Recording Density Enhancement and Material-Process Technologies for Magnetic Hard Disks

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1. Introduction

Recent magnetic recording media for magnetic hard disk drives (HDDs) have made remarkable technological advancement. When Fuji Electric started manufacturing sputtered thin film magnetic disks in 1985, the recording capacity was 10 to 20 Mbytes per 3.5-in disk. Currently, disks with a capacity of 7 Gbytes are available in the market. Moreover, manufacturers are striving to develop 20-Gbyte disks and bring them to market in the year 2000.

The technology that has supported this recording density enhancement has largely been due to the magnetic head that has developed from a thin film head to a magnetoresistive (MR) head and then to giant magnetoresistive (GMR) head. On the other hand, the technological advancement of the magnetic disk (hereinafter referred to as the disk) itself that maintains the stability of extremely small recording bits should not be overlooked.

This paper describes Fuji Electric's magnetic hard disk technology that has supported recording density enhancement, and in addition, discusses the present status and the problems of future development for this technology.

2. Technological Trends of Recording Density

In the 1980s, thin film technology with sputtering instead of coated disk supported magnetic recording density enhancement at an annual rate exceeding 30%. There is also a history of increasing coercive force and decreasing magnetic recording layer thickness, indexes of important disk characteristics, to realize very small recording bits in the course of increasing magnetic head sensitivity.

In the 1990s, the practical use of MR heads increased recording density by 60% annually. In the meantime, with regard to media characteristics, reduction of media noise was carefully studied and more analytical investigation into magnetic materials and film deposition processes was initiated. Also, to solve the problems of low flying-head height to reduce magnetic spacing and thermal asperity due to contact with the media, peculiar to MR heads, smooth disk surfaces for the data zone were realized without irregular projections and particles, ensuring that they would be used in practical applications. In addition to the data zone, a contact start-stop (CSS) zone was realized with a laser texturing process to form a newly controlled surface of high-density bumps. This allowed for separate durability characteristics according to the function.

The GMR head, introduced in the middle 1990s, has raised recording density by 100% annually in some fields of HDD application. Bit cost lowered by advances in recording density and new mechanical characteristics such as the ramp load method instead of the CSS method and high rotational speed technology have established HDD with distinctive features for each application field, and the HDD market is showing indications of further expansion. In response to this situation, there is a clear trend to replace conventional Al/NiP substrates with glass substrates in fields that require impact resistance and rigidity against high-speed rotation. A successful recording density of 20 Gb/in^2 at the research level has been announced[1] and mass production is expected in 2000.

3. Longitudinal Recording System

The details of actual technology for disk used thus far in the longitudinal recording system, classified into the requirements of disk composition and the key formation process, are described below.

3.1 Disk composition

As shown in Fig. 1, disk is composed of a substrate,

Fig.1 Typical layer structure of magnetic hard disks

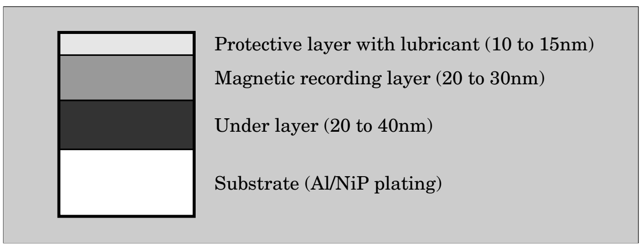


Fig.2 Typical surface texture of a magnetic hard disk (Al substrate)

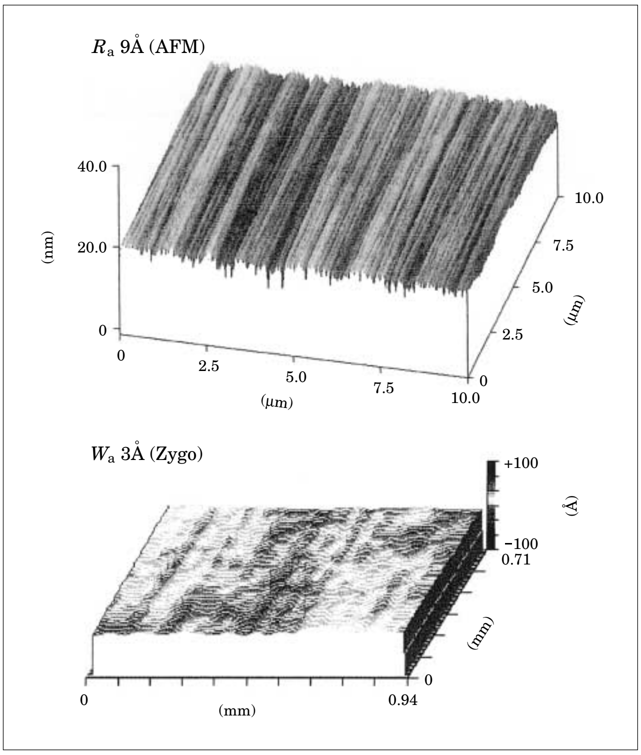
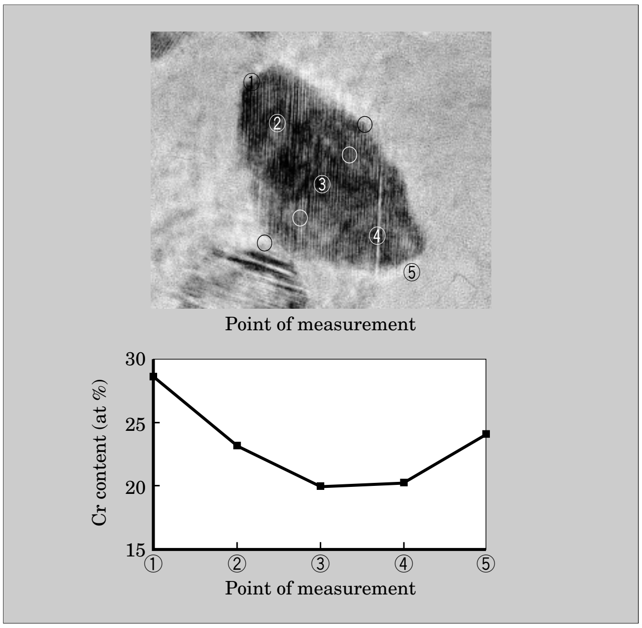


Fig.3 Cr segregation structure of a magnetic grain



a magnetic recording layer, and a protective layer with lubricant. Media characteristics required to increase recording density can be examined by considering how the magnetic transition length a, inversely proportional to linear recording density, can be reduced.

$$a = [\{4M_r \cdot t\,(d + t/2)\}/H_c]^{1/2} \cdots\cdots (1)$$

where M_r : remanence
t : magnetic layer thickness
d : head-disk magnetic spacing

With regard to characteristics required of the substrate, to reduce the head-disk magnetic spacing (d), surface smoothness such as surface roughness (R_a) and micro-waviness (W_a) is most important. As shown in Fig. 2, values below 1nm are in practical use, and further reduction in the values will be required for lower flying-head height or near-contact spacing in the future. To control the circumferential orientation of magnetic characteristics to be discussed later, mechanical texturing is applied within a range that does not effect the flying-head height. The opportunity to expand HDD application fields was made possible by changing the material from conventional Al/NiP to glass. Glass substrates are being used in the market for small, portable personal computers that require impact resistivity, and are accumulating good results. Because of its potential for higher rigidity, the practical use of glass substrates in higher rotational speed applications is expected.

With regard to characteristics required of the magnetic recording layer, maintaining stability of very small recording bits is an important issue from the viewpoints of reading and deterioration with the passage of time. From the above formula, the ratio of the product of remanence and thickness ($B_r \cdot t$) to coercive force (H_c) is a basic magnetic parameter. To support the three digit increase in recording density since thin film magnetic disks were put to practical use until now, H_c has changed from 600Oe to 3,000Oe and $B_r \cdot t$ has changed from 700G·μm to 70G·μm [decrease of one digit in $(M_r \cdot t / H_c)^{1/2}$ during this period]. Co alloys have consistently been used for the magnetic material. However, the composition has greatly changed and an effective composition ratio for optimizing the design of saturated magnetization and for decoupling crystal grains by Cr segregation has been selected from a combination of component elements including Cr, Pt, and Ta. An example of a typical Cr segregation structure currently in practical use is shown in Fig. 3 as examined with a TEM/EDX. Cr segregation can be seen on the grain boundary in the figure. As the layer composition in Fig. 1 shows, the presence of an under layer and a seed layer that realize desirable crystal orientation for the magnetic characteristics of a upper magnetic layer and effect the adjusting of grain size are indispensable prior to magnetic layer formation. Formerly, Cr was used for the under layer; however, a Cr alloy containing W, Mo, and Ti is being commonly used to meet changes in the upper magnetic layer and to optimize conditions. An example X-ray diffraction of a recent typical magnetic layer constructed above an under layer is shown in Fig. 4. The figure shows that the crystal orientation of the Co alloy magnetic layer (110) develops on top of the crystal orientation of the Cr alloy under layer (200), and a desirable in-plane orientation of the c-axis (easy magnetization axis) of the hexagonal close-packed (hcp) structure is realized. Among magnetic characteristics, c-axis alignment with

Fig.4 X-ray diffraction pattern of a magnetic layer

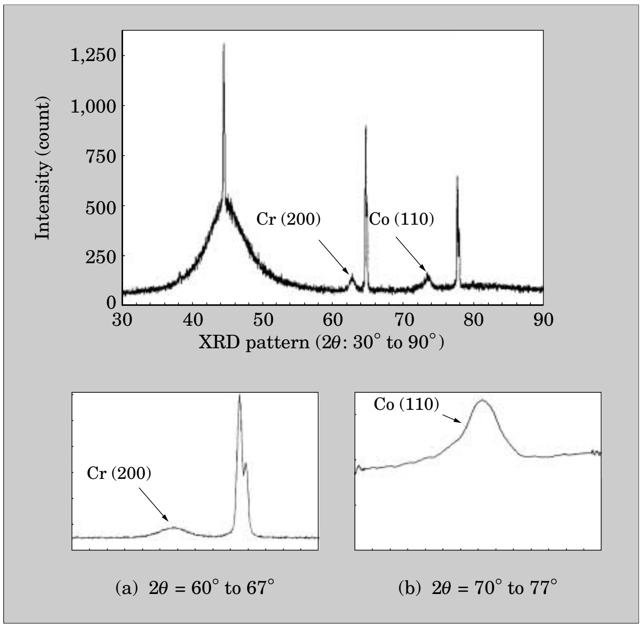
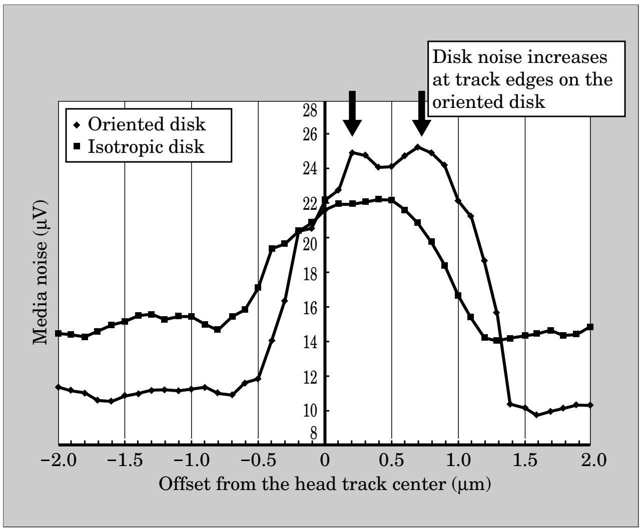


Fig.5 Edge noise characteristics (oriented and isotropic disk)



the circumferential direction due to anisotropic film stress along the substrate texture line is characteristic of Al/NiP substrate systems (so-called oriented disk). On the other hand, it has been determined that the formation of a specific seed layer is effective in forming the desired magnetic layer on a glass substrate, and the NiAl alloy layer has already been put to practical use. As a result, proper magnetic grain size and the in-plane orientation of the c-axis of the magnetic layer are realized even on a texture-less, smooth glass substrate. Because of this absence of texture, different from the Al/NiP system, the c-axis is randomly orientated within the plane and an isotropic magnetic property is obtained. At current recording densities, oriented media is generally superior in on-track parametric performance. However, isotropic disk is superior in track-edge noise as shown in Fig. 5, and in order to improve TPI as recording density increases in the future, there is the possibility that isotropic disk will have the advantage. It is necessary to promote further optimization of high density recording areas, including materials.

The development of magnetic layers has been continued with the goal of reducing media noise to realize a high signal-to-noise (SNR) ratio. However, when recording density exceeds 10 Gb/in^2 (for example, 400 kBPI × 25 kTPI), bit size is less than 0.06 μm × 1 μm, and only several grains exist in a bit along the direction of magnetic transition. In this case, recorded bits cannot be kept stable due to thermal fluctuation with the passage of time, and the possibility of spontaneously decaying output signals grows with reduction of magnetization.

It is important to keep a parameter, given by (magnetic anisotropy constant: K_u) × (activation volume: V), above a certain value to prevent this thermal fluctuation phenomenon[2]. V is related also with the above-mentioned grain size and there is a tradeoff between V and the preferable method for media noise reduction. A solution advantageous to both is to make the distribution of grain sizes as narrow as possible and reduce the proportion of larger and smaller grains. On the other hand, Pt added to the alloy to make small grains thermal-fluctuation-resistant and a segregation structure that diffuses non-magnetic Cr to the grain boundary to raise anisotropy in grains are important. To simply evaluate thermal fluctuation, we applied[3] measuring methods for Hc dependence on temperature and magnetization decay in a reverse magnetic field as shown in Fig. 6, and have utilized this method as an evaluation tool. For present disk, the temperature coefficient of the former ($\Delta H_c/H_c/\Delta$temp) is approximately −0.3%/deg, and the latter is approx. 8%/decade of time (s). These guidelines will be held for future higher recording density. Regardless, the coexistence of noise and thermal fluctuation will surely become more difficult, and we shall have to reevaluate recording systems.

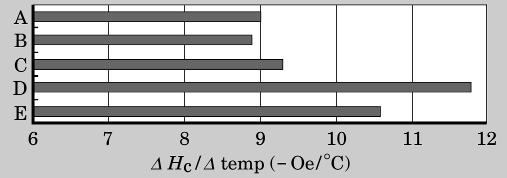
Lastly, details of the protective layer with lubricant are omitted since it is described separately. With magnetic spacing d (magnetic flying height + protective layer thickness), since linear recording density can increase in proportion to $1/\sqrt{d}$, reduction in protective layer thickness is effective when the head flying height is low. Lubricant on the surface that reduces the coefficient of friction between the head and the disk is important not only from the viewpoint of tribology, but also because flying height instability due to the transference of contamination and lubricant to the head will cause defects in parametric performance.

3.2 Process technology

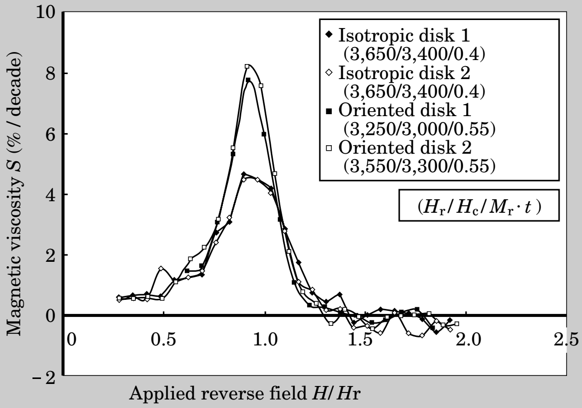
Actual process technology is described below.

Fig.6 Dependence of H_c on temperature and magnetic viscosity in a reverse field

AI⊥	$\Delta H_c/\Delta T$ (Oe/°C)	$\Delta H_c/\Delta T/H_c$ (273K)/°C	H_c (Oe)	$M_r \cdot t$ (emu/cm^2)	Cr+Ta (at %)	Pt (at %)
A	−9	−0.32	2,552	0.68	21	3
B	−8.9	−0.28	2,930	0.55	23	8
C	−9.3	−0.32	2,620	0.66	23	3
D	−11.8	−0.35	3,063	0.45	23	8
E	−10.6	−0.32	3,356	0.58	23	8



(a) Dependence of H_c on temperature



(b) Magnetic viscosity in a reverse field

3.2.1 Substrate process

The correlation between requested characteristics and process parameters in Al/NiP substrates is shown in Fig. 7.

To ensure head stability at a low flying height, local projections or scratches must also be considered in addition to the average smoothness and flatness of the substrate surface, and each step of every machining process requires precise control. In particular, the texturing process that creates the final finish on the substrate surface has to realize extremely low roughness while removing enough stock to eliminate abnormalities (scratches, etc.) on the surface. It is important to select shape-optimized abrasive grids for sufficient stock removal and tape material to fix the grids in place. However, there is a tradeoff between stock removal and surface roughness. To ensure a uniform textured surface with a low rate of stock removal, greater smoothness and flatness at the stage of the polishing process is important. Improvements in Al grinding and NiP plating as well as the utilization of new processing conditions for the polishing process realize very smooth surfaces as shown in Fig. 8. The challenge for future processes will be to realize a surface that ensures stable head flying, assuming that flying-head height is made as low as possible (glide height < 0.3 μin), requiring much more precision control in each process. Smoothness and flatness requirements for processing glass substrates are similar, however changes in the processes are necessary to comply with special physical property requirements (high hardness and high insulating property).

Fig.7 Correlation between characteristics and processes in Al/NiP substrates

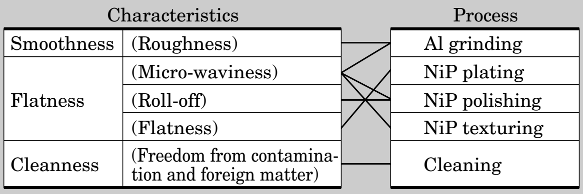


Fig.8 Surface image of a polished substrate (Al/NiP)

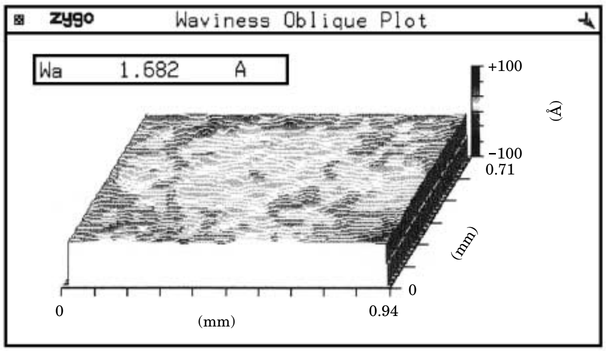


Table 1 Correlation between disk characteristics and deposition processes

Process		Change in media characteristics* due to increase in a process parameter: H_c	Change in media characteristics* due to increase in a process parameter: Noise	Remarks
Degree of vacuum		Increases	Decreases	Higher vacuum necessary
Substrate temperature		There is a maximum value	There is a minimum value	Optimization necessary
Ar gas pressure		Decreases	Decreases	
Under layer thickness (Cr alloy)		Increases	Increases	
Substrate bias		Dependent upon layer structure	Dependent upon layer structure	
Magnetic layer composition	Cr	Decreases	Decreases	
	Ta	Decreases	Decreases	
	Pt	Increases	Increases	

Notes*: Degree of vacuum indicates evacuation to lower pressure. Magnetic layer composition indicates increase in the content of a component.

3.2.2 Magnetic layer deposition process

As mentioned previously, the characteristics required of a magnetic layer to attain high-density recording are high coercive force H_c and low noise. The

Fig.9 Dependence of H_c and noise on several process parameters

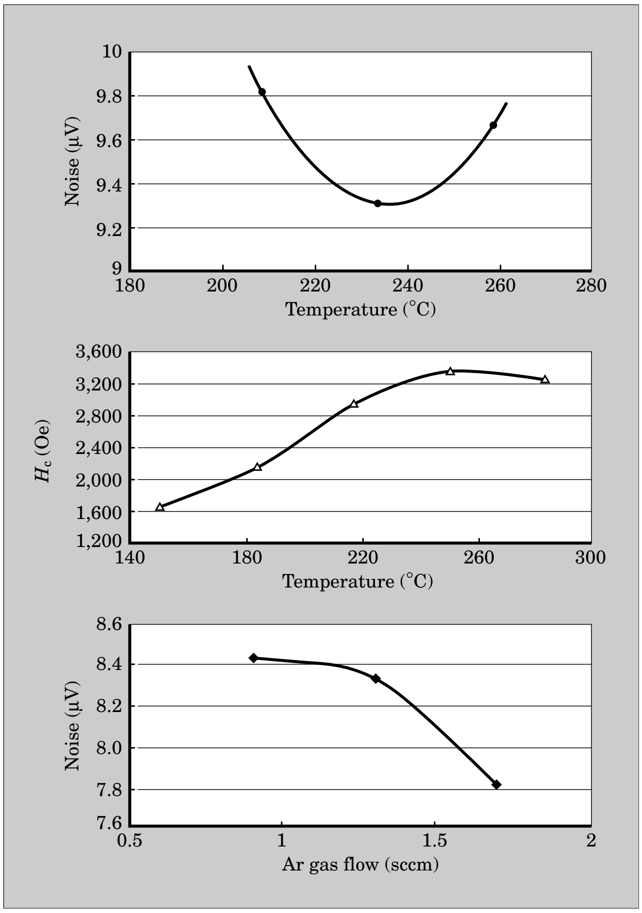


Fig.10 Dependence of Hc on seed layer thickness

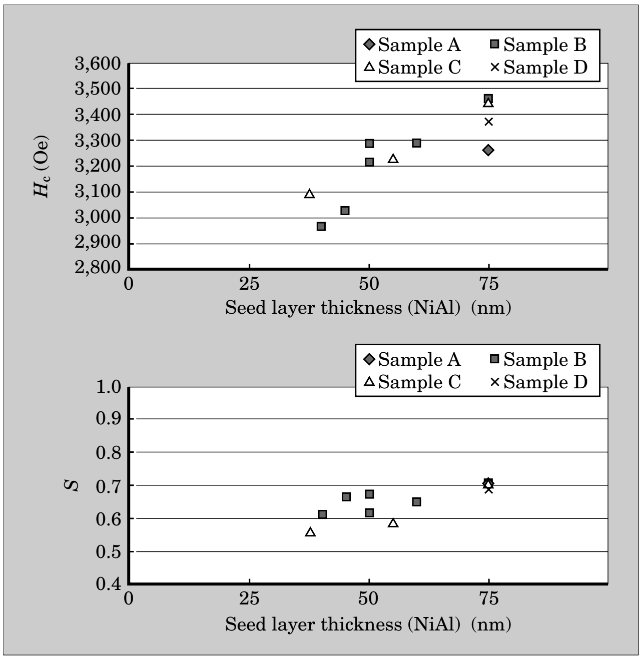
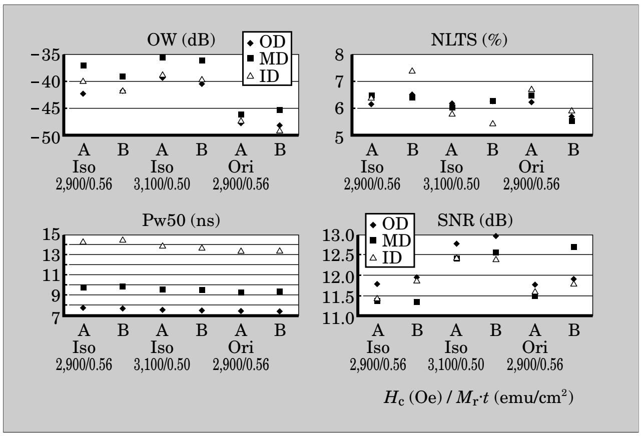


Fig.11 Parametric performances (isotropic and oriented disk)



relation between these and actual film deposition processes is shown in Table 1. It has already been shown that highly purified operation gas, reduced outgas in the vacuum chamber, and increased vacuum level in the chamber increase effectiveness in principle. Other deposition parameters, such as substrate temperature, gas pressure, under layer thickness, and substrate bias, are related to each other and mutually influence the layer structure and film composition, and therefore, it is necessary to optimize each individually. Figure 9 shows the dependence upon several process parameters of H_c and noise on an Al/NiP substrate. Substrate temperature is an important parameter to increase Hc, but from the viewpoint of reducing noise, the optimum value is a lower temperature than the value for maximum H_c. Increased Ar gas flow and higher gas pressure settings are effective in reducing noise. Actually, the magnetic layer components (Pt, Cr, etc.) are optimized to meet the required H_c and $M_r{\cdot}t$ values as shown in Table 1. In the course of process optimization, the goal is to realize higher H_c while decreasing the Pt quantity and to prevent H_c from declining while adding as much nonmagnetic elements, such as Cr and Ta, as possible which are effective in reducing noise. Overall, higher Pt and higher Cr and Ta are desirable to increase recording density in the future. Further, the use of effective nonmagnetic elements in addition to or instead of Cr and Ta is also a subject for further development.

In addition to the above subjects which apply to different substrates, the necessity of a seed layer to realize an isotropic layer, typically utilized with glass substrates, has been described above. By optimizing processing for this seed layer (temperature and film thickness), the desired crystal orientation of a magnetic layer and grain size can be controlled on a glass substrate, and characteristics similar to an oriented magnetic layer on a NiP/Al substrate can be obtained. Examples of experiments are shown in Fig. 10 (process) and Fig. 11 (parametrics). These figures show that seed layer thickness can control H_c, and isotropic disk can have almost the same characteristics (excluding the OW characteristic) as oriented disk by adjusting magnetic characteristics. Irrespective of isotropic or oriented disk, the realization of a magnetic layer for

Table 2 Comparison between longitudinal and perpendicular recording

Item \ Classification	Longitudinal recording: Conventinal recording	Longitudinal recording: Granular type longitudinal recording	Perpendicular recording
Thermal stability $K_uV/kT \geqq 60$	○ Unstable at high density recording ○ Stable at low recording density	○ Unstable at high density recording ○ Stable at low recording density	○ Unstable at low recording density ○ Stable at high density recording
Magnetic layer thickness	Decreasing	Decreasing	Thinness not strongly required
Increase in K_u	Required	Required	Not strongly required
Reduction in noise	○ Cr segregation to the grain boundary ○ Reduction in grain size	○ Dispersion of magnetic particles such as SiO_2 into the nonmagnetic matrix	○ Cr segregation to the grain boundary ○ Reduction of reverse magnetic domains
Problems	○ Reconciliation between thermal stability and noise reduction	○ Thermal stability	○ Reduction in media noise
Solutions	○ Uniform distribution of grain sizes ○ Increase K_u and H_c	○ Uniform distribution of grain sizes ○ Increase K_u and H_c	○ Reduce interactions among magnetic grains ○ Increase the squareness ratio ○ Increase the magnetic field to form reverse magnetic domain neuclei

Notes: K_u: magnetic anisotropy energy V : activation volume
k : Boltzmann constant T : absolute temperature

recording densities greater than 10 Gb/in^2 is a large, challenging subject. To obtain a high SNR while preventing characteristic deterioration due to thermal fluctuation as mentioned above, more precise process control as well as fine adjustment of the optimal material composition is required.

4. Future Recording Systems

In the previous chapter, examination focused on the longitudinal system. However, there is a common perception in the industry that the current disk configuration will limit enhancement of recording density in the near future. In the longitudinal recording system, the so-called granular structure has been proposed as a method of reducing noise to make the grain boundary more definite using oxides such as SiO_2 from Cr segregation in order to decouple the magnetic grains. Further, to increase areal recording density effectively, the importance of lowering the conventional aspect ratio (BPI/TPI), i.e. raising track density (TPI) rather than linear recording density (BPI), is recognized and is being implemented. Eventually, the problem of thermal fluctuation has to be solved. Factors that have an effect on the SNR in a high density recording area are given by Bertram et al[4] as follows:

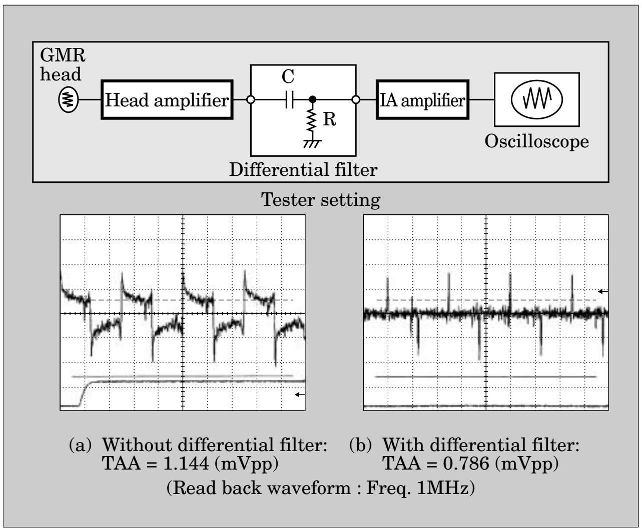
$$\mathrm{SNR} \propto 1/[\mathrm{Density}^{3/2}(W/B)^{1/2}D^3]$$

where

B : bit spacing
W : read track width
D : grain diameter

As discussed before, this formula supports reducing the micro-grain size and aspect ratio to raise the SNR. Because thermal fluctuation is directly related to grain volume D^2t (t : magnetic layer thickness) and a comparatively thicker magnetic layer is desirable for the perpendicular recording system to stabilize magnetization, the perpendicular recording system is superior with respect to the limit of SNR restricted by thermal fluctuation because it can take advantage of film thickness.

Fig.12 Measuring system for perpendicular recording disk



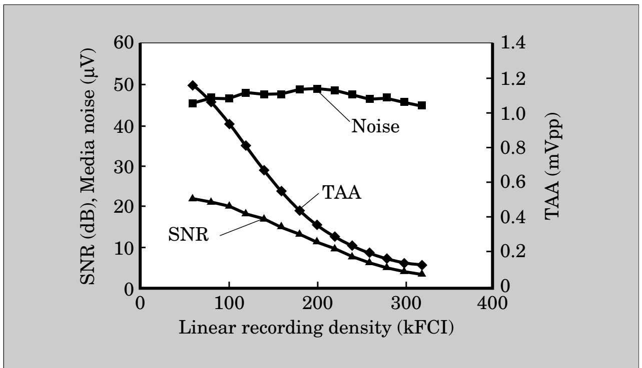
Simplified features of the above-mentioned technologies are listed in Table 2. Although Fuji Electric has just started development, examples of its experiments are presented below. The perpendicular coercivity obtained with a configuration of NiFe/TiCr/CoCrTaPt on an Al/NiP substrate was 2,000 Oe. This was evaluated with a GMR head in the setup shown in Fig. 12. Noise reduction was observed to depend on the thickness of the intermediate layer TiCr, and typically, the frequency characteristics were as shown in Fig. 13. This proved that the noise characteristics lag those of the longitudinal recording system.

Perpendicular recording media has thus far faced a

Table 3 Promising new technologies for high density recording

New technology	Content	Features	Problems
Granular disk	Magnetic particles such as Co and Pt scattered in the nonmagnetic matrix	Low noise and high thermal stability	○ Increase in coercivity
Perpendicular recording	Magnetization in the direction of the C-axis of Co alloy crystals perpendicular to the film	High thermal stability	○ Reduction in noise ○ Thermal stability in low recording density ○ Stabilization of stray fields
Square bit	The ratio of width to length of bit domain is nearly 1 (currently 10 or more) with a small demagnetized field.	High thermal stability	○ Reduction in the track pitch ○ Increase in precision of track servo
Patterned disk	Magnetic domains of several tens of nm in size arranged in a lattice pattern, having little interaction. Can be used for longitudinal and perpendicular media.	Low noise and high thermal stability	○ Increase in writing and reading speed ○ Reduction in cost
Near field recording	Writes and reads with a collimated sub-micron size light beam based on near field optics theory. The solid immersion lens system under development by Tera Store, the same as a magneto-optical disk	High thermal stability	○ Dust control ○ Strict tolerance to optical configuration ○ Low efficiency in light utilization
Optically assisted Winchester	Writes bits with the help of light-induced heat, the same as a magneto-optical disk. Light transmitted to the HDD head through optical fiber is irradiated on the media by micro-mirror and lens to write and read with the magnetic domain. Being developed by Quita/Seagate.	High thermal stability	○ Noise caused by optical fibers ○ Dust control

Fig.13 Example frequency characteristics of perpendicular disk



great problem in media noise reduction. However, the direction of the solution has been clarified in a recent institute paper[5]. It is desired that through further process development in the future, performance superior than that of longitudinal recording in applications above 20 Gb/in^2 will be ensured.

As shown in Table 3, various new recording principles and concepts other than current longitudinal recording have been proposed, and their application to HDDs is expected in the future.

5. Conclusion

Details of the recent technological development of magnetic hard disks for HDDs have been examined, focusing on materials and processes. Recently, the development of conventional longitudinal recording has reached a more difficult technological phase. This paper has proposed important subjects for expanding those boundaries. On the other hand, new recording systems are under development in various locations as replacements to longitudinal recording. It is expected that these new systems will expand the role of HDDs in the future memory market and further widen the main fields of application. Fuji Electric will also support development of the HDD industry through continuous contribution to the technical development of magnetic hard disks.

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