Information Stability in Heat-Assisted Magnetic Recording

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The thermal stability factor $K_{\text{um}}V_{\text{m}}/kT$ and the anisotropy constant ratio $K_{\text{u}}/K_{\text{bulk}}$ necessary for 10 years of archiving in heat-assisted magnetic recording of 2 Tbps are evaluated by employing a bit error rate calculation using a grain error probability P . Although the attempt frequency f_0 in P is a function of the Gilbert damping constant, the Curie temperature, $K_{\text{u}}/K_{\text{bulk}}$, the grain volume, and temperature, f_0 can be treated as a constant. The Gilbert damping constant and the Curie temperature variation are parameters with little impact. On the other hand, the grain size variation, the grain number per bit n , the mean Curie temperature T_{cm} , and the storage temperature T are parameters with a strong impact on bit error rate. Although $K_{\text{um}}V_{\text{m}}/kT$ decreases as n increases due to a statistical problem, a larger $K_{\text{u}}/K_{\text{bulk}}$ is necessary as n increases due to a smaller grain size. A larger $K_{\text{u}}/K_{\text{bulk}}$ is also necessary as T_{cm} decreases. The bit error rate increases rapidly as T increases.

Key words: thermal stability factor, anisotropy constant ratio, bit error rate, probability, attempt frequency

1. Introduction

The long-term stability of archived information is one of the most important properties of magnetic recording media. This stability has been widely discussed using the thermal stability factor $K_{\text{um}}V_{\text{m}}/kT$, where K_{um} , V_{m} , k , and T are the mean grain anisotropy constant, the grain volume for the mean grain size of the medium, the Boltzmann constant, and temperature, respectively¹⁾. We have already estimated the numerical value of $K_{\text{um}}V_{\text{m}}/kT$ by employing a bit error rate calculation using the grain error probability for various grain numbers per bit n and the standard deviations of grain size σ_{D} ^{2),3)}. In that calculation, we used a constant attempt frequency f_0 of $1.0 \times 10^{11} \text{ s}^{-1}$. However, precisely speaking, f_0 is a function of the Gilbert damping constant α , the magnetization M_{s} , the anisotropy field H_{k} , the grain volume V , and T ⁴⁾.

Heat-assisted magnetic recording (HAMR) is a promising candidate as a next generation magnetic recording method that can operate beyond the trilemma limit¹⁾. HAMR is a recording method in which the medium is heated to reduce coercivity during the writing period. We have introduced a HAMR design parameter, namely, the medium anisotropy constant ratio $K_{\text{u}}/K_{\text{bulk}}$ ⁵⁾ in place of the medium anisotropy constant K_{u} since the K_{u} value at the storage temperature is a function of the medium Curie temperature T_{c} , which is strongly related to the writing property. $K_{\text{u}}/K_{\text{bulk}}$ is the intrinsic ratio of the medium K_{u} to bulk FePt K_{u} regardless of T_{c} where FePt is a candidate HAMR medium material thanks to its large K_{u} and a relatively low T_{c} . A medium with a high $K_{\text{u}}/K_{\text{bulk}}$, e.g. 0.6 - 1.0⁶⁾, is difficult to manufacture regardless of T_{c} . M_{s} is a function of T_{c} and T . $H_{\text{k}} = 2K_{\text{u}}/M_{\text{s}}$ is a function of T_{c} , $K_{\text{u}}/K_{\text{bulk}}$, and T . And V_{m} is a function of n under a constant

grain height. Therefore, f_0 is a function of α , T_{c} , T , $K_{\text{u}}/K_{\text{bulk}}$, and n .

In this paper, we evaluate the $K_{\text{um}}V_{\text{m}}/kT$ and $K_{\text{u}}/K_{\text{bulk}}$ necessary for 10 years of archiving in 2 Tbps HAMR by employing a bit error rate calculation using the grain error probability, which includes f_0 as a function of α , T_{c} , T , $K_{\text{u}}/K_{\text{bulk}}$, and n . Furthermore, we also examine the dependence of the bit error rate on the standard deviation of the Curie temperature as well as that of the grain size.

2. Calculation Method

2.1 Attempt frequency

The thermal stability factor $K_{\text{um}}V_{\text{m}}/kT$ and the anisotropy constant ratio $K_{\text{u}}/K_{\text{bulk}}$ necessary for 10 years of archiving in 2 Tbps HAMR were evaluated by employing a bit error rate calculation using the grain error probability P

$$P = 1 - \exp\left(-f_0 t \exp\left(-\frac{K_{\text{u}}V_{\text{m}}}{kT} \cdot \left(\frac{D}{D_{\text{m}}}\right)^2\right)\right) \quad (1)$$

where f_0 , t , K_{u} , V_{m} , k , T , and D are the attempt frequency, time, the grain anisotropy constant, the grain volume for mean grain size D_{m} , the Boltzmann constant, temperature, and the grain size, respectively.

The attempt frequency f_0 has been deduced as

$$f_0 = \frac{\alpha\gamma}{1+\alpha^2} \sqrt{\frac{M_{\text{s}}H_{\text{k}}^3V}{2\pi kT}} \left(1 - \left(\frac{H}{H_{\text{k}}}\right)^2\right) \left(1 + \frac{H}{H_{\text{k}}}\right) \quad (2)$$

under a magnetic field H where α , γ , M_{s} , H_{k} , and V are the Gilbert damping constant, the gyromagnetic ratio, the magnetization, the anisotropy field $H_{\text{k}} = 2K_{\text{u}}/M_{\text{s}}$, and the grain volume, respectively⁴⁾. M_{s} and H change from parallel to antiparallel for $H > 0$, and antiparallel to parallel for $H < 0$.

Fig. 1 Temperature dependence of attempt frequency for various magnetic fields H .

Figure 1 shows the temperature dependence of f_0 for various H values under the conditions where $\alpha = 1$, the Curie temperature $T_c = 700$ K, $K_u / K_{\text{bulk}} = 0.52$, and $V = 83.6 \text{ nm}^3$.

The solid lines were calculated using Eq. (2). The temperature dependence of M_s was determined by employing a mean field analysis⁷⁾, and that of K_u was assumed to be proportional to $M_s^{2.8})$. The T_c value was adjusted by the Cu simple dilution of $(\text{Fe}_{0.5}\text{Pt}_{0.5})_{1-z}\text{Cu}_z$. $M_s(T_c, T)$ is a function of T_c and T , and $M_s(T_c = 770 \text{ K}, T = 300 \text{ K}) = 1000 \text{ emu/cm}^3$ was assumed for FePt (Cu composition $z = 0$). $K_u(T_c, K_u / K_{\text{bulk}}, T)$ is a function of T_c , K_u / K_{bulk} , and T where

$$K_u / K_{\text{bulk}} = \frac{K_u(T_c, K_u / K_{\text{bulk}}, T)}{K_u(T_c, K_u / K_{\text{bulk}} = 1, T)}. \quad (3)$$

$K_u(T_c = 770 \text{ K}, K_u / K_{\text{bulk}} = 1, T = 300 \text{ K}) = 70 \text{ Merg/cm}^3$ was assumed for FePt ($z = 0$). We used $M_s(T_c = 700 \text{ K}, T)$ and $K_u(T_c = 700 \text{ K}, K_u / K_{\text{bulk}} = 0.52, T)$ in Fig. 1.

The filled symbols were obtained with a conventional micromagnetic calculation using the Landau-Lifshitz-Gilbert equation⁹⁾. The calculation step time Δt was 0.1 ps. Usually Landau-Lifshitz-Bloch (LLB) equation is used for the simulation near Curie temperature¹⁰⁾. However we used the Langevin equation with the effect of the temperature on the material parameters, which is the biggest different point between the LLB and the Langevin equation. Therefore the effect of the equation on the simulation is permissible.

Although we discuss the information stability around room temperature in this paper, the comparison was carried out for high temperature region since room temperature is too low to calculate in a short time when employing the micromagnetic calculation. Since the results represented by the solid lines and the filled symbols agree well, the attempt frequency was calculated using Eq. (2) in this paper.

Neither the demagnetizing nor the magnetostatic fields were considered in this paper for simplifying the model calculation. The problem of these fields is a future subject.

2.2 Bit error rate calculation

The bit error rate was calculated using each grain error probability P_i of Eq. (1). For example, for 4 grains/bit, the 1 grain-error bit error rate ${}_4\text{bER}_1$ is expressed as

$${}_4\text{bER}_1 = Er_1 P_1 (1 - P_2)(1 - P_3)(1 - P_4) + \dots + Er_4 (1 - P_1)(1 - P_2)(1 - P_3)P_4, \quad (4)$$

the 2 grain-error bit error rate ${}_4\text{bER}_2$

$${}_4\text{bER}_2 = Er_{12} P_1 P_2 (1 - P_3)(1 - P_4) + \dots + Er_{34} (1 - P_1)(1 - P_2)P_3 P_4, \quad (5)$$

the 3 grain-error bit error rate ${}_4\text{bER}_3$

$${}_4\text{bER}_3 = Er_{123} P_1 P_2 P_3 (1 - P_4) + \dots + Er_{234} (1 - P_1)P_2 P_3 P_4, \quad (6)$$

and the 4 grain-error bit error rate ${}_4\text{bER}_4$

$${}_4\text{bER}_4 = P_1 P_2 P_3 P_4 \quad (7)$$

where

$$Er_j = 1, \text{ if } \frac{\sum M_{si}(T_{ci}, T) D_i^2}{n \cdot M_s(T_{cm}, T) D_m^2} < 0.5, \quad (8)$$

and

$$Er_j = 0, \text{ if } \frac{\sum M_{si}(T_{ci}, T) D_i^2}{n \cdot M_s(T_{cm}, T) D_m^2} \geq 0.5. \quad (9)$$

Errors occur in some grains of a bit. We assume that if the surface magnetic charge of the grains where the magnetization turns in the recording direction $\sum M_{si}(T_{ci}, T) D_i^2$ is more than 50 % (signal threshold) of the total surface magnetic charge in a bit $n \cdot M_s(T_{cm}, T) D_m^2$, the bit is error free where M_{si} , T_{ci} , D_i , n , T_{cm} , and D_m are the magnetization, the Curie temperature, the grain size of the i -th grain, the grain number per bit, the mean Curie temperature, and the mean grain size, respectively.

After all, the total bit error rate ${}_4\text{bER}$ is the summation of each bit error rate ${}_4\text{bER}_k$ as follows

$${}_4\text{bER} = \sum_k {}_4\text{bER}_k. \quad (10)$$

The bit error rate is a function of the anisotropy constant ratio K_u / K_{bulk} . Therefore, we obtained K_u / K_{bulk} for a certain bit error rate. Since the mean anisotropy constant K_{um} is a function of K_u / K_{bulk} , the thermal stability factor $K_{\text{um}} V_m / kT$ was calculated using K_u / K_{bulk} .

3. Calculation Results

3.1 Information stability for 10 years of archiving

The calculation conditions are summarized in Table 1. The recording density is 2 Tbps, and the area S of a bit is 323 nm^2 . The medium was assumed to be

granular in which each bit has n grains/bit. The mean grain size D_m was determined by

$$D_m = \sqrt{\frac{S}{n}} - \Delta \quad (11)$$

where the non-magnetic spacing Δ was assumed to be 1 nm. The grain height h was 8 nm, and so the grain volume V_m for D_m was $D_m \times D_m \times h$.

Table 1 Calculation conditions for 10 years of archiving.

Recording density (Tbps)	2
Non-magnetic spacing Δ (nm)	1
Grain height h (nm)	8
Storage temperature T (K)	300
Storage time t (years)	10
Signal threshold	0.5
Bit number (bits)	10^7
Bit error rate	$1\text{E-}3$

Fig. 2 Thermal stability factor required for 10 years of archiving as a function of the standard deviation of the grain size for various damping constants α and standard deviations of Curie temperature σ_{T_c}/T_{cm} .

Fig. 3 Temperature dependence of anisotropy constant for standard deviation of Curie temperature $\sigma_{T_c}/T_{cm} = 4\%$.

The storage temperature and the storage time were 300 K and 10 years, respectively. The signal threshold was 0.5, and the calculation bit number was 10^7 . The thermal stability factor $K_{um}V_m/kT$ and the anisotropy

constant ratio K_u/K_{bulk} were evaluated for a bit error rate of $1\text{E-}3$. We assumed that the grain size distribution was log-normal with a standard deviation of σ_D , and that the Curie temperature distribution was normal with a mean Curie temperature and standard deviation of T_{cm} and σ_{T_c} , respectively.

Figure 2 shows $K_{um}V_m/kT$ needed for 10 years of archiving as a function of σ_D/D_m for various α and σ_{T_c}/T_{cm} values under the conditions of 4 grains/bit and $T_{cm} = 700$ K. The $K_{um}V_m/kT$ value is strongly dependent on σ_D/D_m . However, $K_{um}V_m/kT$ is weakly dependent on α and σ_{T_c}/T_{cm} . When the error is low, Eq. (1) can be approximated as Eq. (12).

$$P \approx f_0 t \exp\left(-\frac{K_u V_m}{kT} \cdot \left(\frac{D}{D_m}\right)^2\right). \quad (12)$$

The variables in an exponential function become parameters with a strong impact on bit error rate. Therefore, σ_D/D_m has a strong effect.

On the other hand, α is only related to the attempt frequency f_0 , and so a difference of even 10 times α , namely f_0 has little effect on $K_{um}V_m/kT$ needed for 10 years of archiving as shown in Fig. 2 since f_0 is not an exponential variable. Therefore, α has only a weak effect, and some change in f_0 by changing T_c , T , K_u/K_{bulk} , or n also has little effect on $K_{um}V_m/kT$. Therefore, f_0 can be treated as a constant in this paper. Furthermore, from Eq. (12), time t as well as f_0 is a parameter with little impact on bit error rate.

The existence of $\sigma_{T_c}/T_{cm} = 4\%$ ¹¹⁾ also has only a weak effect on the bit error rate as shown in Fig. 2. This is explained using the temperature dependence of K_u as shown in Fig. 3. When σ_{T_c}/T_{cm} is 4 %, the standard deviation of the anisotropy constant σ_{K_u}/K_{um} is 9 % at 300 K. The σ_{K_u}/K_{um} value of 9 % corresponds to σ_D/D_m of only 4.6 % in Eq. (12) since the changes in K_u and D caused by σ_{K_u} and σ_D correspond to $K_u = K_{um} - \sigma_{K_u}$ and $D^2 = (D_m - \sigma_D)^2$ in Eq. (12), respectively. Therefore, even for the same numerical values of σ_{K_u}/K_{um} and σ_D/D_m , σ_{K_u}/K_{um} has little apparent effect.

Next, we discuss $K_{um}V_m/kT$ for various grain numbers per bit using Fig. 4. The dependence of $K_{um}V_m/kT$ on σ_D/D_m weakens as the grain number per bit increases due to a statistical problem. If one bit contains many grains, the bit error rate becomes low since the probability is very low for a simultaneous error for more than half of the grains in one bit. For example, when there are 9 error-free grains and 7 grains with errors, the bit is error free for 16 grains/bit as shown in Fig. 5 (a). However, 2 bits are error free and 2 bits have errors when there are 4 grains/bit even with the same grain magnetization arrangement as shown in Fig. 5 (b). Thus, $K_{um}V_m/kT$ decreases as the grain number per bit increases due to a statistical problem.

Fig. 4 Thermal stability factor necessary for 10 years of archiving as a function of the standard deviation of the grain size for various grain numbers per bit.

Fig. 5 (a) One bit of 16 grains/bit and (b) four bits of 4 grains/bit.

Fig. 6 Anisotropy constant ratio necessary for 10 years of archiving as a function of the mean grain size for various standard deviations of grain size σ_D/D_m .

Figure 6 shows K_u/K_{bulk} necessary for 10 years of archiving as a function of D_m for various σ_D/D_m values. The inserted scale indicates the grain number per bit corresponding to D_m for a recording density of 2 Tbps. Although $K_{\text{um}}V_m/kT$ decreases as the grain number per bit increases, a larger K_u/K_{bulk} is necessary as the grain number per bit increases due to the smaller grain size.

The K_u value at a storage temperature of 300 K is important as regards information stability for 10 years of archiving. And $K_u(T = 300 \text{ K})$ is a function of T_c as shown in Fig. 7. The $K_u(T = 300 \text{ K})$ value for a medium with a low T_c is intrinsically low. Therefore, a larger K_u/K_{bulk} is necessary for a low T_c medium to obtain the same $K_u(T = 300 \text{ K})$ value as that for a high T_c medium.

Fig. 7 Temperature dependence of anisotropy constant for Curie temperatures $T_c = 600$ and 700 K .

Fig. 8 Anisotropy constant ratio necessary for 10 years of archiving as a function of the mean Curie temperature for (a) 4 and (b) 9 grains/bit.

The K_u/K_{bulk} value for 10 years of archiving as a function of T_{cm} is shown in Fig. 8. As expected from the above discussion, a larger K_u/K_{bulk} is required as the mean Curie temperature decreases. A low Curie temperature is advantageous for writing in HAMR. However, it is disadvantageous for media manufacturing. For 9 grains/bit, as shown in Fig. 8 (b), a larger K_u/K_{bulk} is necessary than for 4 grains/bit as shown in Fig. 8 (a) due to the smaller grain size. The results are for a grain height h of 8 nm. If $h = 4 \text{ nm}$, namely half the height, the K_u/K_{bulk} value must be double. The required K_u/K_{bulk} value exceeds 1.0 for the combination of 2 Tbps, 9 grains/bit, $T_{\text{cm}} = 550 \text{ K}$, $\sigma_D/D_m = 20 \%$, and $h = 4 \text{ nm}$ even using an FePt

medium with a large K_u .

Table 2 Calculation conditions for temperature dependence of bit error rate.

Recording density (Tbpsi)	2
Non-magnetic spacing Δ (nm)	1
Grain height h (nm)	8
Grain number (grains/bit)	4
Gilbert damping constant α	0.1
Mean Curie temperature T_{cm} (K)	700
Standard deviation of Curie temp. σ_{Tc}/T_{cm} (%)	0
Signal threshold	0.5
Bit number (bits)	10^7

Fig. 9 Temperature dependence of bit error rate for (a) various anisotropy constant ratios K_u/K_{bulk} , (b) various standard deviations of grain size σ_D/D_m , and (c) various times t .

3.2 Temperature dependence of bit error rate

The storage temperature is also a parameter with a strong impact since temperature is a variable of an exponential function in the grain error probability as shown in Eq. (12). Therefore, we discuss the temperature dependence of the bit error rate in this section. The calculation conditions are summarized in Table 2.

Figure 9 (a) shows the temperature dependence of the bit error rate for $K_u/K_{bulk} = 0.0996$ and 0.125 . When $K_u/K_{bulk} = 0.0996$, the bit error rate is $1E-3$ at 300 K for 10 years. However, the bit error rate increases rapidly as the temperature increases, and it exceeds $1E-2$ at only 325 K. The maximum ambient temperature of a hard disk drive appears to be about 330 K. Therefore, $K_u/K_{bulk} = 0.0996$ is insufficient. If $K_u/K_{bulk} = 0.125$, the information is stable up to 350 K when we take a certain margin for temperature into account.

When σ_D/D_m increases from 10 % to 20 %, the temperature dependence of the bit error rate weakens as shown in Fig. 9 (b). However, $K_u/K_{bulk} = 0.184$ is necessary for $\sigma_D/D_m = 20$ % if we are to obtain the same bit error rate for $\sigma_D/D_m = 10$ % at 300 K.

The storage time t is a weak impact parameter, and so the difference between the temperatures with a bit error rate of $1E-3$ for $t = 1$ and 10 years is about 10 K as shown in Fig. 9 (c).

4. Conclusion

We evaluated the thermal stability factor $K_{um}V_m/kT$ and the anisotropy constant ratio K_u/K_{bulk} required for 10 years of archiving in heat-assisted magnetic recording of 2 Tbpsi employing a bit error rate calculation using the grain error probability under the conditions used in this paper. We classified the calculation parameters as those with a strong and a weak impact on the bit error rate.

The Gilbert damping constant and the Curie temperature variation are weak impact parameters. The attempt frequency can be treated as a constant.

On the other hand, the grain size variation, the grain number per bit n , the mean Curie temperature T_{cm} , and the storage temperature T are strong impact parameters.

The $K_{um}V_m/kT$ value is strongly dependent on the standard deviation of the grain size σ_D/D_m . Although $K_{um}V_m/kT$ decreases as n increases due to a statistical problem, a larger K_u/K_{bulk} is necessary as n increases due to a smaller grain size.

A larger K_u/K_{bulk} is also necessary as T_{cm} decreases. The required K_u/K_{bulk} value exceeds 1.0 for the combination of 9 grains/bit, $T_{cm} = 550$ K, $\sigma_D/D_m = 20$ %, and a grain height of 4 nm even using an FePt medium.

The bit error rate increases rapidly as T increases, and a certain K_u/K_{bulk} margin is required as regards temperature.

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