# Nano-pattern Design and Technology for Patterned Media Magnetic Recording

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**4 authors**, including:

Thomas R Albrecht
Molecular Vista


Masahito Kobayashi
HGST, a Western Digital compnay

Invited Paper

# Nano-pattern Design and Technology for Patterned Media Magnetic Recording

Hiroyuki Kataoka*[a], Yoshiyuki Hirayama [b], Thomas R. Albrecht [c], Masahito Kobayashi [c]
[a] Hitachi Global Storage Technologies Japan, Ltd. (Japan), 2880 Kozu, Odawara-shi, Kanagawa-ken, 256-8510, Japan; [b] Odawara Branch office, Storage Technology Center, Central Research Laboratory, Hitachi, Ltd. , 2880 Kozu, Odawara-shi, Kanagawa-ken, 256-8510, Japan; [c] Hitachi Global Storage Technologies Inc. (USA), San Jose, CA USA 95135

## ABSTRACT

About the patterned media magnetic recording technology, which is anticipated one of the new generation technologies to replace conventional perpendicular magnetic recording beyond 1Tb/in$^2$, the technology back ground, two major options, performance expectations were discussed. Then the requirements for the template (mold) for the nano-imprint lithography, which is irreplaceable technology for pattern media, were discussed.

**Keywords:** HDD, magnetic recording, patterned media, discrete track recording, bit patterned recording

## 1. INTRODUCTION

### 1.1 Growth in Recording density of Hard Disk Drive

The recording capacity of magnetic hard disk drive (HDD) has been increasing by about 40% annually for years with the explosively increasing information storage demand of our IT society. Even though it may be impacted by the WW economy in near team, demand for HDD capacity will keep strong and market growth is forecasted to be 10% per annum or more in the long term.

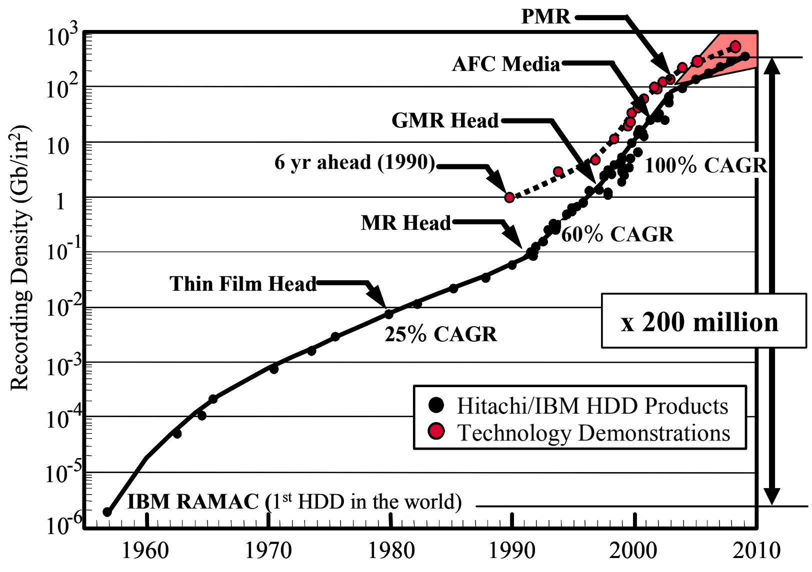


Fig. 1. The recording density of HDD has increased by a factor of 200 million in 54 years since it was first born and brought to the market in 1956. Various innovative new technologies have been invented and demonstrated before being applied to products, while disk size scaled down from 24 to 2.5 and 1.8 in.

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Technology innovations have been driving this as shown in Fig.1. The disk drive was born with coated particular media and composite heads in 1956. In 1980's, the head was replaced with a thin film type head and sputtered film disk followed. In 1990's, the magneto-resistive (MR) sensor head was introduced. Mean while, read-write channel technology innovation brought big progress to push to Gb/in$^2$ density with MR head technology. Since then, more sensitivity was achieved with GMR. TMR head with further sensitivity followed in early 2000's. The latest big change is perpendicular magnetic recording (PMR) technology, which is shown schematically in Fig. 2. The 1st Hitachi PMR drive was put into the PC HDD market in 2006 and all the model moved to PMR soon after.

HDD history lies with innovative new technologies invented one after another. Meanwhile, the recording density increased by the factor of 200 million. It is still increasing by 40% annually and it is believed to reach to 1 Tb/in$^2$ within a few years. A big change derived from an innovative new technology is being anticipated in near future.

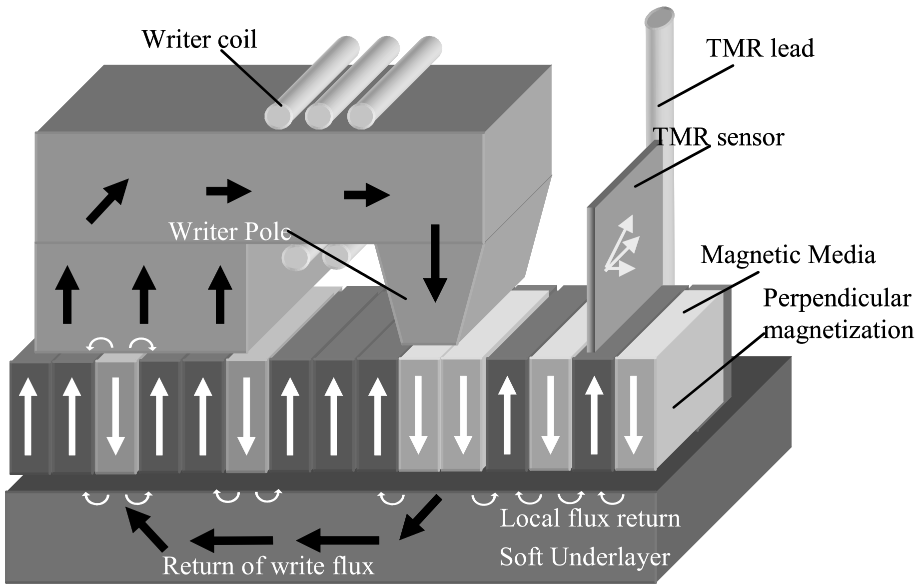



Fig. 2. Perpendicular magnetic recording is schematically shown. A writer coil and a TMR sensor are built in the head. A perpendicularly anisotropic media is sputtered on the soft underlayer on the disk substrate. In the writing process, magnetic flux is collected with the writer pole and generates a perpendicular magnetic field to switch the media magnetization direction. The magnetic flux forms a loop through the soft underlayer and wide area returning yoke or shield, where the returning field does not switch the media magnetization. In reading the magnetization pattern, a tunneling magneto-resistance (TMR) sensor is used.

### 1.2 Limitation of Continuous film PMR Technology

Discussions about magnetic recording technology limit can be found elsewhere. An article by one of the authors also covers this topic [1]. Increasing recording density requires reduction of tack pitch (Tp) and/or bit pitch (Bp). Scaling down the head dimension and precise positioning at 90nm Tp or less require much technology development work, however this is not enough. A head and media combination which simultaneously provides sufficient thermal stability for a recording bit, good writability and high signal-to-noise ratio (S/N), is also necessary for high density recording together with channel LSI and software. In HDD manufacturing, a magnetic servo pattern is written on the disk to control head position properly for reading the recorded signal or to write properly without damaging existing information. This step is called servo track writing (STW) and is a very significant step in HDD manufacturing. Read-write (RW) are done with all those sophisticated parts, procedure and software in HDD. Achieving an increase in recording density is the combined product of all those technologies which are carefully designed to complement one another, and fails if any component is insufficient.

When density is increased, the area of one bit is reduced, and this results in the reduction in the number of magnetic crystal grains composing a bit, which causes an increase in noise. Since a certain level of S/N needs to be maintained to make an HDD operational, a generation to generation increase of S/N is necessary. Continuous reduction of grain size is needed in concert with increasing recording density; however, grain size reduction conflicts with the thermal stability of the magnetization of grains. When the ratio of magnetic crystal anisotropy energy ($K_uV$) and thermal energy ($k_bT$) is reduced with the grain volume (V) reduction, the thermal magnetization reversal probability increases. Due to this thermal stability concern, the limitation of longitudinal magnetic recording (LMR) has been generally recognized [2] and in 2006, PMR started replacing LMR technology, because bit magnetization is fundamentally more stable with PMR.

To realize Tb/in$^2$ or more recording density within a few years, Tp and Bp need to be halved or more. Track width is limited by the head fabrication process and positioning accuracy limitation. The actual read sensor width is about a half of Tp, which is the same or narrower than semiconductor line width (HP) as shown in Fig. 2 [3]. This means that the head dimension control is almost at the lithography technology limit. In the writer, due to the limitation of saturation magnetization of the writer core material and narrow track width, recording magnetic field increase is no longer expected. If magnetic field is not sufficient, the media with high coercivity ($H_c$), which has good thermal stability, is not available. This results in the loss of thermal stability margin even with PMR technology.

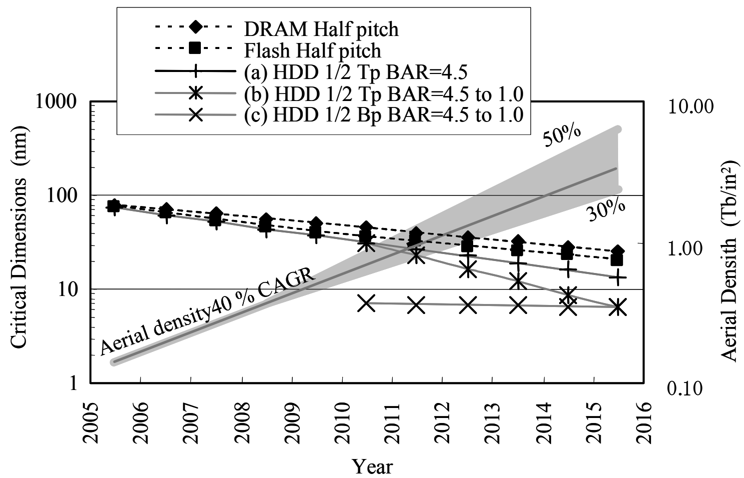



Fig. 3. Critical dimensions of semiconductor device and HDD and recording density of HDD are plotted versus date. Dashed lines are semiconductor CDs and solid lines are HDD dimensions. Assuming 40% compound annual growth rate and constant bit aspect ratio (BAR = Tp/Bp) of 4.5, 1/2 Tp of HDD (a) stays a little lower than flash HP and slowly going apart. With the reduction of BAR down to 1.0 in 2015, Tp will quickly approach Bp and will merge to a same value (b). Actual Tp should be somewhere in the middle between BAR = 5 and 2.

HDD design work includes consideration of adjacent track interference (ATI) robustness, where written data on a track is affected by the magnetic field of the writing head field on the adjacent track. Head misalignment toward the center track and lateral write field leakage are the causes of ATI. Track-to-track space or a track edge region which is not read by the reader provide margin to avoid this interference, however, this space is narrowing down with Tp reduction. HDD design optimization from this aspect is getting more difficult in recent years. Still, there is an announcement that 1 Tb/in$^2$ recording with existing PMR is achievable [4]. The engineering limit of conventional PMR has not been reached yet; however for further increase of recording density with PMR, these technical difficulties need to be resolved.

### 1.3 Comparison of Magnetic recording Technologies

There are two known major which are key candidates for the next generation of high density magnetic recording [1], patterned media technology [5][6] and energy assisted recording technology [7][8]. In Patterned media recording technology, patterned PMR media instead of continuous 2D plane magnetic media is used, where media is patterned into hard magnetic area for recording and non-magnetic area. The methodology to create non-magnetic area is either by topological pattern etching to remove magnetic material[6] or by changing the local magnetic characteristics to non-magnetic [9][10]. As shown in Fig 3(a), concentric circular recording tracks are separated with grooves or non-magnetic separator, to create what is called discrete track recording (DTR). Another type, where recording bits are also separated with non-magnetic spacer along the track as Fig 3(b), is called bit patterned recording (BPR). Each bit consists of a single magnetic island in this case. The media designed for these recording technologies are often called DTM or BPM. Since there is no noise created from magnetization at track to track space with DTR trench structure, the recording density can be increased [11][12] and a demonstration at 800 Gb/in$^2$ was announced in 2008 [13]. Since the bit-to-bit transition space does not cause noise in addition with BPR, non-uniform transition line and transition jitter noise can be eliminated, which will be discussed in 2.2 section.

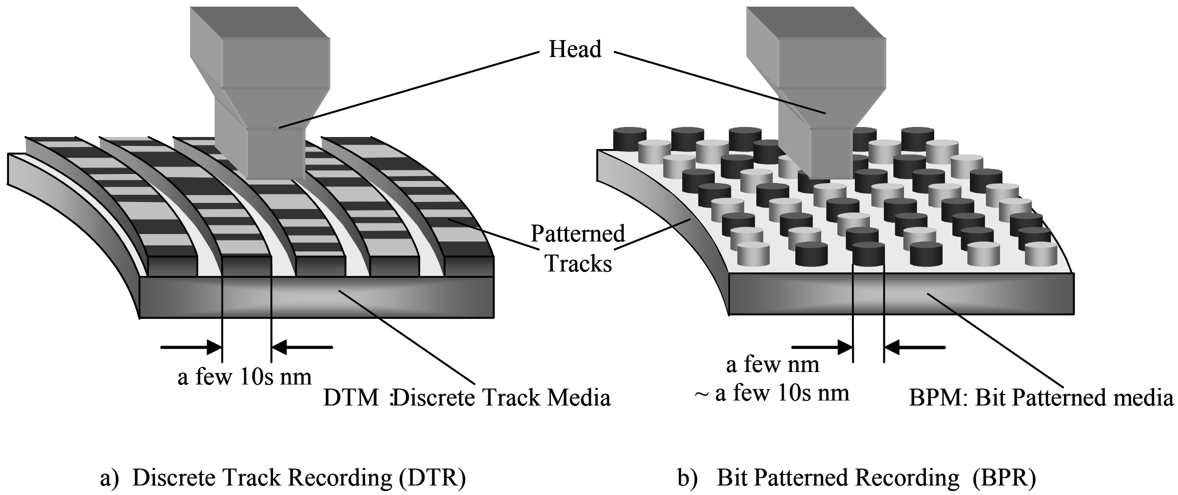



Fig. 4. Schematic picture of head writer pole and media for (a) DTR (b) and BPR are shown. With DTR as shown in (a), magnetic data bits are recorded on the concentric circular lands. Dark and light stand for magnetization direction and they correspond to bits. Bits are not separated along the track in DTR. With BPR as shown in (b), each magnetic island, separated in radial direction and also along track, will hold one bit of magnetic information.

With energy assist recording technology, the magnetic recording layer is designed to be robust against thermal demagnetization with increased magnetic anisotropy $K_u$. Since improved thermal stability means increased $H_c$ in general, the recording performance of the magnetic head degrades. A thermal spot or localized microwave field is proposed for assisting magnetization reversal in combination with the write magnetic field. With this methodology, the assisting mechanism needs to be embedded close to the magnetic writer element in the recording head.

With thermally assisted recording technology, tiny laser spot is generated on the recording media and the local coercivity decreases due to the heat assisted magnetization reversal. A demonstration of this technology seems to have shown at least 140 Gb/in$^2$ or more in assisted recording performance [14]. Some fundamental experiments were reported on microwave assisted magnetization reversal [8]. Modeling calculations have also been published to explore efficient assist conditions and appropriate writer structures [15]. Both technologies requires complex head design. The suitable recording media for assisted recording is either continuous or patterned media. In case of continuous media, magnetic grains must have high $K_u$ for thermal stability and simultaneously very small grain size and grain segregation for high S/N. However, continuous media is preferred for lower cost. Due to the materials limitations for maximum $K_u$ of current Co alloy systems, studies of new alloys are proposed.

There are a few more technology candidates which were not mentioned here. The future of each technology encompasses many exciting challenges and none has yet emerged as the preferred approach, so combinations of technologies should also be considered.

### 1.4 Manufacturing Process for Patterned Media

In contrast to the relatively short manufacturing process for a conventional disk, in which magnetic films, overcoat and lubricant are simply formed step by step on a featureless disk, for patterned media a patterning step follows the film sputtering step and this results in a huge difference. The manufacturing process for patterned media is shown in Fig. 5. Since there is not yet a well process in the industry, major changes or variations can be expected in the future. A conventional continuous film (CF) PMR disk has sputtered multilayers on the clean glass or NiP plated aluminum substrate and has a lubricant coating. The final manufacturing step is inspection. The nanoimprint, pattern transfer and planarization steps are specific processes for patterned media recording disks.

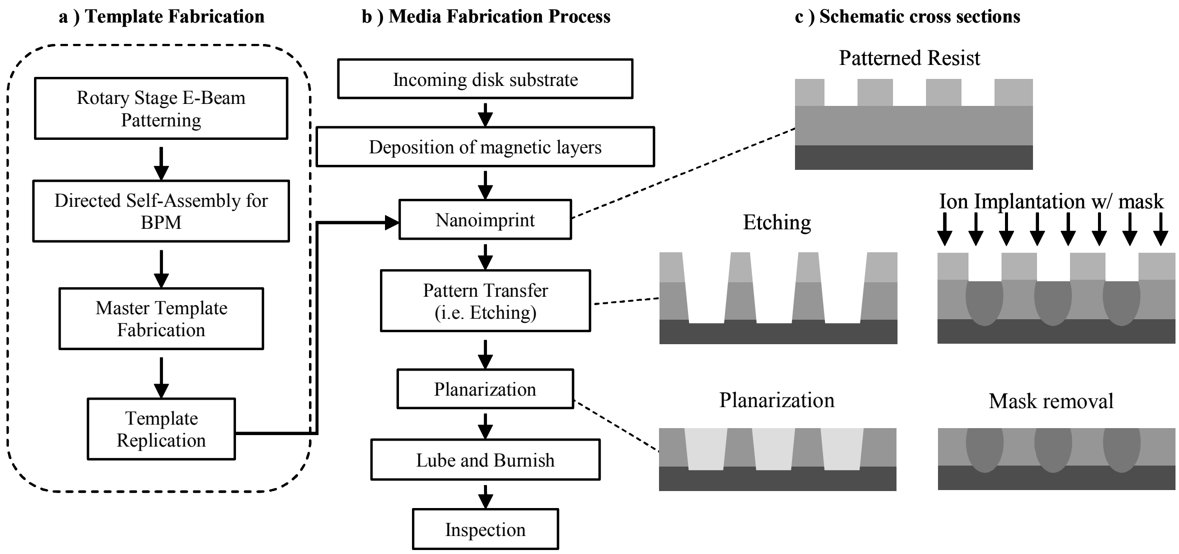



Fig. 5. The fabrication process outline for patterned media is shown. The nanoimprinting template or imprint mold (a) is separately fabricated and used in the nanoimprint step of the patterned media fabrication process (b). A directed self-assembly process in (a) is used for BPR template master patterning only. Schematic cross sections at each process step are shown on the right (c). Instead of etching and planarization (left column), there are publications related to ion-implantation proposals (right column).

There are two major methods for the pattern transfer, which are physical magnetic layer etching and poisoning (turning the magnetic layer into non-magnetic) with ion implantation or irradiation. For both cases, it is necessary to make a resistive mask pattern before etching or irradiation. A planarization methodology, where the etched area is to be backfilled to the non-etched level to planarize the surface, has been proposed for the purpose of realizing stable head flying over the patterned area. After planarization, a lubricant is coated and testing follows in a manner similar to the CF-PMR disk. In the case where ion irradiation is used, the planarization process could be eliminated in theory, which would result in less manufacturing cost.

It is popular to use a projection aligner with short wavelength light for nanoscale lithography in the semiconductor industry. An innovative new nanoimprinting lithography (NIL) method has been attracting attention in recent years. There are positive NIL results for possible application to semiconductor lithography recently, which is encouraging[16][17].

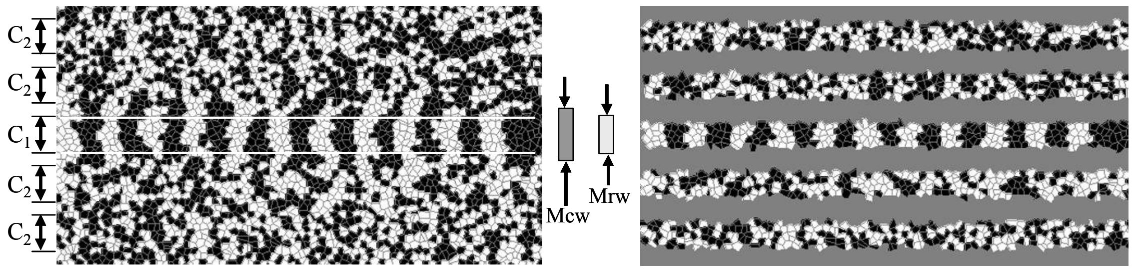
With a NIL process, the template (mold) is brought into contact with a disk having thin polymer layer in between to replicate template surface pattern on to the disk surface. The required ratio of template dimension and disk pattern dimension is 1:1, which is more difficult than a photo mask with reduced projection from pattern fidelity perspective. Template fabrication in Fig. 5 is a preparatory process for disk NIL, which is new to the disk industry but very important from a HDD performance design point perspective. A rotary stage type electron beam (EB) writer is used for creating master template. This master pattern is replicated several times to create a number of working templates having proper image tone and dimensions for NIL. Since this procedure has not been finalized yet and there are several major variations in NIL methodology, more complexity is expected in future real manufacturing.

## 2. MEDIA NOISE IN PATTERNED DISK RECORDING

### 2.1 Media Noise in Magnetic Recording

It is necessary to have a certain read-back S/N for reproducing recorded information without error. The target S/N could be reduced with improvements in signal processing, while there are ongoing engineering challenges to increase read sensitivity and to reduce head noise. The largest contributor to lower S/N is disk noise which originates from recorded magnetization. There are two major disk noise sources. They are related to track center magnetization pattern and track edge magnetization.

Modeling conditions: Tp = 75 nm, Bp = 32nm (800 kfci), Lw/Gw = 0.5 for DTR




(a) Continuous Film PMR (b) Discrete Track PMR

Fig. 6. Comparison of (a) CFM-PMR and (b) DTR modeling. $C_1$ is track center with all "1" data writing and $C_2$ is tracks with no data writing. The plain gray area of DTR is assumed nonmagnetic material.

Figure 6 (a) shows a calculated CF-PMR magnetization pattern. This modeling assumed no head misalignment. The transition curvature at the track edge magnetization is steeply bent and irregularly large magnetized domains are observed. The pattern at the edge is not well defined compared to the center. If the head is aligned off-center to one side within allowance the recording field at the opposite edge is reduced. Hence the track edge is sometimes recorded without sufficient magnetic field, and therefore the previously recorded magnetization is not clearly overwritten. Due to the adjacent track magnetization, the writing field may also be affected and the leakage magnetic field due to the adjacent writing may also affect the track edge magnetization. All these effects enhance the disturbance of magnetic field at the track edge. A certain portion of the magnetic flux from the edge pattern is read by the read sensor together with track center magnetization. This causes track edge noise. As shown in Fig. 6, the magnetic read sensor width (Mwr) is designed to be smaller than the magnetic core width (Mcw) to minimize reading of track edge; however, Mrw of the latest model is about 50nm, which is already small enough and signal amplitude is in proportion to Mrw. Simple narrowing down of Mrw is not the best answer.

The noise from a recorded bit is caused from signal position shift, slope variation and amplitude variation due to various causes in the media or irregularity in the writing process. Fig. 7 (a) shows actual average read back signal from an all "1" longitudinal magnetic recording (LMR) pattern. The signal shape is different; however the nature of disk noise is common between LMR and PMR. LMR is chosen as an example for easier explanation. Since this waveform is averaged, the noise independent of the magnetic pattern is eliminated. The "+" marks are the functionally fitted positions and amplitudes of each peak. Fig. 7 (b) shows the peak shift distribution from an evenly distributed peak center. Fig. 7 (c) shows the positive and negative peak amplitude variation distribution. Fig. 7 (d) is the disk noise calculated from waveform, where the 150kfci peak is the read back signal and the rest of the spectrum is disk noise. Disk noise consists of peak position shifts, amplitude variation and peak width variation on a repeatedly oscillating signal. In the case of PMR, the read back waveform is 90 degree phase shifted; however, the disk still consists of irregularity of the read-back wave form corresponding to magnetization reversal.

The magnetic bit is composed of multiple magnetic crystal grains. The actual bit-to-bit transition line should trace the grain boundaries or some area where the grain-to-grain magnetic coupling is weaker. If a grain is large or the magnetic coupling between grains is strong, the transition line becomes less straight or is shifted from the exact location where head field switching takes place. These are the actual sources of magnetization transition position and switching sharpness variations. Since this noise is related to the transition density, it automatically increases with recording density along the track. Since magnetization on the disk is defined with the patterning process on DTR or BPM media, careful control of pattern related noise is necessary.

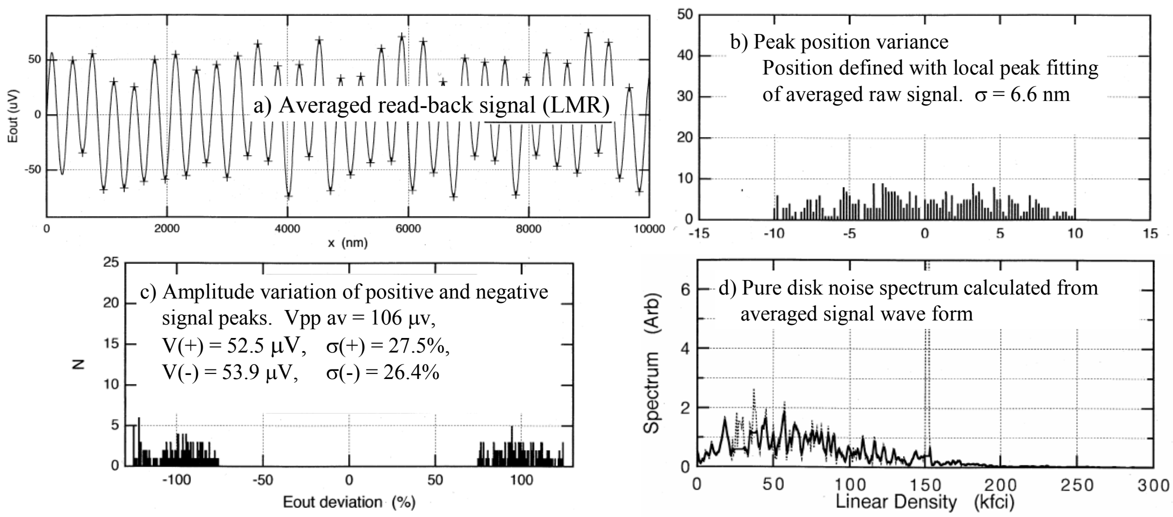



Fig. 7. Disk noise caused by read back signal peak position and amplitude variation is shown. Peak position variation (b) and peak amplitude variation (c) were measured by fitting on an averaged read-back signal wave form (a). The calculated noise spectrum (d) is also shown. This measurement was done with longitudinal media.

### 2.2 Disk Noise of Patterned Media

The magnetic film for DTR is continuous along the track and separated by track edge trenches or bands of non-magnetic material. It has similar to existing CF-PMR media, which has magnetization transition boundaries on the continuous film. From the viewpoint of transition noise, the magnetic material used for CF-PMR media can also be used for DTR with improvements. CF-PMR media with a granular structure and relatively good S/N has been achieved with small magnetic grain size and good grain segregation. Work which improves these characteristics will also results in DTR media material improvement.

Since there is no magnetization at the track edge, no track edge noise is expected. Especially in the case of off-center reading due to the mechanical alignment error, having no source of edge noise is advantageous for preventing S/N degradation; in this case the disk noise of DTM is mainly caused from read back signal jitter. On the other hand, a new noise source, which is track edge roughness noise, probably has to be taken into account. The magnetization of a discrete track will be affected by irregularity of the track edge shape or magnetic properties of the film at the track edge.

The magnetic film on a bit island of BPR has no grain boundary because the entire island has a single magnetic domain. Neither magnetic grain size reduction nor segregation are necessary on an individual island. In the history of sputtered magnetic recording disks, work for reducing the grain size and segregation has been continuously ongoing since the 1980s. BPR media is completely different in that the absence of restrictions on grain size and segregations relaxes the materials requirements. A material which tends to be granular can also be used but in this case, strong intergranular coupling is preferred. Having grains which magnetically act like one crystal is preferable to avoid the case where a magnetic island could have multiple sub-domains, with very little net magnetization due to the anti-parallel configuration.

In BPR, the bit-to-bit boundary between magnetic islands is physically patterned. Since island position or size variations cause signal peak variation, media noise will created from patterning irregularity, such as position shift or edge roughness. If the islands have variation in magnetic performance from island to island, it will create magnetization variation and will also result in disk noise. It is expected that magnetic uniformity is more easily achieved if island area and size are uniform. With the CF-PMR or DTR, the density of the transitions is reduced if the transition-to-transition distance is longer. Since bits are defined islands with BPR, "+" and "0" or "-" and "0" transitions still exist even at low transition density. This causes flat noise dependency versus recording density [25]. BPM noise should continue to be studied, and nm or sub nm class edge position and size control will be required for patterned media templates.

## 3. TEMPLATE REQUIREMENTS

### 3.1 Template Fabrication Process

The pattern generation processes for DTM and BPM templates are different. The directed self-assembly step in Fig. 5 (a) is expected to be necessary for BPM templates, because pattern fidelity requirements are very stringent. The template fabrication process is also affected by the imprint methodology and imprint tools. Different template substrates and template designs are required for each process [18]. The common issue is the creation of the master pattern, and this is discussed in more detail below.

The pattern for DTM is relatively simple and direct writing of the master pattern on the substrate using rotary stage EB tool is the current approach. The writing time for EB mastering takes more than a couple of days depending on the disk size, writing conditions, resist sensitivity, and formatter capabilities. When the Tp is scaled down, the writing time is increased inversely proportion to Tp. After developing and etching, an EB master will become a generation 0 (G-0) master template. It is replicated through several generations as shown in Table 1. The final working template should have a reverse tone image of the target disk surface topography and should have appropriate rotational direction.

If 10 k imprints are assumed as the template lifetime for NIL, one generation of a disk product will require roughly 10 k working templates per side. Assuming similar lifetime in template-to-template imprinting, only one master replica is enough. Four backup master templates, for example, were included in the Table 1. It may not be appropriate to assume that defects and pattern shift or distortion will stay at the same level from generation to generation. The overall process dimension shift can be controlled, however, minimizing the number of template generations is better.

Table 1. EB mastering, replication and disk imprints are shown according to replication generations. Image tone and rotational directions are reversed from generation to generation. Quantity assumes 10k imprint per template lifetime

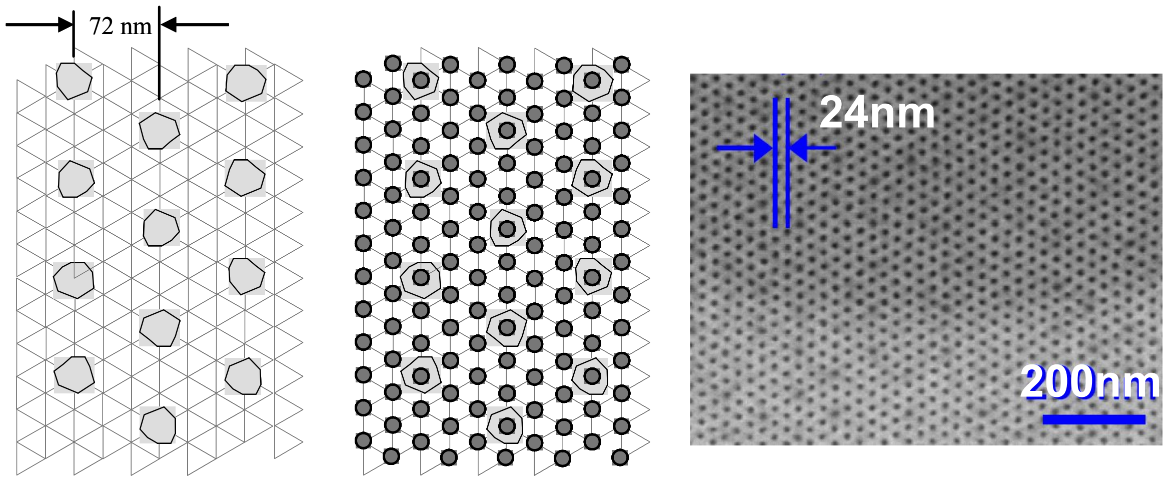
| EB MASTER AND TEMPLATE GENERATIONS | | | |
|---|---|---|---|
| **Replication Generations** | **Tone** | **Rotational direction** | **Qty.** |
| Gen-0 EB Master | Positive | CW | 1 |
| Gen-1 Master replica | Negative | CCW | 5 |
| Gen-2 replica | Positive | CW | 5 |
| Gen-3 working template | Negative | CCW | 10,000 |
| Imprinted disk | Positive | CW | 100,000,000 |

A concentric continuous circular pattern is EB written on the data area of a DTM template, while separated dots are EB-written on BPM template. The electron beam needs to be pulsed for a BPM template. The actual writing process is more complex if the bit aspect ratio (BAR) is larger than one. Since the timing jitter of the pulse and pulse width variation will result in bit position and size variations, these are carefully controlled [23]. In the future, shot noise may contribute to dot size variation as the electron dose per dot decreases with decreasing dot size.

Since a magnetic recording disk is a double-sided unit with two entire 48, 65 or 95 mm recording surfaces, large scale patterning with a limited small number of defects is necessary. The number of the defects does not need to be zero, but must be controlled below a certain level. In a semiconductor fabrication process, a number of lithography steps (each with tight alignment to existing patterns) is required, however, the wafer is diced into many chips, and defective chips may be discarded. The defect control methodology for patterned media disks has to be different than that for semiconductors, and high quality defect free templates are necessary for disk NIL.

### 3.2 Self-Assembly Technology for BPM Patterning

For currently existing EB tools and available resists, generating a 1 Tb/in$^2$ EB master is close to the engineering limit. In addition, the total writing time increases with decreasing Tp, which is a serious concern for direct EB writing of a BPM master template [1]. A novel methodology has been reported, which is the self-assembly patterning method [19][20]. In this technology, a block copolymer, which tends to form self-assembled nano-domain structures under certain conditions, is used to form a nano-cylindrical ordered array on an EB-written underlying precursor pattern. This technology enables nano-patterning beyond the EB lithography resolution limit and reduces the EB writing time.




a ) EB written course under-lying pattern

b ) Self assembled with x 9 multiplication

b ) Photograph of self-assembled polymer dots array matrix at 1Tb/in$^2$

Fig. 8. BPR master template patterning with self-assembly technology. A precursor pattern (a) was written with EB lithography with the line spacing of 72nm. A cylindrical block copolymer patter array (b) was formed on the EB patterned substrate with 9X multiplication self assembly. An SEM micrograph (c) shows the actual block copolymer image with a row pitch of about 24 nm, which corresponds to a 1Tb/in$^2$ hexagonally packed template master pattern.

This technology allows EB writing of larger dots with wider separation than the final bit size and Bp, with the targeted small size and narrow pitch generated by the polymer film. It is very attractive to be able to have 4 or 9 times denser dot array. Since the block polymer cylindrical array is assembled in manner which minimizes energy, it tends to self-assemble into an array of uniform diameter features with uniform separation, all in registration with the underlying EB precursor pattern. This offers the advantage of reduced bit position and size variation. It is expected that higher dot density will be achieved in the future with different block copolymer materials. Although this approach creates a hexagonal pattern with a BAR of only 0.87, this may be a viable approach if Bp reduction needs to be limited as pattern density is increased rapidly.

### 3.3 Requirement of Dimension Accuracies

The latest 2.5 in. drives have a capacity of 250 GB/platter with a recording density of about 375Gb/in$^2$ [21]. The calculated Tp assuming BAR of 4.5 is about 90nm, which is close to full pitch (FP) of DRAM and flash memory dimensions [22]. For the IRTS road map, the required 3$\sigma$ is about 10% of HP and this ratio has been maintained through many generations. It is reported that adjacent track writing (ATW) has a smaller effect with DTR media; however, with reduced ATW head distance, interference to the center track grows steeply[23]. From IRTS roadmap, maintaining the 3$\sigma$ of HDD Tp less than 10% HP (5% FP) seems technically challenging; however, attention should be paid to the ATW effect and land width relationship.

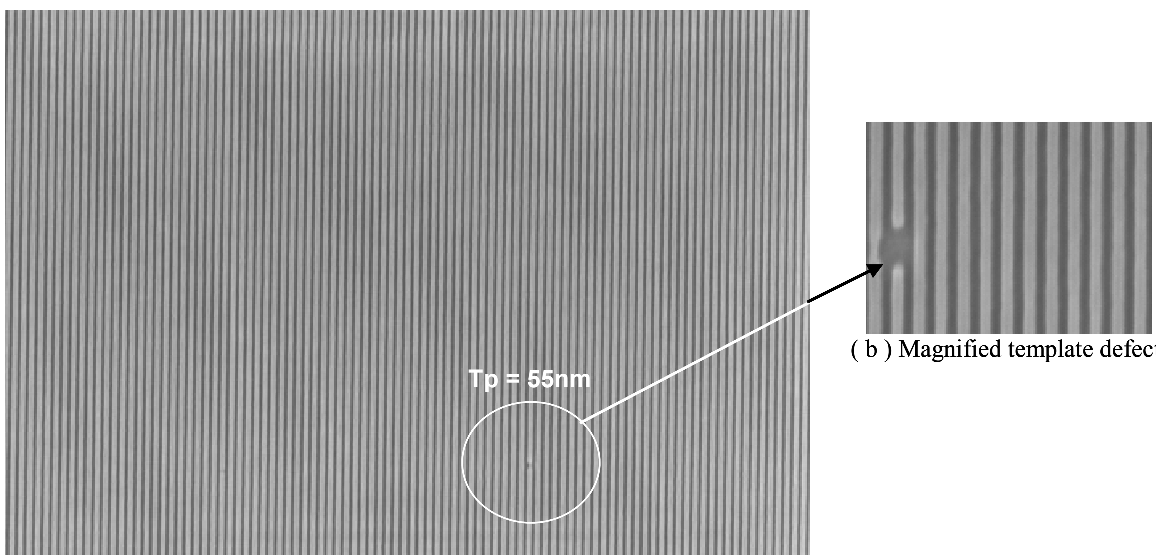
The line edge roughness (LER) of discrete tracks results in disk noise in DTR. Template LER should be as small as possible. Unfortunately, LER degradation and track width shift occur within the disk patterning process. Dimension shift is a rather simple phenomenon for data tracks; however it is more complicated on servo patterns because the patterning process is affected by the complexity of the servo pattern. Template design methodology needs to be established through iteration to take these factors into consideration.

The effect on error rate and S/N of BPR land position variation for 2 $Tb/in^2$ (2000kBPI, 100kTPI) recording model, has been studied [24]. The error rate increased by 20 times when the position dispersion σ increased from 1 to 2 nm. The assumed Bp is 13 nm and BAR was 2. These results suggest that a σ of 2nm is too large. In another report from same team [25], a 1 nm $\sigma_{jitter}$ increase degraded S/N by about 1dB at $2Tb/in^2$. A lithography technology which enables a 1 nm level of position accuracy in master patterning will probably be needed.

### 3.4 DTR Media Template Defects

It is impossible to have defect-freeNIL but it should be possible to control defects to an acceptably low level, where the quality is not impacted. In the NIL process, there are one time or temporary resist pattern defects and permanent defects. There will be defects which are added while template in is use. On the other hand, a permanent template defect causes defects on every imprinted disk, so these should be minimized. The EB master template defect is the most serious because it impacts disks imprinted by all subsequent generations of templates.

An example of template defect is shown in Fig. 10. A wide area SEM picture (a) is taken on 55nm Tp data zone of DTM template. A magnified picture of lower right circle is shown in (b). When this defect is transferred to the disk, two adjacent lands are partially (~80nm) bridged. The signal will not be lost at this spot but robustness to the track edge noise and ATW will be degraded. The opposite type of defect should also exist, where a land is partially missing, which will surely cause a hard error which may require sector remapping in the HDD.




( b ) Magnified template defect

( a ) 55 nm Tp DTR template with line breakage defect

Fig. 9. An example of DTR template defect is shown. In this case, Tp is 55 nm and there is one defect in a 5.3 x 3.6 um area with 95 tracks observed.

If the adhesion force is not enough between the resist and disk surface, imprint resist may adhere to the template surface. To avoid this, ease of separation should be maintained even a Tp or Bp are decreased to the sub-10 nm range. The imprint resist aspect ratio of the first product will be around 1.5 and Tp will decrease by 20% annually, which is challenging. Optimization of the template process to control defect density and to maintain the NIL quality is very important together with disk etching process improvement and magnetic layer design improvement.

### 3.5 Template Lifetime and Cost

The price tends to go down after a new HDD model is brought to market. The price per GB of a 1TB capacity class HDD is less than \$0.10. Especially for low capacity HDDs, cost reduction is the biggest engineering focus. In the manufacturing of HDDs, STW will be simplified or eliminated if patterned media is used, because servo pattern can be pre-patterned on the disk. Since the number of the tracks increases inversely proportionally to Tp reduction and position accuracy requirements are getting tighter, the STW time tends to increase with each new HDD generation. Although the impact is dependent on the STW methodology, in general, STW cost can be reduced by using patterned media.

On the other hand, cost control of the disk is difficult. Even though complicated template fabrication and disk patterning steps must be included for patterned media, high throughput and yield are mandatory in disk manufacturing. Unlike the case for semiconductor fabrication, there is only a single lithographic patterning step for patterned media, and the entire disk (up to 95 mm diameter) is patterned at once, without stepping. NIL is highly advantageous for this application and probably the only viable option. The most important thing in this process is to replicate nano-patterns without distortion with low cost, repeatedly. In-general, longer template lifetime is preferable from cost point of view; however, template cost per disk should be the key indicator.

There is increased risk of on-the-fly template defect generation if a template is to be used for thousands of imprints. Prevention of increase in defects is a big challenge but should be under control, because the reduction of airborne, on-the-work, consumables and tool-related particles has been intensively worked out in HDD industry for decades. In addition, since an HDD allow for remapping of bad sectors, a certain level of defects can be tolerated and does not terminate the template life. If defects in the servo pattern regions reach a certain density, drive performance will start degrading. The amount of remapping and drive performance loss allowance depends on the future patterned media HDD design. The template EOL definition is not established yet. Future careful analysis including HDD tests should drive defect analysis from the HDD performance, reliability, and manufacturing cost perspective.

## 4. CONCLUSIONS

The Tp at which DTR technology will be introduced is currently thought to be around 60 nm. Its introduction should drive further Tp reduction and areal bit density increase. The NIL template master will be EB-written, etched, replicated and working templates will be fabricated. Template quality such as line edge roughness and resist separation will be big challenges.

To move beyond the limitations of EB writing time and resolution for BPR templates, a new self-assembly technology is proposed. This is a novel method for reduction of EB-writing time and magnetic island position and size variation. Although there remain a lot of technical challenges before BPR is adopted for products, a technical route can be seen for achieving recording densities of several Tb/in$^2$.

In order to take advantage of the benefits that patterned media may offer, further advances in template and imprint technology will be needed. Achieving these goals will require tight cooperation between the NIL template industry and the HDD industry.

## REFERENCES

[1] E. Dobisz, Z. Bandic, T. Wu, and T. Albrecht, ”Patterned Media: Nanofabrication Challenges of Future Disk Drive”, Proc. IEEE, Vol. 96, pp.1836-1846, (2008)
[2] Y. Hosoe, I. Tamai, K. Tanahashi, Y. Takahashi, T. Yamamoto, T. Kanbe, and Y. Yajima, "Experimental study of thermal decay in high-density magnetic recording media," IEEE Trans. Magn., Vol. 33, pp. 3023-3030 (1997)
[3] ITRS 2008 Update Overview, http://www.itrs.net/Links/2008ITRS/Update/2008_Update.pdf
[4] Storage Research Consortium (SRC), http://www.srcjp.gr.jp/news/Press.pdf (Japanese)
[5] R. White, R. New, and R. Pearse, “Patterned Media: A Viable Route to 50Gb/in2 and up for Magnetic recording?”, IEEE Trns. Magn., vol. 33, pp. 990-995, (1997)

[6] T. Aoyama, "Fabrication method and feasibility of patterned media (translated from Japanease)", IDEMA JAPAN NEWS", No.48, pp. 22-24, (2002)
[7] M. Kryder, E. Gage, W. Terry, W. McDaniel, W. Challener, R. Rottmayer, G. Ju, Y. Hsia, and M. Erden, "Heat Assisted Magnetic Recording", Proc. IEEE, Vol. 96, (2008)
[8] J. Zhu, X, Zhu, and Y. Tang, "Microwave assisted magnetic recording", IEEE Trans. Magn., vol. 42, pp. 473-480, (2006)
[9] J. Fassbender, J. McCord, "Magnetic Patterning by means of ion irradiation and implantation", J. Magn. Magn. Mater., vol. 320, pp.579-596, (2008)
[10] J. Yasumori, Y. Sonobe, K. Wago, K. Miura, and H. Muraoka, "Magnetics and RW Study on Discrete Track Perpendicular magnetic Recording Medium by Ion Irradiation", The 31st annual Conference on MAGMETICS
[11] A. Kaizu, Y. Soeno, K. Tagami, "New Solution for High Recording Densith with Discrete Track Media", IEICE Tech. Report, MR2007-21, pp.13-14, (2007)
[12] K. Tagami, "Outlook of next generation technologies in HDD", IDEMA JAPAN QUARTARY SEMINOR, Tokyo, Japan, Presentation No.5, 23 Jan, (2009)
[13] TDK Corp. CEATEC 2008 on site presentation, http://www.ceatec.com/2008/ja/exhibition/list/detail.html?exh_id=E080167
[14] M. Seigler, W. Challener, E. Gage, N. Gokemeijer, B. Lu, K. Pelhos, C. Peng, R. Rottmayer, X. Yang, H. Zhou, X. Zhu, and T. Rausch, "Heat Assisted Magnetic Recording with a Fully Integrated Recording Head", Proc. SPIE, vol.6620, 66200P, (2007)
[15] Y. Tang, and J. Zhu, "Narrow Track Confinement by AC Field Generation Layer in Microwave Assisted Magnetic Recording", IEEE Trans. Magn. Vol.44, pp.3376-3379, (2008)
[16] I. Yoneda. S. Mikami, T. Ota, T. Koshiba, M. Ito, T. Nakasugi, and T. HIgashiki, "Study of nanoimprint applications toward 22nm node CMOS devices", Proc. of SPIE, vol. 6921 (2), pp. 692104.1-692104.8, (2008)
[17] T. Nakasugi, "Nanoimprint Applications on CMOS Devices", Digest of International Conference of Nanoimprint and Nanoimpriont technology, Oct. 13-15, (2008)
[18] K. Ichikawa, T. Usa, K. Nishimaki, and K. Usuki, "Design of Ni Mold Discrete Track Media", IEEE Trans. Magn., vol. 44, No.11, pp. 3450-3453, (2008).
[19] R. Ruiz, H. Kang, F. Detcheverry, E. Dobisz, D. Kercher, T. Albrecht, J. de Pablo, and P. Nealey, Science, 321, pp. 936, (2008).
[20] H. Yoshida, http://www.hitachi.co.jp/New/cnews/month/2008/10/1010.html
[21] Hitachi G. S. T., Travelstar 5K500.B, http://www.hitachigst.com/tech/techlib.nsf/techdocs/FFA370A7BF845F87862574FE0003054C/$file/TS5K500.B_DS_final.pdf
[22] ITRS 2008, http://www.itrs.net/Links/2008ITRS/Update/2008_Update.pdf
[23] X. Che, K. Moon, Y. Tang, N. Kim, S. Kim, H. Lee, M. Moneck, J, Zhu, and N. Takahashi, "Study of Lithographically Defined Data Track and Servo Pattern", IEEE Trns. Magn., vol. 43, pp.4106-4112, (2007)
[24] H. Muraoka, S. Greaves, and Y. Kanai, "Modeling and Simulation of the Writing Process on Bit-Patterned perpendicular Mdia" IEEE Trans. Magn., vol. 44, pp. 3423-3429 (2008)
[25] Y. Murakami, K. Miura, H. Muraoka, H. Aoi, and N. Nakamura, "Influence of Dot Shape no Reproducing Characteristics in Perpendicular Patterned Media", IEICE Tech. Report, MR2007-2, (2007)