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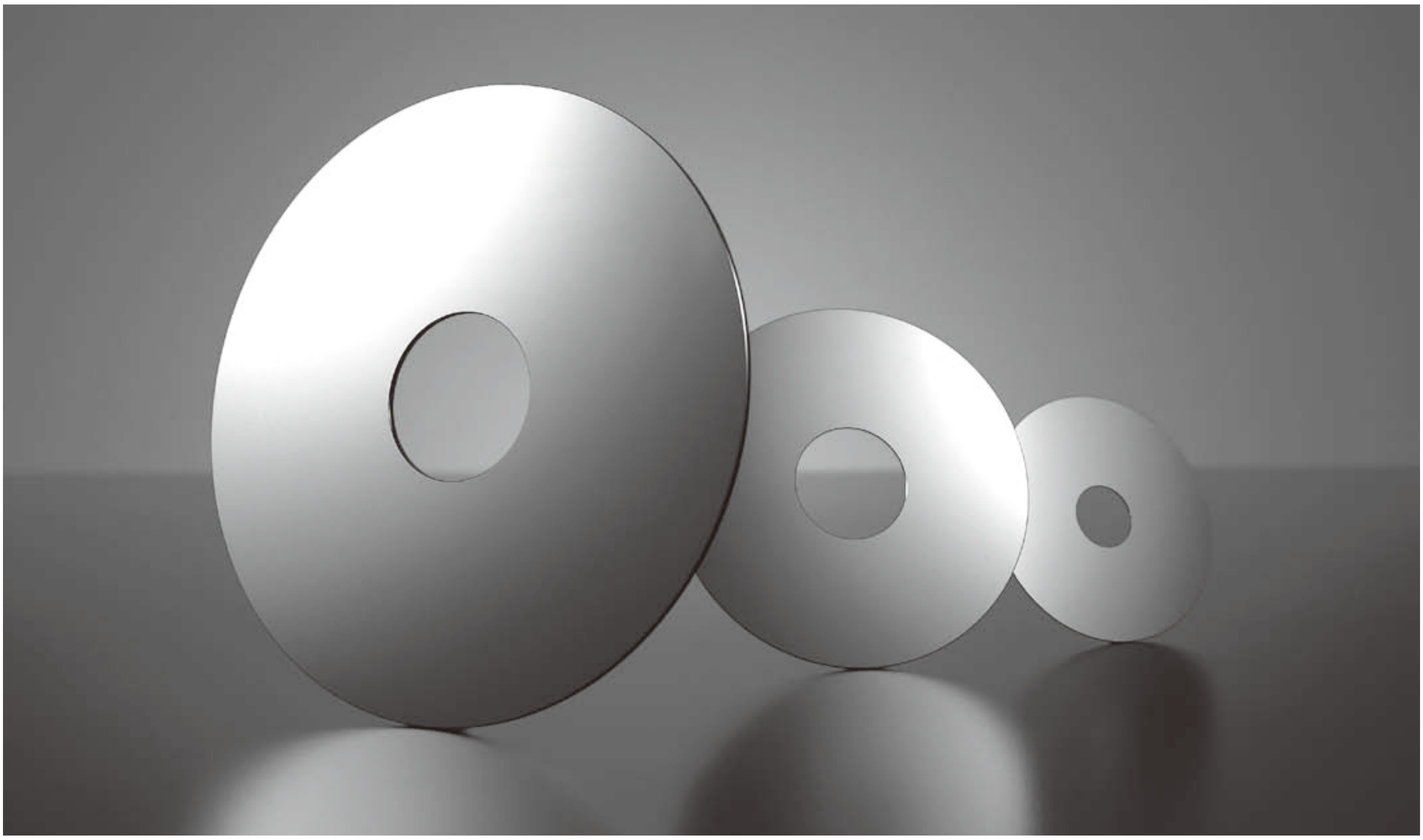
Magnetic Recording Media

Fuji Electric

Meeting the need for large-capacity hard disk drives with unique advanced technologies

e-Front runners



Large-capacity magnetic disks play an important role in a ubiquitous information society where people use and enjoy data-intensive informaion, images, music, and games using a variety of small, mobile terminals.

Magnetic disks installed in hard disk drives (HDDs) are key devices for recording, playing, and storing digital data. With the advancement of IT, a wide variety of entertainment equipment has been developed which requires the high-speed processing of huge amounts of imaging data. Accordingly, the market for HDDs continues to rapidly expand. Fuji Electric Device Technology is preparing to manufacture large-capacity magnetic disks using perpendicular magnetic recording technology, which achieves significant high recording density. By adapting our unique advanced technologies, we will quickly meet next-generation needs.

Fuji Electric's Magnetic Disks

Fuji Electric

FUJI ELECTRIC
REVIEW

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Magnetic Recording Media

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Cover photo:

The amount of information created by humans is said to be growing explosively. Cloud computing for accessing software and services from various terminals via the Internet is expected to continue to develop significantly. Hard disk drives (HDDs) are the main devices for data storage, and increasing their capacities is becoming more and more important.

As an early developer and mass-producer of magnetic recording media compatible with the latest HDD technology, Fuji Electric has continued to contribute to increase HDD capacity.

The cover photo shows a conceptualized image of cloud computing. The content of the cloud is the servers and storage devices used at data centers and the like, and ultimately it can be symbolized by magnetic recording media for recording data.

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The Role of Universities in the Development of Hard Disk Drives

Dr. James W. Harrell †

Hard disk drives (HDDs) represent a remarkable technology. The storage capacity, performance, size and affordability of HDDs have improved dramatically since the first commercial drive, the RAMAC, was introduced by IBM in 1956. The RAMAC had a storage capacity of 5 M Bytes (MB) and consisted of fifty 24 inch disks. The rental price for 1 MB of storage was \$130/month[1]. Today one can purchase a 3.5 inch drive for a desktop PC with a capacity of 2 TB for well under \$200. An often used measure of this improvement is the increase in areal density over time. The RAMAC had a storage density of 2 kbits/in^2; whereas the storage density of high-end drives now exceeds 500 Gbits/in^2. HDD storage densities have increased nearly exponentially in time. Much of this increase has been a result of engineering developments that have allowed a scaling down of all relevant dimensions. However, this growth would not have been sustained without new technologies that were based on discoveries resulting from basic research, much of which has been done at universities throughout the world.

One of the main reasons for the continued increase in storage densities has been the development of read heads with increasing sensitivity, allowing the detection of ever smaller bits. One of the most notable contributions to this development was the discovery of Giant Magnetoresistance (GMR) in 1988 by Abert Fert at the University of Paris-Sud[2] and Peter Grünberg at Julich Research Center[3], for which they received the Nobel Prize in 2007. GMR read heads were first introduced in hard drives in 1997 as a replacement for MR heads and allowed the detection of ever smaller bits. Heads based on Tunneling Magnetoresistance (TMR) began to replace GMR heads in 2005. TMR was discovered by Jullière at the University of Rennes in France[4]. The original effect was observed in Fe/Ge-O/Co at 4.2 K but was very small at room temperature. Research done by Miyazaki at the University of Tohoku[5], Moodera at MIT[6], and others led to the development of TMR stacks with amorphous Al_2O_3 tunnel barriers with high room temperature sensitivity which was used in the first TMR heads. Current TMR read heads now make use of crystalline MgO as the tunnel barrier, which greatly enhances the magnetoresistance. Enhanced TMR using MgO was predicted theoretically by Butler at Oak Ridge National Laboratory (now at the University of Alabama[7]) and Mathon at City University in London[8].

University researchers have also played an important role in the development of new magnetic media. Conventional media have a granular structure with ten's of grains making up a single bit. Decreasing bit sizes have required media with deceasing grain sizes. Grain sizes in current media consisting of CoPt-based alloys are smaller than 10 nm and are rapidly approaching the superparamagnetic (SP) limit. In order to delay the SP limit, materials with higher magnetocrystalline anisotropy energy (MAE) must be employed. For grains with uniform anisotropy which reverse coherently, higher MAE means that higher write fields are required, but this is limited by the saturation magnetization of the head. Beginning in 2005, the HDD industry made a rapid transition from longitudinal to perpendicular recording (PMR) . One of the main advantages of PMR was that it allowed a head configuration giving a larger write field. PMR is attributed to work originally done in 1976 by Iwasaki at Tohoku University[9]. Recent work done by Victora at the University of Minnesota[10] and Suess at Vienna University of Technology[11] has shown that magnetic media with appropriately designed MAE gradients can have a reduced switching field to thermal stability ratio. Appropriately graded media can further extend the SP limit. Other technologies that are under consideration for extending the SP limit include bit patterned media (for increasing the 'grain' size) and heat assisted magnetic recording (for reducing the required write field) .

FePt is a prime candidate high anisotropy material for new media. In the ordered $L1_0$ phase, its anisotropy is approximately 10 times that of the CoPt-based alloys. Shouheng Sun (then at IBM and now at Brown University) demonstrated that FePt nanoparticles with narrow size distribution could be chemically synthesized and could self-assemble into highly ordered arrays[12]. This led to great interest in chemically synthesized nanoparticles as potential new media. Subsequent research, much of which was done at universities, has shown that fabricating media using chemical synthesis is extremely challenging, and more attention is now directed at fabricating FePt media using sputter deposition. As an example, I note some of the work done on FePt at the University of Alabama. Butler and Chepulski showed theoretically that

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FePt nanoparticles cannot be fully ordered and the maximum order parameter decreases with decreasing particle size[13]. Thompson, Nikles, and I demonstrated that certain metal additives can significantly reduce the ordering temperature, but enhance sintered grain growth. We also showed that nanoparticles, although uniform in size, can have a considerable compositional and anisotropy distribution[14]. These findings are also relevant to sputtered granular FePt films. One of the challenges with sputtered FePt films is limiting grain growth while thermally annealing the films to obtain the ordered phase. Yuki Inaba, working with Thompson and myself, recently studied the effect of pulse laser processing on chemical ordering and grain growth of FePt films[15]. The study demonstrated that chemical ordering can be obtained in the millisecond regime and that, compared with conventional annealing, grain growth during ordering is reduced. (Inaba is currently working at Fuji Electric on HDDs.)

Clearly, universities have played a significant role in HDD development and will continue to do so in the future. University-industry interactions are critical in this effort and their research can be complimentary. Universities are not structured for short-term research. Much of the university research is done with and by graduate students whose dissertation projects typically takes several years. Industry, on the other hand, is motivated by market concerns and has the resources for rapid product development. In order to promote university-industry interactions, several university research centers related to magnetic recording have been established in the US during the past few decades. These include the Data Storage Systems Center (DSSC) at Carnegie Mellon University, the Center for Magnetic Recording Research (CMRR) at UC San Diego, the Center for Micromagnetics and Information Technologies (MINT) at the University of Minnesota, and the Center for Materials for Information Technology (MINT) at the University of Alabama, as well as several other centers. The larger centers typically have industrial sponsors which provide financial support for research and provide guidance on technologically relevant problems. In return, the centers hold annual and bi-annual reviews during which the research results are presented. Some centers also host industry scientists and engineers for extended periods of time and sponsor topical workshops for industry. One of the important roles played by universities is training of graduate students and postdoctoral fellows for employment by industry. At the MINT Center at the University of Alabama, the majority of graduate students and postdocs go into the information storage industry. Some of these students hold internships in industry during part of their graduate study.

The great New York Yankees baseball catcher Yogi Berra is famously quoted as saying "It's tough to make predictions, especially about the future." Likewise, no one really knows the future of magnetic recording. What we do know, however, is that it will be unlike the past since exponential growth cannot be indefinitely sustained. It should be a challenging and exciting adventure in which universities are expected to play a critical role.

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Magnetic Recording Media: Technical Trends and Future Outlook

Shunji Takenoiri † **Sota Matsuo** † **Tatsuhiko Fujihira** ‡

ABSTRACT

The areal density of magnetic recording media has increased by about 40% annually. For areal densities to continue to increase at this rate, a technical breakthrough is needed within the next one or two years. For example, SWR (shingled-write recording), energy assisted magnetic recording, patterned media and the like are promising candidates. Fuji Electric is evaluating these technologies. Fuji is also studying the substrate, a laminated ECC (exchange-coupled composite) media structure, the HDI (head-disk interface) and new highly anisotropic magnetic layer materials in order to realize higher densities.

1. Introduction

Nearly five years have passed since hard disk drives (HDDs) that use perpendicular magnetic recording technology were first mass-produced. Currently, most of the magnetic recording media being produced is perpendicular media. Recording densities, which had stagnated at levels just above 100 Gbits/in^2 in the age of longitudinal magnetic recording, are increasing steadily at a rate of about 40% per year. In 2008, an article in the Fuji Electric Journal stated that, "assuming HDD recording densities can continue to grow at this pace, 500 Gbits/in^2 will be achieved at the mass-production level and 1 Tbits/in^2 will be achieved at the research level by 2009." As predicted, recording densities at the mass-production level have reached 500 Gbits/in^2. Meanwhile, at the research level, although the attainment of 1 Tbits/in^2 has not be reported yet, with the announcement of 927 Gbits/in^2 in October 2009 and the use of the shingled-write recording method (to be described later), which has been gaining momentum since 2008, further improvements in recording density are anticipated. Thus, the future pace of technical development is not expected to slow down.

Meanwhile, a major change in the HDD market in recent years has been the competition between emergent flash memory technology and small-diameter HDDs. The 0.8-inch and 1.0-inch small-diameter HDDs had, for a time, been installed in cell phones and mp3 players, but have now disappeared and the 1.8-inch market is also being forced to compete against flash memory. In order to maintain the superiority of HDDs under these circumstances, their price per recording capacity (cost per bit) must be reduced. Additionally, in recent years, insufficient power at data centers has become a concern, and lower power consumption by servers, storage equipment and other types of hardware is requested. Increasing the capacity of the HDDs used in servers and storage equipment will lead to a reduction in power consumption per recording capacity. For this reason, increasing the densities of magnetic recording media is an urgent task.

This paper describes the HDD market and technical trends for which future growth is anticipated, and also briefly explains the status of technical development of Fuji Electric's magnetic recording media.

2. Market Trends of HDDs

From the second-half of 2008 through the first-half of 2009, the HDD industry was affected by the "Lehm-

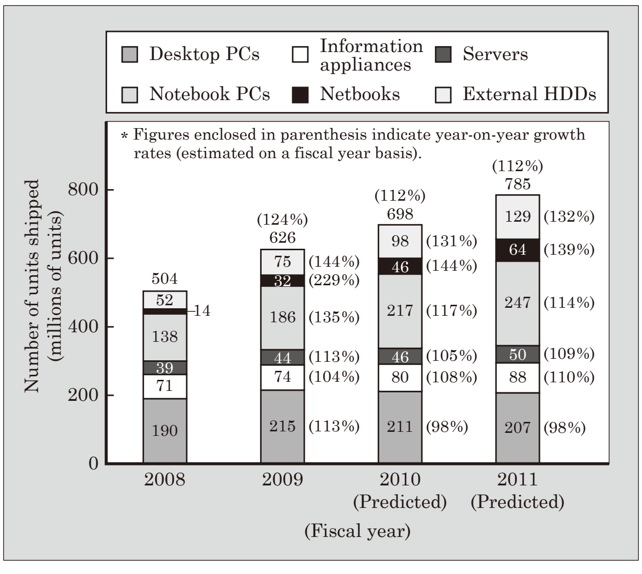

Fig.1 Worldwide shipments of HDDs by application

† Fuji Electric (Malaysia) Sdn. Bhd.
‡ Fuji Electric Co., Ltd.

an shock" and demand decreased dramatically. The PC market and HDD market both hit bottom in 2008, however, and since then have undergone a V-shaped recovery. With the economies of developed countries still exhibiting weakness, the increase in demand has been driven by demand from China and other emerging countries, and it is thought that this trend will continue.

Fig. 1 shows a forecast of the worldwide shipments of HDDs by application. Note that this is Fuji Electric's estimate based upon the opinions of research firms(1). Demand for desktop PCs and servers has not grown significantly, but is expected to remain at a steady level in the future. A characteristic of this forecast is that growth in the field of information appliances, which had been expected to grow significantly in the future, is believed to remain modest. In particular, small-diameter HDDs, mainly 1.8-inch disks, are competing against flash memory for use in products such as portable music players and video cameras. In the future, the usage of HDDs and flash memory will likely be divided according to the application, that is, HDDs will be used primarily in situations requiring large capacities, such as for video, and flash memory will be used primarily for other applications (photographs, music, etc.). Replacing information appliances as a driver of growth will be mobile PCs (notebook PCs, netbooks,) and external HDDs that typically use 2.5-inch disks. Also, accompanying the development of a cloud computing environment within a few years, the servers and storage equipment used in data centers will become even more important. The HDD market, as a whole, is expected to grow at an annual rate of more than 10%, and is considered to be an area of stable growth.

3. Technical Trends of Magnetic Recording Media

To increase the recording density, the problem known as the "trilemma of perpendicular media" needs to be solved. This problem refers to the difficulty of simultaneously establishing "higher recording density," "ease of writing" and "thermal stability." The meanings of these are explained briefly below.

Recording density is the track density (number of tracks per unit length)×linear recording density (number of bits per unit length). To realize "higher density," the track width may be narrowed and the bit length shortened. To narrow the track width, the magnetic pole of the write head may be made narrower, but as a result, the write magnetic field decreases and becomes "unable to write" (Fig. 2(1)). Meanwhile, in order to shorten the bit length, it is necessary to reduce the unit of magnetization reversal in the recording layer. However, if the unit of magnetization reversal is made smaller, the "thermal stability" will decrease. In other words, there will be greater risk that a saved recording would disappear (Fig. 2(2)). In order to maintain sufficient thermal stability, even if the unit of magnetization reversal is made smaller, the anisotropy of the magnetic materials used in the recording layer may be increased. When the anisotropy is increased, however, a larger magnetic field will be required for writing to the media, and the condition of being "unable to write" will result (Fig. 2(3)).

To continue to realize higher recording densities at the current pace, a technical breakthrough is thought to be needed within the next one to two years. The future candidate technologies that make higher densities possible are shingled-mode write recording, energy-assisted magnetic recording and bit patterned media, and these will be described below and their concepts, characteristics and challenges will be discussed.

3.1 Shingled-write recording method (SWR)

The basic concept of shingled-write recording was reported by Roger Wood et al. at TMRC 2008 (The Magnetic Recording Conference 2008, IEEE) as Two Dimensional Magnetic Recording (TDMR)(2). This con-

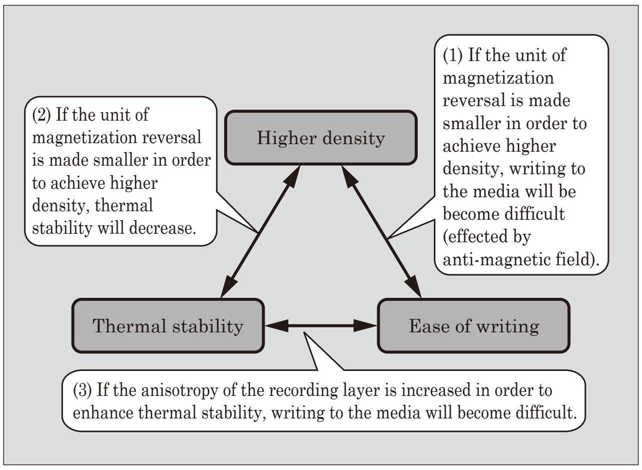

Fig.2 Trilemma of perpendicular magnetic recording media

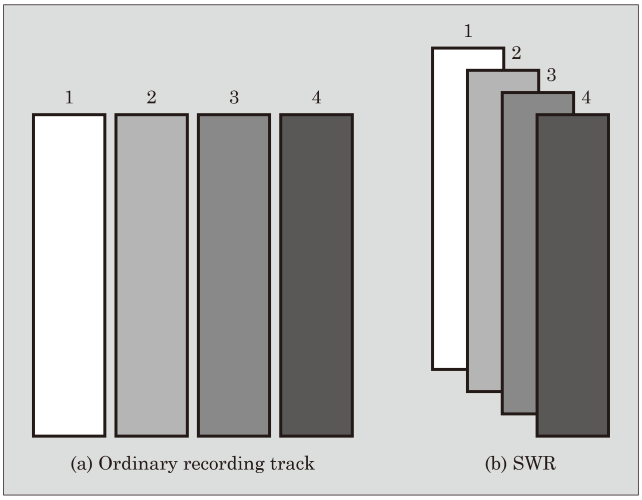

Fig.3 Conceptual diagram of shingled-write recording (SWR) method

cept consists of two parts. The first part is the writing scheme. Ordinarily, tracks are set one-by-one to have a certain pitch, but in this case, the tracks are positioned so as to overlap partly and are written to successively (Fig. 3). The name shingled-write recording (SWR) is derived from this characteristic. Moreover, the other part is the reading scheme. Ordinarily, recorded information is read for each track, but in this case adjacent tracks are processed two-dimensionally. This is a central technology of TDMR.

For TDMR, signal processing techniques and many other factors require further study, and commercialization in the near future would be difficult. On the other hand, the use of SWR only enables the recording density to be improved without significantly changing the current signal processing methods, and has therefore attracted attention recently. SWR technology has the following four characteristics.

(a) Because tracks are overwritten, only one side affects the track density. Therefore, the magnetic pole of the writing head can be enlarged, and the strength of the magnetic field for writing increased.
(b) Only one side is squeezed (affected by magnetic field leakage when writing to adjacent tracks), and therefore the track density can be increased.
(c) Writing is basically performed once, and therefore there is no problem with erasure of adjacent tracks.
(d) The skew (tilting of the writing head with respect to a track) effect enables the use of only the narrow side of the erase band (portion on both edges of a track where magnetization is disordered). This also contributes to higher track density.

The greatest challenges for establishing this technology are thought to be in areas related to the HDD system, such as the data overwrite logic, response speed and so on. Also, media-related challenges include narrowing the erase band and increasing the linear recording density.

3.2 Energy-assisted magnetic recording

Two types of energy-assisted magnetic recording technology have been devised: TAMR (thermally-assisted magnetic recording) and MAMR (microwave-assisted magnetic recording). Both methods are characterized by the application of some sort of assistance in addition to the normal magnetic field to enhance the writing ability.

With TAMR, a heat source is installed in the magnetic head, and recording is performed while applying a magnetic field and heat simultaneously. The magnetic material used in the recording layer of the media has the property whereby as the temperature increases, the magnetic reversal field decreases, and conversely, when the temperature drops, the magnetic reversal field increases. Using this property, heat is applied to temporarily lower the magnetic reversal field of the recording layer and writing is performed. The use of TAMR enables the anisotropy of the recording layer to be set to a high value, enhancing the thermal stability of the media. The greatest challenge facing commercialization of TAMR is considered to be the design of the magnetic head. The magnetic head is equipped with a heat source, and the location of the magnetic field must be aligned precisely with the location of the heating. Moreover, the design must be implemented with precision on the order of nanometers. Challenges for the media include the design of magnetic material for the recording layer having high anisotropy and a low Curie point, and the development of protective film and lubricative film capable of withstanding heating of 200 to 300 °C.

MAMR was proposed by Professor Zhu of CMU (Carnegie Mellon University) at TMRC2007[(3)], and has attracted attention. With MAMR, a high-frequency magnetic field is superimposed on an ordinary magnetic field (DC magnetic field), and using the magnetic resonance of the recording layer, the magnetic reversal field is lowered and writing is performed. With TAMR, in order to avoid an effect on adjacent tracks, the heating spot must be narrowed. With MAMR, however, even if the high-frequency magnetic field applied to adjacent tracks may leak, if the DC magnetic field can be narrowed, the reversal of the magnetization of adjacent tracks is thought to be difficult to accomplish, and therefore MAMR is considered to be more beneficial than TAMR in increasing the track density. The greatest challenge facing MAMR will be also the design of the magnetic head. A high-frequency magnetic field of several GHz or higher is said to be needed, but how to generate such a magnetic field is a challenge. For the media, in order to reduce the magnetic reversal field efficiently, a way to reduce the damping constant of the magnetization reversal of the recording layer is needed. In recent years, the results of simulations using ECC (Exchange-Coupled Composite) media to achieve reversal in a 50 kOe anisotropic hard film with MAMR have been reported, indicating the possibility that the ECC media currently being mass-produced could be enhanced to accommodate MAMR technology.

3.3 Bit patterned media (BPM)

BPM refers to media in which the bits have been physically separated by microfabrication techniques or the like. Because magnetization reversal can be accomplished in 1-bit units, improvement of the thermal stability and reduction of the reversal magnetic field (in order to enhance the ease of writing) are expected. As a method for manufacturing BPM, direct writing by electron beam lithography is used primarily at the research level, but in actual production, nanoimprinting or other techniques suited for mass-production would have to be used. Additionally, as in the case of discrete track media (DTM), techniques for groove-processing tracks and embedding a self-assembled monolayer therein (GSA: Guided Self-Assembly[4]) are also considered. In principle, BPM is capable of higher density, but from the perspective of media production, many challenges remain such as the realization of low-cost manufacturing techniques and these must be overcome. Moreover, system-related challenges, several of which are listed below, have also been pointed out recently.

(a) accurately. In the case of 2 Tbits/in^2, for example, the accurate recording of targeted bits requires a positional accuracy of less than 2 nm. This requires a level of accuracy that is higher than the current level of accuracy by a factor of 2.

(b) Fluctuation in the skew angle may cause writing to targeted bits to become no longer possible. Moreover, regarding the servo signal, the timings of the emergence of a solitary wave will differ for the playback waveforms, and tracking may become difficult.

(c) Because a gap exists between the write device and the read device in the magnetic head (or, writing and reading cannot be performed simultaneously), a non-written area appears whenever the servo signal is read. In total, these non-written areas are estimated to occupy about half of the disk, and may significantly reduce the recording area.

As described above, BPM has considerable potential but faces a number of technical challenges, and its commercialization will still require some time. Quite possibly, BPM technology may be used to realize recording densities of several Tbits/in^2 or even higher in the future.

4. Development Status of Magnetic Recording Media at Fuji Electric

The elemental technologies involved in the development of magnetic recording media at Fuji Electric are described briefly below. For additional details, please refer to the articles that follow in this special issue.

4.1 New high density recording technology

Of the future technologies introduced in section 3, Fuji Electric is primarily considering thermal-assisted magnetic recording. Fuji Electric has previously used computer simulations in the design of the media layer structure and materials, and based on those results, has developed specific materials. At present, Fuji Electric is developing materials having a high thermal stability and large temperature gradient of magnetic field reversal (writable at relatively low temperatures), and is planning their future application to media. Additionally, in a joint project with Tohoku University, Fuji Electric is developing high-anisotropy $L1_1$ type Co-Pt as an elemental technology. In studies thus far, the formation of $L1_1$ type Co-Pt ordered alloy film has been found to be possible at substrate temperatures of 300 to 400 °C, a temperature range that has been reduced to a level at which applicable to commercial media processes. This material is considered for application to the hard layer in ECC media or as recording layer material in thermal-assisted magnetic recording media.

4.2 Magnetism-related technology

In an HDD, data is recorded onto a magnetic layer, which is the recording layer of the media. The media, however, contains not just the magnetic layer, but also a soft magnetic underlayer for assisting writing by the magnetic head, and a seed layer and base layer for aligning the magnetic layer in the appropriate direction. Additionally, the magnetic layer has a laminated construction consisting of multiple layers. To solve the trilemma, several ideas for realizing higher densities have been suggested, i.e., the aforementioned thermal-assisted magnetic media, bit patterned media and the like, but at present, Fuji Electric is mainly considering ECC media[5]. For thermally-assisted magnetic recording, the magnetic head would have to be equipped with a heat source. For patterned media, each bit must be physically separated by microfabrication techniques or the like. In contrast, ECC media has the advantage of not requiring significant changes to the media or the magnetic head, and also does not add any significant changes to the production technology.

Fuji Electric has already applied this technology to mass-produced media, and aiming for higher densities, is improving the magnetic layer by increasing the number of layers and so on. As a future technology, Fuji Electric is moving forward with development, and is also aiming for application to SWR.

4.3 HDI technology

The HDI (Head Disk Interface) refers specifically to the carbon protective film, the lubricative layer and the peripheral technologies for protecting the surface of the media. The thickness of the protective film and the lubricative layer is set according to the sum of the distance between the head element and the media surface, i.e., the distance between the head element and the recording layer surface of the media, which is called the magnetic spacing. As densities are increased, the magnetic spacing is required to be made smaller. However, the reliability performance, such as durability, corrosion resistance and the like, cannot be degraded. In other words, the HDI technology must reduce the magnetic spacing while maintaining or improving the durability.

To reduce the magnetic spacing, Fuji Electric is reducing the thickness of the carbon protective film and the lubricative layer, while at the same time, to ensure reliability, is devising film deposition conditions so that the carbon protective film structure becomes denser.

Fuji Electric is also considering the use of additives so that the thickness of the lubricative layer can be decreased without decreasing the durability.

4.4 Substrate technology

Glass substrates are primarily used in the media of HDDs for mobile applications such as notebook PCs, but aluminum substrates are primarily used in the media of HDDs for desktop PCs or external HDDs.

Of these two types of substrates, Fuji Electric is developing, manufacturing and selling aluminum substrates. Ground substrates that have been processed into predetermined dimensions are received from an outside supplier, and in the aluminum substrate manufacturing process, Fuji Electric deposits NiP by a plating technique onto the surface of those substrates, polishes the surface so that it becomes flat, and finally removes residue containing slurry and the like by washing. As recording densities increase, the flying height of the magnetic head becomes lower, and at the same time, quality requirements for the substrate become stricter. Of course flatness and smoothness are required characteristics, and in the washing process, residue of a size greater than the flying height of the magnetic head, i.e., several nanometers, is not allowed. Moreover, flatness of the end areas is also important because the substrate is used up until its edges in order to ensure the full recording capacity of the media. To reduce surface waviness and roughness, Fuji Electric is presently working to optimize the materials selection and processing conditions for the polishing process and to develop a cleaning agent for washing the surface.

5. Future Issues and Outlook

This paper has introduced several new technologies for achieving higher densities. The appearance of these technologies in actual HDD products, however, will be about 1 to 2 years away at the earliest. Until then, endeavors to improve their characteristics must continue using existing technologies. The greatest challenge is considered to be the creation of media that solves the trilemma. Also, some new ideas relating to the HDI will be needed since the technique of simply reducing the magnetic spacing is limited.

Of the next-generation technologies, SWR is thought to be the closest to practical application. Next, TAMR and MAMR are also thought to hold promise. BPM has high potential, but because of several manufacturing process and system related problems, some sort of technical breakthrough is needed before practical applications will become feasible.

In the field of magnetic recording, limits to the improvement of recording densities have often been mentioned, but each time, a breakthrough technology has appeared and constant improvements have continued. This progress is not attributable to the media only, and mechanical technology, signal processing technology, head technology and the like have also contributed greatly, of course. Several candidate technologies for improving the recording density have been described herein, but to realize these technologies, significant changes in the HDD component parts will also be needed. For example, the recording method in the case of SWR and BPM, and the magnetic head design in the case of TAMR and MAMR will change significantly. In the future, not only the pursuit of better media characteristics, but also the identification of technical trends for HDD component parts and the development of technology suited to those trends will become increasingly important.

6. Postscript

Fuji Electric began mass-producing perpendicular media in the spring of 2006, and in just four years has successfully quadrupled the recording capacity per disk. For HDD technology to survive, recording densities must be improved at a pace surpassing that of other types of competing storage technologies such as flash memory and SSDs (solid state drives), and thus there can be no slowdown in future development. Fuji Electric will continue to endeavor to achieve higher densities so as to contribute to the technical advancement and development of a market for HDDs.

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New High Density Recording Technology: High K_u Magnetic Materials

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ABSTRACT

In collaboration with Tohoku University, Fuji Electric has realized the first successful synthesis of a $L1_1$ type CoPt ordered alloy film having a high magnetic anisotropy constant K_u using sputter technique. The K_u value of this material reached a maximum value of 3.6×10^7 erg/cm^3. Moreover, this material is superior to other ordered alloys even if the order is low and the K_u value is high. Also, a ternary alloy formed by adding Ni to this material is capable of maintaining a crystalline structure and a high K_u value over a wide compositional range while controlling the saturation magnetization M_s. For example, with a ternary alloy having the same magnetic characteristics as a binary alloy of rare Pt at 75 at%, the amount of Pt can be decreased to 25 at%.

1. Introduction

The recording densities of perpendicular magnetic recording media have been steadily increasing. Fuji Electric presently produces 2.5-inch disk having the capacity of 320 GB (recording density of approximately 500 Gbits/in^2). To achieve even higher recording densities in the future, several technical challenges must be overcome. Amongst these, the most formidable technical challenge is preventing degradation of thermal stability in the recording bits, even when miniaturized. The expression $K_u V/k_B T$ (K_u: magnetocrystalline anisotropy constant, V: volume, k_B: Boltzmann constant, and T: absolute temperature) has been used as an indicator of thermal stability. In the design of magnetic recording media, the reduction in magnetic grain volume V accompanying miniaturization of the recording bits must be compensated with an increase in K_u, but the K_u value of the Co-Pt magnetic material having a hcp (hexagonal close-packed) structure and being generally used in the recording layer of perpendicular magnetic recording media at present is limited. Therefore, to realize higher densities in the future, new magnetic materials having an extremely high K_u value, in the order of 10^7 erg/cm^3, must be developed.

Typical magnetic materials having such a high K_u value are Co-Pt binary alloys with an $L1_0$ structure. Additionally, ordered alloy films[(1),(2)] of the type known as m-$D0_{19}$, and $L1_1$ type[(3)] Co-Pt ordered alloy films have been reported. Fig. 1 shows a schematic structure of these ordered alloys.

The aforementioned m-$D0_{19}$, and $L1_1$ type ordered alloy films have been reported to be formed at substrate temperatures ranging from 300 to 400 °C[(1)~(4)]. This range is 200 to 300 °C lower than the typical formation temperature of $L1_0$ type Fe-Pt ordered alloy film, which is also a high K_u thin film, and because the manufacturing process temperature can be limited to a low level, this is extremely advantageous for application to magnetic recording media.

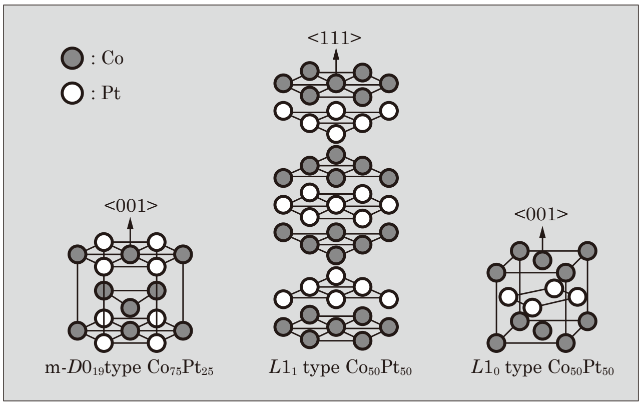

Fig.1 m-$D0_{19}$, $L1_1$ type and $L1_0$ type crystalline structures

However, these m-$D0_{19}$, and $L1_1$ type ordered structures are all metastable phases, and in the major reported cases, were grown epitaxially by MBE (molecular beam epitaxy) on a single crystal substrate in an ultra-high vacuum. These metastable ordered alloys, if they can be formed not by MBE, which is difficult to use in mass-production, but by the sputtering process presently used in the mass-production of magnetic recording media, hold promise as materials having a high K_u value on the order of $L1_0$ type Fe-Pt ordered alloy film.

Fuji Electric, in collaboration with Tohoku University, has applied a UHV (ultra high vacuum) sputtering process to fabricate these m-$D0_{19}$, and $L1_1$ type metastable ordered alloys and has successfully obtained K_u values of 3×10^7 erg/cm^3 or higher[(5)].

This paper presents an overview of the thin film

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structure and magnetic characteristics obtained for $L1_1$ type Co-Pt ordered alloy film, and describes the results of substitution with a third element for use in practical applications.

2. Structure and Magnetic Characteristics

2.1 Structure of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film

Fig. 2 shows X-ray diffraction patterns of $Co_{50}Pt_{50}$ ordered alloy film formed by sputtering on Pt seed layers on top of an MgO (111) substrate and a glass disk substrate. In both cases, the diffraction lines were observed from the close-packed plane only, indicating that the benefit of the $L1_1$ type was ensured, i.e., that the close-packed plane is oriented in parallel to the film surface. Additionally, $L1_1$ (111) plane and $L1_1$ (333) plane diffraction lines resulting from the ordered structure of the $L1_1$ type were observed, confirming the $L1_1$ type crystalline structure of the thin film that was formed.

Fig. 3 shows bright field image of a cross-section of the $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film observed by an electron microscope and electronic diffraction lines of the same region, which is formed by sputtering on a Pt seed layer on top of an MgO (111) substrate. The atomic plane from the Pt underlayer to the $Co_{50}Pt_{50}$ film is formed continuously, showing that a single crystal film is composed by looking the diffraction image.

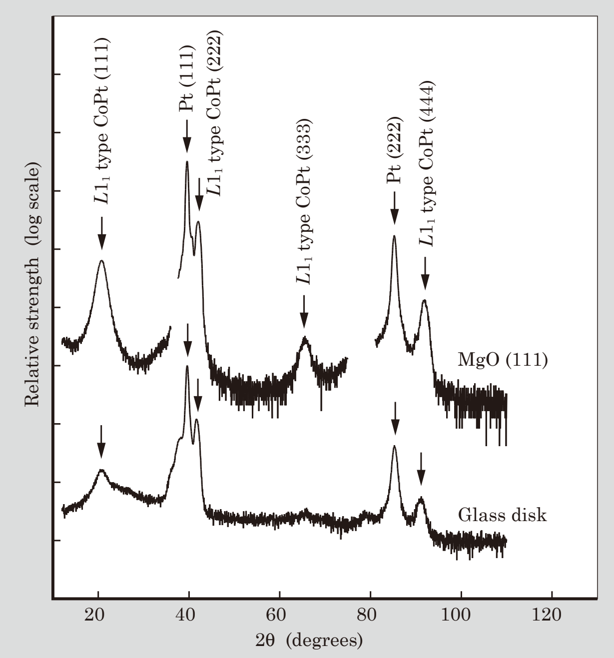

Fig.2 X-ray diffraction patterns of $Co_{50}Pt_{50}$ ordered alloy film formed by sputtering on Pt seed layers on top of an MgO (111) substrate and a glass disk substrate

2.2 Magnetic characteristics of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film

Fig. 4 shows the relationships between the K_u value and the degree of order S (percentage of ordered structure that has been formed) for $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film and m-$D0_{19}$ type $Co_{80}Pt_{20}$ ordered alloy film. As a reference, the results for $L1_0$ type $Fe_{50}Pt_{50}$ are also shown in the figure.

$L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film, despite having a smaller S value than $L1_0$ type $Fe_{50}Pt_{50}$ ordered alloy film, has a K_u value in the order of 10^7 erg/cm^3 and is comparable to that of $L1_0$ type $Fe_{50}Pt_{50}$. Moreover, the K_u value tends to increase rapidly with increasing S, suggesting that the K_u value of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film may exceed that of $L1_0$ type

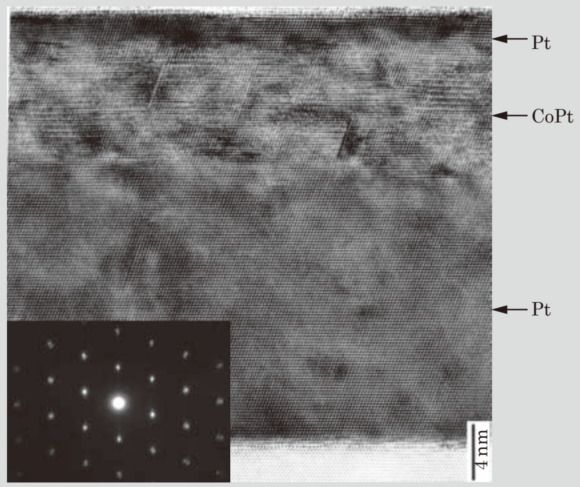

Fig.3 Bright field image of a cross-section of the $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film observed by an electron microscope and electronic diffraction lines of the same region

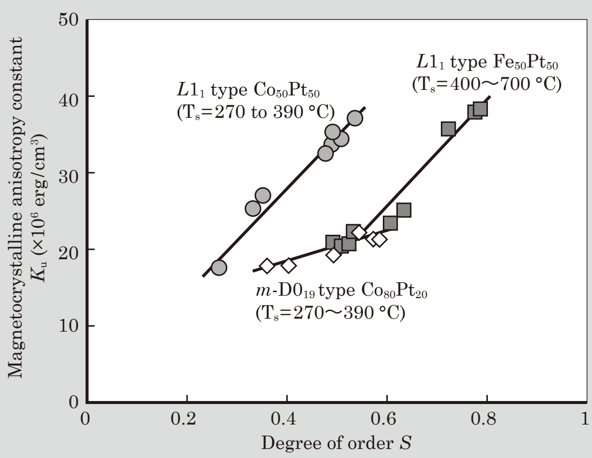

Fig.4 Relationship between K_u and S values of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film and m-$D0_{19}$ type $Co_{80}Pt_{20}$ ordered alloy film

$Fe_{50}Pt_{50}$ ordered alloy film. If $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film having an S value close to the value 1 can be formed, its K_u value is predicted theoretically to be extremely large(6), and this is supported by experimental results.

From a review of the above findings, $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film was confirmed to be a promising material that has the potential to realize a high K_u value as required for higher densities.

3. Control of Magnetic Characteristics by Substitution With a 3rd Element

3.1 $L1_1$ type $(Co_{1-X}Ni_X)_{50}Pt_{50}$ ordered alloy film

When focusing on applications to actual magnetic recording media, a laminated stack structure consisting of a layer with large magnetic anisotropy (hard layer) and a layer with small magnetic anisotropy (soft layer) is often considered for use as the structure of the recording layer. In this case, the saturation magnetization M_s of the hard layer is in the range of 300 to 700 emu/cm^3, indicating that practical thermal stability can be ensured. Consequently, if $L1_1$ type Co-Pt ordered alloy film will be used as the hard layer in a hard/soft stack structure of the future, the M_s value of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film will be approximately 1,000 emu/cm^3. To limit this M_s value to the practical level of 300 to 700 emu/cm^3, the development of a method for controlling M_s is needed while maintaining a high K_u value.

This section describes $L1_1$ type (Co-Ni)-Pt ordered alloy film in which Ni has been substituted for a portion of the Co content in $L1_1$ type Co-Pt ordered alloy film(7).

As a basic experiment, films were deposited on MgO(111) substrates. A Pt seed layers were used for (Co-Ni)-Pt layers, and a protective layer of Pt were deposited on the top of the films. The substrate temperature during deposition of the (Co-Ni)-Pt layer was fixed at 360°C, which is the temperature at which the S and K_u values of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film become maximums.

Fig. 5 shows the X-ray diffraction pattern of $(Co_{1-X}Ni_X)_{50}Pt_{50}$ in the case where the Pt composition is fixed at a stoichiometric composition of 50 at% and an X amount of Ni has been substituted for Co. As in the case of the $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film, because only diffraction lines from the close-packed plane were observed, the close-packed plane was considered to be oriented in parallel with the surface of the film for all Ni compositions. Also, as in the case of $L1_1$ type $Co_{50}Pt_{50}$ ordered alloy film, an $L1_1$ (111) plane indicating the formation of a $L1_1$ type ordered structure is observed in the vicinity of 2θ=21°, and therefore, an $L1_1$ type (Co-Ni)-Pt ordered alloy film is understood to have been formed.

Fig. 6 shows the M_s and S values of these thin films with respect to the X amount of Ni. As the X amount of Ni increases, the M_s value decreases monotonically and is zero for the $Ni_{50}Pt_{50}$ composition. On the other hand, the S value remained nearly constant at 0.5, regardless of the X amount of Ni.

3.2 $L1_1$ type Co-Ni-Pt ordered alloy film

In section 3.1, it was shown that M_s can be controlled by substituting Ni for a portion of the Co. However, because M_s can also be controlled by the amount of Pt, thin films were fabricated for various composition ranges of Co, Ni and Pt, and were examined for changes in their characteristics. The results show that the $L1_1$ type ordered alloy can be fabricated in a wide compositional range where Co is less than about 65 at%. Fig. 7 superimposes S values of the fab-

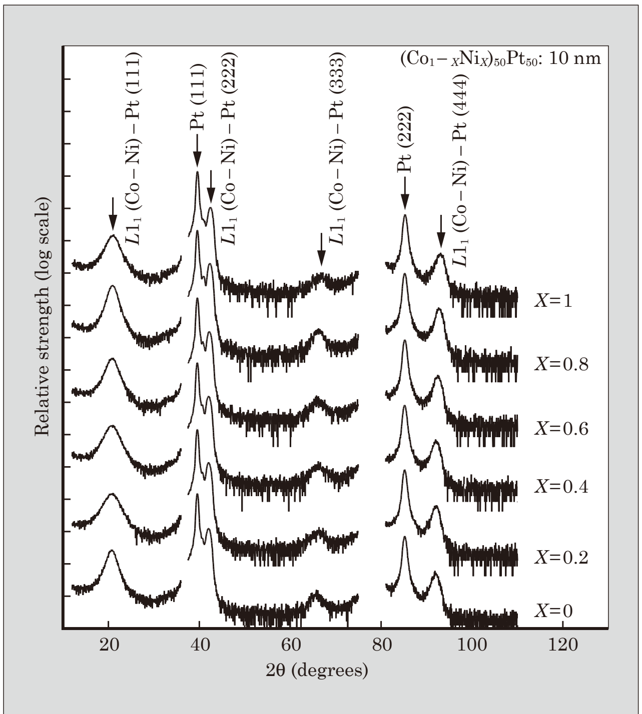

Fig.5 X-ray diffraction pattern of $L1_1$ type $(Co_{1-X}Ni_X)_{50}Pt_{50}$ ordered alloy film

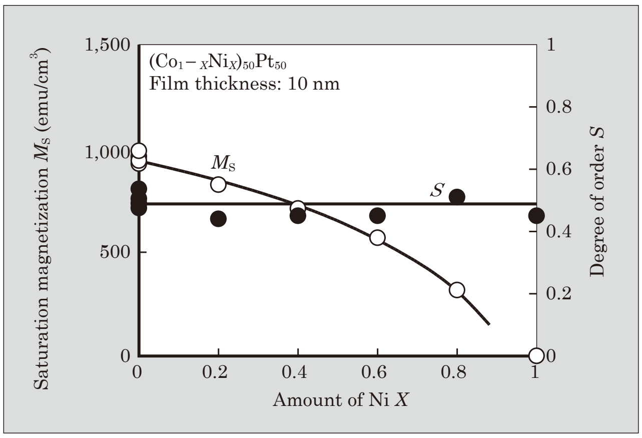

Fig.6 M_s and S values of $L1_1$ type $(Co_{1-X}Ni_X)_{50}Pt_{50}$ ordered alloy film

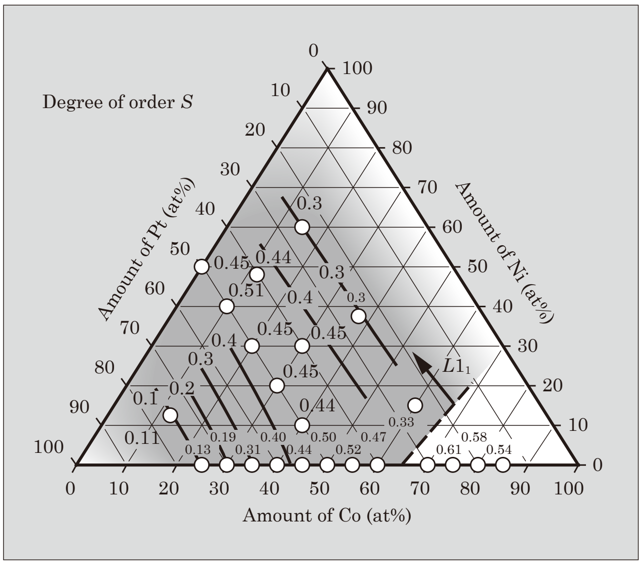

Fig.7 S values of $L1_1$ type Co-Ni-Pt ordered alloy film

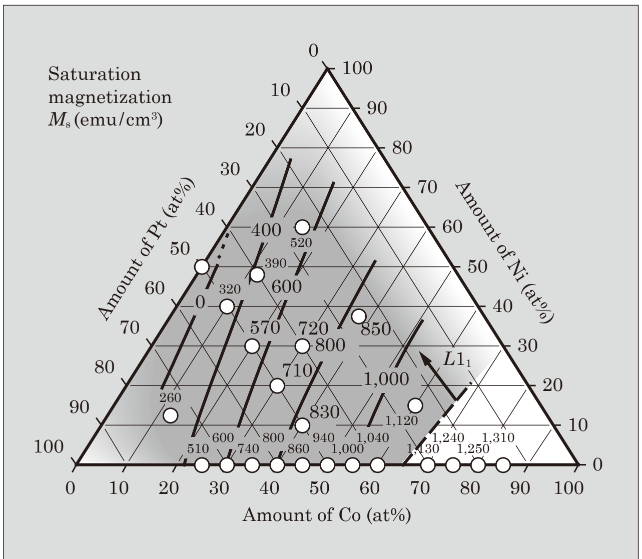

Fig.8 M_s values of $L1_1$ type Co-Ni-Pt ordered alloy film

ricated thin film on a ternary composition diagram. The bottom line of the triangle shows the dependence of the $L1_1$ type Co-Pt ordered alloy on the Pt compositional amount. Looking at the S isolines, the degree of order can be seen to be a maximum in the vicinity of the stoichiometric composition of the aforementioned $(Co_{1-X}Ni_X)_{50}Pt_{50}$ (line from the $Co_{50}Pt_{50}$ point toward the $Ni_{50}Pt_{50}$ point). Furthermore, because the S isolines runs parallel to the Pt composition isolines, the S value can be seen as being determined primarily by the Pt composition. When the Co composition is greater than about 65 at%, m-$D0_{19}$ is formed and the dotted line in the figure indicates the m-$D0_{19}$ phase boundary.

Fig. 8 shows the value of M_s in the same format as that of S shown above. M_s decreases monotonically as the Co composition decreases (Ni composition increases), indicating that M_s can be controlled by the composition.

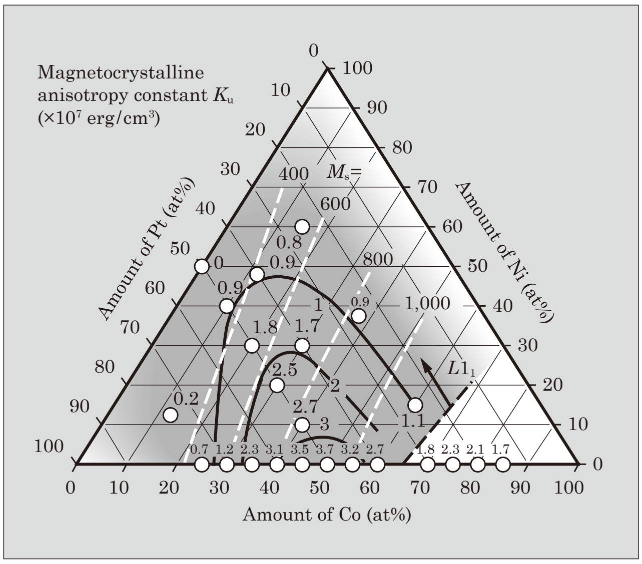

Fig.9 K_u values of $L1_1$ type Co-Ni-Pt ordered alloy film

Table 1 M_s, K_u and S values of representative compositions of $L1_1$ type Co- Pt binary alloys and Co-Ni-Pt ternary alloys

Composition (at%)			Saturation magnetization (emu/cm^3)	Magnetocrystalline anisotropy constant (×10^7 erg/cm^3)	K_u/M_s (kOe)	Degree of order S
Co	Ni	Pt				
50	0	50	940	3.7	39.4	0.5
30	0	70	600	1.2	20.0	0.19
25	0	75	500	0.7	14.0	0.13
20	30	50	570	1.8	31.6	0.45
15	60	25	520	0.8	15.4	0.3

Fig. 9 similarly shows the value of K_u. The M_s isolines are also shown in the figure. The absolute value K_u, as in the case of S, becomes a maximum for the $(Co_{1-X}Ni_X)_{50}Pt_{50}$ composition. On the other hand, in regions displaced away from the stoichiometric composition, the absolute value of K_u can be seen to decrease gradually when the Pt composition is lower, rather than higher. This finding is qualitatively consistent with the results for S.

Table 1 lists representative $L1_1$ type Co-Pt binary alloys and Co-Ni-Pt ternary alloys capable of realizing M_s values in the range of 500 to 600 emu/cm^3, which is suitable for practical applications. When the M_s value is set to approximately 600 emu/cm^3, the K_u value of the binary alloy drops to 1.2×10^7 erg/cm^3. On the other hand, in the case where Ni is substituted to reduce the M_s value, an extremely high K_u value of 1.8×10^7 erg/cm^3 is found to be maintained. Moreover, when the M_s value is set to approximately 500 emu/cm^3, the magnetic characteristics are about the same for both binary and ternary alloys, but a comparison of the amounts of Pt shows that the required amount of Pt has decreased by one-third from 75 at% for the binary alloy to 25 at% for the ternary alloy. That is, the Co-Ni-Pt ternary alloy can realize the same or better magnetic characteristics as the Co-Pt binary alloy, but with a lower Pt composition.

This section has described the $L1_1$ type Co-Ni-Pt ordered alloy film for which the M_s value can be controlled while maintaining a high K_u value. The Co-Ni-Pt ternary alloy forms $L1_1$ type ordered alloy film over a wide compositional range, and in a composition of reduced Pt, which is a rare material, magnetic characteristics that are the same or better than those of the $L1_1$ type Co-Pt ordered alloy film can be realized. This finding indicates that Co-Ni-Pt material is promising as a material for the hard layer in future hard/soft laminated type media.

4. Postscript

If recording densities keep the current pace of increase, the mass-production of magnetic recording media requiring K_u values in the order of about 10^7 erg/cm^3 as exhibited by this material is expected to begin around 2013. For this purpose, Fuji Electric will continue to address future challenges with a sense of urgency.

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New High Density Recording Technology: Energy Assisted Recording Media

Yuki Inaba † **Hitoshi Nakata** † **Daisuke Inoue** †

ABSTRACT

Energy assisted recording, is a next-generation high-density recording technology. This method enables writing even in the case of a low magnetic field by providing external energy to a recording layer, onto which the writing of signals has been difficult at room temperature. Fuji Electric is evaluating two methods of energy assisted recording; thermally assisted magnetic recording and microwave assisted magnetic recording. With thermally assisted magnetic recording using laser light as a heat source, an approximate 3 dB improvement in the SN ratio was confirmed and the inherent feasibility was verified. As material for this application, the coercive force temperature gradient of Co-based materials was improved to −85 Oe/K from the prior value of −15 Oe/K. With microwave assisted magnetic recording, the Pt in Co-Pt was replaced with another element, and a material having a low damping factor is being developed.

1. Introduction

There has been explosion of various information including images and music in our daily lives. In order to store such information, the recording density of the magnetic recording media used in hard disk drives (HDDs) has been increasing at a rapid annual rate of about 40%. In 2010, the recording density achieved at the research level is expected to exceed 1 Tbits/in^2 (equivalent to approximately 1.3 TB per 3.5-inch hard disk).

To realize recording densities higher than 1 Tbits/in^2, the mutually conflicting "trilemma" of reducing media noise, improving thermal stability (long-term reliability) of recorded information, and ensuring the ease of writing must be resolved. Improved noise reduction and thermal stability, in particular, lead to an increase in the coercivity H_c of the media. If the H_c value is greater than the maximum magnetic field that can be output from the existing magnetic recording head, the magnetic field will be insufficient for writing signals, and the signal quality will deteriorate.

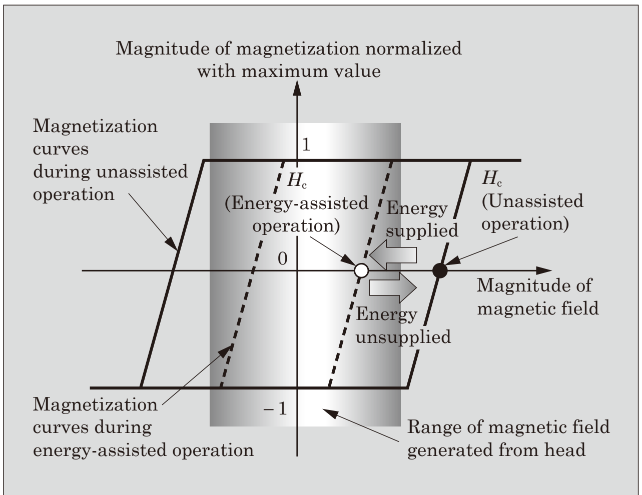

Fig.1 Concept of energy-assisted magnetic recording

As shown in Fig. 1, energy-assisted magnetic recording methods, whereby energy in some form is provided externally, the H_c value when writing signals is made smaller, signal writing is assisted, and the ease of writing is enhanced, are being studied actively to resolve this problem. Of these methods, thermally-assisted magnetic recording and microwave-assisted magnetic recording are introduced in this paper, and the present status of Fuji Electric's media development is discussed with a focus on improving the ease of writing to magnetic recording media.

2. Thermally-Assisted Magnetic Recording Media

2.1 Overview

The H_c value, which determines the ease of writing a signal to the magnetic recording media, is itself determined by the magnetocrystalline anisotropy energy that indicates the strength with which the magnetization attempts to align in one direction. This H_c value differs according to the magnetic material of the recording layer, and decreases with increasing temperature. Accordingly, if the recording layer is heated, the energy barrier that must be overcome in order to reverse the direction of the magnetization will drop, and signal writing will become easier. The thermally-assisted magnetic recording method is a signal writing method that utilizes this characteristic and applies heat only when writing. Fuji Electric is using computer simulations and the like to develop suitable media layer structures and materials.

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2.2 Present status of thermally-assisted magnetic recording media development

Fuji Electric has modified the recording head of a device (spin stand) for evaluating the playback performance of actual HDDs by adding a heating laser (wavelength = 830 μm) having a spot diameter of 10 mm, and is conducting proof-of-principle testing of thermally-assisted magnetic recording. Fig. 2 shows overwrite and playback signal output measurements when the laser power is varied during signal recording in order to vary the temperature while recording. Values of the playback signal output are shown normalized to the output value in the state without an incident laser. The overwrite characteristic shows, when a high-frequency signal having been pre-recorded and then overwritten with a signal having a lower frequency than the previous signal, the extent to which the previously recorded signal has been erased, and is generally used as an indicator of the ease of writing to media. In the experiment, perpendicular magnetic recording media in which film had been deposited on only the front surface of a glass substrate was used, and laser light was irradiated from the back surface of the glass substrate to heat the recording layer and the like, and recording was performed with a magnetic head positioned at the front side of the substrate. Additionally, so that only the thermally-assisted effect would be measured in this experiment, the current flowing through the writing head was not varied so that the magnetic field from the head would be held constant. In the case of no laser irradiation (equivalent to 0 mW), i.e., when a signal is written without heating the media, the signal strength of the overwritten output was approximately −13 dB, but as the laser power increases, the ease of writing improves, and at a laser power of 130 mW, a value of −28 dB was attained. Because of the increased ease of writing to the media, the playback signal output was also found to increase, thereby verifying the thermally-assisted effect resulting from a rise in temperature.

Fig. 3 shows the results of SNR (signal-to-noise ratio) measurements when the laser power is varied during signal recording so as to cause the temperature to vary during recording. The SNR was found to improve with increasing laser power. This behavior is thought result from the increased ease of writing signals to media. Heating with 130 mW of laser power results in a 3 dB improvement compared to a record and playback system in which laser power is not applied. The obtained results clearly show the thermally-assisted effect, thus completing the proof-of-principle testing.

Further study is needed before thermally-assisted magnetic recording media can be used in practical applications, however. Fig. 4 shows the layer structure of the present magnetic recording media without energy assistance, and of the magnetic recording media

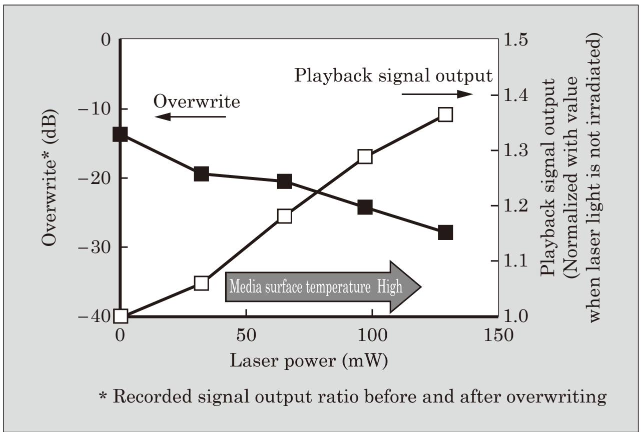

Fig.2 Changes in overwrite and playback signal output according to laser power

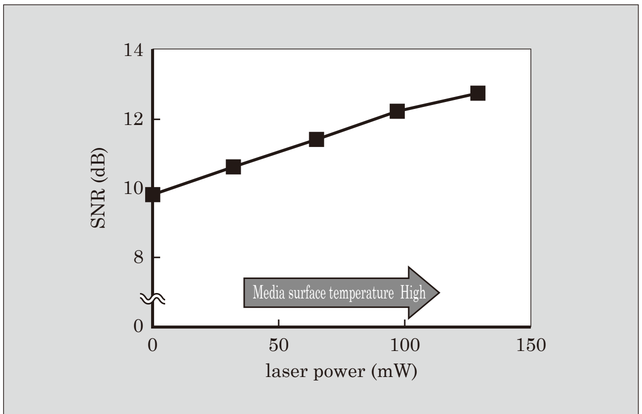

Fig.3 Change in SNR vs. laser power

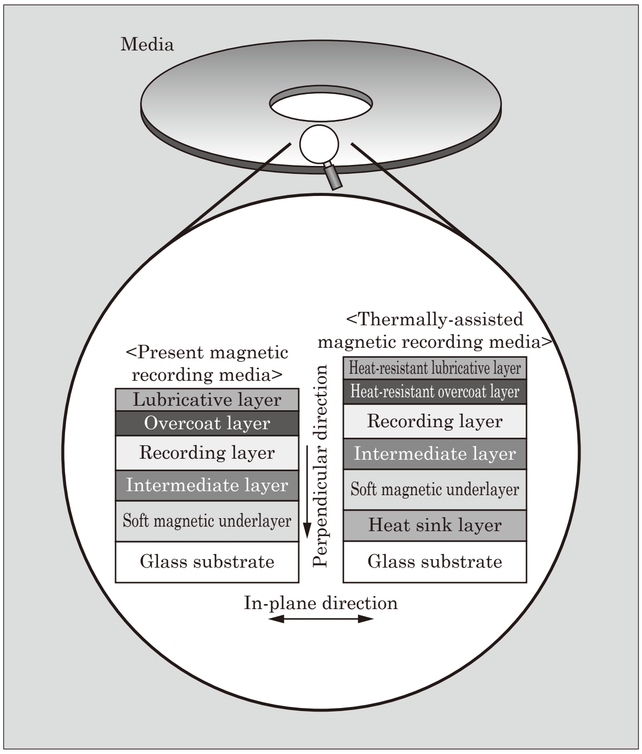

Fig.4 Configuration of thermally-assisted magnetic recording media

under development for thermally-assisted magnetic recording. The design of thermally-assisted magnetic recording media must build upon previous media designs and incorporate new design guidelines for light and heat. So that the recording layer can be heated with good efficiency, not only must the reflectivity be suppressed to a small value and the efficiency of heat absorption from the heating light increased, but other improvements such as providing a heat sink layer to release heat from the recording layer after the recording is complete are also needed. Additionally, improving the thermal resistance of the lubricative layer and the overcoat layer is also an important topic. The upper limit of temperature used with thermally-assisted magnetic recording is determined chiefly by the heat-resistant temperatures of those materials. To achieve the thermally-assisted effect at low-temperatures, the material of the recording layer is desired to have a low Curie temperature and to exhibit a large rate of decrease of the H_c value in response to increasing temperature.

An example of the materials development being undertaken at Fuji Electric is described below. Fig. 5 shows the H_c temperature gradient dHc/dT versus a process parameter. In this paper, the thermally-assisted ease of writing is expressed by the rate of decrease of H_c, and therefore values are expressed as negative numbers, with the assist effect becoming larger as the absolute value increases. The temperature gradient of the Co-Pt-Cr recording layer material used in the non-assisted magnetic recording media presently being mass-produced is −15 Oe/K at most. To limit the value of H_c during heating to less than the maximum magnetic field of the write head, the heating temperature must be rather hot, but this is not suitable for practical use. For large H_c temperature gradient materials, such as Fe-Pt-Cu (−180 Oe/K[1]) and Tb-Fe-Co (−240 Oe/K[2]), that have been studied so far, the thin film deposition temperature has been high, which would make mass-production difficult, and refining of the crystalline grains would also be difficult.

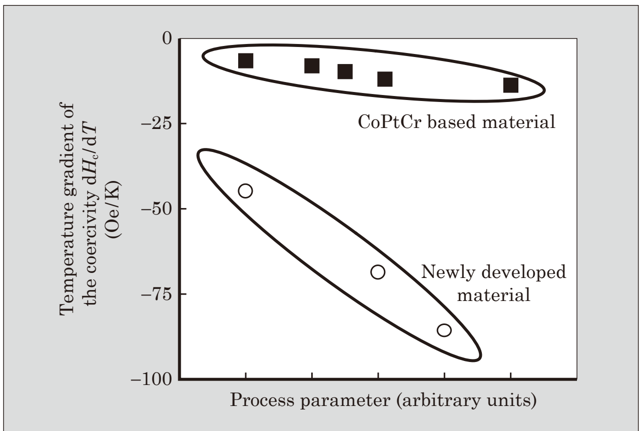

Fig.5 Comparison of the temperature gradient of coercivity for CoPtCr based material and new developed material

Furthermore, because good recording and playback characteristics cannot be obtained, these materials are not considered to be suitable for the recording layer of the media, and have not yet to be commercialized. On the other hand, as shown in Fig. 5, the Co-based new material developed by Fuji Electric exhibits a temperature gradient of more than 3 times that of conventional Co-Pt-Cr material and, at certain process parameters, reaches −85 Oe/K. If the new material is used in the same temperature region as is conventional materials, H_c will be decreased effectively and a high thermally-assisted effect can be expected.

Using media that incorporates this newly developed material, Fuji Electric plans to evaluate thermally-assisted magnetic recording and playback characteristics.

3. Microwave-assisted Magnetic Recording Media

3.1 Overview

In 2007, Zhu et al. proposed, as a novel type of energy-assisted magnetic recording, a microwave-assisted magnetic recording method whereby, instead of thermal energy, an AC magnetic field of high frequency (microwave frequency in the GHz band) is applied to the recording layer to improve the ease of writing[3],[4]. This method, as shown in Fig. 6, applies an AC magnetic field in a microwave band that matches the ferromagnetic resonance frequency of the recording layer material such that the magnetization tilts away from the direction of the easy axis of magnetization, and drives the precession (oscillating movement) of the magnetization, thereby assisting in the magnetic reversal. In principle, the absence of the necessity for significant changes to the configuration of present unassisted media is a large advantage. Presently, research involving both simulations and experiments is being advanced throughout the world mainly by universities.

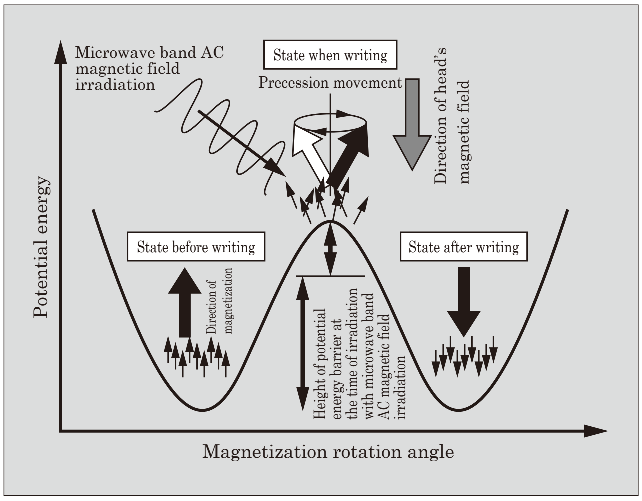

Fig.6 Principles of microwave-assisted magnetic recording

The principles of microwave-assisted magnetic recording have been announced only relatively recently. Verification of assisted magnetization reversal in a magnetic thin film using a microwave-band AC magnetic field was first reported in 2007 using Ni-Fe, which is a soft magnetic material(5). Then, in 2009, assisted magnetization reversal using Co/Pd multilayer film having perpendicular magnetic anisotropy was reported(6). Research of the latter has continued, especially as a material for perpendicular magnetic recording media. As a result of this report, the effectiveness of applying microwave-assisted magnetic recording to perpendicular magnetic recording media has become clear and this technology has attracted attention. Currently, efforts to apply microwave-assisted recording to perpendicular magnetic recording media are accelerating.

3.2 Present status of microwave-assisted magnetic recording media development

Generally, when an external magnetic field is applied to change the direction of magnetization in magnetic material, the magnetization begins a precession motion (oscillation) as shown in Fig. 6. With the passage of time, the angle of oscillation becomes larger, and finally the magnetization becomes aligned in the same direction as the applied magnetic field and the reversal is complete. In the magnetic material, a force acts to align the oscillating magnetic field in the direction of the applied magnetic field, and the strength of that force is called the damping constant. The damping constant is an intrinsic value of the magnetic material, and as the value of damping constant decreases, the reactivity to externally applied microwaves increases and the assisted reversal effect becomes greater as a result. Accordingly, in the development of materials for the microwave-assisted magnetic recording magnetic layer, materials having a small damping constant must be investigated.

As the recording layer material presently used in perpendicular magnetic recording media, hcp-CoPt based alloy material is actively being studied, and by varying the amount of Pt to adjust the magnetic anisotropic energy, long-term stability of the recorded signal can be ensured. Additionally, ordered alloy based materials such as Co-Pt and Fe-Pt, which have ordered structures on the atomic layer level, hold promise as materials that exhibit large magnetic anisotropic energy for next-generation high-density media. The Pt contained in these materials has a large orbital magnetic moment, however, and experiments have shown that the damping constant tends to increase due to the spin-orbit interaction, making these materials unsuitable for microwave-assisted magnetic recording media. Fuji Electric is moving ahead with the development of magnetic material using an element that can substitute for Pt to lower the damping constant and that is able to maintain the same characteristics as existing media. The ultimate aim is the application to recording media of a material that uses less of the scare resource of Pt.

4. Postscript

Fuji Electric continues to study how to use energy-assisted magnetic recording in order to provide magnetic recording media having a recording density of greater than 1 Tbits/in^2. Media material development, with a different approach than before, is needed for both thermally-assisted magnetic recording and microwave-assisted magnetic recording methods. Through working ever more closely with not only the materials development department, but also with the simulation department and outside agencies, Fuji Electric is committed to promoting the early realization of energy-assisted magnetic recording media.

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Magnetic Technology for Perpendicular Magnetic Recording Media

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ABSTRACT

This paper describes three technologies for the recording layer, intermediate layer and soft magnetic underlayer, developed to increase the recording density of perpendicular magnetic recording media. The design and development of an optimal structure for a new multilayer magnetic recording layer constructed from four functionally-separated layers has enabled an increase in track density. A new material of an intermediate layer was developed. The magnetic grain sizes of the magnetic recording layer on the intermediate layer and the distribution of the grain sizes were reduced. The crystalline orientation was also improved. Materials having a high saturation magnetic flux density have been newly developed for the soft magnetic underlayer. The application of these materials has resulted in improved electromagnetic conversion characteristics.

1. Introduction

The recording density of magnetic recording media continues to increase by approximately 40% per year. At present, recording densities of up to approximately 500 Gbits/in^2 have been commercialized. Recording densities of 1 Tbits/in^2 are expected to be achieved at the research level during 2010. Further, it is thought that a new recording method will be needed for recording densities higher than about 1 Tbits/in^2. Fuji Electric has set a goal of achieving 1 Tbits/in^2 with the current method, and is advancing the technical development of magnetic recording media.

Fig. 1 shows the structure of a hard disk drive (HDD) and magnetic recording media. The magnetic recording media is fabricated by sequentially depositing an alloy film, a carbon overcoat layer and a lubricative layer, each having a film thickness ranging from several to several tens of nanometers, onto a substrate having a thickness of approximately 1.0 mm. The alloy film in a multilayer structure contains a magnetic recording layer consisting of magnetic material for retaining information. The alloy film used in recent magnetic recording media consists of about 10 layers, and has become complicated. Magnetic technology is the general term for the technology used in designing the alloy film layer structure in order to increase the areal density.

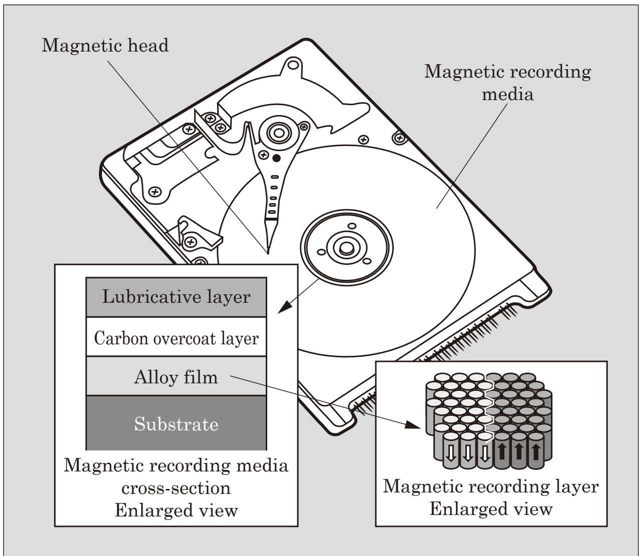

Fig.1 HDD and magnetic recording media structure

This paper describes the technical challenges for realizing higher recording densities (section 2) and topical improvements that have been made to overcome those challenges (section 3).

2. Technical Challenges for Higher Density

To increase the recording density, the performance of the recording layer that forms the recording bits must be improved. Specifically, the magnetic crystalline grains arranged in a columnar structure and dispersed throughout the recording layer should have a small uniform size of several nanometers and their crystalline orientation should be improved to enhance resistance to thermal energy. As a result, large capacity and long-term data retention will be possible. However, if such a method is used to control the recording layer characteristics, typically, the coercivity H_c increases and a large magnetic field is required for magnetization reversal. The recording of “1” and “0” digital signals requires that the direction of magnetization be reversed by 180 degrees, and therefore a magnetic head that generates a field greater than the coercive

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force must be used for the recording. Because there is a limit to the magnetic field that can be generated by a magnetic head, a design simply based on the aforementioned guidelines would not be successful. To overcome this technical challenge, Fuji Electric is actively researching[1] a multilayer recording structure known as the ECC (Exchange-Coupled Composite) structure[2] and is applying this technology as a solution.

On the other hand, the formation process for recording bits is significantly affected by the distribution of the recording magnetic field of the magnetic head. The head's magnetic field that is incident on the recording layer is ideally perpendicular with respect to the film surface. As a result, a sharp recording transition (border with adjacent bits) is formed and good signal quality can be ensured. For this purpose, the distribution of the head's magnetic field incident upon adjacent recording tracks that are formed in concentric circles in an HDD must be suppressed. If the magnetic field component in the cross-track direction is large, the signal strength of pre-recorded adjacent tracks will leak, and the magnetic field will be attenuated. Thus, the track density cannot be increased, and as a result, the areal density does not increase. The magnetic field distribution is largely determined by the magnetic head structure, but the media structure can be devised for optimized control.

In general, the easy axis of magnetization is the direction in which magnetization is stable, and depends on the crystalline structure of the magnetic material. With perpendicular magnetic recording media, the easy axis of magnetization is perpendicular to the film surface. Magnetic film that is magnetized in the direction of the easy axis exhibits the property whereby coercivity H_c decreases as the applied magnetic field tilts with respect to the easy axis of magnetization. Therefore, since magnetization reversal occurs more easily for an oblique magnetic field, not only must the distribution of the head's magnetic field be controlled, but resistance to the oblique component of the recording layer itself must be increased.

The aforementioned technical challenges for magnetic recording media can be summarized as follows.

(a) Improvement of the basic performance of the recording layer (crystalline orientation, refinement and uniformity of grain size)
(b) Ensuring write capability (optimization of ECC structure, etc.)
(c) Formation of a sharp recording transition (control of distribution of magnetic field of head)
(d) Less signal strength attenuation at adjacent recording tracks (improved resistance to oblique magnetic field components)

3. Magnetic Technology Development Statuses

3.1 Design of multilayer magnetic recording layer

As shown in Fig. 2(a), the typical media layer structure consists of three layers: a recording layer, an intermediate layer and a soft magnetic underlayer. Additionally, the recording layer consists of multiple layers separated by function. In a conventional recording layer, a three-layer ECC structure consisting of a hard layer (hard magnetic layer), a coupling force control layer and a semi-hard layer (semi-hard magnetic layer) is used. A method for optimizing the magnetic coupling force between the hard layer and the semi-hard layer is used with the ECC structure.

The hard layer is provided for the purpose of increasing the recording density described above. The hard layer has a high H_c value and the magnetic head cannot write to the hard layer as a single layer. With an ECC structure, a semi-hard layer having a low H_c value is also provided, and a coupling force control layer is positioned between the hard layer and the semi-hard layer to implement control by weakening the magnetic coupling force. The applied magnetic field

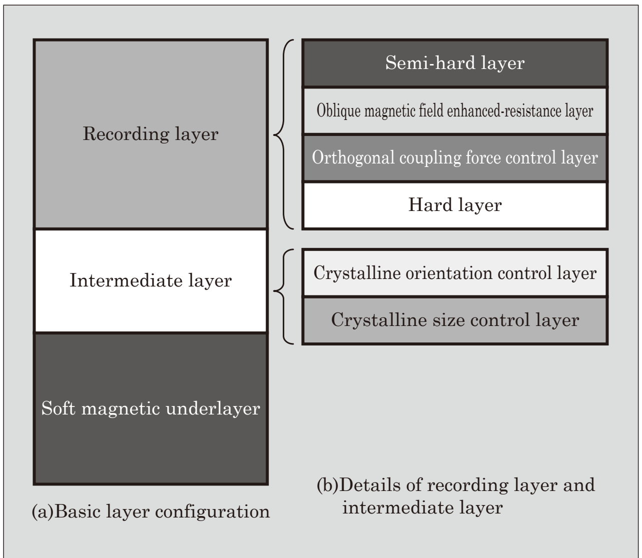

Fig.2 Basic layer configuration and details of media

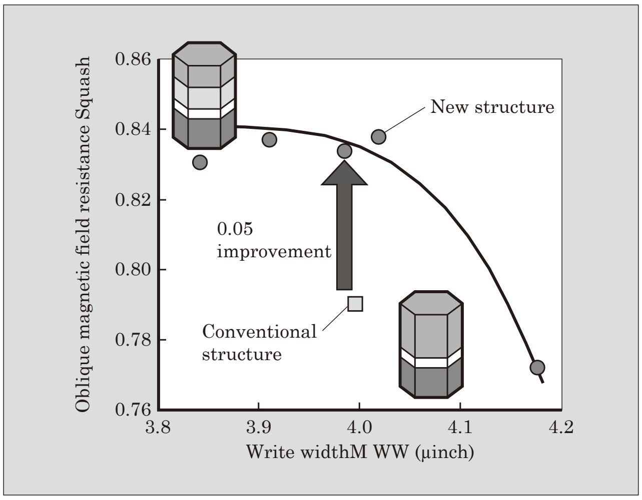

Fig.3 Improvement in oblique magnetic field resistance resulting from use of new structure

Table 1 Comparison of properties of the recording layer (hard layer) micro-structure according to intermediate layer (crystalline grain size control layer) material devices

Intermediate layer material	Avg. grain size (nm)	Average grain boundary width (nm)	Grain size variation (%)	orientation distribution $\Delta\theta_{50}$ (degrees)
Conventional	5.9	1.4	23	2.7
New	5.7	1.8	19	2.5

induces magnetization reversal in the hard layer and the semi-hard layer semi-independently. As a result, the overall H_c value decreases and writing capability increases. By using this type of ECC structure, the requirements of "(b) Ensuring write capability" described above in section 2 have been satisfied.

Meanwhile, in some cases the width of the magnetic field distribution in the cross-track direction due to the magnetic head is large, and measures for "(d) Less signal strength attenuation at adjacent recording tracks" as described in section 2 must be strengthened. Therefore, the new oblique magnetic field enhanced-resistant layer shown in Fig. 2(b) was introduced. The effect of this new layer is shown in Fig. 3. A read/write (R/W) evaluation was performed using a standard tester. After writing several times to both sides of the recording track, the output from the recorded track was measured, and the output value, normalized with respect to the initial output, is shown as the oblique magnetic field resistance (Squash characteristic) on the vertical axis of figure. The horizontal axis of the figure indicates the write width. In general, as the write width becomes narrower, the crosstalk decreases and the Squash characteristic increases. When compared with the same write width, a large improvement (0.05 increase) in the Squash characteristic from 0.79 to 0.84 was realized when a recording layer with the new structure was used.

Measured simultaneously, the overwrite (OW) characteristic and signal-to-noise ratio (SNR) were the same, thereby indicating that the Squash characteristic was improved without degrading the write capability or the signal quality. Because the track density could be increased while maintaining the performance (linear recording density) in the down-track direction, the areal density can be increased. Presently, aiming for further improvement, the material and composition of various magnetic layers, especially the oblique magnetic field enhanced-resistant layer, are being optimized.

3.2 Microstructural control enabled by the intermediate layer

The overall performance of a recording layer is determined not only on the design of the multilayer structure, but also largely by the composition of the magnetic layers included therein and the processes used. Additionally, the grain size and the crystalline orientation depend significantly on the microstructure of the layer immediately below[3]. As discussed above, the resistance to thermal energy must be increased by making the grains finer and uniform in size, and improving their crystalline orientation. A tradeoff relation generally exists between making the grains finer and improving the crystalline orientation. However, both of these factors must be improved simultaneously. The intermediate layer plays an important role in improving this tradeoff relation. The reason for calling this layer the intermediate layer is because it acts as a non-magnetic layer that divides the magnetic coupling between the soft magnetic underlayer and the recording layer. Actually, its function as an underlayer for the recording layer, as described above, is extremely important. As in the case of the recording layer, the intermediate layer is presently divided according to function and basically has a two-layer structure consisting of a layer for grain control and a layer for control of the crystalline orientation (see Fig. 2).

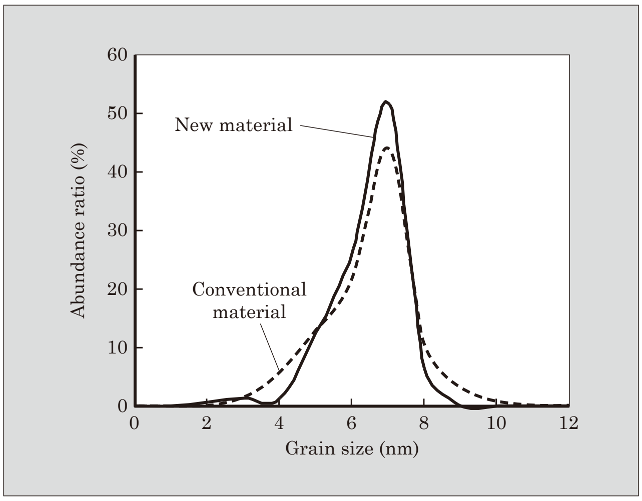

Fig.4 Change of grain size distribution in recording layer according to intermediate layer material

An example of the use of new material in the crystalline grain control layer to realize an improved microstructure of the recording layer (hard layer) is presented below. The grain size and the like were analyzed using a transmission electron microscope (TEM) and the crystalline orient was analyzed using an X-ray diffraction apparatus. Table 1 compares properties relating to the recording layer microstructure when conventional and new materials are used. By using the new material, the average grain size decreased from 5.9 nm to 5.7 nm, the average grain boundary width increased from 1.4 nm to 1.8 nm, and the variation in grain size decreased from 23% to 19%. The orientation

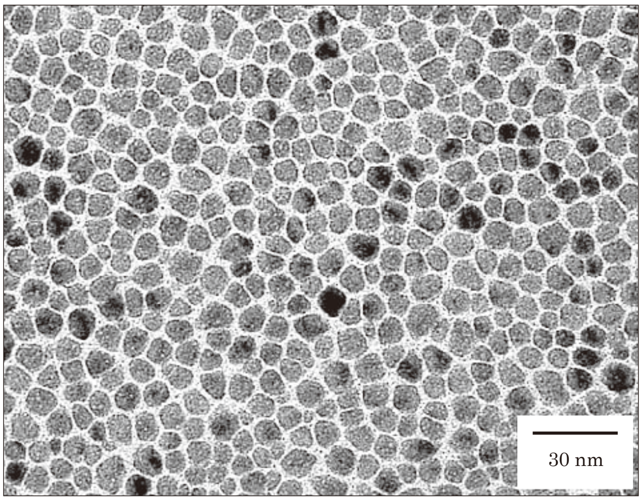

Fig.5 Plan-view TEM image of recording layer using new material

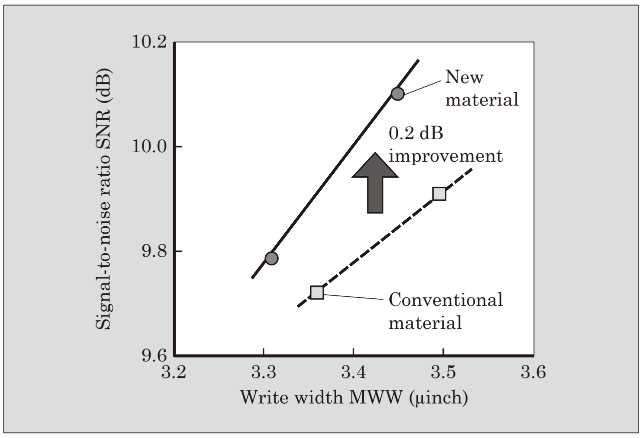

Fig.6 Change in SNR according to soft magnetic underlayer material

distribution $\Delta\theta_{50}$ decreased from 2.7 to 2.5 degrees, and the crystalline orientation also improved at the same time. Particularly noteworthy in this result is that the variation in grain size improved by 4 percentage points. Fig. 4 shows the change in grain size distribution in the recording layer for each intermediate layer material. Previously, many micro-grains of about 4 nm in size and large grains of about 9 nm in size co-existed, but with the change to the new material, the distribution width is found to have narrowed. Fig. 5 shows a plan-view TEM image of a recording layer that uses the new material. Fuji Electric has been actively developing this recording layer material based on (Co-Pt-Cr)-SiO_2.

The uniform distribution of grain size can be considered to be a significant effect of the new material. That is, this example achieves "(a) Improvement of the basic performance of the recording layer" described in section 2.

3.3 Improvement of recording performance with soft magnetic underlayer

For controlling the distribution of the magnetic field, the thickness of each layer and the properties of the materials used in the soft magnetic underlayer are important factors in the design of the media. While limiting the distribution of the magnetic field generated from the magnetic pole of the magnetic head, the magnetic field must be drawn-in sharply toward the soft magnetic underlayer and returned to the return yoke. By shortening the distance between the magnetic head and the soft magnetic underlayer, the magnetic field gradient increases. Considering that this distance affects the performance during playback[4] and that the thickness of the intermediate layer and the recording layer affect the magnetic properties (such as H_c, for example) of the recording layer, the actual design range of film thickness is limited.

Meanwhile, the soft magnetic underlayer is required to exhibit the properties of excellent flatness, high saturation flux density B_s and high permeability. Flatness affects the crystalline orientation of the intermediate layer and the recording layer that are formed above the soft magnetic underlayer. A large surface roughness is directly related to the deterioration of the crystalline orientation. By realizing the magnetic properties of a high B_s value and high permeability, as discussed above, the magnetic field distribution can be controlled. This paper introduces an example of a new material that realizes both a relatively high B_s value and good flatness.

Fig. 6 compares the SNR versus write width for soft magnetic underlayers that use the conventional material and new material. For the same recording width, the new material shows a 0.2 dB improvement in SNR. In this case, the OW characteristic, the Squash characteristic and other characteristics exhibit the same or improved performance. The new material shows the same flatness and an approximate 15% improvement in the B_s value compared to the conventional material, and this effect is thought to be reflected in the R/W characteristics. Of the technical challenges described in section 2, the above results are thought to be particularly applicable to the improvement of "(c) Formation of a sharp recording transition" and also to contribute to improvement of items (b) and (d).

4. Postscript

Design guidelines for the recording layer, intermediate layer and soft magnetic underlayer have been described and examples of improvements have been presented. To meet the challenges for achieving higher density, improvements must be implemented appropriately for the magnetic head of each successive generation of technology. Meanwhile, one anticipated method that may replace the conventional recording method is the "shingled-write recording" method. This method is said to have the potential to attain a 10 Tbits/in^2 recording density[5]. Fuji Electric has also begun to design recording layer structures that use this method. Fuji Electric will continue to develop new materials and process technologies in an attempt to reach the recording density limit.

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HDI Technology for Perpendicular Magnetic Recording Media

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ABSTRACT

To reduce the magnetic spacing and improve media characteristics, (1) a thinner carbon protective film and thinner lubricant layer, and (2) a lower magnetic head flying height are necessary. However, reducing the thickness of the protective film and the lubricant layer causes a significant deterioration in such reliability-related characteristics as corrosion resistance and durability. Thus, Fuji Electric controls the film properties of the protective layer so as to improve the corrosion resistance and sliding durability simultaneously with a reduction in the thickness. By controlling the molecular weight and composition of the PFPE (perfluoropolyether) used in the lubricant layer, and developing additives and post-processing technology, a thinner film with higher reliability can be realized. Additionally, while developing technology for evaluating the flying characteristics of the HDI (Head Disk Interface), Fuji Electric has been reducing the magnetic spacing.

1. Introduction

The hard disk drive (HDD) is an inexpensive storage device capable of handling large amounts of information quickly, and a market has been established for HDDs as external storage for computers. This market, which is also driven by new applications, is expected to expand more and more in the coming years.

The magnetic recording media provided in HDDs has achieved remarkable increases in density. Fuji Electric, in 2009, mass-produced media having a storage capacity of 500 GB per 3.5-inch disk, and then in 2010, developed 750 GB capacity media which will be released to the market.

At the HDI (Head Disk Interface) between the magnetic head and media surface, the main functions of the carbon protective film and the lubricant layer, which are important elements in the media, are to prevent corrosion of the magnetic layer and the like, and to protect the magnetic layer from wear due to the magnetic head. Additionally, the lubricant layer is also required to suppress lubricant pick-up by the magnetic head, enable lower flying height of the magnetic head and to improve flying stability. To support the rapidly increasing high recording densities of the future, the magnetic spacing (flying height+lubricant layer thickness+carbon protective film thickness), i.e., the distance between the magnetic head element and the magnetic layer surface, must be reduced as much as possible. Incidentally, the flying height is 2.5 to 3.0 nm for a 500 GB capacity disk at 3.5 inch disk, and 2.5 nm or less for a 750 GB capacity disk. To reduce the magnetic spacing and increase the recording density, (1) the carbon protective film and the lubricant film must be made thinner, and (2) the flying height of the head must be reduced. In attempting to do so, however, the following problems and issues arise.

If the protective layer is made thinner, the corrosion inhibiting function decreases. The technical challenges to overcome in order to solve this problem include devising more appropriate deposition conditions for the carbon protective layer, and increasing the film density of the carbon protective film structure.

If the lubricant layer is made thinner, the frictional durability with respect to the magnetic head deteriorates significantly. Therefore, advancing the development of lubricant additives for improving frictional durability, and reducing the amount of lubricant pick-up by the magnetic head slider surface, which results in a trade-off with the ensuring of durability, are important issues.

Moreover, in recent HDDs, not only has the flying height of the slider been reduced, but the magnetic heads employ technology whereby thermal expansion causes just the magnetic head element to approach the media side. This technology is known as DFH (Dynamic Flying Height) technology, TFC (Thermal Flying-height Control) technology, FOD (Flying on Demand) technology, and so on. In this paper, however, the technology discussed is called as FOD.

In accordance with Fuji Electric's recent field tests, a thinner lubricant layer was found to be especially effective for making the magnetic head element protrude farther with FOD technology.

This paper introduces recent approaches for attaining higher recording densities from the perspective of HDI technology, and the development status of the increasingly sophisticated carbon protective film and lubricant layer, and the development status of HDI evaluation technology (flyability, reliability) from the perspective of ensuring reliability technology which involves a trade-off with higher recording densities.

† Fuji Electric Device Technology Co., Ltd.

2. Carbon Protective Film Technology

2.1 Goals and challenges of carbon protective film

Carbon protective film provides three representative functions: (1) corrosion resistance, (2) shock resistance (surface hardness), and (3) sliding wear durability. These are important functions for protecting the magnetic layer and the like. If the carbon protective film is made thinner in order to reduce the magnetic spacing, its function will deteriorate. Carbon protective film development faces challenges including achieving a uniform distribution of the thickness of the carbon protective film, realizing the high-rate of deposition required for mass-production processes, and reducing particles, etc.

2.2 Carbon protective film development status

Carbon protective film has a two-layer construction consisting of a high-density layer and a stabilization layer. The high-density layer formed on the magnetic layer functions to protect the magnetic layer, and the stabilization layer formed on the high-density layer functions to stabilize the lubricant layer. By making the high-density layer more dense and making the stabilization layer thinner, corrosion resistance and sliding durability have been improved and the magnetic spacing has been reduced.

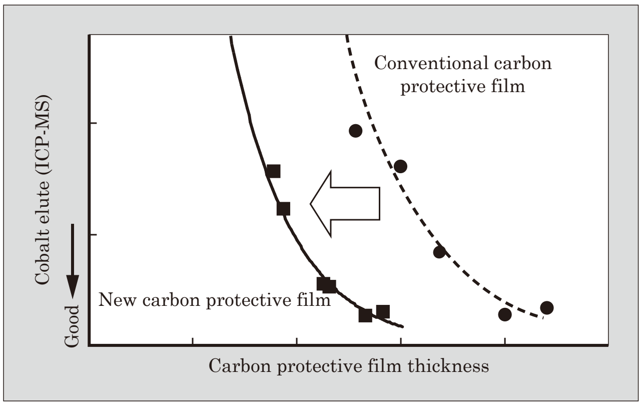

Fig.1 Test and evaluation results of cobalt elution by acid

The high-density layer in the carbon protective layer is fabricated by plasma CVD (Chemical Vapor Deposition). Carbon film formed by CVD exhibits excellent coverage of the magnetic layer and this is especially important because of the surface reaction that accompanies the film fabrication. Additionally, the film quality can be controlled by controlling the ion energy. By optimizing the deposition process, denser and harder film can be formed. Moreover, in the fabrication of the stabilization layer, a new process for improving adhesion with the lubricant was used to realize a thinner film.

The results of a comparison between the newly developed carbon protective film and existing carbon protective film are listed below.

(1) Corrosion resistance

One way to evaluate corrosion resistance is to drop dilute nitric acid onto the media surface, and use ICPMS (Inductively Coupled Plasma-Mass Spectrometry) to measure the small amount of cobalt that elutes from the magnetic layer or the like. The results of evaluation of the amount of cobalt elution from the dilute nitric acid extract are shown in Fig. 1. The new carbon protective film exhibits excellent corrosion resistance, and can be made thinner than conventional carbon protective film.

(2) Surface hardness

Fig. 2 shows the results of using nanoindentation and evaluating the residual mark depth caused by a diamond indenter when a constant load is applied. The new carbon protective layer has a shallow indentation even as a thin film, and therefore is understood to be difficult to deform plastically and to be a hard film.

(3) Sliding durability

To evaluate the sliding durability, a reduced-pressure sliding test was carried out using an actual magnetic head. The results are shown in Fig. 3. The reduced-pressure sliding test is a test to evaluate sliding durability and uses the fact that the magnetic head flying height decreases at reduced pressure to simulate a low flying height state with a HDD. The new carbon protective layer exhibits several times the sliding path durability number of a conventional protective layer,

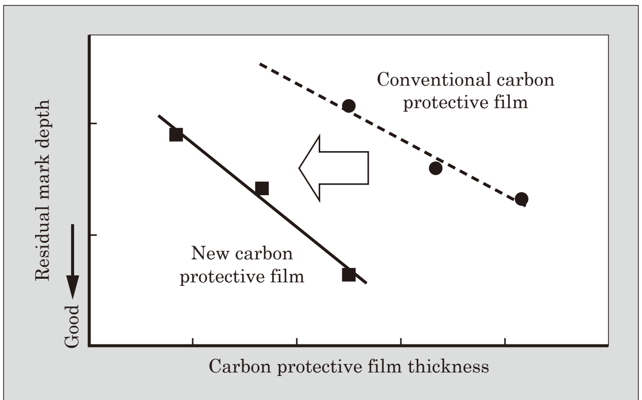

Fig.2 Nanoindentation evaluation results

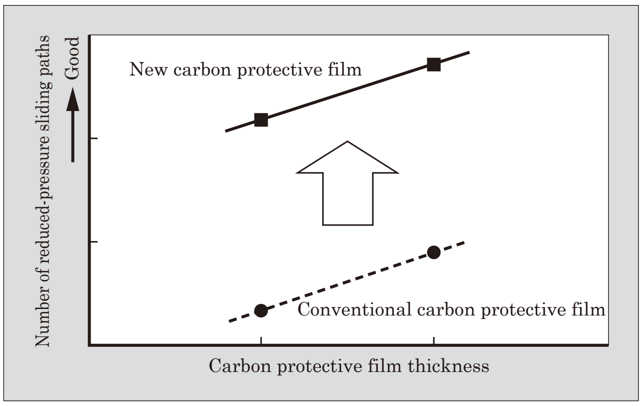

Fig.3 Reduced pressure sliding evaluation results

and the carbon protective surface is found to provide improved carbon film surface durability.

The newly developed carbon protective layer exhibits excellent corrosion resistance, surface hardness and sliding durability, and enables the carbon protective film to be made thinner and the magnetic spacing to be reduced.

3. Lubricant Layer Technology

3.1 Lubricant layer: Objective and challenges

The lubricant layer is fabricated by applying an approximate 1 nm-thick coating of a perfluoropolyether (PFPE)-based liquid lubricant having (-CF_2O-) repeating structural units onto the carbon protective film. The PFPE-based lubricant provides high heat resistance and low friction and low wear properties. Also, the end structure of the PFPE-based lubricant is terminated with a hydroxyl group (-OH). This functional group chemically bonds to the surface of the carbon protective layer to form a stable lubricant layer. For the magnetic head to fly stably over the magnetic media, the lubricant layer is indispensible. Moreover, if the magnetic recording media and the magnetic head make contact, the lubricant layer also functions to protect the surface of the magnetic recording media.

The thickness of the aforementioned lubricant layer, as is the thickness of the carbon protective layer, is a factor that determines the magnetic spacing. The relationship between variation in the lubricant layer thickness and the variation in the magnetic spacing is shown in Fig. 4. When field tests were performed using two types of lubricant agents, the magnetic spacing increased when the lubricant layer become thicker, and the amount of that increase was nearly equal to the thickness of the lubricant layer. That is, the lubricant layer thickness directly increases the magnetic spacing.

Additionally, the lubricant layer thickness also relates to the amount of protrusion of the FOD magnetic head element. Fig. 5 shows the relationship between lubricant layer thickness and the amount of protrusion of the element due to FOD. Increasing the lubricant layer thickness resulted in a reduced amount of protrusion. That is, due to the synergistic effect of the aforementioned reduction in spacing and the FOD projection, making the lubricant layer thinner was found to lead to improved electromagnetic conversion characteristics and higher recording density.

Fig. 6 shows the relationship between the lubricant

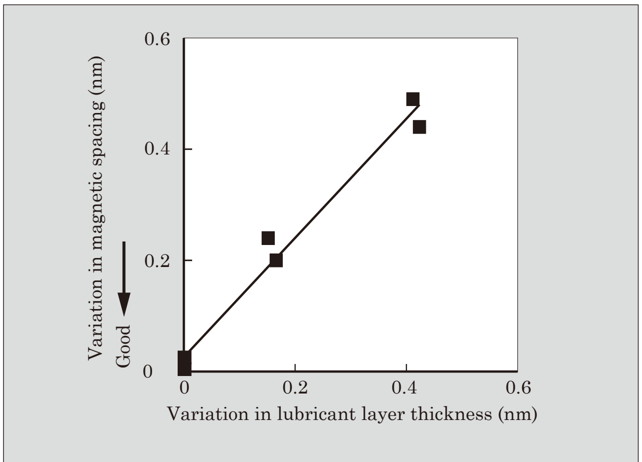

Fig.4 Relationship between lubricant layer thickness and magnetic spacing

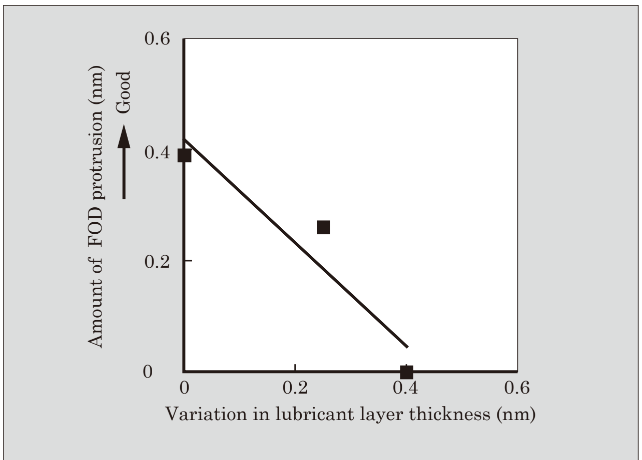

Fig.5 Relationship between lubricant layer thickness and FOD

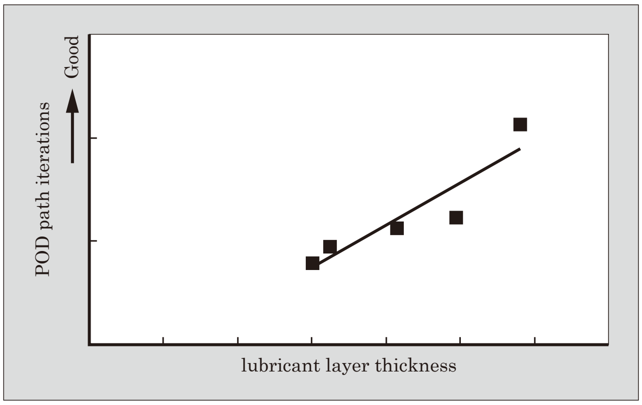

Fig.6 Relationship between lubricant layer thickness and POD path iterations

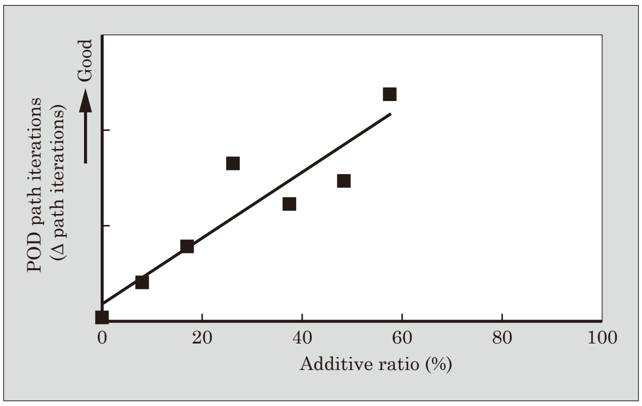

Fig.7 POD durability improvement according to additive ratio

layer thickness and durability. Here, the durability is evaluated based on the results of a POD (Pin On Disk) wear test in which an AlTiC ball is dragged over the surface of the media. As the lubricant layer becomes thinner, the number of drag path iterations decreases. That is, if the lubricant layer is made thinner in order to increase the recording density, the durability will decrease proportionally. So that durability can be maintained even if the recording layer is made thinner in order to increase recording density, improving the durability and reliability of the lubricant layer itself are important issues in lubricant layer development.

3.2 Lubricant layer development status

As described above, in the development work to make a thinner and more durable lubricant layer, the following topics are pursued simultaneously.

(a) Development of an additive that provides enhanced durability to the lubricant layer
(b) Development of material refining technology that appropriately adjusts the molecular weight and composition of the PFPE-based lubricant
(c) Development of techniques for post-processing after application of the lubricant coating

Of these topics, the additive technology of (a) is described below.

Materials having a phosphazene skeleton have been proposed as the additive.

For a mixed lubricant layer consisting of a hydroxyl-terminated PFPE-based lubricant and a phosphazene-based additive, Fig. 7 shows the relationship between the proportion of phosphazene-based additive and the number of drag path iterations in a POD wear test. If the proportion of phosphazene-based additive is increased, the number of path iterations increases. By adding the phosphazene-based additive, durability can be improved and the lubricant layer can be made correspondingly thinner. On the other hand, increasing the proportion of the phosphazene-based additive causes an increase in the lubricant pick-up volume transferred to the surface of the magnetic head slider, thereby inhibiting flying stability. The durability of the lubricant layer and the lubricant pick-up volume are highly dependent on the structure and properties of the phosphazene-based additive. To improve HDI (head disk interface) characteristics, the comprehensive design of a high reliability lubricant layer, including the development of new materials, is extremely important. Moreover, in addition to evaluating the magnetic recording media itself, evaluation of the HDD in various environments and the implementation of the lubricant layer design are also important.

4. HDI (Head Disk Interface) Evaluation Technology

4.1 Flyability test technology

FOD touchdown power measurement is introduced below as an example of a flyability test. FOD technology uses the thermal expansion of a heater built into the magnetic head near the read/write element to cause the element to approach the magnetic recording media surface. Here, the FOD read/write element (FOD element) is considered to protrude by an amount that corresponds to the amount of power applied to the heater. From the state in which the media is rotating and the magnetic head is floating, the FOD touchdown power is measured by gradually increasing the amount of applied power, and the applied power at the time when the FOD elements finally contact (touch down onto) the media surface is measured and evaluated. The larger the FOD touchdown power, the larger the amount of FOD element protrusion that is tolerable without the FOD element making contact with the media, and consequently, the FOD element is able to approach the media more closely. This leads to reduced magnetic spacing, improved electromagnetic conversion characteristics, and higher recording density.

The three main ways for assessing touchdown with this measurement are listed below.

(a) Use of AE (Acoustic Emission)
(b) Use of the saturation characteristics of the recording signal (TAA: Track Average Amplitude)
(c) Use of variations in the modulation of the recording signal

Here, the FOD touchdown power measurement method using AE will be described.

Fig. 8 shows the configuration of the measurement circuit.

The AE sensor detects elastic waves that propagate within a solid. For this measurement, an AE sensor having sensitivity at the vibration frequency (70 to 500 kHz) occurring at the time of touchdown is used. The AE sensor output signal is amplified by the AE preamp, narrowed down to the required frequency band by a bandpass filter, and unwanted noise is removed. Additionally, the AE sensor output signal voltage oscillates between positive and negative polarity, and is therefore difficult to use directly for touchdown detection. Thus, so that the strength of AE sensor output values that vary significantly at the time of touchdown can be expressed statistically using a detection circuit, the output signal is processed into a RMS (root mean square) value to convert it into a form that is easy to use for touchdown detection.

Fig. 9 is a graph showing the power applied to the

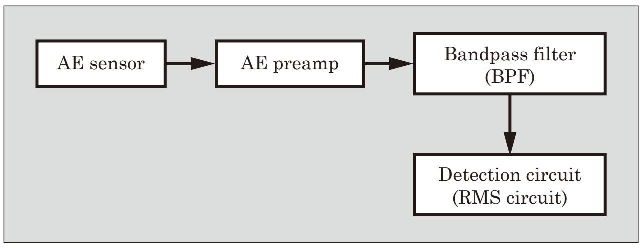

Fig.8 FOD touchdown measurement circuit configuration

heater of the magnetic head and the RMS value of the AE output. Measurement is carried out with the magnetic head floating at a position of radius 20 mm above 2.5-inch diameter media, the applied power is increased at a rate of 0.05 mW/ms, and contact between the FOD element and the media surface is monitored according to the time change of the AE signal. Despite the increase in power, while the FOD element is not in contact with the media, the AE output value remains constant at the noise signal level. When the FOD element contacts the media, the AE output value increases suddenly. A certain level above the non-contact noise signal level is set as a slice line, and when the AE output exceeds this level, touchdown is judged to have occurred and the applied power at that time is taken as the FOD touchdown power.

Fig. 10 shows the results of measurement of the FOD touchdown power for media in which the lubricant layer thickness is varied. As the lubricant layer is made thinner, the touchdown power increases. Therefore, making the lubricant layer thinner was found to be an effective means for increasing the amount of protrusion of the FOD element and reducing the magnetic spacing.

4.2 Durability test technology

An example of FOD applied to an accelerated durability evaluation of magnetic recording media is described below. When starting or stopping an actual HDD, the ramp load method for loading and unloading the magnetic head on a head retreating part, known as a ramp, that is provided beyond the outer periphery of the media is one method for operating the head. A load-unload accelerated test that combines a reduced-pressure environment and FOD was developed for accelerated testing with this method. In the basic operation, a magnetic head is repeatedly moved back and forth between a ramp and the outer periphery of the media, and this is a durability test for measuring the number of back-and-forth cycles (cycle durability) until scratches are visually observed on the media surface.

For magnetic recording media of the same conventional specifications, Fig. 11 compares the cycle durability in the case of a load-unload test performed in a reduced-pressure environment solely and in the case when FOD is used together. The testing in a reduced-pressure environment solely is an accelerated test, but when FOD is used together, the cycle durability is significantly less than in the case where FOD is not used. This means that the evaluation time can be reduced. Thus, in a load-unload test used for durability evaluation, the use of FOD was found to be effective for further accelerating the testing.

That a thinner lubricant layer is effective in reducing the magnetic spacing has already been described.

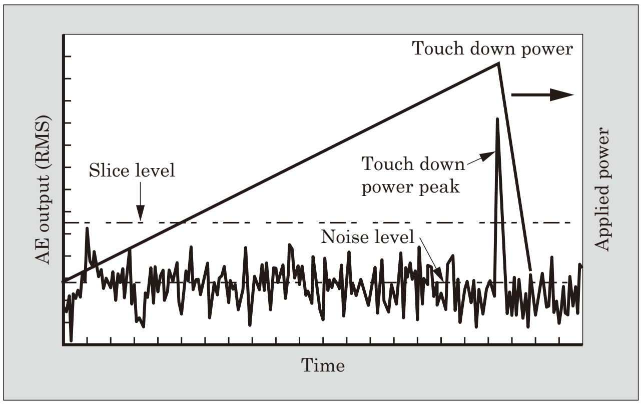

Fig.9 AE signal output vs. applied power

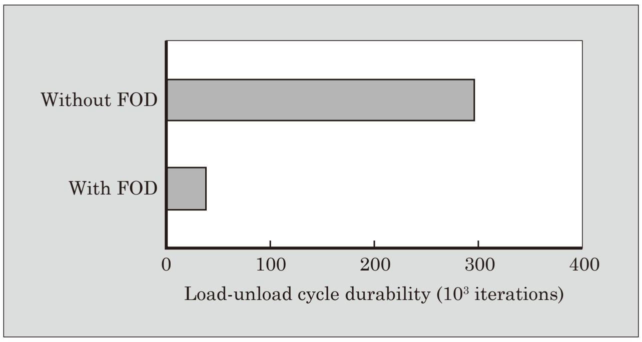

Fig.11 Comparative results with/without FOD in reduced-pressure load-unload test

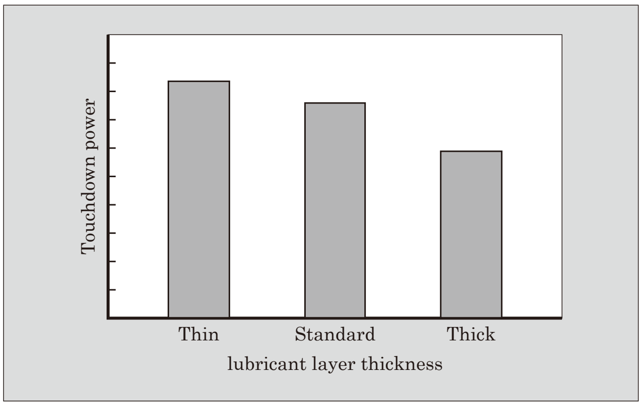

Fig.10 Dependence of touchdown power on lubricant layer thickness

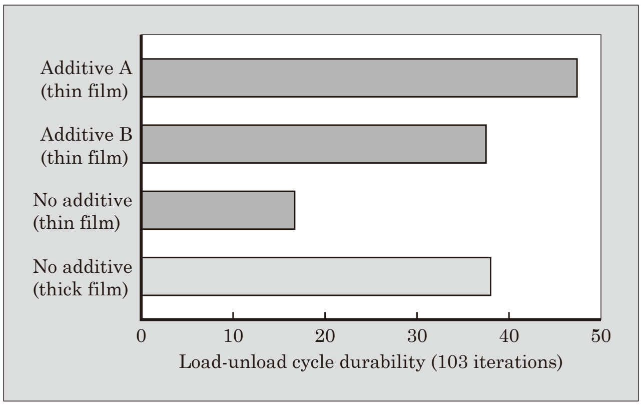

Fig.12 Comparative results of additives to lubricant layer in reduced-pressure load-unload test

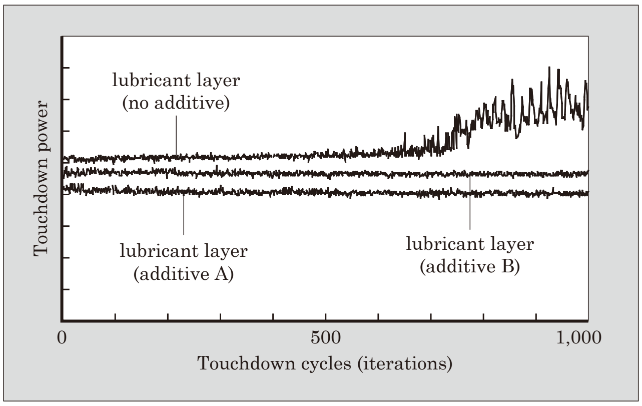

Fig.13 FOD element degradation test results

A thinner lubricant layer leads to degraded durability, however. To enhance the durability, a method of adding an additive to the lubricant has been used. Fig. 12 shows a comparison of magnetic recording media durability when an additive has been added to the lubricant layer using this test method. Without an additive, durability deteriorates when the lubricant layer is made thinner. The addition of an additive to a thinner lubricant layer was found to maintain the same level of durability as conventional media in a thinner lubricant layer. Additionally, durability can be improved further by varying the type of additive.

4.3 Reliability test technology

Lastly, the FOD element degradation test for long-term reliability evaluation is introduced below.

In some cases, depending on the operating environment of a HDD, the magnetic head and the media surface may suddenly come into contact. The part that makes contact first is the FOD element, and depending upon the surface condition of the magnetic recording media, FOD element wear or other damage may occur. If the FOD element becomes worn, the original amount of protrusion cannot be ensured, and moreover, the worn part may become corroded and have a significant adverse effect on the recording characteristics. An FOD element degradation test assesses damage that occurs due to contact between the FOD element and the media surface, and is a reliability test for the purpose of determining the design policy for high reliability recording media. The increase in power due to repeated touchdowns indicates wear of the FOD element, and therefore, measurement of the FOD touchdown power is repeated several thousands of times to evaluate the change in touchdown power.

Fig. 13 shows the FOD element degradation test results for magnetic recording media having a thin lubricant layer and for magnetic recording media that has both a thin lubricant layer and an additive. Magnetic recording media using a lubricant layer formed from a thin film and an additive exhibits stable touchdown power, without fluctuation, even after more than 1,000 touchdown iterations. On the other hand, for magnetic recording media that uses a thin lubricant layer and no additive, power was found to begin to gradually increase after 500 iterations. This suggests that the FOD element easily becomes worn by the magnetic recording media surface, and would likely inhibit recording in an actual HDD.

5. Postscript

So that magnetic recording media can attain even higher recording density, further reduction in the magnetic spacing is required. Therefore, further thinning of the carbon protective film in the protective layer and the use of high-durability lubricant materials in the lubricant layer are being studied, and research and development work is needed to ensure that high reliability (flying performance and durability) can be ensured with close magnetic spacing. Fuji Electric is committed to developing surface technology (carbon protective film and lubricant layer) suitable for 1 Tbit/in^2 recording density and to developing the corresponding reliability evaluation technology.

Evaluation and Analysis Techniques for Perpendicular Magnetic Recording Media

Takashi Hayashi † Ryoichi Kadota † Zenchi Hayashi †

ABSTRACT

Hard disk drives have come to have large capacities as a result of the synergy between the evolution of recording and playback components, as represented by the magnetic head and magnetic recording media, and the advances in signal processing technology, tracking technology and other drive-related technologies. With perpendicular magnetic recording media, Read/Write characteristics, including those of the low-frequency region, are critically important. Also, the realization of tracking precision of up to approximately 1.3 nm paves the way for higher density recording. Additionally, disturbances in the recording magnetization in the vicinity of the side shield of the side shield head were visualized and evaluated to optimize the configuration of the media layer and to mitigate the disturbances.

1. Introduction

Hard disk drive (HDD) recording capacity has continued to grow rapidly at an annual rate of approximately 40%. The various techniques described below including realization of the perpendicular magnetic recording media method have contributed to this achievement. Representative improvements in HDI (Head Disk Interface) technology include a reduction in media noise and improvement in linear recording density resulting from miniaturization of the magnetic grain size in the magnetic recording media, the development of a magnetic head that narrows the writing pole, and a reduction in magnetic spacing (distance between the magnetic head and the magnetic layer of the magnetic recording media). Additionally, there is a diverse array of technologies such as tracking techniques (head positioning techniques) and signal processing techniques for HDDs. With the higher densities of magnetic recording media, new techniques are needed to evaluate the characteristics of those magnetic recording media. This paper describes the development status of Fuji Electric's evaluation and analysis techniques for electromagnetic conversion characteristics.

2. Evaluation Techniques for Electromagnetic Conversion Characteristics

2.1 Evaluation of signal quality in perpendicular magnetic recording and playback

The most significant change concerning HDD recording and playback in recent years is that perpendicular magnetic recording has replaced longitudinal magnetic recording. To make high density recording possible, the distance between bits must be reduced in order to increase the linear recording density. Fig. 1 compares the interactions of two adjacent magnetizations having different orientations for longitudinal magnetic recording and perpendicular magnetic recording, and shows the relationship between the magnetic field generated by the left-side transition point magnetization and the right-side magnetization. With longitudinal magnetic recording, if the distance between bits is reduced, the magnetic field emanating from one bit will be opposite from the direction of magnetization of an adjacent bit. Thus, longitudinal magnetic recording has a weakness of unstable magnetization in a region of reversed magnetization. On the other hand, with perpendicular magnetic recording, if magnetization is reversed and the magnetization is oriented oppositely from that of an adjacent bit, the bit magnetization will be in the same direction as the magnetic field from an adjacent bit. Therefore, perpendicular magnetic recording has the characteristic of increasing stability as the interval between regions of reversed magnetization become narrower. Because of

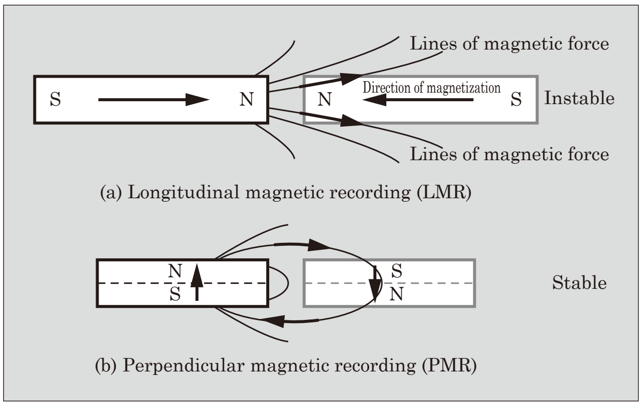

Fig.1 Difference in magnetic interaction between LMR and PMR

† Fuji Electric Co., Ltd.

this characteristic, perpendicular magnetic recording is more advantageous for high density recording.

The use of perpendicular magnetic recording has alleviated the stability problem during high-density recording. Reducing the size of magnetic grains in the recording layer of magnetic recording media and reducing the jitter (signal fluctuation) caused by variations in magnetic grain size are the main challenges for achieving even higher densities. Therefore, in perpendicular magnetic recording media, the SNR (signal to noise ratio) during high density recording, which is typically closely related to jitter, is considered to be important.

To increase the recording capacity of HDDs, the recording code has also been improved. Typically, in digital communications, a DC signal cannot be transmitted as-is and therefore the signal is continuously modulated with restrictions imposed on the continuation of the same code. Imposing stricter restrictions and modulating the signal into one where the same code interval is shorter will increase redundancy and lead to decreased transmission speeds. The loosening of restrictions concerning the same code interval and the ability to handle signals with lower redundancy contribute significantly to improvements in transmission speeds in recent years. For the magnetic record and playback signals in an HDD, efforts are underway to reduce the redundancy of data recorded on actual magnetic recording media[(1)] and a recording code that includes long-period signal components has been adopted. The recording of long-period signals, however, presents difficult challenges for perpendicular magnetic recording, and in addition to the aforementioned efforts for realizing higher recording densities, the realization of long-period signal recording is also sought.

The long-period signal recording performance in magnetic recording media is generally evaluated with a reverse overwrite (ROW) process. ROW is the ratio of the original recorded signal strength to the remaining signal strength when a high-density recording is overwritten with a low-density recording. A higher ROW value indicates that signals are easier to record. Although ROW is used to evaluate the ease of recording, it is not necessarily correlated to an indication of actual recording and playback performance. Moreover, in the design of magnetic recording media, when attempting to increase the ROW value, a recording signal known as the magnetic writing width (MWW), which is correlated to a decrease in surface recording density, will increase in width and this trade-off makes it difficult to optimize the media design for high-density recording. Thus, the various characteristics of today's magnetic recording media have complicated interrelationships, and the direction of technical development for realizing higher densities is not easily discoverable.

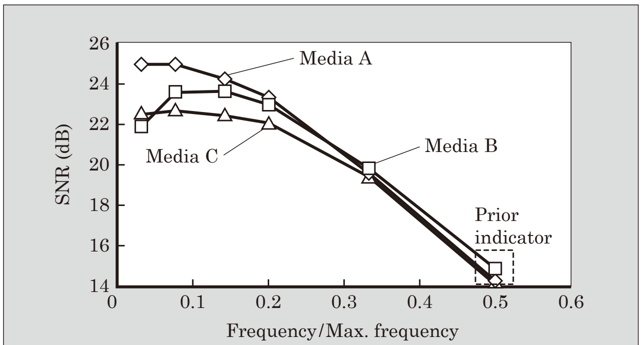

Fig.2 SNR frequency characteristics (horizontal axis is normalized by max. frequency)

Therefore, in order to provide a specific direction for development, assuming the recording and playback characteristics of an actual HDD and aiming for an appropriate improvement in media characteristics, Fuji Electric is presently evaluating media characteristics as follows.

First, single track recording and playback performance are evaluated with a focus on the following three characteristics.

(a) MF-SpiSNR

SNR at 1/2 of the highest recording frequency, higher values indicate that higher density recording is possible

(b) SNR with weighted noise spectrum

Assumes that signal processing is performed inside HDD

(c) SNR during long-period signal recording

Fig. 2 shows the SNR dependency on recording frequency measured using experimental magnetic recording media. The SNR on the high-frequency side has been considered an important characteristic even for longitudinal magnetic recording, and is directly correlated to the resolving power of magnetization for media recording and playback. Regardless of the type of media, the SNR decreases at the high-frequency side. This is chiefly due to interference from oppositely coded signals when playing back signals that have been recorded with high density. The SNR on the low-frequency side is related to characteristics of long-period recording.

As mentioned above, with perpendicular magnetic recording, long-period recording characteristics have a tendency to deteriorate easily. The required bandwidth differs according to the HDD, and in recent

Table 1 Relationship between evaluated characteristics values and HDD characteristics results for the media shown in Fig. 2

Media	HDD characteristics ranking	Frequency-integrated SNR (New evaluation index)	MF-SpiSNR (Conventional index)
Media A	1	19.7 dB	14.3 dB
Media B	2	19.5 dB	14.9 dB
Media C	3	18.8 dB	14.1 dB

years, in order to improve long-period recording characteristics, good recording performance that extends down to the low-frequency side is being required. Because actual HDDs require good recording and playback performance throughout the entire bandwidth, the SNR value weighted for each frequency is defined and evaluated as a comprehensive index for the SNR of the magnetic recording media. Table 1 shows the relationship between the evaluation results based on conventional evaluation criteria and the evaluated results based on the new evaluation index concerning the HDD characteristics results for media A through C of Fig. 2. With the conventional evaluation criteria (MF-SpiSNR), media B has a high SNR and appears to exhibit the highest performance. On the other hand, when compared to the new evaluation criteria (SNR value weighted for each frequency), media A is judged to have the highest performance, and this agrees with the ranking of characteristics in an actual HDD. As can be seen from Fig. 2, media A, which provides the best recording and playback performance based on the HDD characteristics, exhibits poor performance during high frequency (short-period) recording than media B, but exhibits excellent performance during low frequency (long-period) recording. Thus, in the evaluation of media characteristics leading to better HDD performance, it is effective to consider the recording performance down to the low-frequency side.

2.2 Evaluation of track pitch

In addition to evaluating the recording and playback performance of single tracks, evaluating track pitch is also important. With the current combination of magnetic recording media and magnetic heads in HDDs, high density recording is realized by optimizing both the linear recording density and the track density. The evaluation to estimate track density is becoming an increasingly important part of the evaluation of media for high density recording use.

Previously, track density was estimated by evaluating the write width. The write width is a value that indicates the actual average width of magnetic reversal occurring when a signal is written to a track. This value is closely correlated to the track density that could be realized in an actual HDD. With an evaluation based on the write width, however, the border area between a region of magnetization reversal and a region that maintains the original recording, i.e., the erase band is not evaluated. As a result, when media having been evaluated as having a narrow write width is evaluated in an actual HDD, no improvement in track density may be found in some cases. Also, in the evaluation of magnetic recording media, in addition to the evaluation of write width, track pitch is also evaluated in conformance with the method for determining track pitch in an actual HDD, and then development is carried out based on those results.

Fig. 3 shows an example of track pitch evaluation performed in consideration of both the write width and the erase band in experimental magnetic recording media. Media C shows a group in which only the coercivity was changed by adjusting the magnetic layer thickness. Media A and B were evaluated as requiring a track pitch larger than the write width, but media C was evaluated as being capable of realizing a track width that is the same as the write width. The track pitch obtained in a track pitch evaluation performed in consideration of the erase band also corresponds well to the track pitch actually established in an HDD. At present, the evaluation of track pitch, together with the aforementioned signal evaluation, is regarded as important evaluation that correspond to actual HDDs parameters.

In addition to reducing the write width, increasing the tracking precision has also contributed greatly to improving the track density in actual HDDs. Also, the evaluation of magnetic recording media has come to require high tracking precision that is difficult to realize

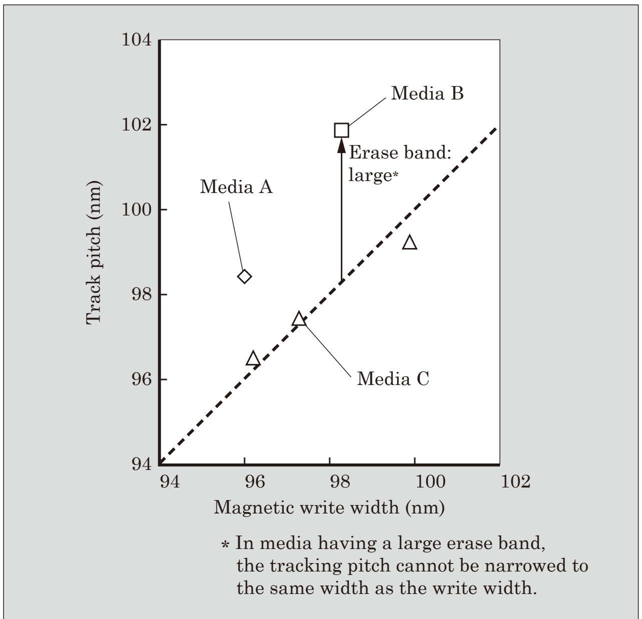

Fig.3 Difference in relationships between magnetic write width and track pitch according to media

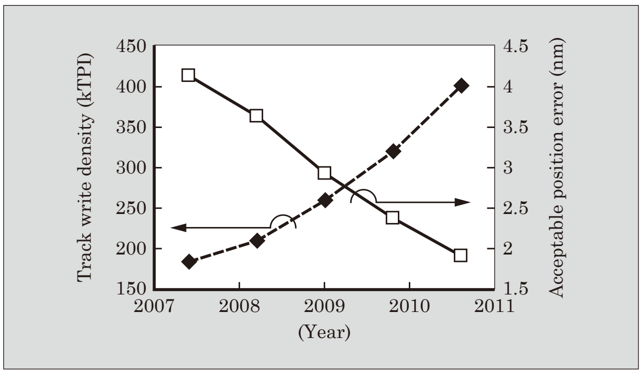

Fig.4 Change in track density and change in required tracking precision

with conventional evaluation equipment. By utilizing a driving mechanism based on piezoelectric actuators capable of highly-reproducible fine adjustments of the head position and by adopting statistically measures, Fuji Electric has increased the evaluation precision to 1.3 nm, realizing tracking precision comparable to that of an actual HDD. Fig. 4 shows the changes in track density and the required tracking precision in recent years. As the track density increases significantly in the future, tracking precision on the order of several nanometers, which is much smaller than the present granular size (of the approximately 4 to 6 nm size crystalline grains in the magnetic layer), will be required, and tracking precision of 1 nm is expected to be required by 2013. This indicates that the granular size is an impediment to not only increasing the linear recording density, but also to increasing the track density, and further refinement of the grain size has become increasingly more important.

2.3 Evaluation and Analysis Techniques for Other Electromagnetic Conversion Characteristics

One type of evaluation relating to electromagnetic conversion characteristics is evaluation involving a side-shielded head, which has become the mainstream in today's magnetic heads. With a side-shielded head, spreading of the write width due to a magnetic field from a main magnetic pole is controlled. As shown in Fig. 5, however, a return magnetic field drawn toward a side shield located a distance several tracks away disturbs the magnetization in that vicinity, and causes the phenomenon known as side track erasure (STE) and this must be evaluated accurately.

Fig. 6 shows a visualization of the STE phenomenon that occurs when a square-wave signal for one track is recorded onto a magnetic recording media that has been completely DC-erased, and the head is moved between adjacent tracks to acquire the playback signal waveform. At a location away from the center track, magnetization in the opposite direction can be seen. Since an actual perpendicular magnetic recording HDD is never completely DC-erased before use, this evaluation has strict conditions. Nevertheless, evaluation of this characteristic is necessary in order to improve the reliability of magnetic recording media. This type of STE phenomenon is affected not only by the magnetic characteristics of the magnetic layer, but also by the magnetic path, which is determined by the layer design of the entire magnetic recording media, including the soft under layer (SUL) and the non-magnetic interlayer disposed on the SUL. Additionally, evaluation of the STE phenomenon often shows a different trend than the evaluation of side erasure in an adja-

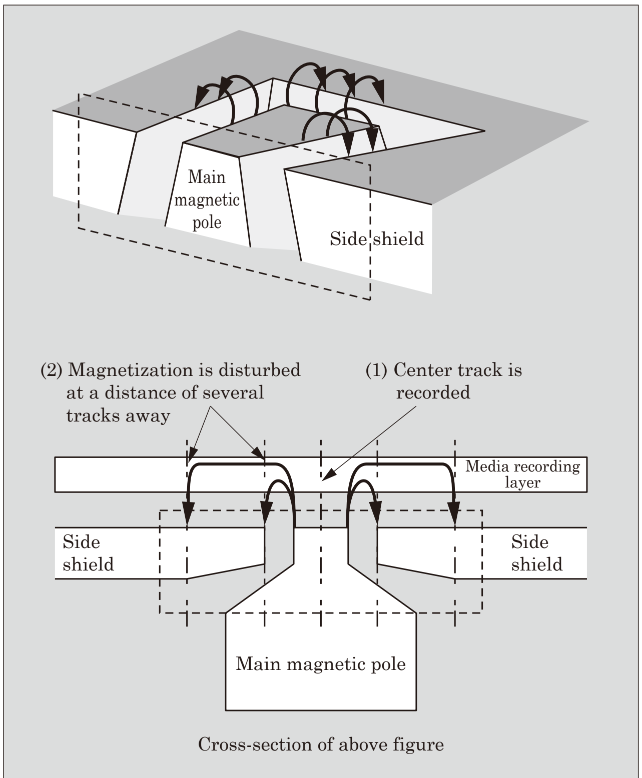

Fig.5 Magnetic flux and side track erasure (STE) in side-shielded head

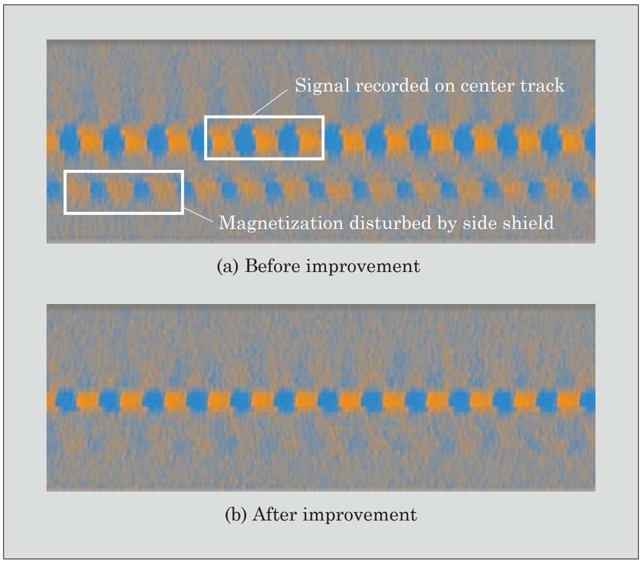

Fig.6 Visualized STE (side-track erasure)

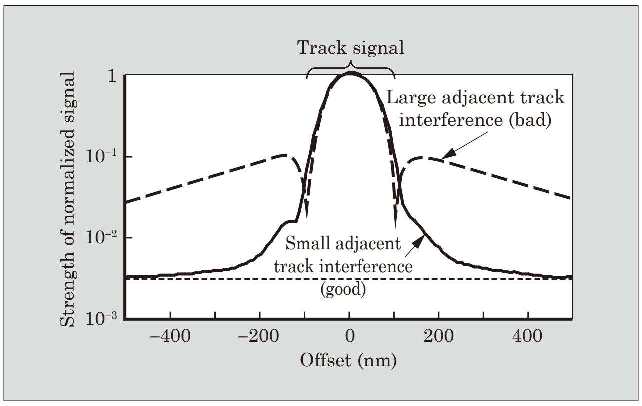

Fig.7 Evaluation of adjacent track interference

cent track, and efforts to improve this phenomenon are being advanced as one of the main focal points for optimization of the layer structure of magnetic recording media.

To achieve high-density recording, in addition to measures for preventing STE, the overlapping of magnetic fields emanating from magnetization recorded in side tracks must be suppressed to the extent possible. This also is closely related to the SUL properties.

Fig. 7 shows, for a signal recorded on a center track, the change in playback signal strength as the head is moved between adjacent tracks, and the arrows in the figure point to levels of interference between tracks. Signals remaining at a distance from the center indicate that signals from different tracks overlapped during playback, and as a result, recording density is difficult to increase. Signals remain between adjacent tracks because the magnetic fields emanating from magnetism recorded on the media spread between adjacent tracks. This spreading of magnetic fields is affected by the magnetic characteristics (particularly the magnetic anisotropy) of the SUL. In the figure, the solid line shows good characteristics, while the broken line shows a phenomenon observed in magnetic recording media when a problem in the SUL characteristics causes the interference between tracks to worsen. In the case of media having an anomalous SUL, particularly when performing low density recording, signals at a distance from the track center are found to be less likely to have been attenuated, and this characteristic is used to detect SUL anomalies.

3. Future Efforts

In future HDD development, progress in increasing the track density is expected to be realized at a faster rate than improvements in linear recording density. Additionally, the shingled-write recording method, presently in its research stage, will likely be realized in the not so distant future. Increasing the tracking precision is the key for these techniques. With evaluation based on the shingled-write recording method, after improving the tracking precision, signals overwritten in one direction must be evaluated, and evaluation of adjacent track interference would be difficult to apply as an extension of conventional thinking. While investigating error-rate evaluations of simulated shingle-write recording and the elemental technology required for two-dimensional recording and playback, which is advocated as a future technology, evaluation methods that can support those technologies and permit faster measurements are being studied.

4. Postscript

With advances in magnetic recording media and magnetic heads that enable higher density recording, coupled with advances in signal processing techniques, tracking techniques and drive technology, the capacities of HDDs are increasing. In order to provide media for realizing even larger capacity HDDs, Fuji Electric intends to incorporate the latest drive technology, promote more sophisticated evaluation and analysis techniques, and develop higher density recording media to contribute to the development and stable production of larger capacity storage devices.

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Aluminum Substrate for 3.5-inch 1 TB Magnetic Recording Media

Kengo Kainuma [†] Shoji Sakaguchi [†] Shinji Takei [†]

ABSTRACT

By 2011, the recording capacity of commercially available magnetic recording media in a single 3.5" disk format is forecast to reach 1 TB. The formation of an ultra-smooth surface and the reduction of 100 nm-class small defects are technical challenges that must be overcome in order to realize higher recording densities. For this purpose, Fuji Electric is improving its aluminum substrate manufacturing processes, which include a ground substrate production process, a plating process, a polishing process, a washing process and the like. The small defects typically occurring during these processes include foreign particles, scratches, pits and so on. By analyzing defects one-by-one, classifying them and then determining their cause, the individual processes can be improved and quality enhanced to establish a substrate manufacturing process suitable for next-generation media.

1. Introduction

In recent years, the hard disk drive (HDD) has been the mainstream large-capacity storage device. With the widespread use, since the first half of 2008, of SSDs (solid state drives) using flash memory, however, requests for even larger capacity HDDs have intensified and the competition for their development has increased. For magnetic recording media used in HDDs, a recording capacity of 500 GB per 3.5-inch disk (500 GB/3.5-inch disk, hereinafter) was the mainstay in the market in 2009. Subsequently, the trend toward higher recording densities has accelerated and a hard disk drive having a recording capacity of 1 TB/3.5-inch disk is expected to be released in 2011.

Two types of substrates, aluminum or glass, are available for use with the magnetic recording media in HDDs. For notebook PCs, mobile consumer electronics and the like, glass substrates are used because of their excellent impact resistance and low power consumption. On the other hand, highly cost-effective aluminum substrates are used for desktop PCs and servers.

Fig. 1 shows the basic layer structure of magnetic recording media that uses an aluminum substrate. The magnetic recording media is fabricated by depositing on the aluminum substrate a soft underlayer, followed by an interlayer, a magnetic layer, carbon overcoat, and then a lubricative layer. A magnetic head flies over this surface of this magnetic recording media at a height of several nanometers to read and write information. Attaining the ability to control surface roughness and micro-waviness on the sub-nanometer order and the ability to reduce surface defects of 100 nm size so that a magnetic head flying at a height of several nanometers is able to record and playback information stably are technical challenges to be overcome in the development of substrates for magnetic recording media.

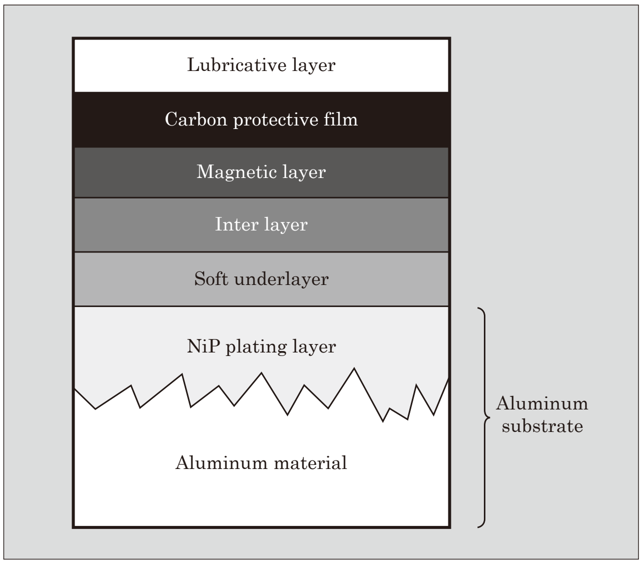

Fig.1 Basic structure of magnetic recording media

With increasing recording densities, the smoothness and uniformity of the substrate surface, which are factors that affect the electromagnetic conversion characteristics and HDI (Head Disk Interface) characteristics, are becoming increasingly important year-by-year. Surface defects include concave defects such as scratches and pits, and protruding defects formed by residues such as abrasives, detergent and NiP polishing residue. The complete elimination of these defects is impossible, but to meet satisfy requirements that become increasingly demanding year-by-year, efforts are particularly focused on reducing the incidence of such defects.

Fuji Electric has been developing, manufactur-

† Fuji Electric Device Technology Co., Ltd.

ing and selling aluminum substrates for magnetic recording media for some time, and has continuously developed technology that supports higher recording densities. This paper introduces Fuji Electric's efforts toward attaining ultra-smooth surfaces and reducing defects in the development of aluminum substrates for magnetic recording media of 500 GB to 1 TB/3.5-inch per disk.

2. Substrate for Magnetic Recording Media

The aluminum substrate manufacturing process, as shown in Fig. 2, is sub-divided into a substrate grinding process wherein a disk of aluminum material is ground into the aluminum substrate known as the ground substrate (G substrate), a plating deposition process wherein NiP plating is formed on the aluminum substrate, and a polishing and washing process that smoothes the surface of the NiP plating.

(1) Ground substrate (G substrate)

An aluminum alloy is melted, casted and rolled, and then cut into a disk shape to form the aluminum material, the inner and outer end surfaces of which are then cut and the surface is ground to produce the G substrate. The dimensional accuracy of the media is determined by this substrate grinding process, and therefore the cutting and grinding are performed with high precision. Additionally, because the composition and cleanliness of the G substrate affect the defects and quality of the plating in the next processing step, the G substrate manufacturing process is constantly under review for improvements. Fuji Electric procures G substrates externally, but performs the plating deposition processing and subsequent manufacturing steps.

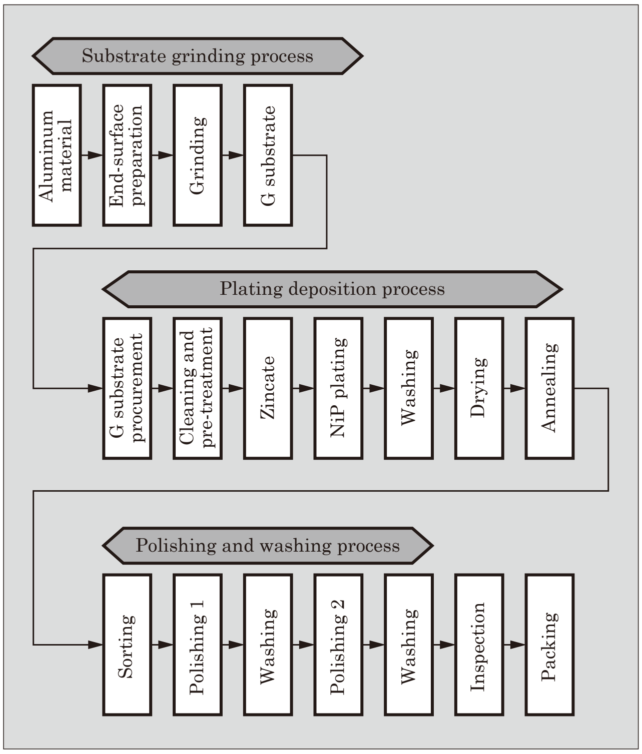

Fig.2 Overview of aluminum substrate manufacturing process

(2) Plating deposition processing

The aluminum alloy is lightweight and is easy to process, but its surface hardness does not meet the requirements for HDDs sufficiently. Therefore, in order to prevent damage when the magnetic head collides with the magnetic recording media, the surface of the substrate is plated with NiP.

The surface of the G substrate is chemically adjusted by cleaning, pre-treating and zincate processing, and then amorphous NiP is deposited to a thickness of ten-odd microns onto the surface by an electroless plating technique. Additionally, annealing is performed to release the internal stress generated during plating.

(3) Polishing process

The substrate surface is polished in order to smooth the substrate surface after plating and to remove grinding machining marks, waviness (wavelength: several tens to several hundred millimeters) and micro-waviness caused by internal stress during the plating.

Using urethane foam pads and a polishing liquid (slurry) containing dispersed abrasive grains, the NiP-plated surface is precision polished in two steps. Typically, the 1st polishing step uses a slurry or the like containing alumina abrasive powder and that is compatible with high-speed processing to remove grinding marks and waviness. The 2nd polishing step uses a colloidal silica slurry or the like to adjust micro-waviness and surface roughness. Furthermore, in order to use the outer peripheral area of the disk more widely as a recording area, it is also important that the end portion of the substrate be flat. A trade-off relation exists between smoothness and edge roll-off, however, and this is one reason why the development of advanced polishing techniques is requested[2].

Quality requirements for micro-waviness and surface roughness are becoming more demanding every year, and therefore the selection of components for the polishing process and optimization of the processing conditions are extremely important[3].

(4) Washing process

If the slurry used in the 1st polishing step remains beyond the 2nd polishing step, there will remain particles (Fig. 5(a)) formed from stuck abrasive grains, scratches (Fig. 5(b)) caused by aggregation of the abrasive grains, and pits (Fig. 5(c)) where the stuck abrasive grains have been removed. The washing after the 2nd polishing step must completely remove residue slurry material (abrasive grains and chemicals) and NiP residue from the surface after polishing.

Residue remaining on the substrate surface after washing will remain intact after the magnetic recording media is processed and may cause damage by colliding with the magnetic head. Therefore, residue and crud taller than the head flying height cannot be allowed. Residue on the substrate surface prior to deposition of the magnetic film is directly related to product defects, and therefore, as the recording density of magnetic recording media increases, higher quality is required of the substrate washing process each year.

3. Relationship Between Technical Issues and Processes for The Aluminum Substrates Used in Magnetic Recording Media

To support higher recording densities of magnetic recording media, aluminum substrate technology must overcome three major issues involving: (1) smoothness, (2) end shape, and (3) micro-defects and residue. Fig. 3 shows the linkage between these major issues on the left side, and the materials used and relevant processes on the right side. Intertwined relationships are shown, with each technical issue being related to multiple material and process technologies. An understanding of these relationships is necessary when promoting improvement and development work for aluminum substrates.

Table 1 shows representative surface characteristics required of aluminum substrates according to the recording capacity of the media. Requirements of the four parameters listed in the table become more demanding as the recording capacity of the magnetic recording media increases. In particular, improvement that reduces the number of defects is an important topic for development.

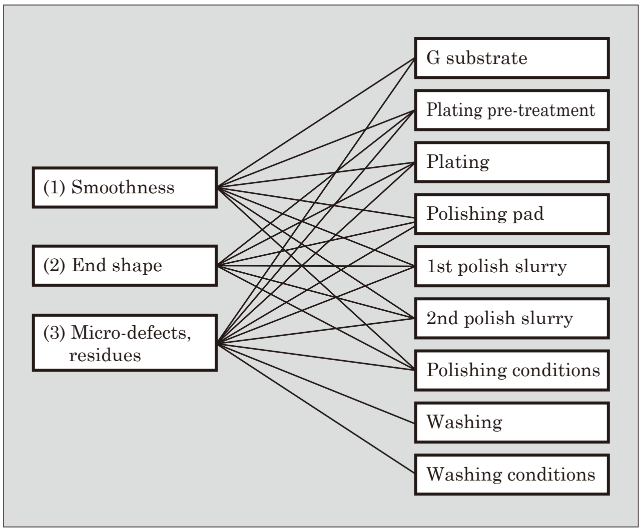

Fig.3 Relationship between main technical issues and materials/processes for aluminum substrates

Table 1 Required surface characteristics for aluminum substrates (3.5-inch)

	250 GB substrate	500 GB substrate	1 TB substrate
Surface roughness (AFM-R_a)	≤0.15 nm	≤0.14 nm	≤0.12 nm
Micro-waviness (W_q)	≤0.23 nm	≤0.14 nm	≤0.12 nm
Edge roll-off	≤15 nm	≤10 nm	≤7 nm
Relative number of defects*	100	70	30

* Relative number of defects assuming the average number of defects for a 250 GB substrate to be 100

4. Surface Smoothing Techniques

As noted in section 3, as recording densities increase year-by-year, the smoothness requirements of the substrate surface become more demanding. In order to develop an aluminum substrate able to satisfy these requirements, Fuji Electric has continuously been improving the polishing technology.

At the time of the transition from 160 GB/3.5-inch disks to 250 GB/3.5-inch disks, development focused mainly on the slurry (2nd step). In the development of substrates for 500 GB/3.5-inch disks and 1 TB/3.5-inch disks, all pad, slurry (1st step, 2nd step) and polishing conditions were reviewed, and technical development was advanced to attain both quality and ease of manufacturing.

The four key points in the development of the slurry are as follows.

(a) Optimization of the average size and distribution of abrasive grains in the slurry
(b) Optimization of chemical ingredients such as surfactants contained in the slurry composition
(c) Optimization of the polishing conditions
(d) Excellent rinsing characteristics

Also, the four key points in the development of pads are as follows.

(a) Provision of a foaming state that stabilizes the polishing rate on upper and lower surfaces
(b) Reduction of particles that cause scratches
(c) Optimization of elasticity to reduce edge roll-off
(d) Minimization of changes with aging (improved ease of production)

To improve the surface precision of the aluminum substrates, Fuji Electric jointly develops various components, such as the slurry and pads, and collaborates closely with the component manufacturers to develop sophisticated new materials and to improve the sub-

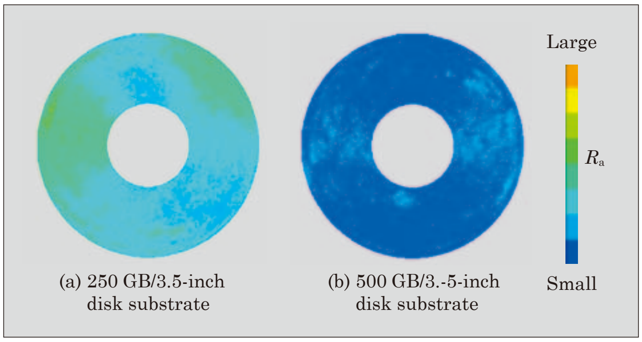

Fig.4 Aluminum substrate surface roughness distribution (R_a)

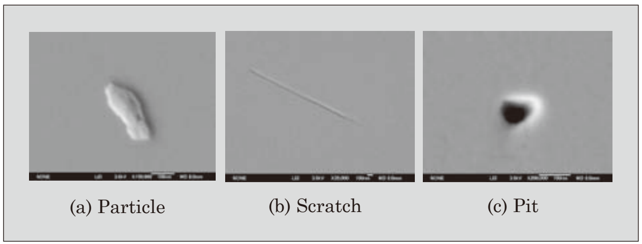

Fig.5 Representative micro-defects in aluminum substrates

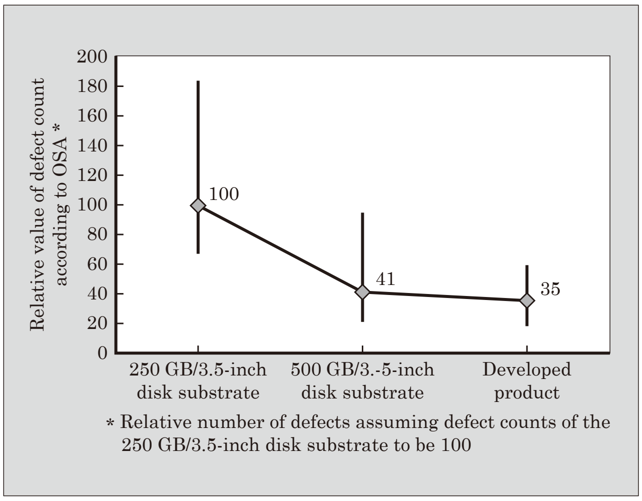

Fig.6 Comparison of number of defects for each generation of substrates

strate characteristics.

Fig. 4 shows the surface roughness of a conventional 250 GB/3.5-inch disk substrate and the 500 GB/3.5-inch disk substrate presently being mass-produced as measured by an OSA (Optical Surface Analyzer). The 250 GB/3.5-inch disk substrate, measured with an atomic force microscope, achieves a surface roughness AFM-Ra of less than Ra 0.12 nm, which is a requirement of the 1 TB/3.5-inch disk substrate. As shown in Fig. 4(a), however, there is a wide distribution of roughnesses on the surface. For the 500 GB/3.5-inch disk substrate, slurry conditions for the 2nd polishing step and the like are improved, and as shown in Fig. 4(b), uniformity has been enhanced significantly by lowering the absolute value and reducing the width of distribution of the surface roughness.

5. Efforts Toward Defect Reduction in Aluminum Substrates for 1 TB/3.5-inch Disk Aluminum Substrates

Of the four surface characteristics listed in Table 1, surface roughness, micro-waviness and end shape have already been confirmed as attaining the required characteristics for 1 TB/3.5-inch disks. The most important issue facing development of 1 TB/3.5-inch disk substrates is reducing the number of defects, especially the reduction of the 100 nm class of defects known as micro-defects. Fig. 5 shows SEM (scanning electron microscope) photographs of typical micro-defects.

(a) Particles

Particles adhere mainly from the content of slurry residue, NiP polishing residue, and from the external environment. The majority of particles are removed by precision washing prior to deposition of the magnetic layer. Remaining particles that adhere or stick to the surface, however, may cause defects in media products.

(b) Scratches

Scratches are often caused by aggregation of abrasive grains and by external contamination of the polishing equipment or washing equipment. The occurrence of scratches is limited by controlling the equipment environment and filtering the slurry.

(c) Pits

Pits are caused by erroneous etching or by the removal of abrasive grains that had become stuck during plating deposition, polishing or washing.

In the development of aluminum substrates for high recording density media, the reduction of micro-defects is a particularly important issue. As described with Fig. 3, because defects involve all materials and processes, optimization of materials and process conditions is being considered for processes ranging from plating deposition to polishing and washing.

Fig. 6 compares the number of defects measured by an OSA for various substrates, according to the recording capacity of the media. For the 500 GB/3.5-inch disk substrate, the plating pre-treatment, which includes the zincate treatment, and the polishing and washing processes have been improved, and all the required characteristics, including the number of defects, listed in Table 1 have been achieved. For 1 TB/3.5-inch disks, further improvements are being developed. The largest source of aluminum substrate particles is abrasive grains in the slurry; NiP polishing residue also tends to remain and presents a challenge for washing. In order to attain a smooth surface, the abrasive grains in the slurry are being made finer, and accordingly, NiP polishing residue is also becoming finer and more difficult to remove. Therefore, the surfactants and other chemical content in the slurry, and the detergent used in the washing processing are becoming more important.

Moreover, in order to eliminate slurry content residue and the NiP polishing residue, Fuji Electric is working to develop a cleaning agent. Accordingly, Fuji Electric is focusing on the following three items.

(a) Surfactant

Improving surfactants, which are low-molecular weight materials, to have high penetration toward particles and excellent rinsing characteristics.

(b) Alkali agent

Aiming to achieve a lift-off effect from etching action, an alkali agent applies an appropriate zeta-potential to a NiP plated surface and adhered particles, thereby enhancing the repulsive force and preventing re-adhesion.

(c) Chelating agent

A chelating agent having a high chelating effect on metal ions (Ni or the like) and excellence dispersion characteristics for abrasive grains.

6. Postscript

This paper has described the development status of Fuji Electric's aluminum substrates. The main challenge facing the development of aluminum substrates for 1 TB per 3.5-inch disks is the reduction of defects. Fuji Electric will continue to focus on this challenge while advancing development. The recording density of magnetic recording media is expected to continue to increase in the future, and further improvement of surface precision is required. This challenge will be solved by new technologies, and in order to attain the aluminum substrate characteristics suitable for evolving generations, Fuji Electric intends to pursuit improvements to plating technology, polishing technology and washing technology.

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