Longitudinal Al Substrate Magnetic Recording Media

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1. Introduction

As recording capacities increase and uses for digitally recorded data expand, the recording methods for magnetic recording media and the types and sizes of substrates used in that media are diversifying. At present, most of the magnetic recording media being manufactured by Fuji Electric is longitudinal aluminum substrate media that uses an aluminum substrate on which NiP is plated over an aluminum alloy, and in which magnetization of recorded bits is oriented in a circumferential (longitudinal) direction in the plane of the substrate. This magnetic recording media is used primarily in personal computers and servers. As storage capacities for electronic media have increased, higher recording densities have been developed for longitudinal aluminum substrate magnetic recording media. The recording densities of products released to the market have increased from 30 Gbits/in^2 in 2001, to more than 60 Gbits/in^2 in 2002, and to more than 90 Gbits/in^2 in 2004.

In order to realize these types of higher densities, Fuji Electric is developing elemental technologies and is focusing on texturing technology, magnetic technology and head-disk interface technology. This paper discusses the status of Fuji Electric's technical developments thus far, and also describes technical trends for realizing high densities of more than 100 Gbits/in^2.

2. Texturing Technology and Cleaning Technology

2.1 The objective of texturing

Magnetic recording media is formed by fabricating multiple layers of metallic and non-metallic thin films on top of a nonmagnetic substrate. The properties of the substrate surface are known to exert a large influence on the characteristics of the magnetic recording media.

At present, the substrate most commonly used for longitudinal recording consists of an aluminum base metal that is plated with a layer of NiP and then processed to a mirror finish. That surface is then textured to form a microroughness in the circumferential direction.

This texturing has the following two objectives:

(1) To ensure flying stability of the magnetic head over the magnetic recording media

(2) To orient the direction of magnetization in the circumferential direction of the substrate

The first objective of ensuring flying stability of the magnetic head can be achieved by performing texturing to form a dense roughness in the circumferential direction of the substrate. Fuji Electric aims to reduce the effective surface area further in order to prevent adhesion with the magnetic head.

The second objective depends largely on the electrical characteristics. With magnetic recording media for longitudinal recording, it is preferable that the magnetic orientation (the direction of easy magnetic alignment) is oriented in the circumferential direction of the substrate. Texturing aligns the magnetic orientation in the circumferential direction of the substrate by generating stress in the thin film crystals along the direction of the texture. This orientation is largely determined by the contour of the texture, and therefore, the quality of magnetic recording media products is largely dependent on the texturing.

2.2 Characteristics and dependencies of textured surfaces

One indicator of texturing is the R_a (center line average roughness) value. This R_a value is closely related to two contradictory characteristics of the abovementioned objectives. Figure 1 shows this relationship. When the R_a of a substrate surface is small, the flying performance of the magnetic head is favorable, but on the other hand, the magnetic orientation ratio (OR, the ratio of magnetism in the circumferential direction to magnetism in the radial direction of the substrate) worsens and the signal to noise ratio (SNR) of the magnetic recording media (ratio of the output signal to noise) also worsens. Accordingly, technical development is needed to improve the OR while maintaining good flying performance of the magnetic head.

As an example, Fig. 2 shows the relationship between the tip radius of curvature and OR at the time of texturing. Even at the same R_a value, OR increases when the tip radius of curvature is small, thereby improving the performance of the media.

The tip radius of curvature is determined according to the processing cloth, slurry (mixture of the coolant and abrasive diamond grains), and the processing conditions.

There are five basic control parameters, and these are listed below:

(1) Workability of the coolant in the slurry
(2) Shape of the abrasive diamond grain in the slurry
(3) Number of rotations of the substrate during texturing
(4) Processing force during texturing
(5) Material and diameter of the fibers in the processing cloth

These parameters can be combined appropriately to produce a surface condition that provides a magnetic flying head performance and OR that are both satisfactory.

2.3 Cleaning quality

The OR described above is largely influenced by the quality of substrate cleaning after the texturing process. It is important that the coolant used in texturing is thoroughly removed in order to obtain a clean surface condition with low residue. Fuji Electric presently maintains media performance by monitoring, at the nanogram-level, the amount of surface residue per disk at the stage prior to magnetic film deposition.

Fig.1 R_a dependence on OR and head flying height

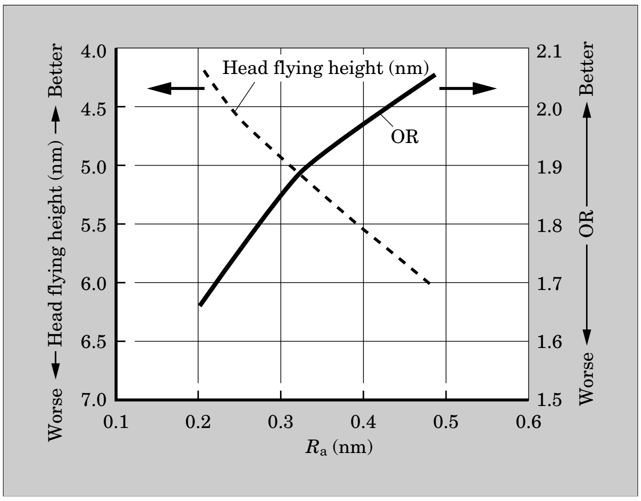
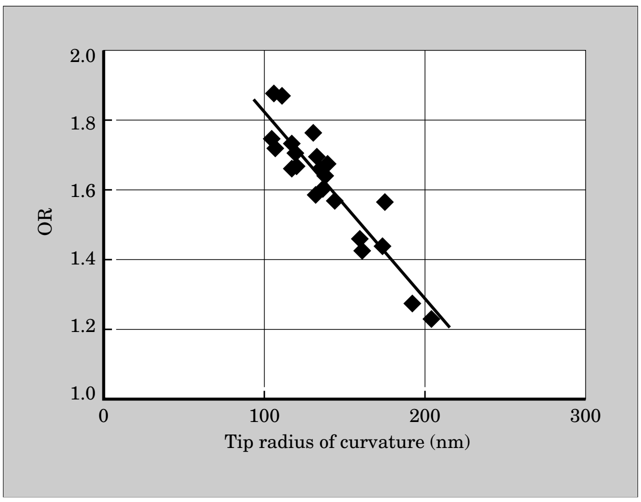


Fig.2 Tip radius of curvature dependence on OR



2.4 Residue reducing methods

Listed below are the three main ways to reduce the amount of substrate surface residue prior to magnetic film deposition:

(1) Use of a coolant with good cleaning performance
(2) Use of a cleaning agent having good cleaning performance and rinsability
(3) Reduction of the occurrence of drying spots

To implement item (1) above, it is necessary to improve the cleaning performance without degrading the texturing performance. Item (2) requires the use of a cleaning agent based on consideration of its permeability (removal of solid matter), emulsification and dispersability (removal of oil content) with regard to the coolant, and also its absorption into the NiP surface. The reduction of drying spots in item (3) is extremely difficult to achieve in magnetic recording media formed with an interior hole.

In the types of media currently being mass-produced, the occurrence of drying spots is controlled by reducing the surface residue. To achieve an even cleaner substrate surface, an advanced hot deionized water pull-up drying method is utilized. A substrate free from drying stains can be produced by immersing the substrate in a tank of heated ultra-pure water, slowing lifting out the substrate to disperse residue components on the substrate into the ultra-pure water and obtain a clean condition, and then to spray a gas such as nitrogen gas or isopropyl alcohol (IPA) having higher volatility than the water onto the substrate at the top of the water tank.

2.5 Next generation-compatible texturing and cleaning technology

For the next generation of magnetic recording media having recording capacities of greater than 120 Gbytes/disk, the space between the flying head and the magnetic disk is expected to become smaller than in the past (less than 5 nm), and technologies capable of texturing more precise roughnesses and providing higher degrees of cleanliness will be required. Rather than extend previous technologies, technical development that incorporates new methodologies will be necessary.

Figures 3 and 4 show the surface contours of an image obtained by an atomic force microscope (AFM) and a comparison of the magnetic head flying performance (glide avalanche) for the textured media used in an existing 80 Gbytes/disk product and for the latest textured media. By reducing the tip radius of curvature, Fuji Electric has developed texturing technology that decreases the R_a value (0.2 nm), maintains the OR, and enhances the magnetic head flying performance. This technology will be used for the first time in next generation products.

With the miniaturization of the size of recording bits, cleaning technology requires lower levels of adherents than in the past and the capability to identify adherent properties. There is also an urgent need to development a new cleaning method that includes analytical techniques.

Fig.3 AFM image of substrate surface

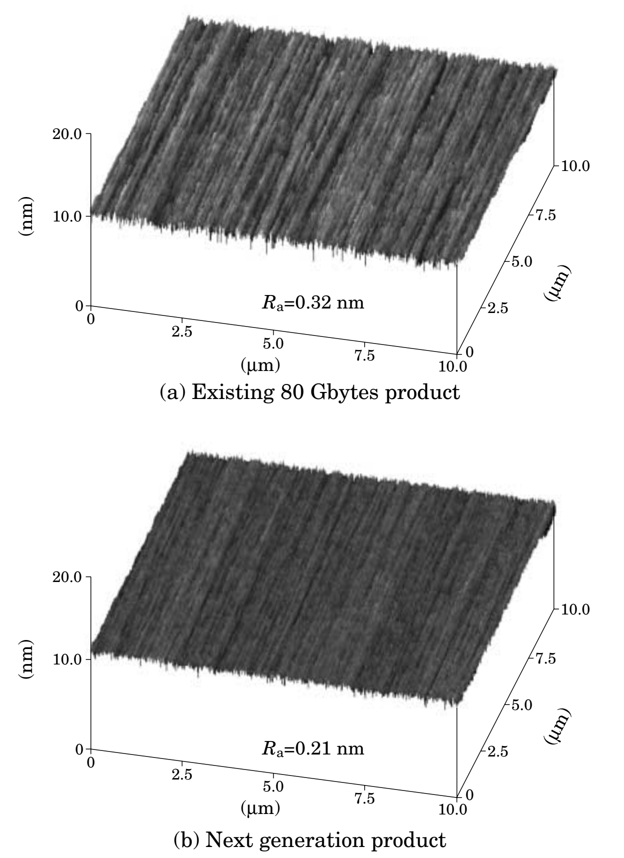
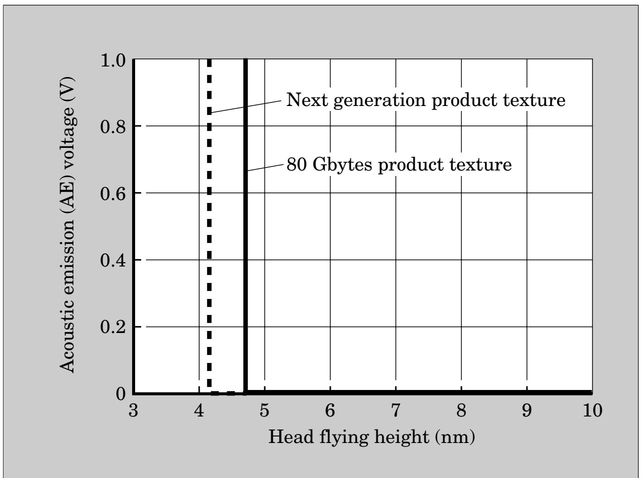


Fig.4 Results of glide avalanche test



3. Magnetic Technology

3.1 Basic layer structure of magnetic recording media

Various magnetic recording technologies are incorporated into magnetic recording media in order to achieve optimal magnetic characteristics.

Figure 5 shows an example of the layer structure of longitudinal aluminum substrate media. Multiple layers of thin metal films are formed on top of a NiP-plated substrate, and on top of those multiple layers, a carbon overcoat layer is formed to protect the magnetic recording media from the sliding contact generated between the media and the magnetic head. Then, a liquid lubricating film is coated on top of the carbon overcoat and the abovementioned texturing of the substrate surface is performed.

The multiple thin metal films are designed to have extremely fine film thicknesses, ranging from about 0.8 nm to about 15 nm for a relatively thick film. These thin metal films each have their own individual function. An underlayer, consisting of Cr and a Cr alloy, is provided so as to align the crystalline orientation of the above magnetic layer in the plane of the substrate. An intermediate layer, formed from a Co alloy thin film, is provided to increase the crystal conformation between the underlayer and the magnetic recording layer, and to reduce crystal defects in the magnetic recording layer. The magnetic recording layer is the film onto which magnetic signals are actually written, and is formed from a Co alloy,

Fig.5 Layer structure of magnetic recording media

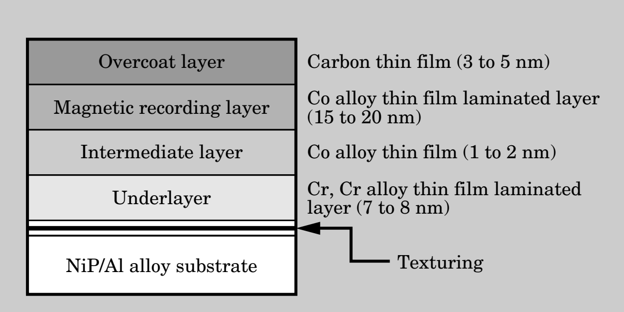
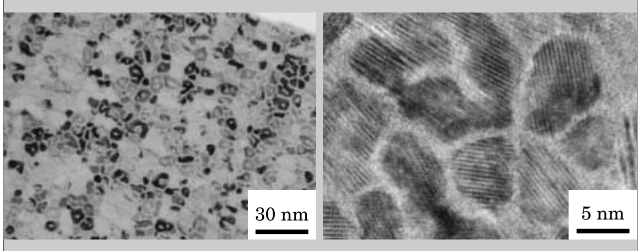


Fig.6 TEM plane image of magnetic recording media

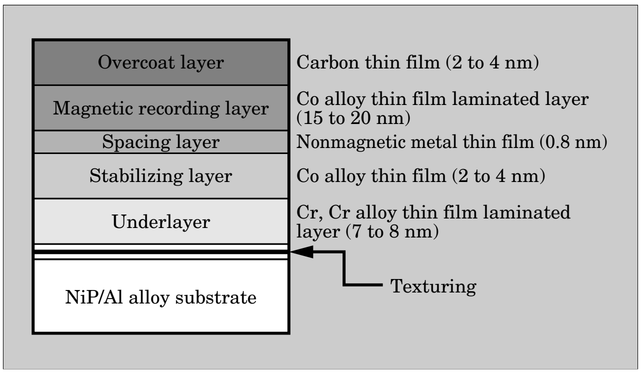


typically consisting of Co with additional elements of Cr and, according to the purpose and function of this layer, Pt, Ta, B, and the like. Figure 6 shows a plane view of a magnetic recording layer imaged using a transmission electron microscope (TEM). The magnetic recording layer is an aggregate of multiple Co alloy grains. At present, the average grain size is approximately 7 nm, and this grain size has been shrinking year after year as recording densities increase. At recording densities greater than 100 Gbits/in^2, the length of a single recording bit will shrink to approximately 30 nm and the size of the Co crystal grains will have to be reduced to about 6 nm. However, when the size of the Co crystal grains is reduced, the problem of thermal decay becomes noticeable. Thermal decay is a phenomenon in which the magnetically recorded signal decays and is eventually erased due to the influence of ambient temperature. As a small magnet will lose its magnetism, smaller sized Co crystal grains more easily lose their magnetism. The Co crystal grain size must be designed based on an understanding of the relationship between recording density and thermal decay.

3.2 Layer structure of AFC media

In order to suppress the problem of thermal decay, Fuji Electric has been using AFC media since 2003 in its magnetic recording media of 60 Gbits/in^2 and above. AFC media is a type of magnetic recording media that relaxes the problem of thermal decay by utilizing antiferromagnetic coupling. The layer structure of AFC media is shown in Fig. 7. In this AFC structure, the intermediate layer of Fig. 5 has been replaced by a stabilizing layer and a nonmagnetic spacing layer. By controlling the thickness of the spacing layer and the magnetic characteristics of the stabilizing layer within certain ranges, the magnetic orientation of the stabilizing layer can be aligned in a direction opposite to the magnetization of the magnetic recording layer. In this manner, resistance to thermal decay can be enhanced by increasing the thickness of the total magnetic layer (magnetic recording layer + stabilizing layer) without increasing the magnetic signal which is a source of media noise.

Fig.7 Layer structure of AFC media



3.3 Improvement of recording density

The direction in which magnetic technology development is being advanced to increase the recording density of magnetic recording media is nearly the same regardless of the size of the recording density. Specifically, the following items are important for development:

(1) Miniaturizing the Co grains
(2) Weakening the magnetic interactions among Co grains
(3) Controlling the crystalline orientation
(4) Increasing the thermal stability of the recorded signal

Although the direction of development does not change, higher recording densities require a higher level of performance. To satisfy those requirements, the alloy design, layer structure design and process design are continuously being optimized.

3.4 Alloy design

Many types of alloys are used in the thin metal films of magnetic recording media according to the desired function.

The underlayer is formed from pure Cr having a favorable crystalline orientation, a Cr alloy containing additional elements of V, Mo, W, Ti or the like in order to regulate the spacing of the crystal lattice and to increase crystal conformation with the Co magnetic thin film, or a Cr alloy containing an additional element of B or the like in order to reduce the size of the crystal grains. Recent magnetic media that exceeds 60 Gbits/in^2 is typically designed with a laminated structure that combines multiple functions in two to three layers of these metal alloy thin films.

The magnetic recording layer is based on the conventionally-used CoCrPt alloy and contains a B additional element in order to reduce the size of the crystals and to promote a segregated structure and additional elements of Ta, Cu and the like to regulate the crystal structure. The types of additional chemical elements and their quantities are important factors in the design of the magnetic layer composition. Increasing the quantities of Cr and B, which are effective in shrinking the size of Co grains and in reducing the magnetic interactions among grains, also effectively reduces the media noise. However, because the magnetism of the Co grains is weakened, the thermal stability of the recorded signal deteriorates. Conversely, if the quantities of Cr and B additional elements are limited to small amounts, the thermal stability improves but media noise increases. Recently, two or more magnetic recording layers having different compositional ratios of Cr and B are being used to maintain a balance between low noise and thermal stability.

3.5 Design of the layer structure

When designing the layer structure, the designer must take care of the thickness of each film and the ratio of film thicknesses. From prior experience it is known that when the film thickness of the Cr and Cr alloy underlayer increases, the size of Co grains also increase in the magnetic recording layer formed above. This phenomenon also applies to the stabilizing layer that is formed between the underlayer and the magnetic recording layer. Figure 8 shows the relationship between Co grain size in the magnetic recording layer and thickness of the stabilizing layer. By simply increasing the designed thickness of the stabilizing layer from its usual value of about 3 nm to a thickness of 5 nm, the Co grain size in the above-laminated magnetic layer will increase by 8 % or more. An increase in crystal grain size invites an increase in media noise and is one cause of SNR degradation as shown in Fig. 9. (A higher SNR value enables recording density to be increased.) As in this example, it is important that the layers of magnetic recording media be designed such that each layer is as thin as possible.

Recent magnetic recording media is typically designed with a laminated layer structure of two or more magnetic thin films, and the ratio of those film thicknesses is an important design consideration. Figure 10 shows the relationship between read and write (R/W) properties and the top magnetic layer thickness ratio in the case where two magnetic layers have been laminated together. The R/W properties have a large dependency on the magnetic layer thickness ratio. The optimal film thickness ratio depends on the combination of magnetic layer compositions and the capability of the magnetic head that reads and writes signals. However, the optimal R/W properties are obtained in a narrow range of magnetic layer thickness ratios, and film deposition technology capable of controlling the thickness ratio within this narrow range is required. Fuji Electric has optimized its film deposition equipment, processes and film thickness control methods in order to achieve a high level of film thickness control and to produce magnetic recording media stably without fluctuation of the magnetic layer thickness ratio. Moreover, by enhancing TEM analysis technology and introducing synchrotron radiation analysis (using the SPring-8 facility) to enable the analysis of crystalline structures having film thicknesses of 1 nm or less, Fuji Electric is strengthening its thin film analysis technology and establishing guidelines for the design of layer structures.

Fig.8 Co grain size dependence on stabilizing layer thickness

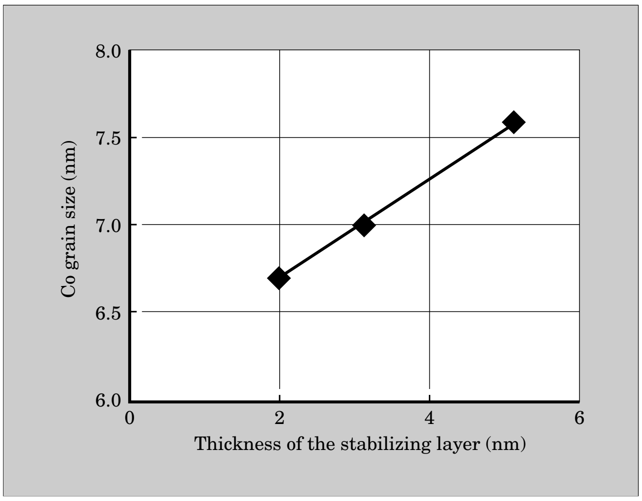


Fig.9 SNR dependence on stabilizing layer thickness

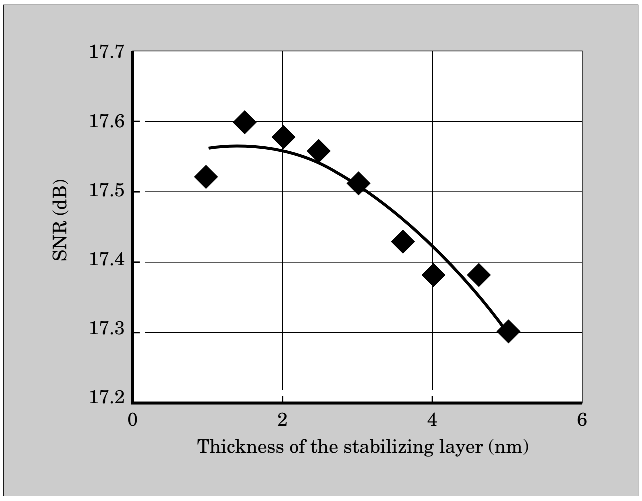
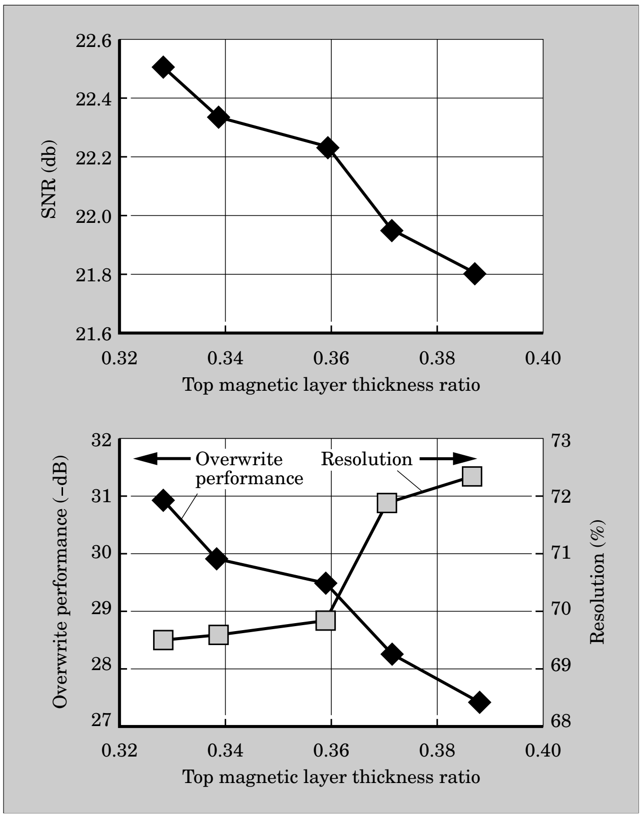


Fig.10 R/W properties dependence on top magnetic layer thickness ratio



3.6 Film deposition process

The magnetic characteristics and R/W properties of magnetic recording media depend on film deposition process conditions including heating temperature of substrate, film deposition pressure, the rate of film deposition, and the substrate bias. As an example, Fig. 11 shows the change in SNR characteristics when a substrate bias is applied during deposition of the magnetic layer. The magnetic recording layer used in this case had a laminated structure consisting of two magnetic layers, and the application of a substrate bias to the bottom magnetic layer (layer closer to the substrate) caused the SNR characteristics to improve, but the application of a substrate bias to the top magnetic layer (layer further from the substrate) resulted in no noticeable improvement in the SNR characteristics. The application of a substrate bias has the effect of increasing the energy of the sputtered grains, thereby forming a dense film with few defects. The application of a substrate bias also has the effect of changing the lattice spacing of the crystals and increasing the substrate temperature. Because these effects interfere with one another, a film can be classified as exhibiting a good effect, no effect or an adverse effect in response to the application of an applied substrate bias.

Fuji Electric optimizes the deposition process to attain the greatest performance for improving its layer and alloy design accompanied by the progress of generation.

Fig.11 SNR dependence on bias

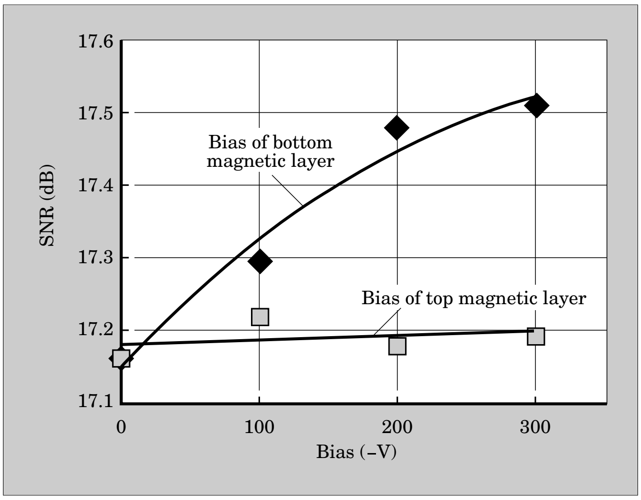


Table 1 Comparison between new media and old media

	End of 2002	February 2004
SNR	15.98 dB	17.15 dB
Overwrite performance	−28.7 dB	−30.4 dB
Resolution	59.1 %	63.1 %
Signal decay rate	−0.35 %	−0.26 %

3.7 Next generation-compatible magnetic technology

Table 1 compares the R/W properties of the 60 Gbits/in^2 class of magnetic recording media that was first produced at the end of 2002 and the magnetic recording media that was mass-produced in February 2004. The magnetic recording media of 2004 employs an AFC structure, has a multilayered underlayer, and a redesigned magnetic layer composition. Moreover, the biasing and heating processes were optimized for the layer structure and composition. As a result, the magnetic recording media of 2004 has better R/W properties than the magnetic recording media of 2002. The signal decay rate, which is a measure of thermal stability, has also been improved (smaller absolute value) through the use of an AFC structure and the redesign of the magnetic layer composition. At present, Fuji Electric is again reviewing the composition of the magnetic layer, is developing magnetic recording media that provides even higher-level performance, and is making final adjustments for application of that media to a 90 Gbits/in^2 product.

Additional performance improvements are necessary in order to realize recording densities in excess of 100 Gbits/in^2 in the future. As described above, a major objective of magnetic technology is to reduce the crystal grain size while maintaining thermal stability. Presently, Fuji Electric is considering reducing the crystal size by redesigning the compositions of the underlayer and magnetic recording layer, and maintaining the thermal stability by redesigning the AFC structure and the magnetic layer structure. For the film deposition process, Fuji Electric is investigating a method for uniformly distributing magnetic characteristics in the plane of the magnetic recording media and is aiming for a comprehensive improvement to media characteristics. Fuji Electric is also investigating methods for maintaining a higher level of cleanliness in the vacuum atmosphere during film deposition in order to reduce crystal lattice defects in the thin metal film and to improve media characteristics.

4. Head-disk Interface (HDI)

4.1 Overcoat layer

An effective way to increase the recording density in a magnetic disk device is to decrease the distance (magnetic spacing) between the magnetic head and the magnetic layer of the recording media. As an example, Fig. 12 shows the relationship between thickness of the carbon overcoat layer and the SNR. When the carbon overcoat layer is made thinner, the magnetic spacing becomes narrower, thereby improving the SNR. In order to decrease the magnetic spacing, it is necessary to lower the flying height of the magnetic head and to reduce the thickness of the overcoat layer. Accordingly, in addition to the texturing technology for creating surfacing conditions that support low flying

Fig.12 Relationship between SNR and overcoat layer thickness

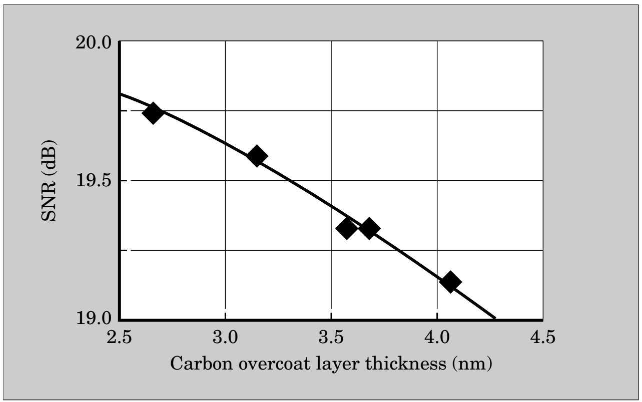
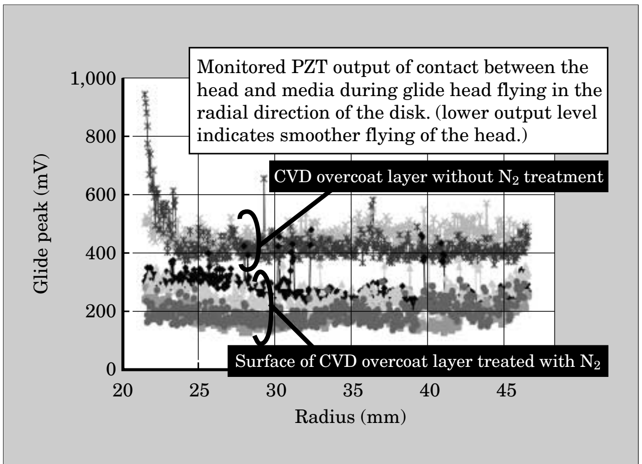


Fig.13 Flying stability improvement by applying N_2 treatment to carbon overcoat



heights of a magnetic head, the overcoat layer and lubricating film must provide sufficient corrosion resistance and durability even as a thin film.

Fuji Electric uses hollow cathode chemical vapor deposition (CVD) to deposit the overcoat layer and to ensure greater corrosion resistance and durability than can be achieved with a sputtered carbon layer. The amount of oxygen and nitrogen contained in the overcoat layer affect properties such as the film density, and can be changed to influence the wear characteristics. It has been learned that the surface potential and interactions with the lubricating film, to be described layer, also influence the flying performance of the magnetic head. Figure 13 shows the glide noise when a glide head flies over a disk in which the nitrogen content on the surface of the overcoat layer has been changed. It has been confirmed that the addition of nitrogen causes the glide noise to decrease. By optimizing the amounts of oxygen and nitrogen in the film based on consideration of flying performance of the head, wear resistance and durability, and by achieving uniform characteristics throughout the plane of the disk, the prospects are favorable for achieving reliability in a film thickness of 2.5 nm. As an overcoat layer capable of providing

Fig.14 Lubricant roughness

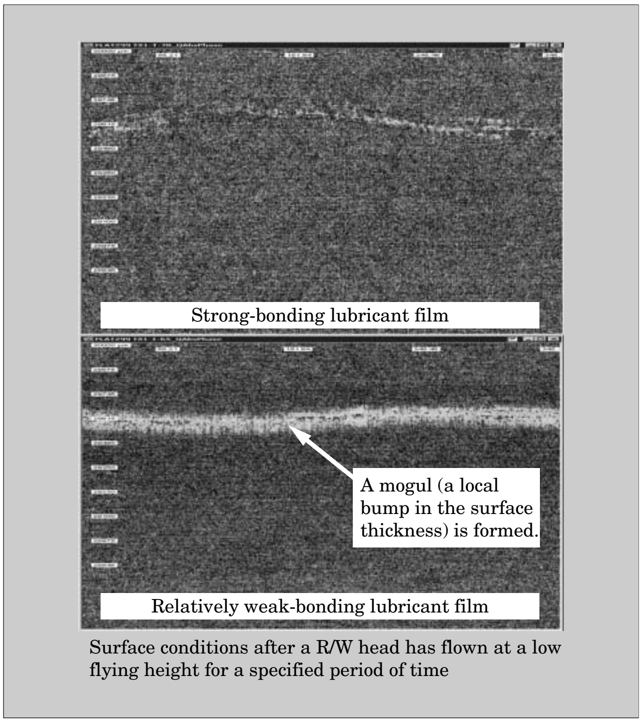
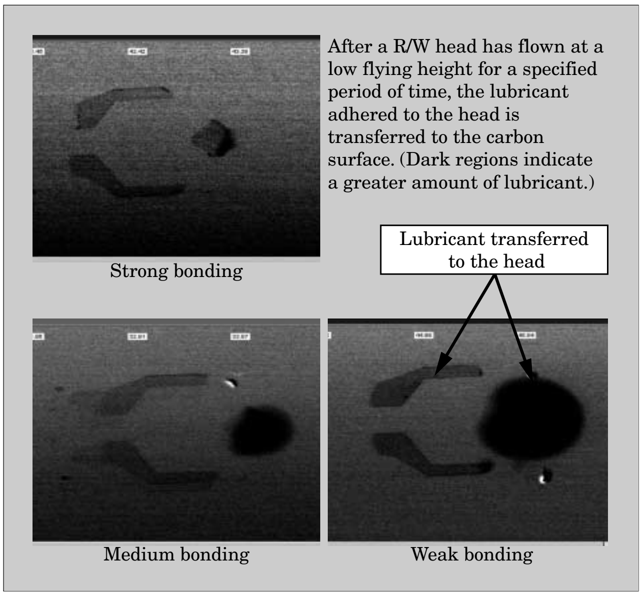


Fig.15 Lubricant-carbon overcoat bonding and head pick-up



satisfactory levels of durability and corrosion resistance at thicknesses of 2 nm or less, Fuji Electric has focused its attention on dense tetrahedral amorphous carbon (ta-C) which is rich in sp^3-bonded carbon, and is currently evaluating such a carbon overcoat layer fabricated using a filtered cathodic arc (FCA).

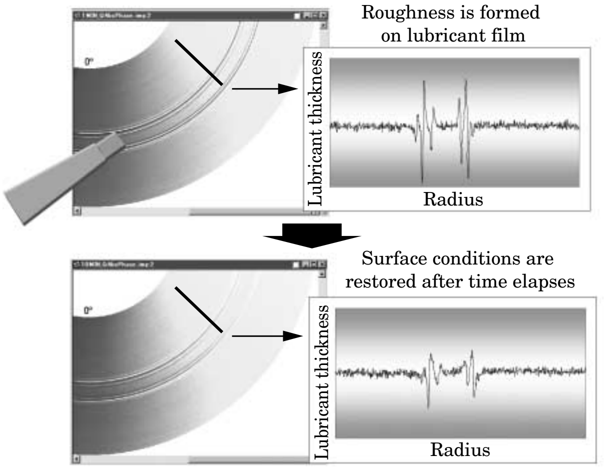
4.2 Lubricating film

At present, HDI reliability of the magnetic disk is ensured by the synergistic function of a fluorine lubricating film of perfluoropolyether (PFPE) that is coated on top of the overcoat layer at a thickness of 1 to

Table 2 Lubricant diffusion coefficients

Lubricant material	Diffusion coefficient of lubricant film ($\mu m^2/s$)
Lubricant A	0.53
Lubricant B	1.19
Lubricant C	0.02

Diffusion coefficients were calculated based on the speed at which lubricant moguls formed during head gliding are restored.



2 nm. Fuji Electric is also investigating functional thin film materials for the lubricating film in order to support the lower head flying height clearances and thinner overcoat layers that accompany higher recording densities.

Lowering the flying height of the magnetic head results in a stronger influence on the lubricating layer of air vibrations under the head slider, and brings an increased opportunity for sporadic surface contact to occur. Accordingly, the lubricating film may, in some cases, form a local roughness (mogul) or be transferred to the head slider. This impairs the flying stability of the magnetic head and causes the output of the R/W signal to fluctuate. Figures 14 and 15 show examples of the results of an investigation for the bonding between the lubricant film material and the overcoat layer. A strong-bonding lubricant film resists forming a roughness even when the head flies at a lower height than the design value. Moreover, the transfer of lubricant film to the slider surface can be reduced by treating the surface after it has been coated with the lubricant film.

To reduce frictional wear, it is important that the lubricant film continuously covers the surface of the overcoat layer. The lubricant film must not dissipate during high-speed rotations or when subject to an environment of stressful heat and humidity, additionally, the loss of lubricant film due to contact between the head and disk during contact start-stop (CSS) operation must be suppressed and diffusibility must be sufficient in order to replenish any lost amounts. Fuji Electric has established a technique for quickly evaluating the diffusibility of a lubricant film and is moving ahead with the optimization of lubricant films suited for designed drive characteristics (Table 2).

Fuji Electric has also developed proprietary refining technology for lubricant materials and aims to enhance the quality and functionality of the lubricant film.

5. Conclusion

Applications for longitudinal aluminum substrate media are limited because of its poorer shock resistance than glass substrate media. For this reason, no large increase in demand is expected, but the market is predicted to continue at its present size. The theoretical limit of longitudinally recording density has long been debated, but it is only a matter of time before the density of mass-produced longitudinal recording media exceeds 100 Gbits/in^2, and development toward the target of 200 Gbits/in^2 is ongoing. In terms of manufacturing costs, longitudinal magnetic recording media continues to maintain its advantage over other types of media. The elemental technologies acquired herein may also be applied to glass substrate media and to perpendicular magnetic recording media, for which practical applications are imminent as the next-generation recording method. It can be said that the technical development of longitudinal aluminum substrate media is becoming even more important. Fuji Electric intends to continue to develop technology to challenge the limits of longitudinal aluminum substrate media and to support our information-based society.