Magnetic Recording Media: Technical Trends and Future Outlook

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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-

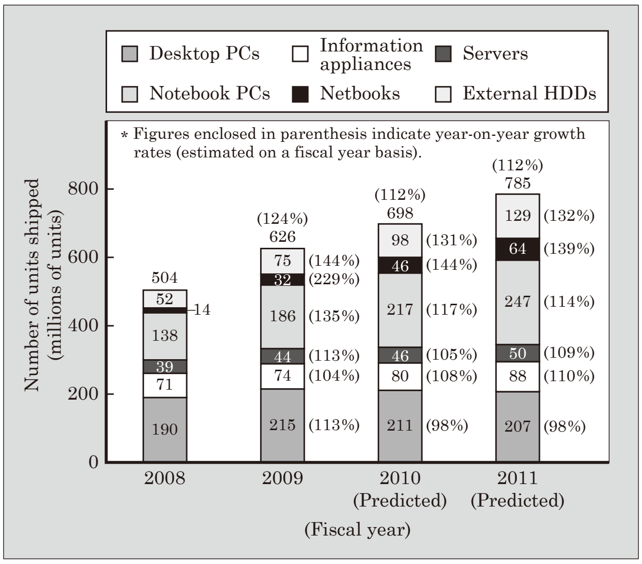

Fig.1 Worldwide shipments of HDDs by application

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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-

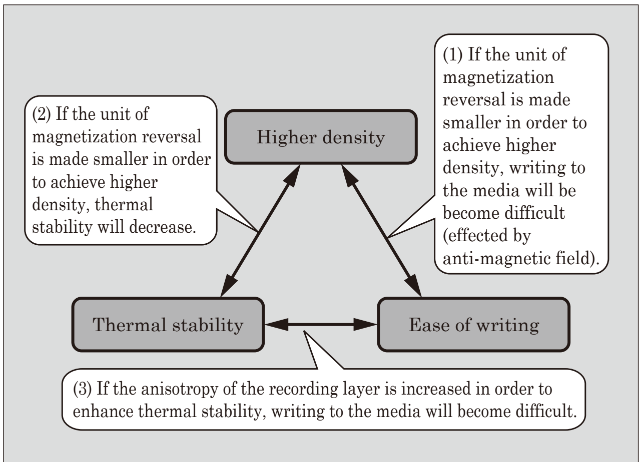

Fig.2 Trilemma of perpendicular magnetic recording media

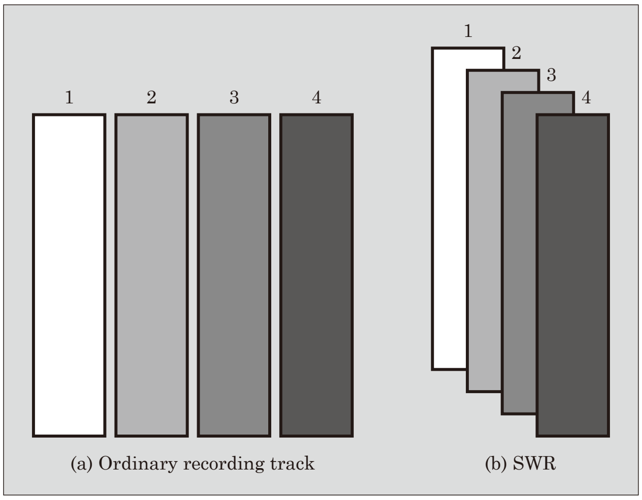

Fig.3 Conceptual diagram of shingled-write recording (SWR) method

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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