Chapter 9
Perpendicular Magnetic Recording Medium for a Density Beyond 1 Tera Bit/inch^2

Kazuhiro Ouchi and Naoki Honda

9.1 Necessity of Patterned Media

Perpendicular magnetic recording was proposed by Professor S. Iwasaki in 1977 [1] as a scheme superior to that of longitudinal recording in terms of high density recording performances. The new HDD (hard disk drive) system of perpendicular recording was commercialized in 2005. The area recording density started at 133 Gbit/inch^2 [2], which far surpassed the achieved density of the conventional HDD of longitudinal recording. In 2006, successful demonstrations of the highest density at around 350–420 Gbit/inch^2 were announced, one after another, by HDD manufacturers [3]; no other new information storage technology superior to magnetic recording has been proposed as yet. Thus, perpendicular recording is expected to dominate over the existing information storage technology in the near future.

Perpendicular magnetic recording (PMR) has the great advantages of a single pole high writeability of recording in the gap between the head and the medium soft under layer, a high recording resolution of anti-parallel magnetization transition with no demagnetizing field, and a high thermal stability with a rather thick recording layer, when compared with the longitudinal magnetic recording (LMR) used so far . These advantages in PMR and the lately diagnosed limitation of thermal stability of the LMR media accelerated the commercialization of PMR at around a density of over 100 Gbits/inch^2,where the PMR media have a large-enough margin for the limit of thermal stability. Construction of the commercialized PMR system is based on the original principle of PMR, in which the combination of a single pole head and a composite medium with a soft magnetic back layer was essential. Presumably, however, as long as granular type media are used, even the PMR system would face thermal

K. Ouchi (✉) and N. Honda
Akita Research Institute of Advanced Technology (AIT), 4-21 Sanuki, Araya, Akita 010-1623, Japan
e-mail: ouchi@rdc.pref.akita.jp

N. Honda
Faculty of Engineering, Tohoku Institute of Technology, 35-1 Yagiyama, Kasumicho, Taihakuku, Sendai, Miyagi 982-8577, Japan

T. Osaka et al. (eds.), *Electrochemical Nanotechnologies,*
Nanostructure Science and Technology, DOI 10.1007/978-1-4419-1424-8_9,

instability of the media or the restriction of writing by single pole heads when a high density over 1 Tera bits/inch^2 is designed. The former issue can be answered by employing very high anisotropy energy materials such as Fe–Pt, Sm–Co, Fe–Nd–B, etc. But it means an extremely high switching field of such media; thus, the latter issue of head writeability would, in the final outcome, become very serious.

In order to solve the dilemma of the PMR system design, heat-assisted magnetic recording (HAMR) [4], discrete track or bit-patterned media have been proposed [5]. HAMR is inevitably based on perpendicular magnetic recording that makes magnetization switching easy with the aid of thermal energy provided by some probe light beams irradiated bit by bit locally or over a wider area. However, there is neither a proper light beam source of 10 nm spot nor practical media with the required thermal properties. Furthermore, a medium of lower coercivity due to an increased temperature may, in principle, show a slower switching speed. Thus, a high speed and a high density may hardly coexist by HAMR.

A discrete track medium has been successfully developed in order to form a very narrow recording track without any adjacent track interference even for a fairly wide track head [6, 7]. However, it has been reported that the discrete media can improve the track margin by around 10% when compared with the conventional media [8]. Furthermore, the technologies to fabricate a few ten nanometer grooves on the disk media have almost the same difficulties as those for a so-called patterned medium. Therefore, it may be necessary to think that bit-patterned array media, rather than the discrete track media, should take over the granular recording layer, as the second-generation perpendicular recording media; hence, introduction of HAMR should preferentially be taken up after the development of patterned media.

The fundamental idea of bit-patterned media was first proposed by I. Nakatani et al. in 1991 [9] followed by a demonstration of the fabrication of 65 Gbits/inch^2 columnar dots by S. Y. Chow et al. in 1994 [10]. However, its superiority in the area density when compared to conventional recording media has not yet been proved. Around the same period, Y. Nakamura [11] proposed a "Tera bit spinic storage" that stores a bit per grain, indicating preferred perpendicular anisotropy in terms of magnetostatic interactions between bits, but with no suggestions for fabrication and design of the media. In 1997, R. L. White et al. [12] refocused attention on patterned media in terms of thermal stability after the suggestion of the thermal stability limit of conventional longitudinal magnetic recording at around 100 Gbit/inch^2 by S. H. Charap [13]. Early studies on patterned media [14, 15], with the exception of the study by Y. Nakamura, had not focused on the media with perpendicular anisotropy. Although many papers on the fabrication of magnetic dot arrays have been published [16, 17], few have focused either on the thermal stability design, the influence of magneto-static interaction between dots, or the recording conditions such as writability of heads. Especially, write conditions without a bit interference with neighbor dots, which may determine the dot array configuration, such as dot separation, shape and magnetic properties have not been discussed. Fundamental read-write simulations were first performed by G. H. Hughes [18], aiming at recording on a 100 Gbits/inch^2 patterned bits array, which had a large margin of the energy ratio of more than 500 for thermal stability of recorded bits. Hence, thermal stability issues were not taken up for discussion. However, since an area density of more than 300 Gbits/inch^2 has become possible with conventional perpendicular media of a granular type, the target area density should be increased to more than 1 Tera bits/inch^2, where the bit size is roughly within 25×25 nm square or less.

9.2 Materials for Patterned PMR Medium

The medium design for a patterned-medium should be reconsidered because the fine granular structure used in the recent PMR system will no longer be required even though the same perpendicular recording scheme will be used. Since the patterned-dot is used for recording a bit unit, the individual dot itself should show very ideal single domain behavior without any magnetic defects for a high-quality signal bit. Moreover, the dot array should be precisely fabricated in terms of the arrangement, the dot pitch, and the dot size. Hence, the original thin film for the patterning of either a single crystal, amorphous or multilayered, should show very high homogeneity without any imperfection. Even where a self-organized dot array is concerned, the individual dots must show exactly the same shape and magnetic properties. The candidate materials have to be chosen from the view point of conditions to simultaneously satisfy the long-term thermal stability of magnetization, a large saturation moment, and the magnetization switching feasibility. For practical use, chemical stability, namely, a high corrosion resistance and mechanical strength are also very essential.

Figure 9.1 shows the relationship between saturation moment M_s and anisotropy energy K_u for various candidate magnetic materials. The larger anisotropy energy

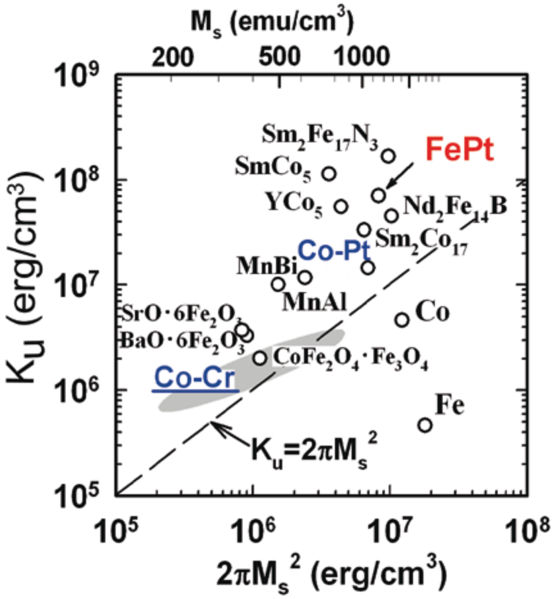

Fig. 9.1 Various candidate materials for perpendicular patterned media on the map of M_s vs. K_u [37]. (2003@IEEE)

provides a smaller critical particle diameter for superparamagnetic behavior independently from the saturation moment M_s. Hence, smaller single domain dots can be realized for materials of a large anisotropy energy constant, K_u, such as Sm–Fe, Sm–Co, Fe–Pt, Co–Pt and so on. Among them, Co–Pt or Fe–Pt alloy would be much better for the patterned-media because of not only a large K_u with high saturation moment M_s but also a high corrosion resistance as a thin film state, differing from Sm–Co, Nd–Fe–B, etc.

It has been reported, for example, that a dot pattern array of Co–Pt films, whose deposited film state showed a maze-pattern-like domain structure implying a single crystal-like structure, has been tentatively fabricated by a focused ion beam (FIB) technique [19].

9.3 Dot Shape and Arrangement

Dot shape of the bit-patterned media could be generally a circular plate, a columnar type or a square type. The shape depends principally upon the fabrication process and the method. A columnar type of Ni dot array is typically obtained by using micro-photolithography [10]. A column-like dot array has been realized by a self-organized chemical synthesis method for Fe–Pt nanometer-scale particles [20, 21]. This type can also be fabricated by an electro-deposition method in the hole of the anodic oxidized layer of Al [22]. The size of the alumite hole can be easily controlled by the conditions of anodic oxidation [23]. A further improved technique, which is based on Si wafer holes etched by electron beam lithography with electroless deposited Co–Ni–P or electrodeposited CoPt, FePt, has been developed recently [24, 25]. The square dot is the most popular shape as in the original patterned medium [9]. This shape has been fabricated by electron beam lithography. Two types of arrangements have been thought of for the bit-patterned media. One is a honeycomb-like arrangement with hexagonally close packed dots obtained for plated dots or self-organized dot patterns. This hexagonal dot array has been found to have the most efficient arrangement to achieve the highest area density in terms of reproducing S/N ratio [26]. However, as far as the writing process is concerned, the hexagonal array is inconvenient to discriminate the neighbor tracks with proper timing, while the influence of the write head on the adjacent tracks is the same. Thus, in the case of e-beam lithography or FIB fabrication, the square-shaped dot might be preferred for either the cost or the fabrication feasibility. The transition width can be small enough for the square-shaped dots when compared with the other shapes in the down track direction.

9.4 Demagnetizing Field Effects of Magnetic Dots Array

Patterned-media have non-magnetic boundaries between the dots so as to discriminately switch and detect the magnetization of each individual dot as an information bit. The localized demagnetizing field around the dots is a very important factor to determine the

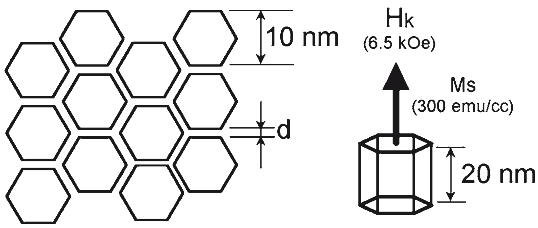

Fig. 9.2 Simulated model for evaluation of the demagnetizing effect on *M–H* loops assumed for a highly packed dots array [27]. © 2002 IEEE

write margin as well as the writing feasibility. Therefore, micromagnetic demagnetizing field or magnetostatic interaction effect on the *M–H* loop is considered first [27].

The media were assumed to consist of a monolayer of hexagonal dots with saturation magnetization of 300 emu/cc, a perpendicular magnetic anisotropy field H_k of 6.5 kOe, a hexagon size of 10 nm, and a height of 20 nm as shown in Fig. 9.2. This model has been used for the design of a perpendicular granular type medium [27]. However, the results can be applicable to the fundamental demagnetization effect on the *M–H* loops of the patterned-media if we assume that the exchange interaction between the grains, that is, the patterned dots, is neglected. It is to be noted that the M_s and the H_k are smaller than those required for a patterned-medium, suggesting a slightly underestimated interaction compared to the practical case.

The hysteresis loops of the dot arrays with the net demagnetizing field are simulated as shown in Fig. 9.3. Figure 9.3a shows the net *M–H* loops of the array indicating that the net smaller saturation magnetization is observed for a larger separation *d*. The loop inclination, α, does not seem to change so much with the separation *d* changes. This means that the change in the net *M–H* loop can be understood by the packing fraction change with the d variations. On the contrary, if we pay attention to magnetization reversal of the individual dot, each dot should have the same M_s as that of the original material for any value of *d*, while the loop inclination α_g changes drastically with the increase in the dot separation, *d*, as shown in Fig. 9.3b. Consequently, the magnetization of each dot switch obeys the grain *M–H* loop but not the net *M–H* loop.

A dramatic increase in the *M–H* loop slope, α_g, is seen with increase in the grain separation, *d*, while H_c and α change a little. According to the increase in α_g, the required maximum magnetic field, namely, the saturation field, H_s, to reverse the dot magnetization in the hardest case becomes small. This can be explained by the reduced magneto-static interaction between the dots as the separation *d* increases. This means that even for a rectangular-shaped *M–H* loop in a state of isolated dots, the *M–H* loop for the dot array is sheared by the dot by dot magnetostatic interaction, indicating the dispersion of the switching field. The slope α_g is the major factor to determine the writing feasibility of the patterned media. Therefore, a very important design factor is paying attention to the separation *d* between dots. It is also implied that the higher M_s of dot material induces much larger magnetostatic interaction while it increases the stored magnetic energy of the dot.

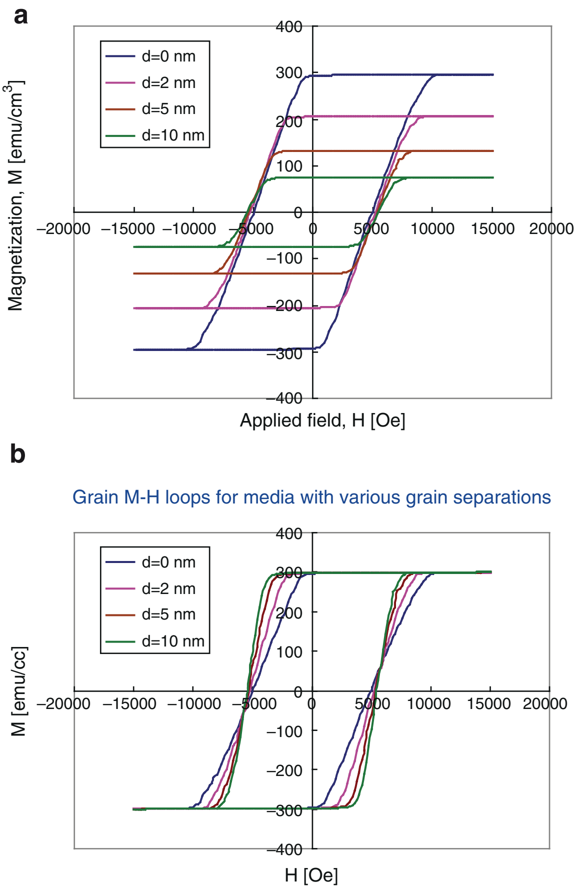

Fig. 9.3 Hysteresis loops for various values of separation d of hexagonal dots array (a) net *M–H* loops with net demagnetizing field, (b) the *M–H* loops in average of individual dot [27]. © 2002 IEEE

9.5 Thermal Stability and Write Feasibility

Let us consider the condition for thermal stability of the patterned-media with perpendicular anisotropy, based on a perpendicular *M–H* loop [28]. The net *M–H* loop for a dot array is the statistic result of small Stoner–Wohlfarth model like square *M–H* loops of each magnetic dot. The thermally stable condition for a magnetic dot array is just that of the condition for a dot, which is the easiest to reverse among the whole dots. Using the beginning field of the reversal, namely, the nucleation field of the magnetic dot array, H_n, the condition is expressed as,

$$E_m / K_B T = \frac{1}{2} H_n M_s V / K_B T \geq 60 \tag{9.1}$$

where, E_m, M_s, V, k_B and T represent magnetic energy, saturation magnetization of dot, dot volume, Boltzmann constant, and temperature in K, respectively. The nucleation field H_n is defined as the value at the time of zero second in the present study. Equation (9.1) assumes the error rate of less than 10^{-7} in 30 years for the weakest dot according to the thermal decay theory of magnetic particles proposed by M. P. Sharrock [29]. The energy ratio E_m/k_BT was set at 70 for $T = 300$ K so that it can maintain the value to be greater than 60 even at +70°C.

The value of H_n is always smaller than the coercivity, H_c, for a dot array as shown in Fig. 9.4. The fact comes from (1) dispersion in H_c of individual dot and/or (2) the magnetostatic interaction between dots. In case (1), the estimation of the magnetic energy by (9.1) is reasonable. However, in case (2), the estimated value may include error because the magnetic energy should be reduced by $(1 - H_d/H_c)^2$, where H_d is the demagnetizing field from the neighboring dot magnetization. Nevertheless, the error is estimated as less than −10% for patterned-media with substantial separation between dots, because $H_d/H_c < 1/10$. The other case of the error may come from incoherent reversal of the magnetization of the dots. The extreme incoherent reversal for the exchange-coupled composite (ECC) medium [30] would cause a 50% error in the estimation of the magnetic energy. However, the error is estimated to be less than 10% even if the dot is stacked on a halved anisotropy softer dot. When the M_s is assumed as 600 emu/cc, the smallest nucleation field $-H_n = 15$ kOe is sufficient to keep thermal stability of magnetization for square dots with 7×7 nm and 11 nm height. The saturation field H_s is estimated as more than 21 kOe. Therefore, the required head field strength is more than 21 kOe on track position and less than 15 kOe on the position of neighbor track of 25 nm distance from the center of pole surface. A field gradient of 240 Oe/nm is, accordingly, sufficient to write on the aimed dot without any interruption against the other dot. This type of head field distribution could be realized only by the multisurface pole head [31].

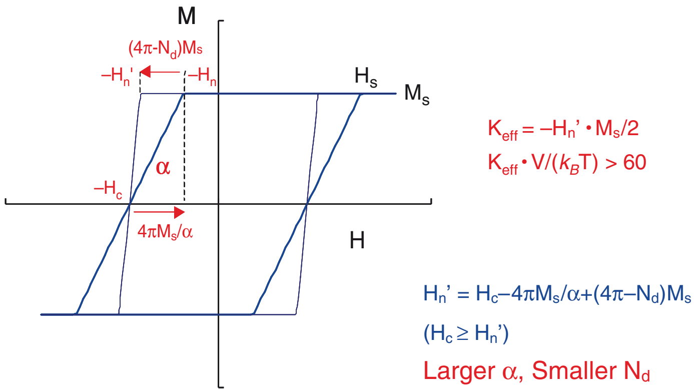

Fig. 9.4 Model M–H loop and definition of H_n, H_c, K_{eff} [28]. © 2002 IEEE

Finally, typical solution to keep thermal stability of the magnetization, together with write feasibility by a perpendicular single pole head is to set the square dot, placed on a soft magnetic underlayer (SUL), in a size of 7.5×7.5×10 nm with $M_s = 1{,}000$ emu/cm^3. Then, magnetic field strength to saturate the dot, H_s, is prospected as 18 kOe with the nucleation field, H_n, of 11 kOe, where H_k of 15 kOe is required for the dot material under the consideration of magnetostatic interaction between dots. The H_k value of 15 kOe corresponds to an anisotropy energy constant, K_u, of 7.5×10^6 erg/cc for $M_s = 1{,}000$ emu/cm^3.

These magnetic properties are easily obtainable with presently well-known high K_u materials such as FePt [32] and Co–Pt alloy [33] as described in the previous section. Consequently, it is very much possible to design a medium for a density of 1 Tera bits/inch^2 in terms of thermal stability, recording feasibility and applicable materials without any corrosion problems.

9.6 Simulation Analysis on Basic Recording Conditions

The authors first simulated the recording process for a model of bit-patterned media of 1 Tera bits/inch^2 as shown in Fig. 9.5. The single pole head main pole has 25×25 nm^2 square surface area. Karlqvist-type field distribution is assumed and the perpendicular field H_y exhibited a half-height width of 42.5 nm with the maximum field of 12.5 kOe in both down and cross track directions at a spacing of 25 nm between the head pole surface and the soft magnetic underlayer (SUL). Various dot models from M1 to M13, shown in Table 9.1, were examined in order to investigate the dot shape effect in terms of recording feasibility and recording characteristics. Each magnetic dot is constituted with 2.5 nm size cubic elements. The elements are exchange-coupled with the nearest neighbor elements with each other. Therefore,

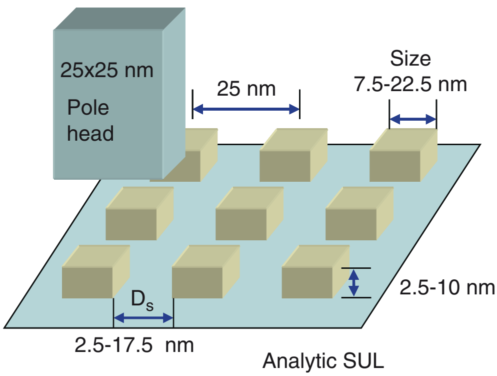

Fig. 9.5 Model scheme used for simulation of recording process on a patterned perpendicular medium with a soft magnetic under layer by a single pole head

Table 9.1 Simulated patterned dot array media of various shapes, sizes, magnetic properties

Media	a [nm]	b [nm]	t [nm]	Volume [nm^3]	H_k [kOe]	H_{nr} [kOe]	H_{cr} [kOe]	H_{sr} [kOe]
M-1	7.5	7.5	10	563	15	12.0	14.8	18.0
M-2	12.5	12.5	5	781	15	84	9.9	12.0
M-3	15	15	2.5	563	22	11.4	13.2	15.0
M-4	17.5	17.5	2.5	766	19	84	9.9	11.7
M-5	75	12.5	10	938	10	72	8.4	10.5
M-6	7.5	15	5	563	19	11.4	13.8	16.5
M-7	7.5	17.5	5	656	18	10.2	12.4	15.0
M-8	75	20	5	750	17	9.6	11.0	13.5
M-9	7.5	22.5	5	844	16	8.1	9.7	12.3
M-10	12.5	15	5	938	15	7.8	9.5	11.1
M-11	12.5	20	5	1,250	13	5.1	6.3	8.7
M-12	12.5	20	2.5	625	21	10.2	12.0	14.1
M-13	12.5	22.5	2.5	703	20	9.0	10.8	12.6

$KV/k_BT > 70$
25 nm period array
Element: $2.5 \times 2.5 \times 2.5$ nm^3, $M_s = 1{,}000$ emu/cm^3, $A \sim 1 \times 10^{-6}$ erg/cm, $\sigma H_k = 15\%$, $\sigma\theta = 2°$, $t_{IL} = 5$ nm, Analytic SUL

an in coherent rotation mode of magnetization reversal in the dot can be treated by this model. Each element has a saturation magnetization of $M_s = 1{,}000$ emu/cm^3, an exchange stiffness of 0.98×10^{-6} erg/cm, dispersion in H_k and perpendicular orientation of 15%, and 1.5°, respectively. A non-magnetic intermediate layer of 5 or 1 nm thick is assumed on the analytic SUL.

Series of M1–M4 are square dot arrays of various sizes of edge and dot thickness. Media of M5–M9 have the same edge size of D_1 but different sizes of D_2 with the same thickness of 5 nm except M5 of 10 nm for comparison. Series of M10–M13 are for investigation of the elongation effect with an increased D_1. The dot size variety is from 7 nm to 22.5 nm, and the thickness is from 2.5 nm to 10 nm.

For these models, thermal stability conditions were first discussed as the absolute prerequisite condition. Consequently, the nucleation field of the each dot arrays H_n has been determined to satisfy the stability conditions of $E_m/kT > 70$ at room temperature, where the required perpendicular anisotropy indicated by anisotropy field H_k has been, beforehand, decided by the simulation of the remanence curve for the objective variety of the dots. Every patterned-medium has a soft magnetic backlayer of infinite permeability. It is noted that the remanence coercivity H_{cr} is substantially smaller than the averaged anisotropy field H_k as seen in Table 9.1. This is caused by the shape anisotropy of the dots and assumed dispersion of 1.5° in orientation. Hence, every dot has slightly different magnetic properties in comparison with the others. This implies occasional error of writing in some critical conditions. Every dot pattern is, needless to say, designed to accommodate 1 Tera bits/inch^2 in terms of thermal stability.

9.7 Recording with Karlqvist Head Field

The model media has three tracks of dots and the center track is just the recorded track in the simulation. All the tracks are initially DC erased before recording. Only the center track is written with all 1's signal. The on-track write error rates for 25 recorded bits with a linear density of 1,016 kFCI (flux reversal per inch, namely, 25 nm bit length) were evaluated by shifting the reverse timing (position) of the recording head field in the down track direction keeping the on-track condition. Evaluation was performed for the four media (M1–M4) of different sizes but similar volume. The remanence nucleation field H_{nr} value for thermal stability is also not so much different among them. The maximum magnetic field required for enough write-ability was at around from 9.6 to 13.7 kOe.

The write shift margin or the write window was 17.5 nm for dots less than 12.5 nm. However, error-free recording was not possible for a large dot of 17.5 nm where the H_s value was larger than the maximum head field of 12.5 kOe. Generally speaking, the ideal shift margin should be 25 nm for a dot array with a period of 25 nm like this case. The write shift margin, W_w, is roughly estimated using $(H_{sr} - H_{nr})$ and perpendicular write field gradient, $\mathrm{d}H_y/\mathrm{d}x$, as $W_w = 25 - (H_{sr} - H_{cr})/(\mathrm{d}H_y/\mathrm{d}x)$. As $(H_{sr} - H_{rc}) = 3.6$ kOe and $\mathrm{d}H_y(\mathrm{eff.})/\mathrm{d}x = 370$ Oe/nm for M-2, where effective field, $H_y(\mathrm{eff.})$, compensating for the angular dependence of the switching field of S–W particle, [35] was used instead of H_y, W_w was estimated as small as 15.3 nm for the simulation value of 17.5 nm. The difference between the estimated and simulated values would be caused by the reduced saturation field in the recording process. As decrease in the field gradient by averaging over the dot width was estimated at about only 10%, the observed reduced W_w for larger dots would be caused by another reason such as, for instance, the incoherent reversal of magnetization in large dots with a small thickness of 2.5 nm.

The reverse rates at an adjacent track, when the head was shifted in the cross track direction, have been also simulated. The error occurrence in this case was different from that in down track writing where the field gradient determines the discriminability of bit writing. The full shift margin in the cross track direction was less than 1/3 of that in the down track direction. The small shift margin in the cross track direction is mainly attributed to the broad field distribution in the cross track direction. Therefore, it is essential to use a write head with a high field gradient in the down track direction and a narrow field distribution in the cross track direction. One of the solutions would be to use shield type heads.

The shift margins were investigated for media in Table 9.1 including dots with elongated shapes in the down track direction as summarized in Fig. 9.6.

It was found that less decreased or even increased shift margin in the down track direction was obtained for the dots with the elongated shape compared with the square dots (solid line indicated by $D_1 = D_2$). The dot length in down track direction, D_2, could be elongated to over 20 nm for dots with the size in the cross track direction, D_1, of less than 12.5 nm. At the same time, the shift margin in cross track direction is larger than that of the square dots. In this case, the dot volume can be increased so that the required H_n for thermal stability could be reduced. In order to

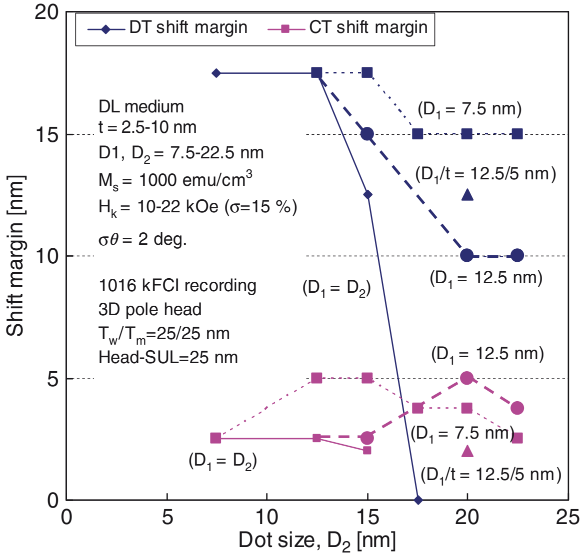

Fig. 9.6 Down track (DT) timing shift margin and cross track (CT) head shift margin for shapes of various D_1, D_2

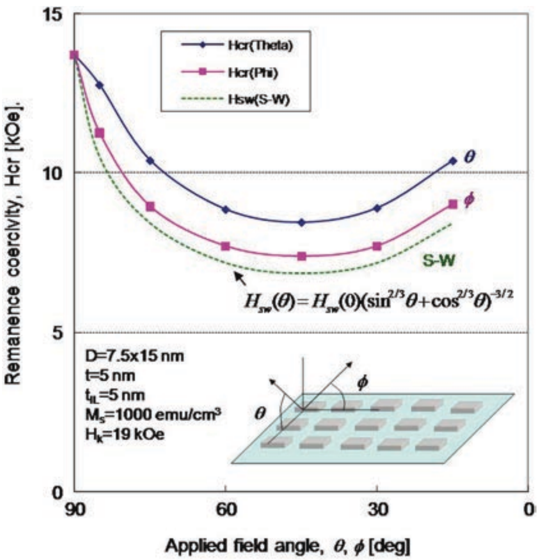

Fig. 9.7 Difference in angular dependence of the switching field, H_{rc}, in the two typical applied field angle directions of the anisotropic shape dot medium, M-6

understand the effect of elongation of the dot, angular dependence of the remanent coercivity for the M-6 medium was calculated for both in the cross track and the down track directions comparing with a so-called Stoner–Wohlfarth model as shown in Fig. 9.7. The angular dependences in ϕ direction (DT) are similar to that of S–W model. However, the variation of the remanence coercivity is larger for ϕ

direction (DT) than that for theta direction (CT), meaning that CT direction is harder to reverse the dot magnetization than that of DT. The fact makes the dot to show a larger shift margin in the cross track direction compared with square dots. It could be concluded that the elongated dot shapes are useful for obtaining patterned-media with larger shift margins in the cross track direction than square dots in terms of the head design.

9.8 Recording with Multi Surface Pole Head

Recording simulation has been carried out using the head field distribution obtained by 3 D-FEM analysis for a multisurface pole head proposed by S. Takahashi et al [36]. The head has a front side shield to make the head field narrower in the cross track direction than conventional single pole heads. The head core and the shield material are assumed to have a saturation flux of 2.4 T. Needless to say, combination with a soft magnetic backlayer of the medium is essentially assumed. The bump core size is 14 × 45 nm and the head-medium magnetic spacing is assumed as 6 nm. The half-height width of the field in the cross track direction was 34 nm, which was smaller than the field for Karlqvist one by 8.5 nm. This multisurface pole head can provide the very strong maximum magnetic field by the flux concentration effect and/or back- side core field superposition effect of the pole shape even for a very narrow track width. This is a large discriminatory property in the cross track direction compared with the conventional single pole head.

The shift margin is wider than that obtained for Karlqvist type head field in both directions. The elongation effect of dots to increase the shift margin in the cross track direction has also been verified for the multisurface head with side shields.

Although our simulation does not include the dynamic reversal of magnetization of the dot, the result means that bit-patterned media of variety of size and shape can realize, principally, an area density of at least 1 Tera bits/inch^2. Furthermore, it is important that considering the shift margins in both cross and down track directions, the size and pitch of the patterned-dot are very much essential for the design of array. In order to make a large margin of healthy recording scheme, the spacing of the dot has some critical conditions from the view point of write feasibility implied by larger *M–H* loop slope of the dot arrays through the reduction of interaction field from the neighboring dots.

9.9 Experiments on Patterned Media

There are many reports on fabrication of patterned-media. However, few papers have discussed the dot-spacing effect in terms of the *M–H* loop shape. From the view point of importance of write feasibility of media, we have investigated experimentally effect of the dot spacing on magnetization reversal. A typical machined pattern

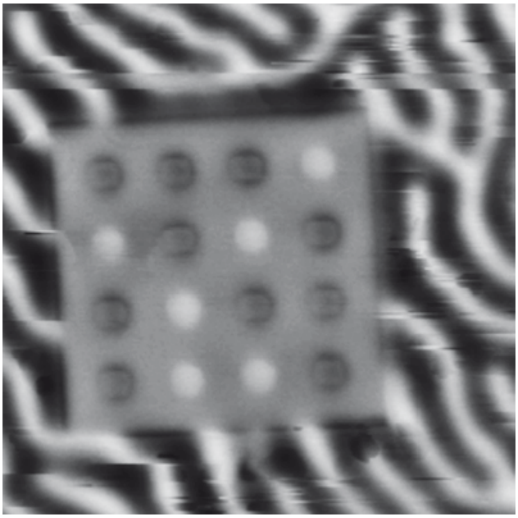

Fig. 9.8 Co_{80}–Pt_{20} patterned dots array fabricated by focused ion beam technique. Pitch of the dots is 200 nm and the dot size is 70 nm [38]

observed by magnetic force microscopy is shown in Fig. 9.8. The source material is Co–Pt as has been mentioned in Sects. 9.1 and 9.4 [19]. The original Co–Pt film showed a continuous structure, which has a maze like domain structure and very low coercivity compared with the anisotropy field, suggesting that wall motion reversal of magnetization is dominant. The 1 μm square was patterned as an array of 16 dots of 70 nm in edge size. The dot shape should be square but seems an edge-rounded shape due to the resolution limit of the used MFM (magnetic force microscopy). The designed size of the dots is at around 70 nm with a dot-by-dot spacing of 200 nm. The bright dots, for instance, represent the reversed domains from the original direction of magnetization of the dark dots by applying external field.

Multiple patterned array areas were formed on the same Co_{80}–Pt_{20} perpendicular anisotropy film to evaluate the DC remanence curve by counting the number of reversed dots with changing applied magnetic field. The Co–Pt film thickness is 15 nm.

Figure 9.9 shows remanent magnetization curves of dot arrays with the same size of 70 nm and various spacing of 20–200 nm. In case of the composite-patterned dots array with a soft magnetic backlayer of Co–Zr–Nb, when the spacing changes from 200 nm to 20 nm, the inclination of the curve decreased as shown in Fig. 9.9a, while the remanence coercivity changed a little. According to these facts, the nucleation field H_n decreases and the saturation field H_s increases when the dot spacing becomes small. The tendency coincides with that of the simulation results shown in Fig. 9.3. Therefore, recording feasibility becomes worse for the high packing of dot arrays of small spacing, while thermal stability of magnetization of the dots also decreases although situation at the recording scheme by a head must differ from that in this experiment of a uniform applied field. On the other hand, the dot array of 200 nm spacing still exhibits a finite inclination and not like S–W model even though, the spacing seems large enough to isolate magnetostatically each dot.

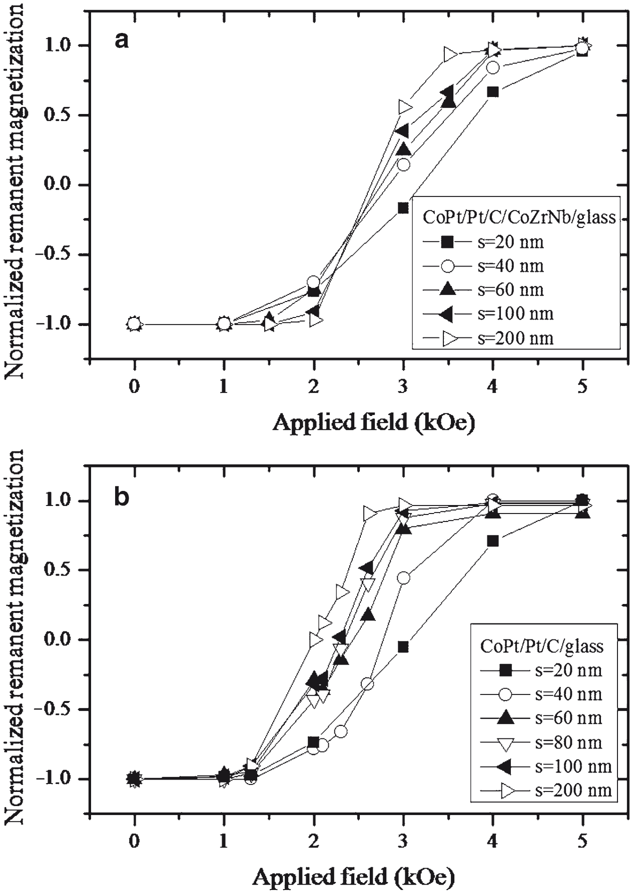

Fig. 9.9 Remanent magnetization curves for (**a**) with SMBL and (**b**) without SMBL [38]

Hence, it was thought that anisotropy distribution for the dots might still be broad presumably by the non-uniformity or fluctuation of machining process by the FIB technique.

On the other hand, in case of single layer of Co–Pt without a soft magnetic back layer, showed different remanent coercivity H_{cr} when the spacing changes, while H_n does not changes but H_s dramatically increases for a larger spacing. According to the calculation considering the surface charges of dots, the magnetostatic interaction from the neighbors is 80 Oe, and 430 Oe for the dot with a soft magnetic backlayer, and without the layer, respectively, for a dot spacing of 200 nm. Consequently, it is suggested that the slope of the curve is larger in the former case than the latter case. However, the experimental results showed similar inclination for both the cases. This discrepancy of the results may come from the too-thick intermediate layer between Co–Pt and Co–Zr–Nb layers. When we aim at 1 Tera bits/inch^2, the intermediate layer should be thinner than present. The other reasons for imperfection in fabrication and so on would also possibly exist. Hence, further study in this direction is very much necessary in the future. In any case, the present experimental study implies that magnetostatic interaction is the key factor to design a proper dot array for the development of a high density recording media.

9.10 Future Issues for 1 Tera bits/inch^2 Density

Patterned dots should be an ideal information-recording medium in terms of thermal stability and write feasibility. This article has discussed writing possibility and thermal stability simultaneously for the patterned media of various dot shapes and sizes, considering interaction effects on the magnetization reversal of the dot. Finally, it was concluded that 1 Tera bits/inch^2 could be realized by using the proper size and shape of dots combined with an advanced head design.

The main phenomena to govern the recording performance of the media are magnetostatic interaction and head medium separation. Both should be *reduced* to achieve a higher density in perpendicular scheme of recording. It is also concluded that *perpendicular* recording seems the best to make easy writing on thermally stable high anisotropy dot media. The most important breakthrough in the future should be nano order fabrication technology since the candidate materials with a high thermal stability are very realistic. The head structure is also an important issue to be improved so as to have higher field strength and gradient. A planar type head proposed recently would have great advantages in this regard.

Because we have not yet found out a hopeful information storage system with a low cost and a high capacity except HDD systems, magnetic recording technology should be advanced more than 20 years at least to answer the demands in the information society in the future. If the manufacturing method is enhanced, patterned-media will be the most hopeful media to realize a density higher than 1 Tera bits/inch^2.

References

1. Iwasaki S, Nakamura Y (1997) An analysis of the magnetization mode for high density magnetic recording. IEEE Trans Magn 13:1272–1277
2. Press Release (Dec. 14, 2004) Toshba 133G
3. Press Release (Aug. 2006) Web 300G-420G
4. Rottmayer RE et al (2006) Heat assisted magnetic recording. IEEE Trans Magn 42:2417–2421
5. Lambert SE et al (1987) Recording characteristics of submicron discrete magnetic tracks. IEEE Trans Magn MAG-23(5):3690–3692
6. Press Release (Oct. 03, 2006) TDK
7. Soeno Y et al (2005) Performance evaluation of discrete track perpendicular media for high recording density. IEEE Trans Magn 41:3220–3222
8. Greaves S, Kanai Y, Muraoka H (2006) Trailing shield head recording in discrete track media. IEEE Trans Magn 42:2408–2410

9. Nakatani I et al (1991) Japan patent 1888363, publication JP03-022211A
10. Chou SY et al (1994) Single-domain magnetic pillar array of 35 nm diameter and 65 Gbits/in.^{2} density for ultrahigh density quantum magnetic storage. J Appl Phys 76:6673–6675
11. Nakamura Y (1994) A challenge to terabit perpendicular spinic storage. J Magn Soc Jpn 18(S1):161–170
12. White Robert L et al (1997) Patterned media: a viable route to 50 Gbits/in^2 and up for magnetic recording? IEEE Trans Magn 33:990–995
13. Charp SH, Lu P, He Y (1997) Thermal stability of recorded information at high densities. IEEE Trans Magn 33:978–983
14. Terris BD et al (1999) Ion-beam patterning of magnetic films using stencil masks. Appl Phys Lett 75:403–405
15. Ross CA et al (1999) Fabrication of patterned media for high density magnetic storage. J Vac Sci Technol B 17:3168–3176
16. Rottner CT, Best ME, Terris BD (2001) Patterniing of granular magnetic media with a focuses ion beam to produce single-domain islands at >140 Gbits/in^2. IEEE Trans Magn 37:1649–1651
17. Aoyama T, Sato I, Ishio S (2003) Fabrication and magnetic properties of patterned magnetic recording media. Oyo Butsuri 72:298–302
18. Hughes GF (2000) Patterned media write designs. IEEE Trans Magn 36:521–526
19. Kondo Y et al (2006) Magnetic properties of magnetic dot arrays with a soft magnetic underlayer. J Magn Soc Jpn 30:112–115
20. Sun S et al (2000) Monodisperse FePt nanoparticles and ferromagnetic FePt nanocrystal superlattices. Science 287:1989–1992
21. Wang S et al (2003) Magnetic properties of self-organized L10 FePtAg nanoparticle arrays. J Magn Magn Mater 266:49–56
22. Gapin AI et al (2006) CoPt patterned media in anodized aluminum oxide templates. J Appl Phys 99:08G902
23. Arai K, Ohoka Y, Wakui Y (1988) Preparation and magnetic properties of anodic oxide magnetic films. IEICE Trans Electron J71-C:994–1000
24. Kawaji J et al (2005) Area selective formation of magnetic nanodot arrays on Si wafer by electroless deposition. J Magn Magn Mater 287:245–249
25. Huang YH et al (2002) CoPt and FePt nanowires by electrodeposition. J Appl Phys 91:6869–6871
26. Nutter PW et al (2005) Effect of island distribution on error rate performance in patterned media. IEEE Trans Magn 41:3214–3216
27. Honda N et al (2002) Role of *M–H* loop slope of media for recording properties in perpendicular magnetic recording. IEEE Trans Magn 38:2030–2032
28. Honda N, Ouchi K, Iwasaki S (2002) Design consideration of ultrahigh–density perpendicular magnetic recording media. IEEE Trans Magn 38:1615–1621
29. Sharrock MP (1990) Time-dependent magnetic phenomena and particle-size effects in recording media. IEEE Trans Magn 26:193–197
30. Victora RH, Shen X (2005) Composite media for perpendicular magnetic recording. IEEE Trans Magn 41:537–542
31. Takahashi S et al (2005) Magnetic recording head for patterned medium with 1 Tbit/inch^2. Abs int'l symp. creation of magnetic recording materials with nano-interfacial technologies, Waseda University, Tokyo, PS08:27
32. Suzuki T, Honda N, Ouchi K (1997) Preparation on magnetic properties of sputter-deposited Fe–Pt thin films with perpendicular anisotropy. J Magn Soc Jpn 21-S2:177–180
33. Shimatsu T et al (2004) High perpendicular magnetic anisotropy of CoPtCr/Ru films for granular-type perpendicular media. IEEE Trans Magn 40:2483–2485
34. Honda N (2005) Design of patterned media for 1 Tbit/in^2 recording.Tech Rep IEICE MR2005-15:51–56

35. Stoner EC, Wohlfarth EP (1948) A mechanism of magnetic hysteresis in heterogeneous alloys. Phil Trans Roy Soc 240:599–644
36. Takahashi S, Yamakawa K, Ouchi K (2003) Design of multisurface single pole head for high-density recording. J App Phy 93:6546–6548
37. Suzuki T et al (2003) Design and recording properties of Fe–Pt perpendicular media. IEEE Trans Magn 39:691–696
38. Kondo Y et al (2006) Magnetic properties of magnetic dot arrays with a soft magnetic underlayer. J Magn Soc Jpn 30:112–115