### Anisotropy Constant Ratio Required for Heat-Assisted Magnetic Recording

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Media for heat-assisted magnetic recording (HAMR) are designed with a minimized anisotropy constant ratio $K_u / K_{bulk}$ by using a model calculation. The design method is improved from the previous rough estimation approach to a statistical estimation of the thermal stability factor of media during writing and rewriting. A comparison is made between HAMR and HAMR combined with shingled magnetic recording. The many relationships between the design parameters and $K_u / K_{bulk}$ are revealed. The parameters are the thickness of the recording layer, the thermal conductivity of interlayer 1, the light-spot diameter, the heat-spot diameter, the linear velocity, the writing temperature, the grain number per bit, and the standard deviation of the grain size. In certain cases, the limiting factor for obtaining the minimum $K_u / K_{bulk}$ value is information stability during 10 years of archiving, which relates to improving media preparation to increase $K_u / K_{bulk}$. In other cases, the limiting factor is the information stability on the trailing side located 1 bit from the writing position during writing and in the adjacent tracks during rewriting, which relates to examining the media structure to increase the heat-transfer thermal gradients.

**Key words**: heat-assisted magnetic recording, thermal stability factor, thermal gradient, anisotropy constant

### 1. Introduction

Various magnetic recording (MR) methods have been proposed with the aim of solving the trilemma problem\(^1\) of magnetic recording. The methods include shingled magnetic recording (SMR), heat-assisted magnetic recording (HAMR), microwave-assisted magnetic recording (MAMR), and the use of bit patterned media (BPM). HAMR is a recording method for Heat-Assisted Magnetic Recording (HAMR) that is expressed as

\[
K_{fs}(T, H) = \frac{K_u(T)V}{kT} \left( 1 \pm \frac{H}{H_c(T)} \right)^2,
\]

where $T$ is the temperature, $H$ is the magnetic field, $K_u(T)$ is the anisotropy constant of the media, $V = D^2 \times h$ ($D$: grain size, $h$: thickness) is the grain volume, $k$ is the Boltzmann constant, $D$ is the mean grain size, the recording layer thickness, and the writing temperature were clarified.

In this study, we improve our design method from the previous rough estimation approach to a statistical estimation of the thermal stability factor of media during writing and rewriting, and the many relationships between the media design parameters and $K_u / K_{bulk}$ are also revealed.

### 2. Media Design Method

#### 2.1 Important design variables

First, some important design variables are explained, namely two thermal stability factors and two thermal gradients.

One of the thermal stability factors is a medium thermal stability factor $K_{fs}(T, H)$ that is expressed as

\[
K_{fs}(T, H) = \frac{K_u(T)V}{kT} \left( 1 \pm \frac{H}{H_c(T)} \right)^2.
\]

where $T$ is the temperature, $H$ is the magnetic field, $K_u(T)$ is the anisotropy constant of the media, $V = D^2 \times h$ ($D$: grain size, $h$: thickness) is the grain volume, $k$ is the Boltzmann constant, $D$ is the mean grain size, the recording layer thickness, and the writing temperature were clarified.

In this study, we improve our design method from the previous rough estimation approach to a statistical estimation of the thermal stability factor of media during writing and rewriting, and the many relationships between the media design parameters and $K_u / K_{bulk}$ are also revealed.

Next, one of the two thermal gradients is a medium thermal gradient, in which $\Delta T / \Delta x$ is the medium thermal gradient for the down-track direction, and...
\( \Delta T / \Delta y \) is that 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 on the trailing side located 1 bit from the writing position during writing and in the adjacent tracks during rewriting, respectively.

The other is a heat-transfer thermal gradient \( \partial T / \partial x \) for the down-track direction, and \( \partial T / \partial y \) for the cross-track direction. \( \partial T / \partial x \) and \( \partial T / \partial y \) are calculated by a heat transfer simulation.

The medium and heat-transfer thermal gradients have been reported in detail elsewhere\(^2\).

Finally, an anisotropy constant ratio is explained. Both \( K_u \) and Curie temperature \( T_c \) should be designated for the HAMR media design. \( K_u \) at room temperature is a function of \( T_c \). The \( K_u \) value of Fe-Pt film is generally smaller than that of bulk Fe-Pt\(^3\). Therefore, we have introduced a new parameter, the anisotropy constant ratio \( K_u / K_{\text{bulk}} \), which shows the intrinsic ratio of film \( K_u \) to bulk \( K_{\text{bulk}} \). If the \( K_u / K_{\text{bulk}} \) values for the media are identical, the difficulties involved in media preparation are the same, even if the \( K_u \) values are different since \( K_u \) can be changed only by changing the composition. On the other hand, increasing \( K_u / K_{\text{bulk}} \) is challenging. Therefore, it is necessary to design a medium with a smaller \( K_u / K_{\text{bulk}} \).

2.2 Media design procedure

The HAMR media were designed to obtain the minimum \( K_u / K_{\text{bulk}} \) value using the procedure shown in Fig. 1.

Four HAMR conditions (1), (2), (3), and (4) are examined after determining the composition of the recording layer at a given writing temperature \( T_w \) and under the initial condition of \( K_u / K_{\text{bulk}} = 1 \). If there are some margins for all four conditions, \( K_u / K_{\text{bulk}} \) can be decreased. When one of the four conditions reaches the limit, the minimum \( K_u / K_{\text{bulk}} \) value can be determined. That condition becomes a limiting factor.

In our previous paper\(^2\), we used the equation

\[
\tau_w = \frac{\exp(K_{\mu}(T_w, H_w))}{\exp(\text{TSF}(10 \text{ years}, n, \sigma_D))},
\]

then,

\[
K_{\mu}(T_w, H_w) = \text{TSF}(10 \text{ years}, n, \sigma_D) \cdot \ln \left( \frac{10 \text{ years}}{\tau_w} \right)
\]

\[
= \text{TSF}_{10} \cdot \ln \left( \frac{10 \text{ years}}{\tau_w} \right)
\]

to determine the composition, where \( \tau_w \) is the writing time, and \( H_w \) is the writing field. However, this equation using TSF\(_{10}\) 10 years and \( \tau_w \) is too rough to estimate the medium thermal stability factor \( K_{\mu}(T_w, H_w) \) during writing. This estimation is valid for \( \sigma_D = 0 \), and invalid for \( \sigma_D \neq 0 \). Hereafter, we use the new equation

\[
K_{\mu}(T_w, H_w) = \text{TSF}(\tau_w, n, \sigma_D)
\]

using TSF(\( \tau_w \), \( n \), \( \sigma_D \)) calculated statistically to determine the composition instead of Eq. (3).

The four HAMR conditions are information stability (1) during 10 years of archiving, (2) on the trailing side located 1 bit from the writing position during writing, (3) in the adjacent tracks during rewriting, and (4) under the main pole during rewriting.

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

\[
K_{\mu}(T = T_a, H = 0) = \frac{K_u(T_a)V_m}{kT_a} \geq \text{TSF}_{10},
\]

where \( T_a = 330 \text{ K} \) is an ambient temperature that is the maximum working temperature of the hard drive, and \( V_m = D_m \times h \) is the grain volume for the mean grain size.

(2) The second condition, namely the information stability on the trailing side during writing, determines \( \Delta T / \Delta x \). Therefore,

\[
\frac{\Delta T}{\Delta x} = \frac{T_w - T_{\text{rec}}}{\Delta x} \leq \frac{\partial T}{\partial x}
\]

is necessary, where \( T_{\text{rec}} \) is the maximum temperature at which the information on the trailing side can be held during writing. \( T_{\text{rec}} \) can be calculated by

\[
K_{\mu}(T_{\text{rec}}, H_w) = \text{TSF}(\tau_w, n, \sigma_D).
\]

The distance \( \Delta x \) from the position of \( T_w \) to that of \( T_{\text{rec}} \) is defined as described in 3.2.

(3) The third condition, namely the information stability in the adjacent tracks during rewriting, determines \( \Delta T / \Delta y \), and then,
\[
\frac{\Delta T}{\Delta y} = \frac{T_w - T_{adj}}{\Delta y} = \frac{\partial T}{\partial y} \tag{8}
\]
is necessary, where \(T_{adj}\) is the maximum temperature at which the information in the adjacent tracks can be held during rewriting. \(T_{adj}\) can be calculated by

\[
K_{fu}(T_{adj}, H_{w}) = TSF(T_w \times N_{rew}, n, \sigma_D) \tag{9}
\]
where \(N_{rew}\) is the maximum number of rewriting operations. The distance \(\Delta y\) from the position of \(T_w\) to that of \(T_{adj}\) is defined as described in 3.2.

![Schematic illustration of writing head configuration.](image)

**Fig. 2** Schematic illustration of writing head configuration.

(4) The fourth condition, namely the information stability under the main pole during rewriting, determines the maximum head field \(H_{adj}\) that can hold the information. Figure 2 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 \(T_k\). \(H_{adj}\) should be higher than \(H_w\),

\[
H_{adj} \geq H_w, \tag{10}
\]
due to the geometrical restriction of the head field since \(H_w\) is the leakage field from the main pole. \(H_{adj}\) can be calculated by

\[
K_{fu}(T_k, H_{adj}) = TSF(T' \times N_{rew} \times N_T, n, \sigma_D) = TSF',
\]

\[
K_u(T_k)V_m \left(1 - \frac{H_{adj}}{H_{u}(T_k)}\right)^2 = TSF', \quad \text{and then},
\]

\[
H_{adj} = H_u(T_k) \left(1 - \frac{TSF'}{K_u(T_k)V_m/kT_u}\right)^{-1}, \tag{11}
\]
where \(T'\) is the transit time of the main pole, and \(N_T\) is the track number under the main pole. And \(H_w\) is determined by

\[
H_w = 16 \text{ kOe} \times \frac{M_s(300 \text{ K})}{1000 \text{ emu/cm}^3} \tag{12}
\]

This condition has some margins for all the cases we examined. Therefore, when this condition becomes the limiting factor in future, the examination of the head size and/or structure will be necessary.

In summary, we estimated the minimum \(K_{fu}/K_{bik}\) from the four HAMR conditions, which relate the information stability.

### 3. Results

#### 3.1 Standard parameter values

Many design parameters are related to each other in a complex manner. This simulation can reveal the relationships between such parameters and \(K_{fu}/K_{bik}\).

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 \(d_b/d_t\) was reported in a previous paper\(^2\). \(D_m\) can be calculated by \(\sqrt{S/n - \Delta}\) where \(\Delta = 1\) nm is a non-magnetic spacing between grains. Various MR methods have been proposed in addition to HAMR. A comparison of HAMR and HAMR combined with SMR (SHAMR) is very interesting. The light-spot diameter \(d_t\) is defined by the full width at half maximum of the light-power profile. On the other hand, the heat-spot diameter \(d_w\) is defined by the temperature profile as mentioned below. Since \(d_w\) can be changed by the light power as well as \(d_t\), the parameters \(d_t\) and \(d_w\) are independent of each other.

| Parameter | Value |
|-----------|-------|
| User areal density (Tbps) | 4 |
| Bit area \(S\) (nm\(^2\)) | 140 |
| MR method | HAMR |
| Medium structure | Figure 2 |
| Thermal conductivity | Table 2 |
| Light-spot diameter \(d_t\) (nm) | 9.0 |
| Heat-spot diameter \(d_w\) (nm) | 10 |
| Linear velocity \(v\) (m/s) | 10 |
| Writing temperature \(T_w\) (K) | 500 |
| Grain number per bit \(n\) (grain/bit) | 4 |
| Standard deviation of grain size \(\sigma_n/D_n\) (%) | 10 |

The standard medium structure is shown in Fig. 3. 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. The writing temperature \(T_w\) is defined at the heat-spot edge and at the center of the RL layer in the thickness direction, and the two positions of \(T_w\) in Fig. 3 are at a distance of \(d_w\) in the cross-track direction where \(d_w\) is defined as the heat-spot diameter. \(T_{max}\) is defined as the maximum surface.
temperature. The lower $T_{\text{max}}$ is better from the viewpoint of the heat resistance of the writing head and/or the surface lubricant.

The standard thermal constants for the heat transfer simulation are shown in Table 2.

Table 2 Standard thermal constants for heat transfer simulation.

| Layer                        | Specific heat $/\text{cm}^2\text{K}$ | Thermal conductivity $/\text{cmK}$ |
|------------------------------|-------------------------------------|-----------------------------------|
| Recording layer              | 3.5 $/\text{cm}^2\text{K}$          | 1 $/\text{cmK}$                  |
| Interlayer 1                 | 2.5 $/\text{cm}^2\text{K}$          | 0.5 $/\text{cmK}$                |
| Interlayer 2                 | 2.5 $/\text{cm}^2\text{K}$          | 1 $/\text{cmK}$                  |
| Heat sink layer              | 4.0 $/\text{cm}^2\text{K}$          | 4 $/\text{cmK}$                  |
| Glass substrate              | 2.5 $/\text{cm}^2\text{K}$          | 0.01 $/\text{cmK}$               |

Fig. 3 Standard medium structure and definition of temperatures.

3.2 HAMR and SHAMR compared

Figure 4 (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 as shown in Fig. 3. 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. The maximum rewriting number $N_{\text{rew}}$ is assumed to be $10^4$. The track number under the main pole $N_T$ is assumed to be (300 nm / 21 nm · 1) / 2 = 6.5. We introduce a new parameter, the effective track width $d_{\text{ET}}$ that is the track width excluding the transition width in the cross-track direction. If $d_w$ in HAMR (Fig. 4 (a)) and $d_{\text{ET}}$ in SHAMR (Fig. 4 (b) or (c)) are the same, HAMR and SHAMR can be directly compared.

On the other hand, $N_{\text{rew}}$ of SHAMR is the maximum retry number for correcting a write error during writing, and $N_{\text{rew}}$ is assumed to be ten. The upper half tracks under the main pole in Fig. 2 are recorded, and the lower half tracks are unrecorded during writing for the case of SHAMR since the tracks are laid to overlap each other as shown in Fig. 4 (b) and (c). Therefore, $N_T$ is assumed to be (300 nm / 21 nm · 1) / 2 = 6.5.
For SHAMR with a wide \( d_w \) as shown in Fig. 4 (c), the white region drifts to the leading side. This problem can be solved with the two-dimensional readback technique that is used in SMR.

The calculated temperature profiles at the surface \( z = 0 \) nm, and at 4 and 8 nm below the surface are shown in Fig. 5 for the cross-track direction under the condition \( d_t = 9.0 \) nm. The light power was changed to adjust \( d_w \) to (a) 10 nm and (b) 20 nm. The temperature profiles for the down-track direction are almost the same as those in Fig. 5. As \( d_w \) increases, \( T_{\text{max}} \) becomes higher, and \( \partial T / \partial y \) becomes somewhat smaller.

![Fig. 5 Temperature profile for the cross-track direction where the heat-spot diameter \( d_w \) is (a) 10 nm and (b) 20 nm.](image)

The comparison of HAMR with \( d_w = 10 \) nm, SHAMR with \( d_w = 10 \) nm, and SHAMR with \( d_w = 20 \) nm is summarized in Table 3. The optimum values of \( T_c \), the magnetic properties at 300 K, \( d_B \), and \( d_T \) are shown in the table. The optimum \( T_c \) value for \( T_w = 500 \) K is 508 K, which is lower than the previously reported value of 532 K due to the use of different estimation method.

Table 3 Comparison of HAMR with the heat-spot diameter \( d_w = 10 \) nm, SHAMR with \( d_w = 10 \) nm, and SHAMR with \( d_w = 20 \) nm.

| MR method | HAMR | SHAMR with \( d_w = 10 \) nm | SHAMR with \( d_w = 20 \) nm |
|-----------|------|-----------------------------|-----------------------------|
| \( d_w \) (nm) | 10   | 10                          | 20                          |
| \( T_c \) (K) | 508  | 508                         | 508                         |
| \( M_r (300 \text{ K}) \) (emu/cm²) | 616  | 616                         | 616                         |
| \( K_r (300 \text{ K}) \) (10⁶ erg/cm²) | 17   | 16                          | 16                          |
| \( H_{r (300 \text{ K})} = H_{e (300 \text{ K})} \) (kOe) | 54   | 53                          | 53                          |
| \( K_s V_s / kT (300 \text{ K}) \) | 78   | 76                          | 76                          |
| \( TSF_{10} \) | 62   | 62                          | 62                          |
| \( (1) K_s V_s / kT (T_c) \geq TSF_{10} \) | 64   | 62                          | 62                          |
| \( \partial T / \partial x(y) \) (K/nm) | 6.9  | 6.9                         | 6.6                         |
| \( (2), (3) \Delta T / \Delta x(y) \) (K/nm) | 6.9  | 5.9                         | 5.9                         |
| \( H_{e (300 \text{ K})} \) (kOe) | 9.85 | 9.85                        | 9.85                        |
| \( (4) H_{adj} \geq H_w \) | 16.7 | 22.6                        | 22.6                        |
| \( K_s / K_{bulk} \) | 0.66 | 0.64                        | 0.64                        |
| \( d_B \) (nm) | 6.57 | 7.91                        | 7.91                        |
| \( d_b \) (nm) | 21.3 | 17.7                        | 17.7                        |
| \( d_T / d_w \) | 3.25 | 2.24                        | 2.24                        |

3.3 RL thickness

As the RL thickness \( h \) decreases from 8 nm to 6 nm, \( K_s / K_{bulk} \) becomes larger as shown in Table 4. The \( h \) ratio is 8 nm / 6 nm = 1.33, which is close to the \( K_s / K_{bulk} \) ratio of 0.84 / 0.66 = 1.27 since the limiting factor for \( h = 6 \) nm is condition (1). On the other hand, although \( h \) increases from 8 nm to 10 nm, the \( K_s / K_{bulk} \) values are almost the same since the limiting factors are conditions (2) and (3), and \( \partial T / \partial x(y) \) is reduced by increasing \( h \) due to the adiabatic effect of RL.
Table 4 Calculated HAMR media design results for various RL thicknesses $h$.

| $h$ (nm) (RL) | 6   | 8   | 10  |
|--------------|-----|-----|-----|
| $D_w$ (nm)   | 4.92| 4.92| 4.92|
| $T_e$ (K)    | 511 | 500 | 505 |
| $M_s$ (300 K) (emu/cm$^3$) | 622 | 616 | 611 |
| $K_s$ (300 K) (10$^9$ erg/cm$^3$K) | 22  | 17  | 16  |
| $H_{cr}$ (300 K) | 70  | 54  | 53  |
| $K_u / kT(300 K)$ | 76  | 78  | 95  |

| $T_{SF_{10}}$ | 62  | 62  | 62  |
| $(1) K_u / kT(T_e) = T_{SF_{10}}$ | 62  | 64  | 77  |
| $\partial T / \partial x(y)$ (K/nm) | 7.7 | 6.9 | 6.2 |
| $(2) (3) \Delta T / \Delta x(y)$ (K/nm) | 5.8 | 6.9 | 6.2 |
| $H_{cr}$ (kOe) | 9.95| 9.85| 9.78|
| $(4) H_{cr}$ (kOe) $\times K_s$ | 21.0| 16.7| 19.4|
| $K_s / K_{bulk}$ | 0.84| 0.66| 0.65|
| $d_w$ (nm) | 6.29| 6.57| 6.66|
| $d_w$ (nm) | 22.3| 21.3| 21.0|
| $d_w / d_b$ | 3.54| 3.25| 3.16|

3.4 Thermal conductivity of IL1

The thermal conductivity $K$ of a film depends on the film structure. If $K$ of IL1 decreases from 0.5 W/(cmK) to 0.04 W/(cmK), the temperature profile for the cross-track direction changes from that in Fig. 5 (a) to that in Fig. 6. Although $T_{max}$ can be decreased, $\partial T / \partial x(y)$ becomes smaller due to the adiabatic effect of IL1. As a result, $K_u / K_{bulk}$ increases from 0.66 to 0.80.

![Fig. 6](image6.png)  
**Fig. 6** Temperature profile when thermal conductivity $K$ of IL1 is 0.04 W/(cmK).

3.5 Light-spot diameter

When the light-spot diameter $d_w$ decreases from 9.0 nm to 7.5 nm, the temperature profile changes from that in Fig. 5 (a) to that in Fig. 7 under the condition $d_w = 10$ nm. Although $\partial T / \partial x(y)$ increases from 6.9 K/nm to 7.4 K/nm, $K_u / K_{bulk}$ decreases only from 0.66 to 0.64 since the limiting factor changes from conditions (2) and (3) to condition (1).

![Fig. 7](image7.png)  
**Fig. 7** Temperature profile when light-spot diameter $d_w$ is 7.5 nm.

3.6 Heat-spot diameter

The temperature profile for various $d_w$ values is shown in Fig. 8 under the condition $d_w = 9.0$ nm. The $\partial T / \partial x(y)$ values for each $d_w$ are almost the same. Therefore, the $K_u / K_{bulk}$ values are almost the same.

When the allowance $\Delta d_w$ of $d_w$ against light power variance is assumed to be 20%, $d_w = \pm 2$ nm, the light power accuracy can be calculated by

$$\frac{T_w - T_{a}}{T_w} \pm \left(\frac{\partial T}{\partial y} \cdot \frac{\Delta d_w}{2}\right) - T_a.$$ (13)

When $T_w$ changes from $T_{w1}$ to $T_{w2}$, $\partial T / \partial y(T_{w1})$ can be calculated using $\frac{\partial T}{\partial y(T_{w1})} = \frac{T_{w1} - T_2}{T_{w1} - T_a}$. (14)

![Fig. 8](image8.png)  
**Fig. 8** Temperature profiles for various heat-spot diameters $d_w$.

3.7 Linear velocity

Although the writing time $\tau_w$ is halved when the linear velocity increases from 10 m/s to 20 m/s, $T_{SF_{rec}}$ decreases only from 7.68 to 6.85. Furthermore, the $\partial T / \partial x$ values for 10 m/s and 20 m/s are almost the same. Therefore, the $K_u / K_{bulk}$ values are almost the same.
3.8 Writing temperature

The temperature profiles for the various \( T_w \) values are shown in Fig. 9 under the conditions \( d_L = 9.0 \) nm and \( d_w = 10 \) nm. The light power should be increased to increase \( T_w \), and the medium \( T_c \) should also be increased to maintain \( d_w \).

The calculation results are summarized in Table 5. As \( T_w \) increases, \( \partial T / \partial x(y) \) becomes larger, then increasing \( T_w \) is effective for reducing \( K_u / K_{bulk} \). The limiting factors are conditions (2) and (3), and the difference between \( K_u V_m / kT \) and TSFI increases when \( T_w \) is increased. Therefore, 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.

![Fig. 9 Temperature profiles for various writing temperatures \( T_w \).](image)

Table 5 Calculated HAMR media design results for various writing temperatures \( T_w \).

| \( T_w \) (K) | 300 | 550 | 600 |
|---|---|---|---|
| \( D_m \) (nm) | 4.92 | 4.92 | 4.92 |
| \( T_c \) (K) | 508 | 557 | 606 |
| \( M_r (300 \text{ K}) \) (emu/cm\(^2\)) | 616 | 696 | 771 |
| \( K_u (300 \text{ K}) \) (10\(^4\) erg/cm\(^2\)) | 17 | 19 | 21 |
| \( H_c (300 \text{ K}) = H_s (300 \text{ K}) \) (kOe) | 54 | 55 | 55 |
| \( K_u V_m / kT \) (300 K) | 78 | 88 | 99 |
| TSFI | 62 | 62 | 62 |
| (1) \( K_u V_m / kT(T_c) \) \( \equiv \) TSFI | 64 | 74 | 84 |
| \( \partial T / \partial x(y) \) (K/\( m \)) | 6.9 | 9.0 | 11.0 |
| (2),(3) \( \Delta T / \Delta x(y) \) (K/\( m \)) \( \approx \) \( \partial T / \partial x(y) \) | 6.9 | 9.0 | 11.0 |
| \( H_s \) (kOe) | 9.85 | 11.1 | 12.3 |
| (4) \( M(H_s) \) (kOe) \( \equiv \) \( H_s \) | 16.7 | 19.5 | 22.0 |
| \( K_u / K_{\text{muk}} \) | 0.66 | 0.58 | 0.52 |
| \( d_m \) (nm) | 6.57 | 6.71 | 6.81 |
| \( d_c \) (nm) | 21.3 | 20.9 | 20.6 |
| \( d_s / d_m \) | 3.25 | 3.11 | 3.02 |

3.9 Grain number per bit

As the grain number per bit \( n \) decreases, TSFI increases larger as shown in Table 6. However, \( D_m \), and then \( V_m \), become larger. As a result, \( K_u / K_{bulk} \) becomes smaller by decreasing \( n \). The minimum \( n \) value can be determined with signal processing. The limiting factors are condition (1) except when \( n = 4 \). This \( n \) dependence is also common to all the MR methods.

Table 6 Calculated HAMR media design results for various grain numbers per bit \( n \).

| \( n \) (grain/bit) | 4 | 5 | 6 |
|---|---|---|---|
| \( D_m \) (nm) | 4.92 | 4.29 | 3.83 |
| \( T_c \) (K) | 508 | 510 | 512 |
| \( M_r (300 \text{ K}) \) (emu/cm\(^2\)) | 616 | 620 | 624 |
| \( K_u (300 \text{ K}) \) (10\(^4\) erg/cm\(^2\)) | 17 | 21 | 25 |
| \( H_c (300 \text{ K}) \) (kOe) | 54 | 66 | 81 |
| \( K_u V_m / kT \) (300 K) | 78 | 73 | 72 |
| TSFI | 62 | 60 | 59 |
| (1) \( K_u V_m / kT(T_c) \) \( \equiv \) TSFI | 64 | 60 | 59 |
| \( \partial T / \partial x(y) \) (K/\( m \)) | 6.9 | 6.9 | 6.9 |
| (2),(3) \( \Delta T / \Delta x(y) \) (K/\( m \)) \( \approx \) \( \partial T / \partial x(y) \) | 6.9 | 6.1 | 5.2 |
| \( H_s \) (kOe) | 9.85 | 9.92 | 9.98 |
| (4) \( M(H_s) \) (kOe) \( \equiv \) \( H_s \) | 16.7 | 19.9 | 24.5 |
| \( K_u / K_{\text{muk}} \) | 0.66 | 0.80 | 0.97 |
| \( d_m \) (nm) | 6.57 | 6.27 | 5.97 |
| \( d_c \) (nm) | 21.3 | 22.3 | 23.4 |
| \( d_s / d_m \) | 3.25 | 3.56 | 3.93 |

3.10 Standard deviation of grain size

The dependence of \( K_u / K_{bulk} \) on the standard deviation of the grain size \( \sigma_D \) is shown in Table 7. As \( \sigma_D \) increases, TSFI increases rapidly when \( n = 4 \). It
should be noted that if \( n \) is much larger than 4, no rapid increase is observed in TSF_{10} against \( \sigma_n \). The limiting factors are also condition (1) except when \( \sigma_n / D_m = 10\% \). Therefore, \( K_u / K_{bulk} \) becomes larger by increasing \( \sigma_n \).

As a result, increasing \( T_w \) is only effective for reducing \( K_u / K_{bulk} \) in comparison with \( K_u / K_{bulk} \) calculated using standard parameter values.

4. Conclusions

Media for heat-assisted magnetic recording (HAMR) were designed to minimize the anisotropy constant ratio \( K_u / K_{bulk} \). We improved our design method, and revealed the many relationships between the media design parameters and \( K_u / K_{bulk} \), which are related to each other in a complex manner.

HAMR combined with shingled magnetic recording (SHAMR) may have some advantage regarding the SN ratio of the reproduced signal due to the longer bit pitch.

The light-spot diameter, heat-spot diameter and linear velocity do not greatly affect the media design.

The limiting factor is the stability of information during 10 years of archiving in certain cases, SHAMR, the thin recording layer, the large grain number per bit, and the large standard deviation of the grain size. This condition is common to all the magnetic recording methods. Therefore, the extra \( K_u / K_{bulk} \) is not needed for realizing HAMR in such cases, and we must increase \( K_u / K_{bulk} \) by improving media preparation to realize high-density magnetic recording.

In other cases, the limiting factors are the information stability on the trailing side from the writing position, and that in the adjacent tracks. These cases are the thick recording layer, the low thermal conductivity of interlayer 1, and the high writing temperature. An examination of a media structure with a large heat-transfer thermal gradient will also be an effective way to realize high density HAMR.

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