Journal of Magnetics 6(4), 109-118 (2001)

Micromagnetic Computer Simulation of Ultra-high density Recording with the Use of a Planar-type Head

S. H. Lim[1,*] and H. J. Kim[2]

[1]*Future Technology Research Division*
[2]*Materials Research Division, Korea Institute of Science and Technology, P.O. Box 131, Cheongryang, Seoul 130-650, Korea*

(Received 7 June 2001)

A computer simulation, utilizing the Landau-Lifshitz-Gilbert equation, of ultra-high- density recording on continuous longitudinal media is carried out. The two important features of this work are the use of a planar-type head, which enables a high write field of 14183 Oe to be generated at the center of the recording medium, and the media with very high coercivities up to 13010 Oe. From a systematic investigation, it is found that the optimum write field is higher than the medium coercivity by only 3400 Oe over a wide coercivity range. This new finding allows one to write an a medium with a very high coercivity by using a planar-type head. It is demonstrated that a reasonably good bit pattern with a bit density of 605 kfci is generated on the medium with a coercivity of 11720 Oe, and, combined with a high track pitch density of 100 ktpi, a recording density of 60 Gb/in^2 can be obtained in a single layer medium. With an improved write- head design, even a higher recording density of 75 Gb/in^2 may be possible since comparison of the results for the bit pattern from the present head profile and the ideal Lindholm profile indicates an increase in the track pitch density of about 20%. Even at this density, the thermal stability parameter (KV/kT) at room temperature is high enough (60) to provide ample room for thermal stability.

1. Introduction

The density of magnetic recording on continuous longitudinal media has been increasing at a very fast rate (approximately 60% per year) for the last several decades. This has mainly been achieved through evolutionary technological refinement (also frequently called scaling) which involves reducing the dimensions of both magnetic and semiconductor devices. Although the current pace of density increase is expected to continue for several years, it is generally recognized that the current recording technology will reach its theoretical limit, the main reason being related to thermal fluctuation [1, 2]. One of the most popular routes to high density recording is to decrease the transition length between the bits by reducing the medium thickness and the grain size [3, 4]. A weak signal due to a small medium thickness is a source of concern, but this problem has been solved with a highly sensitive Giant-Magneto-Resistance (GMR) read sensor. However, the reduction of the medium thickness and the grain size results in a small grain volume so that the magnetization direction of a grain is subjected to thermal fluctuation. This is a fundamental problem that cannot be solved through technological refinements.

Many revolutionary ideas have been suggested to solve this fundamental thermal problem in longitudinal magnetic recording, and the most promising one may be the use of exchange-coupled media. These media consist of 2 or 3 magnetic layers which are exchange-coupled through a very thin (~0.7 nm) non-magnetic layer such as Ru. The new idea appears to be very promising; recently, a very high recording density of 56 Gb/in^2 was achieved in this type of media [5]. The use of exchange-coupled media, however, may cause some problems (a large noise, for example), which remain to be solved in the future. Another route to high density recording is to use the medium with a high value of the magnetocrystalline anisotropy energy (K) because transition length decreases with increasing K [3]. The use of a medium with a high K value is also good for improving thermal stability. This route, however, suffers from a limitation imposed by the low values of the write field that can be generated by conventional heads. In an effort to solve this problem, various types of head designs are under consideration, and one of the candidates is a planar-type head. Apart from its ability to generate a high write field, a planar-type head is considered to be suitable for high-density recording because it fabrication involves only a thin-film process (no mechanical processing) so that a precise dimensional control is possible.

In this work, an attempt is made to achieve very high

---

*Corresponding Author: Tel: +82-2-958-5415, Fax: +82-2-958-6851, e-mail: sangho@kist.re.kr density recording on a single layer of a continuous longitudinal medium by using a newly designed planar-type head. Particular emphasis is placed on the writability of the planar-type head on the medium with a very high value of K.

2. Model and Computation

A schematic illustration of the planar-type head used in this work is shown in Fig. 1. Some important head parameters are the gap length of 0.12 μm, the track width of 0.16 μm (head dimensions) the relative permeability of 500, the saturation flux density of 1.9 T, and the magneto-motive force of 0.4 A·Turn (magnetic properties). The field profile was calculated with an IEM (integral element method) program package, which involved solving the Maxwell equations. The calculated results for the three field components, namely, those in the bit length (H_x), the track width (H_y), and the perpendicular (H_z) directions are shown in Figs. 2(a) and (b) as functions of x and y, respectively. Except for the H_y-x plot, the origin of the horizontal axis corresponds to the location at a distance of 17.5 nm directly below the center of both the head gap and the width. In the case of the H_y-x profile, the origin is displaced in the track width (y) direction by one half of the track width; namely, the head profile is calculated along the track edge. The value of 17.5 nm is the sum of the head-to-medium spacing (d) and one-half of the medium thickness (δ) and corresponds to the distance between the bottom of the head and the center of the recording medium. The head profile of H_x as a function of x shown in Fig. 2(a), which is the most important one for recording, is considered to be sharp, particularly in the high-field range, with a high value of the field slope. The maximum value of H_x obtained from the present planar head is 14183 Oe, which is much higher than the values ranging 6000~8000 Oe from conventional heads.

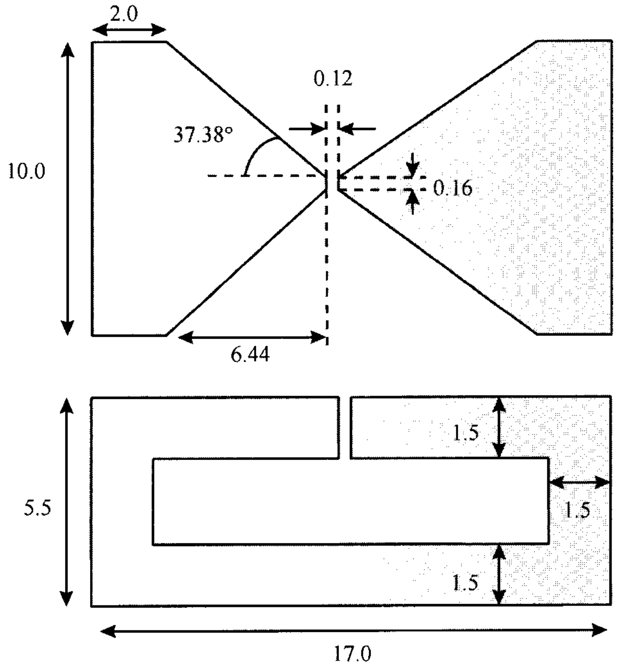


Fig. 1. Shape and dimensions of the planar-type head used in this work. The dimensions are given in mm.

A two-dimensional array of honeycomb-shaped and completely packed hexagons was used to simulate the longitudinal media. The grain size (D), which corresponds to the center-to-center distance between neighboring grains, is 7 nm, and the thickness (δ, the hexagon height) is 13 nm. This gives a grain volume (V) of 552 nm^3. Most of the simulations were carried out for a lattice size of 128×64, which corresponds to a medium area of 0.896 μm $\times$ 0.388 μm. In the lattice size description, the numbers before and after the cross symbol (×) denote the x (or bit) and y (or track width) directions, respectively. In some cases, how-

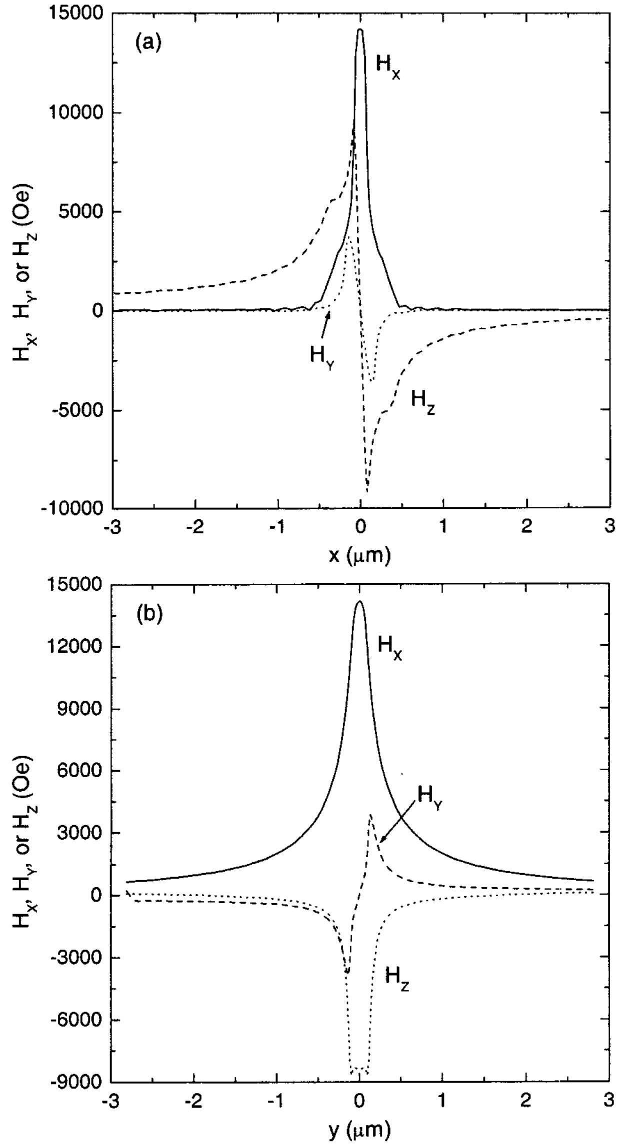


Fig. 2. Head field profiles of H_x (bit direction), H_y (track width direction), and H_z (perpendicular direction) for the present planar-type head as functions of (a) x and (b) y.

ever, a larger size lattice array of 256 × 128 hexagons (1.792 μm × 0.776 μm) was simulated. The grains were assumed to possess only uniaxial crystalline anisotropy. The magnitude of K was the same for all the grains; namely, no anisotropy distribution from grain to grain was considered, but the easy axis was assumed to have 2D randomness. In this study, several media with varying values of K ranging from 1.2×10^5 to 5.0×10^5 J/m^3 were investigated. With the saturation magnetization (M_s) of 0.478 T used for the present media, the anisotropy field (H_k), given by 2 K/M_s, ranged from 5.02×10^5 to 2.09×10^6 A/m. The well-known LLG equation was used to obtain the evolution of the magnetization in time [6, 7], and it is expressed as

$$(1+\alpha^2)\frac{d\vec{M}}{dt} = -\gamma(\vec{M}\times\vec{H}),\ \vec{H} = \vec{H}_{eff} + \alpha\frac{\vec{M}\times\vec{H}_{eff}}{M}. \quad (1)$$

Here, α is the dimensionless damping constant and is fixed at 1 (critical damping), γ is the gyromagnetic ratio (1.93×10^7 s^{-1}Oe^{-1} for a g value of 2.19), and H_{eff} is the effective field. Normally, the following five contributions are incorporated in H_{eff}: the external applied field, the uniaxial anisotropy field, the magnetostatic interaction field, the exchange field, and the thermal excitation field. In this work, however, only the first three contributions were considered; in other words, no exchange interactions between grains were considered, and the calculations were done at a temperature of zero Kelvin.

Written bits were generated by scanning the planar-type head over a DC erased medium at a fixed distance of d (11 nm). The head field applied to the medium is a function of position (x, y, z) and time (t) and can be expressed by the following equation:

$$H(x,y,z,t) = pH_g h(x-vt,\, y,\, z) \times \begin{cases} -1 & t < \frac{T_r}{2} \\ +\frac{2t}{T_r} & -\frac{T_r}{2} \le t \le \frac{T_r}{2} \\ +1 & t > \frac{T_r}{2} \end{cases} \quad (2)$$

Here, p is a variable which is used to vary the write field, H_g is the gap field of the head (the field inside the gap), v is the velocity of the head, h is the function for the normalized head-field profile (see Figs. 2(a) and (b)), and T_r is the head rise time. With d = 11 nm and δ = 13 nm, the value of z was fixed at 17.5 nm during the whole write process. In this work, the value of p was varied in a reasonably small step of 0.05 (in some cases 0.025) to accurately locate the optimum write field (H_w) for a given medium. The determination of H_w, the procedure of which is similar to that used by Igarashi *et al.* [8], takes into account of changes in the recorded magnetization and the gross remanence magnetization as a function of p.

The read signal voltages were calculated with a method based on the reciprocal principle. The read sensor was scanned over the recorded pattern at a distance of 10 nm. The shield-to-shield distance was 14 nm.

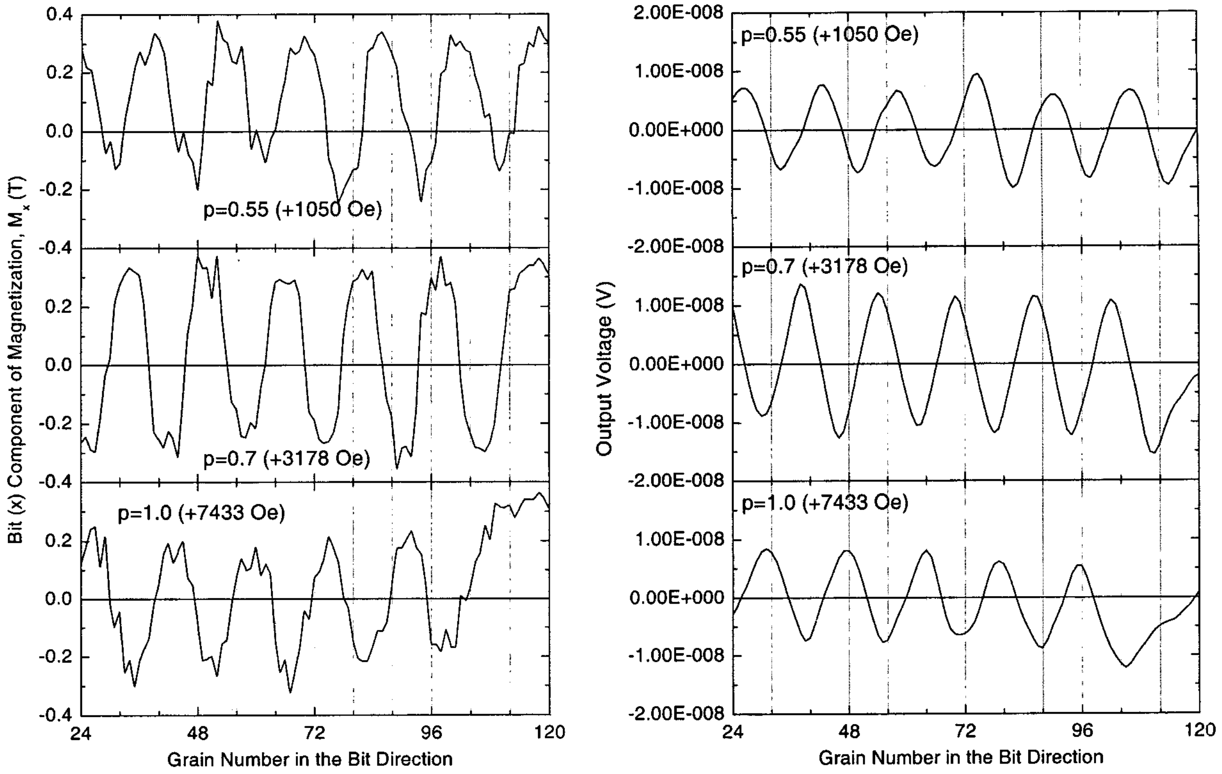
3. Results and Discussion

Several media with varying values of K were investigated in this work, as was already mentioned in the previous sections. In Table 1 are given the summarized results for the magnetic properties and the thermal relaxation parameter (KV/kT) of the media. The values of the coercivity (H_c) in the table were determined from hysteresis loops at a frequency of 2.5 MHz. The calculation at a lower frequency takes a longer computational time, so the simulation at a low frequency corresponding to the usual experimental condition was not done here. However, these H_c values are considered to be not much different from the DC values, such as those measured with a vibrating sample magnetometer (VSM), since the coercivity increase in this frequency range is expected to be small [8]. From Table I, it is seen that the value of H_c varies quite widely from 2790 Oe (at K = 1.2×10^5 J/m^3) to 13010 Oe (at K = 5.0×10^5 J/m^3). The lowest coercivity value of 2790 Oe is at a similar level to those of currently used media. No significant differences in the remanence ratio and the coercive squareness parameter (S*) were observed as a function depending on the magnitude of K, the former being in the range 0.72-0.75, and the latter 0.82-0.86.

Three different values of the bit density, 454, 605, and 907 kfci (kilo flux changes per inch), which correspond to total bit sizes of of 56, 42, and 28 nm, respectively, were used in this work. With the grain size of 7 nm used here, each bit consists of 8 (at 454 kfci), 6 (at 605 kfci), or 4 (at 907 kfci) grains in the bit direction. The other write param-

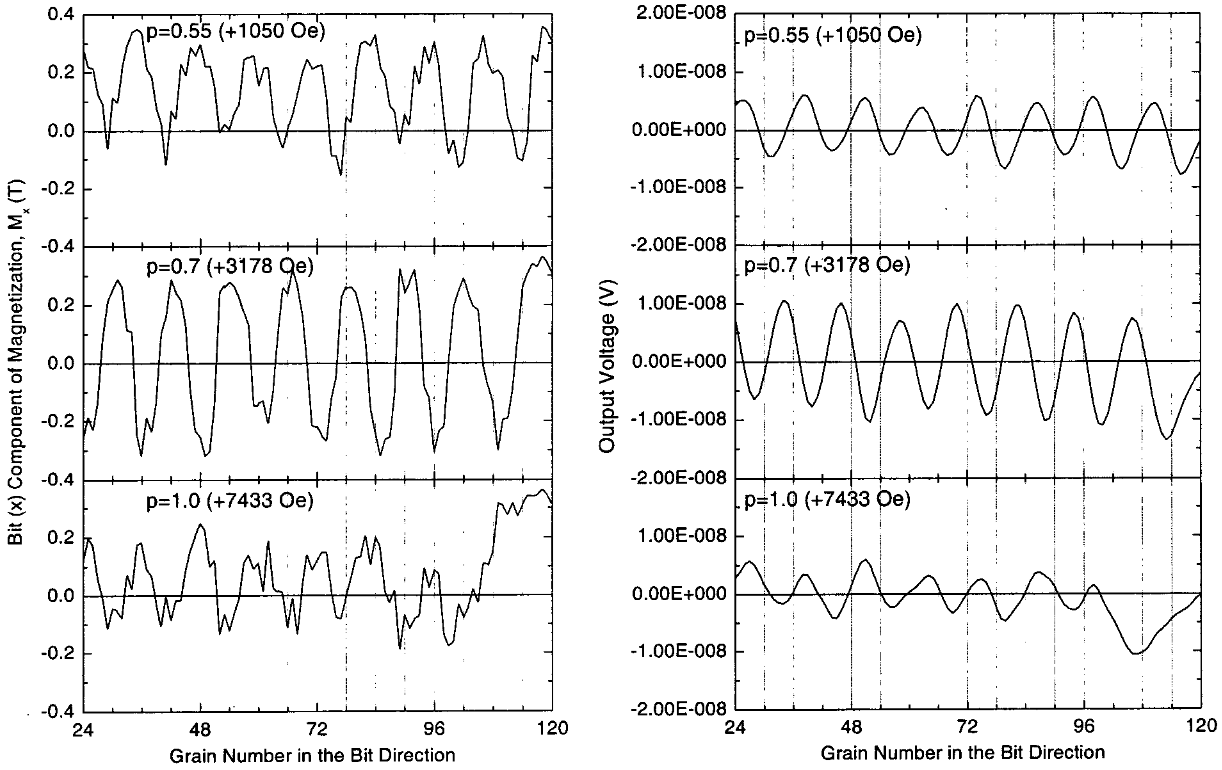
Table 1. The magnetic properties of the coercivity and the anisotropy field, and the thermal relaxation parameter at 300 K for the media with varying values of the uniaxial anisotropy considered in this work. The coercivity was determined from hysteresis loops calculated at a frequency of 2.5 MHz

Uniaxial Anisotropy Energy, 10^5 J/m^3	Coercivity, 10^5 A/m (Oe)	Anisotropy Field, 10^5 A/m (Oe)	Thermal Stability Parameter, KV/kT
1.2	2.235 (2790)	5.02 (6275)	16.0
2.85	5.809 (7260)	11.9 (14875)	38.0
3.0	6.140 (7675)	12.6 (15750)	40.0
3.5	7.218 (9023)	14.6 (18250)	46.6
4.0	8.305 (10380)	16.7 (20875)	53.3
4.5	9.377 (11720)	18.8 (23500)	59.9
5.0	10.41 (13010)	20.9 (26125)	66.6



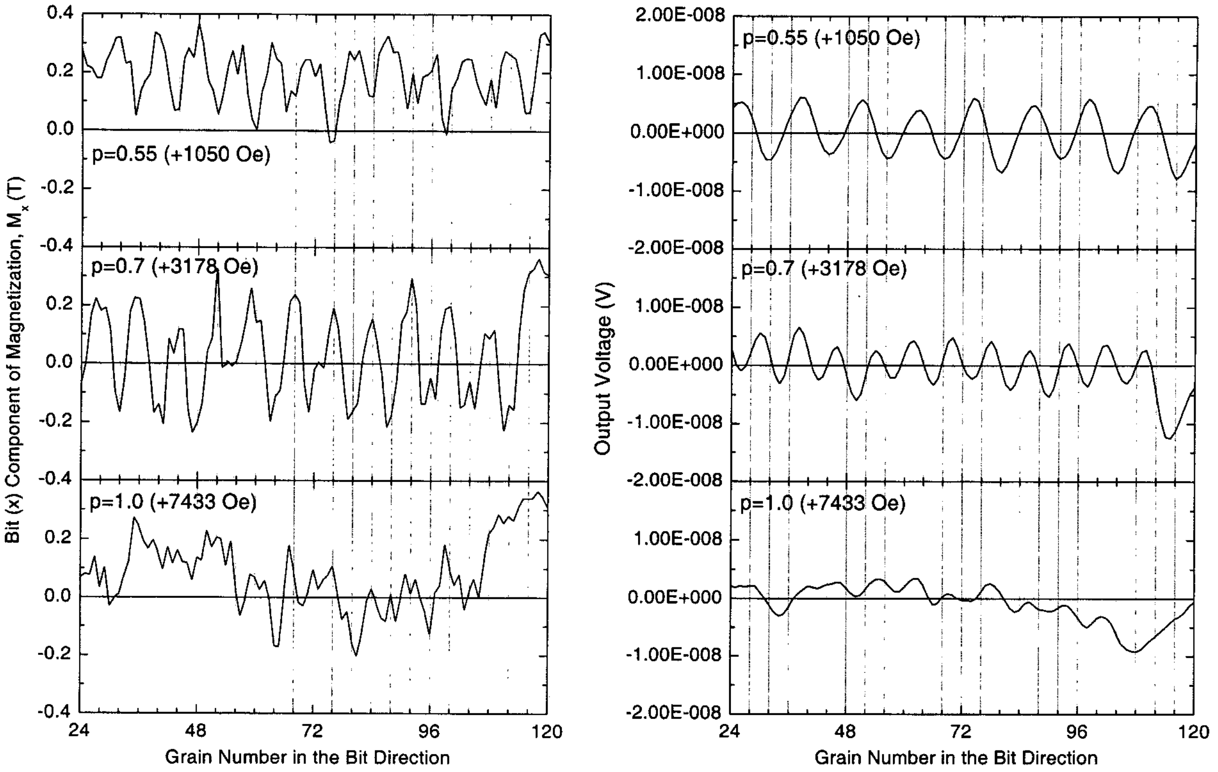
(a) (b)

Fig. 3. (a) Bit component of the magnetization (M_x) and (b) output of the read signal for the medium with $K = 2.85 \times 10^5$ J/m^3 at a bit density of 454 kfci. The results are for three p values of 0.55, 0.7, and 1.0.



(a) (b)

Fig. 4. (a) Bit component of the magnetization (M_x) and (b) output of the read signal for the medium with $K = 2.85 \times 10^5$ J/m^3 at a bit density of 605 kfci. The results are for three p values of 0.55, 0.7, and 1.0.



(a) (b)

Fig. 5. (a) Bit component of the magnetization (M_x) and (b) output of the read signal for the medium with $K = 2.85 \times 10^5$ J/m^3 at a bit density of 907 kfci. The results are for three p values of 0.55, 0.7, and 1.0.

eters used are a head field rise time of 0.25 ns and a head velocity of 50 m/sec. The writing frequency, which can be calculated from the bit size and the head velocity, is 446 MHz (at 454 kfci), 595 MHz (at 605 kfci), or 893 MHz (at 907 kfci). A rise time of 0.25 ns is considered to be too short to be achieved easily with the current technology. However, our write parameters are considered to be reasonable since the calculated results at a slower head rise time (0.5 ns) and head velocity (25 m/sec) are similar to those obtained with the present write parameters (0.25 ns and 50 m/sec).

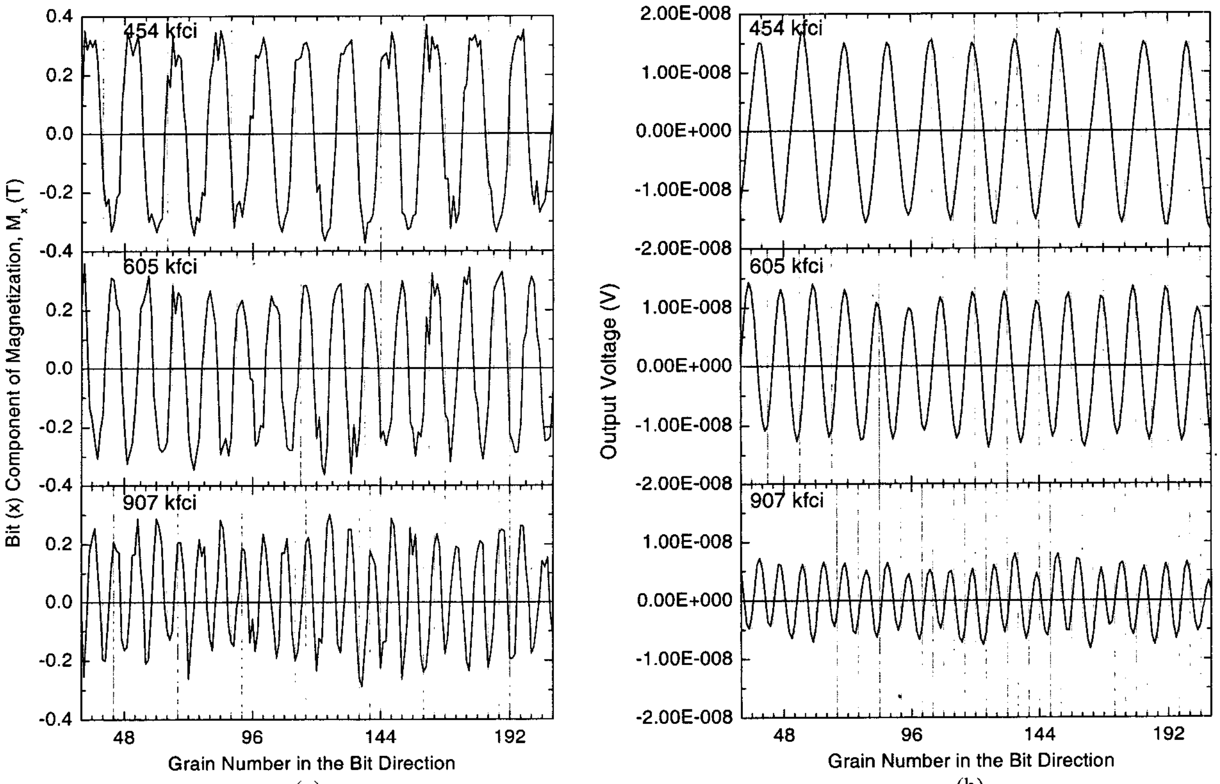
In order to determine the optimum write field (H_w), we examined the changes of the recorded magnetization and the gross remanence magnetization are examined as functions of p, as was mentioned in the previous section, and some of the results are shown in Figs. 3, 4, and 5 for the medium with $K = 2.85 \times 10^5$ J/m^3 at bit densities of 454, 605 and 907 kfci, respectively. In each figure, two sets of results, (a) the bit component of the magnetization (M_x) and (b) the output of the read signal, are shown at p values of 0.55, 0.7, and 1.0. These p values correspond to the head field being greater than the medium coercivity by 1050 ($p = 0.55$), 3178 ($p = 0.7$), and 7433 Oe ($p = 1.0$). The results are obtained for a lattice size of 128 × 64 hexagons, and the horizontal axis indicates the hexagon number in the bit direction. In the figures, the results are only shown at the interior (intermediate region) of the lattice to avoid edge (surface) effects. It is seen from the results for M_x shown in Figs. 3(a), 4(a), and 5(a) that, at a low write field, the bit pattern appears to form, but the gross remanence magnetization deviates significantly from zero (it is positive in this case since the medium was DC-erased in the positive direction), and the deviation increases with increasing bit density. At a high write field, the gross remanence magnetization is close to zero, but the shape of the bit pattern is not clear due to the recording loss, no pattern being formed at the highest bit density of 907 kfci. At the optimum write field ($p = 0.7$), the bit patterns are considered to be reasonably good, except for the highest bit density. It is worth noting here that, even at the optimum write field, the pattern of the written bits becomes poor and the value of M_x decreases as the bit density increases. With the present head velocity of 50 m/sec, the write head spends a time of 0.56 ns in the highest bit density of 907 kfci. This indicates that the full field is applied for a period of 0.31 ns (0.56-T_r (0.25 ns)) per bit, which is considered to be reasonably long for magnetization rotation. It is, therefore, thought that recording loss may be mainly responsible for the bit-density dependence of the bit pattern and M_x. The results for the output signal shown in Figs. 3(b), 4(b), and 5(b) are expected from those for the bit pattern. However, a caution should be exerted for the good signals obtained at a low write field where the gross remanence magnetization is highly positive and hence, the output signal is expected to be poor after over-writing.

Detailed results for the formation of written bits are sum-

Table 2. A qualitative description of the formation of written bits at various values of p and the bit density for the media with $K = 2.85 \times 10^5$, 3.5×10^5, and 4.5×10^5 J/m^3. The symbols × and O are used to indicate no (or very poor) and good recording patterns, respectively, and recording patterns between × and O are denoted by the Δ symbol. The optimum value of p (H_w) is written in bold and larger numbers

Uniaxial Anisotropy Energy, 10^5 J/m^3	Write-head Field Variable, p	Bit Density, kfci		
		454	605	907
2.85	0.55	Δ	×	×
	0.60	O	Δ	×
	0.65	O	O	×
	0.70	O	O	Δ
	0.75	O	O	Δ
	1.00	Δ	×	×
3.5	0.80	O	Δ	Δ
	0.85	O	Δ	Δ
	0.90	O	O	Δ
	0.95	O	O	Δ
	1.00	O	O	Δ
4.5	0.90	O	Δ	Δ
	0.95	O	O	Δ
	1.00	O	O	Δ
	1.05	O	O	Δ
	1.10	O	O	Δ

marized in Table 2 for $K = 2.85 \times 10^5$, 3.5×10^5, and 4.5×10^5 J/m^3. In the table, only a qualitative description of the bit formation is given for various values of p and the bit density. A similar systematic calculation was conducted at $K = 1.2 \times 10^5$ J/m^3, but at that low K value, no clear recording pattern was formed at any p value and bit density. Actually, a medium with such a low K value is not suitable for recording since KV/kT at 300 K is so small (which is 16, see Table 1) that the relaxation time is of the order of 0.01 sec [9, 10]. When an optimum write field is used for recording, a clear recording signal begins to appear at $K = 2.85 \times 10^5$ J/m^3 (the results of which were already shown in Figs. 3-5), and the recording characteristics improve with the increasing of K. In the case of $K = 2.85 \times 10^5$ J/m^3, reasonably good recording signals are obtained at densities of 454 (Fig. 3) and 605 kfci (Fig. 4), but still the recording pattern at 907 kfci (Fig. 5) is observed to be very vague, as was already seen in Figs. 3, 4, and 5. A qualitatively similar behavior is observed at higher K values, $K = 3.5 \times 10^5$ and 4.5×10^5 J/m^3, but the recording characteristics are significantly improved; at $K = 4.5 \times 10^5$ J/m^3, for example, it is possible to write a rather distinct recording pattern even at the highest density of 907 kfci, as can be seen in Figs. 6(a) and (b) where the results for (a) M_x and (b) the output signal are shown for all three bit densities. The results in Figs. 6 (a) and (b) were obtained for a large lattice size of 256 × 128 hexagons. Again, the results are only shown at the inte-



(a)

(b)

Fig. 6. (a) Bit component of the magnetization (M_x) and (b) output of read signal for the medium with $K = 4.5 \times 10^5$ J/m^3 at the bit densities of 454, 605, and 907 kfci. The results are obtained at the optimum write field (p = 1.05).

rior (intermediate region) of the lattice to avoid the edge (surface) effects.

The value of H_w appears to be independent of the bit density, at least in the range investigated in this work, and it is estimated to be p = 0.7 (H_w = 9928 Oe) at K = 2.85 × 10^5 J/m^3, p = 0.9 (H_w = 12765 Oe) at K = 3.5 × 10^5 J/m^3, and p = 1.05 (H_w = 14892 Oe) at K = 4.5 × 10^5 J/m^3. These results for H_w are quite surprising since the magnitude of H_w is not much higher than that of H_c. In the case of currently used media with $H_c \approx 3000$ Oe, an empirical relationship exists between H_w and H_c, which is given by $H_w \approx 2H_c$ [11]. However, this rule does not seem to be valid the media with high H_c (or K) values. Rather, a new relationship, H_w-H_c = 3400 Oe, is found to exist, indicating that the magnitude of H_w is higher than that of H_c by only 3400 Oe. This new relationship can be seen more clearly from Fig. 7, where the values of H_c, H_w, and (H_w-H_c) are plotted as functions of K. With the paucity of simulation data used here, it is hard to put much confidence on the value of 3400 Oe for the difference (H_w-H_c), but the trend is quite clear, as can be seen from Fig. 7. A more detailed and systematic investigation, taking into account various media and recording conditions, is under consideration in order to obtain a more accurate value of the difference. It is of interest to see that, although the new relationship is quite different from the old one, both relationships do predict the magnitude of H_w quite well for the currently used media: $H_w \approx 6000$ Oe and $H_c \approx 3000$ Oe. Of course, this is because, incidentally, the values of H_c for the currently used media at a in the similar level of the difference (H_w-H_c). In order to see if this new relationship between H_w and H_c also holds for different head profiles, we carried out a series of simulations for the medium with K = 3.5 × 10^5 J/m^3 by using the Lindholm head profile [12], and we was found that the value of H_w from the Lindholm profile is similar to that obtained with the present field profile for a planar-type head. From a theoretical viewpoint, the new rule seems to be more reasonable since magnetization dynamics is well explained by (H-H_0), where H_0 is a field related to H_c [7]. We also argue that the old relationship has some theoretical background; one notable one is that $H_w = H_k$. It is quite incidental to see from Table 1 that this relationship only holds for the currently used media (K = 1.2 × 10^5 J/m^3), but is obviously not true for media with high K values. One feature to be noted from the results given in Table 2 is that the window of the write field for a good recording pattern becomes wider at higher K and at lower bit density. This result can be understood from a low recording loss at low density and a high resistance to demagnetization at high K.

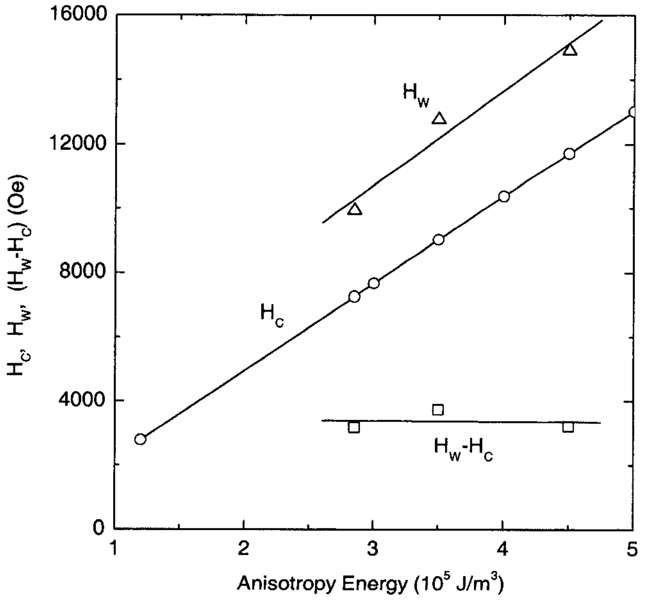


Fig. 7. Values of H_c, H_w, and (H_w-H_c) as functions of K. In the case of H_c, all the values for the media considered in this work are shown.

A relationship between H_w and H_c similar to the present one was previously observed by Igarashi *et al.* [8] for a given media with a low K value ($H_c \approx 3000$ Oe), but over a wide frequency range from 1 to 1000 MHz. In this frequency range, they observed, from a micromagnetic computer simulation, a relatively large increase of H_c with increasing frequency. Also, a similar frequency dependence of H_w was obtained, causing the difference between H_w and H_c to be nearly constant; the difference is 2500 Oe at very low frequencies, but, in the high-frequency region relevant to magnetic recording, it is approximately 1800 Oe. This relationship is quite clear from the results shown in Fig. 4 of their paper [8], although not mentioned explicitly by the authors. Further evidence indicating an overestimate of H_w may be found from the results of Ohashi *et al.* [13], where it was shown experimentally that excellent overwrite properties were achieved on a high coercivity medium (7.0 kOe) at a relatively small write field of 10 kOe.

It is important to point out that the frequencies of H_w and H_c in the expression H_w-H_c = 3400 Oe are different (H_w is at the respective recording frequencies of 446, 595, and 893 MHz while H_c is at 2.5 MHz), and the calculation is done at a temperature of 0 Kelvin. Since the frequency dependence of H_c is a function of both the temperature and the magnitude of K, it will be necessary to estimate the difference (H_w-H_c) for the respective recording condition. Although an accurate evaluation of the frequency and the temperature dependences of H_c is a future research subject, a schematic illustration showing the variation of H_c with frequency at two different temperatures, 0 and 300 Kelvin, is shown in Fig. 8 for media with two different K values. In the figure, it is assumed that the frequency dependence of H_c at a temperature of zero Kelvin is independent of K, but, at a nonzero temperature, the decrease of H_c with decreasing frequency is larger at lower K values due to larger thermal fluctuations [7, 14, 15]. From the figure, it is clear that the difference (H_w-H_c) increases with increasing temperature since the decrease of H_c is greater than that of H_w for a given temperature increase. Also, the difference increases

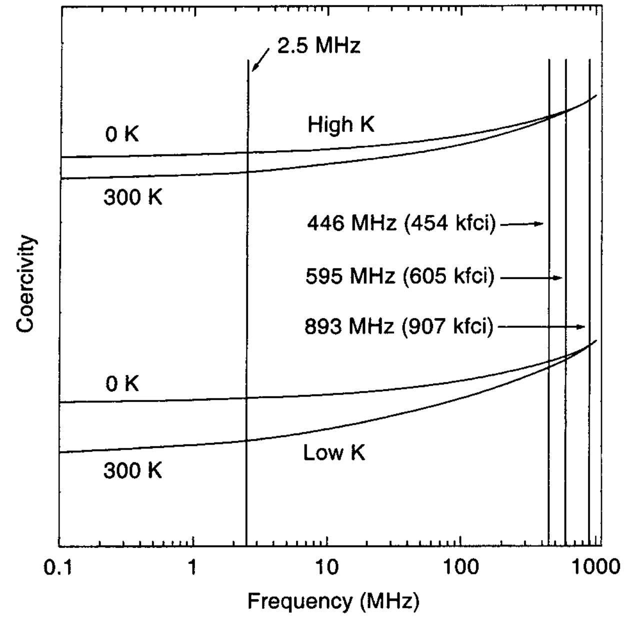


Fig. 8. Schematic illustration showing the variation of H_c with frequency for the media with two different K values at temperatures of 0 and 300 K. The frequency dependence of H_c at zero temperature is assumed to be independent of K, but the decrease of H_c with decreasing frequency is larger at a lower K value due to larger thermal fluctuations. The frequencies of 2.5 MHz (for media characterization) and 446, 595, and 893 MHz (write frequencies) simulated in this work are indicated in the figure.

with decreasing K value due to a larger decrease of H_c at a lower K value. This indicates that, for an actual recording condition, the difference (H_w-H_c) is greater than the present estimate of 3400 Oe, this being more true at lower K values.

The present results for H_w are expected to give a significant impetus to the development of media with very high K values. This will eventually lead to the extension of the current theoretical density limit of 40 Gb/in^2 for continuous longitudinal media consisting of a single layer [2, 10]. The most critical and fundamental problem for high-density recording on continuous longitudinal media is the thermal instability, which is the prime obstacle to reducting the grain volume and, hence, to increasing of the recording density. This problem is likely to be relieved to a somewhat great degree, however. Armed with the new relationship between H_w and H_c, and a new type head, such as the current planar head which enables a very high value of H_g to be generated, it is now possible to write a recording pattern on a medium with very high K. This use of a medium with a high K value will allow a further reduce the grain size and the medium thickness and, hence, an increase in the recording density. Practically, the value of KV/kT should be no less than 40, which gives the relaxation time of 7.5 years [10, 16]. The values of KV/kT at room temperature (300 Kelvin), given in Table 1 for various media, dictate the to use of media with K values greater than 3.0×10^5 J/m^3 if the current grain dimensions (D = 7 nm and δ = 13 nm) are to be used. At K = 4.5×10^5 J/m^3, the value of KV/kT is about 60, which is considered to be safe enough with respect to thermal fluctuations.

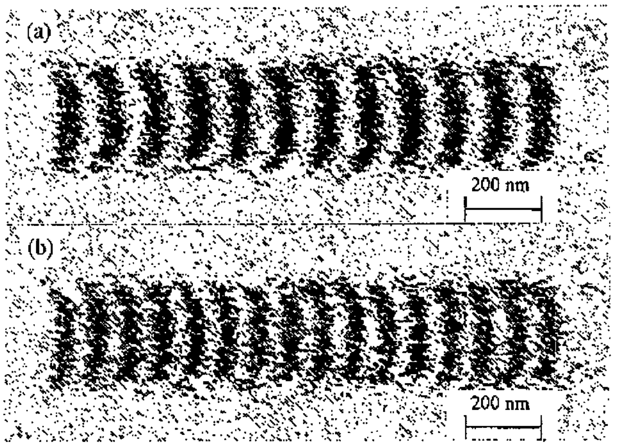


Fig. 9. Recorded bit pattern for the media with K = 3.5×10^5 J/m^3, which was obtained by using the head profile from the planar-type head. The bit densities are (a) 454 kfci and (b) 605 kfci.

In Figs. 9 and 10 are shown the results for the recorded bit pattern for media with K = 3.5×10^5 and 4.5×10^5 J/m^3, respectively. In the case of K = 3.5×10^5 J/m^3, the bit pattern at the highest density is not very clear and, hence, is not shown in Fig. 9. Also, shown in Fig. 11 are similar patterns for the medium with K = 3.5×10^5 J/m^3 which were obtained through the use of the Lindholm write field pro-

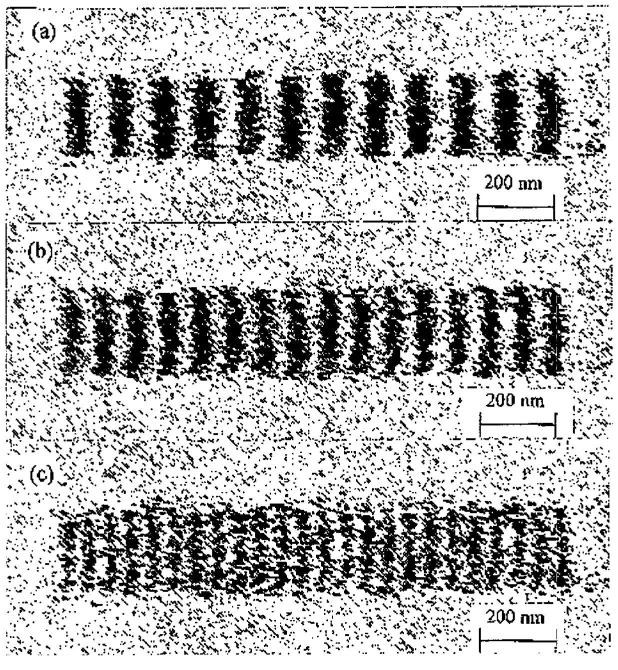


Fig. 10. Recorded bit pattern for the media with K = 4.5×10^5 J/m^3, which was obtained by using the head profile from the planar-type head. The bit densities are (a) 454 kfci, (b) 605 kfci, and (c) 907 kfci.

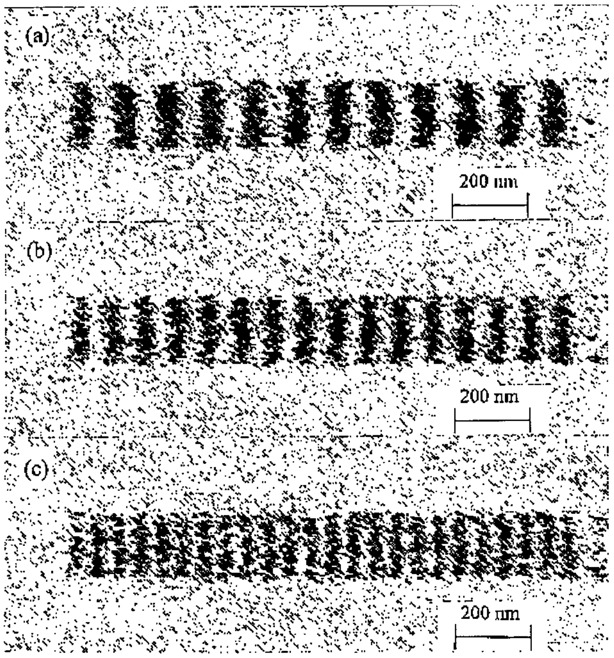


Fig. 11. Recorded bit pattern for the media with $K = 3.5 \times 10^5$ J/m^3, which was obtained by using the Lindholm head profile. The bit densities are (a) 454 kfci, (b) 605 kfci, and (c) 907 kfci.

file. It is seen from Fig. 9 for $K = 3.5 \times 10^5$ J/m^3 that the shape of the bits are substantially curved and that the image is not very clear, this being particularly true at the density of 605 kfci. Furthermore, the track width, being independent of the bit density, is approximately 290 nm, which is much higher than the value of 160 nm for the track width of the write head. Similar bit patterns were observed for the medium with $K = 2.85 \times 10^5$ J/m^3, although the results are not shown here due to space limitation. The recording characteristics are greatly improved with increaing of K, as can be seen from Fig. 10 for the results of $K = 4.5 \times 10^5$ J/m^3. The patterns at this K value are clearer and less curved (this is particularly true at the lowest density of 454 kfci) when they results are compared with those shown in Fig. 9 for the medium with lower K value. Also, the track width is greatly reduced to about 220 nm, but, still, it is significantly larger than the write head width (160 nm). The recorded bits at densities of 454 and 605 kfci are considered to be reasonably good, but those at 907 kfci are still very poor, the bits being percolated to one another. The compared to the bit patterns from the present planar type head for an identical medium ($K = 3.5 \times 10^5$ J/m^3; see Fig. 9), the recorded patterns are significantly improved when a the Lindholm head profile is used (see Fig. 11). It appears that the use of the ideal Lindholm profile results in effects similar those associated with increasing K value since the shape of these bit patterns ($K = 3.5 \times 10^5$ J/m^3 and the Lindholm profile) are similar to those obtained from the head field profile of the planar-type head for the medium with $K = 4.5 \times 10^5$ J/m^3. Another important feature of the results from the ideal profile is the significant reduction of the track width. The track width is observed to be 175 nm, which is slightly higher than the value of 160 nm for the write head width, but much lower than the values from the head profile of the planar-type head. The significant improvement that is obtained by using the ideal Lindholm profile clearly indicates the importance of developing a new type of planar head that will a head profile with a narrow field distribution to be generated.

It is of interest, based on the present simulation results, to consider the limit of the recording density for continuous longitudinal media. At this stage, it seems hard to mention a specific number for the density since the present results are only preliminary and are far from complete. However, the results presented thus far provide a high possibility of increasing the current limit of the recording density. It is expected that a fourfold increase in the value of K, compared with the current media, may be possible. This increases the KV/kT value; hence, the most critical thermal instability problem is expected to be relieved, if not solved. A rough estimate of the maximum density from the present simulation work is approximately 60 Gb/in^2, which can be obtained for a medium with $K = 4.5 \times 10^5$ J/m^3 and a density of 605 kfci (see Fig. 10(b)). The value of 60 Gb/in^2 is based on a bit density of 605 kfci and a track pitch density of 100 ktpi (kilo track pitches per inch). It is noted here that the optimum write field at this K value is obtained at $p = 1.05$, indicating that the required value of H_g is higher than that of the present planar head. This appears to cause a problem, but it is not that serious since our results indicate that, due to the wide window of the write head field for a good recording pattern in this high K value range, as was pointed out earlier, the bit patterns at lower p values ($p = 0.95$, for example) are considered to be reasonably good. Further support may come from our simulation results which showed that, for all bit densities, good recording patterns were achieved on the medium with $K = 5.0 \times 10^5$ J/m^3 ($H_c = 13000$ Oe) by using the present write head (in this case H_w-H_c is only 1183 Oe!). Comparison of the results for the bit pattern from the present head profile and that from the ideal Lindholm profile indicates much room for further improvement of the present planar-type head, particularly with regard to reducing of the track width of the bit pattern. With an improved write-head design, it may be possible to increase the track pitch density by about 20%, and hence, to achieve a recording density of 75 Gb/in^2. It is worth emphasizing here that, even at this high density level, the value of KV/kT (60) is high enough to provide ample room for thermal stability [10].

4. Conclusions

In an effort to increase the density of magnetic recording on continuous longitudinal media, we have carried out computer simulations based on the Landau-Lifshitz-Gilbert equation through with the use of a planar-type head, which enables a high write field of 14183 Oe to be generated, and media with very high coercivities ranging from 2790 to 13010 Oe. It has been shown that, for media with coercivities over a wide range, the optimum write field is higher than the medium coercivity by only 3400 Oe, namely H_w-H_c = 3400 Oe. This new relationship provides a significant increase in the medium coercivity and hence, a further increase of the recording density by relieving, among other things, the most critical and fundamental problem of thermal instability. It has been demonstrated that a medium with a very high coercivity (> 11 kOe) can be written on with a planar-type head. Specifically, a reasonably good bit pattern with a bit density of 605 kfci has been generated on a medium with a coercivity of 11720 Oe, and, combined with a high track pitch density of 100 ktpi, it should be possible to reach a recording density of 60 Gb/in^2 in a single-layer medium. The recording density can be further increased to 75 Gb/in^2 by improving of the design of the present planar-type head, particularly with regard to reducing of the track width of the bit pattern. It is important to note that, even at this density, the media will not suffer from the thermal stability problem since the value of KV/kT at room temperature is approximately 60, which is considered to be high enough to provide ample room for thermal stability.

Acknowledgments

Most of the work was carried out during the visit of SHL to Hitachi CRL, Tokyo, Japan. SHL thanks the Korea Science and Engineering Foundation (KOSEF) and the Hitachi Central Research Laboratory for their financial support of the visit. Thanks are also due to Drs. K. Yoshida and H. Takano for their help in the micromagnetic simulation and the write-head design, respectively. This work was performed under a National Research Lab (NRL) program, "New magnetic thin film technology for information storage.

References

[1] P. L. Lu and S. H. Charap, IEEE Trans. Magn. **31**, 2767 (1995).
[2] R. L. White, J. Magn. Magn. Mater. **209**, 1(2000).
[3] B. K. Middleton, J. Magn. Magn. Mater. **193**, 24 (1999).
[4] M. Futamoto, N. Inaba, Y. Hirayama, K. Ito, and Y. Honda, J. Magn. Magn. Mater. **193**, 36 (1999).
[5] E. N. Abarra, M. Suzuki, and I. Okamoto, Digest of Intermag 2000 (April 9-13, 2000, Toronto, Canada), paper # AA-01.
[6] W. F. Brown, Phys. Rev. **130**, 1677 (1963).
[7] W. D. Doyle, S. Stinnett, C. Dawson and L. He, J. Magn. Soc. Japan **22**, 91(1998).
[8] M. Igarashi, F. Akagi, K. Yoshida, A. Nakamura, Y. Maruyama and H. Takano, IEEE Trans. Magn. **35**, 2721 (1999).
[9] R. Street and J. C. Woolley, Proc. Phys. Soc. A **62**, 562 (1949).
[10] D. E. Speliotis, J. Magn. Magn. Mater. **193**, 29 (1999).
[11] R. L. Comstock, Introduction to Magnetism and Magnetic Recording (John Wiley & Sons, New York, 1999), Chap. 6.
[12] D. A. Lindholm, IEEE Trans. Magn. **13**, 1460 (1977).
[13] K. Ohashi, N. Morita, T. Tsuda and Y. Nokada, IEEE Trans. Magn. **35**, 2538 (1999).
[14] M. P. Sharrok, IEEE Trans. Magn. **26**, 193 (1990).
[15] R. W. Chantrell, J. D. Hannay, M. Wongsam, T. Schrefl and H. -J. Richer, IEEE Trans. Magn. **34**, 1839 (1998).
[16] K. OGrady and H. Laidler, J. Magn. Magn. Mater. **200**, 616 (1999).