A study on high-density recording with particulate tape media for data storage systems

— On the process of introducing barium-ferrite tape media to the market —

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Magnetic tape storage systems are widely used for archive and data backup from their characteristic of low cost and large capacity. Research on magnetic tape targets higher recording densities to meet market needs for continuously increasing storage capacity like in other storage media. Progress on increasing the recording density of magnetic tapes using conventional magnetic metal particles has slowed in the years leading up to 2010. However, progress improved in 2011 with the introduction of tape media using barium-ferrite magnetic particles. In this paper, we describe the process of going from basic research on tape media using barium-ferrite to marketplace introduction.

Keywords : Barium ferrite, particulate tape media, areal recording density, linear tape system, data storage

1 Introduction

At present, the rate of data creation is increasing explosively, because of the advancement of computers, increased communication events through established communication infrastructures, and the improved performance of devices such as sensors. The volume of data generated and duplicated internationally was 0.9, 1.8, and 4.4 ZB (10^{21} bytes) in 2009,[1] 2011,[2] and 2013,[3] respectively. This is an increase of 40 % per year, with this value being expected to reach 44 ZB in 2020. Therefore, continuous increase in recording density for data storage devices is being pursued. Among the various storage systems, magnetic tape continues to be used as a back-up for hard disk drives (HDDs) and for archives requiring long-term data storage,[4] because of the associated low system and bit costs, long lifespan, and energy-saving properties of this technology. As shown in Fig. 1, while the areal recording densities of HDDs, optical disks, and magnetic tape are increasing annually, progress regarding recording density development has recently been on the decline. Further, the rate of improvement of magnetic tape recording density began to decelerate in approximately 2010. This deceleration occurred because a limit was reached regarding the creation of the fine particles essential for achieving high-density with metal-particle (MP) magnetic material, which was the mainstream recording material at that time. Therefore, in 2011, Fujifilm Corporation introduced magnetic tape based on a barium-ferrite (BaFe) magnetic material to the market. The use of BaFe allowed further fine particle formation and succeeded in re-accelerating the rate of recording density enhancement. In this paper, we describe the process from basic research to commercialization for BaFe tape, which is a major technological innovation for the magnetic tape industry.

2 History of magnetic tape

2.1 Use of magnetic tape

Magnetic recording was first introduced in 1898, with the invention of the magnetic recording device by Valdemar Poulsen, a Danish scientist working on audio recording. Later, magnetic recording technology expanded from sound recording to the fields of image and information recording, with the rapid advancement of television, computers, and similar technology.

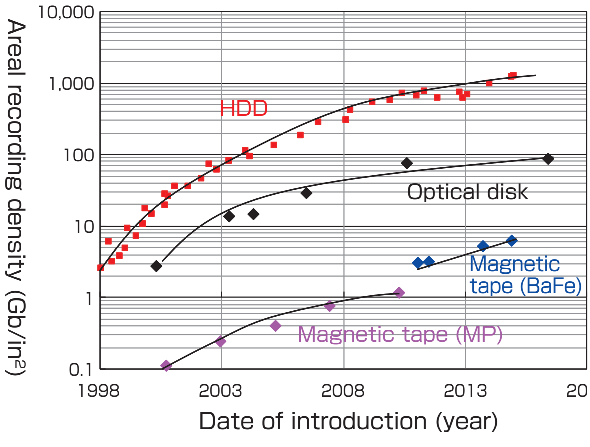

Fig. 1 Transition of the surface recording density of HDD, optical disk, and magnetic tape

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In the audiovisual field, audiocassettes and videotapes associated with technology, such as the video home system (VHS) and the 8-mm video system, were widely used until the 1990s; however, these devices disappeared with the advancement of optical disks such as compact discs (CDs) and digital versatile disks (DVDs). After the 2000s, broadcasting videotapes were replaced by new recording media such as optical disks and HDDs, with videotapes gradually reaching the end of their application lifespan.

On the other hand, in the information recording field, magnetic tapes were employed as memory devices for computers from approximately 1950 onwards. With further development of computers, magnetic tapes, which were characterized by low price and large capacity, were widely employed by data centers, major companies, government agencies, and research institutes. Recently, magnetic tapes have predominantly been employed in the information recording field rather than image recording. Currently, three representative tape systems exist: linear tape-open (LTO), which is most widely used as an open format, and International Business Machines (IBM)'s 3592 and Oracle's T10000, which are closed systems for enterprise use. The recording densities of these three systems are continuously improving. Currently, LTO, 3592, and T10000 have achieved 6,[5] 10,[6] and 8 TB tape cartridges, respectively.[7] All these systems use the BaFe magnetic material.

2.2 Transition of magnetic tape technology

At present, mainstream magnetic tape manufacturing procedures employ a coating method to achieve low cost and mass production. As shown in Fig. 2, a nonmagnetic layer that provides conductivity and surface smoothness is formed on a plastic base film. Then, a magnetic layer for data recording is formed on top of that layer, whereas a backcoat layer is formed on the backside of the base film to provide runability for the tape medium.

High-density recording for magnetic tape was achieved in accordance with the principles of magnetic recording. That is, the following three requirements were satisfied: (1) fine particles of magnetic material; (2) a thin magnetic layer; and (3) surface smoothness of the magnetic layer. Figures 3–5 show the trends for the magnetic-material particle sizes in the magnetic tapes, the magnetic layer thickness, and the average surface roughness *Ra*, which is the surface smoothness index. It is apparent that continuous progress has been made toward finer magnetic particles, thinner magnetic layers, and smoother surfaces. In particular, as is apparent for the magnetic layer thickness trend shown in Fig. 4, the technological innovation that shifted the magnetic tape layer structure from single to multilayer (where the magnetic layer was formed on a nonmagnetic layer) caused the magnetic layer thickness to shift from the order of several microns

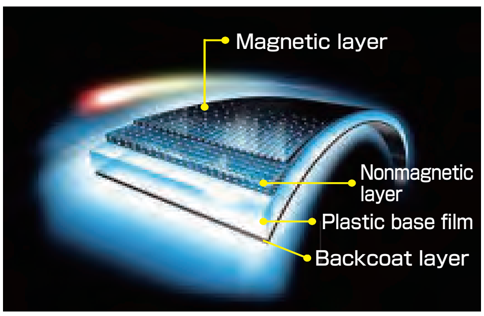


Fig. 2 Structure of the magnetic tape

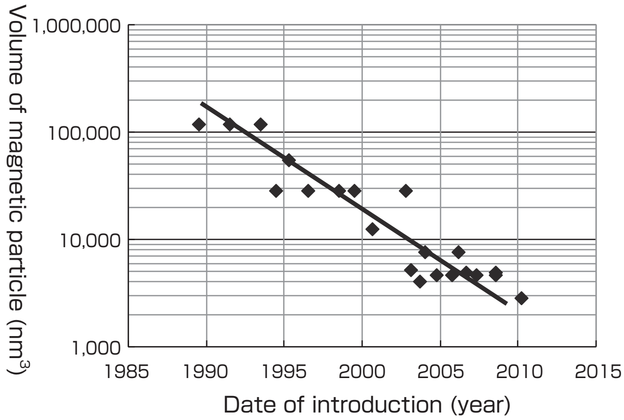


Fig. 3 Transition of the magnetic material volume

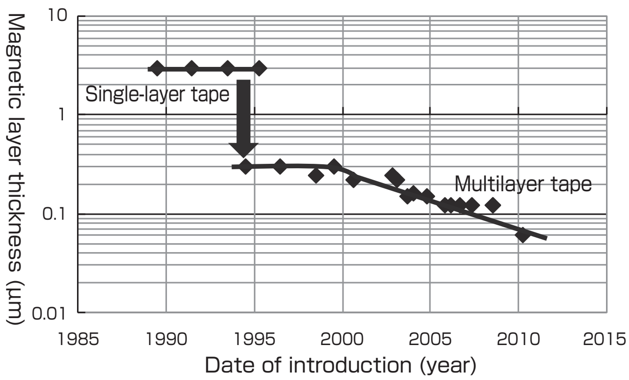


Fig. 4 Transition of the magnetic layer thickness[8][9]

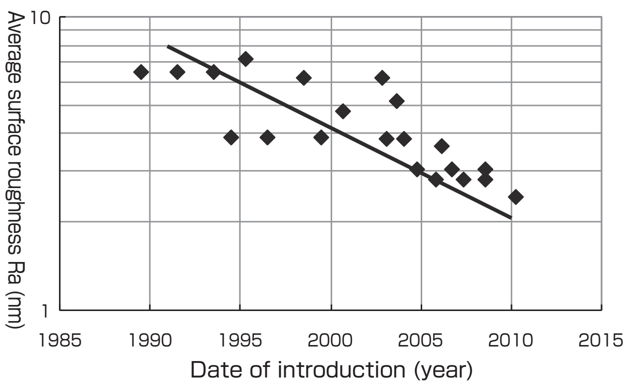
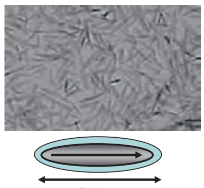
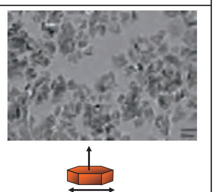


Fig. 5 Transition of the surface smoothness of tape

Table 1. Characteristics of the magnetic material

Magnetic material	MP	BaFe
TEM image and schematic diagram	 35 nm	 20 nm
Raw material	FeCo, Required passivation layer for oxidation-protection	$BaO(Fe_2O_3)_6$, Stable because of oxide
Origin of magnetization	Shape anisotropy	Crystal anisotropy
Direction of magnetization	Longitudinal direction	Perpendicular direction
Saturation magnetization (Ms)	600–900 emu/cc	250–300 emu/cc

to submicron order; hence, the layer thinness decreased dramatically.[8][9] On the other hand, the fineness of the MPs for the magnetic materials approached a limit in the latter half of the 2000s. This was because it became difficult to maintain sufficient coercivity (a property necessary to maintain recorded signals) as the MPs became finer (Fig. 6). On the other hand, in the newly developed BaFe magnetic material, sufficient coercivity is maintained for fine particles of approximately 1000 nm^3 in size, by controlling the composition and synthesis processes. In the next section, the characteristics and issues of the BaFe magnetic material are described.

3 Characteristics and issues of BaFe magnetic material

3.1 BaFe magnetic material characteristics

The characteristics of MPs and BaFe magnetic materials are compared in Table 1. The MP magnetic material is a needle-shaped metal alloy primarily composed mainly of iron (Fe) and cobalt (Co). To inhibit oxidation, a passivation layer of at least several nanometers in thickness is necessary. This material also has magnetic-shaped anisotropy, where the origin of the magnetization comes from the needle-like shape of particle. To increase the anisotropic energy, a high axial ratio (long-axis length/short-axis length) is necessary. On the other hand, the BaFe magnetic material is an oxide with crystal magnetic anisotropy, where the anisotropic energy is determined by the crystal structure of the particle. Further, the axis of easy magnetization of the BaFe magnetic material is perpendicular to the plate surface. This material has the characteristic of a magnetization component that is perpendicular to the magnetic layer when the tape is formed.

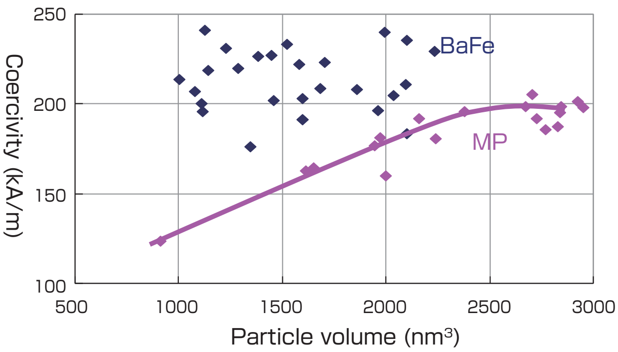


Fig. 6 Particle volume and coercivity of the magnetic material

Based on consideration of these characteristics, we determined that the BaFe magnetic material possesses the following superior properties, concluding that this material was the most likely candidate for a post-MP magnetic material.

(1) Regarding the MP magnetic material, it is difficult to increase the high axial ratio of the particles, passivation layer for oxidation-protection is required, and sufficient coercivity cannot be maintained as the particles become finer. In contrast, the BaFe magnetic material can maintain high coercivity in fine-particle form, because its anisotropic energy is determined by the crystal structure. Further, no passivation layer for oxidation protection is required.

(2) The BaFe magnetic material, which is an oxide, is extremely stable in a high-temperature and high-humidity environment, and has excellent long-term storage properties in tape form (Fig. 7).

(3) As a magnetization component exists perpendicular to the magnetic layer when the tape is formed, application of the BaFe magnetic material to the perpendicular magnetic recording achieved for HDD could be expected.

3.2 Issues related to BaFe magnetic material

As mentioned in the previous subchapter, although the BaFe magnetic material has many characteristics that are advantageous for achieving high density, the following issues required resolution during R&D in order to fully exploit its characteristics.

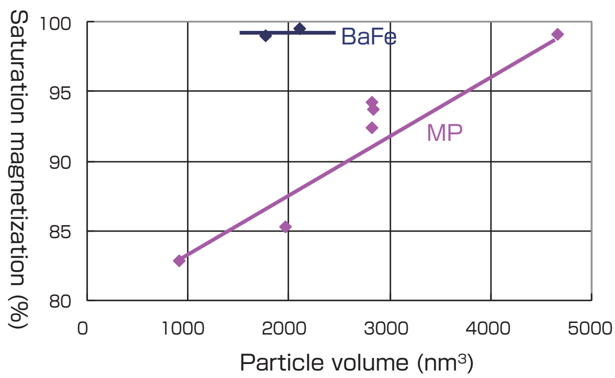


Fig. 7 Change in the saturation magnetization (Ms) for one month storage at 60 °C and 90 % RH (relative humidity)

(1) As the BaFe magnetic material is in fine-particle and plate form, the magnetic materials are likely to aggregate. Thus, it was not possible to create a uniform, smooth, and thin magnetic layer using conventional dispersion or coating technology.
(2) As the saturation magnetization quantity (Ms) of the BaFe magnetic material is small, the reproduced output is lower than that of MP tape; thus, it was necessary to supplement this output with a highly sensitive magnetic head (Fig. 8).
(3) As the BaFe tape has perpendicular magnetization components, the symmetry of the isolated transition response is extremely poor; signal processing technology was required to correct this asymmetry.
(4) No system manufacturers expressed interest in BaFe tape or were willing to conduct joint development.

4 Scenario for market entry and execution

4.1 Scenario for market entry

Research on BaFe tape media was initiated in 1992 by three engineers. After ten years, as we were unable to show results that exceeded the performance of MP tapes, the project was then interrupted several times. Finally, the project was almost terminated. However, with the development of new dispersion and coating technology in 2001, which extracted the potential of the BaFe magnetic material, as well as the introduction of evaluation technology using a high-sensitivity head that enhanced the BaFe tape performance, we could present results that dramatically exceeded the performance of MP tape. Thus, the research project was continued under stimulus (first stage).

Joint research with the IBM Corporation, a system company that possesses leading technology, was later initiated based on these results. We successfully demonstrated a previously unseen high areal recording density, through the development of drive technology that extracted the BaFe tape performance capability (second stage). Based on the results of this joint research, system development was initiated with several tape drive system manufacturers, including IBM. We conducted practical application development and mass-production technology development for the BaFe tape, and introduced various tape products to the market (third stage). Along with product development, we conducted joint research with IBM towards achieving a higher areal recording density using the BaFe tape. The results were published concurrently with the introduction of the aforementioned BaFe tape products to the market. With these announcements, BaFe technology became recognized as being capable of supporting tape systems for several future generations, and this result accelerated the growth of the products that had been introduced to the market (fourth stage). Further details of each of these steps are presented in the following subchapter.

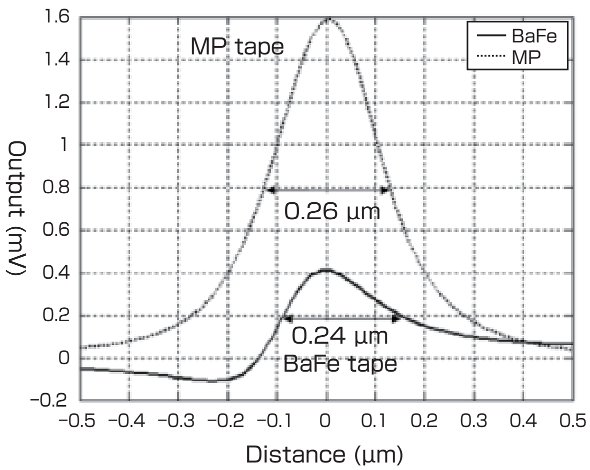


Fig. 8 Comparison of the isolated transition response of BaFe/MP

4.2 Scenario execution

4.2.1 First stage: Basic research (–2003)

Demonstration of recording performance by Fujifilm

To extract the high recording performance expected for BaFe tape by overcoming the issues listed in Subchapter 3.2, we first developed high-dispersion technology and ultra-thin layer coating technology for application to the BaFe tape. In addition, we developed evaluation technology using a high-sensitivity head.

(1)-1: High-dispersion technology

As the BaFe magnetic material is comprised of fine magnetic particles and the shape of the particle is hexagonal plate-like, the plates tend to stack upon each other and aggregate. Thus, the magnetic material must be uniformly dispersed to obtain the fine particle effect. However, when the conventional dispersion method is employed, the fine magnetic particles aggregate into blocks of several to dozens of particles, yielding a non-uniform distribution, as shown in Fig. 9. By shifting from MPs to BaFe magnetic material, we succeeded in achieving monodispersity of the fine particles of the BaFe magnetic material. This was achieved through the development of new organic materials such as dispersants and polymers, as well as the development of a new dispersion process.

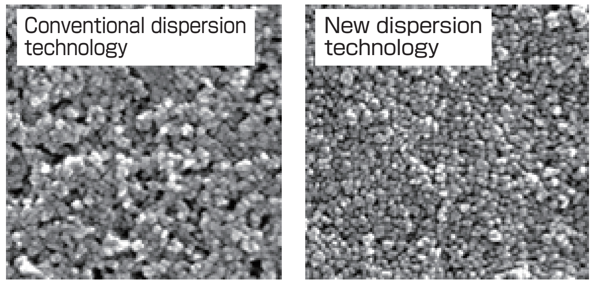


Fig. 9 SEM image of the tape surface

(1)-2: Ultra-thin layer coating technology

Although the achievement of a thin magnetic layer is essential for obtaining a high recording density for a magnetic recording medium, it was difficult to achieve a thin layer of 0.1 µm or less using the conventional coating method. As shown in Fig. 10, it was not possible to obtain a uniform thin magnetic layer using this method because of the turbulence at the interface with the nonmagnetic layer forming the lower layer. This tendency was prominent for the coating solution of the BaFe magnetic material. Therefore, we developed a new coating method and achieved a thin magnetic layer with a thickness of several tens of nanometers, a low thickness variation, and uniformity, with no mixing at the interface with the nonmagnetic lower layer.

(2) Development of evaluation system using high-sensitivity head

At this stage, no high-sensitivity magnetic head had been developed that could adequately extract the BaFe tape performance. Therefore, we decided to conduct media evaluation using the HDD head that was the leading technology at the time. Rather than the tape-evaluating device that was in our possession, we acquired an evaluation device for disks, which featured a merged anisotropic magneto resistive (AMR) head with a 1.9 µm reader-width that was used for HDD. We then conducted the evaluation using a disk-shaped BaFe medium. Figure 11 shows the modulation spectra of the MP medium used at the time and the BaFe medium to which new dispersion and coating technology was applied, at a linear recording density of 180 kfci (flux change per inch). As is apparent from these modulation spectra, the BaFe-medium output was +4 dB compared to that of the MP medium. The BaFe-medium signal-to-noise ratio (indicating the read/write performance of the medium) was +10 dB, which indicated the possibility of achieving a recording density ten times higher than that of the MP medium.[10]

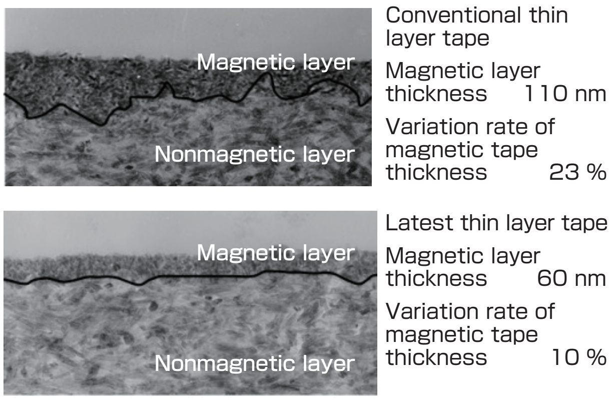


Fig. 10 TEM image of the tape cross-section

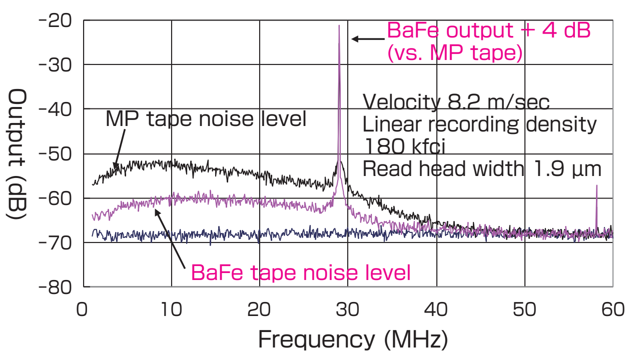


Fig. 11 Modulation spectra of the MP medium and the BaFe medium[10]

4.2.2 Second stage: Research on potential system application (–2006)

Demonstration of recording density for tape-drive system manufacturers

During the first-stage research conducted within our company, we confirmed the high recording performance of the BaFe tape for the first time. However, we were unable to convince tape-drive system manufacturers to begin tape-drive system development for BaFe tape only by the recording performance result of a magnetic tape manufacturer alone. Therefore, in the next research stage, we aimed to conduct joint research involving tape-drive system manufacturers, so as to develop new signal processing technology that would enable waveform correction of the BaFe (as discussed in Subchapter 3.2). In addition, we aimed to build relationships with system manufacturers.

IBM Corporation, the leader in the field of tape-drive system technology, was selected as our partner in this joint research. Following assessment by IBM of our evaluation data and BaFe tape prototypes, along with repeated explanation by the authors of the potential of the BaFe tape, this joint research project was initiated. The major turning point in this research was the selection of the read head. We proposed an evaluation using the giant magneto resistive (GMR) head that was standard for HDD, rather than the AMR head that was used for tape at the time; however, IBM was hesitant in selecting the GMR head, which was unknown in tape industry and was a new device at the time. We conducted evaluation using the GMR head for different systems, such as HDD and demonstrated the high recording performance of the BaFe tape.[11][12] Finally, IBM decided to employ the GMR head and, as a result of this joint research, we succeeded in demonstrating a high areal recording density of 6.7 Gb/in^2 (equivalent to a cartridge volume of 8 TB) for the BaFe tape, which was approximately 17 times the 0.4 Gb/in^2 areal recording density that was common for products in 2006.[13] The technical highlights were as follows: (1) Improved linear recording density was achieved via the combination of the magnetic tape using BaFe fine magnetic particles and the new signal processing technology known as “data dependent noise predictive maximum likelihood” (DD-NPML); (2) Improved track density was obtained using high-precision head-following technology. Through application of the new DD-NPML signal process, which was developed by IBM in this joint research project,[14] the readback waveform distortion that was detrimentally affecting the BaFe tape performance was corrected and the target error rate was reached. Hence, IBM decided to set BaFe tape as the central focus of next-generation tape technology. At this stage, we had solved issues (3) and (4) of Subchapter 3.2, i.e., the need for waveform asymmetry correction and the selection of a partner for system development. Thus, significant progress had been made toward commercial realization of BaFe tape.

Other than the BaFe tape proposed by Fujifilm, Hitachi Maxell, Ltd., proposed an iron nitride (nano-composite advanced particles; NanoCAP) magnetic material tape,[15] whereas Sony Corporation proposed a metal evaporated (ME) tape.[16] Thus, discussions were initiated among the Information Storage Industry Consortium (INSIC), the industrial organization for tape systems, regarding the next-generation tape that would succeed MP tape.

4.2.3 Third stage: Product realization research (–2011) Establishment of mass production technology for BaFe tape

The initial issues were all solved in the first and second research stages, and BaFe tape became widely known to many system manufacturers through technological demonstrations with IBM. In addition, we provided technical descriptions and prototypes of the BaFe tape to Oracle Corporation, Japan, Hewlett-Packard Japan, Ltd., and Quantum Corporation, and advanced to the practical application stage by repeating the performance evaluation of the BaFe tape. In 2011, the BaFe tape was employed in IBM's 3592 fourth-generation drive[17] and Oracle's T10000 third-generation drive,[18] and product realization of 4 and 5 TB tape cartridges were achieved, respectively. In 2012, the BaFe tape was employed in the LTO sixth-generation drive;[19] thus, the BaFe tape had been introduced to all the targeted major tape systems at that point.

Within our company, effort was expended on developing mass production technology and practical use technology. For mass production, we developed a process that enabled stable production of high-density tape, primarily by upscaling the new dispersion and coating technology mentioned in the previous subchapter. For practical use technology, improvements were primarily made to the durability of the BaFe tape. A tape system must clear severe endurance tests, such as a whole-length run, which may reach tens of thousands of passes for a wide range of temperatures and humidity (10–32 °C, 10–80 % relative humidity (RH)). Work was performed regarding the surface profile design, lubrication, and wear. After the development of this mass production technology and practical use technology, market entry of the BaFe tape, our final goal, was realized.[20]

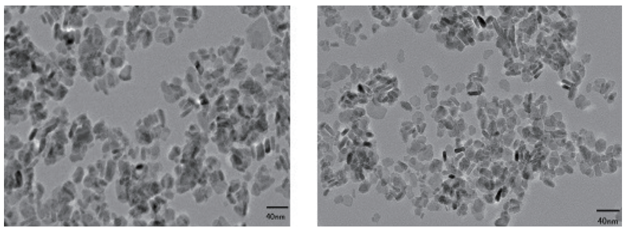
4.2.4 Fourth stage: Research on further possibilities (–2015) Demonstration of higher recording density

The long-desired market entry of the BaFe tape was achieved in 2011. However, the main point of interest for users, who were required to invest highly in accommodating system change, was the potential for future development of the BaFe technology. Therefore, we continued to demonstrate the possibilities for improving the recording density of the BaFe tape, while also implementing product realization research; these future prospects were continuously presented to the market.

In 2010, one year before the market entry of the BaFe product, we achieved a successful technical demonstration of an areal recording density of 29.5 Gb/in^2[21] (equivalent to a 35 TB cartridge volume). For the BaFe tape employed in this technical demonstration, we accomplished the following: (1) a fine particle volume for the BaFe magnetic material of 1600–2100 nm^3 (Fig. 12); (2) an average *Ra* of 0.9–2.0 nm (Fig. 13); and (3) improvement in the degree of orientation in the perpendicular directions from 0.61 to 0.86, by employing perpendicular magnetic field orientation technology for magnetic materials (Fig. 14).

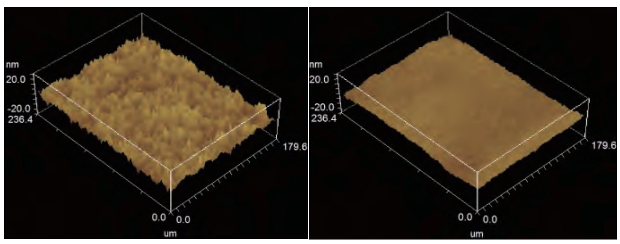
The technology used to achieve these accomplishments ((1) to (3)) were then further advanced and, in 2014, we technically verified an areal recording density of 85.9 Gb/in^2[22] (equivalent to 154 TB). This was later increased to 123 Gb/in^2[23] (equivalent to 220 TB), in 2015.

BaFe tape was introduced to the market more than 20 years after research was initiated. The potential for achieving higher recording density in the next decade has been



BaFe product	29.5 Gb/in^2 demonstration tape
Particle volume 2100 nm^3	Particle volume 1600 nm^3
Coercivity 182 k/Am	Coercivity 203 k/Am

Fig. 12 TEM image of the BaFe magnetic material[21]



BaFe product Ra : 2.0 nm
29.5 Gb/in^2 demonstration tape Ra : 0.9 nm

Fig. 13 Surface profiling using the optical interferometry surface roughness meter[21]

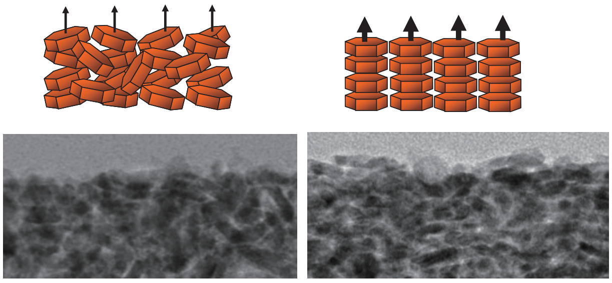
established through the technical demonstrations conducted concurrently with product development. In addition, we have established BaFe tape as the *de facto* standard to replace MP tape.

5 Summary

We successfully responded to the market demand for increased data storage capacity by accelerating the development of high-density tape systems. This was achieved using BaFe magnetic material in place of MP magnetic material, which was approaching its performance limit.

The major factors that enabled this innovation for the establishment of BaFe tape as the *de facto* standard are the following: We pursued the necessary technological development based on a belief in the potential of the BaFe tape, and we sought the involvement of other groups. Of course, the technological innovation of the BaFe magnetic material itself was important; however, the development of peripheral technology to extract the potential of the BaFe magnetic material and BaFe tape was of greater importance. The high density of the BaFe tape could not be achieved without the development of new dispersion and coating technology within our company, along with the development of a high-sensitivity magnetic head and waveform equalization technology outside our company.

A period of approximately 20 years elapsed between the beginning of the research project and product realization. During this time, we continued the research without faltering, because we understood the essential characteristics of the BaFe magnetic material (including its disadvantages), and because we also understood that these characteristics could be effectively employed to achieve high-density magnetic recording in principle. While this case study is not quite the efficient R&D that is in demand today, we hope it constitutes a study of a research process in which the innovation originated from a stance of perseverance, along with the involvement of others based on the essence and characteristics of the developed material.



BaFe product
Orientation ratio (perpendicular direction): 0.61

29.5 Gb/in^2 demonstration tape
Orientation ratio (perpendicular direction): 0.86

Fig. 14 TEM image of the cross-section of magnetic layer[21]

Finally, to respond to the continuously increasing market demand for data storage, we believe further increase to the high density of the tape system will be achieved by incorporating state-of-the-art drive technology innovation for HDD and by developing new high-density technology for tape. A timeline of the main events of this research project is presented in Fig. 15.

1st step	1992	· BaFe tape research started by three researchers.
	2001	· Succeeded in presenting high recording property of BaFe tape for the first time within company, although the research was about to be discontinued.
2nd step	2004	· Started joint research with IBM on recording density demonstration.
	2006	· Fujifilm demonstrated the potential for high recording density of BaFe tape by combination with GMR head.[11][12] · Succeeded in technical demonstration of areal recording density 6.7 Gb/in^2 (volume 8 TB equivalent) for BaFe tape jointly with IBM.[13] · Hitachi Maxell, Ltd. proposed iron nitride tape, Sony Corporation proposed metal evaporated tape, and discussion of post metal tape began in the tape industry.
3rd step & 4th step	2007	· Started providing samples and presentations of BaFe tape to various tape drive system companies.
	2010	· Succeeded in technical demonstration of recording density 29.5 Gb/in^2 (volume 35 TB equivalent) for BaFe tape jointly with IBM.[21]
	2011	· Employed as the tape for Oracle's (SUN at the time) T10000 third-generation system (volume 5 TB). This was the first successful commercialization of BaFe tape. · Succeeded in commercialization as the tape for IBM 3592 fourth-generation system (volume 4 TB).
	2012	· Succeeded in commercialization as the tape for LTO6 (volume 2.5 TB). As a result, BaFe tape was employed in all three major tape storage systems. · Oracle's T10000 fourth-generation system was released. Volume improved to 8.5 TB by using the tape (reuse) for third-generation system.
	2013	· Succeeded in technical demonstration of recording density 85.9 Gb/in^2 (volume 154 TB equivalent) for BaFe tape jointly with IBM.[22]
	2014	· Succeeded in commercialization as the tape for IBM's 3592 fifth-generation system (volume 10 TB). · Succeeded in technical demonstration of recording density 123 Gb/in^2 (volume 220 TB equivalent) for BaFe tape jointly with IBM.[23]
	2015	· Succeeded in commercialization as the tape for LTO7 (volume 6 TB).

Fig. 15 Timeline of the development of BaFe tape

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Received MSc. from the Graduate School of Science and Technology, Niigata University, in 1991. Joined Fuji Photo Film Co., Ltd., in 1991 and was assigned to the Recording Media Research Laboratories (formerly *Jiki Zairyo Kenkyujo* or the Magnetic Material Research Laboratory). Primarily worked on the development of civilian magnetic tape, beginning the development of barium-ferrite tape in 2001. Now primarily works on technical demonstration of areal recording density.

Hitoshi Noguchi

Received MSc. from the Graduate School of Engineering, Kyoto University, in 1987. Joined Fuji Photo Film Co., Ltd. in 1987 and was assigned to the Recording Media Research Laboratories (formerly *Jiki Zairyo Kenkyujo* or Magnetic Material Research Laboratory). Began basic research on barium-ferrite media in 1992 and primarily worked on achieving high density in high-volume floppy disks, along with product development of barium-ferrite tape. Has been the director of Recording Media Research Laboratories since 2012. Received the 46th Ichimura Prize in Industry for Outstanding Achievement in 2014 and the 61st Ohkochi Memorial Prize in 2015.

Discussions with Reviewers

1 Overall

Comment (Kimihiro Ozaki, AIST)

This paper clearly presents the relationship between the demand and potential from material development to practical use and product realization, as well as the importance of external collaboration, and I think it is excellent as a research paper for *Synthesiology*. The elemental technologies and the scenario for product realization are clearly described. The fact that product realization was achieved by continuing R&D for 20 years will provide valuable insight, including topic selection and research method development, to researchers and developers of other fields. The content is easy to understand by people of other fields, and I think it is an outstanding paper.

Comment (Isao Kojima, AIST)

I reviewed this paper from the perspective of establishing the *de facto* standard in the IT (information technology) field. The activities for achieving the goal became clear through this review process and I think the authors have completed a very good paper

2 Issues of symmetry

Question & Comment (Kimihiro Ozaki)

In Subchapter 3.2 “Issues related to BaFe magnetic material,” you organize the issues to be solved from (1) to (4). Of these, I understood that Issue (3) “signal processing technology to correct the symmetry of isolated transition response” was solved “by the new signal processing DD-NPML designed by IBM” as described in Section 4.2.2 “Second stage: Research on potential system application” of Subchapter 4.2 “Scenario execution.” Is my understanding correct?

Is it difficult to solve the symmetry issue through materials? In this paper, it is written that it can’t be done “because it possesses perpendicular magnetization components,” but does the difficulty arise from the phenomenon that cannot be avoided physically due to the magnetic interaction among the fine particles? Does it arise from the magnetic property of BaFe?

Answer (Takeshi Harasawa)

Yes, issue (3) was solved using DD-NPML.

The issue of waveform symmetry essentially arises from the perpendicular magnetization component. This is because the BaFe magnetic material is plate-shaped and the axis of easy magnetization is perpendicular to the plate surface. After coating and drying of the magnetic solution, the plate-shaped BaFe maintains the magnetization component perpendicular to the tape surface, as the plates tend to align parallel to the tape surface. This is not a phenomenon particular to the magnetic property or BaFe interaction.

Further, as HDD shifted towards perpendicular recording, we considered the perpendicular magnetization component as an advantage, and succeeded in increasing the recording density by employing perpendicular orientation (an increased perpendicular magnetization component) in the 35 TB technical demonstration of 2010.

Question (Isao Kojima)

I evaluate the development of DD-NPML as one key point in resolving Issue (3) (need for signal processing technology to correct the asymmetry). Is this included in the result of the joint research with IBM? If this technology was developed only by IBM, please show how the companies other than IBM could solve this problem since setting the *de facto* standard does not mean relying on the technology of a specific company.

Answer (Takeshi Harasawa)

The development of DD-NPML itself was the work of IBM, and the result of the joint research project was the achievement of a high recording density by combining the BaFe tape and DD-NPML.

The DD-NPML contributes to increased recording density by decreasing the error rate, not just correcting the waveform, as it is a state-of-the-art signal process for a tape system. Therefore, DD-NPML is non-essential if waveform equalization only is required, and I assume that waveform equalization can be achieved using other signal processes.

In fact, HP and Quantum were concerned about waveform distortion when they initially considered the use of BaFe tape. Citing the results presented in Refs. [12] and [13], we requested that the tape-drive system manufacturers take BaFe into consideration, as waveform equalization was technologically possible. As a result, HP and Quantum developed their own signal processes that enabled waveform equalization in the course of their practical applications. This is my understanding of this topic.

3 Competing technology

Comment (Isao Kojima)

Can you describe the situation of technological competition with other companies? Although this was first-in-the-world development still holding the top share, many companies, like Hitachi Maxell, and Sony, are also at a similar technological level. It will be useful to show what impact this development by Fujifilm had on these competitors.

Answer (Takeshi Harasawa)

A summary of papers published by competitors on this technology is given below. I have added a description of the competing technology in 2006 to Section 4.2.2.

Hitachi Maxell, Ltd.

Until 2005 or 2006, this company was publishing papers on particulate tape media using iron nitride as post metal tape. No papers on iron nitride were published in 2012; however, magnetic tape produced using the sputtering method with an estimated cartridge volume of 50 TB was announced by this company.

Major papers

Iron nitride (nano-composite advanced particles; NanoCAP)

- Y. Sasaki, N. Usuki, K. Matsuo, and M. Kishimoto: Development of NanoCAP technology for high-density recording, *IEEE Trans. Magn.*, 41 (10), 3241–3243 (2005).

Magnetic tape using sputtering method

- S. Matsunuma, T. Inoue, T. Watanabe, T. Doi, Y. Mashiko, S. Gomi, K. Hirata, and S. Nakagawa: Playback performance of perpendicular magnetic recording tape media for over 50 TB cartridge by facing targets sputtering method, *J. Magnetism and Magn. Matls.*, 324 (3), 260–263 (2012).

Sony Corporation

This company engaged in R&D for metal evaporated tape as post metal tape, which was put to practical use in 8-mm videotapes and digital video cassettes (DVCs). Until approximately 2009, Sony Corp. published papers on the practical durability of linear tape systems and recording density improvement. In 2014, they announced a magnetic tape produced using a sputtering method rather than metal-evaporated tape with a recording density of 148 Gb/in^2 (equivalent to 180 TB volume or higher).

Major papers

Metal evaporated tape

- K. Motohashi, T. Sato, T. Samoto, N. Ikeda, T. Sato, H. Ono, and S. Onodera: Investigation of higher recording density using an improved Co-Co metal evaporated tape with a GMR reproducing head, *IEEE Trans. Magn.*, 43 (6), 2325–2327 (2007).

- P.-O. Jubert, D. Berman, W. Imaino, T. Sato, N. Ikeda, D. Shiga, K. Motohashi, H. Ono, and S. Onodera: Study of perpendicular AME media in linear tape drive, *IEEE Trans. Magn.*, 45 (10), 3601–3603 (2009).

Magnetic tape using sputtering method

- J. Tachibana, T. Endo, R. Hiratsuka, S. Inoue, D. Berman, P.-O. Jubert, T. Topuria, C. Poon, and W. Imaino: Exploratory experiments in recording on sputtered magnetic tape at an areal density of 148 Gb/in^2, *IEEE Trans. Magn.*, 50 (11), Art. ID 3202806 (2014).

4 Technological background for numerical values

Question (Isao Kojima)

In the joint work with IBM, the selection of the head is one of the highlights. Since the references you cite, including References [11] and [12], are of a specialized scientific journal (*IEEE Trans. Magn.*), can you tell us (and also describe in the paper) the technological background such as the numerical values (such as AMR ratio) that supports your claim? According to Reference [11], you achieved 7 Gb/in^2. Does this mean an achievement of the absolute (rather than relative) level?

Answer (Takeshi Harasawa)

I think the supporting points are the high absolute values achieved, including the 7 Gb/in^2 (tape) value reported in Ref. [11] and the 17.5 Gb/in^2 (disk) result reported in Ref. [12].

We convinced IBM to undertake this research based on the demonstration result of the 7 Gb/in^2 recording density, which was more than ten times greater than that of the state-of-the-art system (0.4 Gb/in^2 recording density) at that time. This was achieved through the combination of the BaFe tape and GMR head.

Question (Isao Kojima)

What activities were done in getting the BaFe adopted by LTO? You described the technological presentation to HP and Quantum, but did you aim for the adoption by LTO by promoting it to such various players of LTO including IBM? Or were there direct appeals to LTO by Fujifilm?

Answer (Takeshi Harasawa)

We made appeals to HP and Quantum, which were involved in LTO development, to have the BaFe tape employed in LTO. The activities performed independently by Fujifilm in 2006 and 2007 were as follows:

(1) We developed the GMR head for several types of linear tapes with different read-width jointly with head manufacturers, announced the high performance of our BaFe tape evaluated using this head at the Information Storage Industry Consortium (INSIC), and reported this finding at technical meetings with various tape-drive system manufacturers.

(2) The technically demonstrated 6.7 Gb/in^2 tape released in 2007 was offered to these companies, and we had these tape-drive system manufacturers conduct evaluations.

5 Successful scenario seen from market share

Question (Isao Kojima)

Considering this as a successful scenario, I think it should be eventually reflected in the market share such as shipment volume and share of tapes. I imagine that you have some data which shows the growth of the BaFE tapes and the decline of MP tape shipments, as well as the good standing of Fujifilm in the market. Is it possible to publicize these data?

Answer (Takeshi Harasawa)

The following graph shows the total shipment volume trend for linear tape [number of cartridges × volume/cartridge; the *x*-axis units are exabytes (EB)]. The switch from MP tape to BaFe tape occurred progressively and, in 2016, BaFe tape dominated the market, with an approximately 70 % market share (figures from Fujifilm).