Impact of Curie Temperature Variation on Bit Error Rate in Heat-Assisted Magnetic Recording

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The Curie temperature $T_c$ variation problem in heat-assisted magnetic recording is discussed. We describe the physical implication of the $T_c$ variation problem, and provide ways of improving the writing property by employing our simplified model calculation. The bit error rates for mean Curie temperatures of 600 and 700 K are examined. The $T_c$ variation increases both write-error (WE) and erase-after-write (EAW). The main related calculation parameters are the grain column number in one bit and the thermal gradient for the down-track direction. Increasing the grain column number is effective in reducing WE and EAW caused by the $T_c$ variation. Furthermore, increasing the thermal gradient is necessary since EAW is high. Although a higher writing field of 12 to 14 kOe is necessary, a bit error rate less than $10^{-3}$ can be achieved for recording densities of 4 or 2 Tbps under the conditions used in this study even though the standard deviation of the Curie temperature is 4%.

Key words: heat-assisted magnetic recording, field sensitivity, Curie temperature, variation

1. Introduction

Heat-assisted magnetic recording (HAMR) is a promising candidate as a next generation magnetic recording method that can operate beyond the trilemma limit.

We have already proposed a new HAMR model calculation\(^a\)–\(^d\). We have also shown in our improved model calculation that the signal-to-noise ratio derived by the conventionally used micromagnetic calculation can be explained using the temperature dependencies of the grain magnetization reversal probability and the attempt period, whose inverse is the attempt frequency\(^e\). A feature of our model calculation is that it is easy to grasp the physical implication of the HAMR writing process and the calculation time is short.

Since HAMR is a writing method in which the medium is heated to reduce coercivity at the time of writing, the coercivity of the medium can be reduced by any amount. However, micromagnetic simulation has shown that a relatively high writing field is necessary\(^f\).

The actual HAMR system is very complicated, and various problems are intertwined. Therefore, we have separated problems in a simplified model using our model calculation. We have divided the topic of increasing writing field sensitivity into four problems using the bit error rate calculated with our model for HAMR, and we have discussed the calculation parameters related to the problems\(^g\). The four problems are write-error, erase-after-write\(^h\), a statistical problem\(^i\), and the damping constant\(^j\).

It has been reported that variation in the Curie temperature $T_c$ is a serious problem in HAMR. In this study, we discuss a fifth problem, namely the $T_c$ variation problem, and we provide some ways of improving the writing property employing our model calculation.

2. Calculation Method

2.1 Calculation conditions

The areas $S$ of one bit are 161 and 323 nm\(^2\) for recording densities of 4 and 2 Tbps, respectively. The medium was assumed to be bit patterned media (BPM).

The writing field switching timings for an ordinary granular medium and this BPM model are shown in Figs. 1 (a) and (b), respectively. $H_w$, and $\tau_{\text{min}} = D_{\text{lp}} / v$ are the writing field and the time available for writing each bit, respectively, where $D_{\text{lp}}$ and $v$ are the bit pitch and the linear velocity, respectively. There is a fluctuation of switching timing $\Delta t$ in an ordinary granular medium as shown in Fig. 1 (a). However, we assume $\Delta t = 0$, and when the time $t = 0$, the writing grain temperature $T$ becomes the mean Curie temperature $T_{\text{min}}$ as shown in Fig. 1 (b) for our discussion of the intrinsic phenomenon. The problem of $\Delta t$ is a future subject. The $H_w$ direction is upward between $t = 0$ and $\tau_{\text{min}}$, and downward when $t < 0$ and $t > \tau_{\text{min}}$.

It was assumed that the spatially uniform writing field moves to the down-track direction successively, the direction was perpendicular to the medium plane, and the rise time was zero. Neither the demagnetizing nor the magnetostatic fields were considered during writing since they are negligibly small.

The grain arrangements for an ordinary granular medium and this BPM model are also shown in Figs. 1 (c) and (d), respectively, for an $m \times n = 4 \times 1$ grain arrangement where $m$ and $n$ are the grain numbers in one bit for the cross-track and down-track directions, respectively. $T_{\text{up}}$ and $D_p$ are the Curie temperature and the grain size, respectively. There is also a fluctuation of position $\Delta x \sim (D_m + \Delta)/2$ in an ordinary granular medium as shown in Fig. 1 (c) where $D_m$ and $\Delta$ are the mean grain size and the non-magnetic

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\(^a\)–\(^d\) We have already proposed a new HAMR model calculation.\(^e\) We have also shown in our improved model calculation that the signal-to-noise ratio derived by the conventionally used micromagnetic calculation can be explained using the temperature dependencies of the grain magnetization reversal probability and the attempt period, whose inverse is the attempt frequency.\(^f\) A feature of our model calculation is that it is easy to grasp the physical implication of the HAMR writing process and the calculation time is short.\(^g\) Since HAMR is a writing method in which the medium is heated to reduce coercivity at the time of writing, the coercivity of the medium can be reduced by any amount. However, micromagnetic simulation has shown that a relatively high writing field is necessary.\(^h\) The actual HAMR system is very complicated, and various problems are intertwined. Therefore, we have separated problems in a simplified model using our model calculation.\(^i\) We have divided the topic of increasing writing field sensitivity into four problems using the bit error rate calculated with our model for HAMR, and we have discussed the calculation parameters related to the problems.\(^j\) It has been reported that variation in the Curie temperature $T_c$ is a serious problem in HAMR. In this study, we discuss a fifth problem, namely the $T_c$ variation problem, and we provide some ways of improving the writing property employing our model calculation.
spacing, respectively. However, we assume $\Delta x = 0$ as shown in Fig. 1 (d) in this BPM model, and the problem of $\Delta x$ is also a future subject. The thermal gradient $\partial T / \partial y$ for the cross-track direction was assumed to be 0 K/nm since complex situations disturb our intrinsic discussion. Although the problem of $\partial T / \partial y$ is also a future subject, $\partial T / \partial y \neq 0$ will affect the results.

The mean grain size $D_m$ was determined by

$$D_m = \sqrt{\frac{S}{n_{mn}}} - \Delta$$

(1)

where $\Delta = 1$ nm was assumed. The track and bit pitches were $D_{tr} = m(D_m + \Delta)$ and $D_{bp} = n(D_m + \Delta)$, respectively, and then $S = D_{tr} \times D_{bp}$.

The calculation conditions are summarized in Table 1, and the calculation parameters were the recording density, the grain number per bit $mn$, the mean Curie temperature $T_{cm}$, the standard deviations of the Curie temperature $\sigma_c / T_{cm}$, the Gilbert damping constant $\alpha$, the anisotropy constant $K_u / K_{bulk}$, the linear velocity $v$, and the thermal gradient $\partial T / \partial x$. $\partial T / \partial x$ was assumed to be constant regardless of the position, and the heat distribution moves to the down-track direction successively. The standard deviation of the grain size $\sigma_g / D_m$ and the grain height $h$ were 10 % and 8 nm, respectively, and so the mean grain volume $V_m$ for $D_m$ was $D_{tr} \times D_{bp} \times h$.

The medium was characterized by (1) $T_{cm}$, (2) $\alpha$, and (3) $K_u / K_{bulk}$, which is the intrinsic ratio of the medium anisotropy constant $K_u$ to bulk Pt $K_u^{bulk}$.

(1) If $T_{cm}$ is low, a larger $K_u / K_{bulk}$ is necessary.$^{[9]}$

Therefore, we chose $T_{cm}$ values of 600 and 700 K. The standard deviations of the Curie temperature $\sigma_c / T_{cm}$ were assumed to be 0, 2, and 4 %.

(2) The $\alpha$ value of FePt just below the Curie temperature $T_c$ is unknown. Therefore, we calculated the bit error rate using $\alpha = 0.1$ and 0.01.

(3) The $K_u / K_{bulk}$ value must be larger than the value required for 10 years of archiving.

Figure 2 shows the minimum $K_u / K_{bulk}$ value for 10 years of archiving as a function of the mean grain size $D_m$. The inserted scales indicate the grain number per bit $mn$ corresponding to $D_m$ for recording densities of 4 and 2 Tbps. The minimum $K_u(300 \text{K})$ value was roughly estimated using

$$\frac{K_u(300 \text{K})V_m}{kT} > 60$$

(2)

where $k$ and $T = 300 \text{K}$ are the Boltzmann constant and temperature, respectively. And then, the minimum $K_u / K_{bulk}$ value was obtained using the relationship between $K_u(300 \text{K})$ and $T_c$ for various $K_u / K_{bulk}$ values.$^{[7]}$

It is also confirmed from Fig. 2 that if $T_{cm}$ is low, a larger $K_u / K_{bulk}$ is necessary.$^{[10]}$ Experimentally obtained results, namely those for FeNiPt$^{[11]}$ and FePtRu$^{[12]}$ films, are at most between $K_u / K_{bulk} = 0.4$ and 0.6.$^{[7]}$

![Fig. 1](image1)

**Fig. 1** (a), (b) Writing field switching timing, and (c), (d) grain arrangement for (a), (c) an ordinary granular medium and (b), (d) this BPM model.

<table>
<thead>
<tr>
<th>Table 1 Calculation conditions.</th>
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<tbody>
<tr>
<td>Recording density (Tbps)</td>
<td>2, 4</td>
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<tr>
<td>Grain number per bit $mn$ (1 / bit)</td>
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<td>Standard deviation of grain size $\sigma_g / D_m$ (%)</td>
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<td>Grain height $h$ (nm)</td>
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<tr>
<td>Mean Curie temperature $T_{cm}$ (K)</td>
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<tr>
<td>Standard deviation of Curie temp. $\sigma_c / T_{cm}$ (%)</td>
<td>0, 2, 4</td>
<td></td>
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<tr>
<td>Gilbert damping constant $\alpha$</td>
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<tr>
<td>Linear velocity $v$ (m/s)</td>
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<tr>
<td>Thermal gradient $\partial T / \partial x$ (K / nm)</td>
<td>15, 20</td>
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![Fig. 2](image2)

**Fig. 2** Minimum anisotropy constant ratio $K_u / K_{bulk}$ necessary for 10 years of archiving as a function of mean grain size.

### 2.2 Bit error rate calculation

The magnetization direction of the grains was calculated using the magnetization reversal probability for every attempt time in our model calculation.$^{[23-30,7]}

The initial magnetization direction, namely upward or downward, is randomly decided. The switching probability $P$ for each attempt where the magnetization $M_z$ and the writing field $H_w$ change
from antiparallel to parallel is expressed as

$$P = \exp(-K_h).$$  \hspace{1cm} (3)

On the other hand,

$$P = \exp(-K_{ih})$$  \hspace{1cm} (4)

is the probability for each attempt where $M_i$ and $H_w$ change from parallel to antiparallel. In these equations,

$$K_{h}(T, H_w) = \frac{K_n(T) V}{kT} \left( 1 - \frac{H_w}{H_x(T)} \right)^2 \left( H_x(T) \geq H_w \right),$$  \hspace{1cm} (5)

and

$$K_{h}(T, H_w) = \frac{K_n(T) V}{kT} \left( 1 + \frac{H_w}{H_x(T)} \right)^2,$$  \hspace{1cm} (6)

where $K_n$, $V$, $k$, $T$, and $H_x = 2K_n/M_i$ are the anisotropy constant, the grain volume, the Boltzmann constant, the writing temperature, and the anisotropy field, respectively.

The temperature dependence of $M_i$ was determined by employing a mean field analysis\(^{(13)}\), and that of $K_n$ was assumed to be proportional to $M_i^{12}$. The Curie temperature $T_c$ was adjusted by the Cu simple dilution of (Fe$_{0.5}$Pt$_{0.5}$)$_{1-x}$Cu$_x$. $M_i(T, T)$ is a function of $T$ and $T$, and $M_i(T, T) = 770 K, T = 300 K$ = 1000 emu/cm$^3$ was assumed for FePt (Cu composition $z = 0$). $K_n(T, T/k_{bulk})$ is a function of $T$, the anisotropy constant ratio $K_n/k_{bulk}$, and $T$. $K_n(T, T) = 770 K, K_n/k_{bulk} = 1, T = 300 K = 70$ Merg/cm$^3$ was assumed for FePt ($z = 0$). We used $M_i(T, T)$ and $K_n(T, T/k_{bulk})$ for $T_{cm}$ = 600 and 700 K in this paper.

On the other hand, the attempt time $t_i$, whose interval is the mean of the attempt period $\tau_{AP}$, is determined in the following\(^{5}\). The inverse of the attempt period is the attempt frequency $f_0 = 1/\tau_{AP}$. Since there was a very good linear relationship between $f_0$ and $T$, we used

$$f_0(T) = \frac{2a \alpha}{1 + \alpha^2} \frac{V}{V_0} \left( \frac{K_n}{k_{bulk}} \right) \left( T_c - T \right)$$  \hspace{1cm} (7)

where $a = 4.67$ and 5.0 (ns)$^{-1}$ for $T_{cm} = 600$ and 700 K, respectively, and $V_0 = 193$ nm$^3$. The $f_0$ value becomes zero at $T = T_c$, as shown in Eq. (7).

We defined the initial time $t_{ini}$ at $T = T_{th} = T - 1 K$, which is close to $T_c$ using

$$t_{ini} = \frac{T_c - T_{th}}{\sqrt(\partial T/\partial \alpha)}$$  \hspace{1cm} (8)

since $\tau_{AP} = 1/f_0$ diverges to infinity at $T = T_c$. The next initial time $t_{ini2}$ was calculated using the mean attempt period $\tau_{APm}$ from $t_{ini}$ to $t_{ini2}$ expressed by

$$t_{ini2} - t_{ini} = \tau_{APm} = \frac{1}{1 - t_{ini2} - t_{ini}} \int_{t_{ini}}^{t_{ini2}} \tau_{AP}(T) dT.$$  \hspace{1cm} (9)

We assumed that the first attempt time $t_i$ is randomly decided between $t_{ini}$ and $t_{ini2}$. And the attempt time $t_{ini} (k \geq 1)$ is determined with the following recurrence formula:

$$t_{k+1} - t_k = \tau_{APm} = \frac{1}{1 - t_{k+1} - t_k} \int_{t_k}^{t_{k+1}} \tau_{AP}(T) dT.$$  \hspace{1cm} (10)

Errors occur in some grains of a bit. We assume that if the surface magnetic charge of the grains where the magnetization turns in the recording direction $\sum M_k(T_c, 300 K)D_k$ is more than 50% of the total surface magnetic charge in one bit, the bit is error free. Namely, if

$$\frac{\sum M_k(T_c, 300 K)D_k}{mn \cdot M(T_c, 300 K)D_m} > 0.5,$$  \hspace{1cm} (11)

the bit is error free. The number of calculation bits is $10^3$. The criterion determining whether or not recording is possible was assumed to be a bit error rate (BER) of $10^{-3}$. Increasing the writing field sensitivity means lowering the writing field at which the bER value is $10^{-3}$. The bER in this study is useful only as a comparison.

The calculation procedure is described below. First, the medium was characterized by $T_{cm}$, $\alpha$, and $K_n/k_{bulk}$. The grain temperature fell with time from $T_c$ according to the linear velocity $v$ and the thermal gradient $\partial T/\partial \alpha$ for the down-track direction. The attempt times were calculated. The magnetic property and then $P_{th}$ were calculated by undertaking a mean field analysis for every attempt time. The magnetization direction was determined by the Monte Carlo method for every attempt time. Then the bER was obtained.

### 3. Calculation Results

We have divided the topic of increasing the writing field sensitivity into four problems for heat-assisted magnetic recording, and we have discussed the calculation parameters related to the problems\(^{3}\) as follows.

(1) Write-error problem

Reducing the anisotropy constant ratio $K_n/k_{bulk}$ and/or the linear velocity $v$ is effective in reducing write-error (WE), namely, in increasing the writing field sensitivity.

(2) Erasure-after-write problem

Erasure-after-write (EAW) must be sufficiently low in a low writing field region. Increasing $K_n/k_{bulk}$, the thermal gradient $\partial T/\partial \alpha$ for the down-track direction, and/or the grain column number in one bit $n$ is effective in reducing EAW.

(3) Statistical problem

Increasing the grain number per bit $mn$ under a constant mean grain size is effective in increasing the
writing field sensitivity for a statistical reason. However, increasing mm under a constant recording density is ineffective when there is no Curie temperature variation. Nevertheless, there is a statistical effect since the recording time window decreases and the attempt period increases.

(4) Damping constant problem
When the Gilbert damping constant $\alpha$ is small, writing is difficult and a high writing field is necessary since the attempt period is long. Reducing $\nu$ is effective in increasing the writing field sensitivity since WE is dominant for a small $\alpha$.

In this study, we discuss a fifth problem, namely:

(5) Curie temperature variation problem
The main related parameters are $n$ and $\partial T / \partial x$.

3.1 $\alpha = 0.1, T_{cm} = 700 \text{ K}$, and $\partial T / \partial x = 15 \text{ K/nm}$
First, we deal with the damping constant $\alpha = 0.1$, the mean Curie temperature $T_{cm} = 700 \text{ K}$, and the thermal gradient $\partial T / \partial x = 15 \text{ K/nm}$. As shown in a previous paper, when $\alpha = 0.1, T_{cm} = 700 \text{ K}$, and the standard deviation of the Curie temperature $\sigma_{Tc}/T_{cm} = 0 \%$, a 4 Tpsi recording (4 x 1 grain arrangement) can be achieved as shown in Fig. 3, which shows the bit error rate (bER) dependence on writing field $H_w$. An anisotropy constant ratio $K_u / K_{bulk}$ of about 0.35 is the best condition under a linear velocity $v$ of 10 m/s and a thermal gradient $\partial T / \partial x$ of 15 K/nm even though the minimum $K_u / K_{bulk}$ value for 10 years of archiving is 0.19 as shown in Fig. 2. If there is a Curie temperature $T_c$ variation, the signal-to-noise ratio will be degraded, and then the bER will increase as shown in Fig. 3. The decrease and increase in bER as $H_w$ increases are caused by a reduction in the write-error (WE) and an increase in erase-after-write (EAW), respectively. Therefore, the $T_c$ variation increases both WE and EAW.

This is explained using Fig. 4, which shows the time dependence of the grain magnetization reversal probabilities $P$ for grains with $T_c$ of $T_{cm} + \sigma_{Tc}, T_{cm}$, and $T_{cm} - \sigma_{Tc}$. The filled circles indicate the attempt times $t_i$ when $t_i = t_{min}$ and $t_i = t_{max}$. In this paper, figures of $P$ with time are shown in the same format.

The time $t = 0$ is the onset of the writing time, which corresponds to the 1st column grain temperature becoming $T_{cm}$. The attempt frequency $f_o$ is low just below $T_{c}$ as shown in Eq. (7), and then the attempt period $\tau_{ap} = 1/f_o$ is long just after $t = 0$ for a grain with $T_c = T_{cm}$. The temperature decreases with time, and the mean attempt period $\tau_{apm}$, which is the interval between the attempt times, decreases accordingly. The time $t = \tau_{min}$ is the end of the writing time, which corresponds to the time available for writing each bit and $\tau_{min} = D_{bit} / v$ as shown in Fig. 1.

![Fig. 3](image)

**Fig. 3** Dependence of bit error rate on writing field for various standard deviations of Curie temperature $\sigma_{Tc}/T_{cm} (\alpha = 0.1, T_{cm} = 700 \text{ K}, 4 \times 1 \text{ grain arrangement}).

![Fig. 4](image)

**Fig. 4** Time dependence of grain magnetization reversal probabilities $P$ and temperature for grains with Curie temperatures of $T_{cm} + \sigma_{Tc}, T_{cm}, T_{cm} - \sigma_{Tc}$.

WE means that the magnetization does not switch to the recording direction, and WE occurs during writing $(0 \leq t \leq \tau_{min})$. If there is a $T_c$ variation, WE increases from grains with a higher $T_c$, for example, $T_c = T_{cm} + \sigma_{Tc}$ in Fig. 4. We introduce a new parameter, namely a Curie temperature variation window $\tau_{Tc}$:

$$\tau_{Tc} = \frac{\sigma_{Tc}}{v(\partial T / \partial x)}.$$  \hspace{1cm} (12)

The writing time is advanced for higher $T_c$ grains, for example, by $\tau_{Tc}$ for a grain with $T_c = T_{cm} + \sigma_{Tc}$. Even at a time before zero, the grain temperature is lower than $T_c$, and then the grain is magnetized in the downward direction, namely opposite to the recording direction. At time zero, the direction of the writing field changes. The $P$ value for a grain with $T_c = T_{cm} + \sigma_{Tc}$ at $t = 0$ designated by the open circle in Fig. 4 is low. Therefore, the probability with which the magnetization reverses to the recording direction is low. Then, WE increases.

On the other hand, EAW is grain magnetization reversal in the opposite direction to the recording
direction caused by changing the $H_u$ direction at the end of the writing time $\tau_{\text{min}}$, and EAW occurs after writing $(t > \tau_{\text{min}})$. If there is a $T_c$ variation, EAW increases from grains with a lower $T_c$, for example, $T_c = T_{\text{cm}} - \sigma_{\text{TC}}$ in Fig. 4. The writing time is delayed for lower $T_c$ grains, for example, by $\tau_{\text{TC}}$ for a grain with $T_c = T_{\text{cm}} - \sigma_{\text{TC}}$. The $P_v$ value at $\tau_{\text{min}}$ is important for EAW. The $P_v$ value for a grain with $T_c = T_{\text{cm}} - \sigma_{\text{TC}}$ at $\tau_{\text{min}}$ designated by the open circle in Fig. 4 is high. Therefore, the probability with which the magnetization reverses to the direction opposite to that of recording is high. Then, EAW increases.

**Fig. 5** Dependence of bit error rate on writing field for $4 \times 1$, $2 \times 2$, and $3 \times 3$ grain arrangements ($\alpha = 0.1$, $T_{\text{cm}} = 700 \, \text{K}$, $\sigma_{\text{TC}} / T_{\text{cm}} = 4 \%$).

Figure 5 shows the bER dependence on $H_u$ for $4 \times 1$, $2 \times 2$, and $3 \times 3$ grain arrangements where $\sigma_{\text{TC}} / T_{\text{cm}}$ is 4 %. A comparison of the bER for $m \times n = 4 \times 1$ and that for a $2 \times 2$ grain arrangement where the grain numbers per bit $mn$, the $K_u / K_{\text{bulk}}$ values, and the mean grain sizes $D_m$ are the same for avoiding these problems, reveals that the bER for the latter is lower than that for the former in all calculated $H_u$ ranges. In other words, both WE and EAW decrease. This is also explained using Fig. 6 in which the time dependences of $P_v$ for (a) the 1st and (b) the 2nd columns of a $2 \times 2$ grain arrangement are shown. The $P_v$ values in Fig. 4 and Fig. 6 (a) are identical. However, the $\tau_{\text{min}}$ value in Fig. 6 (a) is twice that in Fig. 4. The $P_v$ value at $\tau_{\text{min}}$ in Fig. 6 (a) is sufficiently low even for a grain with $T_c = T_{\text{cm}} - \sigma_{\text{TC}}$. Accordingly, EAW for the 1st column of the $2 \times 2$ grain arrangement decreases. On the other hand, the $P_v$ values in Fig. 4 and Fig. 6 (b) are also identical except for time, and the writing time in Fig. 6 (b) is delayed by a time corresponding to the grain pitch $D_m + \Delta$. Consequently, the $P_v$ values at $\tau_{\text{min}}$ in Fig. 4 and Fig. 6 (b) are the same, and EAW for the 2nd column of the $2 \times 2$ grain arrangement does not change. Comprehensively increasing the grain column number $n$ is effective in reducing EAW.

Increasing $n$ is also effective in reducing WE. The $H_u$ switching timings at $t = 0$ in Fig. 4 and Fig. 6 (a) are identical. Hence, WE for the 1st column of the $2 \times 2$ grain arrangement does not change. On the other hand, the writing time for the 2nd column of the $2 \times 2$ grain arrangement is delayed by a time corresponding to a grain pitch $D_m + \Delta$ as shown in Fig. 6 (b). The $H_u$ direction is the recording direction even at a time that corresponds to the grain temperature with $T_c = T_{\text{cm}} + \sigma_{\text{TC}}$ becoming $T_c$. Therefore, WE for the 2nd column of the $2 \times 2$ grain arrangement decreases.

**Fig. 6** Time dependence of grain magnetization reversal probabilities $P_v$ and temperature for (a) 1st and (b) 2nd columns of a $2 \times 2$ grain arrangement.

Next, we make a comparison between bER for the $2 \times 2$ grain arrangement and that for the $3 \times 3$ grain arrangement in Fig. 5. It was assumed that $\sigma_{\text{TC}}$ does not increase even if $D_m$ is reduced. When the $2 \times 2$ grain arrangement (the grain number per bit $mn = 4$), $D_m = 5.4 \, \text{nm}$, and $K_u / K_{\text{bulk}} = 0.35$ is necessary for a low bER. On the other hand, when the $3 \times 3$ grain arrangement ($mn = 9$), $D_m = 3.2 \, \text{nm}$, and then $K_u / K_{\text{bulk}} = 0.52$ is necessary for 10 years of archiving.

Reducing $D_m$, and then increasing $n$ is effective in reducing both WE and EAW as shown in Fig. 5. This is also explained using Fig. 7, which shows the time dependences of $P_v$ for (a) the 1st, (b) the 2nd, and (c) the 3rd columns of the $3 \times 3$ grain arrangement. The rate at which $P_v$ decreases with time becomes slow according to Eq. (5), in which $K_u$, $V$, and
\( H'_u = 2K_u/M_s \), namely \( K_u/K_{\text{bulk}} \) and \( D_m \) have different values. Furthermore, the recording time window \( \tau_{\text{RW}} \) becomes short where \( \tau_{\text{RW}} \) is the time for \( P_r = 1 \), namely \( H'_u < H_u \) according to Eq. (5). And the attempt period \( \tau_{\text{AP}} = 1/f_0 \) for \( 3 \times 3 \) is somewhat longer than that for the \( 2 \times 2 \) grain arrangement according to Eq. (7) since \( D_m \cdot K_u/K_{\text{bulk}} \) for \( 3 \times 3 \) is somewhat smaller than that for the \( 2 \times 2 \) grain arrangement. Although various factors are involved, the EAW reduction is roughly explained by the fact that the \( P_r \) value at \( \tau_{\text{min}} \) in Fig. 7 (b) is smaller than that in Fig. 6 (b). The WE reduction is explained as follows.

The \( H_u \) direction is the recording direction when the temperature of the 2nd and the 3rd column grains becomes \( T_c \) as shown in Figs. 7 (b) and (c), respectively.

### 3.2 \( \alpha = 0.1, \ T_{\text{cm}} = 700 \ \text{K}, \) and \( \partial T/\partial x = 20 \ \text{K}/\text{nm} \)

A bER less than \( 10^{-3} \) cannot be achieved as shown in Fig. 5 since EAW is high. Therefore, we calculate the bER using the thermal gradient \( \partial T/\partial x = 20 \ \text{K}/\text{nm} \) instead of \( 15 \ \text{K}/\text{nm} \) for the suppression of EAW. The bER calculation results are shown in Fig. 8. A bER less than \( 10^{-3} \) can be achieved for the \( 3 \times 3 \) grain arrangement and \( \partial T/\partial x = 20 \ \text{K}/\text{nm} \) as shown in Fig. 8 (b).

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**Fig. 7** Time dependence of grain magnetization reversal probabilities \( P_r \) for (a) 1st, (b) 2nd, and (c) 3rd columns of the \( 3 \times 3 \) grain arrangement.

**Fig. 8** Dependence of bit error rate on writing field for thermal gradients \( \partial T/\partial x = 15 \) and \( 20 \ \text{K}/\text{nm} \) (\( \alpha = 0.1, \ T_{\text{cm}} = 700 \ \text{K}, \)) (a) \( 2 \times 2 \) and (b) \( 3 \times 3 \) grain arrangements.

Figure 9 shows the time dependence of \( P_r \) for the respective columns. When \( \partial T/\partial x \) increases, the Curie temperature variation window \( \tau_{\text{TC}} \) will be reduced according to Eq. (12). \( \tau_{\text{TC}} \) is the time during which grain with \( T_c = T_{\text{cm}} + \sigma_{T_c} \) is exposed to \( H_u \) opposite to the recording direction as shown Fig. 9 (a). Therefore, the reduction of \( \tau_{\text{TC}} \) is advantageous for the suppression of WE caused by the \( T_c \) variation. On the other hand, as \( \partial T/\partial x \) increases, the writing field sensitivity becomes somewhat worse \(^7 \) since the rate at which \( P_r \) decreases with time becomes steep, and the attempt number is somewhat reduced when \( P_r \) is high.
as shown in Fig. 9. Comprehensively increasing $\partial T / \partial x$ is not effective in reducing WE as shown in Fig. 8.

As shown in a previous paper\textsuperscript{7} and as seen by comparing Fig. 7 and Fig. 9, increasing $\partial T / \partial x$ is effective in reducing EAW since the $T_c$ values at $\tau_{\min}$ become low. The resultant bER is shown in Fig. 8, and a bER less than $10^{-3}$ can be achieved. However, a higher writing field is necessary if there is a $T_c$ variation.

\[ H_a \downarrow \]
\[ T = \frac{\beta}{x} \]
\[ \tau_{\min} \]
\[ T_c/T_{cm} = 4 \%

\[ T_{cm} = 700 \text{ K} \]
\[ \sigma_{Tc}/T_{cm} = 4 \%

$P_c$ for 1st col.
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ \tau_{\min} \]

$P_c$ for 2nd col.
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ \tau_{\min} \]

$P_c$ for 3rd col.
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ \tau_{\min} \]

**Fig. 9** Time dependence of grain magnetization reversal probabilities $P_c$ for (a) 1st, (b) 2nd, and (c) 3rd columns of the 3 x 3 grain arrangement ($\partial T / \partial x = 20$ K/nm).

### 3.3 $\alpha = 0.1$ and $T_{cm} = 600 \text{ K}$

Next, we discuss a mean Curie temperature $T_{cm} = 600 \text{ K}$ rather than $T_{cm} = 700 \text{ K}.$

Figure 10 (a) shows the bER dependence on $H_a$ for a $2 \times 2$ grain arrangement. Although the minimum anisotropy constant ratio $K_u/K_{bulk}$ for 10 years of archiving is 0.27 as shown in Fig. 2, $K_u/K_{bulk} = 0.35$ is necessary for a low bER. However, a bER less than $10^{-3}$ cannot be achieved even for $\partial T / \partial x = 20 \text{ K/nm}.$

The results for a $3 \times 3$ grain arrangement are shown in Fig. 10 (b). A large $K_u/K_{bulk}$ value of 0.75 is necessary for 10 years of archiving. A bER less than $10^{-3}$ can be achieved for $\partial T / \partial x = 20 \text{ K/nm}.$

\[ H_a \downarrow \]
\[ T = \frac{\beta}{x} \]
\[ \tau_{\min} \]
\[ T_c/T_{cm} = 4 \%

$K_u/K_{bulk} = 0.52$
\[ 2 \text{ col.} \]
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ (T_{cm}) \]

$K_u/K_{bulk} = 0.35$
\[ 2 \text{ col.} \]
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ (T_{cm}) \]

\[ H_a \downarrow \]
\[ T = \frac{\beta}{x} \]
\[ \tau_{\min} \]
\[ T_c/T_{cm} = 4 \%

$D_m = 5.4 \text{ nm}$
\[ 3 \text{ col.} \]
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ (T_{cm}) \]

\[ H_a \downarrow \]
\[ T = \frac{\beta}{x} \]
\[ \tau_{\min} \]
\[ T_c/T_{cm} = 4 \%

$D_m = 3.2 \text{ nm}$
\[ 3 \text{ col.} \]
\[ v = 10 \text{ m/s} \]
\[ \partial T / \partial x = 20 \text{ K/nm} \]
\[ H_a = 10 \text{ kOe} \]
\[ (T_{cm}) \]

**Fig. 10** Dependence of bit error rate on writing field for thermal gradients $\partial T / \partial x = 15$ and 20 K/nm ($\alpha = 0.1, T_{cm} = 600 \text{ K}$, (a) $2 \times 2$ and (b) $3 \times 3$ grain arrangements).

We summarize the writing field $H_a$ required for the damping constant $\alpha = 0.1$ in Table 2. A recording density of 4 Tbpsi is available for a linear velocity $v = 10 \text{ m/s}$ under the conditions used in this study. When the mean Curie temperatures $T_{cm} = 700 \text{ K}$, $2 \times 2$ (the mean grain size $D_m = 5.4 \text{ nm}$) and $3 \times 3$ ($D_m = 3.2 \text{ nm}$) are necessary for the standard deviations of the Curie temperature $\sigma_{Tc}/T_{cm} = 0$ % and 4 %, respectively. Although the minimum anisotropy constant ratios $K_u/K_{bulk}$ for 10 years of archiving are 0.19 and 0.52, the $K_u/K_{bulk}$ values necessary for bER $< 10^{-3}$ are 0.35 and 0.52 for $\sigma_{Tc}/T_{cm} = 0$ % and 4 %,
respectively. Furthermore, a larger thermal gradient $\partial T / \partial x$ of 20 K/nm is necessary for $\sigma_{Tc} / T_{cm} = 4 \%$. In summary, $H_w > 8$ and 12 kOe are necessary for $\sigma_{Tc} / T_{cm} = 0 \%$ and 4 \%, respectively.

When $T_{cm} = 600$ K, a $K_u / K_{bulk}$ of 0.75, which is larger than that of 0.52 for $T_{cm} = 700$ K, is necessary for $\sigma_{Tc} / T_{cm} = 4 \%$ due to a low $T_{cm}$ (see Fig. 2).

### Table 2: Writing field $H_w$ required for damping constant $\alpha = 0.1$.  

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\delta T / \delta x$ (K/nm)</th>
<th>$K_u / K_{bulk}$</th>
<th>$v$ (m/s)</th>
<th>$\sigma_{Tc} / T_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
<td>0.3</td>
<td>15</td>
<td>0.01</td>
</tr>
<tr>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>15</td>
<td>0.01</td>
</tr>
<tr>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>15</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Fig. 11 Dependence of bit error rate on writing field for thermal gradients $\delta T / \delta x = 15$ and 20 K/nm ($\alpha = 0.01$, $T_{cm} = 700$ K, (a) $3 \times 3$ and (b) $4 \times 4$ grain arrangements).  

Fig. 12 Dependence of bit error rate on writing field for $\delta T / \delta x = 15$ and 20 K/nm ($\alpha = 0.01$, $T_{cm} = 600$ K, (a) $3 \times 3$ and (b) $4 \times 4$ grain arrangements).

#### 3.4 $\alpha = 0.01$

In this section, we discuss a damping constant $\alpha = 0.01$ instead of $\alpha = 0.1$. In previous papers[8,9], we have shown that if $\alpha$ is small, WE is dominant and writing is difficult since the attempt period is long and there is almost no opportunity for writing. Since WE is dominant, we used a slow linear velocity $v$ of 5 m/s.

Figures 11 (a) and (b) show the bER dependence on $H_w$ for $3 \times 3$ and $4 \times 4$ grain arrangements, respectively, where $T_{cm} = 700$ K. A larger $\delta T / \delta x$ of 20 K/nm is necessary in both cases. With the $4 \times 4$ grain arrangement, a higher $H_w$ is necessary since a larger $K_u / K_{bulk}$ is required for 10 years of archiving. The results for $T_{cm} = 600$ K are shown in Fig. 12 where the same tendency can be seen.

We also summarize the writing field $H_w$ required for the damping constant $\alpha = 0.01$ in Table 3. A recording density of only 2 Tpsi is available even for a linear velocity $v = 5$ m/s under the conditions used in this study since writing is difficult. The grain arrangement and the anisotropy constant ratio $K_u / K_{bulk}$ are $3 \times 3$ (the mean grain size $D_m = 5.0$ nm) and about 0.3, respectively, regardless of the mean Curie temperature $T_{cm}$ and the standard deviation of the Curie temperature $\sigma_{Tc} / T_{cm}$. A larger thermal gradient $\delta T / \delta x$ of 20 K/nm is necessary for $\sigma_{Tc} / T_{cm} = 4 \%$. In summary, $H_w > 12$ and 14 kOe are needed for $\sigma_{Tc} / T_{cm} = 0 \%$ and 4 \%, respectively.

To solve the small $\alpha$ problem it may be effective to use an exchange-coupled composite medium with a large $\alpha$ layer and a large $K_u / K_{bulk}$ layer.
Table 3 Writing field $H_w$ required for damping constant $\alpha = 0.01$.

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>0.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording density (Tbps)</td>
<td>2</td>
</tr>
<tr>
<td>$T_{cm}$ (K)</td>
<td>700</td>
</tr>
<tr>
<td>$\sigma_{Tc}/T_{cm}$ (%)</td>
<td>0</td>
</tr>
<tr>
<td>$m \times e$ (grain / bit)</td>
<td>3 \times 3</td>
</tr>
<tr>
<td>$D_w$ (nm)</td>
<td>5.0</td>
</tr>
<tr>
<td>$K_r/K_{inh}$ for $K_r V_{w} / dT &gt; 60$</td>
<td>&gt; 0.22</td>
</tr>
<tr>
<td>$K_r/K_{inh}$ for $BER &lt; 10^{-3}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$v$ (m / s)</td>
<td>5</td>
</tr>
<tr>
<td>$\dot{\theta} / \dot{\theta}$ (K / mm)</td>
<td>15</td>
</tr>
<tr>
<td>$H_w$ (kOe)</td>
<td>&gt; 12</td>
</tr>
</tbody>
</table>

4. Conclusion

We used our simplified model calculation to discuss the Curie temperature $T_c$ variation problem in heat-assisted magnetic recording. The $T_c$ variation increased both write error (WE) and erase after write (EAW). Increasing the grain column number in one bit was effective in reducing WE and EAW caused by the $T_c$ variation. Furthermore, increasing the thermal gradient for the down-track direction was necessary since EAW was high. A higher writing field of 12 to 14 kOe was necessary when the standard deviation of the Curie temperature $\sigma_{Tc}/T_{cm} = 4\%$.

When the damping constant $\alpha$ was 0.1, a recording density of 4 Tbps was available for a linear velocity $v = 10$ m/s under the conditions used in this study even though $\sigma_{Tc}/T_{cm} = 4\%$. When the mean Curie temperature $T_{cm} = 600$ K, a larger anisotropy constant ratio of 0.75 than that of 0.52 for $T_{cm} = 700$ K was necessary due to a low $T_{cm}$.

When $\alpha = 0.01$, WE is dominant and writing is difficult. Therefore, it is necessary to lower $v$. A recording density of 2 Tbps was available for $v = 5$ m/s and $\sigma_{Tc}/T_{cm} = 4\%$ under the conditions used in this study.

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References


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