Adjacent Track Interference in Three-Dimensional Heat-Assisted Magnetic Recording

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We examine the adjacent track interference (ATI) problem that arises during three-dimensional heat-assisted magnetic recording (3D HAMR) at 2 Tbps per layer (total density of 4 Tbps) where the medium consists of a high Curie temperature (HC) layer and a low Curie temperature (LC) layer. To evaluate the grain error distribution, the expected magnetization value is calculated using the grain error probability. Prior to considering the ATI in 3D HAMR, we examine the ATI problem for conventional HAMR. Since the temperature of the LC layer in the adjacent tracks while writing in the HC layer (HC writing) exceeds the LC Curie temperature, HC writing will erase the data of the LC layer in the adjacent tracks. Therefore, we investigate 3D HAMR combined with shingled magnetic recording. The ATI in an LC (upper, namely, surface) / HC (lower) layer structure is compared with that in an HC / LC layer structure. The latter is disadvantageous in relation to ATI caused by the small thermal gradient in the LC layer.

Key words: HAMR, 3D HAMR, ATI, information stability, error distribution

1. Introduction

Heat-assisted magnetic recording (HAMR) is a candidate as a next-generation magnetic recording method for achieving a high recording capacity. HAMR is a recording technique where the medium is heated to reduce coercivity during the writing period. Three-dimensional HAMR (3D HAMR) has been proposed¹⁾ where the medium consists of a high mean Curie temperature T_{HC} (HC) layer and a low mean Curie temperature T_{LC} (LC) layer with an isolation layer inserted between the two layers to suppress exchange coupling between them. With 3D HAMR, once data have been written in the HC layer, other data can be written in the LC layer by employing lower temperature heating. Yamane *et al.* reported dual structure, namely 3D, HAMR on bit patterned media²⁾.

On granular media, we have previously discussed the information stability in the LC and HC layers for 10 years of archiving³⁾, the stability of the information in the HC layer while writing is under way in the LC layer³⁾, 3D HAMR media design⁴⁾, and the comparison of two layer structures of an LC (upper, namely, surface) / HC (lower) layer and an HC / LC layer⁵⁾. In the LC / HC layer structure, the LC layer has a T_{LC} of 650 K and a layer thickness h_{LC} of 4.5 nm, and the HC layer has a T_{HC} of 750 K and an h_{HC} of 6.0 nm. A T_{HC} of 725 K may be applicable with the aim of improving the heat resistance of the writing head and/or the surface lubricant by reducing their temperatures⁵⁾. On the other hand, the HC layer has a T_{HC} of 750 K and an h_{HC} of 3.5 nm, and the LC layer has a T_{LC} of 550 K and an h_{LC} of 7.0 nm in the HC / LC layer structure. The results show that each of the two layer structures has benefits and drawbacks.

On the basis of our examination, we believe the LC / HC layer structure to be preferable.

In this paper, we discuss the information stability in adjacent tracks during the writing period, namely, adjacent track interference (ATI). To evaluate the grain error distribution, the expected value of the magnetization is calculated using the grain error probability. First, we examine the ATI problem for conventional HAMR, and then we concentrate on ATI for 3D HAMR combined with shingled magnetic recording in the LC / HC and HC / LC layer structures.

2. Calculation Method and Conditions

2.1 Grain arrangement and writing conditions

We assumed the medium to be granular and the recording density to be 2 Tbps per layer (total density of 4 Tbps). The bit pitch D_{B} and track width D_{T} are both 18 nm as shown in Fig. 1, and therefore the bit aspect ratio $D_{\text{T}}/D_{\text{B}}$ is one. One bit has $m = 3$ grains ($i = 1, 2, m$) in the cross-track (row) direction and $n = 3$ grains in the down-track (column) direction, and thus there are $m \times n = 9$ grains/bit.

We examine ATI, namely, the information stability in the N -th track while writing in the $(N + 1)$ -th track. The Curie temperature T_{c} distribution was assumed to be normal with a mean Curie temperature T_{cm} and a standard deviation $\sigma_{\text{Tc}}/T_{\text{cm}}$ of 2 %. The writing temperature of the grains at the track edges was assumed to be $T_{\text{cm}} + 2\sigma_{\text{Tc}}$, taking account of the T_{c} distribution. While writing in the $(N + 1)$ -th track, the probabilities are 93.3 and 99.8 % where the T_{c} values of all 3 grains and 2 grains or more are lower than $T_{\text{cm}} + 2\sigma_{\text{Tc}}$, respectively, at the track edge. Furthermore, the probability is more than 99.9 % where the T_{c} value of all 3 grains is lower than the temperature at the track center. Therefore, almost all grains are heated above their T_{c} values during the writing period. If we use a

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writing temperature of $T_{cm} + \sigma_{Tc}$ instead of $T_{cm} + 2\sigma_{Tc}$, the probability is only 59.6 % where the T_c value of all 3 grains is lower than $T_{cm} + \sigma_{Tc}$ at the track edge, and then we can assume that there will be a write-error increase. Although the condition of $T_{cm} + \sigma_{Tc}$ is useful for reducing the medium surface temperature, which relates to the heat resistance of the writing head and/or the surface lubricant, the condition $T_{cm} + 2\sigma_{Tc}$ may be required.

Figure 2 shows schematic illustrations of the (a) LC / HC and (b) HC / LC layer structures published in a previous paper⁵⁾. The Curie temperatures (T_{LC} and T_{HC}) and layer thicknesses (h_{LC} and h_{HC}) were determined taking account of the information stability in the LC and HC layers for 10 years of archiving and the stability of the information in the HC layer while writing in the LC layer (LC writing) under conditions where $T_{HC} = 750$ K and $h_{HC} + h_{LC} = 10.5$ nm⁵⁾. The readout temperature was assumed to be 330 K.

Fig. 1 Grain arrangement and writing conditions.

Fig. 2 Layer structures for (a) LC / HC and (b) HC / LC⁵⁾.

We assumed that the grain size D distribution was log-normal with a mean grain size D_m of 5.0 nm and a standard deviation σ_D/D_m of 15 %. The intergrain

spacing Δ_G was 1.0 nm. The isolation layer is used to suppress exchange coupling between the upper and lower layers. The layer thickness h_{iso} must be smaller in order to obtain a high field strength from the lower layer at the reader. We chose an h_{iso} value of 1.0 nm. This problem is a future subject.

2.2 Magnetic properties

The temperature dependence of the magnetization M_s was calculated by employing a mean field analysis⁶⁾, and that of the anisotropy constant K_u was assumed to be proportional to M_s^2 ⁷⁾. $M_s(T_c, T)$ is a function of T_c and temperature T . And $M_s(T_c = 770$ K, $T = 300$ K) = 1000 emu/cm³ was assumed for FePt. With this assumption, the M_s value can be calculated for all T_c and T values.

We introduced an HAMR design parameter, namely, the medium anisotropy constant ratio K_u/K_{bulk} ⁸⁾, which is the intrinsic ratio of the medium K_u to bulk FePt K_u regardless of T_c . Although a low T_c medium is easy to write when employing HAMR, a high K_u/K_{bulk} is needed for a low T_c medium for 10 years of archiving⁹⁾, and a medium with a high K_u/K_{bulk} is difficult to manufacture regardless of T_c ¹⁰⁾. Moreover, a high K_u/K_{bulk} must be achieved in 3D HAMR³⁾. $K_u(T_c, K_u/K_{bulk}, T)$ is a function of T_c , K_u/K_{bulk} , and T . And $K_u(T_c = 770$ K, $K_u/K_{bulk} = 1$, $T = 300$ K) = 70 Merg/cm³ was assumed for bulk FePt. We used a K_u/K_{bulk} value of 0.8 in this paper. With this assumption, the K_u value can be calculated for all T_c and T values. No intrinsic distribution of K_u was assumed. However, there was a fluctuation in K_u caused by σ_{Tc} .

The T_c value can be adjusted by adjusting the Cu composition z for $(Fe_{0.5}Pt_{0.5})_{1-z}Cu_z$.

2.3 Temperature profile

We used data published in a previous paper⁵⁾, in which a heat transfer simulation was carried out using Poynting for Optics software (Fujitsu Ltd.), for the temperature profiles of the LC and HC layers during the writing period. The light spot diameter was about 9.0 nm (FWHM) in the down-track and cross-track directions. The linear velocity was 10 m/s. The ambient temperature T_{amb} is the maximum working temperature of the hard disk drive, and was assumed to be 330 K.

We focused on the thermal gradient $\partial T/\partial y$ in the cross-track directions at the track edges during LC and HC writing, the medium surface temperature T_{surf} at the track center during HC writing, and the grain temperature difference ΔT_{HL} between the HC and LC layers at the track edges during LC writing. The $\partial T/\partial y$ value is important for ATI.

We have previously reported the thermal gradient in 3D HAMR⁴⁾:

(1) The thermal gradient for the upper layer is intrinsically larger than that for the lower layer due to a heat flow in the in-plane direction in the deep part of the layer.

(2) The thermal gradient $\partial T_H / \partial y$ for the HC layer is intrinsically larger than $\partial T_L / \partial y$ for the LC layer due to their respective Curie temperatures as given by

$$\frac{\partial T_H}{\partial y} = \frac{T_{HC} + 2\sigma_{THC} - T_{amb}}{T_{LC} + 2\sigma_{TLC} - T_{amb}} \cdot \frac{\partial T_L}{\partial y}. \quad (1)$$

The result calculated with a heat transfer simulation was used as the temperature profile for the cross-track direction during the writing period in 3.2, 3.3, and 3.4.

2.4 Information stability

The information stability for ATI was estimated using the grain error probability P^3 ,

$$P = 1 - \exp\left(-f_0 t \exp\left(-\frac{K_{\text{ueff}} V}{kT} \left(1 + \frac{H_w}{H_{\text{keff}}}\right)^2\right)\right), \quad (2)$$

($|H_w| < H_{\text{keff}}$)

taking account of the shape anisotropy $M_s H_d / 2$ using a self-demagnetizing field $H_d^{(4)}$ where $K_{\text{ueff}} = K_u - M_s H_d / 2$, $V = D \times D \times h$, k , and $H_{\text{keff}} = 2K_{\text{ueff}} / M_s$ are the effective anisotropy constant, the grain volume, the Boltzmann constant, and the effective anisotropy field, respectively. The writing field H_w and time t were assumed to be -10 kOe and 1 ns, respectively. The attempt frequency f_0 is a function of the damping constant α , and we used an α value of 0.1 . The calculation bit number was $1\text{E}+7$.

To evaluate the grain error distribution, we calculated the expected value of the magnetization $E[M_s]$,

$$E[M_s] = (1 - P)M_s + P(-M_s) = (1 - 2P)M_s. \quad (3)$$

The $E[M_s]$ value was averaged over one row of grains ($n = 3$) as

$$E[M_{si}] = \frac{\sum_{j=1}^n (1 - 2P_{ij}) M_{sij}(T_{cij}, 330 \text{ K})}{n} \quad (4)$$

for the information stability in the N -th track while writing in the $(N + 1)$ -th track since there is a temperature distribution in the cross-track direction.

Fig. 3 Number of bits against expected value of magnetization $E[M_{si}]$ in the N -th track while writing in the $(N + 1)$ -th track.

3. Calculation Results

3.1 ATI for conventional HAMR

In 3D HAMR, T_{cm} , h , and $\partial T / \partial y$ change in a complex manner for each layer. Therefore, first, we examined the ATI problem for conventional HAMR by changing only one calculation parameter. The magnetic properties were calculated by the method described in 2.2.

Fig. 4 Bit number fraction for $E[M_{si}] < 0$ in the N -th track while writing in the $(N + 1)$ -th track for various (a) T_{cm} , (b) h , and (c) $\partial T / \partial y$ values.

Fig. 5 Bit number fraction for $E[M_{si}] < 0$ in the N -th track while writing in the $(N+1)$ -th track for $T_{cm} = 550$ K ($\partial T/\partial y = 7.0$ K/nm), 650 K (10 K/nm), and 750 K (13 K/nm).

The bit error rate is a function of various parameters, *e.g.* the magnetization direction, the grain size, and the readout track width. Since the bit error rate depends on the readout track width, the bit error rate was not examined in this paper. We focused on the magnetization direction using $E[M_{si}]$ to evaluate the grain error distribution for the cross-track direction. The bit error rate will increase qualitatively as the bit number for the negative $E[M_{si}]$ increases since the negative $E[M_{si}]$ means that the magnetization direction is opposite to the recorded direction. The number of bits against $E[M_{si}]$ in the N -th track while writing in the $(N+1)$ -th track, namely, the grain error distribution, is shown in Fig. 3 for $T_{cm} = 650$ K, $h = 5$ nm, and $\partial T/\partial y = 10$ K/nm which was assumed to be constant everywhere. The peaks in the figure represent grain error for the grain with the mean Curie temperature, and the $E[M_{si}]$ value is negative for 2 or 3 grain errors since the total row grain number is three. For all grains, the negative $E[M_{si}]$ represents more than half of 3 grain errors. The grain error increases in the order of $i = 1, 2$, and 3 since the temperature increases in this order. Some information degradation can be seen even in the 2nd row ($i = 2$) grains. Since there is a large degradation of the information in the 3rd row ($i = 3$) grains, at least the 3rd row grains must be used as a guard band for ATI.

Figure 4 shows the bit number fraction for $E[M_{si}] < 0$, namely, the ratio of the bit number for $E[M_{si}] < 0$ in Fig. 3 to all the bits, for various (a) T_{cm} , (b) h , and (c) $\partial T/\partial y$ values. The fraction increases slightly and ATI worsens as T_{cm} increases, as shown in Fig. 4 (a). Although K_{ueff} increases as T_{cm} increases, T also increases as T_{cm} increases. Therefore, the $K_{ueff}V/(kT)$ value in Eq. (2) decreases as T_{cm} increases. When h is thin, ATI worsens as shown in Fig. 4 (b) since the $K_{ueff}V/(kT)$ value simply becomes smaller. When $\partial T/\partial y$ is small, ATI becomes worse not only in the 2nd row ($i = 2$) grains but in the 1st row ($i = 1$) grains as shown in Fig. 4 (c) since K_{ueff} is small and T is high.

The T_{cm} and the $\partial T/\partial y$ values are closely related by Eq. (1). Therefore, ATI was calculated by changing the $\partial T/\partial y$ and T_{cm} values at the same time according to Eq. (1) under the condition $\partial T/\partial y = 10$ K/nm when $T_{cm} = 650$ K. As a result, ATI becomes worse as T_{cm} decreases, as shown in Fig. 5.

3.2 ATI for 3D HAMR

Next, we examined the ATI problem for 3D HAMR. Figure 6 shows the temperature profiles of the LC and HC layers in the cross-track direction during HC writing. The solid lines indicate the temperatures at the layer boundaries, and the dotted lines indicate those at the layer centers.

Fig. 6 Temperature profile in cross-track direction for (a) LC / HC and (b) HC / LC layer structures during HC writing.

The writing temperature of the HC layer in the $(N+1)$ -th track at -12 and -24 nm is $T_{HC} + 2\sigma_{THC} = 780$ K. For the LC / HC layer structure shown in Fig. 6 (a), the temperatures of the LC layer in the N -th track at 6 ($i = 1$), 0 ($i = 2$), and -6 nm ($i = 3$) are 616, 671, and 745 K, respectively. The temperatures at 0 ($i = 2$) and -6 nm ($i = 3$) are higher than the T_{LC} of 650 K. On the other hand, for the HC / LC layer structure shown in Fig. 6 (b), although the LC layer in the N -th track at 6 ($i = 1$), 0 (i

$= 2$), and -6 nm ($i = 3$) has low temperatures of 573, 617, and 669 K, respectively, since LC is the lower layer, all temperatures are higher than T_{LC} of 550 K since the T_{LC} value must be reduced to realize information stability in the HC layer during LC writing⁵⁾.

Since the temperature of the LC layer in the adjacent tracks during HC writing exceeds the LC Curie temperature, HC writing will erase the data of the LC layer in the adjacent tracks. Therefore, it is necessary to devise a suitable writing method to address this issue, *e.g.* combination with shingled magnetic recording. The following deals with shingled 3D HAMR.

3.3 ATI for LC / HC layer structure

In this section, we discuss the information stability in the N -th track of the LC and HC layers while writing in the $(N + 1)$ -th track of the LC and HC layers (LC and HC ATI), respectively, for the LC / HC layer structure.

We have carried out a heat transfer simulation for 3D HAMR media as reported in a previous paper⁵⁾. The results are summarized in Table 1. The difference between the $\partial T / \partial y$ values for LC and HC writing is relatively small due to the combinations of the upper LC layer and the lower HC layer. The T_{surf} value of 957 K is relatively high since HC is the lower layer. This is disadvantageous in terms of the heat resistance of the writing head and/or the surface lubricant. The ΔT_{HL} value of -42 K is negative, which means that the temperature in the HC layer during LC writing is lower than that in the LC layer, and this is advantageous in relation to the information stability in the HC layer.

Table 1 Results of heat transfer simulation for LC / HC layer structure⁵⁾.

	LC writing	HC writing
LC / HC layer structure		
T_{cm} (K)	650	750
h (nm)	4.5	6.0
$\partial T / \partial y$ (K / nm)	12.0	9.0
T_{surf} (K)		957
ΔT_{HL} (K)	-42	

The grain error distribution is shown in Fig. 7 as regards (a) LC and (b) HC ATI. Although the LC layer is thinner than the HC layer, the thermal gradient of the LC layer is larger than that of the HC layer (see Fig. 4). Then the error distributions are roughly the same for (a) LC and (b) HC ATI since the vertical axis is the logarithmic scale. Although some information degradation can be seen in the 2nd row ($i = 2$) grains, the bit number for $E[M_{si}] < 0$ is small.

Figure 8 shows the bit number fraction for $E[M_{si}] < 0$. The fractions are less than $1E-7$ in both the LC and HC layers for $i = 1$, and are only $4E-5$ and $3E-7$ in the LC and HC layers, respectively, for $i = 2$. However, the fractions are as high as $7E-1$ and $6E-1$ in the LC and HC

layers, respectively, for $i = 3$. The magnetization reversal for more than half of the grains can be seen for $i = 3$.

Fig. 7 Number of bits against expected value of magnetization $E[M_{si}]$ in (a) the N -th track of the LC layer while writing in the $(N + 1)$ -th track of the LC layer (LC ATI) and (b) HC ATI for LC / HC layer structure.

Fig. 8 Bit number fraction for $E[M_{si}] < 0$ in LC and HC ATI for LC / HC layer structure.

Using the above result, we illustrate ATI for shingled 3D HAMR schematically in Fig. 9, in which the gray regions indicate the magnetization transition. The 3rd row ($i = 3$) grains used as a guard band, and the readout track width effectively decreases to about 12 nm from 18 nm as shown in Fig. 1.

Fig. 9 Schematic illustration of ATI for LC / HC layer structure.

3.4 ATI for HC / LC layer structure

Next, we discuss ATI for the HC / LC layer structure.

The results of a heat transfer simulation reported in a previous paper⁵⁾ are summarized in Table 2. The T_{surf} value of 874 K compared with the value of 957 K in Table 1 is relatively low since HC is the upper layer. This is advantageous in terms of heat resistance. The positive ΔT_{HL} value of 35 K compared with -42 K in Table 1 is disadvantageous in relation to the information stability in the HC layer during LC writing. Therefore, the T_{LC} value must be lower than that in Table 1. As a result, compared with the results in Table 1, the difference between the $\partial T / \partial y$ values for HC and LC writing is relatively large due to the lower T_{LC} value in addition to the combinations of the upper HC layer and the lower LC layer.

Table 2 Results of heat transfer simulation for HC / LC layer structure⁵⁾.

	HC writing	LC writing
HC / LC layer structure		
T_{cm} (K)	750	550
h (nm)	3.5	7.0
$\partial T / \partial y$ (K / nm)	16.4	5.0
T_{surf} (K)	874	
ΔT_{HL} (K)		35

The grain error distribution is shown in Fig. 10 as regards (a) HC and (b) LC ATI. Compared with the result in Table 1, although the HC layer in Table 2 is thinner, the HC thermal gradient is larger (see Fig. 4). Then the error distributions are roughly the same in Fig. 7 (b) and Fig. 10 (a). In contrast, large information degradation can be seen even in the 2nd row ($i = 2$) grains for the LC

layer as shown in Fig. 10 (b) since the LC thermal gradient is small (see Fig. 4) as shown in Table 2.

Fig. 10 Number of bits against expected value of magnetization $E[M_{si}]$ as regards (a) HC and (b) LC ATI for HC / LC layer structure.

Fig. 11 Bit number fraction for $E[M_{si}] < 0$ in HC and LC ATI for HC / LC layer structure.

The above results are reflected in the results in Fig. 11 which shows the bit number fraction for $E[M_{si}] < 0$. The fraction in the LC layer reaches $7E-2$ for $i = 2$ and $9E-1$ for $i = 3$. Therefore, both the 3rd row ($i = 3$) and 2nd row ($i = 2$) grains are used as a guard band in the LC layer, and the readout track width will be narrow as shown in Fig. 12.

In conclusion, the LC / HC layer structure is preferable as regards ATI.

Fig. 12 Schematic illustration of LC ATI for HC / LC layer structure.

4. Conclusions

We examined the adjacent track interference (ATI) problem in conventional HAMR and 3D HAMR combined with shingled magnetic recording in LC (upper, namely, surface) / HC (lower) and HC / LC layer structures.

(1) Conventional HAMR

When the medium is thin, ATI worsens since the grain volume simply becomes smaller.

Curie temperature and thermal gradient are closely related. Therefore, ATI worsens as the Curie temperature decreases since the thermal gradient decreases at the same time.

(2) Shingled 3D HAMR

The thermal gradient in the LC layer is small for the HC / LC layer structure since LC is the lower layer, and the LC Curie temperature is lower than that in the LC / HC layer structure. Therefore, ATI in the LC layer is worse for the HC / LC layer structure.

The LC / HC layer structure is preferable as regards ATI.

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