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<Paper>

Impact of Damping Constant on Bit Error Rate in Heat-Assisted Magnetic Recording

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We calculate the writing field dependence of the bit error rate for Gilbert damping constants of 0.1 and 0.01 in heat-assisted magnetic recording (HAMR) using a new model calculation. The attempt period used in the new model calculation is considered in detail. The writing properties are examined for various thermal gradients, linear velocities, and anisotropy constants. When the damping constant is equal to 0.1, write-error is smaller, and erasure-after-write is larger than that for 0.01 since the attempt period is short. The physical implication of the results is discussed. We also compare the results of the new model calculation and the conventionally used micromagnetic calculation. The overall tendencies of the results are the same. Therefore, the outline of the impact of the damping constant on the bit error rate in HAMR can be understood by the grain magnetization reversal probability and the attempt period used in the new model calculation.

Key words: heat-assisted magnetic recording, damping constant, thermal gradient, linear velocity, anisotropy constant

1. Introduction

Heat-assisted magnetic recording (HAMR) is a promising candidate for high-density magnetic recording beyond the trilemma limit[1].

We have already proposed a new HAMR model calculation[2] using the grain magnetization reversal probability for each attempt. The new model calculation can obtain the bit error rate (bER) as a function of the writing field H_w for a given anisotropy constant ratio K_u/K_{bulk} [3]. We discussed the physical implication of the recording time window using the new model calculation. And then, we provided the allowable ranges of H_w and K_u/K_{bulk} for various Curie temperatures.

The grain magnetization reversal probability and the attempt period, whose inverse is the attempt frequency f_0, are key physical quantities in the new model calculation. The reversal probability is a function of the anisotropy field H_k, and H_k is a function of temperature. The temperature dependence of experimental H_k values can be represented by a mean field analysis[4]. On the other hand, the f_0 value is a function of the anisotropy constant K_u, and K_u is a function of temperature, and then f_0 at the writing temperature is necessary. Furthermore, f_0 is a function of the damping constant α [5], and α is also a function of temperature[6, 7]. Therefore, although knowledge of α at the writing temperature is necessary, it is unknown.

In this study, we calculate the f_0 value at the writing temperature employing the conventionally used micromagnetic calculation, and then we calculate the writing field dependence of the bER for α = 0.1 and 0.01 in HAMR using the new model calculation, and discuss the physical implication of the results for various thermal gradients, linear velocities, and anisotropy constants. We also compare the results with those obtained using the micromagnetic calculation.

2. Calculation Method

2.1 Calculation conditions

The medium was assumed to be granular. The calculation conditions are summarized in Table 1. Since we assume high-density magnetic recording such as 4 Tbpsi, we suppose the grain number per bit n and the bit pitch d_B to be 4 and 6.8 nm, respectively. The grain volume V_m for the mean grain size D_m is $D_m^2 \times h$ = 193 nm³ where h is the grain height. The standard deviations of the grain size σ_D/D_m, the anisotropy constant, and the Curie temperature are assumed to be 10, 0, and 0 %, respectively.

Errors occur in some grains of a bit. We assume that if the area ΣD_i^2 of the grains where the magnetization turns in the recording direction is more than 50 % (signal threshold) of nD_m^2 in one bit, the bit is error-free. The bit error rates in this paper are useful only in a comparison.

The medium can be designated by the Curie temperature T_c = 700 K and the anisotropy constant ratio K_u/K_{bulk} = 0.4 or 0.8 where K_u/K_{bulk} is the intrinsic ratio of the medium anisotropy constant K_u to bulk FePt K_u [3].

Figure 1 shows schematic illustrations of the writing field switching timing and grain arrangement. Four grains are arranged in the cross-track direction. It is assumed that the thermal gradient is zero for the cross-track direction. H_w and $\tau_{min} = d_B/v$ are the writing field and the minimum magnetization transition window, respectively, where v is the linear velocity. There are fluctuations of switching timing $\Delta\tau$ and position Δx in a granular medium as shown in Fig. 1 (a). However, we assume $\Delta\tau$ = 0 and Δx = 0 for our discussion of the intrinsic phenomenon as shown in Fig. 1 (b). The H_w direction (recording direction) is upward when $0 \le \tau \le \tau_{\min}$ and downward otherwise. When the medium temperature T becomes T_c, the time τ is set at zero.

Table 1 Calculation conditions.

Grain number per bit n (grain / bit)	4
Bit pitch d_B (nm)	6.8
Mean grain size D_m (nm)	4.9
Grain height h (nm)	8
Standard deviation of grain size σ_D / D_m (%)	10
Signal threshold	0.5
Curie temperature T_c (K)	700
Anisotropy constant ratio K_u / K_{bulk}	0.4, 0.8

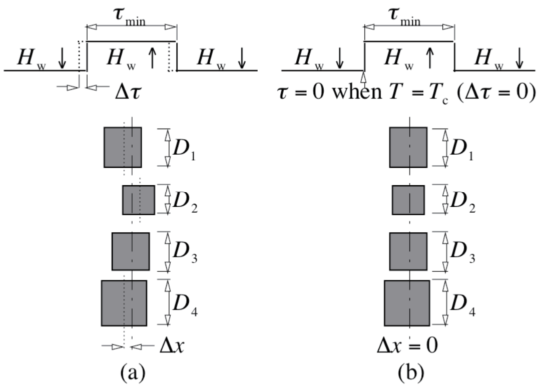

Fig. 1 Writing field switching timing and arrangement of grains for (a) a granular medium and (b) this model.

2.2 Model calculation

The grain magnetization reversal number N during τ is given by[1)]

$$N = f_0 \tau \exp(-K_\beta), \tag{1}$$

where f_0 and K_β are the attempt frequency and the medium thermal stability factor. When τ = 10 years, Eq. (1) is frequently used as a guideline for 10 years of archiving. And, when $\tau = 1/f_0 = \tau_{AP}$ (attempt period), Eq. (1) becomes

$$P = \exp(-K_\beta), \tag{2}$$

which can be used as a guideline for writing and for the grain magnetization reversal probability P for each attempt. This will be confirmed later employing the conventionally used micromagnetic calculation. $K_{\beta+}$ where the grain magnetization M_s is parallel to H_w, and $K_{\beta-}$ where M_s is antiparallel to H_w, are expressed by

$$K_{\beta+}(T, H_w) = \frac{K_u(T)V}{kT}\left(1 + \frac{H_w}{H_k(T)}\right)^2, \tag{3}$$

and

$$K_{\beta-}(T, H_w) = \frac{K_u(T)V}{kT}\left(1 - \frac{H_w}{H_k(T)}\right)^2 \quad (H_w \le H_k(T)),$$

$$K_{\beta-}(T, H_w) = 0 \quad (H_k(T) < H_w), \tag{4}$$

respectively, where K_u, V, k, and $H_k = 2K_u / M_s$ are the anisotropy constant, the grain volume, the Boltzmann constant, and the anisotropy field, respectively. The probability P_+ for each attempt where M_s and H_w change from parallel to antiparallel is expressed by

$$P_+ = \exp(-K_{\beta+}). \tag{5}$$

On the other hand,

$$P_- = \exp(-K_{\beta-}) \tag{6}$$

is the probability for each attempt where M_s and H_w change from antiparallel to parallel.

The key physical quantities in the new model calculation are $P_\pm$, f_0, and their temperature dependence. The temperature dependence of M_s was determined using a mean field analysis[3)], and that of K_u was assumed to be proportional to M_s^2. T_c can be adjusted by the Cu simple dilution of $(Fe_{0.5}Pt_{0.5})_{1-z}Cu_z$. $M_s(T_c, T)$ is a function of T_c and T, and $M_s(T_c = 770\text{ K}, T = 300\text{ K})$ = 1000 emu/cm^3 was assumed. On the other hand, $K_u(T_c, K_u / K_{bulk}, T)$ is a function of T_c, K_u / K_{bulk}, and T, and $K_u(T_c = 770\text{ K}, K_u / K_{bulk} = 1, T = 300\text{ K})$ = 70 Merg/cm^3 was assumed. $P_\pm$ is a function of H_k. If the Curie temperature is high, the temperature dependence of the experimental H_k values can be represented by a mean field analysis[3, 4)].

On the other hand, since f_0 is a function of K_u, and K_u is decreased by elevating the temperature during writing, we require f_0 at the writing temperature rather than that at room temperature. We calculate the f_0 value at the writing temperature with a micromagnetic calculation using the Landau-Lifshitz-Gilbert (LLG) equation[5)].

Furthermore, f_0 is a function of the Gilbert damping constant α[5)]. We have already presented the formula for the temperature dependence of α for ferrimagnetic materials[6)]. This was confirmed experimentally[7)]. The temperature dependence of α can also be expected for ferromagnetic materials used in HAMR. Although α at the writing temperature is necessary, it is unknown. Therefore, we deal with α = 0.1 and 0.01 in this paper.

The calculation procedure is described below. First, the medium is determined by T_c and K_u / K_{bulk}. The grain temperature falls from T_c according to the thermal gradient $\partial T / \partial x$ for the down-track direction and according to v during the writing process. The magnetic property and then $P_{\pm}$ are calculated by employing a mean field analysis for each τ_{AP}. The magnetization direction can be determined by the Monte Carlo method for each τ_{AP}. The bit error rate (bER) is obtained from the mean value of 10^6 bits since the results are scattered. Then the bER can be calculated as a function of H_w [2].

2.3 Micromagnetic calculation

We carried out a micromagnetic calculation using the LLG equation and the temperature dependences of the magnetic properties used in the model calculation. The calculation conditions were also the same except that thirty-two grains were used in the cross-track direction instead of four to achieve a good signal-to- noise ratio (SNR). The writing field is assumed to be spatially uniform, the direction is perpendicular to the medium plane, and the rise time is zero. Both the demagnetizing and the magnetostatic fields are neglected during writing.

The output signal, media noise, and media SNR were calculated using a sensitivity function[8] of 218 nm, which is the same as the cross track width of the simulation region, a wide magnetoresistive read head with a 15 nm shield-shield spacing, and a 4.0 nm head-medium spacing.

3. Calculation Results

3.1 Attempt frequency

First, we calculate the attempt frequency f_0 for media where α = 1 and T_c = 700 K at T = 650 K for various K_u/K_{bulk} values. Figure 2 shows the grain volume V dependence of f_0. Since we use the values of V_m = 193 nm^3 and K_u/K_{bulk} = 0.4 or 0.8 in this paper, f_0 is about 4×10^{11} s^{-1} or 14×10^{11} s^{-1}, respectively. Since f_0 is proportional to $\alpha/(1+\alpha^2)$ [5], the $\tau_{AP}=1/f_0$ values used for α = 0.1 and 0.01 are 0.013 and 0.13 ns, respectively, when K_u/K_{bulk} = 0.4. If K_u/K_{bulk} = 0.8, τ_{AP} is 0.036 ns for α = 0.01.

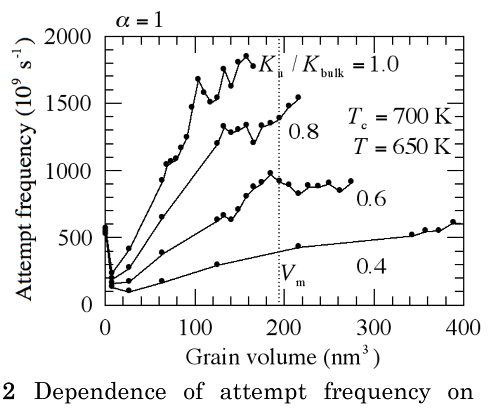

Fig. 2 Dependence of attempt frequency on grain volume for various anisotropy constant ratios K_u/K_{bulk}.

3.2 Thermal gradient

Next, we examine the dependence of the bER on H_w for various $\partial T/\partial x$ values when v = 10 m/s. Figure 3 (a) shows the result for α = 0.1. The decreasing bER as H_w increases from 0 to about 5 kOe is caused by a reduction of normal write-error (WE), and the bER that increases as H_w increases to more than about 5 kOe is caused by erasure-after-write (EAW)[2]. WE occurs during writing. On the other hand, EAW occurs after writing ($\tau_{min} \le \tau$), and the grain magnetization reverses in the opposite direction to the recording direction by changing the H_w direction at τ_{min}. No dependence of WE on $\partial T/\partial x$ is observed, and EAW can be suppressed by increasing $\partial T/\partial x$. This is explained using the time dependence of H_k as shown in Fig. 4 and the time dependence of P_- for each attempt as shown by filled circles in Fig. 5 (a). Since the increase rate of H_k with time becomes steep as $\partial T/\partial x$ increases as shown in Fig. 4, the decrease rate of P_- with time becomes steep as $\partial T/\partial x$ increases in Fig. 5 (a). The writing time is the duration from τ = 0 to a certain time where the P_- value is relatively high, for example 10^{-1} or 10^{-2}. The τ_{AP} value is only 0.013 ns and much shorter than the writing time. The attempt number of magnetization reversal N_{AN} during writing is sufficiently large regardless of the $\partial T/\partial x$ values. Therefore, no dependence of WE on $\partial T/\partial x$ is observed.

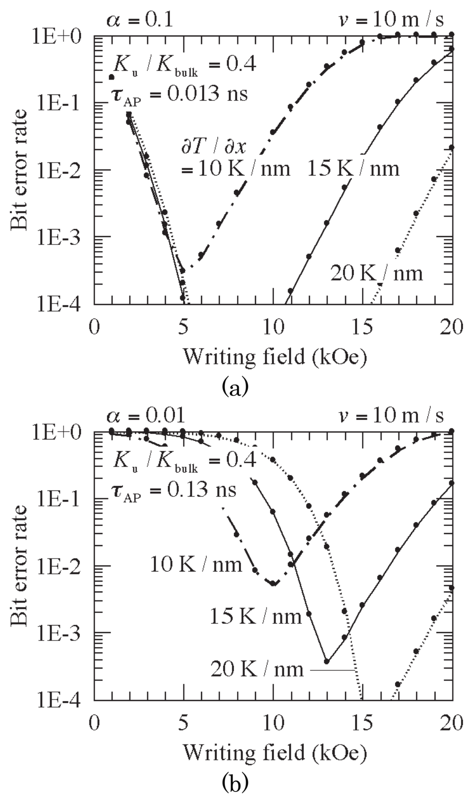

Fig. 3 Dependence of bit error rate (bER) on writing field H_w for various thermal gradients $\partial T/\partial x$ when linear velocity v = 10 m/s where (a) damping constant α = 0.1 and (b) 0.01.

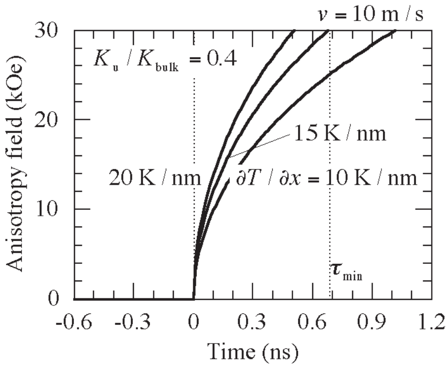

Fig. 4 Dependence of anisotropy field on time for various $\partial T / \partial x$ values.

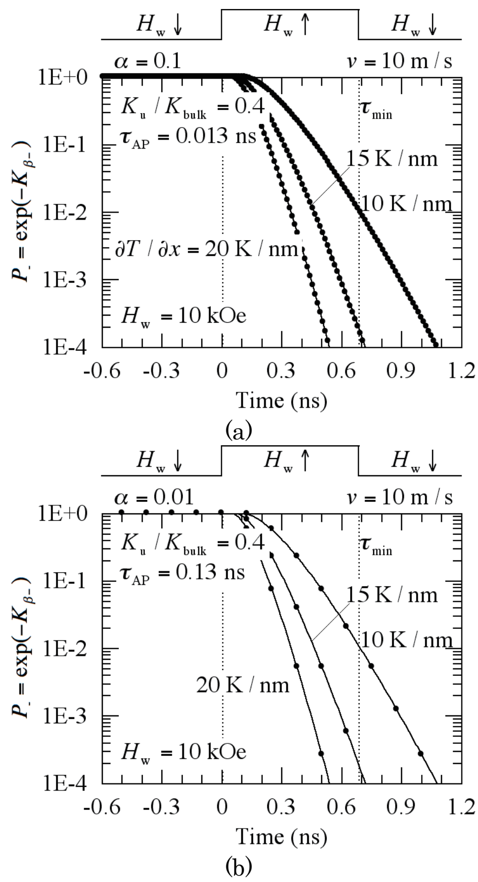

Fig. 5 Dependence of grain magnetization reversal probability P_- on time for various $\partial T / \partial x$ values where (a) α = 0.1 and (b) 0.01.

EAW is determined by P_- after τ_{min} and τ_{AP}. P_- after τ_{min} is decreased as $\partial T / \partial x$ increases as shown in Fig. 5 (a). Therefore, EAW can be suppressed by increasing $\partial T / \partial x$ as shown in Fig. 3 (a).

The dependence of the bER on H_w for α = 0.01 is shown in Fig. 3 (b). The dependence of WE on $\partial T / \partial x$ can be seen, and EAW can be suppressed by increasing $\partial T / \partial x$. This is also explained using the time dependence of P_- for each attempt as shown in Fig. 5 (b). Although the time dependences of P_- are the same in Figs. 5 (a) and (b), τ_{AP} for α = 0.01 is 0.13 ns and much longer than that for α = 0.1. Since N_{AN} during writing is very small, writing becomes difficult and a higher H_w is necessary[2]. Furthermore, since N_{AN} during writing depends on the $\partial T / \partial x$ values, the dependence of WE on $\partial T / \partial x$ can be seen.

Furthermore, EAW for α = 0.01 in Fig. 3 (b) becomes smaller than that for α = 0.1 in Fig. 3 (a) when compared at the same H_w value. Since N_{AN} after writing for α = 0.01 becomes much smaller than that for α = 0.1, EAW for α = 0.01 becomes small.

We also compared the results of the new model calculation and the conventionally used micromagnetic calculation. Figure 6 shows the dependence of the SNR on H_w, which is calculated with a micromagnetic simulation. Figures 6 (a) and (b) correspond to Figs. 3 (a) and (b), respectively. The bER value of 10^{-2} in Fig. 3 may be compared with the SNR value of zero or a few dB in Fig. 6. When α = 0.1 (Fig. 6 (a)), writing is possible in a low H_w, and the tendency of EAW in Fig. 6 (a) is the same as that in Fig 3 (a). On the other hand, when α = 0.01 (Fig. 6 (b)), the tendency for writing to be difficult in a low H_w is also the same as that in Fig. 3 (b).

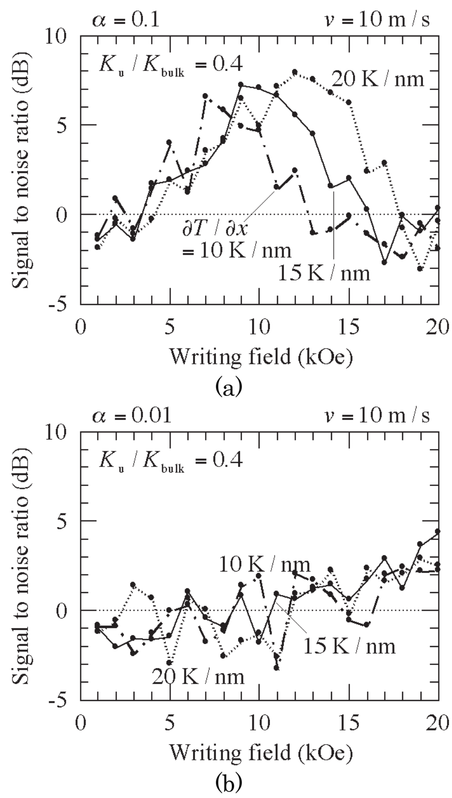

Fig. 6 Dependence of signal-to-noise ratio (SNR) on H_w for various $\partial T / \partial x$ values where (a) α = 0.1 and (b) 0.01.

3.3 Linear velocity

The dependence of bER on H_w for various v values when $\partial T / \partial x$ = 15 K/nm is also examined. Figure 7 (a) shows the result for α = 0.1. WE and EAW are almost independent of v. This is explained using the time dependence of P_- for each attempt as shown by the filled circles in Fig. 8 (a). Since $\tau_{\min}$ is d_B/v, $\tau_{\min}$ changes and decreases with v. However, since d_B and $\partial T/\partial x$ are constant, the temperature at $\tau_{\min}$, that is $T_c - d_B \cdot \partial T/\partial x$, does not change with v. The P_- values at $\tau_{\min}$ are the same regardless of the v values. In addition, τ_{AP} is very short, and N_{AN} during writing is sufficiently large regardless of the v values. Therefore, WE and EAW have almost no dependence on v.

The bER dependence on H_w for α = 0.01 is shown in Fig. 7 (b). The WE dependence on v can be seen, and is suppressed by decreasing v. This is also explained using the time dependence of P_- for each attempt as shown in Fig. 8 (b). Although N_{AN} is only two when $0 \le \tau < \tau_{\min}$ for v = 20 m/s, it becomes ten for v = 5 m/s. Therefore, N_{AN} during writing is increased as v decreases, and WE can be suppressed by decreasing v. In other words, since τ_{AP} is long, it is effective to write slowly by reducing v on the reduction of WE.

Figure 9 shows the SNR dependence on H_w, which is calculated with a micromagnetic simulation. Figures 9 (a) and (b) correspond to Figs. 7 (a) and (b), respectively. When α = 0.1, the tendency of the bER value of 10^{-2} in Fig. 7 (a) is the same as that of the SNR value of zero or a few dB in Fig. 9 (a). Furthermore, when α = 0.01, the tendency for SNR to improve by decreasing v in Fig 9. (b) corresponds to the fact that WE decreases as v decreases in Fig. 7 (b).

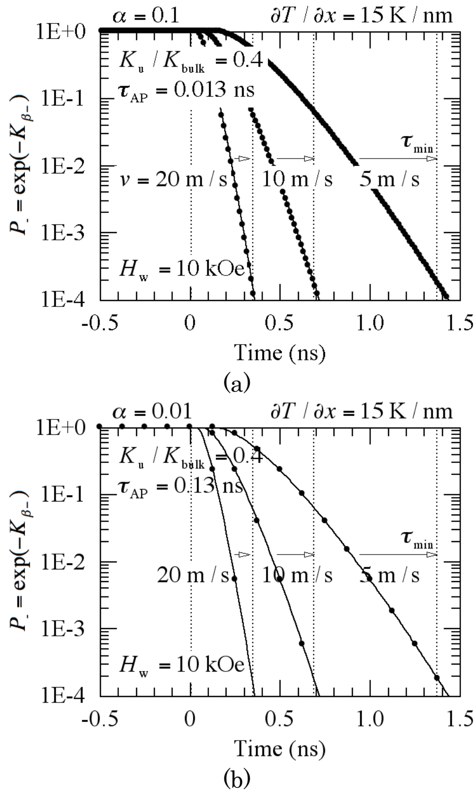

Fig. 8 Dependence of P_- of grain on time for various v values where (a) α = 0.1 and (b) 0.01.

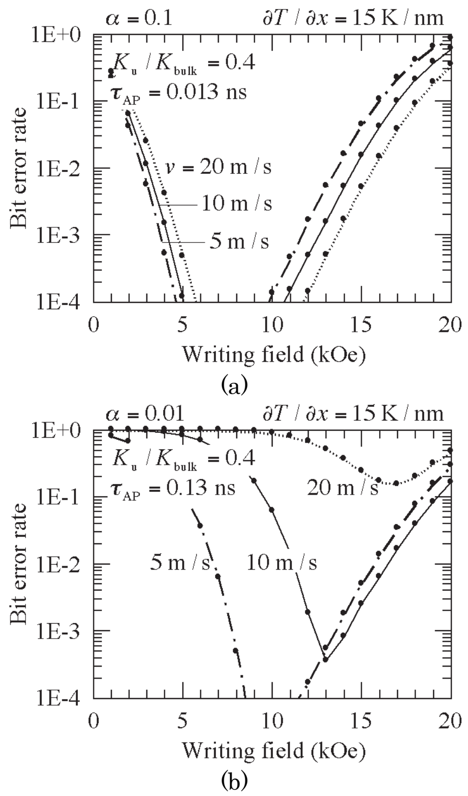

Fig. 7 Dependence of bER on H_w for various v values when $\partial T/\partial x$ = 15 K/nm where (a) α = 0.1 and (b) 0.01.

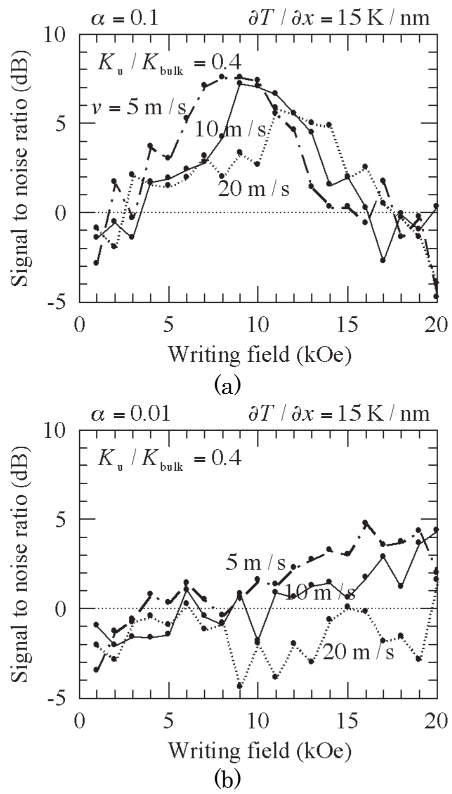

Fig. 9 Dependence of SNR on H_w for various v values where (a) α = 0.1 and (b) 0.01.

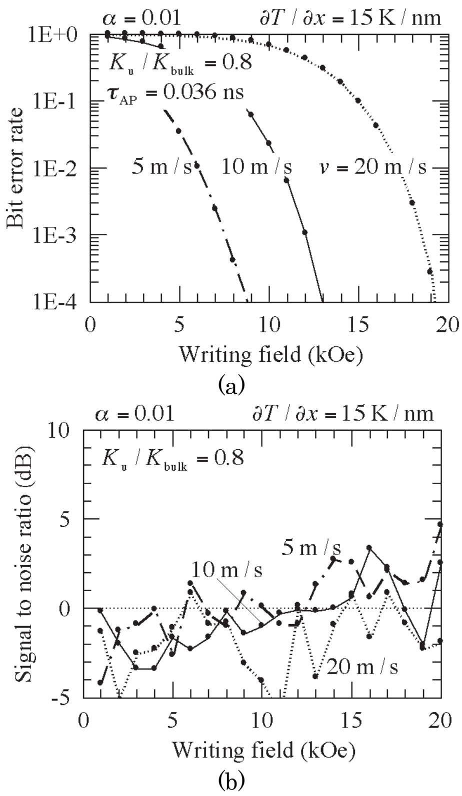

Fig. 10 (a) Dependence of bER and (b) dependence of SNR on H_w for α = 0.01 and K_u/K_{bulk} = 0.8.

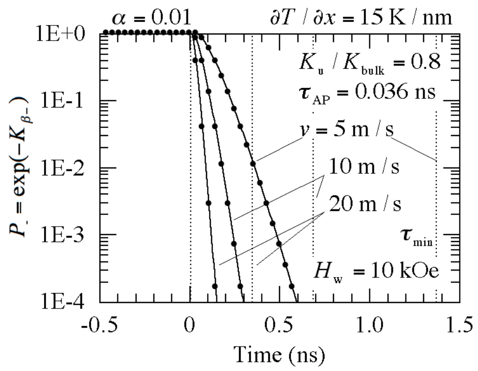

Fig. 11 Dependence of P_- of grain on time for α = 0.01 and K_u/K_{bulk} = 0.8.

3.4 Anisotropy constant

When α = 0.01, τ_{AP} is too long to write with a low H_w. Since f_0 can be increased, then τ_{AP} can be reduced by increasing K_u/K_{bulk} as shown in Fig. 2, we examine the writing properties for a high K_u/K_{bulk}.

Figure 10 shows (a) the dependence of bER and (b) the corresponding dependence of SNR on H_w for α = 0.01 and K_u/K_{bulk} = 0.8 instead of K_u/K_{bulk} = 0.4 in Fig. 7 (b) and Fig. 9 (b), respectively. The overall tendencies for WE are the same in Fig. 10 (a) and Fig. 7 (b). This can be explained using Fig. 11. The τ_{AP} value for α = 0.01 and K_u/K_{bulk} = 0.8 is 0.036 ns, which is decreased from 0.13 ns by increasing K_u/K_{bulk}. However, the reduction rate of P_- becomes steep by increasing K_u/K_{bulk} as shown in Fig. 11 in comparison with Fig. 8 (b). Therefore, the WE values are almost the same for K_u/K_{bulk} = 0.4 and 0.8.

A comparison of Fig. 10 (a) and Fig. 7 (b) shows that EAW is suppressed by increasing K_u/K_{bulk}. This can be understood clearly from the steep P_- decrease in Fig. 11.

4. Conclusions

We calculated the writing field dependence of the bit error rate (bER) for the Gilbert damping constants α = 0.1 and 0.01 in heat-assisted magnetic recording (HAMR) using a new model calculation.

When α = 0.1, write-error (WE) is smaller, and erasure-after-write (EAW) is larger than that for α = 0.01 since the attempt period τ_{AP} is short. EAW decreases as the thermal gradient increases.

When α = 0.01, writing becomes difficult and a high writing field is necessary since τ_{AP} is long. WE decreases as the thermal gradient or the linear velocity decreases.

EAW can be decreased by increasing the anisotropy constant.

We confirmed the results of the new model calculation by comparison with those of the conventionally used micromagnetic calculation. The overall tendencies were the same. Therefore, the outline of the impact of α on bER in HAMR can be understood by the grain magnetization reversal probability and the attempt period used in the new model calculation.

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References

1) S. H. Charap, P. -L. Lu, and Y. He: *IEEE Trans. Magn.*, **33**, 978 (1997).
2) T. Kobayashi, F. Inukai, K. Enomoto, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **41**, 1 (2017).
3) T. Kobayashi, Y. Isowaki, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **39**, 8 (2015).
4) T. Kobayashi, Y. Isowaki, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **40**, 28 (2016).
5) Y. Nakatani, Y. Uesaka, N. Hayashi, and H. Fukushima: *J. Magn. Magn. Mat.*, **168**, 347 (1997).
6) T. Kobayashi, H. Hayashi, Y. Fujiwara, and S. Shiomi: *IEEE Trans. Magn.*, **41**, 2848 (2005).
7) C. D. Stanciu, A. V. Kimel, F. Hansteen, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing: *Phys. Rev. B*, **73**, 220402(R) (2006).
8) Y. Kanai, Y. Jinbo, T. Tsukamoto, S. J. Greaves, K. Yoshida, and H. Muraoka: *IEEE. Trans. Magn.*, **46**, 715 (2010).

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