Magnetic Hard Disks for Audio-Visual Applications

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1. Introduction

Since about three years ago, it has been expected (mainly in the United States) that a new home-oriented service, in which communications, computers and consumers converge, will grow to become a gigantic market in the 21st century along with the development of digital broadcasting (see Fig. 1). The "convergence" of this service will create a trend of global cooperation, absorption and mergers to overcome business or national barriers and existing industrial structures will evolve to reintegrate their overall associated infrastructures (see Fig. 2).

More specifically, this trend will, for example, develop at homes in the following way.

A set top box (STB) capable of temporarily storing audio-visual (AV) information such as a digital broadcast will be set up at input and output points that interface between users and society. The STB will be connected with home AV equipment such as digital TVs through an IEEE 1394 high-speed communication system. Needless to say, handheld AV equipment can also be connected to the STB. Home AV equipment will be controllable by a home server equipped with a man-machine interface that is superior than that of today's personal computers (PCs). In the 21st century, consumers will be able to freely edit and distribute musical or pictorial data or personal AV information.

The "convergence" will tend to popularize the above home information service in the short-term and data broadcasting service in the mid-term. In the long-term, it will lead to a future system that guarantees consumer comfort with regard to electronic commerce (EC) and security control.

More accurately, the "convergence" is expected to spread throughout homes and society in the following three stages. In the first stage, the diffusion of data broadcasting after the year 2000 will become a turning point, and individual AV equipment and associated networks will come into wide use responding to increasing information volume. In the second stage, utilizing the opportunity provided by the world cup soccer games, home servers with higher functions will spread into homes as broadcasting stations. In the third stage, from the year 2004 or 2005 and thereafter, new on-demand service will burgeon for EC and security control.

Fig.1 Flow of "convergence" advancing in the 21st century

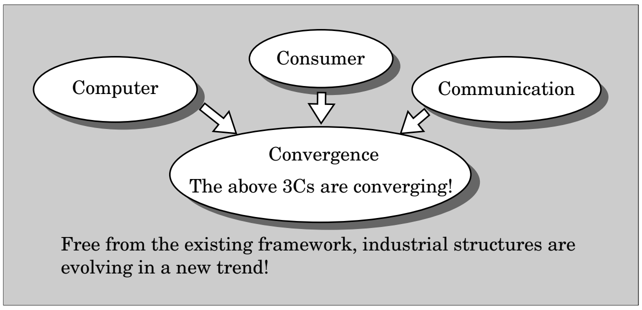
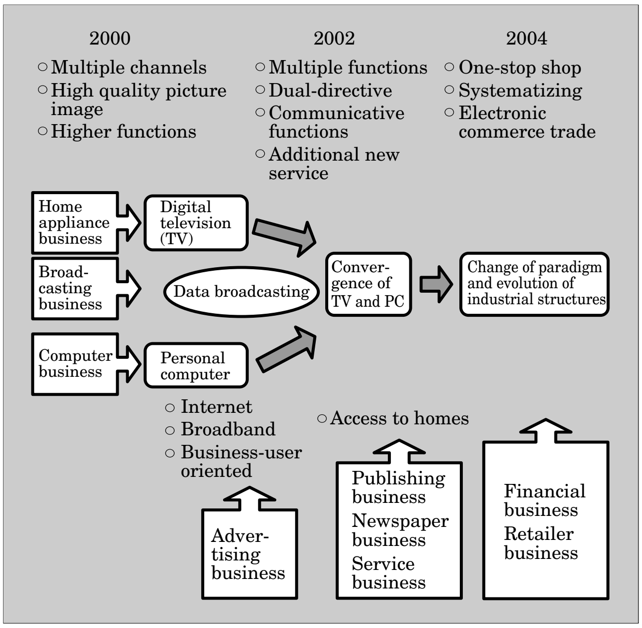


Fig.2 Evolution of industrial structures with "convergence"



The key technology for achieving "convergence" is to develop an "AV information cash memory" capable of handling quality AV information with a fast, versatile and cost-effective means. As shown in Table 1, among the candidates for external memory devices, those having all of the above features are unexpectedly few (see Table 1). The hard disk drive (HDD), having

Table 1 Performance comparison of main external memories

Category / Item	Flash memory		HDD	Magnetoptical disk drive
Product	SanDisk Corp. Compack Flash	Toshiba Smart Media	Quantum Corp. Eagle	Sony MD data
Memory size	48 MB	16 MB	25 GB	650 MB
Data transfer velocity	24 Mbit/s	8 Mbit/s	288 Mbit/s	4.6 Mbit/s
Access time	10 µs	7 µs	12ms	500ms

Example from products on sale

been an indispensable device for PCs, is once again in the spotlight.

These trends will finally lead to use of various AV-HDDs (custom HDDs for the AV equipment) having different specifications and shapes in the STB, digital TV, home server and handheld AV devices. The era when consumers can readily walk around with handheld AV information will arrive very soon.

In consideration of the future aspects of 3-D televisions and handheld devices for personal use, AV-HDDs as well as their core elements, that is, magnetic hard disk (hereinafter referred to as the disk) for AV use, will be most promising.

This paper describes the development of the latest AV magnetic hard disk that Fuji Electric is focusing on.

2. Plastic Disks

An HDD uses magnetic heads flying above its disk surfaces for fast read-out and write-in. Therefore, aluminum or glass substrate has mainly been utilized to create a super smooth surface. On the other hand, optronical devices such as CDs, MDs, PDs and DVDs use injection-molded plastics, because their optical heads do not require high surface precision for reading and writing, but only need groove formation. Therefore, plastics are most advantageous in cost since plastic disks can be fabricated by injection molding. Recently, injection-molding techniques have advanced to fabricate plastic substrates having surface precision that is suitable for the flying head of HDDs.

Moreover, digitalization in the AV field has been advancing. It is expected that the start of digital broadcasting will accelerate expansion of the digital AV market, and HDDs that can quickly handle large volumes of data will play an essential role. This market necessarily demands large-capacity and price-effective HDDs.

Plastic disks completely match these needs. Plastic disks not only have inexpensive material costs but also require few fabricating processes, and therefore offer lower cost, because substrates can be formed simply by injection molding. Their light weight lowers the energy consumption and reduces acoustic noise caused by rotation. These features are optimal for AV recording devices. Elasticity of the plastic disk absorbs mechanical shocks from the head, and therefore makes it possible to design damage-resistant disk for the ramp load mechanism.

Different from the case of ordinary processing of computers, defective bits of AV data are not as serious a problem as long as people cannot sense the defect in pictorial images or musical sounds. However, it causes serious problems when the pictorial images are blacked out or the music does not sound smooth.

HDDs are sometimes handled by people not familiar with mechanics, or are exposed to direct sunlight or mechanical impacts. The data processing of computers and AVs is different as summarized in Table 2. In view of this table, HDDs for AV applications demand another kind of reliability, not as computers but as home appliances.

Let us imagine, for instance, the situation when digital broadcasting gets started in the future.

You have a handheld set with an HDD and an image display device. Before leaving home, you can record the news of the day from an STB in an instant, and watch it on the way to work. During the recess after lunch, you can also watch the drama that you

Table 2 Comparison of the hard disk drives for PC and AV applications

Category / Item	PC applications	AV applications			
	PC	Home server	Set top box	Handheld drive	Handheld media
Use	Data processing	Video editor Home TV Internet data	Image data Digital TV	Video camera Cellular phone Navigator	Video camera Portable video set Music distribution
Error rate	10^{-10}	10^{-10}	10^{-3} to 10^{-4}	10^{-3} to 10^{-4}	10^{-3} to 10^{-4}
Environment	33°C, 80%RH	80°C, 80%RH	80°C, 80%RH	80°C, 80%RH	80°C, 80%RH
Data preservation term	2 to 3 years	3 to 5 years	1 to 7 days	1 to 2 weeks	1 to 2 weeks
Frequency of operations	A few times per day	A few times per day	Continuous operation	A few times per day	A few times per day
Access speed	High speed rotation Low speed seek	Medium speed rotation High speed seek	Low speed rotation High speed seek	Low speed rotation Low speed seek	Low speed rotation Low speed seek
Media	Al, glass	Al, glass	Glass, plastics	Glass	Plastics

Table 3 Comparison of material performance

Item \ Category	Resin A	Resin B	Poly-carbonate
Longitudinal expansion coefficient (1/°C)	$<5\times10^{-5}$	6×10^{-5}	8×10^{-5}
Temperature of thermal decomposition (°C)	420	400	360
Water contents (ppm)	5	5	150

missed on the day before. Or, you can record distributed music and listen to it at any time you want.

The HDD you use should be compact, lightweight, shock-resistant, low in acoustic noise, and energy consumption. Above all, it should be low in price. Only the plastic disk can achieve these features.

To form the plastic disk, we have to solve three major problems:

- ○ Technology of plastic materials
- ○ Precision molding technology for plastic substrates
- ○ Low temperature deposition of the magnetic layer on the disk surface for high recording density use Since plastics are weak at high temperature, low temperature deposition is required.

2.1 Technology of plastic materials

Application of conventional plastic substrates for MDs, DVDs, etc. to magnetic disk substrates that usually demand precise surface characteristics result in difficulties in reading and writing due to the insufficient head flying-height caused by undulation (waviness) of the substrate surface. Even if the surface characteristics are sufficient, ordinary plastic substrates such as those made of polycarbonate resin are mechanically weak, thermally transformable and humidity-absorbent, and therefore cause deformation of the substrates in hot or humid environmental conditions.

The performance required of plastic substrate materials for magnetic disks are as follows:

(1) Extremely small residual stress on the molded substrate and preservation of stable shape under hot and humid environmental conditions

(2) Preservation of low roughness, no defects and precision of the substrate surface

(3) Cleanliness with controlled outgas and contaminants

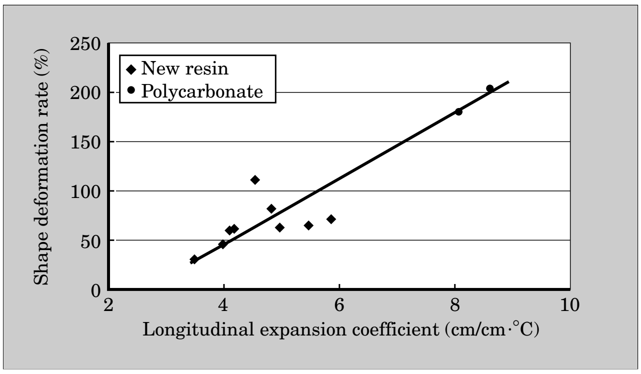
Conventional resin materials such as polycarbonates or polyachrilates cannot attain the above level of performance. We are currently promoting development of new resins and their applications.

Required performance characteristics are higher rigidity, three-dimensionally combined molecular structure, high mechanical strength, creep-resistance and small thermal expansion.

Table 3 shows a comparison of the main characteristics of the resin materials.

The new resin is superior to polycarbonate in mechanical strength, heat-resistance, creep characteristic and thermal expansion. From the viewpoint of molecular structures having high rigidity, resin is copolymerized with more three-dimensionally combined and heat-resistant monomer units.

Fig.3 Comparison of shape deformation rate versus longitudinal expansion coefficient



The above-mentioned shape stability is the most important requirement. Shape deformation is considered to take place by the following mechanism.

Upon filling resin into the molding die, the hot resin in the cavity center flows in a radial direction with a small gradient of temperature and velocity, and orientates the substrate bulk in this direction. On the other hand, the hot resin cools and solidifies at the inside surface of the die. The gradient temperature and velocity between the boundary of the above two resin fluids generates shearing stress, and therefore the entangled molecules solidify without orientation. The larger the difference in the molecule orientations at the surface and bulk of the substrate, the stronger the residual stress will be near the substrate surface. A molded substrate with large residual stress will undergo a large transformation of shape while left under hot and humid environmental conditions. Moreover, accelerated by the humidity-absorbent characteristic inherent in the resin, a substrate with larger residual stress deforms so much that it cannot preserve its original shape.

The degree of deformation and residual stress of the substrate depends upon the creep and thermal expansion characteristics inherent in the resin structures.

Figure 3 shows the relation of the longitudinal expansion coefficient and the shape deformation ratio of substrates under various molding conditions of resin A, B and polycarbonates. In these experiments, the substrates were left for 500 hours under 60°C and 80% relative humidity.

The longitudinal expansion coefficients decrease in order of polycarbonate, resin B and then resin A. After these materials are left under hot and humid environmental conditions, their shape deformation ratios are also smaller in this order. However, the longitudinal expansion coefficient and the shape deformation ratio of resin A varies in a wide range depending upon the molding conditions.

The following investigations are necessary to obtain plastic substrates with smaller shape deformation ratios.

- ○ Investigation of excellent precision molding technology attaining smaller residual stresses and longitudinal expansion coefficient ($< 4 \times 10^{-5}$)
- ○ Application of new heat-resistant materials having a more rigid three-dimensional structure with better creep characteristics and mechanical strength

On the other hand, in order to attain "precise surface characteristics", it is necessary to lower the viscosity of the molten resin and use clean resin. We must inject and mold resin in a better fluid state. As discussed below in section 2.2, we must remove as many contaminants as possible such as outgas components and particles causing surface defects.

(1) Upgrade of resin fluidity
  (a) Control of molecular weight distribution to lower the viscosity of melting resin
  (b) Application of heat-resistant resin to mold at high temperature and speed
(2) Prevention of surface defects
  (a) Preservation of a clean environment during fabrication and conveyance process to reduce particle contamination

The HDDs for PC applications have become more complex due to the explosive increase in recording density. On the other hand, HDDs for AV applications are required to be less expensive than before, while preserving their high performance. Plastic disks are most promising to solve the above contradictory problem.

Regardless of the common conception of conventional plastic substrates, it is most important to enhance the technology of plastic materials as well as that of molding and dies. It is necessary not only to positively improve performance and quality of the current plastic materials but also to actively promote development of new materials of higher performance.

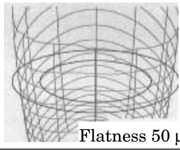
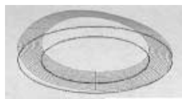
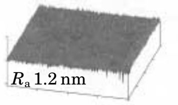
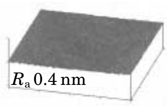
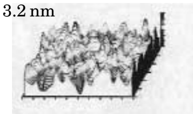
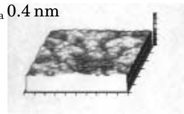
2.2 Precision molding technology

Additionally, magnetic disk substrates for AV applications have the following quality requirements:

(1) Precise surface characteristics
  Surface roughness and surface undulation (waviness)
(2) Good mechanical characteristics
  Flatness, total index runout and surface acceleration
(3) Few surface defects
  Abnormal bumps, pits, scratches and particles
(4) Heat-resistance stability
  Material physical property and after treatment

Plastic substrates for conventional optical disks are controlled for the performance of pattern copying

Fig.4 Comparison of surface characteristics

Item	Magnetoptical disk (PC)	Hard disk (Al)
Shape	 Flatness 50 μm	 Flatness 3 μm
Surface flatness (AFM)	 R_a 1.2 nm	 R_a 0.4 nm
Undulation (ZYGO)	W_a 3.2 nm 	W_a 0.4 nm 

and light refraction in addition to the above items (2), (3) and (4). Item (1), "precise surface characteristics", of the optical disks is controlled above a certain level but not more than necessary. Therefore, actual surface characteristics of optical disks are quite different from those of current magnetic disks (see Fig. 4).

The important factors that affect molding of magnet disk substrates are as follows:

- ○ Pellet materials
- ○ Accuracy of dies
- ○ Molding conditions
- ○ Atmospheric conditions
- ○ Fabrication facilities

In this paper, we discuss the molding conditions and the results of their study.

Important factors related to precision injection molding and the mold shape are assumed as follows:

- ○ Die temperature
- ○ Resin temperature (nozzle temperature)
- ○ Injection speed
- ○ Molding pressure
- ○ Cooling time (molding cycle)

We assessed the effects of these five factors on the shape figures by varying them parametrically. In addition, we have found that annealing after molding releases internal stress caused by the molding process and annealing is also another influential factor in the fabrication of precision plastic substrates. At the same time, we have also confirmed the actual effects of annealing (see Fig. 5).

The resin property is closely related to the appropriate die temperature, the die temperature should be higher for resins with higher glass transition temperatures (T_g). Regarding die temperature settings, the temperature of the movable die should be different from that of the fixed die, as this is also an important factor affecting surface characteristics.

The larger the temperature difference, the better the surface flatness before annealing. After annealing,

Fig.5 Flatness of the substrate versus die temperature difference

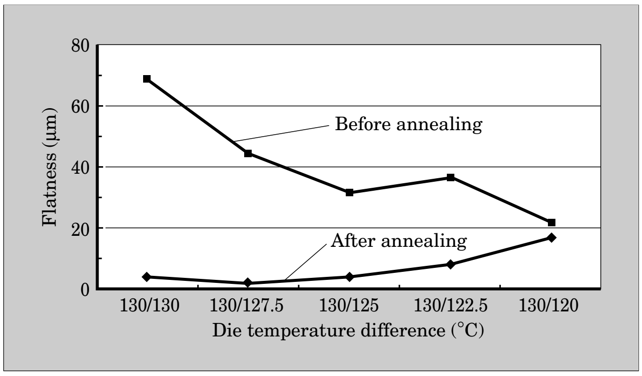


Fig.6 Flatness versus important factors for molding

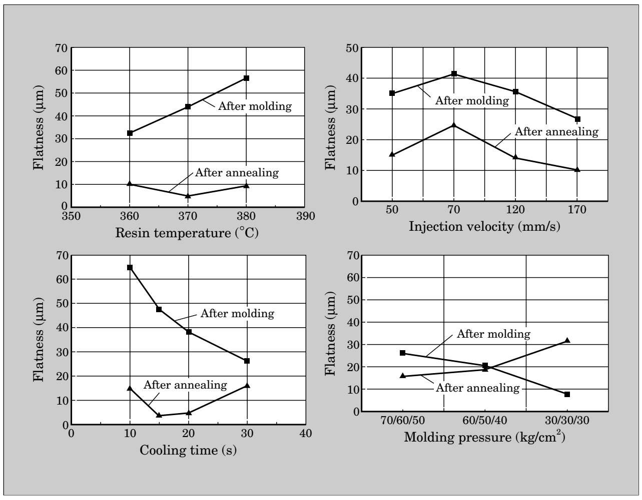


Fig.7 Substrate shape and related surface characteristics under optimal molding conditions

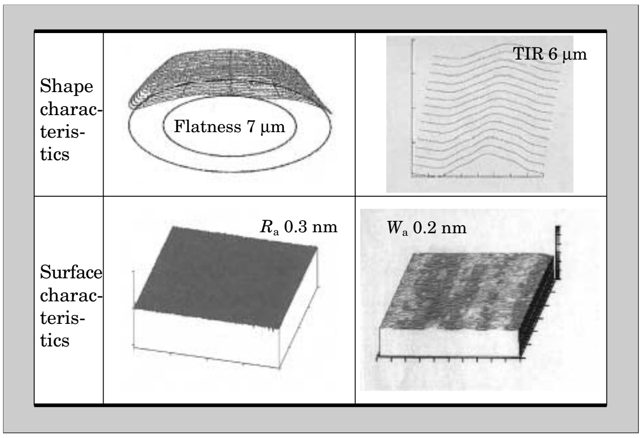
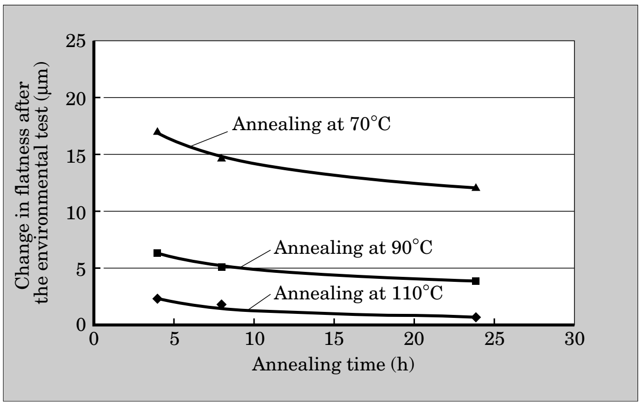


Fig.8 Change in flatness versus annealing time



however, the surface flatness worsens. The stored stresses after molding differ in the outermost surface layer and the internal bulk. These stresses are released by annealing. However, residual stress may strain the substrate at a side where final residual stresses remain. Analysis demonstrates that the longitudinal expansion coefficients are not equal at both sides of the substrate. This phenomenon has been verified as the relation between shape deformation by annealing and stress.

As shown in Fig. 6, each other important factor affecting the shape has its own optimum range. It is necessary to ultimately set up the molding conditions in view of the mutual influence of these factors.

Figure 7 shows the shape and surface characteristics of plastic substrates fabricated under optimum molding conditions currently available.

A microscopic assessment demonstrates that it is possible to fabricate substrates that exceed the Al disks in precision surface characteristics.

When we observe the overall surface of the substrate, we will find some partial molding defects such as surface roughness, silver streaks, pits, etc.

However, the problems of these defects are currently unresolved and solutions must be found in the future.

About heat-resistance stability, it is necessary to control fluidity inherent in the resin after molding by measures that suppress changes of the physical property and shape of the substrates due to heat. The essential points are how to make rigid molecular structures and uniformly distributed internal stresses. It is necessary, for the former, to develop new resin materials as discussed in section 2.1, and for the latter, to investigate post-molding treatments.

After investigating the post-treatments, we have found that "heat processing; annealing" can suppress shape deformation to some extent.

More accurately, the two factors of "temperature and time" are capable of controlling both shape quality and heat-resistance stability of the substrate. Figure 5 refers to the surface characteristics of the substrate versus thermal conditions of the die. The result of the environmental test (60°C-80%RH-500h) for heat-resistance stability is shown in Fig. 8. If optimal annealing conditions to release internal stresses are found, it is possible to suppress deformation of the substrate shape after the environmental test and to offer more stabilized substrates fabricated by plastic molding.

In order to produce precision moldings of stable

Fig.9 TEM image of granular magnetic layer

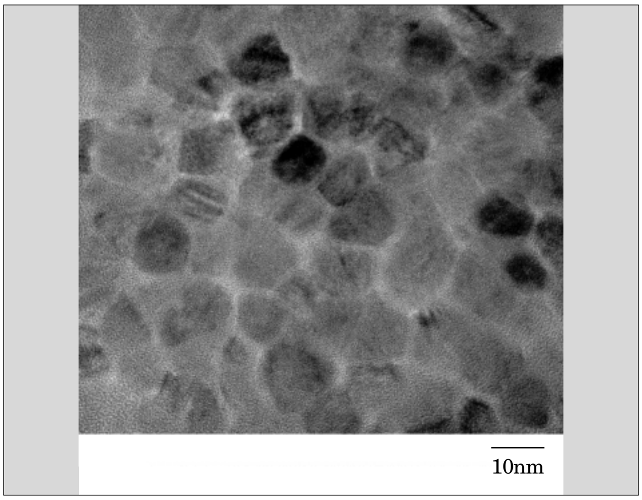
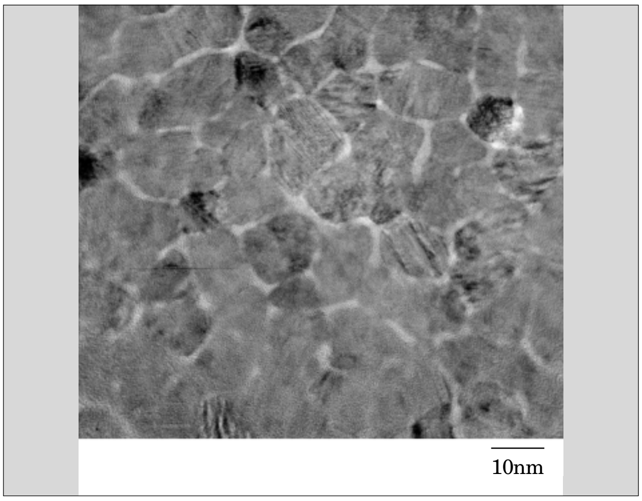


Fig.10 TEM image of granular magnetic layer with modified outermost surface



quality in a quick and inexpensive way, it is essential to systematize overall processes involving product design, die work, injection molding, release of stress and verification as well as to shorten these processing times. Most molding techniques have been established by trial and error. Accumulation of the data thus obtained and its effective use as a database will lead to enhancement of the precision molding techniques.

2.3 Low temperature deposition technology for magnetic layers

Conventional magnetic hard disks are generally produced at high temperature in the following manner.

After heating the substrate up to approximately 300°C, a Cr-alloy is sputtered onto a substrate as an under layer, and then a CoCrPtTa-alloy is sputtered onto the top surface as a magnetic layer. The high substrate temperature accelerates the Cr in the magnetic layer to segregate towards the grain boundary of the Co-alloy grains, and therefore to reduce the magnetic interactions between the Co-alloy grains. This process helps create a disk of high magnetic coercive force H_c and low noise. These features are desirable for high recording density.

On the other hand, plastic substrates are heat-resistant only up to approximately 100°C. Therefore, it was necessary to develop a significantly new deposition technology for the magnetic layer, which the magnetic layer was deposited at low temperature so that Co-alloy grains could be isolated from each other and their magnetic interactions could be reduced. Because oxide additives such as SiO_2 are almost insoluble in a Co-alloy solid at equilibrium, they were added to help isolate Co-alloy grains in the magnetic layer. This layer is called the granular magnetic layer. Instead of the conventional DC magnetron sputtering method, we introduced the RF sputtering method capable of depositing insulation additives such as oxides.

Figure 9 demonstrates a TEM planar image of the granular magnetic layer. As the under layer, the Cr-alloy was deposited onto the plastic substrate, and then RF deposition was performed using the composite target of a CoCrPt-alloy and an additive of 5 mol% SiO_2. We can observe that the grain boundary phase (whitish area) surrounding the magnetic alloy grain forms the so-called granular structure. The magnetic properties and noise of the disk are superior to those of the low temperature-deposited CoCrPt disk without oxide additives. We consider that boundary segregation by oxide additives has the favorable effect of reducing the magnetic interactions between the magnetic alloy grains and the granular disk, resulting in excellent characteristics even for a low temperature-deposited magnetic layer.

However, the characteristics of the granular disk are inferior to those of the conventional high temperature-deposited disk. Therefore, it is important to enhance grain segregation with oxide additives and to lower transition noises. It is believed that the microstructure of the grains and their related boundary segregation and grain size distributions depend upon the method with which the deposited layer is grown initially. Therefore, we changed the conditions for depositing the outermost surface of the Cr-alloy under layer, to control the physical conditions bordering the magnetic layer and finally control the initial growth of this layer. As the result, we have enhanced the granular structure and have found that its magnetic property and electromagnetic conversion characteristics can greatly be improved.

Figure 10 shows a TEM image of the magnetic layer of the disk, which is sequentially composed of a plastic substrate, a Cr-alloy under layer, a modified outermost surface of the under layer and a CoCrPt-SiO_2 granular magnetic layer. Only the depositing conditions of the outermost surface of the under layer differ from those of Fig. 9. Comparing Fig. 9 and

Table 4 Comparison of main figures with or without modified outermost surface

Modified layer	H_{cr} (Oe)	$M_r t$ (menu/cm^2)	O/W (dB)	SNR (dB)
Without modified outermost layer	2,200	0.77	36.7	26.6
With modified outermost layer	2,500	0.73	38.3	32.5

Fig. 10, we can clearly identify the grain boundary areas in Fig. 10, and understand that grain boundary segregation is greatly enhanced with a SiO_2 additive.

Table 4 compares the above two disks with regard to magnetic coercive force H_c, $M_r t$ (product of remanence magnetization and layer thickness), O/W value and SNR. An AMR head with recording density of 200kFCI is used to measure the O/W value and SNR.

We have changed the depositing conditions of the outermost surface of the under layer to control the physical conditions that border the magnetic layer. Under the low temperature-deposited conditions, we finally have achieved better performance of the new disk comparable with that of the conventional one.

The conventional CoCrTaPt high temperature-deposited magnetic layer has encountered the other difficulty of "thermal decay of magnetism" which causes loss of the recording bits under normal ambient temperature. In order to suppress noise, the high temperature-deposited magnetic layer increases its Cr contents for the grain boundary segregation. At the same time, however, the level of saturating magnetic moment is reduced and thermal energy becomes greater than magnetic energy. On the other hand, the oxide additive promotes the grain boundary segregation for the granular magnetic layer, without reducing the level of saturating magnetic moment. Therefore, an excellent magnetic hard disk of high recording density, high thermal stability and low noise can be fabricated. Low temperature-deposited magnetic layer technology can also be applied to Al or glass substrates without difficulties.

We are currently promoting development of higher performance disk media in this way.

3. Conclusion

In the 21st century, the information revolution that personal computers and the Internet have brought about will also extend into homes, and everyone will have the ability to handle images, music and information as desired. In this situation, one of the indispensable devices will be a capable but inexpensive hard disk drive. We have been promoting the development of magnetic hard disk for this drive.

In the future, society will demand a variety of HDDs in applications not only for computers but also for audio-visual devices, and will encourage further expansion of these devices. To respond to the impending demand and supply of versatile magnetic hard disk, we will successively improve hard disk so that it is optimized for each application.