TRANSITION CHARACTERISTICS OF PERPENDICULAR HEAT-ASSISTED MAGNETIC RECORDING WITH PEAK TEMPERATURE AND CROSS-TRACK VARIATIONS

Adisorn Kaewpukdee[1], Nitthita Chirdchoo[2], Piya Kovintavewat[3], and Lunchakorn Wuttisittikulkij[4]

[1,2,3]Data Storage Technology Research Center, Nakhon Pathom Rajabhat University, Thailand
[4]Department of Electrical Engineering, Chulalongkorn University, Thailand

[1]adisorn@npru.ac.th, [2]nitthita@yahoo.com, [3]piya@npru.ac.th, [4]wlunchak@chula.ac.th

ABSTRACT

Currently, a conventional magnetic recording system is approaching its storage capacity known as a super paramagnetic limit. Heat-assisted magnetic recording (HAMR) is one of new technologies that can achieve an areal density beyond this limit. In HAMR, the heat is applied in a medium during writing process resulting in unique transition characteristics if compared to a conventional system. This paper studies the effect of peak temperature and cross-track variations on the transition characteristics of a perpendicular HAMR system. Numerical results based on thermal Williams-Comstock and micro-track models show that these two variations cause the transition center and the transition parameter to vary, thus affecting the transition response of the HAMR system.

Keywords: *Peak temperature and cross-track variation, Perpendicular HAMR, Transition characteristics*

1. INTRODUCTION

A perpendicular magnetic recording (PMR) technology will soon reach its super paramagnetic limit at about 1 Tb/in^2 [1]. Several new technologies that can surpass this limit have been proposed in literature, for example, heat-assisted magnetic recording (HAMR), bit-patterned media recording (BPMR), and two-dimensional magnetic recording (TDMR) [1]. Nevertheless, HAMR is chosen by hard disk drive manufacturers to be the next technology that will replace the PMR because it can be implementable with reasonable investment.

In practice, high areal densities can be achieved by reducing a volume of a grain size (V) required to store one single bit in magnetic medium. A magnetic grain is characterized by its uniaxial anisotropy coefficient (K_u) such that the higher the K_u, the harder the magnetization of the media to be changed. Generally, the magnetic energy (K_uV) can determine the thermal stability of a magnetic grain. Specifically, magnetic grain is stable when the magnetic energy is much greater than the thermal energy (k_BT), i.e.,

$$\frac{K_uV}{k_BT} > \alpha, \tag{1}$$

where $k_B = 1.38\times10^{-23}$ is a Boltzmann's constant, T is a temperature in Kelvin, and α is any large positive integer, e.g., 60 [2-3]. Apparently, if we reduce V to increase an areal density, K_u must be increased to keep K_uV constant. Unfortunately, because the medium coercivity (H_c) is proportional to K_u, increasing K_u will require higher magnetic field density to change the direction of medium magnetization.

Since H_c is inversely proportional to the temperature [3], we heat the medium during writing process so that H_c can be reduced, which leads to a lower magnetic field required to write a data bit into that medium. After the data bit has been written, the medium is rapidly cooled down until it reached the ambient temperature at which H_c returns to its typical high value so as to guarantee the thermal stability of the stored data bit. With this technique, it is possible to write a data bit into the medium with high K_u by using a small amount of magnetic field.

Many works have investigated the behavior of the HAMR system [2-8]. Rausch *et al*. [2] proposed a thermal Williams-Comstock model (TWCM) to study the transition characteristics of longitudinal recording systems. Results indicated that many parameters such as alignment, write current, and laser power, are needed to be optimized to obtain high performance in HAMR implementation. The effects of cross-track transition location and transition parameter in longitudinal HAMR systems were investigated in [3]. The variation of transition responses of HAMR systems as a function of laser spot position was studied in [4]. Furthermore, many crucial parameters (e.g., peak temperature, media coercivity, write head gap, deep gap field, and fly height) were investigated in longitudinal HAMR systems [5]. Finally, the behavior of the transition location and the transition parameter in a perpendicular HAMR system has been extensively investigated in [6-8].

This paper investigates how peak temperature and cross-track variations affect the behavior of transition characteristics in perpendicular HAMR systems. To do so, we use the TWCM and a microtrack model to study the effect of these parameters on the transition center, the transition parameter, and the PW_{50} [2]. This study will serve as a guideline for a system designer to carefully design an HAMR system to avoid these variations so as to obtain the best system performance.

The rest is organized as follows. A perpendicular HAMR system, including TWCM and a microtrack model, is summarized in Section 2. Section 3 presents simulation settings and results. Finally, Section 4 concludes this paper.

2. PERPENDICULAR HAMR

PMR is a conventional magnetic recording system that is currently used in hard disk drives. By integrating a laser in the read head to heat a medium before writing a data bit, we arrive at a perpendicular HAMR system. Figure 1 displays the structure of both PMR and perpendicular HAMR systems. To analyze the HAMR system, TWCM and a microtrack model are needed.

2.1 Thermal Williams-Comstock Model

The thermal Williams-Comstock model (TWCM) was proposed in [2], which captures the effect of temperature variations on H_c and the remanent magnetization M_r of the medium. The analytical expression of the TWCM is expressed as [2]

$$\left.\frac{dM(x)}{dx}\right|_{x_0} = \left.\frac{dM(H_{tot})}{dH_{tot}}\right|_{H_c(T_0)} \left[\left.\frac{dH_h(x)}{dx}\right|_{x_0} + \left.\frac{dH_d(x)}{dx}\right|_{x_0} - \left.\frac{dH_c(T_0)}{dT}\right|_{T_0} \left.\frac{dT}{dx}\right|_{x_0} \right], \quad (2)$$

where H_{tot} is total applied field, H_h is head field, H_d is demagnetization field, M is medium magnetization, and $T(x)$ is the temperature profile in a medium.

Practically, a transition from $-M_r$ to $+M_r$ is assumed to occur when the total applied field $H_{tot} = H_h + H_d$ is equal to coercivity H_c, i.e.,

$$H_c(T(x_0)) = H_h(x_0) + H_d(T(x_0)), \quad (3)$$

where $T(x_0) = T_0$ is the temperature at the transition center x_0. For large spot thermal recording where the thermal gradient and the effect of the demagnetization field are small, (4) reduces to

$$H_c(T(x_0)) \approx H_h(x_0). \quad (4)$$

Generally, (4) can be solved numerically for the transition center x_0, whereas (2) is used to solve for the transition parameter a, where the transition length is defined as πa [2]. Therefore, both the transition center x_0 and the transition parameter a can completely characterize the HAMR system.

To solve (2), each term in (2) is needed to be evaluated, which can be summarized as follows. The derivative of head field H_h at the transition center $x = x_0$ is given by [6, 9]

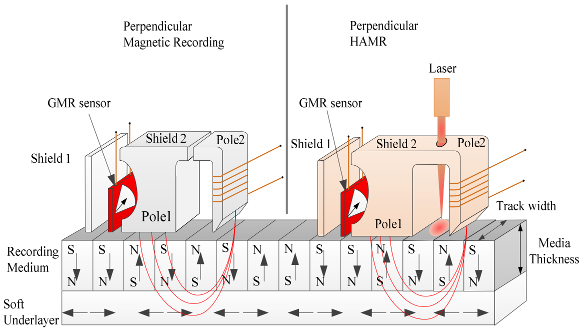

Fig. 1. Perpendicular magnetic recording (PMR) and perpendicular HAMR system.

$$\left.\frac{dH_h(x)}{dx}\right|_{x_0} = \frac{H_g}{\pi}\left[\frac{A}{x^2+A^2} - \frac{B}{x^2+B^2}\right], \quad (5)$$

where H_g is deep gap field, $A = y - g/2$, $B = y + g/2$, $g = 2d + 2t$ is a spacing between the head pole and its image pole, d is the fly height, t is medium thickness, and $y = d + t/2$ is the distance between the bottom of the pole and the center of the medium. Next, the derivative of demagnetization field at the transition center x_0 is [9]

$$\left.\frac{dH_d(x)}{dx}\right|_{x_0} = -\frac{2M_r(T(x))}{\pi(a+t/2)}, \quad (6)$$

where M_r is remanent magnetization of media. Finally, for large spot HAMR, the transition during recording can be described as an arctangent magnetization transition [2], whose magnetization gradient at x_0 is

$$\left.\frac{dM(x)}{dx}\right|_{x_0} = \frac{2M_r(T_0)}{\pi a}. \quad (7)$$

Also, the derivative of the magnetization with respect to the total applied field evaluated at x_0 is given by

$$\left.\frac{dM(H)}{dH}\right|_{H_c(T_0)} = \left|\frac{M_r(T_0)}{(1-S^*(T_0))H_c(T_0)}\right|, \quad (8)$$

where S^* is a parameter associated with the squareness of the hysteresis (M-H) loop [2].

2.2 Microtrack Model

In general, TWCM alone is not enough to describe the HAMR process because it ignores variations in the transition. Since the thermal profile is assumed to be Gaussian, there is not only an along-track variation in H_c, but also a cross-track variation. To account for these variations, a microtrack model was used to approximate transition curvature [2]. Specifically, a magnetic track is divided into N subtracks with equal width as depicted in Fig. 2. Then, the TWCM is applied for each subtrack to determine a transition center and a transition parameter.

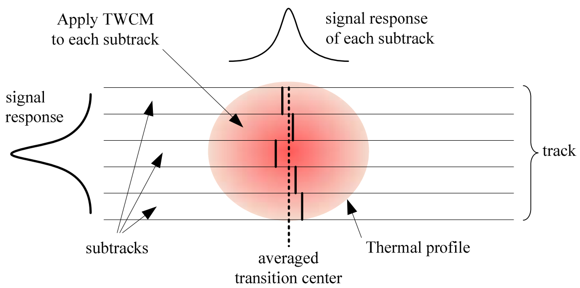

Fig. 2. A microtrack model with thermal profile.

Table 1. Parameters setting.

Coercivity (H_c)	-2000 $T(x)$ + 21×10^5 A/m
Remanent magnetization (M_r)	-1200 $T(x)$ + 12×10^5 A/m
Coercive squareness (S^*)	0.7
Media thickness (t)	17 nm
Write head to keeper layers (g)	80 nm
Head field (H_g)	19×10^5 A/m
Width of the track (W_t)	180 nm
Number of subtracks (N)	14

The transition responses of each subtrack are sufficient to determine the characteristics of HAMR system. If the system response of an individual microtrack is $h(a,t)$, the total response for the whole track will be expressed as [2]

$$p(t) = \frac{1}{N}\sum_{i=1}^{N} h(a_i, t-\tau_i), \tag{9}$$

where $h(t)$ is the microtrack response, a_i is the transition parameter, and $t-\tau_i$ is a relative location of the transition center for each microtrack.

3. NUMERICAL RESULTS

The parameter settings used to investigate the transition characteristics of the perpendicular HAMR system when experiencing peak temperature and cross-track variation are shown in Table 1.

To study the effect of peak temperature variation, we assume that the peak temperature T_{peak} used to heat the medium is a white random process with mean T_p = 400 C^o and variance σ^2, i.e., $T_{\text{peak}} \sim \mathcal{N}(T_p, \sigma^2)$. Here, we set $\sigma = 2(1 \pm x/100)$ to capture the peak temperature variation of x% in the HAMR system, and truncate the resulting peak temperature to $T_{\text{peak}} \pm 20$ C^o.

Fig. 3 illustrates the transition center x_0 and the transition parameter a for all subtracks when the peak temperature variation is 10%. Clearly, x_0 varies within several nanometers, whereas a changes only few nanometers. Moreover, it seems that small variation is occurred at the track edge, but large variation is found in the track center. This is because the laser position is

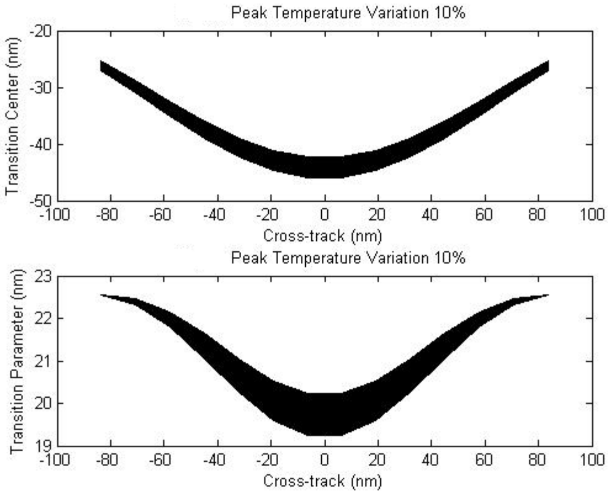

Fig. 3. (Top) The transition center and (Bottom) the transition parameter with peak temperature variation of 10%.

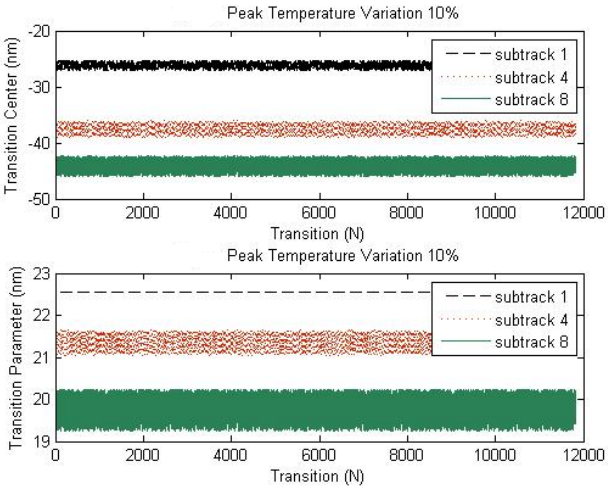

Fig. 4. (Top) The transition center and (Bottom) the transition parameter with peak temperature variation of 10% at the 1-st, 4-th-and 8-th subtrack.

pointed at the track center. To confirm this result, we plot the values of x_0 and a at the 1-st, 4-th-and 8-th subtrack for 12000 magnetic transitions. Again, same result is obtained.

Furthermore, we show the averaged transition center x_0 and the averaged transition parameter a in Table 2 for different peak temperature variations (average based on 14 subtracks), when there is peak temperature variation in the HAMR system so as to understand the behavior of x_0 and a. We can see that the mean of x_0 and a is almost constant, but the standard deviation (std.) of x_0 and a is increasing when variation is large. In addition, the std. of x_0 and a is getting large when the subtrack is close to the track center (i.e., the 8-th subtrack). We also show the PW_{50} of the total response in (9) in Table 2, which is the width at half of its maximum. It is clear that PW_{50} is not primarily affected by peak temperature variation. Note that the smaller the PW_{50}, the higher the achievable storage capacity [2].

Table 2. The averaged transition center and the averaged transition parameter for different peak temperature variations.

Peak Temperature Variation					
1st subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-26.181	-26.164	-26.171	-26.163
	a (nm)	22.557	22.556	22.556	22.556
Std.	x_0 (nm)	0.0000	0.15335	0.19678	0.2206
	a (nm)	0.0000	0.0000	0.0000	0.0000
4th subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-37.559	-37.526	-37.539	-37.523
	a (nm)	21.363	21.366	21.362	21.365
Std.	x_0 (nm)	0.0000	0.49845	0.6395	0.7172
	a (nm)	0.0000	0.01967	0.0252	0.0283
8th subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-44.167	-44.125	-44.140	-44.120
	a (nm)	19.759	19.768	19.763	19.768
Std.	x_0 (nm)	0.0000	0.7282	0.9342	1.0478
	a (nm)	0.0000	0.0568	0.0729	0.0818
PW_{50}		**0%**	**3%**	**5%**	**10%**
Maximum (nm)		79.585	79.823	79.823	79.823
Minimum (nm)		79.585	79.312	79.314	79.312

Table 3. The averaged transition center and the averaged transition parameter for different cross-track variations.

Cross-track Variation					
1st subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-26.181	-26.828	-27.268	-28.393
	a (nm)	22.557	22.547	22.533	22.478
Std.	x_0 (nm)	0.0000	0.1988	0.5656	2.3700
	a (nm)	0.0000	0.0000	0.0004	0.0061
4th subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-37.559	-38.165	-38.551	-39.448
	a (nm)	21.363	21.238	21.155	20.951
Std.	x_0 (nm)	0.0000	0.1677	0.4420	1.5124
	a (nm)	0.0000	0.0073	0.0203	0.0779
8th subtrack		**0%**	**3%**	**5%**	**10%**
Mean	x_0 (nm)	-44.167	-44.032	-43.913	-43.510
	a (nm)	19.759	19.797	19.830	19.940
Std.	x_0 (nm)	0.0000	0.0103	0.0404	0.3101
	a (nm)	0.0000	0.0008	0.0031	0.0228
PW_{50}		**0%**	**3%**	**5%**	**10%**
Maximum (nm)		79.585	79.970	80.226	80.885
Minimum (nm)		79.585	79.232	78.997	78.498

Normally, the laser should point at the center of the track to obtain best performance. However, when the laser is moved away from the track center, it causes cross-track variation, which affects the behavior of the transition characteristics. To study this effect, we define x% of cross-track variation as the distance that the laser position moves away from the track center by $xW_t/100$ nm, where W_t = 180 nm is the track width in this study (see Table 1).

Table 3 displays the averaged transition center x_0 and the averaged transition parameter a at different cross-track variations. Clearly, the mean of x_0 and a is varied, especially when cross-track variation is large. It can be implied that cross-track variation has more impact to the x_0 and a than peak temperature variation. Furthermore, we found that the standard deviation of x_0 and a is large when the subtrack is further away from the track center. Again for PW_{50}, it seems that PW_{50} is not affected by cross-track variation.

4. CONCLUSION

This paper studied the effect of peak temperature and cross-track variation on the transition characteristics (e.g., the transition center x_0, the transition parameter a, and the PW_{50}) of the perpendicular HAMR system, based on the TWCM and the microtrack model. From our study, it is shown that these two variations cause the x_0 and a of each subtrack to vary, thus affecting the PW_{50} of the total transition response. In practice, the smaller the PW_{50}, the higher the achievable storage capacity. Consequently, the system designer should carefully design all components to be robust against the peak temperature and cross-track variations that might occur in a perpendicular HAMR system. Additionally, it should be noted out that there are still challenges to be overcome (e.g., an efficient light delivery system, cooling system, etc.) before a real implementation can be achieved.

5. ACKNOWLEDGMENTS

This work was supported by a research grant from Nakhon Pathom Rajabhat University, Nakhon Pathom, 73000, Thailand.

6. REFERENCES

[1] Y. Shiroishi, K.Fukuda, I. Tagawa, H. Iwasaki, S. Takenoiri, H. Tanaka, H. Mutoh, and N. Yoshikawa, Future options for HDD storage, IEEE Trans. Magn., 2009, pp. 3816-3822.

[2] T. Rausch, J. A. Bain, D. D. Stancil, and T. E. Schelesinger, "Thermal Williams-Comstock model for predicting transition length in a heat-assisted magnetic recording system," *IEEE. Trans. Magn.*, vol. 40, no. 1, pp. 137-147, Jan. 2004.

[3] M. Fatih Erden, T. Rausch, and W. A. Challener, "Cross-track transition location and transition parameter effects in heat-assisted magnetic recording," *IEEE. Trans. Magn.*, vol. 41, no.6, pp. 2189-2194, Jun. 2005.

[4] R. Radhakrishan, M. Fatih Erden, C. He and B. Vasic, "Transition response characteristics of heat-assisted magnetic recording and their performance with MTR codes," *IEEE. Trans. Magn.*, vol. 43, no. 6, pp. 2298-2300, Jun. 2007.

[5] A. Kaewpukdee, N. Chirdchoo, and P. Kovintavewat, "Transition characteristics of longitudinal heat-assisted magnetic recording systems," *Procedia Engineering (32)*, March 2012, pp.315-322.

[6] K. Thongkhome, A. Kaewpukdee, P. Kovintavewat, W. Pijitrojana, "Transition characteriztion for perpendicular heat-assisted magnetic recording," *in Proc. of I-SEEC 2012*. December 2012.

[7] R. Wongsathan and P. Supnithi, "Channel response of HAMR with linear temperature-dependent coercivity and remanent magnetization," *ECTI-Conference, Petchaburi, Thailand*, May 2012.

[8] Piya Kovintavewat, Signal processing for digital data storage, Volume III: Advance receiver design, August 2011.