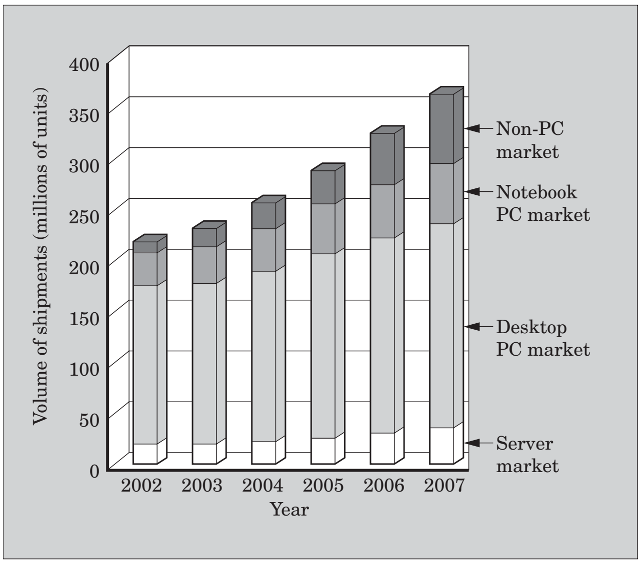
Development of Granular-type Perpendicular Magnetic Recording Media

Akihiro Otsuki

1. Introduction

Hard disk drives (HDDs) were developed in 1956 and initially were applied mainly as external memories for mainframe computers. Subsequent advances in HDD technologies leading to higher areal density, smaller size and lower cost have brought HDDs into widespread use for their convenience. HDDs are now the mainstream external memories used for personal computers and mainframe computers. Recently, the technology of longitudinal recording, which has been in use for a long time, is approaching its technical limit. Perpendicular magnetic recording technology, however, which realizes higher areal density, has been edging closer to practical use in recent years. In the year 2005 and thereafter, large capacity and small size HDDs that utilize perpendicular magnet recording technology are expected to acquire a large share of the market. In the ubiquitous society of the 21st century, we predict that the HDD market will continue to expand as HDDs come to be used in vehicle equipment, home information appliances and cellular phones (Fig. 1). The main component that is mounted in these HDDs and that stores more than 100 Gbytes (800×10^9 bits) of data is the magnetic recording media which we have developed.

Fig.1 HDD market trends



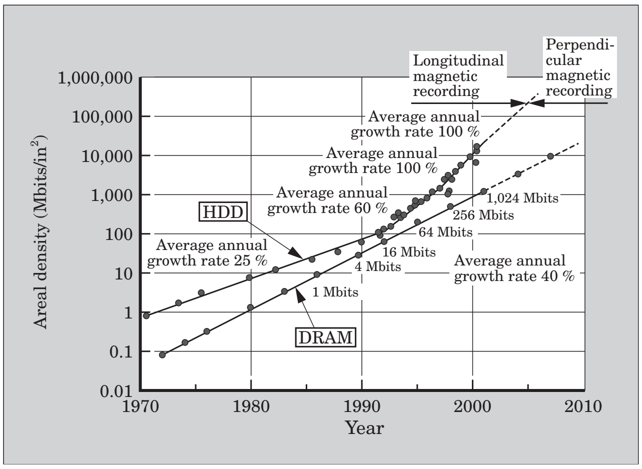
In 1985, Fuji Electric succeeded in developing a sputtered Co-alloy magnetic recording media to replace the coated γ-Fe_2O_3 media that had been in use previously. Since then, Fuji Electric has been a major manufacturer of media and a worldwide supplier of longitudinal magnetic recording media. Recently, Fuji Electric succeeded in developing the world's highest areal density perpendicular magnetic recording media. Below, we shall describe the development status of our perpendicular magnetic recording media.

2. Changes in Magnetic Recording Technology and Fuji Electric's R&D Activities

The average annual growth rate of areal density of HDDs has exceeded that of DRAM (dynamic random access memory) since 1992 (Fig. 2). Consequently, in 2005 or later, HDDs may reach the critical areal density (up to 200 Gbits/in^2) at which longitudinal recording media causes a thermal decay problem.

The difference between longitudinal magnetic recording and perpendicular magnetic recording is illustrated in Fig. 3. The longitudinal magnetic method aligns recording bits in the plane of a magnetic layer. Longitudinal recording has a problem, however, in that

Fig.2 HDD areal density trends

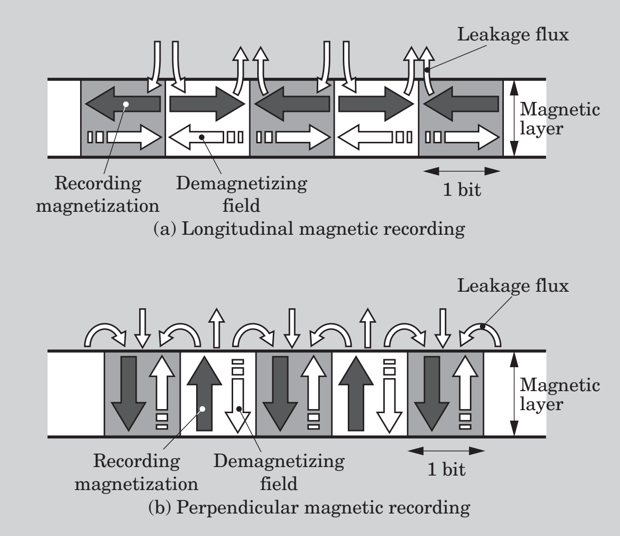


recording bits become thermally unstable at high areal densities due to a demagnetization field oriented in a direction opposite to the recording bits and that acts to erase the magnetization of the recorded bits. At high areal densities, if the size of a recording bit becomes small, the magnetic energy maintaining the recording bit also becomes small causing the recording bit to be erased thermally at room temperature (the so-called thermal decay problem). In contrast, perpendicular magnetic recording is thought to be able to realize several times the areal density (up to 1 Tbits/in^2) of longitudinal recording. In the future, perpendicular magnetic recording will be able to realize areal densities of 40 to 50 Tbits/in^2 when used in combination with thermal assist recording and patterned media (Fig. 4).

Leading HDD makers worldwide are racing to develop perpendicular magnetic recording HDDs because they know that perpendicular magnetic recording technology will drastically change the HDD business (creation of new markets) and HDD technology.

Fuji Electric started to develop perpendicular magnetic recording in 1999 in order to position itself as the leading company in the worldwide memory market. Specifically, we started to develop both granular-type longitudinal magnetic recording media and amorphous Co alloy perpendicular magnetic recording media in order to correct the thermal decay problem. We integrated these two media into granular-type perpendicular magnetic recording media in 2000, began shipping samples to several laboratories in 2001, and demonstrated an areal density of 150 Gbits/in^2, which was the highest in the world at the end of 2002. In March 2003, we began to envision the prospects for practical application of 200 Gbits/in^2 perpendicular magnetic recording media.

Fig.3 Schematic diagram of longitudinal recording and perpendicular recording



3. Configuration of Perpendicular Magnetic Recording Media and Development Challenges

The configuration of perpendicular magnetic recording media is shown in Fig. 5 and the manufacturing process flow is shown in Fig. 6. Perpendicular

Fig.5 Configuration of perpendicular magnetic recording media

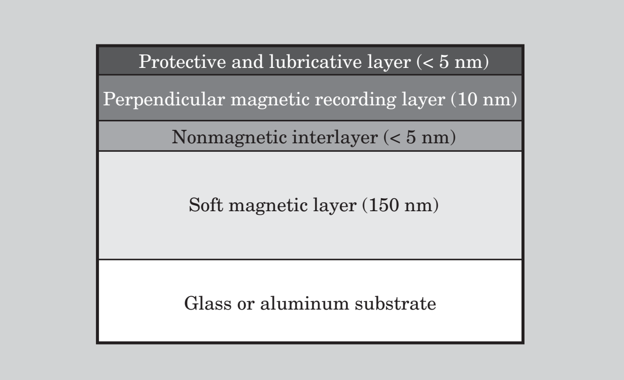
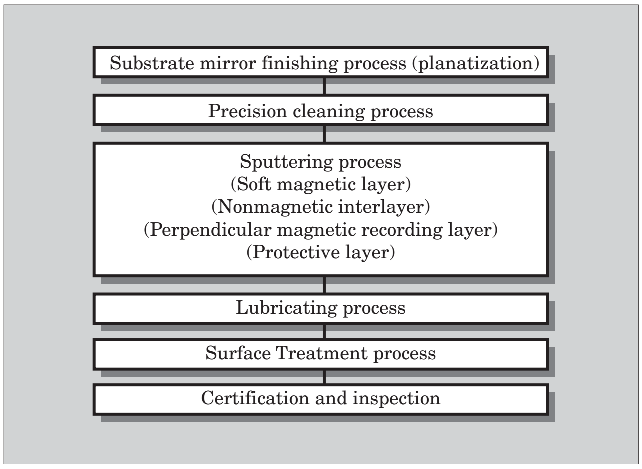


Fig.4 Roadmap of magnetic recording technologies

Year		2002	2003	2004	2005	2006	2007	···	2010
Areal density (bits/in^2)		120G	200G	400G	550G	750G	1T		5T
Coercive force (A/m)		4 to 5×10^5		6 to 7×10^5					
K_u (J/m^3)		3 to 4×10^5		5 to 6×10^5		>1×10^6			
D_{grain}/D_{act} (nm)		6/9		5/5					
Media design	Recording method	Longitudinal recording	Perpendicular recording (conventional)				(Thermal assist recording)		(Patterned media)
	Magnetic material	Granular-type Co alloy		Multilayer (CoX/Pt)			Ordered alloy		

Remarks: D_{grain} = Physical grain size, D_{act} = Grain size calculated from activation volume

Fig.6 Manufacturing process flow of perpendicular magnetic recording media



magnetic recording media consists of aluminum and glass substrates on which soft magnetic layers are formed, and above which are fabricated perpendicular magnetic layers and then protective and lubricative layers. Although the manufacturing process shown in Fig. 6 is simple, each layer is a multilayer and is produced with advanced precision equipment. The following technologies are used in the fabrication of perpendicular magnetic recording media.

(1) Substrate manufacturing and cleaning technologies (Super-polished substrate technology which produces a surface roughness of 0.1 nm for assuring a minimum flying height of 3.7 nm and cleaning technology to eliminate small particles)
(2) Soft magnetic layer technologies (Soft magnetic layer technology that supports the perpendicular magnetic recording head appropriately and is unaffected by electromagnetic noise)
(3) Granular-type magnetic layer technology (Low-noise magnetic layer that supports 200 Gbits/in^2)
(4) Protective and lubricative layer technologies (Protective and lubricative layers that ensure the continuous seek operation of magnetic recording heads at a low flying height of 6 to 7 nm in HDDs)
(5) Durability technologies (Technologies that ensure high durability in computer, vehicular and consumer electronics environments)

4. Development Status

4.1 Substrate technology

Substrates used for perpendicular recording media had to satisfy the required characteristics for surface smoothness and surface cleanliness so as not to inflict mechanical or electrical damage to heads which fly at a low flying height of 6 to 7 nm.

In order to achieve our goal of 200 Gbits/in^2, it was necessary to design the magnetic recording head glide assurance height to be 3.7 nm. This required that the surface be polished to a roughness of 0.1 nm, but there

Fig.7 AFM image of aluminum substrate surface

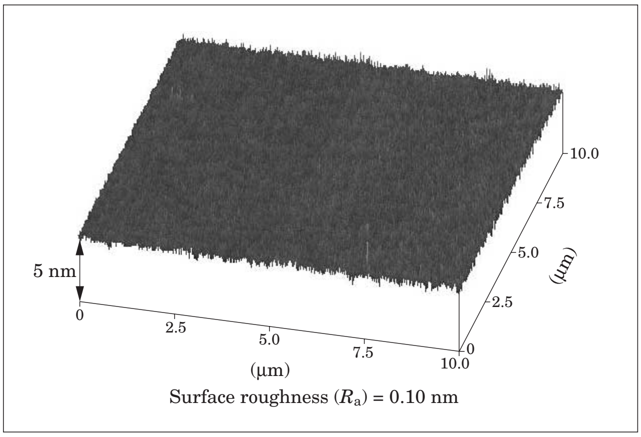
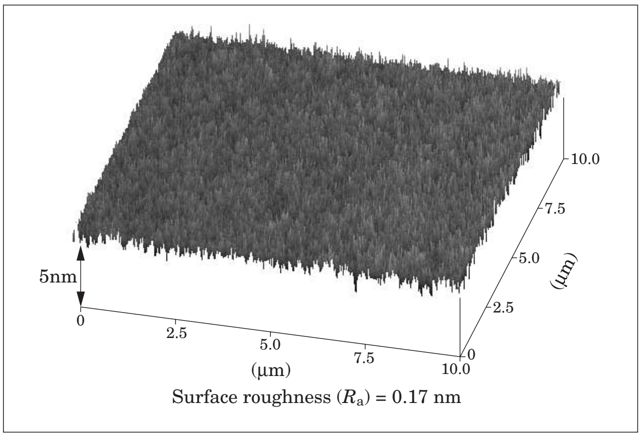


Fig.8 AFM image of glass substrate surface



were no available aluminum or glass substrates that could achieve such a smooth surface. Fortunately, Fuji Electric had become the world-leading producer of aluminum substrates for magnetic recording media and had acquired much expertise in substrate production and polishing. Consequently, Fuji Electric was able to develop substrate manufacturing technologies and succeeded in achieving the necessary surface roughness for aluminum and glass substrates. The image obtained by an atomic force microscope (AFM) of a polished aluminum substrate is shown in Fig. 7. The AFM image of a polished glass substrate is shown in Fig. 8. In both cases, it can be seen that the substrate surfaces have been made highly uniformly. Perpendicular magnetic recording media have a good signal-to-noise ratio (SNR) characteristic when the surface roughness is small as shown in Fig. 9. The good SNR characteristic of Fuji Electric's perpendicular magnetic recording media is achieved by using such substrates.

The substrates used for perpendicular magnetic recording media require a surface cleanliness of 0.01 nm in order to assure the signal quality of very small recording bits. Also, the cleanliness of the substrate surface dominates the bit error rate characteristic which has a strong influence on HDD performance. Therefore, we introduced a new dry cleaning

Fig.9 Relationship between surface roughness and signal-to-noise ratio

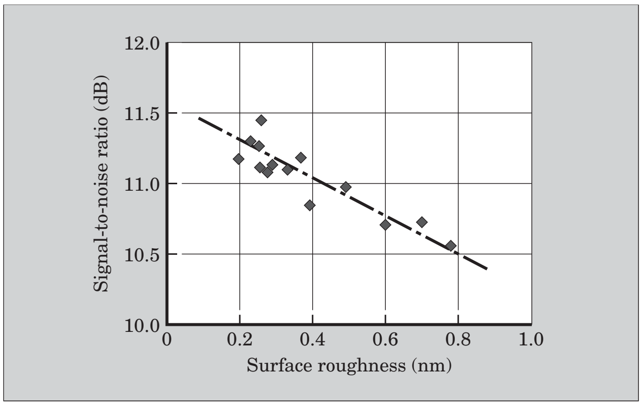
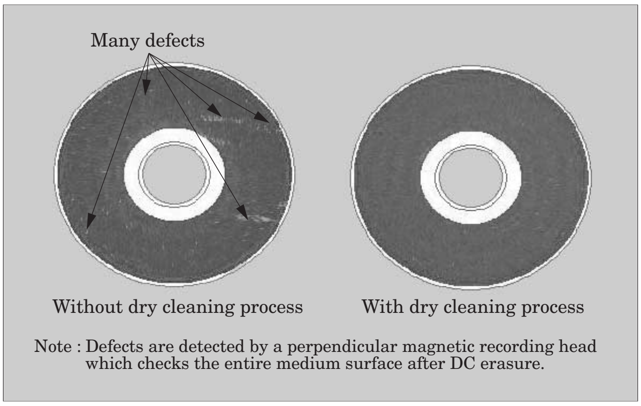


Fig.10 Improvement of substrate cleanliness by dry cleaning



process after the precision cleaning process used in longitudinal recording media, and have succeeded in achieving a high level of substrate surface cleanliness. As shown in Fig. 10, the new dry cleaning process has resulted in a dramatic decrease in media noise due to very small media defects.

4.2 Soft magnetic layer technology

The soft magnetic layer is an additional layer unique to perpendicular magnetic recording media and it forms the underlayer that attracts leakage magnetic flux generated from the perpendicular magnetic recording head when the head records bit data. Therefore, the soft magnetic layer is desired to have a high saturation flux density, uniform ability to attract flux by magnetic domain control, and low noise due to control of microcrystalline and amorphous microstructures.

We chose a soft magnetic layer made from the amorphous CoZrNb to strike a balance between high saturation flux density and low noise. We also designed the composition of an amorphous alloy having high heat resistance capability for the post-process heat treatment and having no problem in passing field reliability tests under severe conditions.

On the other hand, the width of the soft magnetic layer, the thickest among all layers of the perpendicular magnetic recording media, was a factor that limited the sputtering process throughput speed and the production cost. We tried to increase the thickness of the sputtering target used for a soft magnetic layer in order to lengthen the sputtering target life and to reduce production cost. However, such a target would not discharge in a vacuum process because the soft magnetic material has high permeability and traps the magnetic flux used for magnetron sputtering. Consequently, we examined two methods for increasing the thickness of the sputtering target. One method was to change the alignment of magnets in the sputtering cathode, and this succeeded in extending the target life by 30 to 50 percent. The other method was to reduce the thickness of the soft magnetic layer from 400 nm to 150 nm by optimizing the sputtering conditions. The combination of these two methods greatly increased the productivity of perpendicular magnetic recording media.

We are trying to improve the productivity of perpendicular magnetic recording media even further, and these efforts are summarized as follows:

(1) Development of soft magnetic material having higher saturation flux density (2.2 T, twice that of the present material)

(2) Development of soft magnetic material capable of super high-speed film deposition (10 times the present deposition rate)

Additionally, we are developing two technologies for the magnetic domain control of a soft magnetic layer and aim to commercialize two products based on these results.

(1) Development of the pinning layer, which is deposited between the substrate and soft magnetic layer, and acts to control the magnetic domain of the soft magnetic layer (Because the soft magnetic layer of this product has a high permeability, this product will be suitable for high-end HDDs that require a high transfer rate)

(2) Development of a soft magnetic layer for which magnetic domain control is unnecessary (This product will be suitable for low-end HDDs in which low cost is the first priority)

4.3 Granular magnetic layer technology

The ideal microstructure for either a longitudinal or perpendicular recording magnetic layer will have the following characteristics.

(1) Epitaxial growth in the desired crystal plane only (Epitaxial growth in the plane of the c-axis in the case of longitudinal recording media, or epitaxial growth perpendicular to the c-axis in the case of perpendicular recording media)

(2) A segregated structure that achieves magnetic separation between grains (Reduction of media noise due to magnetic interference)

(3) A grain size that is sufficiently small but not to the extent that causes thermal decay; low varia-

tion in the grain size

Conventionally, a metallic magnetic layer was deposited after heating of the substrate and thermally nonmagnetic materials of Cr and B were thermally diffused to grain boundaries to realize a segregated structure. However, the inducing of a segregated structure by a heating process caused the crystals to grow too. After all we could not have it both ways (Fig. 11).

On the other hand, a granular-type magnetic layer, which is characterized by low temperature deposition, realized a segregated structure by diffusing nonmagnetic material (e.g. SiO_2) at room temperature. That is to say, as it was unnecessary to heat the substrate of the granular-type magnetic layer, the crystal growth was more regular and there was less variation in grain size than with a metallic magnetic layer (Fig. 12).

A granular-type magnetic layer, however, presents some major technical challenges. The main challenge concerned initial crystal growth. In contrast to a metallic magnetic layer, thermal energy does not induce crystal growth and a segregated structure in a granular-type magnetic layer. So it was very difficult for a granular-type magnetic layer to achieve good crystallinity and good segregated structures from its initial deposition layer. Fuji Electric has successfully resolved these problems by improving deposition process technologies for soft magnetic layers and magnetic layers and by redesigning the composition of these magnetic layers.

Fig.11 Transmission electron microscope image of longitudinal magnetic recording media

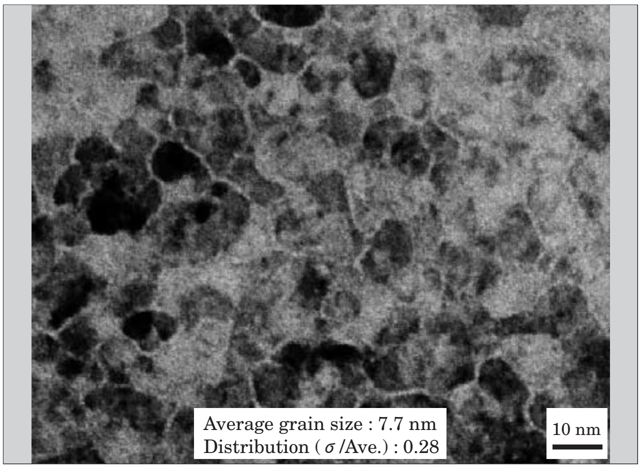
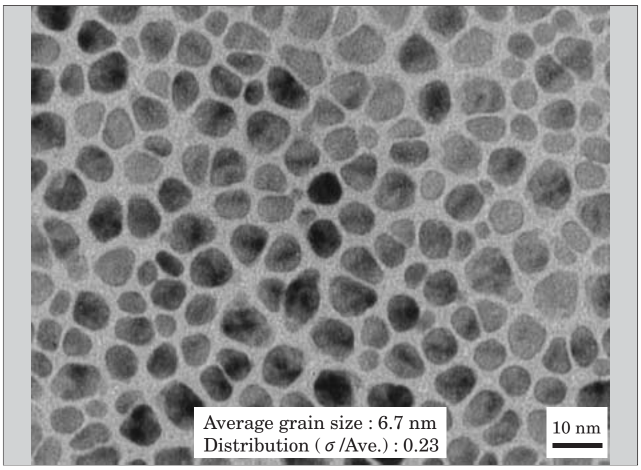


Fig.12 Transmission electron microscope image of granular-type perpendicular magnetic recording media



Several problems were encountered in achieving an areal density of more than 200 Gbits/in^2. One was the development of a technology to prevent the growth of face centered cubic (fcc) structures that reduce the magnetic anisotropic energy of the magnetic layer. A granular-type magnetic layer formed from Co alloy material needs to form a hexagonal close-packed (hcp) structure, but Co alloy material has the problem of tending to grow fcc structures when the doping concentration of Pt increased to realize a high coercive force. Since the microstructure of nm-order thin film was very difficult to analyze with regular analytical equipment, in 1999, Fuji Electric started to develop analysis technology for microstructures of magnetic layers used by Japan's SPring-8 Synchrotron Radiation Research Institute, which is the world's largest third-generation synchrotron radiation facility, and we have verified the existence of fcc structures in a granular-type magnetic layer (Fig. 13). Based on such analytical results, we hope to be able to develop high performance perpendicular magnetic recording media that is almost completely free of fcc structures, because we will be able to control precisely the deposition process of the thin film.

4.4 Protective and lubricative layers technology

Establishment of the following technologies is critical for developing protective and lubricative layers for perpendicular magnetic recording media.

(1) Highly reliable technology for assuring trouble-free seeking operation of a perpendicular magnetic recording head even at a low flying height, and in severe conditions of the temperature, vibration and impact occurred in a vehicle or mobile device.

Fig.13 Analysis of granular-type magnetic layer

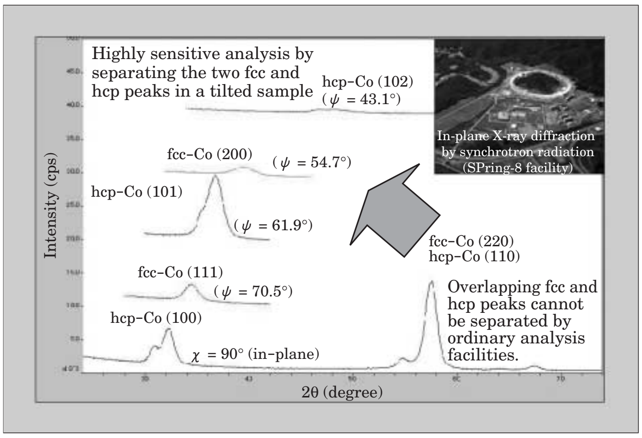


Fig.14 Schematic diagram of protective and lubricative layers

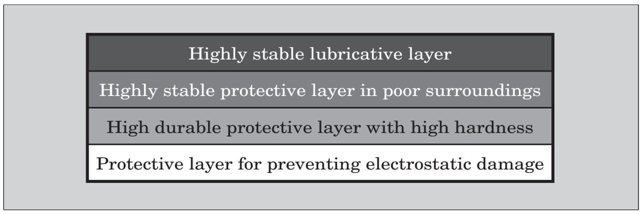


Table 1 Demonstration of areal density

Time	Areal density (Gbits/in^2)	Linear density (kbits/in^2)
Nov. 2001	61	616
May 2002	105	727
Sep. 2002	134	793
Nov. 2002	146	813
July 2003	—	867

(2) Technology for preventing electrostatic damage, because the resistivity of a granular-type magnetic layer is higher than that of a metallic magnetic layer

Fuji Electric has developed new protective and lubricative layers that have a functionally separated structure. Figure 14 shows a schematic diagram of this structure. Perpendicular magnetic recording media based on these technologies have been experimentally verified to achieve performance and corrosion resistance equal to that of the present longitudinal recording media.

4.5 Read-write characteristics

The read-write characteristics of our perpendicular magnetic recording media produced by these technologies has been verified by several laboratories throughout the world. Table 1 shows some of the data. Each data value in the table indicates that our perpendicular magnetic recording media achieved the highest areal density level in the world at that time.

5. Conclusion

It has been more than 25 years since Emeritus Professor Iwasaki of Tohoku University published his pioneering work of perpendicular magnetic recording media. Thereafter, longitudinal recording has been predicted to be about to reach its limit of areal density again and again, but each time, that limit has been surpassed by technical innovation of the magnetic recording head, circuitry and HDD mechanism. However, longitudinal recording is reaching its practical limit at last, because it is impossible to increase the areal density to more than 160 to 200 Gbits/in^2 due to the thermal decay problem of magnetic recording media. Fortunately, Fuji Electric's perpendicular magnet recording media will be able to surpass this limit.

We at Fuji Electric have not developed perpendicular magnetic recording media by ourselves, however. Compared to other companies, we were late to begin developing perpendicular magnetic recording media. Fortunately we have been able to compensate for this late start in development by receiving assistance from many people in various laboratories, including Emeritus Professor Nakamura of Tohoku University, Emeritus Professor Muraoka of Tohoku University and Assistant Professor Shimazu of the Research Center for 21st Century. We would like to express our appreciation to all these individuals.

Fuji Electric expects that the year of 2005 will be a turning point for its media business and is planning to start mass-producing perpendicular magnetic recording media in that year. Moreover, in addition to the perpendicular magnetic recording media business, we are also thinking about the possibilities for our substrate business. In our medium-term business plan, the perpendicular magnetic recording media business is a very important part of Fuji Electric. We have already started to develop future perpendicular magnetic recording media of 400 Gbits/in^2, and we aim to become a leading media manufacturer in the external memory market and to contribute to the safe and convenient ubiquitous computing society of the 21st century.

References

(1) Iwasaki, S. et al. An Analysis for the Circular Mode of Magnetization in Short Wavelength Recording. IEEE Trans. Magn. vol.11, no.6, 1975, p.1137-1139.

(2) Takano, H. et al. A Practical Approach for Realizing High-Recording Density Hard Disk Drives. Abstracts of The 8th Joint MMM-Intermag Conference. CA-01, 2001, p.131.

(3) Oikawa, T. et al. Microstructure and Magnetic Properties of CoPtCr-SiO_2 Perpendicular Recording Media. IEEE Trans. Magn. vol.38, no.6, 2002, p.1976-1978.

(4) Uwazumi, H. et al. CoPtCr-SiO_2 Granular Media for High Density Perpendicular Recording. Digest of Joint [NA] PMRC 2003. 2003, p.47.

(5) Wood, R. The Feasibility of Magnetic Recording at 1 Terabit per Square Inch. IEEE Trans. Magn. vol.36, no.1, 2000, p.36-42.

(6) Iwasaki, S. et al. Perpendicular Magnetic Recording with Composite Anisotropy Film. IEEE Trans. Magn. vol.15, no.6, 1979, p.1456-1459.

(7) Ohsawa, M. et al. In-Plane Diffraction of Co-based Perpendicular Magnetic Recording Media. SPring-8 User Experiment Report. no.10, 2002B, 2003, in press.

e-Front runners