

Design Parameter and Anisotropy Constant Ratio for Heat-Assisted Magnetic Recording

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A design guideline for heat-assisted magnetic recording (HAMR) is presented with a view to obtaining a minimized anisotropy constant ratio K_u / K_{bulk} for media by using a model calculation. We investigated the relationship between the design parameters and the limiting factors of HAMR design. The parameters, namely the writing temperature T_w and recording layer thickness h , are related to the medium thermal stability factor of the limiting factor. In addition, inter-grain exchange coupling J is related to the statistical thermal stability factor. HAMR combined with shingled magnetic recording (SHAMR) has the advantage of reducing the medium thermal gradient, and increasing T_w is also effective in increasing the heat-transfer thermal gradient of the limiting factor. The combination of increasing h and SHAMR or increasing J and SHAMR can successfully reduce K_u / K_{bulk} . Furthermore, K_u / K_{bulk} can be reduced by the combination of increasing T_w and SHAMR.

Key words: heat-assisted magnetic recording, media design, anisotropy constant ratio, thermal stability factor, thermal gradient

1. Introduction

Heat-assisted magnetic recording (HAMR) has been proposed with the aim of solving the trilemma problem¹⁾ of magnetic recording. HAMR is a recording method in which the medium is heated to reduce the coercivity at the time of writing.

We have already reported the design method for HAMR^{2, 3)}. We have 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 ²⁾. If the K_u / K_{bulk} values for two media are identical, the difficulties involved in preparing those media are the same, even if the K_u values are different. On the other hand, increasing K_u / K_{bulk} is a challenging task. Therefore, it is necessary to design a medium with a smaller K_u / K_{bulk} . The many relationships between design parameters and K_u / K_{bulk} have been revealed³⁾. We have reported the dependence of K_u / K_{bulk} on one parameter change. As a result, we find that increasing the writing temperature T_w is only effective for reducing K_u / K_{bulk} when we compare the K_u / K_{bulk} value calculated using standard parameter values. Although the combination of more than two parameters may be expected to reduce K_u / K_{bulk} , it is difficult to examine all parameter combinations. Our method is a model calculation, and it is easy to understand the physical meanings of the parameters.

In this study, we investigate the relationship between the design parameters and limiting factors of HAMR design with the aim of reducing K_u / K_{bulk} , and we provide the examination results of K_u / K_{bulk} for the combination of more than two parameters.

2. Media Design Method

From the following four conditions, we estimated

whether or not the media have the potential for HAMR. That is, information stability (1) during 10 years of archiving, (2) on the trailing side located 1 bit from the writing position during writing, (3) in adjacent tracks during rewriting, and (4) under the main pole during rewriting^{2, 3)}.

(1) The first condition, namely the information stability during 10 years of archiving, is expressed as

$$\frac{K_u(T_a)V_m}{kT_a} \geq \text{TSF}_{10}, \quad (1)$$

where $K_u(T_a)V_m / kT_a$ is a medium thermal stability factor, T_a is the ambient temperature (assumed to be 330 K), which is the maximum working temperature of the hard drive, V_m is the grain volume for the mean grain size, k is the Boltzmann constant, and TSF_{10} is the statistical thermal stability factor during 10 years of archiving.

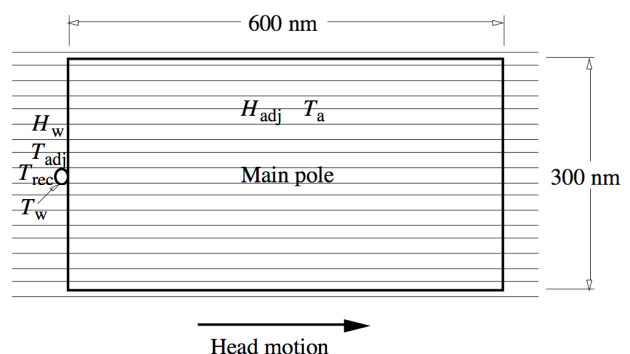


Fig. 1 Schematic illustration of writing-head configuration.

Figure 1 shows the writing-head configuration. It is assumed that the main-pole size of the head is 600 nm (down-track direction) \times 300 nm (cross-track

direction), and the writing position is located on the trailing side of the main pole. The maximum temperature under the main pole is T_a .

(2) The second condition, namely the information stability on the trailing side during writing, is expressed as

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

where $\Delta T / \Delta x$ is the medium thermal gradient for the down-track direction, T_w is the writing temperature, and T_{rec} is the maximum temperature at which the information on the trailing side can be held during writing as shown in Fig. 1. Δx is the distance from the position of T_w to that of T_{rec} , and $\partial T / \partial x$ is the heat-transfer thermal gradient for the down-track direction.

(3) The third condition, namely the information stability in adjacent tracks during rewriting, is expressed as

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

where $\Delta T / \Delta y$ is the medium thermal gradient for the cross-track direction, and T_{adj} is the maximum temperature at which the information in adjacent tracks can be held during rewriting as shown in Fig. 1. Δy is the distance from the position of T_w to that of T_{adj} , and $\partial T / \partial y$ is the heat-transfer 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. $\partial T / \partial x$ and $\partial T / \partial y$ are the thermal gradients calculated by a heat-transfer simulation³⁾.

(4) The fourth condition, namely the information stability under the main pole during rewriting, is expressed as

$$H_{\text{adj}} \geq H_w, \quad (4)$$

where H_{adj} is the maximum head field that can hold the information under the main pole, and H_w is the writing field at the position of T_w as shown in Fig. 1.

The details have been reported elsewhere³⁾.

The HAMR media were designed to obtain the minimum K_u / K_{bulk} value using the procedure shown in Fig. 2³⁾. First, the design parameters and $K_u / K_{\text{bulk}} = 1$ were set. Four HAMR conditions (1), (2), (3), and (4) were examined after determining the composition of the recording layer. If there are some 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.

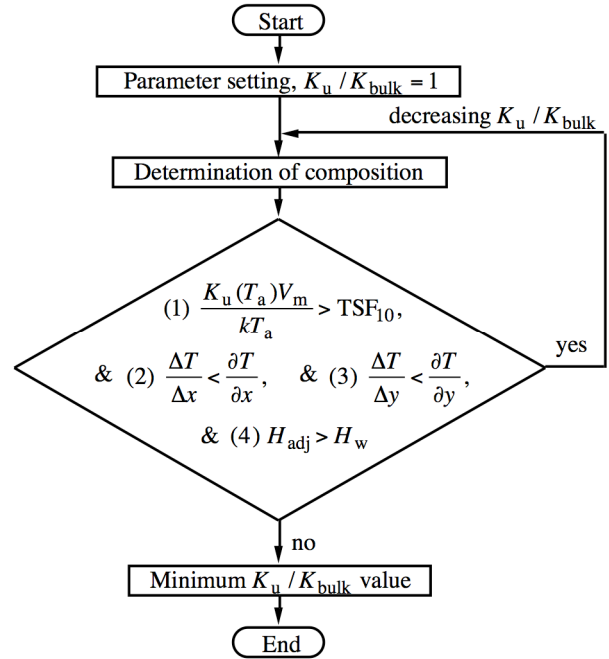


Fig. 2 HAMR media design procedure for obtaining the minimum K_u / K_{bulk} value³⁾.

The medium was assumed to be granular. The standard parameter values of the media design are summarized in Table 1. The bit area S is fixed, and S is the product $d_B \times d_T$ 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 paper²⁾. The arrangement of the grains is not considered. The effective track width d_{ET} has been explained in a previous paper³⁾. The standard medium consists of four layers, that is, a recording layer RL (Fe-Pt base, thickness $h = 8$ nm), interlayer 1 IL1 (MgO base, 5 nm), interlayer 2 IL2 (Cr base, 10 nm), and a heat-sink layer HSL (Cu base, 30 nm). D_m is the mean grain size, and $V_m = D_m^2 \times h$. The inter-grain exchange coupling $J^4)$ is a newly introduced design parameter. A comparison of magnetic recording (MR) method was carried out of HAMR and HAMR combined with shingled magnetic recording (SHAMR). The light-spot diameter d_L and the heat-spot diameter d_w have also been defined in previous papers^{2, 3)}.

Figure 3 (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. The transition region spreads to adjacent tracks as a result of rewriting operations on the i th track.

On the other hand, the maximum rewriting number for SHAMR is considerably smaller than that for HAMR since the tracks are laid to overlap each other as shown in Fig. 3 (b).

Table 1 Standard parameter values of 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
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

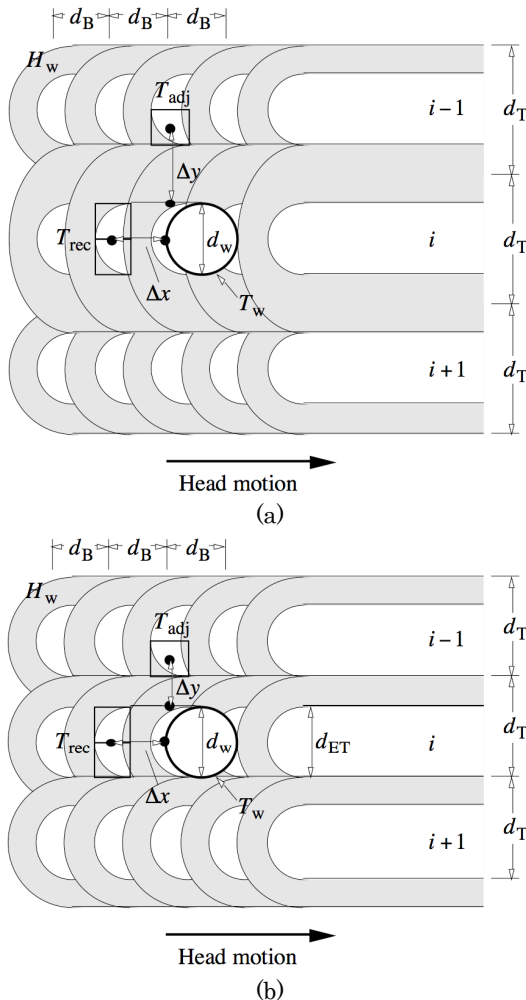


Fig. 3 Schematic illustrations of writing position for (a) HAMR and (b) SHAMR.

3. Design Parameters and Limiting Factors

We have reported the dependence of K_u/K_{bulk} on one parameter change³. As a result, increasing T_w is only effective for reducing K_u/K_{bulk} when we compare

the K_u/K_{bulk} value calculated using standard parameter values. Increasing J from 0 to 0.19 erg/cm² has little effect. Although the combination of more than two parameters may be expected to reduce K_u/K_{bulk} , it is difficult to examine all parameter combinations. Therefore, we investigated the relationship between the parameters and the limiting factors. Conditions (2) and (3) can be combined as

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

since $\partial T/\partial x \approx \partial T/\partial y$ ². Condition (4) has some margins for all the cases we examined. Therefore, the major limiting factors in the media design are condition (I) given by Eq. (1) ($K_u(T_a)V_m/kT_a \geq \text{TSF}_{10}$) and condition (II) 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 $\Delta T/\Delta x(y) \leq \partial T/\partial x(y)$).

3.1 Condition (I) - increasing $K_u(T_a)V_m/kT_a$

$K_u(T_a)V_m/kT_a$ must be increased or TSF_{10} decreased to relax condition (I) given by Eq. (1) $K_u(T_a)V_m/kT_a \geq \text{TSF}_{10}$. First, we discuss the parameter for increasing $K_u(T_a)$.

Figure 4 (a) shows the dependence of $K_u(300\text{ K})$ on Curie temperature T_c , in which the calculation parameter is K_u/K_{bulk} . The dotted line shows the $K_u(300\text{ K})$ value that satisfies $K_u(T_a)V_m/kT_a = \text{TSF}_{10}$. Although the $K_u(T_a)$ value that satisfies $K_u(T_a)V_m/kT_a = \text{TSF}_{10}$ is independent of T_c , the $K_u(300\text{ K})$ value that satisfies $K_u(T_a)V_m/kT_a = \text{TSF}_{10}$ increases as T_c decreases, and it diverges at $T_a = 330\text{ K}$. The intersections of the solid lines and the dotted line show the K_u/K_{bulk} dependence that satisfies $K_u(T_a)V_m/kT_a = \text{TSF}_{10}$ on T_c . Therefore, the required K_u/K_{bulk} can be reduced by increasing T_c , and then, K_u/K_{bulk} can be reduced by increasing T_w as shown in Fig. 4 (b). In other words, if K_u/K_{bulk} is constant, increasing T_w is effective for increasing $K_u(T_a)$. If T_w is low, the extra K_u/K_{bulk} is needed to realize HAMR.

Furthermore, K_u/K_{bulk} is a function of the heat-transfer thermal gradient $\partial T/\partial x(y)$ as shown in Fig. 4 (c). 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 factor is condition (II) $\Delta T/\Delta x(y) \leq \partial T/\partial x(y)$. And it is condition (I) $K_u(T_a)V_m/kT_a \geq \text{TSF}_{10}$ in the range where K_u/K_{bulk} is constant. The constant K_u/K_{bulk} value in Fig. 4 (c) corresponds to that in Fig. 4 (b). Although increasing T_w is effective for reducing K_u/K_{bulk} (Fig. 4 (b)), a higher $\partial T/\partial x(y)$ is needed to obtain a lower K_u/K_{bulk} (Fig. 4 (c)). The closed circles show the K_u/K_{bulk} values and their $\partial T/\partial x(y)$ values calculated for the standard medium structure and the standard thermal constants². Increasing T_w is effective for reducing K_u/K_{bulk} in consideration of calculated $\partial T/\partial x(y)$.

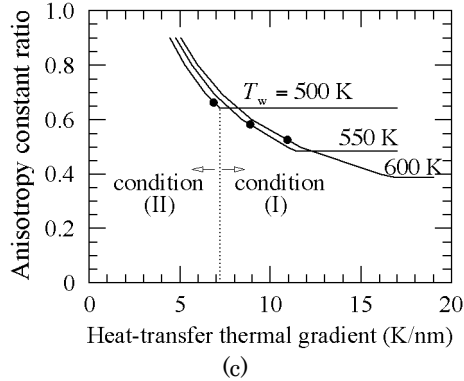
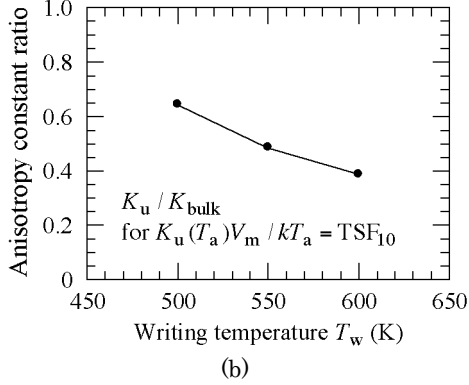
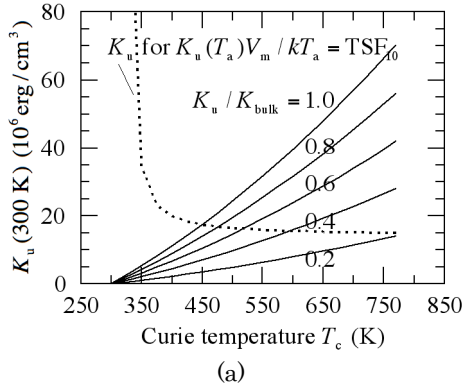


Fig. 4 (a) Dependence of anisotropy constant $K_u(300\text{ K})$ on Curie temperature T_c , (b) dependence of anisotropy constant ratio K_u/K_{bulk} on writing temperature T_w , and (c) dependence of K_u/K_{bulk} on heat-transfer thermal gradient $\partial T/\partial x(y)$.

Next, we discuss the parameter for increasing V_m .

One way of increasing $V_m = D_m^2 \times h$ is to reduce the grain number per bit n . Although TSF_{10} becomes larger as n becomes smaller⁴⁾, $D_m = \sqrt{S/n - \Delta}$ increases as n decreases where S is the bit area and $\Delta = 1\text{ nm}$ is the non-magnetic spacing between grains (e.g., $D_m = 4.92\text{ nm}$ for $n = 4$). The solid line, in the range where K_u/K_{bulk} is constant in Fig. 5, becomes noticeably low as n decreases. In that range, the limiting factor is condition (I) as mentioned above. Therefore, reducing n relaxes condition (I) through increasing V_m . Furthermore, the closed circles can also be reduced as n decreases. Therefore, reducing n is effective for reducing K_u/K_{bulk} . When we compare (a) $T_w = 500\text{ K}$ and (b) 550 K , the n dependence of the K_u/K_{bulk} values of the closed circles is reduced by

increasing T_w since the limiting factor becomes condition (II).

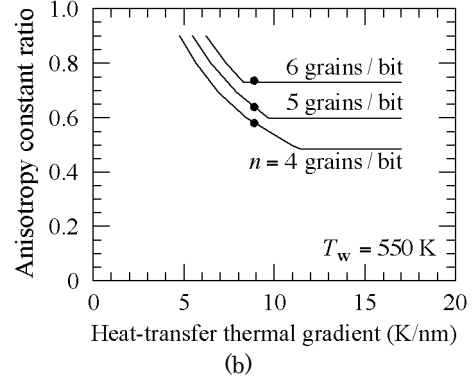
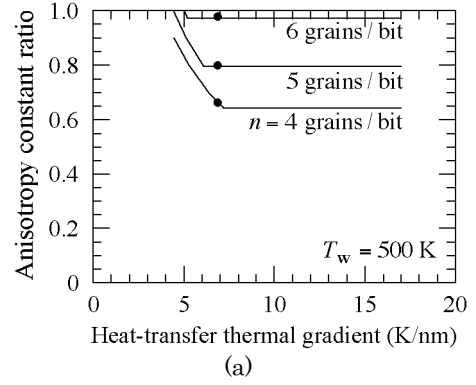


Fig. 5 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500\text{ K}$ and (b) 550 K (calculation parameter: grain number per bit n).

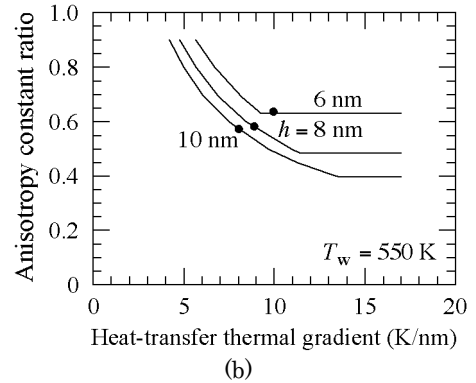
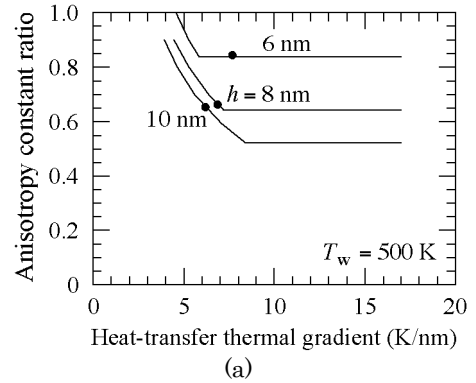


Fig. 6 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500\text{ K}$ and (b) 550 K (calculation parameter: RL thickness h).

Another way of increasing $V_m = D_m^2 \times h$ is to increase the RL thickness h . It can also be seen from the solid lines where K_u/K_{bulk} is constant in Fig. 6 that increasing h relaxes condition (I). However, when h increases from the standard value of 8 to 10 nm, the K_u/K_{bulk} values of the closed circles are almost the same for both (a) $T_w = 500$ K and (b) 550 K since the limiting factor is condition (II), and $\partial T/\partial x(y)$ is decreased by increasing h due to the adiabatic effect of RL². If $\Delta T/\Delta x(y)$ can be decreased or $\partial T/\partial x(y)$ can be increased in some way, increasing h will be effective for reducing K_u/K_{bulk} . The way of decreasing $\Delta T/\Delta x(y)$ will be discussed in 3.3, and the combination of the parameters will be discussed in 3.5.

3.2 Condition (I) - decreasing TSF_{10}

TSF_{10} must be decreased to relax condition (I) given by Eq. (1) $K_u(T_a)V_m/kT_a \geq \text{TSF}_{10}$.

One way of decreasing TSF_{10} is to reduce the standard deviation of the grain size σ_D/D_m ⁴. Decreasing σ_D/D_m relaxes condition (I) as seen from the solid lines in Fig. 7. Furthermore, the K_u/K_{bulk} values of the closed circles can be reduced by decreasing σ_D/D_m as shown in Fig. 7 (a). However, it seems that σ_D/D_m cannot be reduced from the standard value of 10 %.

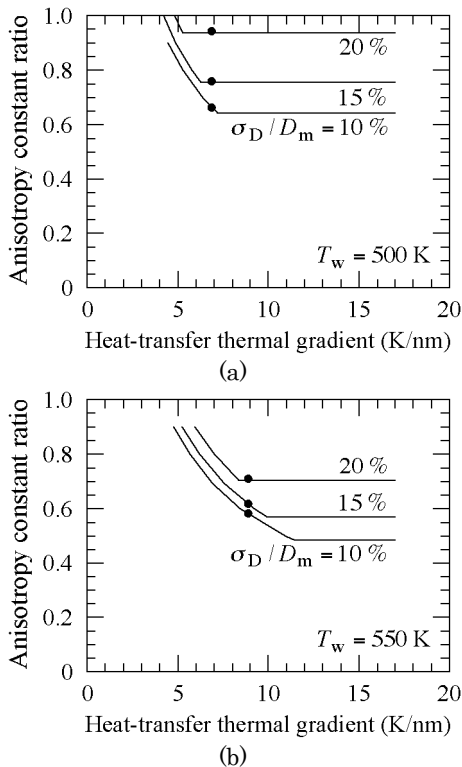


Fig. 7 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500$ K and (b) 550 K (calculation parameter: standard deviation of grain size σ_D/D_m).

In Fig. 7 (b), it should be noted that the difference between the K_u/K_{bulk} values of the closed circles ($\sigma_D/D_m = 10\%$ and 15 %) is very small. If T_w can be

increased, a relatively large σ_D/D_m value may be allowable.

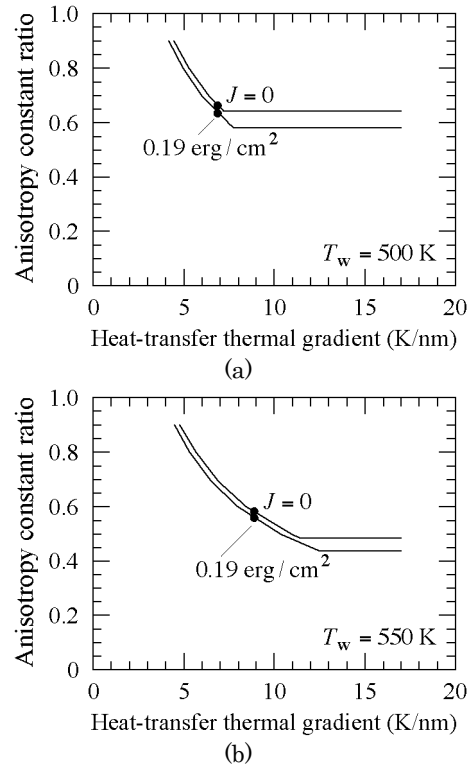


Fig. 8 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500$ K and (b) 550 K (calculation parameter: inter-grain exchange coupling J).

Although another way of decreasing TSF_{10} is to introduce inter-grain exchange coupling J ⁴ as seen from the solid lines in Fig. 8. $J = 0.19$ erg/cm² corresponds to an inter-grain exchange coupling e_m of 1.1⁴ for D_m . The inter-grain exchange coupling e makes the statistical thermal stability factor e times larger. It has little effect on reducing the K_u/K_{bulk} values of the closed circles since the limiting factor is condition (II). As seen from Fig. 8 (b), increasing T_w has little effect for the same reason. If $\Delta T/\Delta x(y)$ can be decreased or $\partial T/\partial x(y)$ can be increased in some way, introducing J will also be effective for reducing K_u/K_{bulk} . The combination of the parameters will be discussed in 3.5.

3.3 Condition (II) - decreasing $\Delta T/\Delta x(y)$

$\Delta T/\Delta x(y)$ must be decreased or $\partial T/\partial x(y)$ increased to relax condition (II) given by Eq. (5) $\Delta T/\Delta x(y) \leq \partial T/\partial x(y)$.

Introducing SHAMR is effective for decreasing $\Delta T/\Delta x(y)$ as seen from the solid lines where K_u/K_{bulk} changes in Fig. 9 (a). T_{adj} in Eq. (3) for SHAMR is higher than that for HAMR since the maximum rewriting number for SHAMR is considerably smaller than that for HAMR³. However, the K_u/K_{bulk} values of the closed circles are almost the same since the limiting factor is condition (I). If we

can find a way to increase $K_u(T_a)V_m/kT_a$ or decrease TSF_{10} , introducing SHAMR will be effective for reducing K_u/K_{bulk} . Figure 9 (b) shows the results for $T_w = 550$ K. Since the limiting factor can be changed to condition (II), introducing SHAMR becomes effective.

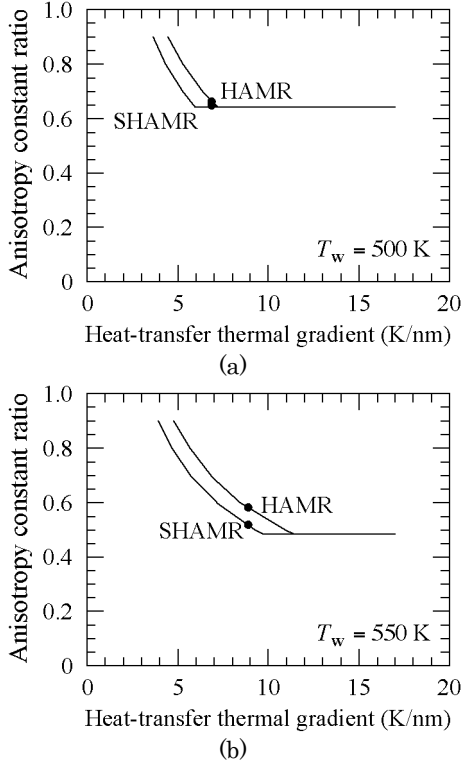


Fig. 9 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500$ K and (b) 550 K (calculation parameter: HAMR and SHAMR).

3.4 Condition (II) - increasing $\partial T/\partial x(y)$

Although increasing T_w is effective for increasing $\partial T/\partial x(y)$ as mentioned above in 3.1, $\partial T/\partial x(y)$ can be changed very little by changing the parameters, namely the light-spot diameter d_L , the heat-spot diameter d_w , and the linear velocity v ³⁾. If the thermal conductivity K of IL1 decreases from 0.5 W/(cmK), $\partial T/\partial x(y)$ becomes smaller as shown in a previous paper³⁾. One possibility for increasing $\partial T/\partial x(y)$ involves examining a media structure with a large $\partial T/\partial x(y)$.

3.5 Combination of parameters

The combination of one parameter that relaxes condition (I) and another that relaxes condition (II) may be useful for reducing K_u/K_{bulk} .

When we replaced parameter $h = 8$ nm with 10 nm, K_u/K_{bulk} changed from 0.66 to 0.65, and when only SHAMR was utilized, K_u/K_{bulk} became 0.64 at $T_w = 500$ K. Alone they had scarcely any effect on reducing K_u/K_{bulk} . Next, we combined $h = 10$ nm, which increases $K_u(T_a)V_m/kT_a$ of condition (I), and SHAMR, which decreases $\Delta T/\Delta x(y)$ of condition (II). Figure 10 (a) shows the result of the combination, and

the resultant K_u/K_{bulk} is 0.58. The case where $T_w = 550$ K is shown in Fig. 10 (b). When we compare HAMR and SHAMR, we find that SHAMR is more effective. This can be explained by Fig. 9 (b). On the other hand, when we compare a SHAMR of $h = 8$ nm and a SHAMR of $h = 10$ nm, the K_u/K_{bulk} values are almost the same since the limiting factor is condition (II) as seen in Fig. 6.

Therefore, the design parameters of HAMR, SHAMR, h , and T_w are related in a complex manner in terms of reducing K_u/K_{bulk} .

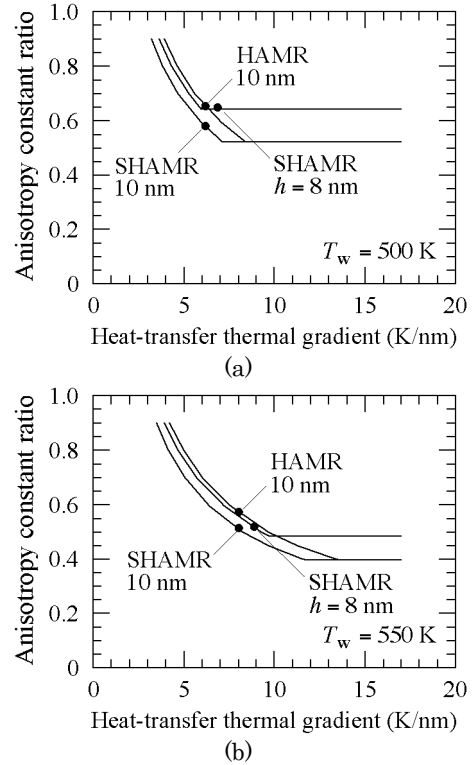


Fig. 10 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500$ K and (b) 550 K (calculation parameter: HAMR, SHAMR, and h).

Next, we consider the relationship between HAMR, SHAMR, J , and T_w .

We combined $J = 0.19$ erg/cm², which decreases TSF_{10} of condition (I), and SHAMR, which decreases $\Delta T/\Delta x(y)$ of condition (II). Figure 11 (a) shows the result of the combination, and the resultant K_u/K_{bulk} is 0.58. The case of $T_w = 550$ K is shown in Fig. 11 (b). When we compare a SHAMR of $J = 0$ and a SHAMR of $J = 0.19$ erg/cm², the K_u/K_{bulk} values are almost the same since the limiting factor is condition (II).

The results are summarized in Fig. 12. The standard K_u/K_{bulk} value (calculated using the standard parameter values) is 0.66. The parameters T_w , h , and J relax condition (I) $K_u(T_a)V_m/kT_a \geq \text{TSF}_{10}$, and the K_u/K_{bulk} values become 0.58, 0.65, and 0.63, respectively, by changing the parameters. And the parameters HAMR or SHAMR and T_w relax condition (II) $\Delta T/\Delta x(y) \leq \partial T/\partial x(y)$, and the K_u/K_{bulk}

values become to be 0.64 and 0.58, respectively.

If $h = 10$ nm and SHAMR or $J = 0.19$ erg/cm² and SHAMR are combined, $K_u/K_{\text{bulk}} = 0.58$ can be achieved without increasing T_w . A lower T_w is better from the viewpoint of the heat resistance of the writing head and/or the surface lubricant.

If T_w can be increased to 550 K, we can expect a K_u/K_{bulk} value of 0.51 by combination with SHAMR.

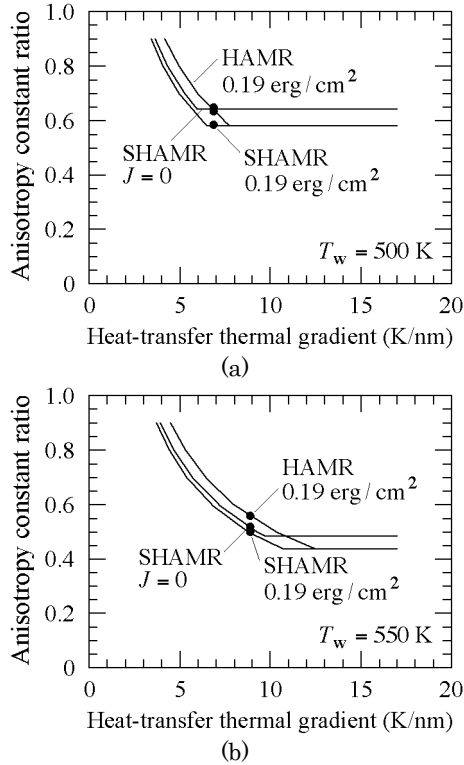


Fig. 11 Dependence of K_u/K_{bulk} on $\partial T/\partial x(y)$ at (a) $T_w = 500$ K and (b) 550 K (calculation parameter: HAMR, SHAMR, and J).

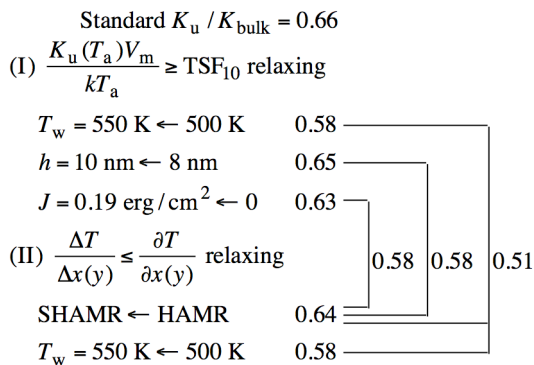


Fig. 12 Media design guideline.

4. Conclusions

The major limiting factors as regards obtaining the minimum anisotropy constant ratio K_u/K_{bulk} for media are (I) the information stability during 10 years of archiving and (II) the information stability on the trailing side during writing and in adjacent tracks during rewriting.

The parameters, namely the writing temperature T_w , the recording layer thickness h , and the inter-grain exchange coupling J , relax condition (I). On the other hand, HAMR combined with shingled magnetic recording (SHAMR) and T_w relax condition (II).

The combination of one parameter that relaxes condition (I) and another that relaxes condition (II) is useful for reducing K_u/K_{bulk} . If increasing h and SHAMR or increasing J and SHAMR are combined, K_u/K_{bulk} can be reduced successfully without increasing T_w . If T_w can be increased, K_u/K_{bulk} will be reduced by the combination with SHAMR.

It is important for the media design to distinguish whether the limiting factor is condition (I) or (II).

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