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Advantages of Increasing Writing Temperature in Heat-Assisted Magnetic Recording

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The advantages of increasing the writing temperature T_w in heat-assisted magnetic recording (HAMR) are summarized. As T_w increases, the anisotropy constant ratio, which is a new parameter we introduced, can be decreased since the anisotropy constant at the working temperature and the heat-transfer thermal gradient are increased. A relatively thin recording layer (RL) is allowable since the heat-transfer thermal gradient is reduced by increasing the RL thickness because of the adiabatic effect of the RL. Relatively large standard deviations in grain size and anisotropy are permissible since the probability of magnetization reversal is low even for small grains and grains with small anisotropy during the writing period, respectively. A relatively large standard deviation in the Curie temperature is allowable since the heat-transfer thermal gradient is increased. For Fe-Ni-Pt films, the temperature dependence of the anisotropy field is suitable for HAMR when T_w is high. All of the above are advantageous when preparing HAMR media.

Key words: heat-assisted magnetic recording, writing temperature, anisotropy constant ratio, standard deviation, temperature dependence

1. Introduction

Heat-assisted magnetic recording (HAMR) is a candidate for solving the trilemma problem[1)] of magnetic recording (MR). HAMR is a recording method in which the medium is heated to reduce the coercivity during the writing period.

We have reported a design method that uses a model calculation for HAMR media[2)]. In that paper, we introduced a new parameter, the anisotropy constant ratio K_u/K_{bulk}, which is the intrinsic ratio of film anisotropy constant K_u to bulk K_u. Finding a way to increase K_u/K_{bulk} is a challenging task. Therefore, it is necessary to design a medium with a smaller K_u/K_{bulk}. The dependences of K_u/K_{bulk} on the grain number per bit n, the standard deviation of the grain size σ_D, the recording layer thickness h, and the writing temperature T_w were clarified.

We have subsequently improved our design method, and many relationships between the media design parameters and K_u/K_{bulk} have been revealed[3)]. The design parameters we examined were the MR method (HAMR and HAMR combined with shingled MR (SHAMR)), h, the thermal conductivity of the interlayer 1 (shown in Fig. 2), the light-spot diameter, the heat-spot diameter, the linear velocity, T_w, n, and σ_D. As a result, we found that increasing T_w is only effective for reducing K_u/K_{bulk} when we compare it with the K_u/K_{bulk} value calculated using standard parameter values.

The above-mentioned examinations were carried out by changing one parameter. Next, we provided examination results for a combination of more than two parameters[4)]. In conclusion, the combinations that can reduce K_u/K_{bulk} always have SHAMR as one parameter. However, the use of SHAMR degrades the read/write performance of the hard drive. Although a lower T_w is better in terms of the heat resistance of the writing head and/or the surface lubricant, increasing T_w appears to be the only way of reducing K_u/K_{bulk} for HAMR media.

Increasing T_w has many advantages in addition to reducing K_u/K_{bulk}. In this study, we summarize the advantages of increasing T_w.

2. Calculation Conditions

The medium was assumed to be granular. The arrangement of the grains was not considered. Figure 1 (a) is a schematic illustration of the area near the writing position for HAMR. The writing field H_w is applied to a wide area including the writing position. The circle denoted by T_w is an isotherm of T_w, and d_w is the heat-spot diameter. The white regions indicate upward or downward magnetization, and the gray regions indicate the magnetization transition that contains upward and downward magnetization grains. The transition region spreads to adjacent tracks as a result of rewriting operations on the i th track.

T_{rec} is the maximum temperature[3)] at which the information on the trailing side can be held during writing. Δx is the distance[3)] from the position of T_w to that of T_{rec}. On the other hand, T_{adj} is the maximum temperature[3)] at which the information in adjacent tracks can be held during rewriting. Δy is the distance[3)] from the position of T_w to that of T_{adj}.

The bit area S is fixed, and S is the product of the bit pitch d_B and the track pitch d_T. The method for determining d_T/d_B was reported in a previous paper[2)].

Figure 1 (b) shows the writing-head configuration. It was assumed that the main-pole size of the head is 600 nm (down-track direction) × 300 nm (cross-track direction), and the writing position is located on the trailing side of the main pole. H_{adj} is the maximum head field[3] that can hold the information under the main pole during rewriting. The maximum temperature under the main pole is T_a, which is the maximum working temperature of the hard drive, and was assumed to be 330 K.

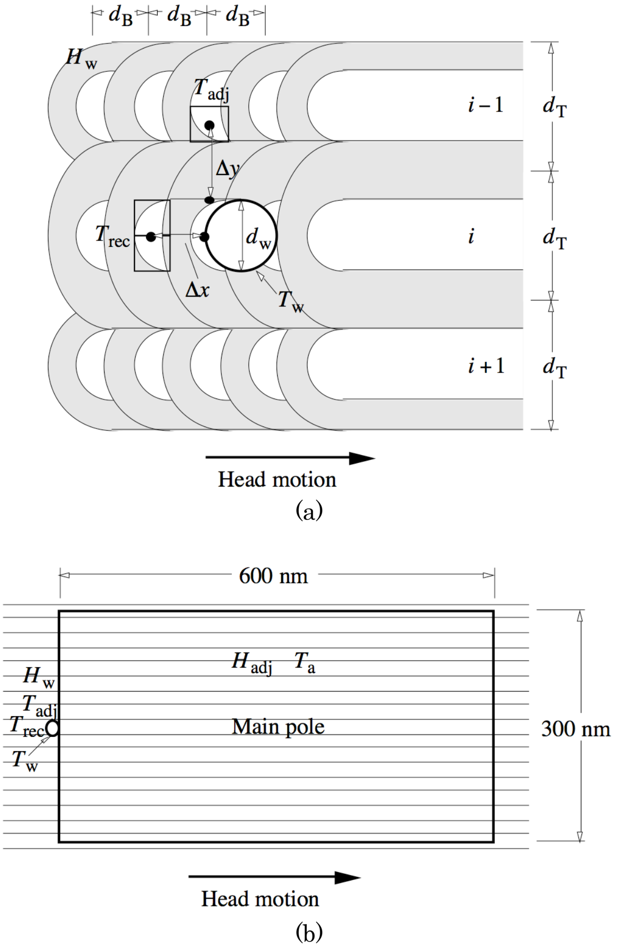

Fig. 1 Schematic illustrations of (a) writing position and (b) writing-head configuration.

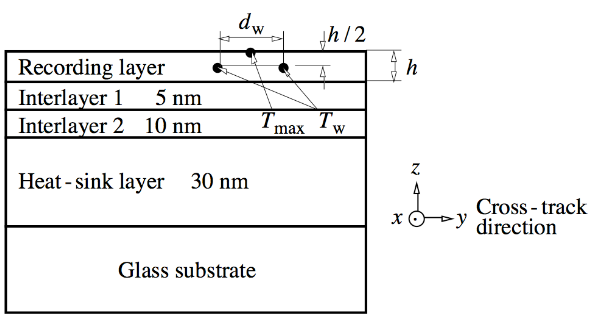

Fig. 2 Medium structure and definition of temperatures.

The standard medium structure is shown in Fig. 2. The standard medium consists of four layers, that is, a recording layer RL (Fe-Pt base, thickness h = 8 nm), an interlayer 1 IL1 (MgO base, 5 nm), an interlayer 2 IL2 (Cr base, 10 nm), and a heat-sink layer HSL (Cu base, 30 nm). The x, y, and z axes are the down-track, cross-track, and thickness directions, respectively. T_w is defined at the heat-spot edge and is at the center of the RL layer in the thickness direction. The two positions of T_w in Fig. 2 are at a distance of d_w in the cross-track direction as shown in Fig. 1 (a). T_w and d_w are the design parameters. T_w can be changed by the light power used for heating. T_{max} is defined as the maximum surface temperature.

Figure 3 (a) shows the heat-transfer thermal gradient $\partial T/\partial x$ for the down-track direction and $\partial T/\partial y$ for the cross-track direction at T_w and the center of the RL layer in the thickness direction as a function of the RL thickness h. $\partial T/\partial x$ and $\partial T/\partial y$ were calculated by a heat-transfer simulation[2], and $\partial T/\partial x \approx \partial T/\partial y$ can be seen. The dependence of T_{max} on h is shown in Fig. 3 (b).

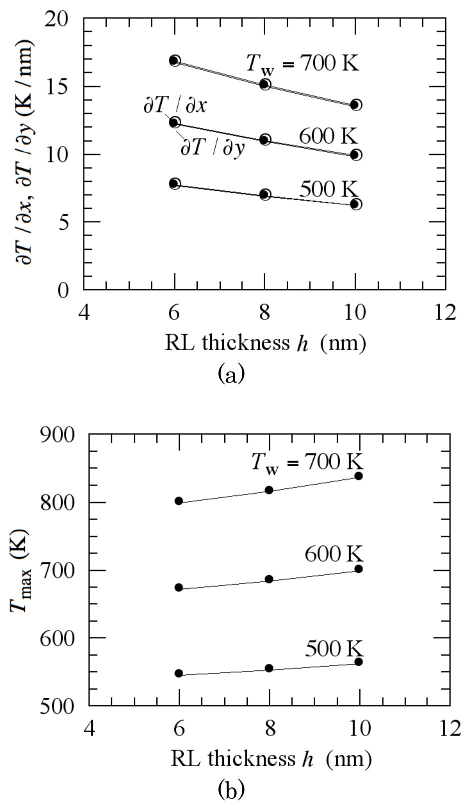

Fig. 3 (a) Heat-transfer thermal gradients $\partial T/\partial x$ for down-track direction and $\partial T/\partial y$ for cross-track direction, and (b) maximum surface temperature T_{max} as a function of RL thickness h.

The standard parameter values used for the media design are summarized in Table 1. The standard deviations of the anisotropy constant σ_K and the Curie temperature σ_{Tc} are newly introduced design parameters.

The HAMR media are designed to obtain the minimum K_u/K_{bulk} value using the procedure shown in Fig. 4. First, the design parameters and K_u/K_{bulk} = 1 are set. Four HAMR conditions (1), (2), (3), and (4) are examined after determining the composition of the recording layer. If there are margins for all four conditions, K_u / K_{bulk} can be reduced. When one of the four conditions reaches the limit, the minimum K_u / K_{bulk} value can be determined. That condition becomes a limiting factor.

Table 1 Standard parameter values used for media design.

User areal density (Tbpsi)	4
Bit area S (nm^2)	140
Effective track width d_{ET} (nm)	10
Ambient temperature T_a (K)	330
Writing temperature T_w (K)	500
Grain number per bit n (grain / bit)	4
RL thickness h (nm)	8
Standard deviation of grain size σ_D / D_m (%)	10
Standard deviation of anisotropy σ_K / K_{um} (%)	0
Inter - grain exchange coupling J (erg / cm^2)	0
MR method	HAMR
Light - spot diameter d_L (nm)	9.0
Heat - spot diameter d_w (nm)	10
Linear velocity v (m / s)	10
Thermal conductivity of IL1 K (W / (cmK))	0.5
Standard deviation of Curie temp. σ_{Tc} / T_c (%)	0

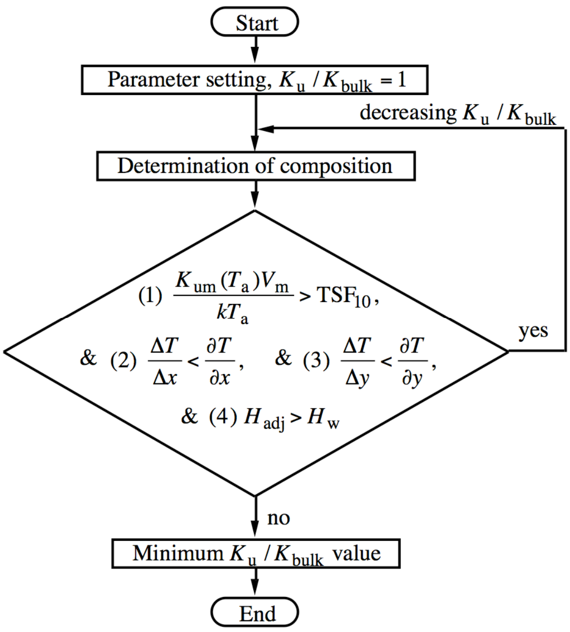

Fig. 4 HAMR media design procedure for obtaining the minimum anisotropy constant ratio K_u / K_{bulk} [3].

Condition (1), the information stability during 10 years of archiving, is expressed as

$$\frac{K_{um}(T_a)V_m}{kT_a} \geq \mathrm{TSF}_{10}, \qquad (1)$$

where $K_{um}(T_a)V_m / kT_a$ is a medium thermal stability factor, $K_{um}(T_a)$ is the mean anisotropy constant, $V_m = D_m{}^2 \times h$ is the grain volume for the mean grain size D_m, k is the Boltzmann constant, and TSF_{10} is the statistical thermal stability factor during 10 years of archiving[3] calculated statistically using grain-error probability and many bits under the condition of a 10^{-3} bit error rate. The statistical thermal stability factor $\mathrm{TSF}(\tau, n, \sigma_D, \sigma_K)$ is generally a function of the archiving period τ, the grain number per bit n, the standard deviation of the grain size σ_D, and the standard deviation of the anisotropy σ_K [5]. TSF is unrelated to K_u . And TSF_{10} means $\mathrm{TSF}(10 \text{ years}, n, \sigma_D, \sigma_K)$.

Condition (2), the information stability on the trailing side during writing, is expressed as

$$\frac{\Delta T}{\Delta x} = \frac{T_w - T_{rec}}{\Delta x} \leq \frac{\partial T}{\partial x}, \qquad (2)$$

where $\Delta T / \Delta x$ is the medium thermal gradient for the down-track direction.

Condition (3), the information stability in adjacent tracks during rewriting, is expressed as

$$\frac{\Delta T}{\Delta y} = \frac{T_w - T_{adj}}{\Delta y} \leq \frac{\partial T}{\partial y}, \qquad (3)$$

where $\Delta T / \Delta y$ is the medium thermal gradient for the cross-track direction. $\Delta T / \Delta x$ and $\Delta T / \Delta y$ are the minimum thermal gradients required by the medium for information stability[3].

Condition (4), the information stability under the main pole during rewriting, is expressed as[3]

$$H_{adj} \geq H_w. \qquad (4)$$

Conditions (2) and (3) can be combined as

$$\frac{\Delta T}{\Delta x} = \frac{\Delta T}{\Delta y} \leq \frac{\partial T}{\partial x} = \frac{\partial T}{\partial y}, \qquad (5)$$

since $\partial T / \partial x \approx \partial T / \partial y$. Condition (4) has margins for all the cases we examined. Therefore, the major limiting factors in the media design are condition (1) given by Eq. (1) ((1) $K_{um}(T_a)V_m / kT_a \geq \mathrm{TSF}_{10}$) and conditions (2) and (3) given by Eq. (5) (hereafter, shown as $\Delta T / \Delta x = \Delta T / \Delta y \equiv \Delta T / \Delta x(y)$, $\partial T / \partial x = \partial T / \partial y \equiv \partial T / \partial x(y)$, and (2), (3) $\Delta T / \Delta x(y) \leq \partial T / \partial x(y)$).

3. Calculation Results

3.1 Anisotropy constant ratio

The dependence of the required K_u / K_{bulk} value on T_w is shown in Table 2. We extended the calculation range up to T_w = 700 K. The Curie temperature T_c is 4 - 8 K higher than T_w. T_w is determined by the light power used for heating, and the T_c of the medium is determined by T_w. 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 magnetization M_s, K_{um}, the mean coercivity H_{cm}, and $K_{um}V_m/kT$ at 300 K are also shown in the table. H_{cm} was assumed to be equal to the mean anisotropy field $H_{km} = 2K_{um}/M_s$. TSF_{10} in condition (1) is constant for T_w, and $K_{um}(T_a)V_m/kT_a$ increases as T_w increases since $K_{um}(T_a)$ increases[4]. $\partial T/\partial x(y)$ in conditions (2) and (3) also increases as T_w increases[3]. The limiting factors are conditions (2) and (3). H_{adj} in condition (4) is sufficiently larger than H_w. Although $K_{um}(300\ \mathrm{K})$ apparently increases as T_w increases, K_u/K_{bulk} can decrease from 0.66 for T_w = 500 K to 0.45 for T_w = 700 K. The optimum d_B, d_T, and d_T/d_B values are shown in the table.

K_u/K_{bulk} is a function of the heat-transfer thermal gradient $\partial T/\partial x(y)$ as shown in Fig. 5. As $\partial T/\partial x(y)$ increases, K_u/K_{bulk} first becomes lower, and then becomes constant with respect to $\partial T/\partial x(y)$. In the range where K_u/K_{bulk} changes, the limiting factors are conditions (2) and (3) $\Delta T/\Delta x(y) \le \partial T/\partial x(y)$. And it is condition (1) $K_{um}(T_a)V_m/kT_a \ge TSF_{10}$ in the range where K_u/K_{bulk} is constant. Although increasing T_w is effective for reducing K_u/K_{bulk}, a higher $\partial T/\partial x(y)$ is needed to obtain a lower K_u/K_{bulk}. The filled circles show the K_u/K_{bulk} values and their $\partial T/\partial x(y)$ values calculated by a heat-transfer simulation. The values correspond to those in Table 2. If we can realize a greater increase in $\partial T/\partial x(y)$ by examining the media structure, we can expect to reduce K_u/K_{bulk} even further.

Table 2 Calculation results of HAMR media design for various writing temperatures T_w.

T_w (K)	500	600	700
D_m (nm)	4.92	4.92	4.92
T_c (K)	508	606	704
M_s(300 K) (emu/cm^3)	616	771	912
K_{um}(300 K) (10^6 erg/cm^3)	17	21	26
H_{cm}(300 K) = H_{km}(300 K) (kOe)	54	55	57
$K_{um}V_m/kT$(300 K)	78	99	120
TSF_{10}	62	62	62
(1) $K_{um}(T_a)V_m/kT_a \ge TSF_{10}$	64	84	105
$\partial T/\partial x(y)$ (K/nm)	6.9	11.0	15.1
(2), (3) $\Delta T/\Delta x(y)$ (K/nm) $\le \partial T/\partial x(y)$	6.9	11.0	15.1
H_w (kOe)	9.85	12.3	14.6
(4) H_{adj} (kOe) $\ge H_w$	16.7	22.0	26.3
K_u/K_{bulk}	0.66	0.52	0.45
d_B (nm)	6.57	6.81	6.95
d_T (nm)	21.3	20.6	20.1
d_T/d_B	3.25	3.02	2.90

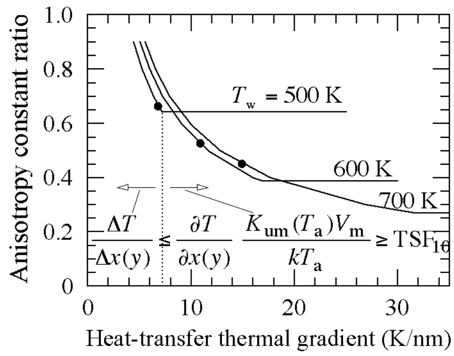

Fig. 5 Dependence of anisotropy constant ratio K_u/K_{bulk} on heat-transfer thermal gradient $\partial T/\partial x(y)$ for various writing temperatures T_w.

3.2 RL thickness

The dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ is shown in Fig. 6 where the calculation parameter is the RL thickness h. When (a) T_w = 500 K, K_u/K_{bulk}, shown by the filled circles, is increased by changing h from 8 nm to 6 nm as previously reported[4]. On the other hand, when (b) T_w = 700 K, the K_u/K_{bulk} values are almost the same for the h = 6 to 10 nm calculation range since the limiting factors become conditions (2) and (3) $\Delta T/\Delta x(y) \le \partial T/\partial x(y)$ for h = 6 nm, and $\partial T/\partial x(y)$ is reduced by increasing h due to the adiabatic effect of RL. Therefore, when T_w is high, a relatively thin RL thickness is allowable.

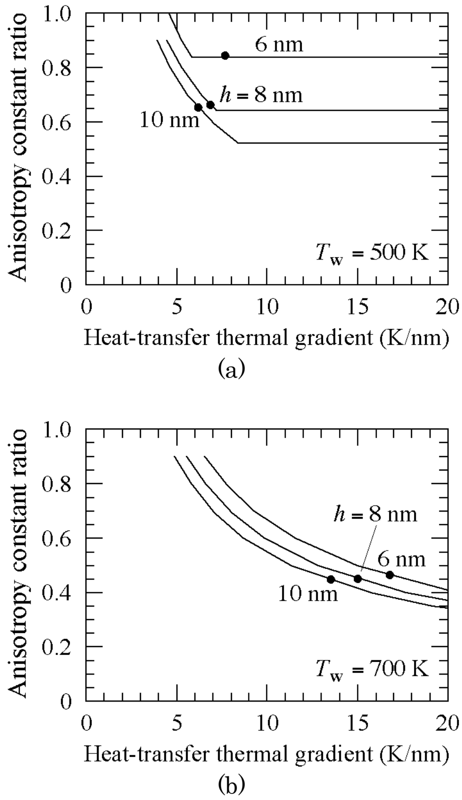

Fig. 6 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) T_w = 500 K[4] and (b) 700 K for various RL thicknesses h.

3.3 Standard deviation of grain size

The calculation results for the standard deviation of the grain size σ_D are shown in Fig. 7.

As σ_D increases, K_u / K_{bulk}, shown by the filled circle, is greatly increased when (a) T_w = 500 K[4]. On the other hand, when (b) T_w = 700 K, the increase in K_u / K_{bulk} caused by increasing σ_D is not great.

The limiting factor is largely (1) $K_{um}(T_a)V_m / kT_a \geq TSF_{10}$ when (a) T_w = 500 K. Figure 8 shows the dependence of the statistical thermal stability factor TSF_{10} on σ_D during τ = 10 years of archiving. As σ_D increases, the number of small size grains increases, and the probability of magnetization reversal for these small size grains is high over long periods, *e.g.* τ = 10 years. Therefore, K_{um} and K_u / K_{bulk} must be increased to maintain a low bit error rate when σ_D is large.

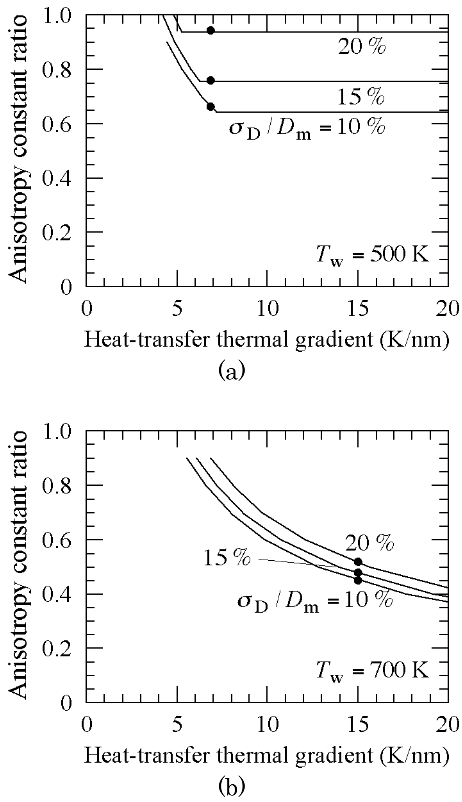

Fig. 7 Dependence of K_u / K_{bulk} on $\partial T / \partial x(y)$ at (a) T_w = 500 K[4] and (b) 700 K for various standard deviations of grain size σ_D / D_m.

On the other hand, the limiting factor is (2), (3) $\Delta T / \Delta x(y) \leq \partial T / \partial x(y)$ when (b) T_w = 700 K. ΔT of $\Delta T / \Delta x$ is determined by the statistical thermal stability factor $TSF_{rec} = TSF(0.65 \text{ ns}, n, \sigma_D, \sigma_K)$ for the writing period of 0.65 ns[3]. Figure 8 also shows the dependence of TSF_{rec} on σ_D. The TSF_{rec} increase rate is smaller than that of TSF_{10} since the probability of magnetization reversal is low even for a small size grain during a short period, *e.g.* 0.65 ns. Therefore, a large σ_D is allowable during the writing process. After writing, the medium is cooled to T_a, and then K_{um} becomes sufficiently large to hold information for 10 years even when the grain size is small.

Figure 9 shows the temperature dependence of K_{um} for T_w = 500 K and 700 K. K_u / K_{bulk} is 0.45 for both cases. $K_u(T_a)$ for T_w = 700 K is sufficiently larger than that for $K_{um}(T_a)V_m / kT_a = TSF_{10}$ since the temperature difference between T_a and T_w is sufficiently large. On the other hand, $K_u(T_a)$ for T_w = 500 K is insufficient for $K_{um}(T_a)V_m / kT_a = TSF_{10}$.

With conventional magnetic recording, microwave-assisted magnetic recording, and bit-patterned media, the limiting factor is $K_{um}(T_a)V_m / kT_a \geq TSF_{10}$, and σ_D must be restricted to a small value. With HAMR, a relatively large σ_D is allowable when T_w is high. This is the advantage of HAMR, which utilizes the change of temperature.

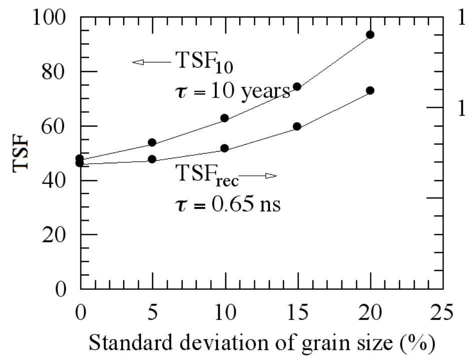

Fig. 8 Dependence of statistical thermal stability factor TSF on standard deviation of grain size σ_D / D_m for a period τ = 10 years and 0.65 ns.

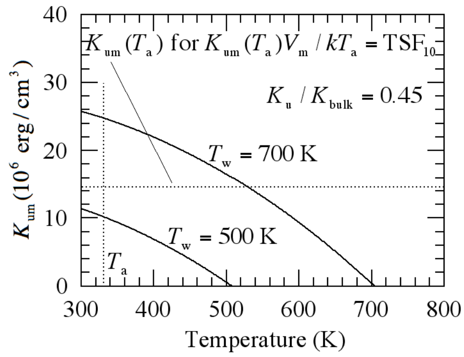

Fig. 9 Temperature dependence of K_{um} for T_w = 500 K and 700 K.

3.4 Standard deviation of anisotropy

A normal distribution was used for the K_u distribution. The calculation results for the standard deviation of the anisotropy σ_K are shown in Fig. 10. A comparison of σ_D in Fig. 7 (a) and σ_K in Fig. 10 (a) reveals that the dependence of K_u / K_{bulk} on σ_K is smaller than that on σ_D. This difference can be explained by the formula of the grain-error probability,

$$1 - \exp\left(-f_0 \tau \exp\left(-TSF \cdot \frac{D^2}{D_m{}^2} \cdot \frac{K_u}{K_{um}}\right)\right), \quad (6)$$

where $f_0 = 10^{11}$ s^{-1} is an attempt frequency. In the parenthesis in the formula, the variables of grain size and anisotropy are D^2 and K_u, respectively. Therefore, the dependence of K_u / K_{bulk} on σ_K is small.

As σ_K increases, K_u / K_{bulk}, shown by the filled circle in Fig. 10, is greatly increased when (a) T_w = 500 K. On the other hand, when (b) T_w = 700 K, there is little increase in K_u / K_{bulk} when σ_K is increased. The reason is the same as with the grain size distribution. Therefore, a relatively large σ_K is allowable when T_w is high, and this is also an advantage of HAMR.

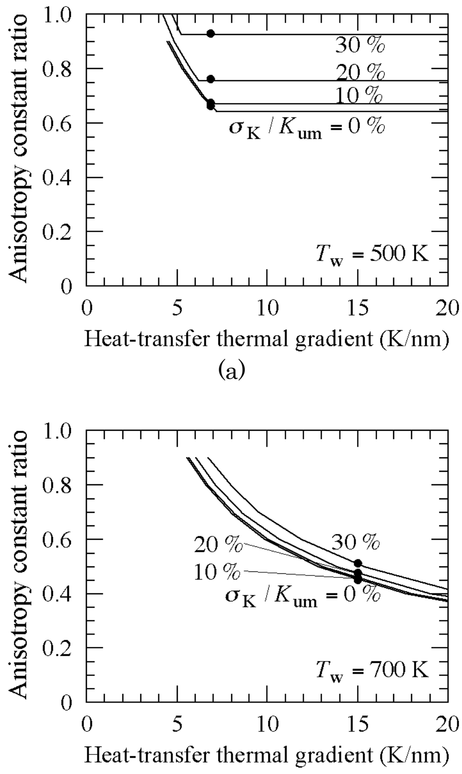

Fig. 10 Dependence of K_u / K_{bulk} on $\partial T / \partial x(y)$ at (a) T_w = 500 K and (b) 700 K for various standard deviations of anisotropy σ_K / K_{um}.

3.5 Standard deviation of Curie temperature

Next, we discuss the T_c distribution. A normal distribution was used for the standard deviations of the writing temperature σ_{Tw} and the Curie temperature σ_{Tc}. We assumed n = 1. Figure 11 shows how σ_{Tw} is calculated. The temperature at the center of the bit pitch d_B is T_w, and the temperature at the edge is $T_w \pm \Delta T_w$. Then ΔT_w is expressed as

$$\Delta T_w = \frac{\partial T}{\partial x} \cdot \frac{d_B}{2}. \tag{7}$$

If $\Delta T_w = 3.29\sigma_{Tw}$, the bit error rate of the write error becomes 10^{-3}, that is,

$$\int_{-3.29\sigma}^{3.29\sigma} f(x)dx = 1 - 10^{-3}, \tag{8}$$

where $f(x)$ is a normal distribution. Therefore, σ_{Tw} is expressed as

$$\sigma_{Tw} = \frac{1}{3.29} \cdot \frac{\partial T}{\partial x} \cdot \frac{d_B}{2}. \tag{9}$$

$\sigma_{Tw} \approx \sigma_{Tc}$ is assumed, and the calculation results are summarized in Table 3. As T_w increases, $\partial T / \partial x$ increases, and then, σ_{Tc} increases. σ_{Tc} / T_c also increases despite the increase in T_c. Therefore, when T_w is high, a relatively large σ_{Tc} / T_c is allowable.

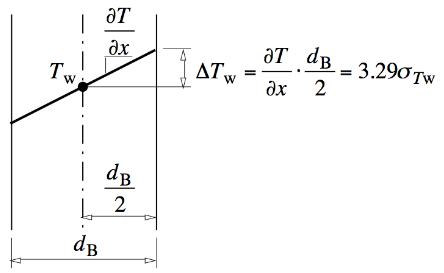

Fig. 11 Standard deviation of writing temperature σ_{Tw} for a bit error rate of 10^{-3}.

Table 3 Dependence of standard deviation of Curie temperature σ_{Tc} / T_c on writing temperature T_w.

T_w (K)	500	600	700
n (grain / bit)	1	1	1
$\partial T / \partial x$ (K / nm)	6.92	11.0	15.1
d_B (nm)	6.57	6.81	6.95
σ_{Tw} (K)	6.91	11.4	15.9
$\sigma_{Tc} \approx \sigma_{Tw}$ (K)	6.91	11.4	15.9
T_c (K)	508	606	704
σ_{Tc} / T_c (%)	1.4	1.9	2.3

3.6 Temperature dependence of anisotropy field

The temperature dependence of the magnetic properties is important in HAMR[6]. Figure 12 (a) shows the temperature dependence of the normalized anisotropy field H_k / H_k(300 K) for a low T_c = 580 K. The solid line was calculated using a mean field theory. The filled circles are experimental data for Fe-Ni-Pt reported by Thiele *et al.*[7]. The values of the experimental data are somewhat lower than those predicted by the theory. We think that this experimental behavior is a disadvantage of HAMR in terms of the writing field range for a good signal-to-noise ratio[6]. In contrast, the experimental data are well fitted to the calculation line for a high T_c = 770 K as shown in Fig. 12 (b). Since T_w must be increased to increase T_c, increasing T_w also has an advantage in terms of the temperature dependence of the anisotropy field.

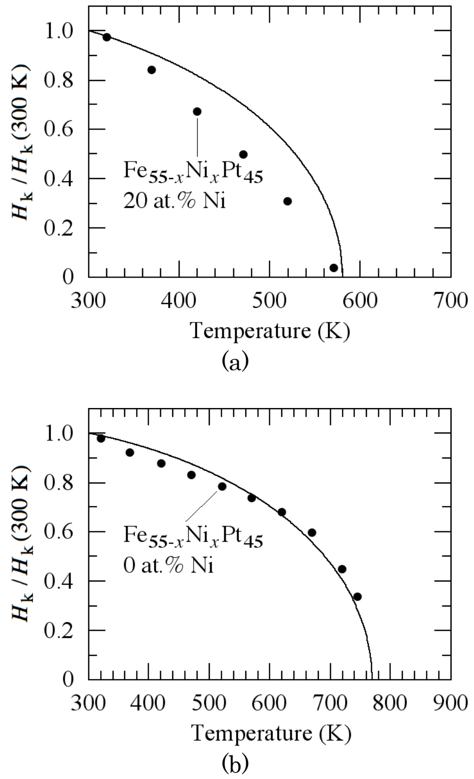

Fig. 12 Temperature dependence of normalized anisotropy field H_k / H_k(300 K) for (a) Curie temperature T_c = 580 K and (b) 770 K (filled circles: Fe-Ni-Pt data[7]).

4. Conclusions

We summarized the advantages of increasing the writing temperature T_w in heat-assisted magnetic recording (HAMR).

(1) Since $K_{um}(T_a)$ and $\partial T / \partial x(y)$ are increased, the anisotropy constant ratio K_u / K_{bulk} can be decreased where $K_{um}(T_a)$ is the mean anisotropy constant at the maximum working temperature T_a of the hard drive, and $\partial T / \partial x(y)$ is the heat-transfer thermal gradient calculated by a heat-transfer simulation.

(2) The K_u / K_{bulk} values are almost the same for the calculation range from the recording-layer (RL) thickness h = 6 nm to 10 nm since $\partial T / \partial x(y)$ is reduced by increasing h due to the adiabatic effect of RL. Therefore, a relatively thin RL thickness is allowable.

(3) A relatively large standard deviation of grain size σ_D is allowable since the probability of magnetization reversal is low even for small size grains during the writing period.

(4) A relatively large standard deviation of anisotropy σ_K is allowable.

(5) A relatively large standard deviation of Curie temperature σ_{Tc} is allowable since $\partial T / \partial x(y)$ is increased. σ_{Tc} / T_c also increases despite the increase in the Curie temperature T_c.

(6) For Fe-Ni-Pt films, the temperature dependence of the anisotropy field is suitable for HAMR when T_w is high.

All the above-mentioned factors are advantageous when preparing HAMR media.

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