We improve our model calculation for heat-assisted magnetic recording (HAMR) considering the temperature dependence of the attempt frequency. Then, the signal-to-noise ratio dependence on writing field is calculated for various calculation parameters by employing both our model calculation and the conventionally used micromagnetic calculation. The tendencies of the results of our model calculation and of the micromagnetic calculation are almost the same by this improvement. Therefore, our model calculation can be used for HAMR design. The writing process can be described using the temperature dependences of the grain magnetization reversal probability and the attempt number. If the Gilbert damping constant is small, writing is difficult since the attempt number is small. Write-error can be described using the temperature dependences of the grain magnetization reversal probability and the attempt period, whose inverse is the thermal gradient and/or the grain column number.

**Key words**: heat-assisted magnetic recording, signal-to-noise ratio, grain magnetization reversal probability, attempt number

### 1. Introduction

Heat-assisted magnetic recording (HAMR) is a promising candidate as a next generation magnetic recording method beyond the trilemma limit\(^1\). We have already proposed a new HAMR model calculation\(^2,3\). The grain magnetization reversal probability and the attempt period, whose inverse is the attempt frequency \(f_0\), are key physical quantities in our model calculation. We used a constant \(f_0\) value in our previous model calculation. We have also calculated the temperature dependence of \(f_0\)\(^4\) employing the conventionally used micromagnetic calculation.

In this study, we improve our model calculation considering the temperature dependence of \(f_0\). Then, we calculate the dependence of the signal-to-noise ratio (SNR) on the writing field for various calculation parameters in HAMR. And we compare the results with those calculated employing the conventionally used micromagnetic calculation at the same time to determine whether our model calculation can be used for HAMR design. Furthermore, we provide the SNR results with physical implications employing our model calculation with a view to HAMR design.

### 2. Calculation Method

#### 2.1 Calculation conditions

The medium was assumed to be granular. The writing field switching timing and the calculation conditions are summarized in Fig. 1 (a). The mean grain size \(D_m\), the standard deviation of the grain size \(\sigma_i/D_m\), and the grain height \(h\) were 4.9 nm, 10 %, and 8 nm, respectively, and so the grain volume \(V_m\) for \(D_m\) was \(D_m \times D_m \times h = 193 \text{ nm}^3\). The Curie temperature \(T_c\) and the standard deviation of the Curie temperature \(\sigma_{T_c}/T_c\) were 700 K and 0 %, respectively, since a higher anisotropy constant ratio \(K_a/K_{ bulk}\) is necessary if \(T_c\) is low\(^5\) where \(K_a/K_{ bulk}\) is the intrinsic ratio of the medium anisotropy constant \(K_a\) to bulk FePt \(K_a\)\(^6\). The \(K_a/K_{ bulk}\) value of the medium was 0.4. The calculation parameters were the bit pitch \(D_{bp}\), the Gilbert damping constant \(\alpha\), the thermal gradient \(\partial T/\partial x\) for the down-track direction, and the linear velocity \(v\).

\[ \begin{align*}
\tau_{mp} &= \frac{D_{mp}}{v} \\
H_s &\downarrow \\
H_r &\uparrow \\
H_k &\downarrow \\
\end{align*} \]

\[ \begin{align*}
D_m &= 4.9 \text{ nm} \\
\sigma_i/D_m &= 10 \% \\
h &= 8 \text{ nm} \\
V_m &= D_m 	imes D_m \times h \\
D_{bp} &= 6.8, 27.3 \text{ nm} \\
T_c &= 700 \text{ K} \\
\sigma_{T_c}/T_c &= 0 \% \\
K_a/K_{ bulk} &= 0.4 \\
\alpha &= 0.1, 0.01 \\
\partial T/\partial x &= 15 \text{ (typical), } 10, 20 \text{ K/nm} \\
v &= 10 \text{ (typical), } 5, 20 \text{ m/s} \\
\end{align*} \]

\[ \begin{align*}
\tau_{mp} &= \frac{D_{mp}}{v} \\
H_s &\downarrow \\
H_r &\uparrow \\
H_k &\downarrow \\
\end{align*} \]

**Fig. 1** (a) Writing field switching timing and calculation conditions, and (b) grain arrangement for signal-to-noise ratio calculation.
We used the damping constants $\alpha = 0.1$ and 0.01 since the value of $\alpha$ just below $T_c$ is unknown. Typical values were $\partial T/\partial y = 15$ K/nm and $v = 10$ m/s. The thermal gradient $\partial T/\partial y$ for the cross-track direction was assumed to be 0 K/nm.

$H_u$ and $\tau_{\text{min}} = D_{\text{ap}}/v$ are the writing field and the time available for writing each bit, respectively. The $H_u$ direction is upward when time $t$ is $2n\tau_{\text{min}} < t < (2n+1)\tau_{\text{min}}$, and downward when $(2n+1)\tau_{\text{min}} < t < (2n+2)\tau_{\text{min}}$ where $n$ is an integer. When $t = n\tau_{\text{min}}$, the writing grain temperature $T$ becomes $T_c$. There are fluctuations in the switching timing $\Delta t$ and position $\Delta x$ in a granular medium\(^3\). However, we assumed $\Delta t = 0$ and $\Delta x = 0$ in our discussion of the intrinsic phenomenon.

Figure 1 (b) shows the grain arrangement for the signal-to-noise ratio (SNR) calculation. We used a pattern consisting of 32 grains for the cross-track direction and 64 grains for the down-track direction, and we used 32 patterns for the SNR calculation. One bit consisted of 32 × 1 or 32 × 4 grains, namely one or four grain columns per bit, and $D_{\text{ap}} = 6.8$ or 27.3 nm, respectively. An initial magnetization direction, namely upward or downward, is randomly decided.

2.2 Model calculation

The magnetization direction of the grains was calculated using the magnetization reversal probability for every attempt time in our model calculation\(^2\)–\(^5\).

The switching probability $P_s$ for each attempt where the magnetization $M_s$ and the writing field $H_u$ change from antiparallel to parallel is expressed as

$$P_s = \exp(-K_{p_s}). \quad (1)$$

On the other hand,

$$P_a = \exp(-K_{p_a}) \quad (2)$$

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

$$K_{p_s}(T, H_u) = \frac{K_s(T)V}{kT} \left(1 - \frac{H_u}{H_k(T)}\right)^2 (H_k(T) \geq H_u),$$

$$K_{p_a}(T, H_u) = 0 \quad (H_k(T) < H_u), \quad (3)$$

and

$$K_{p_a}(T, H_u) = \frac{K_s(T)V}{kT} \left(1 + \frac{H_u}{H_k(T)}\right)^2, \quad (4)$$

where $K_s$, $V$, $k$, $T$, and $H_k = 2K_s/M_s$ are the anisotropy constant, the grain volume, the Boltzmann constant, temperature, and the anisotropy field, respectively.

The temperature dependence of $M_s$ was determined employing a mean field analysis\(^3\), and that of $K_s$ was assumed to be proportional to $M_s^2$\(^8\). The Curie temperature $T_c$ can be adjusted by the Cu simple dilution of $(\text{Fe}_{0.5}\text{Pt}_{0.5})_1\text{Cu}_z$. $M_s(T, T)$ is a function of $T_c$ and $T$. $M_s(T_c = 770\, \text{K}, T = 300\, \text{K}) = 1000$ emu/cm\(^3\) was assumed. $K_s(T_c, K_s/K_{\text{bulk}} \cdot T)$ is a function of $T_c$, the anisotropy constant ratio $K_s/K_{\text{bulk}}$, and $T$. $K_s(T_c = 770\, \text{K}, K_s/K_{\text{bulk}} = 1, T = 300\, \text{K}) = 70$ Merg/cm\(^3\) was assumed. We used $M_s(T_c = 700\, \text{K}, T$) and $K_s(T_c = 700\, \text{K}, K_s/K_{\text{bulk}} = 0.4)$ for the calculation in this paper.

On the other hand, the attempt time $t_\text{min}$, which falls within an attempt period $\tau_{\text{ap}}$, is determined as follows. The inverse of the attempt period is an attempt frequency $f_0 = 1/\tau_{\text{ap}}$. We improve our model calculation considering the temperature dependence of $f_0$. We have determined the temperature dependence of $f_0$ employing a conventionally used micromagnetic calculation with the Landau-Lifshitz-Gilbert (LLG) equation\(^9\) where we calculated the temperature dependence of the magnetic properties used in the $f_0$ calculation with a mean field analysis. The results can be fitted using

$$f_0(T) = \frac{2\alpha}{1 + \alpha} \frac{V}{V_m} \frac{600}{K_s(T)} \frac{K_s(T)}{K_s(600\, \text{K})} \quad (5)$$

in consideration of reference 10) where $f_0 = 500$ (ns)\(^{-1}\), $V_m = 193$ nm\(^3\), and $K_s(600\, \text{K}) = 8.0$ Merg/cm\(^3\). Since there was a very good linear relationship between $f_0$ and $T$, we used

$$f_0(T) = \frac{2\alpha}{1 + \alpha} \frac{V}{V_m} \frac{K_s/K_{\text{bulk}}}{0.4} (T_c - T) \quad (6)$$

instead of Eq. (5) in our calculation where $a = 5$ (nsK)\(^{-1}\). The $f_0$ value becomes zero at $T_c$ as shown in Eq. (6).

We defined an initial time $t_\text{init}$ at $T = T_m = 699$ K, which is close to $T_c = 700$ K, using

$$t_\text{init} = \frac{T_c - T_m}{(\partial T/\partial x)v} \quad (7)$$

since $\tau_{\text{ap}} = 1/f_0$ diverges to infinity at $T = T_c$. The next initial time $t_{\text{init}2}$ can be calculated using the mean attempt period $\tau_{\text{ap}2}$ from $t_{\text{init}}$ to $t_{\text{init}2}$ expressed by

$$t_{\text{init}2} - t_{\text{init}} = \tau_{\text{ap}2} \int_{t_{\text{init}}}^{t_{\text{init}2}} \tau_{\text{ap}}(t)dt. \quad (8)$$

We assumed that the first attempt time $t_1$ is randomly decided between $t_{\text{init}}$ and $t_{\text{init}2}$. And the attempt time $t_{\text{init}2}(k \geq 1)$ is determined with the following recurrence formula:

$$t_{\text{init}2} - t_1 = \tau_{\text{ap}2} \int_{t_1}^{t_{\text{init}2}} \tau_{\text{ap}}(t)dt. \quad (9)$$

Figure 2 shows the time dependence of the grain magnetization reversal probability $P_s$ for $t_1 = t_{\text{init}}$ and $t_2 = t_{\text{init}2}$. In this paper, figures of $P_s$ with time
are shown in the same format. The filled circles indicate the attempt times whose interval is the mean attempt period \( \tau_{APm} \). The \( f_0 \) value is low just below \( T_c \) as shown in Eq. (6), and then \( \tau_{AP} = 1/f_0 \) is long just after \( t = 0 \) since the time \( t = 0 \) corresponds to the writing grain temperature \( T \) becoming \( T_c \). The temperature decreases with time, and \( \tau_{AP} \) decreases accordingly. Therefore, \( \tau_{APm} \) decreases with time.

The writing field was assumed to be spatially uniform, 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 output signal, media noise, and media signal-to-noise ratio (SNR) were calculated using the sensitivity function\(^{11}\) of a magnetoresistive head with the medium was characterized by the arrangement matrix \((m, n)\), the vertical axis is normalized by \( 32 \times M_{mn} D_{mn}^2 \), and \( M_{mn} = M_s \) since \( \sigma_{\parallel}/T_c = 0 \). The surface charge summation is proportional to the signal amplitude read by the head with infinite resolution. The surface charge summations for Figs. 4 (a) and (c) are unsaturated according to the grain magnetization patterns for Figs. 3 (a) and (c), respectively.

This can be explained using the time dependence of the grain magnetization reversal probability \( P_c \) for various \( H_w \) values as shown in Fig. 5. Normal write-error (WE)\(^{20}\) means that the magnetization does not switch to the recording direction, and WE occurs during writing \((0 \leq t < \tau_{min})\). The attempt number is important when \( P_c \) is high. For \( H_w = 3 \) kOe, since the attempt number, that is, the filled circle number, is small when \( P_c \) is high, WE occurs. On the other hand, erase-after-write (EAW)\(^{20}\) is the grain magnetization reversal in the opposite direction to the recording direction caused by changing the \( H_w \) direction at the end of the writing time \( \tau_{min} \), and EAW occurs after writing \((t \geq \tau_{min})\). The \( P_c \) value is important at the end of the writing time \( \tau_{min} \). For \( H_w = 17 \) kOe, since the \( P_c \) value at \( \tau_{min} \) designated by an open circle is not sufficiently low, EAW occurs. For \( H_w = 10 \) kOe, the attempt number is sufficiently large when \( P_c \) is high.

### 3. Calculation Results

#### 3.1 1 column/bit and \( \alpha = 0.1 \)
Representative grain magnetization patterns calculated employing our model are shown in Fig. 3 under the conditions of 1 column/bit, damping constant \( \alpha = 0.1 \), and typical values. A writing field \( H_w \) of about 10 kOe is the best condition (see Fig. 6 (a)), \( H_w = 3 \) kOe is too small, and \( H_w = 17 \) kOe is too large.

Figure 4 shows the summation of the surface magnetic charge \( M_{mn} D_{mn}^2 \) for the cross-track direction \( m \) as a function of the position for the down-track direction \( n \) where \( M_{mn} \) and \( D_{mn} \) are the magnetization and the grain size for the grain arrangement matrix \((m, n)\), respectively, the vertical axis is normalized by \( 32 \times M_{mn} D_{mn}^2 \), and \( M_{mn} = M_s \) since \( \sigma_{\parallel}/T_c = 0 \). The surface charge summation is proportional to the signal amplitude read by the head with infinite resolution. The surface charge summations for Figs. 4 (a) and (c) are unsaturated according to the grain magnetization patterns for Figs. 3 (a) and (c), respectively.
Figure 4 Summation of surface magnetic charges $M_{mn}D_{mn}$ for cross-track direction $m$ as a function of position for down-track direction $n$ under conditions of 1 column/bit, $\alpha = 0.1$, and typical values.

Figure 5 Time dependence of grain magnetization reversal probability $P$ for various $H_w$ values under conditions of 1 column/bit, $\alpha = 0.1$, and typical values.

and the $P$ value at $\tau_{\text{min}}$ designated by an open circle is sufficiently low. Therefore, both WE and EAW are low.

Figure 6 (a) shows the dependence of the signal-to-noise ratio (SNR) on the writing field $H_w$ for various thermal gradients $\partial T/\partial x$ calculated employing our model. The increase in SNR as $H_w$ increases in a low $H_w$ region is caused by a reduction in WE since WE means that the magnetization does not switch to the recording direction during writing, and WE is caused by an insufficient $H_w$. The decrease in SNR as $H_w$ increases in a high $H_w$ region is caused by EAW since EAW is the magnetization reversal in the opposite direction to the recording direction after writing, and EAW is caused by an excessive $H_w$. The increase in SNR as $H_w$ increases at more than about 14 kOe for $\partial T/\partial x = 10 \text{ K/nm}$ in Fig. 6 (a) is caused by after-write (AW). AW occurs after writing ($t \geq \tau_{\text{min}}$).
Therefore, if the written data is “101010” for “write”, it is “010101” for “after-write”.

The results in Fig. 6 (a) can be compared with those in Fig. 6 (b), which were determined employing a micromagnetic calculation using the LLG equation. Although AW for $H_{w}/T = 10$ K/nm in Fig. 6 (b) is underestimated, the tendencies are almost the same.

The maximum SNR value in Fig. 6 (b) is lower than that in Fig. 6 (a). This is attributed to the difference between the grain magnetization patterns in Fig. 7 and in Fig. 3 (b). There are many error grains in the grain pattern calculated employing a micromagnetic calculation for $H_{w} = 10$ kOe as shown in Fig. 7. The writing field at which the SNR value shows the maximum in Fig. 6 (b) is somewhat higher than that in Fig. 6 (a). This is attributed to the determination method of the attempt time in our model calculation described in 2.2. In this way, although our model calculation is a coarse estimation, the tendencies of the results in Figs. 6 (a) and (b) are almost the same.

**Fig. 8** Time dependence of grain magnetization reversal probability $P_{r}$ for various $\partial T/\partial x$ values under conditions of 1 column/bit, $\alpha = 0.1$, and $v = 10$ m/s.

A large dependence of EAW on $\partial T/\partial x$ can be seen in Fig. 6. Figure 8 shows the time dependence of grain reversal probability $P_{r}$ for various thermal gradients $\partial T/\partial x$ at $H_{w} = 10$ kOe. The $P_{r}$ values at $\tau_{\text{min}}$ designated by open circles are important for EAW, and $P_{r}$ abruptly decreases as $\partial T/\partial x$ increases as shown in Fig. 8. Therefore, increasing $\partial T/\partial x$ is effective in decreasing EAW as shown in Fig. 6.

On the other hand, the attempt number is important for WE when $P_{r}$ is high. The attempt numbers are about 11, 7, and 5 for $\partial T/\partial x = 10$, 15, and 20 K/nm, respectively, when $0.1 \leq P_{r} \leq 1$ as shown in Fig. 8. Even if the attempt number for $\partial T/\partial x = 20$ K/nm is five, it is enough to suppress WE. Therefore, the dependence of WE on $\partial T/\partial x$ is small as shown in Fig. 6.

Next, Fig. 9 shows the dependence of SNR on $H_{w}$ for various linear velocities $v$. A large dependence of WE and a small dependence of EAW on $v$ can be seen. The $\tau_{\text{min}} = D_{\text{IP}}/v$ ($D_{\text{IP}} = 6.8$ nm) values are 1.36, 0.68, and 0.34 ns for $v = 5$, 10, and 20 m/s, respectively, as shown in Fig. 10. The attempt numbers are about 14, 7, and 3 for $v = 5$, 10, and 20 m/s, respectively, when $0.1 \leq P_{r} \leq 1$ at $H_{w} = 10$ kOe. Since the attempt number for $v = 20$ m/s is not sufficiently large to suppress WE, reducing $v$ is effective in decreasing WE. In other words, reducing $v$ is effective in increasing the writing field sensitivity.
the same regardless of the \( v \) values designated by open circles in Fig. 10. Therefore, the dependence of EAW on \( v \) is small.

In addition to the fact that the tendencies of the results in Figs. 6 (a) and (b) are almost the same, those in Figs. 9 (a) and (b) are also almost the same. Therefore, our model calculation can be used for HAMR design. The writing process can be described using the temperature dependences of the grain magnetization reversal probability and the attempt number in our model. A feature of our model calculation is that the interpretation of the result and the establishment of HAMR design policy are easy. Furthermore, since the calculation time of our model is short, we can calculate the bit error rate using \( 10^5 \) or \( 10^6 \) bits in a short time. Bit error rate data are useful for determining whether or not recording is possible, and our work on this topic will be published elsewhere\(^{12}\).

3.2.1 column/bit and \( \alpha = 0.01 \)

We also discuss the writing property with the damping constant \( \alpha = 0.01 \) instead of 0.1.

Figure 11 shows representative grain magnetization patterns calculated employing our model. When \( \alpha = 0.1 \), the surface charge summation saturated at \( H_w = 10 \) kOe, as shown in Fig. 4 (b). However, when \( \alpha = 0.01 \), the surface charge summation increased slowly with \( H_w \) and was unsaturated even at \( H_w = 17 \) kOe, as shown in Fig. 12. Therefore, WE was dominant and writing was very difficult when \( \alpha = 0.01 \).
The decreasing SNR as $H_w$ increases for a high $H_w$ region in Fig. 15 is caused by EAW. EAW begins with a higher $H_w$ than that when $\alpha = 0.1$ in Fig. 9 since the attempt number for $t \propto \tau_{\min}$ is also small for $\alpha = 0.01$ as shown in Fig. 16. EAW in Fig. 15 (a) begins with a lower $H_w$ than that in Fig. 15 (b). This is also attributed to the determination method of the attempt time as described in 3.1.

![Figure 13](image1.png)

**Fig. 13** Time dependence of grain magnetization reversal probability $P_+$ for various $H_w$ values under conditions of 1 column/bit, $\alpha = 0.01$, and typical values.

![Figure 14](image2.png)

**Fig. 14** Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $\tau / \alpha$ values under conditions of 1 column/bit, $\alpha = 0.01$, and $v = 10$ m/s.

![Figure 15](image3.png)

**Fig. 15** Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $\tau / \alpha$ values under conditions of 1 column/bit, $\alpha = 0.01$, and $\tau / \alpha = 15$ K/nm.

![Figure 16](image4.png)

**Fig. 16** Time dependence of grain magnetization reversal probability $P_+$ for various $\tau / \alpha$ values under conditions of $\alpha = 0.01$, and $\tau / \alpha = 15$ K/nm.

A serious problem in HAMR is that writing becomes difficult if the damping constant just below the Curie temperature is small. Whether or not writing is possible can be determined only by the bit error rate. Although the bit error rate data will be published elsewhere, the bit error rate for the medium with $\alpha = 0.01$ is very high.

### 3.3 4 columns/bit and $\alpha = 0.1$

Next, we discuss the writing property for 4 columns/bit instead of 1 column/bit.
Representative grain magnetization patterns calculated employing our model are shown in Fig. 17. The dotted lines indicate bit boundaries. In Fig. 17 (a) the writing field $H_w = 3$ kOe, write-error (WE) for 4 columns/bit is almost the same as that for 1 column/bit as shown in Fig. 3 (a). The $H_w$ value of about 10 kOe is also the best condition for 4 columns/bit (see Fig. 20 (a)). However, when $H_w = 17$ kOe, the degradation of the grain magnetization pattern caused by erase-after-write (EAW) for 4 columns/bit as shown in Fig. 17 (c) is remarkably small compared with that for 1 column/bit as shown in Fig. 3 (c). EAW occurs only at the 4th column in one bit as shown in Fig. 17 (c). This is confirmed by the summation of the surface magnetic charge $M_{mn}D_{mn}^2$ as shown in Figs. 4 and 18. The surface charge summation is unsaturated only at the 4th column in one bit as shown in Fig. 18 (c) according to the grain magnetization patterns for Fig. 17 (c). The same phenomenon can be seen in a previous paper.

This can be explained using the time dependence of the grain magnetization reversal probability $P$ for $H_w = 17$ kOe as shown in Fig. 19. The times corresponding to the Curie temperatures $T_{c1}$, $T_{c2}$, $T_{c3}$, and $T_{c4}$ are 0, 0.68, 1.37, and 2.05 ns for the 1st, 2nd, 3rd, and 4th column, respectively, and the end of the writing time $\tau_{\text{min}}$ is 2.73 ns. Therefore, the writing time for the 1st column is 2.73 ns ($= 2.73 - 0$ ns). Since the writing time is long, $P$ for the 1st column at $\tau_{\text{min}}$ is sufficiently low and EAW does not occur. Similarly, the writing times for the 2nd and 3rd column are 2.05 ($= 2.73 - 0.68$) and 1.36 ns ($= 2.73 - 1.37$ ns), respectively. EAW does not occur since the writing times are long. However, the writing time for the 4th column is only 0.68 ns ($= 2.73 - 2.05$ ns), which is the same as in Fig. 5. Therefore, EAW occurs only at the 4th column in one bit since $P$ at $\tau_{\text{min}}$ designated by an open circle is insufficiently low only for the 4th column.
Fig. 20 Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $\partial T/\partial x$ values under conditions of 4 columns/bit, $\alpha = 0.1$, and $v = 10$ m/s.

Figure 20 shows the dependence of SNR on $H_w$ for various thermal gradients $\partial T/\partial x$. Since increasing $\partial T/\partial x$ is effective in decreasing EAW as mentioned in 3.1, this effect can be seen in Fig. 20. However, the SNR improvement for EAW realized by increasing $\partial T/\partial x$ is small since EAW occurs only in the 4th column. EAW and AW in Fig. 20 (a) begin with a lower $H_w$ than that in Fig. 20 (b). This is also attributed to the determination method of the attempt time as described in 3.1.

On the other hand, WE occurs in every column. Therefore, decreasing linear velocity $v$ is effective in improving the SNR for WE as shown in Fig. 21. In other words, reducing $v$ is effective in increasing the writing field sensitivity.

The SNR values necessary for a certain value of bit error rate (bER), for example $10^{-3}$, are approximately the same for 1 and 4 columns/bit. The SNR value for 4 columns/bit is higher than that for 1 column/bit. This implies that the writing field necessary for bER $= 10^{-3}$ decreases and the writing field sensitivity increases as the column number increases. This issue is a statistics problem and will be discussed elsewhere.

Fig. 21 Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $v$ values under conditions of 4 columns/bit, $\alpha = 0.1$, and $\partial T/\partial x = 15$ K/nm.

3.4 4 columns/bit and $\alpha = 0.01$

Finally, we discuss the writing properties for 4 columns/bit and $\alpha = 0.01$.

Representative grain magnetization patterns calculated employing our model are shown in Fig. 22. Although EAW can be seen only in the 4th column in Fig. 17 (c) for $\alpha = 0.1$ and $H_w = 17$ kOe, error occurs in every column in Fig. 22 (c) for $\alpha = 0.01$ and $H_w = 17$ kOe. Furthermore, the surface charge summation increases as $H_w$ increases as shown in Fig. 23. Therefore, WE is dominant even for $H_w = 17$ kOe.

Fig. 22 Representative grain magnetization patterns for (a) $H_w = 3$ kOe, (b) 10 kOe, and (c) 17 kOe under conditions of 4 columns/bit, $\alpha = 0.01$, and typical values. Dotted lines indicate bit boundaries.
The dependence of SNR on $H_w$ for various thermal gradients $\partial T / \partial x$ is shown in Fig. 24, and for various linear velocities $v$ in Fig. 25. Since WE is dominant, no SNR improvement in $\partial T / \partial x$ or improvement in $v$ can be seen in Figs. 24 and 25, respectively.

The SNR value for 4 columns/bit and $\alpha = 0.01$ is higher than that for 1 column/bit and $\alpha = 0.01$. Therefore, writing becomes possible for 4 columns/bit even if $\alpha = 0.01$. This issue is also a statistics problem and will be discussed elsewhere\textsuperscript{12).

**Fig. 23** Summation of surface magnetic charges $M_{mn}D_{mn}^2$ for cross-track direction $m$ as a function of position for down-track direction $n$ under conditions of 4 columns/bit, $\alpha = 0.01$, and typical values.

**Fig. 24** Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $\partial T / \partial x$ values under conditions of 4 columns/bit, $\alpha = 0.01$, and $v = 10$ m/s.

**Fig. 25** Dependence of signal-to-noise ratio on writing field. (a) Model calculation and (b) micromagnetic (LLG) calculation for various $v$ values under conditions of 4 columns/bit, $\alpha = 0.01$, and $\partial T / \partial x = 15$ K/nm.
4. Conclusions

We calculated the dependence of the signal-to-noise ratio on the writing field for heat-assisted magnetic recording (HAMR) for various calculation parameters by employing both our improved model calculation and the conventionally used micromagnetic calculation. The tendencies of the results in the model calculation and the micromagnetic calculation were almost the same. Therefore, our model calculation can be used for HAMR design. The writing process can be described using the temperature dependences of the grain magnetization reversal probability and the attempt number.

If the Gilbert damping constant is small, writing is difficult and a higher writing field is necessary since the attempt number is small.

Write-errors can be reduced by reducing the linear velocity since the attempt number increases when the grain magnetization reversal probability is high.

Erasure-after-write can be reduced by increasing the thermal gradient and/or the grain column number since the grain magnetization reversal probability becomes low at the end of the writing time.

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