Information Stability in Magnetic Recording

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This study reveals the relationship between the grain number per bit, thermal stability factor, and standard deviation of grain size to bit error rate (bER) after 10 years of archiving in granular magnetic recording media when the grain number is reduced. Furthermore, this discussion is extended to 1 grain per bit (bit patterned media, BPM). To simulate the bER, random grain sizes with a normal distribution are generated, and the grain error probability is calculated. The bER worsens when the grain number per bit is decreased. Increasing the thermal stability factor and decreasing the standard deviation of the grain size improve the bER. We found that the BPM requires a higher thermal stability factor and/or a lower standard deviation of the grain size than granular media. The speed at which information degrades with a high thermal stability factor is different from that with a low factor even if the bERs after 10 years are the same.

Key words: magnetic recording, granular media, bit patterned media, bit error rate, grain number

1. Introduction

Information stability after 10 years of archiving in magnetic recording media has been widely discussed using the thermal stability factor $K_u V / kT$ ¹⁾, where K_u , V , k , and T are the anisotropy constant of the media, the grain volume of the media, the Boltzmann constant, and temperature, respectively. However, the bit error rate (bER) is an intrinsic index for the archival stability of information. The bER in granular media is a function of grain number per bit and the standard deviation of grain size as well as the thermal stability factor. The grain number per bit has tended to decrease for high-density recording in granular media.

In this study, we reveal the relationship between the grain number per bit, the thermal stability factor, and the standard deviation of grain size to the bER, when the grain number is reduced from 10 to 4. This discussion is extended to 1 grain per bit (bit patterned media, BPM). Furthermore, the speed at which information degrades is also discussed.

2. Calculation Method

We made four assumptions in this simulation:

- (1) The mean grain-size a_m is 4.5 nm.
- (2) The standard deviation of the grain size σ is 0.9 nm (20 % of a_m) (typical).
- (3) The thermal stability factor of the mean grain $K_u V_m / kT$ is 80 (typical), where V_m is the mean grain volume, namely,
 $V_m \propto a_m^2 h$ (h : thickness).
- (4) The grain error probability P for an archive period t is $f_0 t \exp(-K_u V / kT)$ ¹⁾, where V and f_0 are the grain volume and the attempt frequency, respectively, namely,
 $V \propto a^2 h$ (a : grain size),
 $f_0 = 1.0 \times 10^{11} \text{ s}^{-1}$ (typical)^{2, 3)}, and
 $t = 3.2 \times 10^8 \text{ s}$ (10 years) (typical).

To simulate the bER, we use a computer to generate random grain sizes with a normal distribution, where

the mean is 4.5 nm and the standard deviation is 0.9 nm (20 %), as shown in Fig. 1. The total grain number is 1×10^7 , and a normal distribution was confirmed.

The probability of the mean grain error P_m for 10 years of archiving is given as

$$P_m = f_0 t \exp\left(-\frac{K_u V_m}{kT}\right) = 5.7 \times 10^{-16} \quad (1)$$

from the assumptions. And the grain error probability P for any grain size can be calculated as shown below.

Fig. 1 Generation of random grain size a with a normal distribution using a computer.

Fig. 2 Grain error probability and probability density function of grain size a as a function of a .

$$P = f_0 t \exp\left(-\frac{K_u V}{kT}\right) = f_0 t \exp\left(-\frac{K_u V_m}{kT} \cdot \frac{V}{V_m}\right) \\ = f_0 t \exp\left(-\frac{K_u V_m}{kT} \cdot \frac{a^2}{a_m^2}\right). \quad (2)$$

The dependence of the grain error probability on the grain size is shown in Fig. 2. Figure 2 also shows the probability density function of the grain size. When the grain size decreases from $a_m = 4.5$ nm, the grain error probability is greatly increased. The probability exceeds one when the grain size is less than 3.4 nm using Eq. (2). This means that the magnetization of the grain will be reversed many times over a period of 10 years. Since such a case can be interpreted as one error, the probability is defined as one for a grain size of less than 3.4 nm in this simulation.

It should be noted that the probability density function for a grain size of less than 3.4 nm is not very small.

Next we explain our method for calculating the total ${}_4\text{bER}_{\text{tot}}$ when there are 4 grains per bit. The probability of a 3 grain-error bit ${}_4\text{bER}_3$ is given by

$${}_4\text{bER}_3 = P_1 P_2 P_3 (1 - P_4) + P_1 P_2 (1 - P_3) P_4 \\ + P_1 (1 - P_2) P_3 P_4 + (1 - P_1) P_2 P_3 P_4, \quad (3)$$

where P_i is the probability of the i -th grain error calculated by Eq. (2). Similarly, the probability of a 4 grain-error bit ${}_4\text{bER}_4$ is obtained by

$${}_4\text{bER}_4 = P_1 P_2 P_3 P_4. \quad (4)$$

The total bER (${}_4\text{bER}_{\text{tot}}$) is the sum of these bERs, that is,

$${}_4\text{bER}_{\text{tot}} = {}_4\text{bER}_3 + {}_4\text{bER}_4. \quad (5)$$

An error-correcting code (ECC) is assumed to be able to correct signals from bits having grain-error less than 65 % (e. g. 2 and 1 grain-error bits for 4 grains per bit). The grain-size effect on reproduction signal is ignored.

The total bER (${}_{10}\text{bER}_{\text{tot}}$) for 10 grains per bit, and ${}_1\text{bER}_{\text{tot}}$ for 1 grain per bit are defined as

$${}_{10}\text{bER}_{\text{tot}} = {}_{10}\text{bER}_7 + {}_{10}\text{bER}_8 + {}_{10}\text{bER}_9 + {}_{10}\text{bER}_{10}, \text{ and} \quad (6)$$

$${}_1\text{bER}_{\text{tot}} = {}_1\text{bER}_1, \quad (7)$$

respectively.

3. Bit Error Rate

First of all, we discuss calculation accuracy. Calculated bERs are shown in Fig. 3 (a) for 10 grains, 4 grains, and 1 grain per bit. For example, the bER for bit number "1E+4" implies the mean bER for a 1E+4 bit calculation. We performed ten calculations for each bit number. When the bit number is relatively small, the bER calculation results are scattered for the same bit number. However, if the bit number is sufficiently large ($> 100 / (\text{bER for } 1\text{E}+7 \text{ bit calculation})$), the results of the ten calculations are almost the same.

The bER for 4 grains per bit is two orders worse than that for 10 grains per bit. Furthermore, the bER for 1 grain per bit (BPM) is one order worse than that for 4 grains per bit. If one bit contains many grains, the bER becomes low since the probability of simultaneous errors for most of the grains in one bit is very low.

Fig. 3 (a) bER as a function of bit number, and (b) bER as a function of attempt frequency f_0 for 10 grains, 4 grains, and 1 grain per bit.

For example, when $P = 0.1$, the bER for 10 grains per bit is only ${}_{10}\text{bER}_{\text{tot}} \approx {}_{10}\text{bER}_7 = {}_{10}\text{C}_7 P^7 (1 - P)^{10-7} = 9\text{E}-6$. On the other hand, the bER for 4 grains per bit is as high as ${}_4\text{bER}_{\text{tot}} \approx {}_4\text{bER}_3 = {}_4\text{C}_3 P^3 (1 - P)^{4-3} = 4\text{E}-3$. Therefore, the bER becomes worse when the grain number per bit is decreased.

The attempt frequency is an uncertain parameter. Figure 3 (b) shows the bER dependence on the attempt frequency. The overall tendency of the bERs is not greatly changed by changing the attempt frequency by a few orders.

Increasing $K_u V_m / kT$, decreasing σ , and enhancing the ECC can improve the bER.

Figure 4 shows the bER dependence on $K_u V_m / kT$ for 4 grains and 1 grain per bit. With 4 grains per bit, increasing $K_u V_m / kT$ is effective in decreasing the bER. Increasing the thickness as well as increasing the anisotropy constant is effective in decreasing the bER. On the other hand, the bER of 1 grain per bit for $K_u V_m / kT = 230$ is as high as $3\text{E}-3$.

Figure 5 shows the bER dependence on σ for 4 grains and 1 grain per bit. Although, with 4 grains per bit, decreasing σ is also effective in decreasing the bER, the bER of 1 grain per bit for $\sigma = 0.45$ nm (10 %) is as high as $8\text{E}-3$.

These results show that the BPM needs a higher $K_u V_m / kT$ and/or lower σ than granular media. Therefore we examine the bER of the BPM in more detail.

Fig. 4 bER as a function of thermal stability factor $K_u V_m / kT$ for 4 grains and 1 grain per bit.

Fig. 5 bER as a function of the standard deviation of grain size σ for 4 grains and 1 grain per bit.

The dependence of the bER on σ for 1 grain per bit (BPM) is shown in Fig. 6 for several $K_u V_m / kT$ values. When $K_u V_m / kT$ is high, for example $K_u V_m / kT = 120$, decreasing σ is effective in decreasing the bER, and a bER of $1E-3$ can be achieved for $\sigma = 0.555$ nm (12 %). The bER is $1E-3$ for $K_u V_m / kT = 100$ and for $\sigma = 0.468$ nm (10 %). On the other hand, when $K_u V_m / kT = 80$, the bER is $1E-3$ only for $\sigma = 0.351$ nm (8 %). Even if a granular type medium of 4 grains per bit is used, a bER of $1E-3$ can be achieved for $K_u V_m / kT = 80$ and for only $\sigma = 0.716$ nm (16 %).

Figure 7 shows why the BPM requires a higher $K_u V_m / kT$ value and/or a lower σ . When $K_u V_m / kT$ is low (60) as shown Fig. 7 (a), the grain size at which the probability of the grain error becomes one is 3.9 nm. At grain sizes of less than 3.9 nm, the probability density functions for $\sigma = 0.9$ nm (20 %) and 0.45 nm (10 %) are not very small. Therefore decreasing σ is not very effective in decreasing the bER. By contrast, when $K_u V_m / kT$ is high (120) as shown Fig. 7 (b), the grain size for a probability of 1 decreases to 2.8 nm ($\propto \sqrt{1/(K_u V_m / kT)}$). Although the probability density function for $\sigma = 0.9$ nm (20 %) is not very small at grain sizes of less than 2.8 nm, the probability density function for 0.45 nm (10 %) is sufficiently small. Therefore if $K_u V_m / kT$ is high, σ is very effectively decreased.

Fig. 6 bER as a function of standard deviation of grain size σ for 1 grain per bit (bit patterned media).

Fig. 7 Grain error probability and probability density function as a function of grain size for (a) $K_u V_m / kT = 60$ and (b) $K_u V_m / kT = 120$.

Calculation results are summarized in Table 1. Improvement of $K_u V_m / kT$, σ or the ECC in future is an uncertain parameter. Therefore we represent the results with various combinations of $K_u V_m / kT$, σ and the ECC as a guideline for development.

When the bER $< 2E-5$, a media with 10 grains per bit requires only $K_u V_m / kT = 80$ and $\sigma = 20$ % (Table 1 (a)).

On the other hand, a 4 grains per bit medium needs $K_u V_m / kT = 80$ and $\sigma = 11$ %, or $K_u V_m / kT = 138$ and $\sigma = 20$ % (Table 1 (b) and (c)). It appears to be difficult to realize bER $< 2E-5$. The calculation results

Table 1 Calculation results.

	Grain # (1/bit)	$K_u V_m / kT$	σ (nm)	σ (%)	bER
(a)	10	80	0.9	20	2E-5
(b)	4	80	0.515	11	2E-5
(c)	4	138	0.9	20	2E-5
(d)	4	80	0.716	16	1E-3
(e)	4	95	0.9	20	1E-3
(f)	1	80	0.351	8	1E-3
(g)	1	100	0.468	10	1E-3
(h)	1	120	0.555	12	1E-3

are also shown in Table 1 (d) and (e), when the bER is permitted to be less than 1E-3 by enhancing the ECC. To realize a 4 grains per bit medium requires $K_u V_m / kT = 80$ and $\sigma = 16\%$, or $K_u V_m / kT = 95$ and $\sigma = 20\%$.

The results for BPM are shown as examples in Table 1 (f), (g), and (h). For example, $K_u V_m / kT = 80$ and only $\sigma = 8\%$ are needed. The grain size is randomly distributed in the granular media. On the other hand, the dot size is artificially controlled in the BPM. Therefore, it is difficult to decide whether or not it is easy to realize a low σ in the BPM compared with the granular media.

In other words, the high $K_u V_m / kT$ has been regarded as the advantage of BPM over granular media. However, BPM have or do not have this advantage depending on whether or not it is easy to fabricate the BPM with a low σ .

4. Speed of Information Degradation

Equation (2) is a function of an archive period. Therefore, we can calculate the speed at which information degrades using Eq. (2). Figure 8 (a) shows the bER as a function of an archive period for 10 grains per bit, (b) and (c) 4 grains per bit, and (d) 1 grain per bit media. 3.2E+8 s is 10 years, and 3.2E+4 s is 0.001 year or about 9 hours.

The initial bER for 10 grains per bit must be less than 1E-7 for $K_u V_m / kT = 80$ when the bER is 2E-5 after 10 years of archiving (Fig. 8 (a)). The initial bER for 4 grains per bit is also 1E-7 for $K_u V_m / kT = 80$ as shown in Fig. 8 (b). These bERs are almost the same. The degradation speed for $K_u V_m / kT = 138$ is much slower than that for $K_u V_m / kT = 80$ even if the bERs after 10 years for 4grains per bit are the same as shown in Fig. 8 (b). Since $K_u V_m / kT$ gives the grain error probability, increasing $K_u V_m / kT$ reduces the degradation speed.

Figure 8 (c) shows the speed at which information degrades for 4 grains per bit, and Fig. 8 (d) shows that for 1 grain per bit, when the bER is 1E-3 after 10 years of archiving. The degradation speed for 1 grain per bit seems to be somewhat faster than that for 4 grains per bit even if the $K_u V_m / kT$ values are the same.

Fig. 8 bER as a function of an archive period for (a) 10 grains per bit, (b) and (c) 4 grains per bit, and (d) 1 grain per bit media. The bERs after 10 years of archiving are (a) and (b) 2E-5, and (c) and (d) 1E-3.

In any case, the initial bER has to be one or two orders lower than that after 10 years of archiving.

5. Conclusions

The bERs were calculated for 10 grains, 4 grains, and 1 grain per bit media (BPM) after 10 years of archiving.

The bER for 4 grains per bit was two orders worse than that for 10 grains per bit. Furthermore, the bER for 1 grain per bit was one order worse than that for 4 grains per bit.

If one bit contains many grains, the bER becomes low since the probability of simultaneous errors for most of the grains in one bit is very low. Therefore, the bER worsens when the grain number per bit is decreased.

With 4 grains per bit, increasing the thermal stability factor $K_u V_m / kT$ is effective in decreasing the bER. Increasing both the thickness and the anisotropy constant is effective in decreasing the bER, as is decreasing the standard deviation of the grain size σ .

We found that the BPM require a higher $K_u V_m / kT$ and/or a lower σ than the granular media. The high $K_u V_m / kT$ has been regarded as the advantage of BPM over granular media. However, the BPM have or do not have this advantage depending on whether or not BPM with a low σ are easy to fabricate.

The speed at which information degrades was also calculated. The degradation speed for a high $K_u V_m / kT$ value is slower than that for a low $K_u V_m / kT$ value even if the bERs after 10 years are the same. Since $K_u V_m / kT$ gives the grain error probability, increasing $K_u V_m / kT$ makes the degradation speed slow. In any case, the initial bER has to be one or two orders lower than that after 10 years of archiving.

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