Model Calculation Considering Recording Time Window
for Heat-Assisted Magnetic Recording

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We improve our model calculation for heat-assisted magnetic recording (HAMR) by introducing the concept of the recording time window proposed in the micromagnetic calculation. The improved model calculation includes all the equations for the HAMR conditions used in the previous model. The difference is the introduction of the recording time window to determine the composition of the medium and the writing field. This improvement means that the results obtained using the model calculation become consistent with those obtained using a micromagnetic calculation. The minimum anisotropy constant ratio of the medium at 2, 3, and 4 Tbpsi can be determined using the improved model calculation.

Key words: heat-assisted magnetic recording, model calculation, recording time window, areal density, anisotropy constant ratio

1. Introduction

Heat-assisted magnetic recording (HAMR) is a recording method in which the medium is heated to reduce coercivity during the writing period. HAMR has been studied with the aim of solving the trilemma problem\(^1\) of magnetic recording (MR). In most cases, a micromagnetic calculation is used for the HAMR design. A feature of the micromagnetic calculation is its precise simulation based on the actual situation. On the other hand, this calculation requires a long time, and it is sometimes difficult to grasp the physical implications of the obtained results.

We have reported a design method that uses a model calculation for the HAMR design\(^2\) of 4 Tbpsi in order to shorten the calculation time and grasp the physical implications. In that paper, we revealed the complex relationship between certain design parameters and the anisotropy constant ratio \(K_u / K_{\text{bulk}}\). In this study, we improve our model calculation by introducing \(\tau_{\text{RW}}\), and we fix \(\tau_{\text{RW}}\) to 0.1 ns. This improvement means that the results obtained using the model calculation become consistent with those obtained using the micromagnetic calculation. Then, we provide the dependence of \(K_u / K_{\text{bulk}}\) on the areal density.

2. Previous Model Calculation

The medium was assumed to be granular. The arrangement of the grains was not considered.

The HAMR design procedure for obtaining the minimum \(K_u / K_{\text{bulk}}\) value using the previous model calculation is shown in Fig. 1. First, \(K_u / K_{\text{bulk}} = 1\) and the design parameters are set. Then, the composition of the medium and the writing field \(H_w\) are determined using the equation:

\[
K_{\beta_s}(T_v, H_w) = \text{TSF}_w, \tag{1}
\]

where

\[
K_{\beta_s}(T_v, H_w) = \frac{K_{\text{mum}}(T_v)V_m}{kT_v} \left(1 + \frac{H_w}{H_{\text{cm}}(T_v)}\right)^2 \tag{2}
\]

is the medium thermal stability factor\(^3\) \(K_{\text{mum}}\); mean anisotropy constant, \(V_m\): grain volume for mean grain size \(D_m\), \(k\): Boltzmann constant, \(H_{\text{cm}}: \text{mean coercivity assumed to be equal to mean anisotropy field}\)

\[
2K_{\text{mum}}/M_s, M_s: \text{magnetization}, \text{and}
\]

\[
\text{TSF}_w = \text{TSF}(\tau_v, n, \sigma_{\text{D}}, \sigma_{\kappa}) \tag{3}
\]

is the statistical thermal stability factor\(^3\) \(\tau_v = d_B / \nu\); writing period, \(d_B\): bit pitch, \(\nu\): linear velocity \(n\): grain number per bit, \(\sigma_{\text{D}}, \sigma_{\kappa}\): standard deviation of grain size, \(\sigma_{\kappa}\): standard deviation of anisotropy). \(\text{TSF}_w\) is calculated statistically using many bits and grain error probability.
where $H_{adj}$ is the maximum head field that can hold the information under the main pole during rewriting.

Conditions II and III can be combined as

$$\frac{\Delta T}{\Delta x} = \frac{\partial T}{\partial x} \leq \frac{\partial T}{\partial y},$$

(9)

since $\partial T / \partial x = \partial T / \partial y$. Condition IV has margins for all the cases we examined. Therefore, the major limiting factors in the design are condition I given by Eq. (5) (I. $K_{um}(T_w) V_m / kT_c \geq TSF_{10}$) and conditions II and III given by Eq. (9) (hereafter, $\Delta T / \Delta x = \Delta T / \Delta y$, $\partial T / \partial x = \partial T / \partial y$, and Eq. (9) are expressed as $\Delta T / \Delta x(y)$, $\partial T / \partial x(y)$, and $\Delta T / \Delta x(y) \leq \partial T / \partial x(y)$, respectively).

When the areal density is 2 Tbpsi, $V_m$ becomes large, and the Curie temperature $T_c$ approaches $T_w$. Then, the calculation cannot be carried out, and this also arises a problem from a physical point of view. A certain time is necessary during cooling from $T_c$ to $T_w$.

### 3. Improved Model Calculation

#### 3.1 Recording time window

We introduce the concept of the recording time window $\tau_{rw}$ proposed in the micromagnetic calculation for the purpose of improving our model calculation.

First, we examine the physical implication of $\tau_{rw}$. The magnetization $M_s$ reversal number during a time $\tau$ is given by

$$f_5 \exp(-K_{\mu}),$$

(10)
where $K_\beta$ is the medium thermal stability factor. When $\tau = 1/\dot{f}_s = 10^{-11}$ s = 0.01 ns, Eq. (10) becomes
\[ \exp(-K_\beta). \tag{11} \]

Equation (11) is the $M_s$ reversal probability for each attempt. For example, when $K_\beta = 0$, $\exp(-K_\beta)$ becomes one, where the $M_s$ reversal always occurs for each attempt. $K_{\beta+}$ where $M_s$ is parallel to $H_w$, and $K_{\beta-}$ where $M_s$ is antiparallel to $H_w$ are expressed by
\[ K_{\beta+}(T, H_w) = \frac{K_{\text{cm}}(T)V_m}{kT} \left(1 + \frac{H_w}{H_{\text{cm}}(T)}\right)^2, \tag{12} \]
and
\[ K_{\beta-}(T, H_w) = \frac{K_{\text{cm}}(T)V_m}{kT} \left(1 - \frac{H_w}{H_{\text{cm}}(T)}\right)^2 \left(H_w \leq H_{\text{cm}}(T)\right), \tag{13} \]
respectively. Therefore, the probability for each attempt where $M_s$ and $H_w$ change from parallel to antiparallel is expressed by
\[ \exp(-K_{\beta+}). \tag{14} \]

On the other hand,
\[ \exp(-K_{\beta-}) \tag{15} \]
is the probability for each attempt where $M_s$ and $H_w$ change from antiparallel to parallel.

In this paper, $\tau_{\text{RW}}$ is defined by
\[ \tau_{\text{RW}} = \frac{T_c - T_w}{(\partial T/\partial t) \cdot v}, \tag{16} \]
where $v$ is the linear velocity. Since $\dot{v} = \partial \mathbf{x} / \partial t$, $(\partial T/\partial t) \cdot v$ is the cooling rate $\partial T/\partial t$. Therefore, $\tau_{\text{RW}}$ is the cooling time from $T_c$ to $T_w$. Then, the relationship between $H_w$ and $T_w$ is defined by
\[ H_w = H_{\text{cm}}(T_w) = \frac{2K_{\text{cm}}(T_w)}{M_s(T_w)}. \tag{17} \]

From this definition, the probability $\exp(-K_{\beta+})$ is always equal to one during the cooling time $\tau_{\text{RW}}$.

Figure 2 shows the dependence of the magnetization reversal probability on time. The calculation conditions and parameters are the same as those reported elsewhere2, 3). The closed circles are the probabilities for each attempt. $T_{\text{rec}}$ is the temperature at the position 1 bit before the writing position. A lower $\exp(-K_{\beta+})$ and a higher $\exp(-K_{\beta-})$ are better during the cooling time $\tau_{\text{RW}}$ from $T_c$ to $T_w$ in terms of stable writing, and both lower $\exp(-K_{\beta+})$ and $\exp(-K_{\beta+})$ are better around the time corresponding to $T_{\text{rec}}$ in terms of information (written bit) stability at the position 1 bit before the writing position.

The result is shown in Fig. 2 (a) when $T_w = 500$ K and $H_w = H_{\text{cm}}(T_w) = 13.4$ kOe according to Eq. (17). The time corresponding to $T_c$ is 0 ns, that corresponding to $T_{\text{rec}}$ is 0.1 ns, and that corresponding to $T_{\text{rec}}$ is 0.67 ns. The resultant $\tau_{\text{RW}}$ value is 0.1 ns. It is reported that a $\tau_{\text{RW}}$ value of around 0.1 ns is suitable for the micromagnetic calculation4). The $\exp(-K_{\beta+})$ and $\exp(-K_{\beta-})$ values are both one at the time corresponding to $T_c$ since $K_{\beta+} = 0$. The $\exp(-K_{\beta+})$ values are almost zero, and the attempt number is ten during the cooling time $\tau_{\text{RW}}$, which is suitable for stable writing. The $\exp(-K_{\beta+})$ and $\exp(-K_{\beta+})$ values are both almost zero around the
time corresponding to \( T_{rec} \), which is suitable for information stability at the position 1 bit before the writing position.

Figure 2 (b) shows the result when \( T_u = 500 \text{ K} \) and \( H_u = 0.5H_{cm}(T_u) = 6.7 \text{ kOe} \) instead of Eq. (17) where the composition and \( K_u/K_{bulk} \) are the same as those in Fig. 2 (a). The resultant \( \tau_{RW} \) value is 0.02 ns. \( \exp(-K_{\beta_s}) \) has a non-zero value, and the attempt number is only two during \( \tau_{RW} \), which is not suitable for stable writing. This corresponds to “write-error”.

On the other hand, Fig. 2 (c) shows the result when \( T_u = 500 \text{ K} \) and \( H_u = 1.5H_{cm}(T_u) = 20.1 \text{ kOe} \) instead of Eq. (17) where the composition and \( K_u/K_{bulk} \) are the same as those in Fig. 2 (a). The resultant \( \tau_{RW} \) value is 0.22 ns. In this case, \( \exp(-K_{\beta_s}) \) has a non-zero value around the time corresponding to \( T_{rec} \), which is unsuitable as regards the information stability at the position 1 bit before the writing position. This corresponds to “erasure-after-write”.

### 3.2 Design procedure

The improved design procedure for obtaining the minimum \( K_u/K_{bulk} \) value is shown in Fig. 3. We fix \( \tau_{RW} \) to 0.1 ns. First, \( \tau_{RW} = 0.1 \text{ ns}, K_u/K_{bulk} = 1 \), and the design parameters including \( T_u \), \( \partial T/\partial x \) and \( v \) are set. \( T_c \) is determined from Eq. (16) as

\[
T_c = T_u + \tau_{RW} \frac{\partial T}{\partial x} v. \tag{18}
\]

Then, the Cu composition \( z \) in \((Fe_{0.5}Pt_{0.5})_{1-z}Cu_{z}\) of the medium is determined using the equation9;

\[
T_c = \frac{2J(4(1-z))(s+1)}{3k}, \tag{19}
\]

where \( J \) is the exchange integral and \( s \) is the spin. The temperature dependence of the magnetic properties is determined by \( z \) and \( K_u/K_{bulk} \). The composition is independent of \( K_u/K_{bulk} \). The \( H_u \) value is determined using Eq. (17), which is dependent on \( K_u/K_{bulk} \). The above means that the \( \tau_{RW} \) of the cooling time from \( T_c \) to \( T_u \) is necessary during the writing process at which \( M_s \) aligns with the direction of \( H_u \).

Next, new condition, which is the information stability at the writing position during \( \tau_u = d_h/v \) (\( d_h \); bit pitch) expressed by

\[
K_{\beta_s}(T_u, H_u) \geq TSF_{u}, \tag{20}
\]

is added instead of Eq. (1). Then, the four HAMR conditions I, II, III, and IV mentioned above, that is Eqs. (5), (6), (7), and (8), respectively, are examined. If there are margins for all five conditions, \( K_u/K_{bulk} \) can be reduced. Since \( H_u \) is a function of \( K_u/K_{bulk} \), \( H_u \) must be recalculated for reducing \( K_u/K_{bulk} \). When one of the five conditions reaches the limit, the minimum \( K_u/K_{bulk} \) value can be determined. That condition becomes a limiting factor.

The improved model calculation includes Eq. (20) instead of Eq. (1), and Eqs. (5), (6), (7), and (8) in the previous model calculation. Therefore, this calculation is almost the same as the previous model calculation. The difference is the introduction of the time \( \tau_{RW} \). \( \tau_{RW} \) (Eqs. (16) and (17)) is the time from \( T_c \) to \( T_u \) for aligning \( M_s \) with \( H_u \) (writing bit), and \( \tau_u \) (Eq. (20)) is the time from \( T_u \) to \( T_{rec} \) for the information (written bit) stability during the writing process. “Write-error” as regards \( \tau_{RW} \) (writing bit) and \( \tau_u \) (the written bit stability during the writing process) can be suppressed by Eqs. (16), (17) and Eq. (20), respectively. “Erasure-after-write” as regards the time after \( \tau_u \) (the written bit stability after the writing process) can also be suppressed by Eq. (6).

**Fig. 3** HAMR design procedure for obtaining the minimum anisotropy constant ratio \( K_u/K_{bulk} \) using an improved model calculation.

### 3.3 Calculation results

The calculation conditions and parameters are the same as those reported elsewhere5, 9.

The dependences of the minimum \( K_u/K_{bulk} \) value on \( T_u \) are shown in Tables 1, 2, and 3 for user areal densities of 2, 3, and 4 Tbps, respectively. The areal density calculated from the bit area \( S \) is larger than the user areal density. The difference is for the code of error correction, etc. The \( S \) value is inversely proportional to the areal density, and the heat-spot diameter \( d_m \) is inversely proportional to the square root of the areal density. The mean grain size \( D_m \) is
calculated using $\sqrt{S/n} - \Delta$ where $n = 4$ is the grain number per bit, and $\Delta = 1$ nm is the non-magnetic spacing between grains.

The Curie temperature $T_c$ is $T_{RW} \cdot (\partial T / \partial \chi) \cdot v \cdot (v = 10$ m/s) higher than $T_w$. $T_w$ is determined by the $T_c$ of the medium and not by the light power used for heating. If the light power alone is increased for a medium with the same $T_w$, the written bits will be spread in the cross-track direction, and it becomes impossible to keep the track pitch constant. Therefore, $T_c$ must be increased to increase $T_w$.

The tables also show the magnetization $M_s$, the mean anisotropy constant $K_{um}$, the mean coercivity $H_{cm}$, and $K_{um}V_m/kT$ at 300 K.

$TSF_w$ under the condition $K_{um}(T_w, H_w) \approx TSF_w$ is constant for $T_w$, and is dependent on the areal density since the bit pitch decreases as the areal density increases. $TSF_{10}$ under condition I is constant for $T_w$ and the areal density, and $K_{um}(T_w)V_m/kT_c$ increases as $T_w$ increases since $K_{um}(T_w)$ increases. $\partial T / \partial \chi(y)$ under conditions II and III also increases as $T_w$ increases. $H_{cm}$ under condition IV is sufficiently larger than $H_w$.

The optimum bit pitch $d_B$, track pitch $d_T$, and $d_T/d_B$ values are shown in the table.

### Table 1 Calculation results of HAMR design for 2 Tbpsi and various writing temperatures $T_w$.

| User areal density (Tbpsi) | $S$ (nm$^2$) | $d_w$ (nm) | $T_w$ (K) | $D_m$ (nm) | $z$ (at.% | $T_c$ (K) | $M_s(300$ K) (emu/cm$^3$) | $K_{um}(300$ K) (10$^6$ erg/cm$^3$) | $H_{cm}(300$ K) (kOe) | $K_{um}V_m/kT(300$ K) | $TSF_w$ | $K_{um}(T_w, H_w) \approx TSF_w$ | $TSF_{10}$ | $K_{um}(T_w)V_m/kT_c \approx TSF_{10}$ | $\partial T / \partial \chi(y)$ (K/mm) | $\Delta T / \Delta \chi(y)$ (K/mm) | $\chi \Delta T / \chi \Delta \chi(y)$ (K/mm) | $H_w$ (kOe) | $IV. H_w$ (kOe) $\approx H_w$ | $K_u/K_{bulk}$ | $d_B$ (nm) | $d_T$ (nm) | $d_T/d_B$ |
|-----------------------------|--------------|------------|------------|------------|---------|------------|----------------------------|------------------------------|-----------------------------|----------------|----------------|----------------|----------------|
| 2                           | 280          | 14.1       | 500        | 7.37       | 34      | 507        | 614                         | 7                           | 24                          | 76              | 8.15           | 8.15           | 8.15           |
| 2                           | 280          | 14.1       | 600        | 7.37       | 34      | 507        | 614                         | 7                           | 24                          | 76              | 8.15           | 8.15           | 8.15           |
| 2                           | 280          | 14.1       | 700        | 7.37       | 34      | 507        | 614                         | 7                           | 24                          | 76              | 8.15           | 8.15           | 8.15           |

### Table 2 Calculation results of HAMR design for 3 Tbpsi and various writing temperatures $T_w$.

| User areal density (Tbpsi) | $S$ (nm$^2$) | $d_w$ (nm) | $T_w$ (K) | $D_m$ (nm) | $z$ (at.% | $T_c$ (K) | $M_s(300$ K) (emu/cm$^3$) | $K_{um}(300$ K) (10$^6$ erg/cm$^3$) | $H_{cm}(300$ K) (kOe) | $K_{um}V_m/kT(300$ K) | $TSF_w$ | $K_{um}(T_w, H_w) \approx TSF_w$ | $TSF_{10}$ | $K_{um}(T_w)V_m/kT_c \approx TSF_{10}$ | $\partial T / \partial \chi(y)$ (K/mm) | $\Delta T / \Delta \chi(y)$ (K/mm) | $\chi \Delta T / \chi \Delta \chi(y)$ (K/mm) | $H_w$ (kOe) | $IV. H_w$ (kOe) $\approx H_w$ | $K_u/K_{bulk}$ | $d_B$ (nm) | $d_T$ (nm) | $d_T/d_B$ |
|-----------------------------|--------------|------------|------------|------------|---------|------------|----------------------------|------------------------------|-----------------------------|----------------|----------------|----------------|----------------|
| 3                           | 187          | 11.5       | 500        | 5.83       | 34      | 507        | 614                         | 12                          | 38                          | 76              | 7.86           | 7.86           | 7.86           |
| 3                           | 187          | 11.5       | 600        | 5.83       | 21      | 611        | 779                         | 12                          | 31                          | 79              | 8.19           | 8.05           | 7.98           |
| 3                           | 187          | 11.5       | 700        | 5.83       | 7       | 611        | 779                         | 12                          | 31                          | 79              | 8.19           | 8.05           | 7.98           |

### Table 3 Calculation results of HAMR design for 4 Tbpsi and various writing temperatures $T_w$.

| User areal density (Tbpsi) | $S$ (nm$^2$) | $d_w$ (nm) | $T_w$ (K) | $D_m$ (nm) | $z$ (at.% | $T_c$ (K) | $M_s(300$ K) (emu/cm$^3$) | $K_{um}(300$ K) (10$^6$ erg/cm$^3$) | $H_{cm}(300$ K) (kOe) | $K_{um}V_m/kT(300$ K) | $TSF_w$ | $K_{um}(T_w, H_w) \approx TSF_w$ | $TSF_{10}$ | $K_{um}(T_w)V_m/kT_c \approx TSF_{10}$ | $\partial T / \partial \chi(y)$ (K/mm) | $\Delta T / \Delta \chi(y)$ (K/mm) | $\chi \Delta T / \chi \Delta \chi(y)$ (K/mm) | $H_w$ (kOe) | $IV. H_w$ (kOe) $\approx H_w$ | $K_u/K_{bulk}$ | $d_B$ (nm) | $d_T$ (nm) | $d_T/d_B$ |
|-----------------------------|--------------|------------|------------|------------|---------|------------|----------------------------|------------------------------|-----------------------------|----------------|----------------|----------------|----------------|
| 4                           | 140          | 10         | 500        | 4.92       | 34      | 507        | 614                         | 20                          | 64                          | 91              | 7.68           | 7.68           | 7.68           |
| 4                           | 140          | 10         | 600        | 4.92       | 21      | 611        | 779                         | 20                          | 64                          | 91              | 7.68           | 7.68           | 7.68           |
| 4                           | 140          | 10         | 700        | 4.92       | 7       | 611        | 779                         | 20                          | 64                          | 91              | 7.68           | 7.68           | 7.68           |
The dependence of \( K_u / K_{\text{bulk}} \) on the user areal density for various \( T_w \) values is summarized in Fig. 4. The dotted lines show results calculated using the previous model. \( K_u / K_{\text{bulk}} \) at 2 Tpsi can be obtained using the improved model calculation. \( K_u / K_{\text{bulk}} \) and/or \( T_w \) must be increased to achieve a high areal density.

4. Conclusions

We improved our model calculation for heat-assisted magnetic recording (HAMR) by introducing the concept of the recording time window proposed in the micromagnetic calculation. This improvement means that the results obtained using the model calculation become consistent with those obtained using a micromagnetic calculation.

The minimum anisotropy constant ratio \( K_u / K_{\text{bulk}} \) of the medium at 2, 3, and 4 Tpsi can be obtained using the improved model calculation. \( K_u / K_{\text{bulk}} \) and/or the writing temperature must be increased to realize a high areal density.

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References


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