Information Degradation during Archiving in Heat-Assisted Magnetic Recording

T. Kobayashi, Y. Nakatani*, and Y. Fujiwara

Graduate School of Engineering, Mie Univ., 1577 Kurimamachiya-cho, Tsu 514-8507, Japan

*Graduate School of Informatics and Engineering, Univ. of Electro-Communications, 1-5-1 Chofugaoka, Chofu 182-8585, Japan

We examine the dependence of information stability on certain medium parameters, namely mean Curie temperature, grain height, and anisotropy constant ratio in 4 Tbps heat-assisted magnetic recording, for 10 years of archiving. We introduce a minimum normalized readout field H_0 after 10 years of archiving and an information degradation rate R_0 during 10 years of archiving. To interpret the results, we investigate whether there is a correlation between H_0 or R_0 and an effective thermal stability factor for 9 and 6 grains/bit. We find that there is a strong correlation since the anisotropy constant is much larger than the shape anisotropy. The H_0 and R_0 values are functions of the effective thermal stability factor and grain number, and are independent of grain number per bit. The effective thermal stability factor necessary for no information degradation is more than about 120. Furthermore, there is a weak correlation between the initial readout field or minimum readout field after 10 years of archiving and the effective thermal stability factor.

Key words: HAMR, bit error rate, degradation rate, thermal stability factor, grain number

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 $K_u V / (kT)$, where K_u , V , k , and T are the grain anisotropy constant, grain volume, Boltzmann constant, and temperature, respectively¹⁾. 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 an HAMR medium parameter, namely, the medium anisotropy constant ratio K_u / K_{bulk} ²⁾ 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_u / K_{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 relatively low T_c .

We have already calculated the numerical values of $K_u V / (kT)$ and K_u / K_{bulk} necessary for 10 years of archiving in 2 Tbps HAMR by employing a bit error rate calculation using the grain error probability³⁾. We used an error (signal) threshold of 0.5 as a calculation condition.

In this paper, we estimate the minimum normalized readout field related to the minimum error threshold, that must be readable without error after 10 years of archiving in 4 Tbps HAMR. Furthermore, we also

examine the information degradation rate during 10 years of archiving. The mean Curie temperature T_{cm} affects various properties in HAMR. The larger grain aspect ratio h / D_m of the grain height (medium layer thickness) h to the mean grain size D_m appears to make it too difficult to manufacture the medium. Furthermore, there is a concern that K_u , namely, K_u / K_{bulk} decreases as D_m decreases. Thus, we examine the dependence of information stability on the medium parameters T_{cm} , h , and K_u / K_{bulk} .

2. Calculation Method and Conditions

2.1 Magnetic properties

The temperature dependence of the magnetization M_s was calculated by employing a mean field analysis⁴⁾, and that of the anisotropy constant K_u was assumed to be proportional to M_s^2 ⁵⁾. $M_s(T_c, T)$ 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. With this assumption, the M_s value can be calculated for all T_c and T values.

The anisotropy constant $K_u(T_c, K_u / K_{\text{bulk}}, T)$ is a function of T_c , K_u / K_{bulk} , and T . And $K_u(T_c = 770 \text{ K}, K_u / K_{\text{bulk}} = 1, T = 300 \text{ K}) = 70 \text{ Merg/cm}^3$ was assumed for bulk FePt. With this assumption, the K_u value can be calculated for all T_c , K_u / K_{bulk} , and T values. No intrinsic distribution of K_u was assumed. However, there was a fluctuation in K_u caused by T_c variation.

The T_c value can be adjusted by changing the Cu composition z for $(\text{Fe}_{0.5}\text{Pt}_{0.5})_{1-z}\text{Cu}_z$.

2.2 Field strength

The recording density is 4 Tbps, and the bit area S is 161 nm^2 . We assumed the medium to be granular. One bit has m grains in the cross-track direction and n grains in the down-track direction, namely, there are $m \times n$ grains/bit. The mean grain size D_m was

Corresponding author: T. Kobayashi (e-mail: kobayashi@phen.mie-u.ac.jp).

determined by

$$D_m = \sqrt{\frac{S}{m \times n}} - \Delta_G, \quad (1)$$

where Δ_G is the intergrain spacing. The bit aspect ratio is $D_T/D_B = m/n$ where $D_T = m(D_m + \Delta_G)$ and $D_B = n(D_m + \Delta_G)$ are the track width and bit pitch, respectively. The flying height $h_{fly} = 4.0$ nm is the distance between the magnetic head reader and the recording layer surface.

The magnetic field strength from the medium at the center of m grains and the reader position was calculated using $m \times 30$ grains with no grain size distribution when calculating the field strength.

2.3 Bit error rate

The bit error rate bER was calculated by employing each grain error probability P_i ,

$$P_i = 1 - \exp\left(-f_0 t \exp\left(-\frac{K_{u\text{eff}} V}{kT}\right)\right), \quad (2)$$

taking account of the shape anisotropy $M_s H_d/2$ using a self-demagnetizing field H_d where f_0 , $t = 10$ years, and $K_{u\text{eff}}$ are the attempt frequency⁶⁾, time, and effective anisotropy constant, respectively. And $K_{u\text{eff}} = K_u - M_s H_d/2$, $H_d = 8M_s \arctan(D^2/(h\sqrt{2D^2 + h^2}))$, $V = D \times D \times h$ where D is the grain size. Since H_d does not affect the results as mentioned below, the magnetostatic field from surrounding grains can also be ignored. It was assumed that there is no exchange coupling between grains. For example, for 4 grains/bit, the 1 grain-error bit error rate ${}^4\text{bER}_1$ is expressed as

$${}^4\text{bER}_1 = Er_1 P_1 (1 - P_2)(1 - P_3)(1 - P_4) + \dots + Er_4 (1 - P_1)(1 - P_2)(1 - P_3)P_4, \quad (3)$$

the 2 grain-error bit error rate ${}^4\text{bER}_2$ as

$${}^4\text{bER}_2 = Er_{12} P_1 P_2 (1 - P_3)(1 - P_4) + \dots + Er_{34} (1 - P_1)(1 - P_2)P_3 P_4, \quad (4)$$

the 3 grain-error bit error rate ${}^4\text{bER}_3$ as

$${}^4\text{bER}_3 = Er_{123} P_1 P_2 P_3 (1 - P_4) + \dots + Er_{234} (1 - P_1)P_2 P_3 P_4, \quad (5)$$

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

$${}^4\text{bER}_4 = P_1 P_2 P_3 P_4, \quad (6)$$

where

$$Er_k = 1, \text{ if } \frac{\sum_{i,j} M_{sij}(T_{cij}, 330 \text{ K}) D_{ij}^2}{(m \times n) M_s(T_{cm}, 330 \text{ K}) D_m^2} \leq E_{th}, \quad (7)$$

and

$$Er_k = 0, \text{ if } \frac{\sum_{i,j} M_{sij}(T_{cij}, 330 \text{ K}) D_{ij}^2}{(m \times n) M_s(T_{cm}, 330 \text{ K}) D_m^2} > E_{th}. \quad (8)$$

Errors occur in some grains of a bit. We assumed that if

the ratio of $\sum_{i,j} M_{sij}(T_{cij}, 330 \text{ K}) D_{ij}^2$ to $(m \times n) M_s(T_{cm}, 330 \text{ K}) D_m^2$ in Eqs. (7) and (8) is more than the error threshold E_{th} , the bit is error-free after 10 years of archiving where the numerator $\sum_{i,j} M_{sij}(T_{cij}, 330 \text{ K}) D_{ij}^2$ is the surface magnetic charge of the grains for which the magnetization turns in the recording direction, and the denominator $(m \times n) M_s(T_{cm}, 330 \text{ K}) D_m^2$ is the total surface magnetic charge at the readout temperature of 330 K. M_{sij} , T_{cij} , and D_{ij} are the magnetization, the Curie temperature, and the grain size of the ij -th grain, respectively. The total bit error rate ${}^4\text{bER}$ is the summation of each bit error rate ${}^4\text{bER}_k$ as follows

$${}^4\text{bER} = \sum_k {}^4\text{bER}_k. \quad (9)$$

The calculation bit number was $1\text{E}+7$. The criterion determining whether or not information is stable was assumed to be a bER of $1\text{E}-3$.

The minimum normalized readout field H_0 after 10 years of archiving can roughly be represented by E_{th} as

$$H_0 = 2E_{th} - 1. \quad (10)$$

We defined the information degradation rate R_0 during 10 years of archiving as

$$R_0 = \frac{\text{bER}(10.0 \text{ yrs}) - \text{bER}(0.001 \text{ yrs})}{\text{bER}(0.001 \text{ yrs})}. \quad (11)$$

For example, the R_0 values are 99, 9.0, and 0.25 when the $\text{bER}(0.001 \text{ yrs})$ values are $1\text{E}-5$, $1\text{E}-4$, and $8\text{E}-4$, respectively, since the $\text{bER}(10.0 \text{ yrs})$ value is $1\text{E}-3$. The R_0 value for no information degradation is less than about 0.25.

The conditions used when calculating the bER are summarized in Table 1. We assumed that the intergrain spacing Δ_G was 1.0 nm. The grain size distribution was log-normal with a standard deviation σ_D/D_m of 15 %, and the T_c distribution was normal with a standard deviation σ_{Tc}/T_{cm} of 2 %. The attempt frequency f_0 is a function of the Gilbert damping constant α ⁶⁾, and we used an α value of 0.1. The storage temperature T_{sto} was 350 K since we take a certain margin for temperature into account.

Table 1 Conditions for bit error rate calculation.

Recording density (Tbps)	4
Intergrain spacing Δ_G (nm)	1.0
Standard deviation σ_D/D_m (%) of D_m	15
Standard deviation σ_{Tc}/T_{cm} (%) of T_{cm}	2
Gilbert damping constant α	0.1
Storage temperature T_{sto} (K)	350

3. Calculation Results

3.1 Various medium parameters

The bER value as a function E_{th} and H_0 after 10 years of archiving for various T_{cm} values in $m \times n = 3 \times 3 = 9$ grains/bit is shown in Fig. 1 (a) where $h = 10.5$ nm and $K_u/K_{bulk} = 0.8$. The bER value increases as the

T_{cm} value decreases. There is no E_{th} more than 0.5, namely, no H_0 more than 0 that satisfies $bER = 1E-3$ for $T_{cm} = 600$ K. The time dependence of the bER is shown in Fig. 1 (b) where 0.001 years corresponds to about 9 hours. Errors increase over time for $T_{cm} = 650$ K, therefore the initial bER before archiving must be low, for example, $1E-4$. On the other hand, the error scarcely increases for $T_{cm} = 750$ K.

Fig. 1 (a) Bit error rate as a function of error threshold and normalized field amplitude after 10 years of archiving and (b) time dependence of bit error rate during 10 years of archiving for various mean Curie temperatures T_{cm} ($h = 10.5$ nm and $K_u/K_{bulk} = 0.8$).

Figure 2 shows (a) the z component H_z of the initial readout field for the down-track direction and (b) the minimum readout field $H_0 \times H_z$ that must be readable without error after 10 years of archiving. Although the error scarcely increases for $T_{cm} = 750$ K as shown in Fig. 1 (b), the $H_0 \times H_z$ value is small as shown in Fig. 2 (b). This means that the error is caused by the cluster of small grains. The grain number per bit may increase at that time, and the $H_0 \times H_z$ value may be larger. This problem is a future subject for study. In contrast, since errors increase over time for $T_{cm} = 650$ K as shown in

Fig. 1 (b), the $H_0 \times H_z$ value becomes small as shown in Fig. 2 (b).

Fig. 2 (a) Initial readout field H_z and (b) minimum readout field $H_0 \times H_z$ after 10 years of archiving for various mean Curie temperatures T_{cm} ($h = 10.5$ nm and $K_u/K_{bulk} = 0.8$).

If $T_{cm} = 750$ K, $h = 6.5$ nm, and $K_u/K_{bulk} = 0.8$, or if $T_{cm} = 750$ K, $h = 10.5$ nm, and $K_u/K_{bulk} = 0.5$, there is no E_{th} more than 0.5, or no H_0 more than 0 that satisfies $bER = 1E-3$.

The results for various medium parameters, namely T_{cm} , h , and K_u/K_{bulk} , are summarized in Tables 2 and 3 for $m \times n = 3 \times 3 = 9$ grains/bit and $m \times n = 3 \times 2 = 6$ grains/bit, respectively. H_{zpeak} is the peak z component H_z of the initial readout field, and $H_0 \times H_{zpeak}$ is the minimum peak readout field that must be readable without error after 10 years of archiving. When adjacent track interference is considered, some grains are used as a guard band. Therefore, we also examined H_0 , R_0 , H_{zpeak} , and $H_0 \times H_{zpeak}$ for $m \times n = 2 \times 3 = 6$ grains in 9 grains/bit and $m \times n = 2 \times 2 = 4$ grains in 6 grains/bit.

The information during 10 years of archiving is stable for 9 grains/bit media with $T_{cm} = 750$ K, $h = 10.5$ nm, and $K_u/K_{bulk} = 0.8$ as shown in Table 2.

Table 2 Minimum normalized readout field H_0 , information degradation rate R_0 , initial readout field H_{zpeak} , and minimum readout field $H_0 \times H_{zpeak}$ after 10 years of archiving for 9 and 6 grains in 9 grains/bit.

9 grains / bit	$D_m = 3.2 \text{ nm}$						
$T_{cm} \text{ (K)}$	750	700	650	750	750	750	750
$h \text{ (nm)}$	10.5	10.5	10.5	8.5	7.5	10.5	10.5
K_u / K_{bulk}	0.8	0.8	0.8	0.8	0.8	0.7	0.6
h / D_m	3.2	3.2	3.2	2.6	2.3	3.2	3.2
$K_{ueff} V / (kT)$ ($T = 350 \text{ K}$)	113	96	79	91	80	99	84
9 grains							
H_0	0.46	0.38	0.18	0.34	0.19	0.40	0.27
R_0	0.71	5.8	64	12	47	4.0	26
$H_{zpeak} \text{ (Oe)}$	1378	1278	1173	1320	1276	1378	1378
$H_0 \times H_{zpeak} \text{ (Oe)}$	636	489	206	450	240	558	366
6 grains							
H_0	0.34	0.23	n / a	0.18	n / a	0.26	0.08
R_0	1.2	8.4	n / a	15	n / a	6.0	28
$H_{zpeak} \text{ (Oe)}$	1190	1103	1012	1146	1112	1190	1190
$H_0 \times H_{zpeak} \text{ (Oe)}$	405	254	n / a	201	n / a	308	96

Table 3 Minimum normalized readout field H_0 , information degradation rate R_0 , initial readout field H_{zpeak} , and minimum readout field $H_0 \times H_{zpeak}$ after 10 years of archiving for 6 and 4 grains in 6 grains/bit.

6 grains / bit	$D_m = 4.2 \text{ nm}$						
$T_{cm} \text{ (K)}$	600	750	750	650	650	750	750
$h \text{ (nm)}$	10.5	6.5	10.5	7.5	10.5	7.5	7.5
K_u / K_{bulk}	0.8	0.8	0.5	0.8	0.6	0.6	0.6
h / D_m	2.5	1.6	2.5	1.8	2.5	1.8	1.8
$K_{ueff} V / (kT)$ ($T = 350 \text{ K}$)	107	115	117	94	99	100	100
6 grains							
H_0	0.31	0.35	0.36	0.21	0.27	0.27	0.27
R_0	2.3	0.82	0.63	9.8	5.6	5.0	5.0
$H_{zpeak} \text{ (Oe)}$	1057	1240	1371	1098	1167	1290	1290
$H_0 \times H_{zpeak} \text{ (Oe)}$	331	434	491	236	313	353	353
4 grains							
H_0	0.14	0.21	0.22	0.02	0.08	0.09	0.09
R_0	4.9	1.6	1.2	9.1	8.0	7.8	7.8
$H_{zpeak} \text{ (Oe)}$	950	1127	1232	994	1049	1168	1168
$H_0 \times H_{zpeak} \text{ (Oe)}$	136	231	268	23	86	103	103

Although the T_{cm} , h , and K_u/K_{bulk} values can be reduced to 700 K, 8.5 nm, and 0.6, respectively, simultaneous reduction cannot be realized. The h/D_m value necessary for information stability is especially large due to the small grain size D_m of 3.2 nm. The medium parameters to be reduced must be selected

depending on the difficulty of manufacturing the medium.

Since the mean grain size D_m for 6 grains/bit increases to 4.2 nm from 3.2 nm in 9 grains/bit as shown in Table 3, the degree of freedom in design increases. The grain area D_m^2 ratio is 1.68 and more than $9 / 6 = 1.5$ between 6 and 9 grains/bit since the Δ_G value is independent of the grain number per bit.

3.2 Effective thermal stability factor

To enable us to interpret the above calculated results, we plot the H_0 and R_0 values against

$$K_{ueff} V / (kT) = (K_u - M_s H_d / 2) (D_m \times D_m \times h) / (kT)$$

at 350 K in Figs. 3 and 4 for 9 and 6 grains/bit, respectively. All the calculated data for 9 and 6 grains in 9 grains/bit and for 6 and 4 grains in 6 grains/bit are on their lines. Furthermore, the H_0 and R_0 values for 6 grains in 9 and 6 grains/bit are the same as shown in Figs. 4 (a) and (b), respectively. H_0 and R_0 are functions of $K_{ueff} V / (kT)$ and grain number, and are independent of grain number per bit since $K_u \gg M_s H_d / 2$ in K_{ueff} .

Fig. 3 (a) Minimum normalized readout field H_0 and (b) information degradation rate R_0 against effective thermal stability factor $K_{ueff} V / (kT)$ for 9 and 6 grains in 9 grains/bit.

Fig. 4 (a) Minimum normalized readout field H_0 and (b) information degradation rate R_0 against effective thermal stability factor $K_{\text{uff}}V/(kT)$ for 6 and 4 grains in 6 grains/bit.

The H_0 value for 9 grains is larger than that for 6 grains in 9 grains/bit as shown in Fig. 3 (a) due to a statistical factor. The statistical factor can be explained using the following example. If one bit contains many grains, the bER becomes low since the probability of a simultaneous error is very low for more than half of the grains in one bit. For example, when all the grains are assumed to be homogeneous, and P and E_{th} are 0.1 and 0.5, respectively, the bER calculated for 5 grains/bit is

$$\text{bER} = \sum_{k=3}^5 \binom{5}{k} P^k (1-P)^{5-k} \approx 0.009. \quad (12)$$

On the other hand, the bER for 9 grains/bit is

$$\text{bER} = \sum_{k=5}^9 \binom{9}{k} P^k (1-P)^{9-k} \approx 0.0009, \quad (13)$$

which is much lower than that for 5 grains/bit. Therefore, to obtain the same bER, P must be reduced for 5 grains/bit, and a larger $K_{\text{uff}}V/(kT)$ value is necessary.

And the H_0 value for 6 grains in 9 grains/bit is larger than that for 4 grains in 6 grains/bit as shown in Fig. 4 (a). Although it is necessary to increase the $K_{\text{uff}}V/(kT)$ value for 6 grains/bit to obtain the same H_0 value for 9

grains/bit, it is easy to increase the $K_{\text{uff}}V/(kT)$ value for 6 grains/bit since the one grain area is 1.68 times larger. However, there is a concern that the readout SNR for 6 grains/bit is smaller than that for 9 grains/bit due to the small grain number.

A linear relationship was found between logarithmic R_0 and $K_{\text{uff}}V/(kT)$, and the R_0 value decreases slightly in the order of 4, 6, and 9 grains as shown in Figs. 3 (b) and 4 (b). The $K_{\text{uff}}V/(kT)$ value necessary for no information degradation is more than about 120.

The H_{zpeak} and $H_0 \times H_{\text{zpeak}}$ values are plotted against $K_{\text{uff}}V/(kT)$ in Figs. 5 and 6 for 9 and 6 grains/bit, respectively. The lines in the figures are guides for the eye. The cause of data scattering is that H_0 is a function of $K_{\text{uff}}V/(kT)$, and H_{zpeak} is a function of M_s , D_m , and h . And although the M_s value is a function of T_c , it is independent of K_u/K_{bulk} . Roughly, all calculation data for 9 and 6 grains in 9 grains/bit and for 6 and 4 grains in 6 grains/bit are on their lines as shown in Figs. 5 and 6, respectively.

Fig. 5 (a) Initial readout field H_{zpeak} and (b) minimum readout field $H_0 \times H_{\text{zpeak}}$ against effective thermal stability factor $K_{\text{uff}}V/(kT)$ for 9 and 6 grains in 9 grains/bit.

Fig. 6 (a) Initial readout field $H_{z\text{peak}}$ and (b) minimum readout field $H_0 \times H_{z\text{peak}}$ against effective thermal stability factor $K_{\text{ueff}}V/(kT)$ for 6 and 4 grains in 6 grains/bit.

The $H_0 \times H_{z\text{peak}}$ value for 9 grains is larger than that for 6 grains in 9 grains/bit as shown in Fig. 5 (b) since both H_0 and $H_{z\text{peak}}$ for 9 grains are larger than those for 6 grains as shown in Figs. 3 (a) and 5 (a). Furthermore, the $H_0 \times H_{z\text{peak}}$ values for 6 grains in 9 and 6 grains/bit are roughly the same as shown in Fig. 6 (b).

There are many factors to be considered when designing the medium. A high T_{cm} is disadvantageous in terms of the heat resistance of the writing head and/or the surface lubricant. On the other hand, a low T_{cm} is disadvantageous in terms of information stability for 10 years of archiving since K_u at the storage temperature becomes small³⁾. A low T_{cm} is also disadvantageous since the thermal gradient becomes small⁷⁾. A larger h/D_m seems to make it too difficult to manufacture the medium. There is a concern that K_u decreases as D_m decreases.

We must comprehensively examine all the factors if we are to determine the medium parameters. Since these factors are currently being experimentally investigated by many researchers, it is currently impossible to determine the medium parameters. However, the above calculations will be useful for determining them in the future.

4. Conclusions

We examined the dependence of information stability for 10 years of archiving on various medium parameters, namely T_{cm} , h , and K_u/K_{bulk} , in 4 Tbps HAMR. As a result, we found that the minimum normalized readout field H_0 and information degradation rate R_0 are functions of the effective thermal stability factor $K_{\text{ueff}}V/(kT)$ and grain number, and are independent of grain number per bit since $K_u \gg M_s H_d/2$ in K_{ueff} . The $K_{\text{ueff}}V/(kT)$ value necessary for no information degradation is more than about 120. Furthermore, there is a weak correlation between the initial readout field $H_{z\text{peak}}$ or the minimum readout field $H_0 \times H_{z\text{peak}}$ and $K_{\text{ueff}}V/(kT)$.

Although the T_{cm} , h , and K_u/K_{bulk} values can be reduced to 700 K, 8.5 nm, and 0.6, respectively, for 9 grains/bit, a simultaneous reduction cannot be realized. The h/D_m value necessary for information stability is especially large due to the small grain size D_m of 3.2 nm. Depending on the difficulty involved in manufacturing a medium, we must select the medium parameters to be reduced.

It is easy to increase the $K_{\text{ueff}}V/(kT)$ value for 6 grains/bit since the one grain area is 1.68 times larger.

Acknowledgement We acknowledge the support of the Advanced Storage Research Consortium (ASRC), Japan.

References

- 1) S. H. Charap, P. -L. Lu, and Y. He: *IEEE Trans. Magn.*, **33**, 978 (1997).
- 2) T. Kobayashi, Y. Isowaki, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **39**, 8 (2015).
- 3) T. Kobayashi, Y. Nakatani, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **43**, 114 (2019).
- 4) M. Mansuripur and M. F. Ruane: *IEEE Trans. Magn.*, **MAG-22**, 33 (1986).
- 5) J. -U. Thiele, K. R. Coffey, M. F. Toney, J. A. Hedstrom, and A. J. Kellock: *J. Appl. Phys.*, **91**, 6595 (2002).
- 6) E. D. Boerner and H. N. Bertram: *IEEE Trans. Magn.*, **34**, 1678 (1998).
- 7) T. Kobayashi, Y. Nakatani, and Y. Fujiwara: *J. Magn. Soc. Jpn.*, **44**, 122 (2020).

Received Oct. 8, 2021; Accepted Oct. 26, 2021