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_{bulk} that we introduced. K_u / K_{bulk} is the intrinsic ratio of medium anisotropy constant K_u to bulk K_u. It is necessary to design a medium with a smaller K_u / K_{bulk} in terms of achieving good media productivity. We have subsequently improved our design method, and revealed the relationships between the many design parameters and K_u / K_{bulk} [3)]. Then, we applied the physical implications to the many design parameters using our model calculation.

Our model calculation has a problem in that the minimum K_u / K_{bulk} value cannot be obtained at 2 Tbpsi. The reason is that the Curie temperature T_c approaches the writing temperature T_w as the areal density decreases in previous calculations[2, 3)] since the grain volume increases. A certain time is necessary during cooling from T_c to T_w. The recording time window τ_{RW} proposed in the micromagnetic calculation[4)] is a time during cooling from T_c to T_w. It is reported that a τ_{RW} value of around 0.1 ns is suitable for the micromagnetic calculation[4)]. In this study, we improve our model calculation by introducing τ_{RW}, and we fix τ_{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_{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_{bulk} value using the previous model calculation is shown in Fig. 1. First, K_u / K_{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:

$$K_{\beta+}(T_w, H_w) = \mathrm{TSF}_w, \tag{1}$$

where

$$K_{\beta+}(T_w, H_w) = \frac{K_{um}(T_w) V_m}{k T_w} \left(1 + \frac{H_w}{H_{cm}(T_w)}\right)^2 \tag{2}$$

is the medium thermal stability factor[3)] (K_{um}: mean anisotropy constant, V_m: grain volume for mean grain size D_m, k: Boltzmann constant, H_{cm}: mean coercivity assumed to be equal to mean anisotropy field $2K_{um} / M_s$, M_s: magnetization), and

$$\mathrm{TSF}_w = \mathrm{TSF}(\tau_w, n, \sigma_D, \sigma_K) \tag{3}$$

is the statistical thermal stability factor[5)] ($\tau_w = d_B / v$: writing period, d_B: bit pitch, v: linear velocity n: grain number per bit, σ_D: standard deviation of grain size, σ_K: standard deviation of anisotropy). TSF_w is calculated statistically using many bits and grain-error probability

$$P = 1 - \exp\left(-f_0\tau_{\mathrm{w}} \exp\left(-\mathrm{TSF}_{\mathrm{w}} \cdot \left(\frac{D}{D_{\mathrm{m}}}\right)^2 \cdot \frac{K_{\mathrm{u}}}{K_{\mathrm{um}}}\right)\right) \quad (4)$$

(f_0 = 10^{11} s^{-1}: attempt frequency, D: grain size, K_{u}: anisotropy constant) with a 10^{-3} bit error rate.

The compositions of the medium and H_{w} are determined using Eq. (1). This means that writing completion is defined as the state in which the written bit is stable at T_{w} under H_{w} during τ_{w} for the medium with n, σ_{D}, and σ_{K}.

Next, four HAMR conditions I, II, III, and IV are examined. If there are margins for all four conditions, $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ can be reduced. When one of the four conditions reaches the limit, the minimum $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ value can be determined, and that condition becomes a limiting factor[3].

Condition I, which is the information (written bits) stability during 10 years of archiving, is expressed by

$$\frac{K_{\mathrm{um}}(T_{\mathrm{a}})V_{\mathrm{m}}}{kT_{\mathrm{a}}} \geq \mathrm{TSF}_{10}, \quad (5)$$

where T_{a} is the maximum working temperature of the hard drive, and TSF_{10} is the statistical thermal stability factor during 10 years of archiving $\mathrm{TSF}(10\ \text{years}, n, \sigma_{\mathrm{D}}, \sigma_{\mathrm{K}})$.

Condition II, which is the information stability on the trailing side located 1 bit from the writing position during writing, is expressed by

$$\frac{\Delta T}{\Delta x} = \frac{T_{\mathrm{w}} - T_{\mathrm{rec}}}{\Delta x} \leq \frac{\partial T}{\partial x}, \quad (6)$$

where $\Delta T/\Delta x$ is the medium thermal gradient for the down-track direction, which is the minimum thermal gradient required by the medium for information stability, T_{rec} is the maximum temperature at which the information on the trailing side located 1 bit from the writing position can be held during writing, and $\partial T/\partial x$ is the heat-transfer thermal gradient for the down-track direction, which is calculated by a heat-transfer simulation.

Condition III, which is the information stability in adjacent tracks during rewriting, is expressed by

$$\frac{\Delta T}{\Delta y} = \frac{T_{\mathrm{w}} - T_{\mathrm{adj}}}{\Delta y} \leq \frac{\partial T}{\partial y}, \quad (7)$$

where $\Delta T/\Delta y$ is the medium thermal gradient for the cross-track direction, T_{adj} is the maximum temperature at which the information in adjacent tracks can be held during rewriting, and $\partial T/\partial y$ is the heat-transfer thermal gradient for the cross-track direction.

Condition IV, which is the information stability under the main pole during rewriting, is expressed by

$$H_{\mathrm{adj}} \geq H_{\mathrm{w}}, \quad (8)$$

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

$$\frac{\Delta T}{\Delta x} = \frac{\Delta T}{\Delta y} \leq \frac{\partial T}{\partial x} = \frac{\partial T}{\partial y}, \quad (9)$$

since $\partial T/\partial x \approx \partial T/\partial y$. 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. $K_{\mathrm{um}}(T_{\mathrm{a}})V_{\mathrm{m}}/kT_{\mathrm{a}} \geq \mathrm{TSF}_{10}$) 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}.

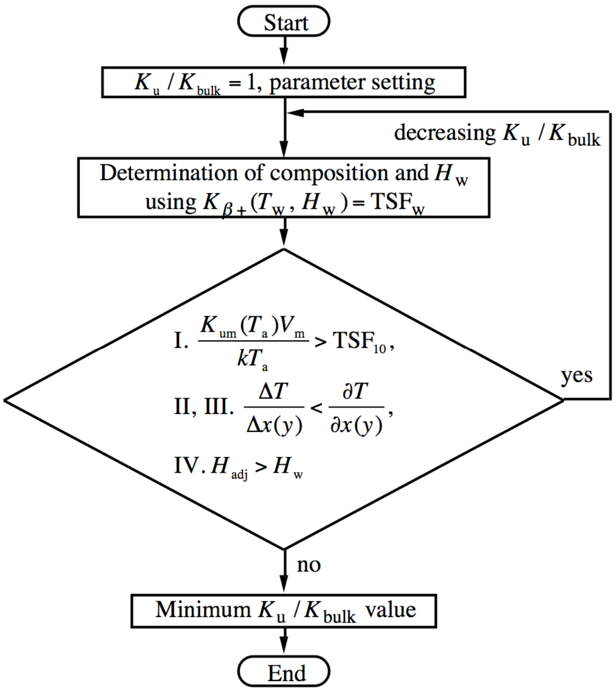

Fig. 1 HAMR design procedure for obtaining the minimum anisotropy constant ratio $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ using a previous model calculation.

3. Improved Model Calculation

3.1 Recording time window

We introduce the concept of the recording time window[4] τ_{RW} proposed in the micromagnetic calculation for the purpose of improving our model calculation.

First, we examine the physical implication of τ_{RW}. The magnetization M_{s} reversal number during a time τ is given by

$$f_0\tau \exp(-K_\beta), \quad (10)$$

where K_β is the medium thermal stability factor. When $\tau = 1/f_0 = 10^{-11}$ s = 0.01 ns, Eq. (10) becomes

$$\exp\left(-K_\beta\right). \tag{11}$$

Equation (11) is the M_s reversal probability for each attempt. For example, when K_β = 0, $\exp\left(-K_\beta\right)$ 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

$$K_{\beta+}(T,\, H_\mathrm{w}) = \frac{K_\mathrm{um}(T)V_\mathrm{m}}{kT}\left(1+\frac{H_\mathrm{w}}{H_\mathrm{cm}(T)}\right)^2, \tag{12}$$

and

$$K_{\beta-}(T,\, H_\mathrm{w}) = \frac{K_\mathrm{um}(T)V_\mathrm{m}}{kT}\left(1-\frac{H_\mathrm{w}}{H_\mathrm{cm}(T)}\right)^2 \quad \left(H_\mathrm{w} \le H_\mathrm{cm}(T)\right),$$

$$K_{\beta-}(T,\, H_\mathrm{w}) = 0 \quad \left(H_\mathrm{cm}(T) < H_\mathrm{w}\right), \tag{13}$$

respectively. Therefore, the probability for each attempt where M_s and H_w change from parallel to antiparallel is expressed by

$$\exp\left(-K_{\beta+}\right). \tag{14}$$

On the other hand,

$$\exp\left(-K_{\beta-}\right) \tag{15}$$

is the probability for each attempt where M_s and H_w change from antiparallel to parallel.

In this paper, τ_RW is defined by

$$\tau_\mathrm{RW} = \frac{T_\mathrm{c} - T_\mathrm{w}}{\left(\partial T/\partial x\right)\cdot v}, \tag{16}$$

where v is the linear velocity. Since $v = \partial x/\partial t$, $\left(\partial T/\partial x\right)\cdot v$ is the cooling rate $\partial T/\partial t$. Therefore, τ_RW is the cooling time from T_c to T_w. Then, the relationship between H_w and T_w is defined by

$$H_\mathrm{w} = H_\mathrm{cm}(T_\mathrm{w}) = \frac{2K_\mathrm{um}(T_\mathrm{w})}{M_\mathrm{s}(T_\mathrm{w})}. \tag{17}$$

From this definition, the probability $\exp\left(-K_{\beta-}\right)$ is always equal to one during the cooling time τ_RW.

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

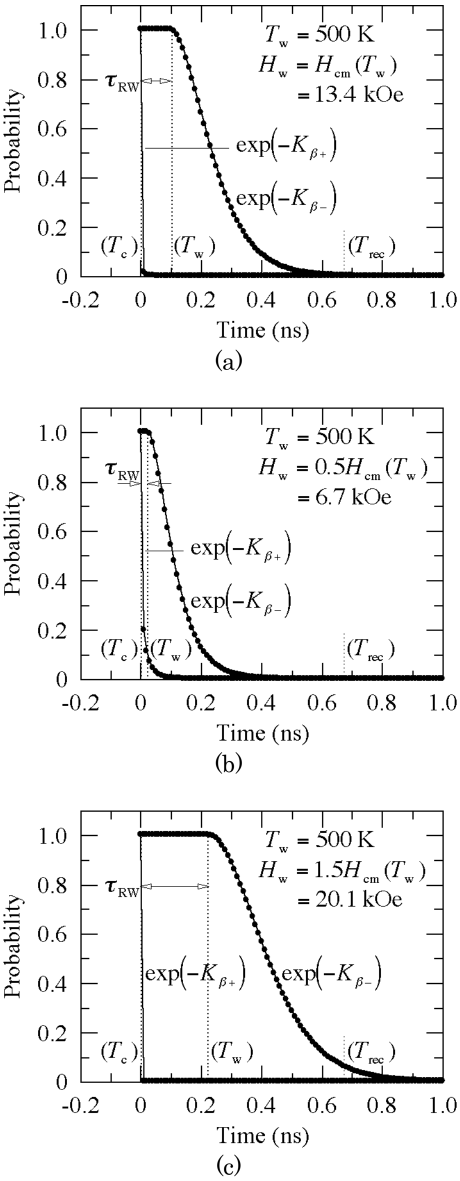

Fig. 2 Dependence of magnetization reversal probability on time for (a) $H_\mathrm{w} = H_\mathrm{cm}(T_\mathrm{w})$, (b) $H_\mathrm{w} = 0.5H_\mathrm{cm}(T_\mathrm{w})$, and (c) $H_\mathrm{w} = 1.5H_\mathrm{cm}(T_\mathrm{w})$.

The result is shown in Fig. 2 (a) when T_w = 500 K and $H_\mathrm{w} = H_\mathrm{cm}(T_\mathrm{w})$ = 13.4 kOe according to Eq. (17). The time corresponding to T_c is 0 ns, that corresponding to T_w is 0.1 ns, and that corresponding to T_rec is 0.67 ns. The resultant τ_RW value is 0.1 ns. It is reported that a τ_RW value of around 0.1 ns is suitable for the micromagnetic calculation[4]. The $\exp\left(-K_{\beta+}\right)$ and $\exp\left(-K_{\beta-}\right)$ values are both one at the time corresponding to T_c since $K_{\beta\pm}$ = 0. The $\exp\left(-K_{\beta+}\right)$ values are almost zero, and the attempt number is ten during the cooling time τ_RW, which is suitable for stable writing. The $\exp\left(-K_{\beta+}\right)$ and $\exp\left(-K_{\beta-}\right)$ 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_{w} = 500 K and $H_{\mathrm{w}} = 0.5H_{\mathrm{cm}}(T_{\mathrm{w}})$ = 6.7 kOe instead of Eq. (17) where the composition and $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ are the same as those in Fig. 2 (a). The resultant τ_{RW} value is 0.02 ns. $\exp\left(-K_{\beta+}\right)$ has a non-zero value, and the attempt number is only two during τ_{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_{w} = 500 K and $H_{\mathrm{w}} = 1.5H_{\mathrm{cm}}(T_{\mathrm{w}})$ = 20.1 kOe instead of Eq. (17) where the composition and $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ are the same as those in Fig. 2 (a). The resultant τ_{RW} value is 0.22 ns. In this case, $\exp\left(-K_{\beta-}\right)$ 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 $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ value is shown in Fig. 3. We fix τ_{RW} to 0.1 ns. First, τ_{RW} = 0.1 ns, $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ = 1, and the design parameters including T_{w}, $\partial T/\partial x$ and v are set. T_{c} is determined from Eq. (16) as

$$T_{\mathrm{c}} = T_{\mathrm{w}} + \tau_{\mathrm{RW}} \cdot \frac{\partial T}{\partial x} \cdot v\,. \qquad (18)$$

Then, the Cu composition z in $(\mathrm{Fe}_{0.5}\mathrm{Pt}_{0.5})_{1-z}\mathrm{Cu}_z$ of the medium is determined using the equation[6]:

$$T_{\mathrm{c}} = \frac{2J(4(1-z))s(s+1)}{3k}, \qquad (19)$$

where J is the exchange integral and s is the spin. The temperature dependence of the magnetic properties is determined by z and $K_{\mathrm{u}}/K_{\mathrm{bulk}}$. The composition is independent of $K_{\mathrm{u}}/K_{\mathrm{bulk}}$. The H_{w} value is determined using Eq. (17), which is dependent on $K_{\mathrm{u}}/K_{\mathrm{bulk}}$. The above means that the τ_{RW} of the cooling time from T_{c} to T_{w} is necessary during the writing process at which M_{s} aligns with the direction of H_{w}.

Next, new condition, which is the information stability at the writing position during $\tau_{\mathrm{w}} = d_{\mathrm{B}}/v$ (d_{B}: bit pitch) expressed by

$$K_{\beta+}(T_{\mathrm{w}},\, H_{\mathrm{w}}) \geq \mathrm{TSF}_{\mathrm{w}}, \qquad (20)$$

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, $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ can be reduced. Since H_{w} is a function of $K_{\mathrm{u}}/K_{\mathrm{bulk}}$, H_{w} must be recalculated for reducing $K_{\mathrm{u}}/K_{\mathrm{bulk}}$. When one of the five conditions reaches the limit, the minimum $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ 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 τ_{RW}. τ_{RW} (Eqs. (16) and (17)) is the time from T_{c} to T_{w} for aligning M_{s} with H_{w} (writing bit), and τ_{w} (Eq. (20)) is the time from T_{w} to T_{rec} for the information (written bit) stability during the writing process. "Write-error" as regards τ_{RW} (writing bit) and τ_{w} (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 τ_{w} (the written bit stability after the writing process) can also be suppressed by Eq. (6).

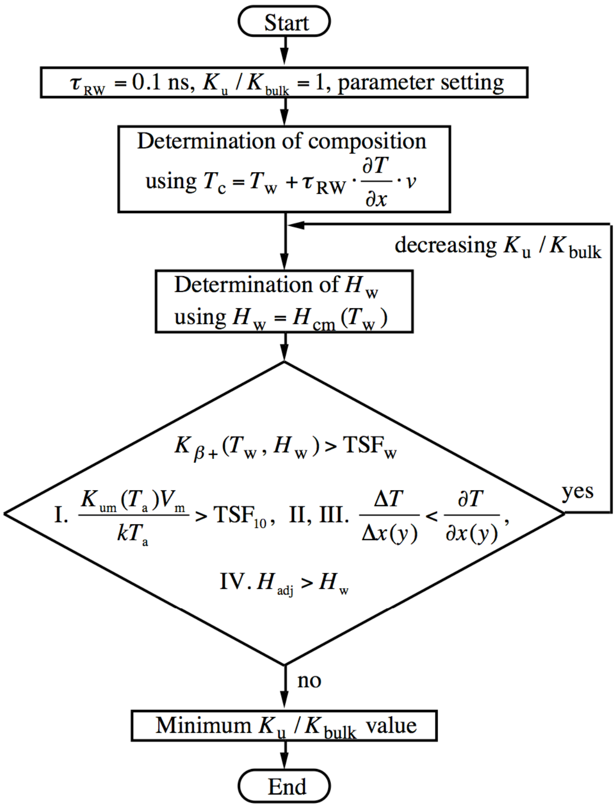

Fig. 3 HAMR design procedure for obtaining the minimum anisotropy constant ratio $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ using an improved model calculation.

3.3 Calculation results

The calculation conditions and parameters are the same as those reported elsewhere[3, 4].

The dependences of the minimum $K_{\mathrm{u}}/K_{\mathrm{bulk}}$ value on T_{w} are shown in Tables 1, 2, and 3 for user areal densities of 2, 3, and 4 Tbpsi, 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_{w} 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 Δ = 1 nm is the non-magnetic spacing between grains.

The Curie temperature T_c is $\tau_{RW}\cdot\left(\partial T/\partial x\right)\cdot v$ (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_c, 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.

$\mathrm{TSF_w}$ under the condition $K_{\beta+}(T_w, H_w) \geq \mathrm{TSF_w}$ is constant for T_w, and is dependent on the areal density since the bit pitch decreases as the areal density increases[2, 3]. $\mathrm{TSF_{10}}$ under condition I is constant for T_w and the areal density, and $K_{um}(T_a)V_m/kT_a$ increases as T_w increases since $K_{um}(T_a)$ increases[7]. $\partial T/\partial x(y)$ under conditions II and III also increases as T_w increases[3]. H_{adj} 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)	2	2	2
S (nm^2)	280	280	280
d_w (nm)	14.1	14.1	14.1
T_w (K)	500	600	700
D_m (nm)	7.37	7.37	7.37
z (at.%)	34	21	7
T_c (K)	507	611	715
M_s(300 K) (emu/cm^3)	614	779	927
K_{um}(300 K) (10^6 erg/cm^3)	7	8	8
H_{cm}(300 K) (kOe)	24	19	17
$K_{um}V_m/kT$(300 K)	76	80	85
$\mathrm{TSF_w}$	8.15	8.15	8.15
$K_{\beta+}(T_w, H_w) \geq \mathrm{TSF_w}$	8.19	8.15	8.15
$\mathrm{TSF_{10}}$	62	62	62
I. $K_{um}(T_a)V_m/kT_a \geq \mathrm{TSF_{10}}$	62	68	74
$\partial T/\partial x(y)$ (K/nm)	6.9	11.0	15.1
II, III. $\Delta T/\Delta x(y)$ (K/nm) $\leq \partial T/\partial x(y)$	5.7	9.1	12.3
H_w (kOe)	5.02	4.41	4.14
IV. H_{adj} (kOe) $\geq H_w$	7.25	6.66	6.52
K_u/K_{bulk}	0.29	0.18	0.14
d_B (nm)	9.59	9.64	9.69
d_T (nm)	29.2	29.0	28.9
d_T/d_B	3.05	3.01	2.99

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

User areal density (Tbpsi)	3	3	3
S (nm^2)	187	187	187
d_w (nm)	11.5	11.5	11.5
T_w (K)	500	600	700
D_m (nm)	5.83	5.83	5.83
z (at.%)	34	21	7
T_c (K)	507	611	715
M_s(300 K) (emu/cm^3)	614	779	927
K_{um}(300 K) (10^6 erg/cm^3)	12	12	13
H_{cm}(300 K) (kOe)	38	31	27
$K_{um}V_m/kT$(300 K)	76	79	83
$\mathrm{TSF_w}$	7.86	7.86	7.86
$K_{\beta+}(T_w, H_w) \geq \mathrm{TSF_w}$	8.19	8.05	7.98
$\mathrm{TSF_{10}}$	62	62	62
I. $K_{um}(T_a)V_m/kT_a \geq \mathrm{TSF_{10}}$	62	67	73
$\partial T/\partial x(y)$ (K/nm)	6.9	11.0	15.1
II, III. $\Delta T/\Delta x(y)$ (K/nm) $\leq \partial T/\partial x(y)$	6.9	11.0	15.1
H_w (kOe)	8.01	6.95	6.46
IV. H_{adj} (kOe) $\geq H_w$	11.4	10.3	9.93
K_u/K_{bulk}	0.46	0.29	0.21
d_B (nm)	7.77	7.81	7.84
d_T (nm)	24.0	23.9	23.8
d_T/d_B	3.10	3.06	3.03

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

User areal density (Tbpsi)	4	4	4
S (nm^2)	140	140	140
d_w (nm)	10	10	10
T_w (K)	500	600	700
D_m (nm)	4.92	4.92	4.92
z (at.%)	34	21	7
T_c (K)	507	611	715
M_s(300 K) (emu/cm^3)	614	779	927
K_{um}(300 K) (10^6 erg/cm^3)	20	20	21
H_{cm}(300 K) (kOe)	64	52	46
$K_{um}V_m/kT$(300 K)	91	95	100
$\mathrm{TSF_w}$	7.68	7.68	7.68
$K_{\beta+}(T_w, H_w) \geq \mathrm{TSF_w}$	9.76	9.69	9.63
$\mathrm{TSF_{10}}$	62	62	62
I. $K_{um}(T_a)V_m/kT_a \geq \mathrm{TSF_{10}}$	74	81	88
$\partial T/\partial x(y)$ (K/nm)	6.9	11.0	15.1
II, III. $\Delta T/\Delta x(y)$ (K/nm) $\leq \partial T/\partial x(y)$	6.9	11.0	15.1
H_w (kOe)	13.4	11.8	11.0
IV. H_{adj} (kOe) $\geq H_w$	22.5	20.2	19.3
K_u/K_{bulk}	0.77	0.49	0.36
d_B (nm)	6.70	6.73	6.75
d_T (nm)	20.9	20.8	20.7
d_T/d_B	3.12	3.09	3.07

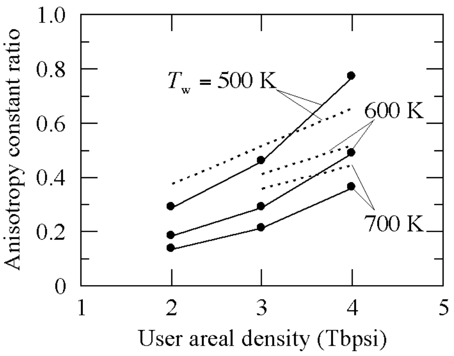

Fig. 4 Dependence of anisotropy constant ratio K_u / K_{bulk} on user areal density for various writing temperatures T_w. Dotted lines are results calculated using a previous model.

The dependence of K_u / K_{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_{bulk} at 2 Tbpsi can be obtained using the improved model calculation. K_u / K_{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_{bulk} of the medium at 2, 3, and 4 Tbpsi can be obtained using the improved model calculation. K_u / K_{bulk} and/or the writing temperature must be increased to realize a high areal density.

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