Medium Layer Structure in Three-Dimensional Heat-Assisted Magnetic Recording

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We examine a medium layer structure in 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. We perform a heat transfer simulation for 3D HAMR media including the isolation layer. To evaluate the grain error distribution, the expected value of the magnetization is calculated using the grain error probability. The error threshold and the time dependence of the bit error rate are discussed for 10 years of archiving. The information stability in the HC layer while writing in the LC layer is estimated using the temperature profile calculated by the heat transfer simulation. An LC (upper, namely, surface) / HC (lower) layer structure is compared with an HC (upper) / LC (lower) layer structure. The former is disadvantageous in relation to the medium surface temperature as regards writing in the HC layer. The latter may be disadvantageous in relation to the difference between the thermal gradients for HC and LC writing.

Key words: 3D HAMR, heat transfer simulation, temperature profile, information stability, error distribution

1. Introduction

Microwave-assisted magnetic recording (MAMR), heat-assisted magnetic recording (HAMR), and three-dimensional magnetic recording are candidates as next generation magnetic recording methods 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 proposed where the medium consists of a high Curie temperature $T_{HC}$ (HC) layer and a low 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.

We have previously discussed the information stability in the HC and LC layers for 10 years of archiving, and the stability of the information in the HC layer while writing is under way in the LC layer. We have also discussed 3D HAMR media design. We used these results to roughly determine the preferable layer structure for 3D HAMR, namely an LC (upper, namely, surface) / HC (lower) layer, where the LC layer has a $T_{LC}$ of 625 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. However, we analytically estimated the temperature profile in it using previously published data where the recording layer thickness was 8.0 nm without the isolation layer.

In this paper, we carry out a heat transfer simulation for 3D HAMR media where the recording layer thickness is 11.5 nm including an isolation layer of 1.0 nm. To evaluate the grain error distribution, the expected value of the magnetization is calculated using the grain error probability. We discuss both the error threshold and the time dependence of the bit error rate for 10 years of archiving. We then estimate the information stability in the HC layer while writing in the LC layer using a temperature profile calculated by using a heat transfer simulation. Furthermore, we examine two layer structures consisting of an LC / HC layer and an HC / LC layer.

2. Calculation Method

2.1 Magnetic properties

The temperature dependence of the magnetization $M_s$ was calculated by employing a mean field analysis, and that of the anisotropy constant $K_a$ was assumed to be proportional to $M_s^2$. $M_s(T, T_c)$ is a function of the Curie temperature $T_c$ and temperature $T$. And $M_s(T_c = 770 K, T = 300 K) = 1000$ emu/cm$^3$ was assumed for FePt.

We introduced an HAMR design parameter, namely, the medium anisotropy constant ratio $K_a/K_{bulk}$ since the $K_a$ value is a function of $T_c$. $K_a/K_{bulk}$ is the intrinsic ratio of the medium $K_a$ to bulk FePt $K_a$ regardless of $T_c$. Although a low $T_c$ medium is easy to write when employing HAMR, a high $K_a/K_{bulk}$ is needed for a low $T_c$ medium for 10 years of archiving, and a medium with a high $K_a/K_{bulk}$ is difficult to manufacture regardless of $T_c$. Moreover, a high $K_a/K_{bulk}$ must be achieved in 3D HAMR to realize information stability in the LC layer for 10 years of archiving, and to realize information stability in the HC layer while writing in the LC layer $K_a(T, K_a/K_{bulk}, T)$ is a function of $T_c$, $K_a/K_{bulk}$, and $T$. And $K_a(T_c = 770 K, K_a/K_{bulk} = 1, T = 300 K) = 70$ Merg/cm$^3$ was assumed for bulk FePt. We used $K_a/K_{bulk} = 0.8$ in this paper.

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

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2.2 Field strength
We assumed the medium to be granular and the recording density to be 2 Tbpsi per layer (total density of 4 Tbpsi). The magnetic field strength from the upper and lower layers, as shown in Fig. 1, was calculated using an analytical equation. One bit has \( m = 3 \) grains for the cross-track direction and \( n = 3 \) grains for the down-track direction, namely, there are \( m \times n = 9 \) grains/bit. The bit aspect ratio is one. The grain size \( D_{g1} \) and the intergrain spacing \( \Delta D \) are 5.0 nm and 1.0 nm, respectively, with no grain size distribution. The grain heights (layer thicknesses) and the magnetizations for the upper and lower layers are \( h_U \), \( h_L \), \( M_{g1} \), and \( M_{g1} \), respectively. The flying height \( h_f \) = 4.0 nm is the distance between the magnetic head reader and the upper layer surface.

The isolation layer is used to suppress the exchange coupling between the upper and lower layers. That layer thickness \( h_{iso} \) must be thinner due to the higher field strength from the lower layer at the reader since the field strength decreases exponentially with a \( h_f + h_{iso} \) value of more than 3 nm. On the assumption that we had selected an appropriate material for the isolation layer, we chose an \( h_{iso} \) value of 1.0 nm.

![Fig. 1 Grain arrangement for field calculation. (a) Top and (b) side views.](image)

2.3 Temperature profile
We needed to determine the temperature profiles of the LC and HC layers at the time of writing for the 3D HAMR design. A heat transfer simulation was carried out using Poynting for Optics (Fujitsu Ltd.). Figure 2 shows a schematic illustration of the structure of a medium that consists of four layers, namely, a recording layer (RL) (FePt base, upper + isolation + lower layers = 11.5 nm), interlayer 1 (IL1) (MgO base, 5 nm), interlayer 2 (IL2) (Cr base, 10 nm), and a heat-sink layer (Cu base, 30 nm). Since suitable intergrain and isolation layer materials are currently unknown, we used the optical and thermal constants of FePt for these materials. The total layer thickness of the LC and HC layers was 11.5 – 1.0 = 10.5 nm. IL1 is a layer for the c-axis orientation control of RL, and IL2 is a seed layer for IL1. The x, y, and z axes are the down-track, cross-track, and film normal directions, respectively, where \( y = 0 \) at the track center and \( z = 0 \) at the RL surface. The writing temperature of the grains at the track edges \( y = \pm 6.0 \) nm was assumed to be \( T_{cm} + 2\sigma_{tc} \) for the HC and LC layers where \( T_{cm} \) and \( \sigma_{tc} \) are the mean Curie temperature and the standard deviation of \( T_{cm} \), respectively, taking account of the Curie temperature variation.

![Fig. 2 Medium structure for heat transfer simulation.](image)

| Table 1 (a) Calculation conditions, (b) optical constants, and (c) thermal constants for heat transfer simulation. |
| --- |
| **(a)** | Wavelength \( \lambda \) (nm) | 780 |
| Light-spot diameter \( D_L \) (nm) | 9.0 (FWHM) |
| Linear velocity \( v \) (m/s) | 10 |
| Ambient temperature \( T_{amb} \) (K) | 330 |
| **(b)** | Refractive index | Extinction coefficient |
| Recording layer | 3 | 4 |
| Interlayer 1 | 1.73 | 0 |
| Interlayer 2 | 4.11 | 4.35 |
| Heat-sink layer | 0.242 | 4.85 |
| Glass substrate | 1.5 | 0 |
| **(c)** | Specific heat \( c_p \) (J/(kg K)) | Thermal conductivity \( k \) (W/(m K)) |
| Recording layer | 200 | 100 |
| Interlayer 1 | 500 | 4 |
| Interlayer 2 | 360 | 100 |
| Heat-sink layer | 440 | 400 |
| Glass substrate | 1000 | 1 |
We focused on the medium surface temperature $T_{\text{surf}}$ while writing in the HC layer, the thermal gradients for the down-track $\partial T/\partial x$ and cross-track $\partial T/\partial y$ directions while writing in the LC and HC layers, and the grain temperature difference $\Delta T_{\text{HL}}$ between the HC and LC layers while writing in the LC layer at the track edges $y = \pm 6.0$ nm.

Table 1 summarizes (a) calculation conditions, (b) optical constants, and (c) thermal constants used in the simulation. The light spot diameter (FWHM) is about 9.0 nm for the down-track and cross-track directions. The linear velocity is 10 m/s. The ambient temperature is the maximum working temperature of the hard disk drive, and is assumed to be 330 K.

### 2.4 Information stability

The information stability in 3D HAMR was estimated using the grain error probability $P^2$, taking account of the shape anisotropy $M_s H_d/2$ using a self-demagnetizing field $H_d$. The conditions used when calculating the information stability in the LC and HC layers are summarized in Table 2.

We assumed that the grain size distribution was log-normal with a mean grain size $D_m$ of 5.0 nm and a standard deviation $\sigma_D/D_m$ of 15%. The $T_c$ distribution was assumed to be normal with a mean Curie temperature $T_{cm}$ and a standard deviation $\sigma_{Tc}/T_{cm}$ of 2%. No intrinsic distribution of $K_u$ was assumed. However, there was a fluctuation in $K_u$ caused by $\sigma_{Tc}$.

The calculation results were achieved using a heat transfer simulation in 2.3 was used as the temperature profile for the cross-track direction while writing in the LC layer.

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

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

The $E[M_g]$ value was averaged over one-bit grains $(m \times n = 9)$ to give the information stability during 10 years of archiving.

$$E[M_g] = \frac{\sum_i \sum_j (1 - 2P)_{ij} M_{s,ij} (T_{c,ij} = 330 \text{ K})}{m \times n}, \quad (2)$$

and was averaged over one-row grains $(n = 3)$ for the information stability in the HC layer while writing in the LC layer.

$$E[M_{a,ij}] = \frac{\sum_j (1 - 2P)_{ij} M_{s,ij} (T_{c,ij} = 330 \text{ K})}{n}, \quad (3)$$

since there is a temperature distribution for the cross-track direction.

Furthermore, we introduced an error threshold $E_{th}$ to estimate the bit error rate (bER). Errors occur in some grains of a bit. We assume that if the ratio of the surface magnetic charge $\sum_i M_{s,ij} (T_{c,ij} = 330 \text{ K}) D_{ij}^2$ of the grains where the magnetization turns in the recording direction to the total surface magnetic charge $(m \times n) M_s (T_{cm} = 330 \text{ K}) D_m^2$ in a bit is more than $E_{th}$, namely,$$
\frac{\sum_i M_{s,ij} (T_{c,ij} = 330 \text{ K}) D_{ij}^2}{(m \times n) M_s (T_{cm} = 330 \text{ K}) D_m^2} > E_{th}, \quad (4)$$

the bit is error free where $M_{s,ij}$, $T_{c,ij}$, and $D_{ij}$ are the magnetization, the Curie temperature, and the grain size of the $ij$-th grain, respectively.

The readout magnetic field at the reader will be degraded after 10 years of archiving or writing in the LC layer. The lowest normalized magnetic field $H_b$ that must be readable without error can roughly be represented by $E_{th}$ as

$$H_b = 2E_{th} - 1. \quad (5)$$

### Table 2 Calculation conditions for information stability.

| Parameter                        | Value   |
|----------------------------------|---------|
| Recording density (Tbps/layer)   | 2       |
| Total density (Tbps)             | 4       |
| Grain number $m \times n$ (grains/bit) | 3 x 3   |
| Intergrain spacing $\Delta c$ (nm) | 1.0     |
| Mean grain size $D_m$ (nm)       | 5.0     |
| Standard deviation $\sigma_D/D_m$ | 15      |
| Bit pitch $P_b$ (nm)             | 18.0    |
| Track width $D_t$ (nm)           | 18.0    |
| Bit aspect ratio $D_t/P_b$        | 1.0     |
| Standard deviation $\sigma_{Tc}/T_{cm}$ (T/cm) | 2       |
| Anisotropy constant $K_u/K_{bulk}$ | 0.8     |
| Gilbert damping constant $\alpha$ | 0.1     |

### 3. Calculation Results

#### 3.1 LC / HC layer structure

First, we discuss the structure as shown in Fig. 3 (a) where the upper layer is LC with $T_{LC} = 650$ K and $h_{LC} = 4.5$ nm, and the lower is HC with $T_{HC} = 750$ K and $h_{HC} = 6.0$ nm. The $T_{LC}$ value was revised to 650 from 625 K in a previous paper due to information stability in the LC layer during 10 years of archiving.

Figure 3 (b) shows the $z$ component $H_z$ of the magnetic field at the track center and the reader position from the LC and HC layers for the down-track direction using 3 grains for the cross-track direction. The peak $z$ component $H_{peak}$ values are 1151 and 570 Oe from the LC and HC layers, respectively, where $h_{LP}$ is 4.0 nm.

#### 3.1.1 Temperature profile

Figure 4 shows the temperature profiles calculated employing a heat transfer simulation for the cross-track direction. The solid lines indicate the temperatures at the layer boundaries, and the dotted lines indicate those at the layer centers.

(a) When writing in the LC layer (LC writing), the temperature at $y = \pm 6.0$ nm and $z = -2.25$ nm is $T_{LC} + 2\Delta T_{LC} = 676$ K at which $\partial T_{LC}/\partial y$ is 12.9 K/nm. The $\Delta T_{HL}$ value is $-42$ K.
Fig. 3 (a) Layer structure for LC / HC and (b) field strength $H_0$ from LC and HC layers for the down-track direction.

(b) When writing in the HC layer (HC writing), the temperature at $y = \pm 6.0$ nm and $z = -8.5$ nm is $T_{HC} + 2\sigma_{HC} = 780$ K at which $\partial T / \partial y$ is 9.0 K/nm. The $T_{surf}$ value is 957 K. It should be noted that the temperature of the LC layer ($z = -2.25$ nm) in the center of adjacent tracks ($y = \pm 18.0$ nm) is 671 K, which is higher than $T_{LC}$, and 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 results obtained for $T_{HC} = 750$ K are summarized in Table 3 (a). 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.

We have reported as regards the thermal gradient in 3D HAMR:

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 for the HC layer is intrinsically larger than that for the LC layer due to their respective Curie temperatures.

The difference between the thermal gradients for LC and HC writing is relatively small due to the combinations of the upper LC layer and the lower HC layer.

The $\Delta T_{HL}$ value of $-42$ K is negative, which means that the temperature in the HC layer while writing in the LC layer is lower than that in the LC layer, and this is advantageous in relation to the information stability in the HC layer.

By reducing $T_{HC}$, $T_{surf}$ can be reduced. Furthermore, the heating power $P_w$ can also be reduced. The results for $T_{HC} = 725$ K are summarized in Table 3 (b). In comparison with the result for $T_{HC} = 750$ K, $T_{surf}$ is reduced to 920 from 957 K and $P_w$ can be reduced to 0.94.

### 3.1.2 Information stability for 10 years of archiving

We estimated the information stability for 10 years of archiving with no writing field $H_w$ using the grain error probability. The storage temperature is 350 K since we take a certain margin for temperature into account. The calculation bit number was $1E+7$. The allowable bER is assumed to be $1E-3$. 

![Temperature profile in the cross-track direction for an LC (upper) / HC (lower) layer structure while writing in the (a) LC and (b) HC layers.](image)
Table 3 Results of heat transfer simulation for LC / HC layer structure ((a) \( T_{HC} = 750 \) and (b) 725 K).

| (a) LC / HC layer structure | LC writing | HC writing |
|----------------------------|------------|------------|
| \( T_{cm} \) (K)          | 650        | 750        |
| \( h \) (nm)              | 4.5        | 6.0        |
| \( T_{surf} \) (K)        |            | 957        |
| \( \delta T / \Delta x \) (K / nm) | 12.2 | 8.9 |
| \( \delta T / \Delta y \) (K / nm) | 12.0 | 9.0 |
| \( \Delta T_{HL} \) (K)   | -42        |            |

(b) LC / HC layer structure

| LC / HC layer structure | LC writing | HC writing |
|-------------------------|------------|------------|
| \( T_{cm} \) (K)        | 650        | 725        |
| \( h \) (nm)            | 4.5        | 6.0        |
| \( T_{surf} \) (K)      |            | 920        |
| \( \delta T / \Delta x \) (K / nm) | 12.2 | 8.4 |
| \( \delta T / \Delta y \) (K / nm) | 12.0 | 8.4 |
| \( P_w / P_c (T_{HC} = 750 \) K) | 0.94 | |

Grain error distributions are shown in Figs. 5 (a) LC and (b) HC layers for 10 and 0.001 yrs where 0.001 yrs corresponds to about 9 hrs. The peaks in the figures represent grain error, and the \( E[M_{s}] \) value is negative for 5 or more grain errors since the total grain number is nine. For (a) the LC layer, 3 grain errors can be seen even after 0.001 yrs, and 5 grain errors will occur after 10 yrs since the LC layer has a low Curie temperature and a thin layer. For (b) the HC layer, only 1 grain error can be seen after both 0.001 and 10 yrs due to a high Curie temperature and a thick layer.

Figure 6 shows \( b_{ER} \) as a function of \( E_{th} \) for 10 years of archiving. The second horizontal axis is the lowest \( H_{0} \) value that must be readable without error, which was estimated using Eq. (5). \( E_{th} \) values of 0.581 and 0.744 are required for the LC and HC layers, respectively.

The information will be degraded in the LC layer and it will be scarcely degraded in the HC layers as shown in Fig. 5. Figure 7 shows time dependence of \( b_{ER} \). Errors increase over time in the LC layer, and the error does not increase in the HC layer with both \( T_{HC} = 750 \) K and 725 K (not shown). The bit error rate \( b_{ER}_{10} \) after 10 years of archiving is expressed as

\[
b_{ER}_{10} = b_{ER}_{ini} + \Delta b_{ER},
\]

where \( b_{ER}_{ini} \) and \( \Delta b_{ER} \) are the initial bit error rate before archiving and the increase in the bit error rate during archiving, respectively. For the LC layer, \( \Delta b_{ER} \) is about 1E–3 for \( E_{th} = 0.581 \). Therefore, \( b_{ER}_{ini} \) must be low, for example, 1E–4. In this case, \( b_{ER}_{10} \) will be 1.1E–3. On the other hand, \( b_{ER}_{ini} = 1E–3 \) is allowable for the HC layer since there was no change in \( b_{ER} \) over ten years.

Fig. 5 Number of bits against expected value of magnetization during 10 years of archiving for the LC / HC layer structure ((a) LC and (b) HC layers).

Fig. 6 Bit error rate as a function of error threshold and normalized field amplitude for 10 years of archiving for the LC / HC layer structure.
3.1.3 Information stability in HC layer while writing in LC layer

We estimated the information stability in the HC layer while writing in the LC layer using the temperature profile in 3.1.1 and the grain error probability. The writing field $H_w$ and time $t$ were assumed to be $-10$ kOe and 1 ns, respectively. Since the temperature of the 2nd row grains (track center, $i = 2$) is higher than that of the 1st row grains (track edge, $i = 1$), the number of bits against $E[M_a]$ averaged over one-row grains is shown in Fig. 8. The $E[M_a]$ value is negative for 2 or 3 grain errors since the total row grain number is three. The grain error is higher for $i = 2$ due to its higher temperature. For (a) $T_{HC} = 750$ K, only 1 grain error occurs at most in each row, and the number of errors in one bit is at most 3 in 9. On the other hand, there is 1 grain error at $i = 1$, and 2 grain errors at $i = 2$ for (b) $T_{HC} = 725$ K. The number of errors in one bit is at most 4 in 9. Therefore, the information in the HC layer is almost stable during writing in the LC layer.

Figure 9 shows $bER$ as a function of $E_{th}$ and $H_0$ during writing in the LC layer. When $T_{HC} = 750$ K, the results in Figs. 6 (HC layer) and 9 ($T_{HC} = 750$ K) are almost the same. Therefore, the information in the HC layer is scarcely degraded. Furthermore, there is a little degradation in the information for $T_{HC} = 725$ K. Since there was no change in $bER$ over ten years in the HC layer, a $bER_{ini}$ of $10^{-9}$ is the HC layer after writing in the LC layer can be allowable, and $E_{th}$ values of 0.736 and 0.672 are required for $T_{HC} = 750$ and 725 K, respectively.

In short, the results obtained in 3.1.2 and 3.1.3 are summarized in Table 4.

Although the $H_{peak}$ value is high for the LC layer as shown Fig. 3 (b), $E_{th}$ and $H_0$ are low. On the other hand, $E_{th}$ and $H_0$ are high in the HC layer for which $H_{peak}$ is low.

The $bER$ value in the HC layer with $T_{HC} = 725$ K is higher after writing in the LC layer as shown in Fig. 8. However, the HC layer with $T_{HC} = 725$ K as well as that with $T_{HC} = 750$ K may also be a candidate for 3D HAMR media with the aim of lowering $T_{surf}$.
Table 4 Information stability results for LC / HC layer structure (a) $T_{HC} = 750$ and (b) 725 K.

| LC / HC layer structure | LC reading | HC reading |
|-------------------------|------------|------------|
| $T_{cm}$ (K)            | 650        | 750        |
| $h$ (nm)                | 4.5        | 6.0        |
| $E_{th}$ (10 yrs of archiving) | 0.581 | 0.744 |
| $H_0$ (10 yrs of archiving) | 0.16 | 0.49 |
| $E_{th}$ (LC writing)   | 0.736      |            |
| $H_0$ (LC writing)      | 0.47       |            |
| $H_{peak}$ (Oe)         | 1151       | 570        |

3.2 HC / LC layer structure

Next, we discuss the structure as shown in Fig. 10 (a) where the upper layer is an HC layer with $T_{HC} = 750$ K and $h_{HC} = 3.5$ nm, and the lower layer is an LC layer with $T_{LC} = 550$ K and $h_{LC} = 7.0$ nm. The $T_{LC}$ value must be reduced to realize information stability in the HC layer while writing in the LC layer since the $\Delta T_{HL}$ value is positive, which means that the temperature in the HC layer while writing in the LC layer is higher than that in the LC layer. Furthermore, the $h_{LC}$ value must be increased to realize information stability in the LC layer for 10 years of archiving since $T_{LC}$ became low.

Figure 10 (b) shows $H_z$ at the reader from the HC and LC layers for the down-track direction. The $H_{peak}$ values are 1139 and 513 Oe from the HC and LC layers, respectively, where $h_{hy}$ is 4.0 nm.

3.2.1 Temperature profile

The results for the HC / LC layer structure are summarized in Table 5. The $T_{surf}$ value of 874 K is relatively low since the HC layer is the upper layer. This is advantageous in terms of heat resistance.

The difference between the thermal gradients for HC and LC writing is relatively large due to the combinations of the upper HC layer and the lower LC layer. This may be disadvantageous in relation to HC and LC writing. If $\partial T / \partial x$ is too large, the writing temperature decreases before writing, and write-error increases. If $\partial T / \partial x$ is too small, it is difficult to reduce the writing temperature, and the magnetization is reversed by the head field when writing the next bit. Then, erasure after write increases. Furthermore, if $\partial T / \partial y$ is small, the information in tracks adjacent to the writing track becomes unstable. Therefore, a small difference in the thermal gradients for HC and LC writing is preferable in terms of the writing property.

The $\Delta T_{HL}$ value of 35 K is positive. Therefore, the $T_{LC}$ value must be reduced to realize information stability in the HC layer while writing in the LC layer, and $h_{LC}$ must be thick to achieve information stability in the LC layer during 10 years of archiving.

Table 5 Results of heat transfer simulation for HC / LC layer structure.

| HC / LC layer structure | HC writing | LC writing |
|-------------------------|------------|------------|
| $T_{cm}$ (K)            | 750        | 550        |
| $h$ (nm)                | 3.5        | 7.0        |
| $T_{surf}$ (K)          | 874        |            |
| $\partial T / \partial x$ (K / nm) | 16.6 | 4.9 |
| $\partial T / \partial y$ (K / nm) | 16.4 | 5.0 |
| $\Delta T_{HL}$ (K)     |            | 35         |
3.2.2 Information stability for 10 years of archiving

Figure 11 shows the $bER$ as a function of $E_{th}$ and $H_0$ for 10 years of archiving. In comparison with the results in Fig. 6, the information stability in the HC layer has degraded since $h_{HC}$ became thin. And although $T_{LC}$ became low, the information stabilities in the LC layer in Figs. 6 and 11 are roughly the same since $h_{LC}$ became thick.

The time dependence of $bER$ is shown in Fig. 12. In comparison with Fig. 7, errors increase over time in both the HC and LC layers since $h_{HC}$ became thin.

3.2.3 Information stability in HC layer while writing in LC layer

Figure 13 shows the $bER$ in the HC layer as a function of $E_{th}$ and $H_0$ during writing in the LC layer. Since the information in the HC layer will degrade during 10 years of archiving, $bER_{ini}$ in the HC layer after writing in the LC layer must be low, for example, $1E^{-4}$. Therefore, an $E_{th}$ value of 0.598 is required.

4. Conclusions

We examined the medium layer structure in 3D HAMR at 2 Tbps (total density of 4 Tbps), taking account of a heat transfer simulation and information stability in high Curie temperature $T_{HC}$ (HC) and low Curie temperature $T_{LC}$ (LC) layers.

(1) An LC $T_{LC} = 650$ K, 4.5 nm) / HC ($T_{HC} = 750$ K, 6.0 nm) layer structure

The medium surface temperature $T_{surf}$ while writing in the HC layer is relatively high since the HC layer is the lower layer. This is disadvantageous in terms of the
heat resistance of the writing head and/or the surface lubricant.

The temperature in the HC layer while writing in the LC layer is lower than that in the LC layer, and this is advantageous in relation to the information stability in the HC layer.

Although the bit error rate in the HC layer with $T_{HC} = 725$ K is higher than that with $T_{HC} = 750$ K after writing in the LC layer, the HC layer with $T_{HC} = 725$ K may also be a candidate for 3D HAMR media with the aim of reducing $T_{surf}$.

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