impact of the transducer tip size on media thermal responses has been studied and the results showed that the thermal performance of media cannot meet the requirements for the recording density of 4 Tb/in² even with a transducer tip size of 10nm [5]. Short pulse laser heating is one way to improve media thermal response. Its benefits include the reduction of the thermal spot size, increase of the thermal gradient, relaxation of the demand for media thermal properties, and reduction of the transducer temperature rise [6,7]. With a transducer tip size of 15nm, it is possible to achieve density of 4 Tb/in² using 100ps pulse laser heating[5].

In this paper, we will study the recording performances and recording density potentials with short pulse laser heating by systematic simulations.

II. MODELING STRUCTURE

The near field optical transducer being used is of Lollipop structure. It is made of Gold (Au) material with a disk diameter of 150 nm and a tip length of 10 nm. The tip size and thickness of the transducer are assumed to be 15 nm. The air gap between the transducer and medium surface is 4 nm. The media structure is FePtC(10 nm)/MgO(4 nm)/Cu(50 nm)/glass substrate [8,9]. The material optical and thermal parameters are the same as in Ref. 5. The environment temperature and heated peak temperature of the medium are 300 K and 800 K, respectively. The linear speed of the media is 10 m/s. The anisotropy constant $K_u$ and saturation magnetization $M_s$ are $2.4 \times 10^6$ erg/cm³ and 800 emu/cm³ with the distributions of 3% at temperature of 0 K. The temperature dependences of $K_u$ and $M_s$ are the same as those in Ref. 10. The grain size is 4 nm (grain pitch of 4.5 nm) with a distribution of 18%. The Curie temperature ($T_c$) of grains is 660 K with a distribution of 2%. The write magnetic field distribution is generated by the simulation of a magnetic head and the space between main pole and transducer tip is 20nm. The reader width is 16 nm.

The layout of transducer and main pole structures in air-bearing surface is shown in Fig. 1. The simulated temperature distribution and magnetic field distribution along the central line of a track are also plotted in Fig. 1 for clear understanding of the relationship between temperature distribution and magnetic field distribution.

FIG. 1 HERE

The optical distribution within the media generated by the transducer is simulated by the finite-difference time-domain method (numerical FDTD). The media thermal profiles and responses in time are obtained by simulations with commercial software COMSOL. The analysis of magnetic recording performance is carried out by dynamic micromagnetic modeling with Landau-Lifshitz-Bloch (LLB) equation.

III. RESULTS AND DISCUSSION

The effect of the laser pulse width on the thermal spot size in cross-track direction and the thermal gradient in down-track direction at a transducer tip size of 15nm are shown in Fig. 2. The required thermal spot sizes and gradients for densities of 4 Tb/in² and 5 Tb/in² are also plotted in the figure as in Ref. 5. The pulse width affects the thermal spot size and gradient
significantly. As the pulse width reduces, the cross track thermal spot size decreases and the down track thermal gradient increases. The thermal gradient can meet the requirements for 4 Tb/in² and 5 Tb/in² at pulse widths of 400ps and 300ps, respectively. However, the cross track thermal spot size cannot meet 4 Tb/in² requirement even at a pulse width of 100 ps. At a pulse width of 100 ps, the gradient is 44% better than that needed for 4 Tb/in², although the thermal spot size is 7% worse than that required for 4 Tb/in².

**FIG. 2 HERE**

In laser heating process, the generated thermal profile width and gradient are the integrative result of the heating energy accumulation and thermal diffusion in the media. A large thermal diffusion will lead to a large thermal profile which has a large thermal spot and small thermal gradient. In short pulse laser heating, there is a small thermal diffusion (because of shorter time) before the media reaches the desired temperature, which leads to a small thermal width and a large thermal gradient. Clearly, in order to heat the media locally up to the desired temperature, the laser pulse power has to be higher. The shorter the heating laser pulse, the higher the required laser peak power [7].

For HAMR media, its coercivity is much higher than the magnetic field provided by the write head. In the writing process, magnetic domain switching happens only at a critical temperature ($T_c$) which is near $T_w$, depending on the media magnetic properties and applied magnetic field $H$. For a short pulse heating, the medium keeps its temperature at above $T_w$ for a very short time frame. For example, it is about 100ps for 100ps pulse laser heating. Therefore, it is necessary to understand whether the domain switching speed of the media is fast enough to respond to short pulse laser heating.

The magnetic domain switching time is proportional to $(1+\alpha^2)/\alpha$, where $\alpha$ is damping constant. The fastest switching happens at an $\alpha$ value of 1. However, due to the interaction between grains, the shortest switching time of magnetic film is obtained at an optimized value $\alpha_{opt}$ which is smaller than 1 [11-13]. During switching, when $\alpha$ is larger than $\alpha_{opt}$, the magnetization vector moves slower. On the other hand, when $\alpha$ is smaller than $\alpha_{opt}$, the magnetization vector moves faster but oscillates around the applied magnetic field such that it stops in a longer time.

With micromagnetic modeling based on LLB equation, the magnetic domain switching speeds at laser heating were studied [14,15]. For a single grain, the switching time decreases with increasing $H$ and working temperature. When the temperature is near $T_c$, the switching time of around 100ps can be obtained for an $\alpha$ of 0.1. For short pulses laser heating, continuously keeping an applied field after heating is very useful for magnetic domain to complete its switching [15]. For the granular magnetic media, the switching speed is affected by not only laser pulse duration, but also by $\alpha$ and the intergranular exchange coupling. The slower the media intergranular exchange coupling, the slower the switching speed [14].

In theory, with assumption of single domain sheet, an approximation formula to calculate the switching time $t_F$ can be expressed as [11]

$$t_F < \alpha \frac{Z c}{\gamma H} + \frac{I}{\gamma M_2 \alpha}$$

(1)

$\alpha_{opt}$ is

$$\alpha_{opt} = \sqrt{\frac{I H}{2cM_2}}$$

(2)

where $I$ and $c$ are the parameters associated with media magnetic properties and $H$; $\gamma$ is gyromagnetic ratio; $M_s$ is saturated magnetization. Equations (1) and (2) may be used to evaluate the domain switching time in the case of HAMR.

At the moment of HAMR writing, the media local temperature is near $T_c$. As shown in Fig. 3(a), $M_s$ is about 150 emu/cm³ for an applied magnetic field of 10 KOe, which is much smaller than its value at room temperature. With the media parameters used in this study, the effects of $\alpha$ on $t_F$ at $M_s$ of 100, 150 and 200 emu/cm³ are plotted in Fig. 3(b) for the applied $H$ of 10 KOe. The optimal damping constant, $\alpha_{opt}$, is larger than 0.5. The switching times for $\alpha=0.1$ and 0.2 are less than 250 ps and 150 ps, respectively. The larger the damping constant, the faster the switching speed.

**FIG. 3 HERE**

The above results indicate that HAMR with short pulse laser heating, such as 100 ps pulse laser heating, is possible. The writing strategy used in this paper to study the recording performance and recording density potential is schematically shown in Fig. 4. The short laser pulses are synchronized with the write timing clock. Regardless of the laser pulse width, the writing speed (determined by magnetic field switching) keeps the same for the same bit density writing. Because of the thermal response of the media, the temperature change of media in time domain exhibits a different shape compared with that of the laser pulse. After pulse laser heating, the applied magnetic field is still being applied to the media.

**FIG. 4 HERE**

Figure 5 shows the dependences of the signal to noise ratio (SNR) of readout signals on pulse widths at different $\alpha$ for recording bit lengths of 6.5 nm (corresponding to bit densities of 3908 KFCI). When the laser pulse width is equal to or longer than 200 ps, SNR remains larger than 12 dB for all $\alpha$ values. The effect of $\alpha$ becomes pronounced when the pulse width is 100 ps. A shorter pulse heating does not lead to a higher SNR for small $\alpha$ even that a shorter pulse heating generates a larger thermal gradient. It indicates that at short pulse laser heating, when the pulse width is less than 200 ps, the recording performance is dominated by the magnetic domain switching time instead of thermal gradient. It is consistent with the above analysis of magnetic switching time. For long pulse heating, there is a long time for magnetic
domain switching. When the pulse width is 100 ps, it needs fast switching time to flip the magnetic domain. This can be accomplished with a large $\alpha$ value. Due to distributions of magnetic properties, the switching time varies from grain to grain. Uncompleted switching of grains will lead to a reduced $\text{SNR}$. The simulations with bit lengths of 7.0 nm and 7.5 nm all show that the effect of $\alpha$ becomes significant when the pulse width is smaller than 200 ps. As expected, for the same recording condition, a recording scheme with larger bit lengths shows a large $\text{SNR}$.

**FIG. 5 HERE**

The dependence of the switching time on $\alpha$ becomes more pronounced at pulse width of 100ps. The switching time is also associated with the applied field $H$. The dependences of $\text{SNR}$ on $\alpha$ at different $H$ for a laser pulse width of 100ps are plotted in Fig. 6. For a fixed $H$, $\text{SNR}$ increases with increasing $\alpha$. A large $H$ has a large $\text{SNR}$ before $\text{SNR}$ reaches 12 dB. Generally speaking, a large $\alpha$ of media and high $H$ are desired for obtaining high bit density. However, a higher $H$ will lead to a broader recorded track which will reduce the recording track density.

**FIG. 6 HERE**

In HAMR with CW laser heating, there is a so-called “transition-broadening-after-write” phenomenon, which happens when the applied magnetic field is higher than a critical value [1]. With this critical value, $H_{\text{max}}$, the maximal $\text{SNR}$ is obtained. When $H$ is smaller than $H_{\text{max}}$, as $H$ increases, the value of $\text{SNR}$ increases. However, when $H$ is larger than $H_{\text{max}}$, $\text{SNR}$ decreases with increasing $H$. During the recording with $H$ larger than $H_{\text{max}}$, after the initially created transitions are written, the partial magnetization reversal continues in the transition region as the medium moves, causing the transition to broaden. It is severer for high bit density recording. In short pulse laser heating, this phenomenon also exists. It has been reflected in Fig. 6 for $\alpha$ of larger than 0.2. In order to show this phenomenon more clearly, a re-plotted Fig. 6 as the dependences of $\text{SNR}$ on $H$ at different $\alpha$ as well as the $\alpha$ effect on $H_{\text{max}}$ at bit length of 6.5 nm and 7.0 nm are shown in Fig. 7. As $\alpha$ increases, the $H_{\text{max}}$ decreases. For a fixed $\alpha$, $H_{\text{max}}$ increases with increasing bit length. This means that this phenomenon is more critical for the cases of high bit density and large $\alpha$.

**FIG. 7 HERE**

Different $\alpha$ and $H$ will lead to different $\text{SNR}$. For a recording system to maintain a reliable performance, there is a $\text{SNR}$ criterion. Figure 8 illustrates the dependences of the required $H$ and the minimal $\alpha$ on areal densities for $\text{SNR}$ criteria of 10 dB and 8 dB at bit lengths of 6.5 nm and 7.5 nm. A high density recording requires not only a small $H$ to write narrow track (high track density), but also a larger $\alpha$ to meet $\text{SNR}$ criteria (high bit density). For a fixed areal density, there are different $H$ requirements for different recording bit lengths. A smaller $H$ is required for a longer bit recording, but it needs media with larger $\alpha$ because a larger $\alpha$ can compensate the switching speed loss caused by smaller $H$. For instance, if 4 Tb/in$^2$ density is targeted and recording bit length is 6.5 nm, an $H$ of around 8.3 KOe and $\alpha$ of $\geq$ 0.20 (or 0.16) are needed for $\text{SNR}$ criterion of 10 dB (or 8 dB). Otherwise, if the recording bit length is 7.5 nm, $H$ and minimal $\alpha$ will be 6.8 KOe and 0.23 for 10 dB, respectively. For a recording density of 5 Tb/in$^2$ with a bit length of 6.5 nm, an $H$ of about 6 KOe and $\alpha$ of 0.38 (or 0.36) can meet the requirements for criteria $\text{SNR}$ of 10 dB (or 8 dB).

**FIG. 8 HERE**

The above analysis shows that $\alpha$ is a critical parameter for high density HAMR with short pulse laser heating. FePt is a promising material for HAMR media. Experimental result has shown that its $\alpha$ is around 0.3 (0.26–0.38) [16]. Dynamic magnetization experiments have also presented that the demagnetization time and recovery time of FePt thin films are about 1ps and 100ps, respectively [17,18]. All of these indicate that more than 4.5 Tb/in$^2$ density recording with FePt media is achievable by 100ps pulse laser heating for a transducer with reasonable tip size of 15 nm (for a density of 4.5 Tb/in$^2$, $\alpha$>0.26, $H$=7.1 KOe and bit length of 6.5 nm).

IV. CONCLUSION

Due to thermal diffusion, it is very difficult for CW laser heating to generate desired thermal distribution in the HAMR media to meet the requirements for 4 Tb/in$^2$ recording density. Short pulse laser heating is an excellent solution to solve this problem. The micro-magnetic simulation results show that the media magnetic switching time becomes a key factor to determine the recording performance for short pulse heating recording with pulse width of less than 200 ps. A relatively large $\alpha$ is desired to speed up its switching time. For a high density recording with short pulse laser heating, a relatively high bit density is preferable because a lower track density could be recorded by applying a higher $H$ which can relax the demand for a large $\alpha$. 4.5 Tb/in$^2$ recording density is achievable for FePt recording media with pulse width of 100ps. It is understood from Eq. (1) that a larger $M_r$ will lead to a fast switching speed. Therefore, using a media with a large $M_r$, a recording density of 5 Tb/in$^2$ may also be possible.

In this paper, it is the first time to demonstrate that 4-5 Tb/in$^2$ density recording is actually achievable with practical optical near field transducer size and FePt HAMR media, from a simulation point of view. In real implementation, the effort in generation of short pulse laser with pulse width of about or even shorter than 100 ps should be paid attention. Gain-switching is a good way for laser diode to generate short pulse output [19]. When using this method in HAMR head, a well impedance matched driving circuit is needed so as to have a
low electric power to drive the laser diode for the desired pulse laser output.

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REFERENCES

Fig. 3. (a) Dependences of $M_s$ and $H_k$ on temperature and (b) Effects of damping constant $\alpha$ on switching time $t_s$ at different $M_s$ ($H=10$ KOe).

Fig. 5. Dependences of SNR of readout signals on pulse widths at different $\alpha$ for recording bit length of 6.5 nm ($H=8000$ Oe).

Fig. 6. Dependences of SNR on $\alpha$ at different $H$ for bit length of 6.5 nm (laser pulse width: 100 ps).

Fig. 4. Writing strategy for pulse laser heating.
Fig. 8. Dependences of required $H$ and minimal $\alpha$ on areal densities for criteria SNR of 8 dB and 10 dB at bit lengths (BL) of 6.5 nm and 7.5 nm (laser pulse width: 100 ps).

Fig. 7. (a) Dependences of SNR of readout signal on $H$ at different $\alpha$ for recording bit lengths of 6.5 nm, (b) Relationships between $H_{\text{max}}$ and $\alpha$ for bit length of 6.5 nm and 7.0 nm.