Anisotropy Constant Required for Thermally Assisted Magnetic Recording

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An anisotropy constant K_u required for thermally assisted magnetic recording (TAMR) was calculated. First, a heat transfer simulation was carried out to obtain the thermal gradient of media at the time of writing for the K_u calculation. Both the Curie temperature T_c and K_u should be designated for TAMR media design. K_u is a function of T_c . Therefore, we introduce a parameter K_u / K_{bulk} that shows the intrinsic ratio of film K_u to bulk K_u . From the information stability conditions, we estimated whether or not the media have the potential for TAMR. The limiting factor is the thermal gradient related to the information stability on the trailing side located 1 bit from the writing position during writing and at the adjacent track during rewriting, and the limiting factor determines the minimum K_u / K_{bulk} . Therefore, the minimum K_u / K_{bulk} strongly depends on the thermal gradient. Consideration was also given to the dependence of the grain number per bit on K_u / K_{bulk} , the dependence of the standard deviation of the grain size on K_u / K_{bulk} , the dependence of the thickness of the recording layer on K_u / K_{bulk} , and the dependence of the writing temperature on K_u / K_{bulk} .

Key words: thermally assisted magnetic recording, anisotropy constant, heat transfer simulation, thermal stability factor

1. Introduction

Simultaneously satisfying the three conditions of minute magnetic grains, an appropriate thermal stability factor, and suitable coercivity is difficult with high-density magnetic recording¹⁾ beyond several Tbits/inch² (Tbpsi). Thermally assisted magnetic recording (TAMR) has been proposed as a way of solving this problem. TAMR is a recording method in which the medium is heated to reduce the coercivity at the time of writing.

We have already proposed a new media design method for 2 Tbpsi TAMR²⁾ that takes account of information stability during writing³⁾. Many TAMR media design parameters are related to each other in a complex manner. This new method can reveal the relationships between such parameters as anisotropy, Curie temperature, thickness and writing temperature. In our earlier work, we dealt with a hypothetical medium in which the magnetization, anisotropy, and Curie temperature are independent of each other. However, the magnetization and anisotropy are functions of the Curie temperature in actual materials.

We have also shown that the bit error rate (BER) after 10 years of archiving in granular media is a function of the grain number per bit n and the standard deviation of the grain size σ_D as well as the thermal stability factor TSF_{10} ⁴⁾.

In this study, we simulated our media design for 4 Tbpsi TAMR with this new method. We also considered improvement of the design method, the dependence of the magnetic properties on the Curie temperature, and BER dependence on TSF_{10} , n , and σ_D . As a result, we determined the anisotropy constant required for 4 Tbpsi TAMR.

2. Heat Transfer Simulation

To deduce the required anisotropy constant, we must first determine the thermal gradient of media at the time of writing. A heat transfer simulation was carried out using Poynting for Optics (Fujitsu Ltd.). Figure 1 is a schematic illustration of the structure of a medium that consists of four layers, that is, a recording layer RL (Fe-Pt base, t 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). The x , y , and z axes are the down-track, the cross-track, and the thickness directions, respectively. The writing temperature T_w is defined at the heat-spot edge and at the center of the RL layer in thickness direction, and the two positions of T_w in Fig. 1 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.

(a) Calculation conditions, (b) optical constants, and (c) thermal constants used in the simulation are summarized in Table 1. Ambient temperature T_a is the maximum working temperature of the hard drive, and is assumed to be 330 K.

Fig. 1 Medium structure and definition of temperatures.

A perfect conductor with a $12 \text{ nm} \times 12 \text{ nm}$ aperture is positioned 2 nm above the RL surface to generate a light spot with a diameter of several nanometers, and circularly polarized light at a wavelength of 780 nm is irradiated. Figure 2 shows the beam profile for the cross-track direction, and the light-spot diameter d_L (FWHM) is about 9.0 nm . The profile for the down-track direction is almost the same as that in Fig. 2.

The calculated temperature profiles at the surface $z = 0 \text{ nm}$, and at 4 and 8 nm below the surface are shown in Fig. 3 for the cross-track direction. The two positions of T_w in Fig. 3 correspond with those in Fig. 1. A significant temperature gradient can be seen for the RL thickness direction. The temperature profile near T_w for the down-track direction is almost the same as that in Fig. 3.

Figure 4 (a) shows the calculated thermal gradients $\partial T / \partial x$ for the down-track direction and $\partial T / \partial y$ for the cross-track direction as a function of the RL thickness t , and $\partial T / \partial x \approx \partial T / \partial y$. The dependence of $T_{\max}$ on t is shown in Fig. 4 (b).

Table 1 (a) Calculation conditions, (b) optical constants, and (c) thermal constants for heat transfer simulation.

(a)		
Wavelength λ (nm)	780	
Light-spot diameter d_L (nm)	9.0	
Heat-spot diameter d_w (nm)	10	
Linear velocity v (m/s)	10	
Ambient temperature T_a (K)	330	

(b)		
	Refractive index	Extinction coefficient
Recording layer	3	4
Interlayer 1	1.73	0
Interlayer 2	4.11	4.35
Heat-sink layer	0.242	4.85
Glass substrate	1.5	0

(c)		
	Specific heat	Thermal conductivity
Recording layer	$3 \text{ J}/(\text{cm}^3\text{K})$ $200 \text{ J}/(\text{kgK})$	$1 \text{ W}/(\text{cmK})$
Interlayer 1	$2 \text{ J}/(\text{cm}^3\text{K})$ $500 \text{ J}/(\text{kgK})$	$0.5 \text{ W}/(\text{cmK})$
Interlayer 2	$2.5 \text{ J}/(\text{cm}^3\text{K})$ $360 \text{ J}/(\text{kgK})$	$1 \text{ W}/(\text{cmK})$
Heat-sink layer	$4 \text{ J}/(\text{cm}^3\text{K})$ $440 \text{ J}/(\text{kgK})$	$4 \text{ W}/(\text{cmK})$
Glass substrate	$2 \text{ J}/(\text{cm}^3\text{K})$ $1000 \text{ J}/(\text{kgK})$	$0.01 \text{ W}/(\text{cmK})$

Fig. 2 Beam profile for the cross-track direction where the light-spot diameter d_L (FWHM) is about 9.0 nm .

Fig. 3 Temperature profile for the cross-track direction where the heat-spot diameter d_w is 10 nm and writing temperature T_w is 500 K .

Fig. 4 (a) 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 t .

Fig. 5 Schematic illustrations of (a) writing position and (b) writing-head configuration.

Fig. 6 Anisotropy constant K_u as a function of Curie temperature T_c for Fe-Pt systems.

As t increases, the thermal gradient becomes smaller, and the maximum surface temperature becomes higher since the thick RL works adiabatically.

3. Media Design Calculation Method

Figure 5 (a) is a schematic illustration of the area near a writing position. The medium was assumed to be granular. A head field H_w is applied to a wide area including the writing position. The circle denoted T_w is an isothermal of T_w heated by the light, and d_w is the heat-spot diameter as shown in Fig. 1. The bit area $S = d_B \times d_T$ is fixed where d_B and d_T are the bit

pitch and track pitch, respectively.

The white regions indicate upward or downward magnetization, and the gray regions indicate the magnetization transition. This figure shows the situation after many rewriting operations on the i th track. The transition region spread to adjacent tracks as a result of the repetition of rewriting. Therefore, the stability of information on adjacent tracks during rewriting should be considered. The maximum temperature at which information can be held at an adjacent track is defined as T_{adj} . The distance Δy from the isothermal T_w to the position of T_{adj} was assumed to be $\Delta y = d_T - d_w + a_m/2$, where a_m is the mean grain size. Then $(T_w - T_{adj})/\Delta y \equiv \Delta T/\Delta y$ is the minimum thermal gradient required by the medium for the cross-track direction, and it should be smaller than the thermal gradient $\partial T/\partial y$ calculated by the heat transfer simulation. T_{adj} can be calculated from the thermal stability factor as mentioned in 4.4.

Of course, the minimum thermal gradient required by the medium for the down-track direction $\Delta T/\Delta x$ should also be considered. The maximum temperature that can hold the information recorded in 1 bit former during writing is defined as T_{rec} . The distance Δx from the isothermal T_w to the position of T_{rec} was assumed to be the bit pitch $\Delta x = d_B$. Then $\Delta T/\Delta x = (T_w - T_{rec})/\Delta x$ should be smaller than the thermal gradient $\partial T/\partial x$ calculated by the heat transfer simulation. T_{rec} can also be calculated from the thermal stability factor as mentioned in 4.3.

d_B , d_T , and the bit aspect ratio d_T/d_B can be decided by $\Delta T/\Delta x = \Delta T/\Delta y$ since $\partial T/\partial x \approx \partial T/\partial y$ as shown in Fig. 4 (a). Since T_{rec} and T_{adj} are almost constant in spite of a few changes of Δx as mentioned in 4.1,

$$\frac{T_w - T_{rec}}{T_w - T_{adj}} = \frac{\Delta x}{\Delta y} = \frac{d_B}{d_T - d_w + a_m/2} \equiv C$$

is constant. Thus we can obtain d_B and d_T :

$$d_B = \frac{-C(d_w - a_m/2) + \sqrt{C^2(d_w - a_m/2)^2 + 4CS}}{2}$$

and

$$d_T = \frac{S}{d_B}. \quad (1)$$

The head field around the position at T_w , T_{rec} or T_{adj} is H_w , and H_w is determined from

$$H_w = 16 \text{ kOe} \times \frac{M_s(300 \text{ K})}{1000 \text{ emu/cm}^3} \quad (2)$$

taking the stray field from the surrounding magnetization $M_s(300 \text{ K})$ into consideration.

The writing-head configuration is shown in Fig. 5 (b). It is also assumed that the main-pole size of the head is 600 nm (down-track direction) $\times$ 300 nm (cross-track direction). The writing position as shown in Fig. 5 (a) is located on the trailing side of the main pole. The maximum temperature that can hold the information under the head field during rewriting is defined as T'_{adj} , and $T'_{adj} = T_a$. From $T'_{adj} = T_a$, the

maximum head field H_{adj} that can hold the information can be deduced from the thermal stability factor as mentioned in 4.5, and H_{adj} should be higher than H_w due to the geometrical restriction of the head field.

The user areal density and the bit area S were assumed to be 4 Tbps and 140 nm², respectively. The simulation was carried out for grain numbers per bit n of 4, 5, 6, and 7. The non-magnetic spacing Δ between grains is 1 nm, and the mean grain size a_m can be calculated from $\sqrt{S/n} - \Delta$.

The temperature dependence of the magnetization M_s was determined using the mean field theory⁵⁾, and that of the anisotropy constant K_u was assumed to be proportional to M_s^2 ⁶⁾. The M_s of Fe-Pt with a Curie temperature T_c of 770 K was assumed to be 1000 emu/cm³ at 300 K. And the M_s (300 K) of the medium is reduced with reducing T_c .

Both T_c and K_u should be designated for TAMR media design. $K_u(T_c)$ at room temperature is a function of T_c as shown in Fig. 6. The closed circles in the figure are an example experimental result for Fe-Ni-Pt films⁶⁾. $K_u(T_c, T)$ is also a function of temperature T . It is intrinsic that K_u is reduced by reducing T_c since $K_u(T_c = RT, T = RT) = 0$ (RT : room temperature). The K_u value of bulk Fe-Pt was assumed to be 70 Merg/cm³, and is shown as a closed triangle in the figure. The K_u value of Fe-Pt film is generally smaller than that of bulk Fe-Pt. Therefore, we introduce a parameter K_u/K_{bulk} that shows the intrinsic ratio of film K_u to bulk K_u . The solid line is a result calculated using the mean field theory for Fe-Pt by Cu simple dilution. The calculation result reproduces the experimental result well for $K_u/K_{\text{bulk}} = 0.66$. If the K_u/K_{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, e.g., the Ni composition in (Fe-Ni)-Pt or the Cu composition in (Fe-Pt)-Cu. On the other hand, increasing K_u/K_{bulk} is challenging. Therefore, it is necessary to design a smaller K_u/K_{bulk} medium.

4. Thermal Stability Factor

The thermal stability factor K_β is generally a function of temperature T and magnetic field H , and is expressed as

$$K_{\beta\pm}(T, H) = \frac{K_u(T)V}{kT} \left(1 \pm \frac{H}{H_c(T)} \right)^2, \quad (3)$$

where $V = a^2 \times t$ (a : grain size) and k are the grain volume and the Boltzmann constant, respectively, and the upper plus sign corresponds to a case where H is parallel to M_s and the lower minus sign that where H is antiparallel to M_s . The coercivity H_c is assumed to be equal to the anisotropy field $H_k = 2K_u/M_s$.

4.1 Determination of composition

We simulated the media design using the mean field theory for Fe-Pt by Cu simple dilution rather than using that for Fe-Pt by the Ni substitution of Fe because the calculation was simpler.

First, the Cu composition x in $(\text{Fe}_{0.5}\text{Pt}_{0.5})_{1-x}\text{Cu}_x$ should be determined. x can be determined unambiguously from the writing temperature T_w under a certain K_u/K_{bulk} .

Writing completion is defined as the state in which the direction of the recorded magnetization is stable for a certain time τ' under head field H_w at temperature T_w . For example, τ' is $\Delta x/v = (7.5 \text{ nm}) / (10 \text{ m/s}) = 0.75 \text{ ns}$ (linear velocity $v = 10 \text{ m/s}$). Since H_w is parallel to M_s , the thermal stability factor $K_{\beta+}(T_w, H_w)$ is given by

$$\frac{\tau'}{\tau} = \frac{0.75 \times 10^{-9}}{3.2 \times 10^8} = \frac{\exp(K_{\beta+}(T_w, H_w))}{\exp(\text{TSF}_{10})}, \text{ then}$$

$$K_{\beta+}(T_w, H_w) = \text{TSF}_{10} - \ln\left(\frac{\tau}{\tau'}\right) = \text{TSF}_{10} - 40.6,$$

where TSF_{10} is the thermal stability factor calculated using many bits⁷⁾, in which each bit has n grains and each grain is of various sizes, under the condition of 10⁻³ bit error rate. TSF_{10} is calculated statistically using grain-error probability $P = 1 - \exp(-f_0 \tau \exp(-\text{TSF}_{10} \cdot (a/a_m)^2))$ ($f_0 = 10^{11} \text{ s}^{-1}$: attempt frequency) for exactly $\tau = 10$ years of archiving. TSF_{10} is a function of the grain number per bit n and the standard deviation of the grain size σ_D , and TSF_{10} has no relation with K_u since TSF_{10} is calculated statistically. TSF_{10} is for the grain of mean size $a = a_m$. Then $K_{\beta+}(T_w, H_w)$ becomes

$$K_{\beta+}(T_w, H_w) = \frac{K_u(T_w)V_m}{kT_w} \left(1 + \frac{H_w}{H_c(T_w)} \right)^2, \quad (4)$$

$$= \text{TSF}_{10} - 40.6$$

where $V_m = a_m^2 \times t$ is the mean grain volume. From Eq. (4), the Cu composition x can be determined.

If $\Delta x = 6.5 \text{ nm}$, $K_{\beta+}(T_w, H_w) = \text{TSF}_{10} - 40.7$, and the difference of 0.1 in $K_{\beta+}(T_w, H_w)$ corresponds to a temperature difference of less than 1 K. Therefore, $K_{\beta+}(T_w, H_w) = \text{TSF}_{10} - 40.6$ is applicable in this simulation in spite of a few changes of Δx .

4.2 Condition (1)

We estimated from the following four conditions whether or not the media have the potential for TAMR. That is, information stability (1) for 10 years of archiving, (2) on the trailing side located 1 bit from the writing position during writing, (3) in an adjacent track during rewriting, and (4) under the main pole during rewriting. The limiting factor under these conditions determines the minimum K_u/K_{bulk} .

The first condition, namely the information stability for 10 years archiving, is expressed using $K_{\beta\pm}(T_a, H = 0) = K_{\beta 0}(T_a)$ as

$$K_{\beta 0}(T_a) = \frac{K_u(T_a)V_m}{kT_a} > \text{TSF}_{10}. \quad (5)$$

4.3 Condition (2)

The second condition, namely the information stability on the trailing side located 1 bit from the writing position during writing, determines the minimum thermal gradient $\Delta T / \Delta x$ required by the medium for the down-track direction.

The grains on the trailing side from the position of T_w are exposed to the head field H_w during the cooling process after the writing has taken place for a certain time τ' at a certain temperature. Of course, the information recorded in the grains should be preserved. The maximum temperature that can hold the information is T_{rec} as defined in 3. Since H_w may be antiparallel to M_s , T_{rec} can be calculated using the thermal stability factor $K_{\beta-}(T_{\text{rec}}, H_w)$ as

$$K_{\beta-}(T_{\text{rec}}, H_w) = K_{\beta 0}(T_{\text{rec}}) \left(1 - \frac{H_w}{H_c(T_{\text{rec}})} \right)^2 = \text{TSF}_{10} - 40.6 \quad (6)$$

Then $\Delta T / \Delta x = (T_w - T_{\text{rec}}) / \Delta x$ should be smaller than the thermal gradient $\partial T / \partial x$ calculated by the heat transfer simulation.

4.4 Condition (3)

The third condition, namely the information stability in an adjacent track during rewriting, determines the minimum thermal gradient $\Delta T / \Delta y$ required by the medium for the cross-track direction.

The maximum temperature that can hold the information in an adjacent track is T_{adj} as defined in 3. Assuming that the maximum number of rewriting operations is 10^4 , T_{adj} can be calculated using the thermal stability factor $K_{\beta-}(T_{\text{adj}}, H_w)$ as follows:

$$\frac{\tau' \times 10^4}{\tau} = \frac{\exp(K_{\beta-}(T_{\text{adj}}, H_w))}{\exp(\text{TSF}_{10})}, \text{ then}$$

$$K_{\beta-}(T_{\text{adj}}, H_w) = K_{\beta 0}(T_{\text{adj}}) \left(1 - \frac{H_w}{H_c(T_{\text{adj}})} \right)^2 = \text{TSF}_{10} - 31.4 \quad (7)$$

Then $\Delta T / \Delta y = (T_w - T_{\text{adj}}) / \Delta y$ should be smaller than the thermal gradient $\partial T / \partial y$ calculated by the heat transfer simulation.

4.5 Condition (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.

The grains in the adjacent tracks are exposed to the head field at each time of rewriting, for a certain time τ'' at temperature $T'_{\text{adj}} = T_a$. From the assumption, τ'' is $(600 \text{ nm}) / (10 \text{ m/s}) = 60 \text{ ns}$. The head field is simultaneously applied to about other 15

tracks at each time of rewriting.

Since the head field may be antiparallel to M_s , H_{adj} can be calculated using the thermal stability factor $K_{\beta-}(T'_{\text{adj}} = T_a, H_{\text{adj}})$ as follows:

$$\frac{\tau'' \times 10^4 \times 15}{\tau} = \frac{\exp(K_{\beta-}(T_a, H_{\text{adj}}))}{\exp(\text{TSF}_{10})},$$

$$K_{\beta-}(T_a, H_{\text{adj}}) = K_{\beta 0}(T_a) \left(1 - \frac{H_{\text{adj}}}{H_c(T_a)} \right)^2, \text{ then}$$

$$= \text{TSF}_{10} - 24.3$$

$$H_{\text{adj}} = H_c(T_a) \left(1 - \sqrt{\frac{\text{TSF}_{10} - 24.3}{K_{\beta 0}(T_a)}} \right). \quad (8)$$

The maximum head field H_{adj} should be higher than H_w .

5. Results

5.1 Dependence of grain number per bit

Table 2 summarizes our calculation results. The calculation parameters are grain number per bit n , the standard deviation of the grain size σ_D , the RL thickness t , and the writing temperature T_w . Since the optimum Cu composition in Fe-Pt-Cu should be adjusted for each parameter change, the calculation results for the T_c , M_s , K_u , H_c , and $K_u V_m / kT$ values at 300 K are different. TSF_{10} is the thermal stability factor for 10 years of archiving calculated with n and σ_D . Table 2 also shows the optimum d_B , d_T , and d_T / d_B values.

First, we considered the required K_u / K_{bulk} value for a case where the grain number per bit n is changed with a fixed areal density. The conditions of (1) $K_u V_m / kT(T_a) > \text{TSF}_{10}$ and (4) $H_{\text{adj}} > H_w$ have some margin, and the limiting factors are conditions (2) $\Delta T / \Delta x < \partial T / \partial x$ and (3) $\Delta T / \Delta y < \partial T / \partial y$ (shown as (2), (3) $\Delta T / \Delta x(y)$ in the table since $\partial T / \partial x = \partial T / \partial y$). These limiting factors determine the minimum K_u / K_{bulk} .

For example, TSF_{10} is 63, and $K_u V_m / kT(T_a)$ is 97 for $n = 4$. If the medium has $K_u V_m / kT(T_a) = 63$, it can archive information for 10 years. However, a medium with $K_u V_m / kT(T_a) = 63$ is not suitable for TAMR, and $K_u V_m / kT(T_a) = 97$ is necessary. If the thermal gradient $\partial T / \partial x(y)$ can be increased, for example to 13.5 K/nm, a medium with $K_u V_m / kT(T_a) = 64$ becomes suitable for TAMR, and K_u / K_{bulk} can be reduced to 0.55 from 0.87. As a result, the minimum K_u / K_{bulk} value strongly depends on the thermal gradient $\partial T / \partial x(y)$. If the thermal gradient exceeds 13.5 K/nm, the limiting factors will change from conditions (2) and (3) to condition (1) or (4).

As n decreases, the required TSF_{10} becomes larger. However, both the grain size a_m and the volume become larger. As a result, the required K_u , and therefore the required K_u / K_{bulk} , become smaller by decreasing n ⁷⁾. The minimum n value can be determined by the SN ratio of the reproduced signal,

that is the complex matter of signal processing.

Table 2 Calculation results of TAMR media design for various grain numbers per bit n .

n (grain/bit)	4	5	6	7
σ_D (%)	10	10	10	10
t (nm)	8	8	8	8
T_w (K)	500	500	500	500
a_m (nm)	4.92	4.29	3.83	3.47
T_c (K)	532	536	542	544
M_s (300 K) (emu/cm ³)	655	662	672	676
K_u (300 K) (10 ⁶ erg/cm ³)	25	28	31	33
H_c (300 K) = H_k (300 K) (kOe)	77	84	93	98
$K_u V_m / kT$ (300 K)	118	99	88	77
$TSF_{10} = f(n, \sigma_D)$	63	60	59	57
(1) $K_u V_m / kT(T_a) > TSF_{10}$	97	82	74	64
$\partial T / \partial x(y)$ (K/nm)	6.9	6.9	6.9	6.9
(2), (3) $\Delta T / \Delta x(y)$ (K/nm) $< \partial T / \partial x(y)$	6.9	6.9	6.9	6.9
H_w (kOe)	10.5	10.6	10.8	10.8
(4) H_{adj} (kOe) $> H_w$	27.2	27.1	27.5	26.6
K_u / K_{bulk}	0.87	0.94	1.02	1.07
d_B (nm)	7.48	7.21	7.02	6.80
d_T (nm)	18.7	19.4	20.0	20.6
d_T / d_B	2.50	2.69	2.84	3.03

5.2 Dependence of standard deviation of grain size

The dependence of the required K_u / K_{bulk} value on the standard deviation of the grain size σ_D is shown in Table 3. As σ_D increases, the required TSF_{10} becomes larger. Therefore, the required K_u / K_{bulk} becomes larger by increasing σ_D .

5.3 Dependence of RL thickness

Although the grain volume increases by increasing the RL thickness t , the required K_u / K_{bulk} values are almost the same as those shown in Table 4.

Figure 7 shows the dependence of $\Delta T / \Delta x(y)$ on K_u / K_{bulk} for each t . As K_u / K_{bulk} increases, $\Delta T / \Delta x(y)$ becomes smaller. The dotted lines in the figure show $\partial T / \partial x(y)$ for each t , and $\Delta T / \Delta x(y)$ should be smaller than $\partial T / \partial x(y)$. If $\partial T / \Delta x(y)$ is constant in spite of the change of t , K_u / K_{bulk} can be decreased by increasing t . However, $\partial T / \Delta x(y)$ is reduced by increasing t due to the adiabatic effect of RL. Therefore, increasing the thickness has little merit as regards reducing K_u / K_{bulk} .

5.4 Dependence of writing temperature

The dependence of the required K_u / K_{bulk} on the writing temperature T_w is shown in Table 5.

Figure 8 shows the dependence of $\Delta T / \Delta x(y)$ on K_u / K_{bulk} for each T_w . The dotted lines in the figure show $\partial T / \Delta x(y)$ for each T_w . As T_w increases, $\partial T / \Delta x(y)$ becomes larger as shown in Fig. 4 (a). Therefore, increasing the writing temperature T_w is effective in reducing K_u / K_{bulk} .

Table 3 Calculation results of TAMR media design for various standard deviations of grain size σ_D .

n (grain/bit)	4	4	4	4
σ_D (%)	5	10	15	20
t (nm)	8	8	8	8
T_w (K)	500	500	500	500
a_m (nm)	4.92	4.92	4.92	4.92
T_c (K)	517	532	548	571
M_s (300 K) (emu/cm ³)	632	655	682	718
K_u (300 K) (10 ⁶ erg/cm ³)	20	25	31	40
H_c (300 K) = H_k (300 K) (kOe)	63	77	92	112
$K_u V_m / kT$ (300 K)	93	118	146	188
$TSF_{10} = f(n, \sigma_D)$	54	63	75	94
(1) $K_u V_m / kT(T_a) > TSF_{10}$	76	97	122	159
$\partial T / \partial x(y)$ (K/nm)	6.9	6.9	6.9	6.9
(2), (3) $\Delta T / \Delta x(y)$ (K/nm) $< \partial T / \partial x(y)$	6.9	6.9	6.9	6.9
H_w (kOe)	10.1	10.5	10.9	11.5
(4) H_{adj} (kOe) $> H_w$	22.8	27.2	31.4	36.4
K_u / K_{bulk}	0.74	0.87	1.00	1.15
d_B (nm)	7.21	7.48	7.67	7.85
d_T (nm)	19.4	18.7	18.2	17.8
d_T / d_B	2.69	2.50	2.38	2.27

Table 4 Calculation results of TAMR media design for various RL thicknesses t .

n (grain/bit)	4	4	4
σ_D (%)	10	10	10
t (nm)	6	8	10
T_w (K)	500	500	500
a_m (nm)	4.92	4.92	4.92
T_c (K)	544	532	524
M_s (300 K) (emu/cm ³)	675	655	643
K_u (300 K) (10 ⁶ erg/cm ³)	28	25	24
H_c (300 K) = H_k (300 K) (kOe)	82	77	74
$K_u V_m / kT$ (300 K)	97	118	139
$TSF_{10} = f(n, \sigma_D)$	63	63	63
(1) $K_u V_m / kT(T_a) > TSF_{10}$	81	97	115
$\partial T / \partial x(y)$ (K/nm)	7.7	6.9	6.2
(2), (3) $\Delta T / \Delta x(y)$ (K/nm) $< \partial T / \partial x(y)$	7.7	6.9	6.2
H_w (kOe)	10.8	10.5	10.3
(4) H_{adj} (kOe) $> H_w$	24.5	27.2	29.8
K_u / K_{bulk}	0.90	0.87	0.86
d_B (nm)	7.39	7.48	7.55
d_T (nm)	18.9	18.7	18.6
d_T / d_B	2.56	2.50	2.46

Fig. 7 Required thermal gradient $\Delta T / \Delta x(y)$ by medium as a function of intrinsic anisotropy constant K_u / K_{bulk} . The calculation parameter is RL thickness t .

Table 5 Calculation results of TAMR media design for various writing temperatures T_w .

n (grain/bit)	4	4	4
σ_D (%)	10	10	10
t (nm)	8	8	8
T_w (K)	500	550	600
a_m (nm)	4.92	4.92	4.92
T_c (K)	532	583	634
M_s (300 K) (emu/cm ³)	655	737	813
K_u (300 K) (10 ⁶ erg/cm ³)	25	28	31
H_c (300 K) = H_k (300 K) (kOe)	77	76	77
$K_u V_m / kT$ (300 K)	118	131	146
$TSF_{10} = f(n, \sigma_D)$	63	63	63
(1) $K_u V_m / kT(T_a) > TSF_{10}$	97	112	126
$\partial T / \partial x(y)$ (K/nm)	6.9	9.0	11.0
(2), (3) $\Delta T / \Delta x(y)$ (K/nm)	6.9	9.0	11.0
$< \partial T / \partial x(y)$ (K/nm)			
H_w (kOe)	10.5	11.8	13.0
(4) H_{adj} (kOe) $> H_w$	27.2	30.5	33.4
K_u / K_{bulk}	0.87	0.76	0.69
d_B (nm)	7.48	7.58	7.66
d_T (nm)	18.7	18.5	18.3
d_T / d_B	2.50	2.43	2.39

Fig. 8 Required thermal gradient $\Delta T / \Delta x(y)$ by medium as a function of intrinsic anisotropy constant K_u / K_{bulk} . The calculation parameter is writing temperature T_w .

6. Conclusions

The anisotropy constant K_u required for thermally assisted magnetic recording (TAMR) at 4 Tbps was evaluated by simulation. We introduced a parameter K_u / K_{bulk} that shows the intrinsic ratio of film K_u to bulk K_u . It is necessary to design a smaller K_u / K_{bulk} medium.

The limiting factor whether or not the media have the potential for TAMR is the thermal gradient $\partial T / \partial x(y)$ calculated by a heat transfer simulation, and it determines the minimum K_u / K_{bulk} .

(1) Dependence of grain number per bit n

As n decreases, the thermal stability factor TSF_{10} calculated statistically becomes larger. However, the grain volume becomes larger. As a result, K_u / K_{bulk} becomes smaller by reducing n .

(2) Dependence of standard deviation of grain size σ_D

As σ_D increases, TSF_{10} becomes larger. Therefore, K_u / K_{bulk} becomes larger with increasing σ_D .

(3) Dependence of recording layer (RL) thickness t

Although the grain volume increases with increasing t , $\partial T / \partial x(y)$ becomes smaller with increasing t due to the adiabatic effect of RL. Therefore, the K_u / K_{bulk} values are almost the same.

(4) Dependence of writing temperature T_w

As T_w increases, $\partial T / \partial x(y)$ becomes larger. Therefore, increasing T_w is effective in reducing K_u / K_{bulk} .

Though optimum conditions can't be decided since there are many trade-off conditions, it can be point out that increasing K_u / K_{bulk} by an improvement of media preparation is necessary to realize 4 Tbps TAMR. An investigation of media structure with large $\partial T / \partial x(y)$ will also be effective to realize 4 Tbps TAMR.

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