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Information Storage for the Broadband Network Era – Fujitsu's Challenge in Hard Disk Drive Technology –

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As the network-computing infrastructure expands around the world, information storage systems are becoming key elements of information technology (IT). The amount of original information created in 2000 has been estimated at about 5 EB, and there is now a worldwide information stock of about 100 EB. Commercial models of hard disk drives (HDDs) now have 18 million times the magnetic recording density of the world's first hard disk drive and are the only candidate solution for storing the bulk of the world's information stock. In this paper, we analyze the size of the information stock and the future capacity of HDD media. We also describe Fujitsu's breakthrough technology of synthetic ferrimagnetic media (SFM), which can extend the recording limit to up to 300 Gbit/in^2.

1. Introduction

Fujitsu has announced an aggressive plan to capitalize on the exploding demand for hard disk drive (HDD) products for enterprise servers, workstations, and non-traditional applications. The growth within the compact HDD segment, for example, in the emerging market for smaller hard drives in consumer-oriented appliances, audio-video products, and other non-PC applications, is strong. To accommodate this new push, Fujitsu will shift development, manufacturing, and sales resources away from the 3.5-inch ATA desktop drive market, which recorded an industry-wide negative growth in the first half of 2001.

The evolution of electronics technology in the 20th century enabled great advances in information network systems (i.e., computers, telecommunications equipment, and mass storage). Now, we are approaching the stage when there will be sufficient capacity to store the entire worldwide stock of information in digital form. We are at the beginning of the broadband information network era, and the enormous amounts of information that will be generated will make storage device technology as important as data processing and transmitting technologies.

Analog information has a very limited value in the network society; however, currently only 3% of the information stock is in digital form. Among the various storage devices, only HDDs will be able to store all of the worldwide information stock in digital form.

The history of Fujitsu's HDD storage subsystem business started in 1965 with the shipment of the first F631. Then, in 1994, Fujitsu entered the desktop PC HDD market for desktop PCs by starting high-volume offshore assembly in Southeast Asia. Since then, Fujitsu has become a vertically integrated manufacturer of HDDs, involved in all aspects: from research and development to manufacturing of key components.[1] The HDD is a typical technology-driven device, so the ability to do advanced R&D is essential for maintaining competitiveness in this area. Because of the slump in the PC market, Fujitsu has decided to terminate its 3.5-inch ATA

HDD business and focus on HDDs for the enterprise segment (AL-series), mobile HDDs (HN-series), 2.5-inch HDDs for desktop PCs, and emerging HDD application markets.[2),3)]

An HDD looks like a simple device, but actually it is an integration of various key components and advanced technologies, for example, giant magnetoresistive (GMR) heads and inductive write elements, a head positioning servo, spindle motor and actuator mechanisms, drive control and interface systems, design and manufacturing processes of wafers, low-noise media design, materials for heads and media, an ultra-narrow head-to-disk spacing, and signal processing.

Working in light of the predicted "superparamagnetic" limit on recording density, Fujitsu has led the academic world by demonstrating record-breaking densities on a yearly basis. For example, in 1996 we achieved 5 Gbit/in^2 and in August 2001 we demonstrated the milestone density of 106 Gbit/in^2.[4),5)]

In this paper, we look at the worldwide information stock and the media that is used to store it. Then, we discuss the future of information storage in the broadband network world. Finally, we give an overview of Fujitsu's latest challenges in advanced magnetic recording technology for HDDs.

This paper refers to a very wide range of numbers, the meanings of which are as follows:

MB (Megabyte)	= 10^6 bytes
GB (Gigabyte)	= 10^9 bytes
TB (Terabyte)	= 10^{12} bytes
PB (Petabyte)	= 10^{15} bytes
EB (Exabyte)	= 10^{18} bytes

2. Emerging broadband network technology

The expansion of high-speed access lines to the home marks the beginning of the broadband network era. Information storage, processing, and transport are three of the fundamentals of information technology (IT). **Figure 1** shows the evolution of these three fundamentals in terms of the areal density of hard disk drives, CPU clock frequency, and the traffic speed of access lines to the home. The values are normalized to the values in 2000. The HDD business has been driven by the expanding PC business, but the current rapid progress of recording technology has caused some people to say that HDDs are "over-technology products" for PCs. However, to enable the mass flow of movie information, there will be a strong demand for PC storage capacities exceeding 100 GB. HDD video recorders and home servers will be big emerging HDD markets in the near future.[6),7)]

Much of our lives is now defined by our relationship with the Internet. Conventional postal mail is called "snail mail" because it is much slower than e-mail, which has become the standard method of written communication. **Figure 2** shows the growth of World Wide Web (WWW) sites and e-mail boxes. There are now more than 100 million WWW sites and 500 million e-mail boxes. It is estimated that between 600 billion and 1100 billion e-mail messages were sent last year.[8)]

There will be a big discussion about whether local or personal storage will become dominant in a broadband environment. A rapid increase in the number of Internet Web sites requires not only an increase in the number of network servers, but also a huge storage capacity. This requirement

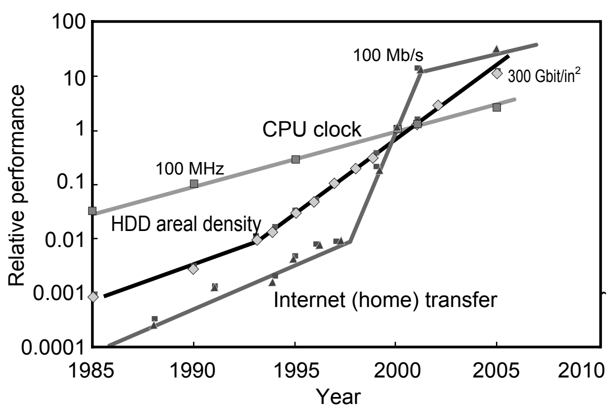


Figure 1
Performance comparison of key technologies.

makes high-performance, high-reliability HDDs for server applications much more important. Personal information storage will also increase. Information storage will change the structure of society itself and will occupy a major position in the social infrastructure. **Figure 3** shows an image of the future information network era. Processors, networks, and information storages are the key driving force for the broadband era, and they will eventually form the huge network computer shown in **Figure 4**.

A storage area network (SAN) is a dedicated, centrally managed, secure information infrastructure that enables any-to-any connections between servers and storage systems. The move to SANs has been motivated by the need to manage the dramatically increasing volume of business data and to mitigate its effect on network performance. Distributed computing, client/server applications, and open systems give today's

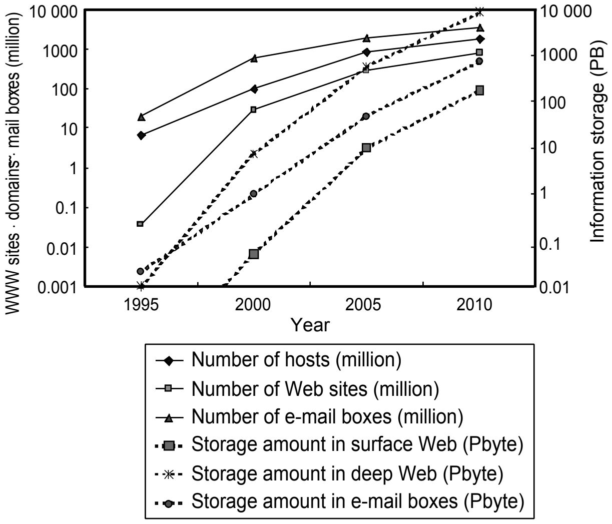


Figure 2
Internet and e-mail growth.

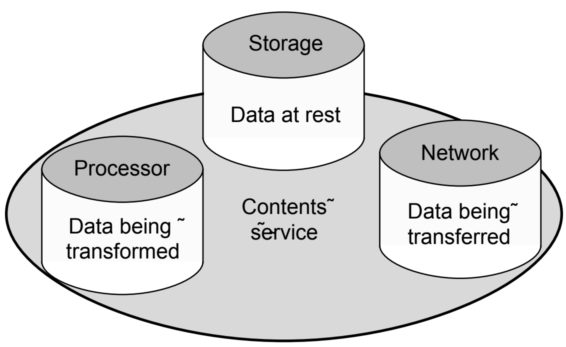


Figure 4
Key engines for the information network era.

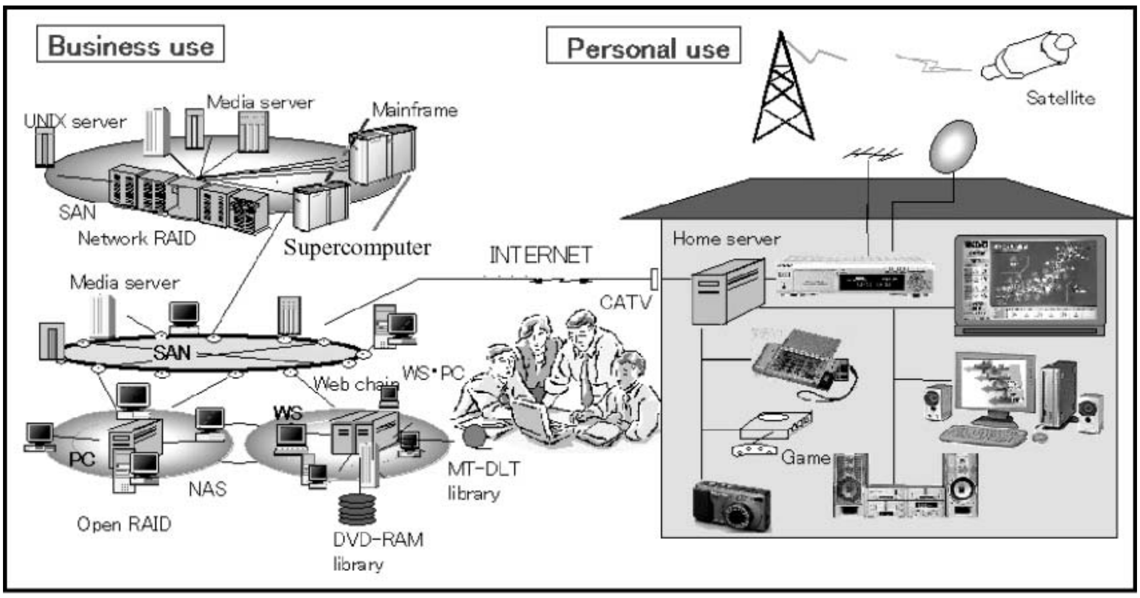


Figure 3
Image of information network era.

enterprises the power to fully integrate hardware and software from different vendors to create systems tailored to their specific needs. These systems can be fast, efficient, and capable of providing a competitive edge.[9]

With the explosive growth of e-business, IT managers are working hard to keep up with the exabytes of new data being created every year. They are installing high-performance storage systems to meet the demands for smaller backup windows and greater application availability. To improve data access and reduce costs, IT managers are now seeking innovative ways to simplify storage management. The SAN is a promising solution for universal access.

Network attached storage (NAS) devices are high-performance storage appliances that provide shared data to clients and other servers on a local area network (LAN). NAS provides a robust platform for complete data management solutions such as e-mail archiving, disk-to-disk backup, and disk aggregation.

Storage is increasingly recognized as a distinct resource – one that is best thought of separately from the computer systems that use it. Storage is increasingly being shared by multiple hosts and acquired and managed independently from them.[10] As the network-computing infrastructure expands on a global scale, information storage systems are becoming essential for IT. HDD storage devices are the only practical candidates for the exploding demand for information storage.

Since the first shipment of the Eagle drive in 1981, Fujitsu has been a pioneer of high-end drives for many OEM customers. In 1992, we shipped the first 3.5-inch AL-1 with MR heads. After the AL-2, 3, and 4 series, in 1998 we started shipping a new series of unique drives, the AL-5s. Among the models of this generation, there were 10 krpm, high-performance drives with smaller 84 mm diameter media (so called 3-inch media).

Recently, Fujitsu has started shipping the newest generation AL-7 series. This series consists of the AL-7LE devices, which have 10 krpm drives, 18 to 73 GB capacities, and 3-inch media and the AL-7LX devices, which have new 15 krpm high-end drives, 18 to 36 GB capacities, and 2.75-inch (70 mm diameter) media. The AL-7 series devices have Ultra160 SCSI and 2 Gb/s Fibre Channel interfaces.[2] We believe the AL-7 series will meet the demands of rapidly growing network storage systems.

3. The information stock and digital storage

In this section we investigate how much information there is in the world and whether it can all be stored in digital form. Advances in broadband network technology enable us to process much more information on a network. **Figure 5** shows the worldwide flow of unique information that was generated in 2000 based on “How Much Information” from the University of California at Berkeley.[11] In 2000, almost 5000 PB, or 5 EB, of original data was generated and transmitted. Needless to say, a much larger amount of duplicated data was also transmitted.

Original TV and movie content, at about 220 PB, no longer makes up the bulk of original content. Computer data, meaning the sum of all unique data on servers and personal computers,

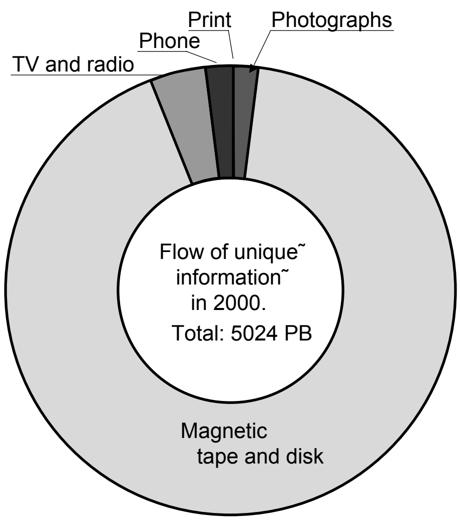


Figure 5
Worldwide flow of unique information generated in 2000.

amounted to 500 PB in 2000 and 1000 PB in 2001. We are surprised that as much as 40 PB of photographic information has been generated in a single year. On the other hand, you might be surprised that the amount of original data stored on optical disks was only about 110 TB (0.11 PB). The amount of text data, 30 TB, was relatively negligible, but the total amount of printed data, including that of scanned pictures, was estimated at more than 300 TB.

It will be valuable to analyze the usage of media in personal life. **Figure 6** shows the media usage in a typical home in the U.S.[12] People spent most of their media-usage time watching and listening to the radio and recorded music. The average person spent 4.3 hours a day watching TV. These activities account for 94% (3142 GB) of the total flow of information in the U.S.

Any estimation of the size of the world's information stock must take into account the number of home video recordings in existence: for example, if 300 million homes worldwide each have 50 VHS videotapes, this would amount to about 60 EB of information.

Clearly, we have a tremendous amount of printed material both in our homes and in public libraries. So, how much stock is there in the world? The worldwide information stock in 2000 is estimated to have been 102 EB. **Figure 7** shows an estimation of the worldwide information stock in 2000 and the media on which they were stored. According to the estimation, two thirds of all information was stored on magnetic media, a quarter on optical disks, and 7.3% as photographs. However, only 12.6% of the stock was in digital form and only 3% was on hard disk drives.

4. Information storage in the future

We have 100 EB of information in the world today. Most of it is stored on magnetic and optical media; however, it is recorded as analog information in the form of, for example, videotape and audiotape recordings. The worldwide total hard disk drive capacity produced in 2000 was enough to store 3 EB of digital data.[12]

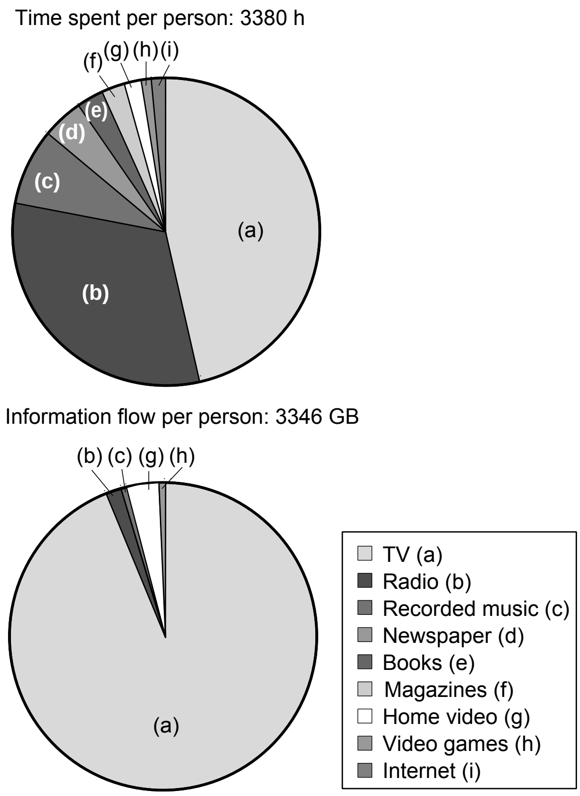


Figure 6
Media usage in a typical U.S. home.

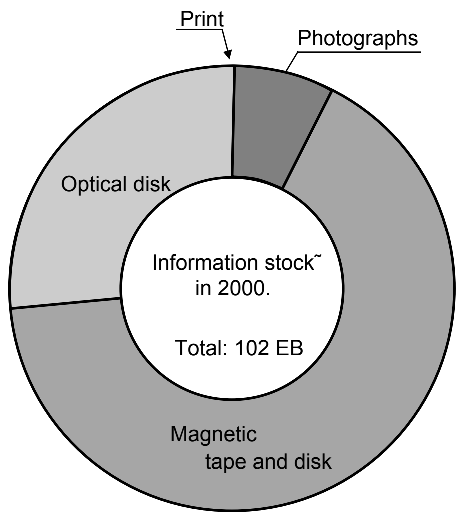


Figure 7
Estimated worldwide information stock and storage media in 2000.

Figure 8 shows the anticipated trend for the stock of information. The information stock should increase rapidly with the progress of broadband networks. In 2005, it is expected to increase to 160 EB. In 2010, it is expected to increase to 260 EB, which is equivalent to 52 GB of data each for 5 billion people.[8] This is why we need to extend the Internet protocol from 32-bit IPv4 (4.3 billion addresses) to 128-bit IPv6 (3.4×10^{38} addresses).

The amount of data stored on hard disks depends on the computing environment and the types of consumer electronics (CE) equipment in which the disks are deployed. **Figure 9** shows forecasted total storage capacities of yearly HDD productions according to system category. Here, we assume that the total HDD storage capacity will increase 70% annually. Based on this assumption, the total HDD storage capacity addition will be 33 EB in 2005 and 170 EB in 2010.

All HDDs can be placed into one of three categories: personal, departmental, or company-wide. Personal computers, laptops, and workstations account for approximately 55% of the disk storage capacity currently being shipped. Emerging CE equipment must be added to the personal user category, but in terms of the share, it will gradually decrease. Departmental servers will commonly be found in business, government, education, and other organizational settings. This class of subsystem accounts for about 30% of the overall storage market. Company-wide servers and network servers account for about 15% of the hard disk storage. As the broadband network environment grows, server storage will grow much faster than other storage.[11]

The above discussion can be summarized as shown in **Figure 10**. The ratio of digital information storage capability to the total information stock will grow very rapidly. We should realize that HDD technology has the potential to store almost all of the expected information stock. Broadband network technology has enabled us to build global interconnected network computer systems.

As is well known, RAID (Redundant Arrays

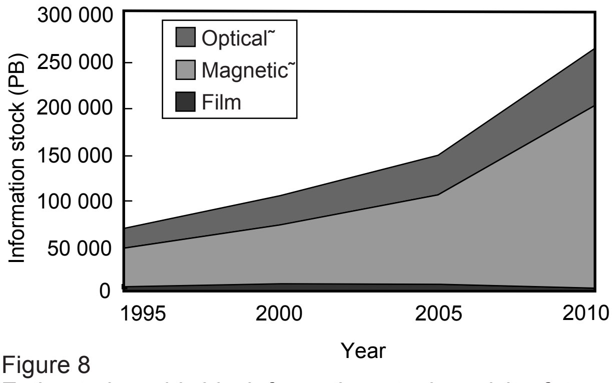


Figure 8
Estimated worldwide information stock and its future growth.

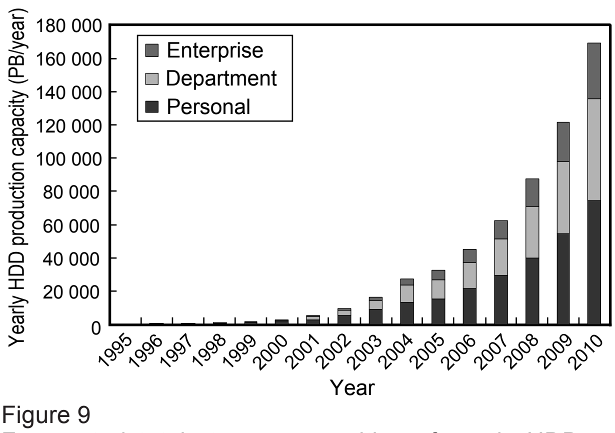


Figure 9
Forecasted total storage capacities of yearly HDD productions.

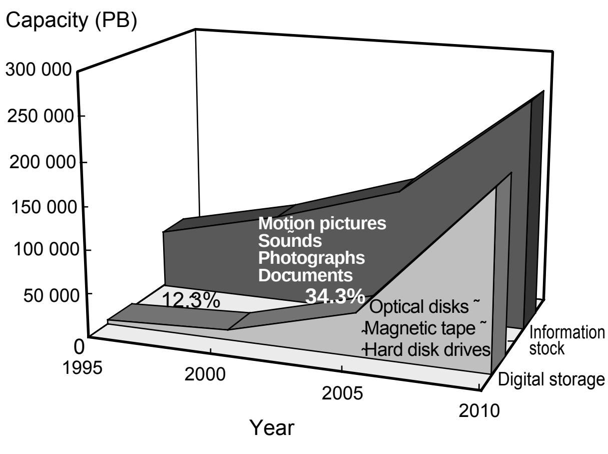


Figure 10
Trends of information stock and digital storage capability.

of Independent Disks) technology has significantly improved the reliability and performance of storage systems. Therefore, to achieve systems with higher performance and better security, a new storage system technology has to be developed for both very small HDDs and huge-capacity ones. The problem here is to create convenient data managing software that can swiftly handle huge amounts of information. Copyright issues will also be important in the future digital society.

5. Evolution of magnetic recording technology

The magnetic recording density of commercial hard disk drives has been increased 18 million times to 36 Gbit/in^2 since the first hard disk drive, RAMAC, was introduced to the computer in 1956 (RAMAC's density was only 2 kbit/in^2). The amazing progress in storage capacity accelerates price erosion and has caused some people to say that HDD technology is excessive for the PC. Today's advanced HDD technologies have been established by overcoming the various density limits that have been predicted in the past.[13]

Figure 11 compares the evolution of the areal densities of optical disks, magnetic tape, and hard disks. Before 1990, the areal density of HDDs was lower than that of optical disks and magnetic tapes. Once, there was the opinion that HDDs would soon be replaced by optical disks or solid-state memory. Moreover, the superparamagnetic limit theory was published in 1994, which covered the future of HDDs with a black cloud until Fujitsu reported an ingenious way to overcome the limit.[14] Since then, Fujitsu's engineers have overcome the so-called physical limit of magnetic recording by elegant breakthrough technologies.

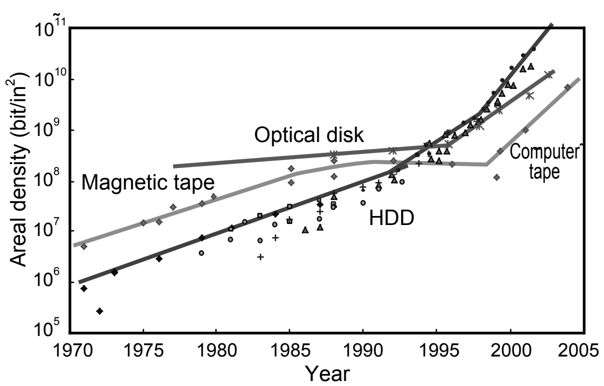


Figure 11
Evolution of information storage technologies.

It is interesting to see how HDD capacities have been improved beyond various, predicted theoretical limits. These advancements have been achieved because of steady improvements in the main technologies that are required to produce an HDD, for example, 1) giant magnetoresistive (GMR) heads, inductive write elements, design and processing, 2) low-noise media design, the deposition process and materials, 3) an ultra-narrow spacing in the head-to-disk interface, 4) signal processing, 5) the head positioning servo, spindle motor, and actuator mechanism, and 6) the drive interface system (**Figure 12**).

The pace of HDD improvement has accelerated since 1 Gbit/in^2 recording was demonstrated with a magnetoresistive (MR) head and granular media technology in 1990. Fujitsu has been working hard in this area since then and finally achieved a world record 106 Gbit/in^2 in the summer of 2001. As shown in **Figure 13**, Fujitsu has consistently been leading the research and development of magnetic recording.

Figure 14 shows how the key dimensions of hard disk drives have shrunk as a function of recording density. In spite of the many technological breakthroughs, from the 2 kbit/in^2 density of RAMAC to the recent 106 Gbit/in^2 demonstrations, there is no significant jump in the key dimensions except the media thickness. We have to emphasize that, not only GMR element and media processes, but also every dimension of magnetic recording, for example, track width, gap length, head flying height, and media thickness, have entered the nanometer realm. In the following paragraphs, we will overview Fujitsu's advanced recording technologies.

5.1 Magnetic heads

MR head technology extends the potential of magnetic recording. Because it is an active element, an MR/GMR head has a higher output capability.[15] In addition, an MR/GMR head is free from the LC resonance noise enhancement effect, which was a barrier for S/N improvement when inductive heads were used for reading. The MR/GMR is a high-sensitivity element that detects both magnetized signals and grain boundary noise from the disk media. Consequently, the MR/GMR head and media design concept had to be changed from the pursuit of higher output to the pursuit of low noise.

Figure 15 shows the technology roadmap for GMR heads. It shows the increase of required sensitivity and reduction in GMR track width as a function of recording density. We have extended

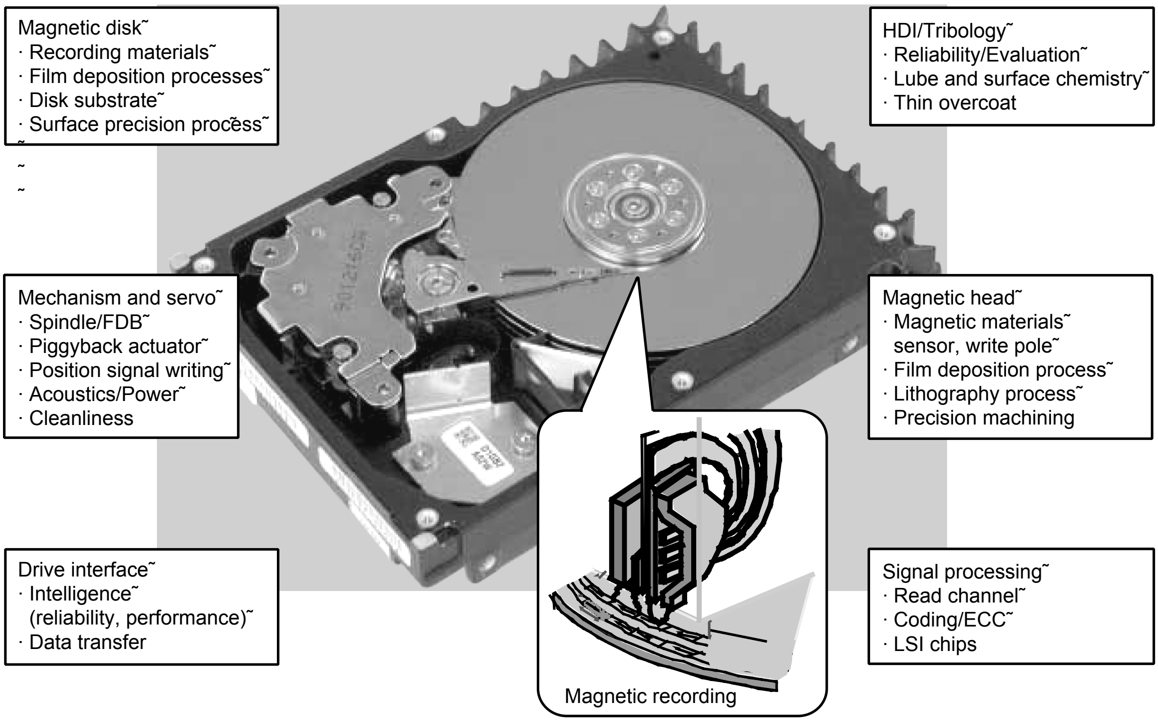


Figure 12
The main technologies of hard disk drives.

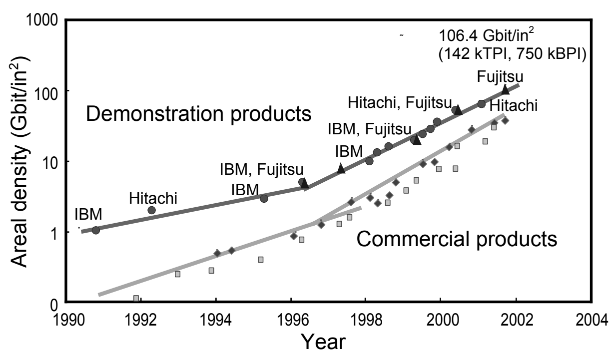


Figure 13
HDD areal density history.

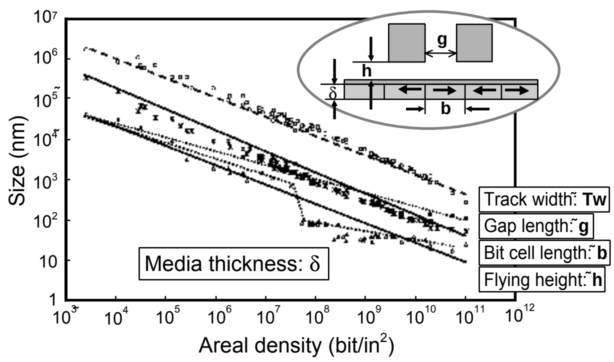


Figure 14
Shrinking key dimensions of hard disk drives.

the spin-valve (SV) GMR head performance up to 106 Gbit/in^2.[5] Fujitsu's evolutions of SV GMR heads are shown in **Figure 16**. In order to increase the sensitivity, it was essential to reduce the thickness of the magnetic free layer and eliminate the demagnetization effect of the pinned layer by introducing a synthetic ferrimagnetic structure. This structure gave us a small sensitivity increase in GMR heads. Electron scattering loss is increased at the capping layer, underlayer,

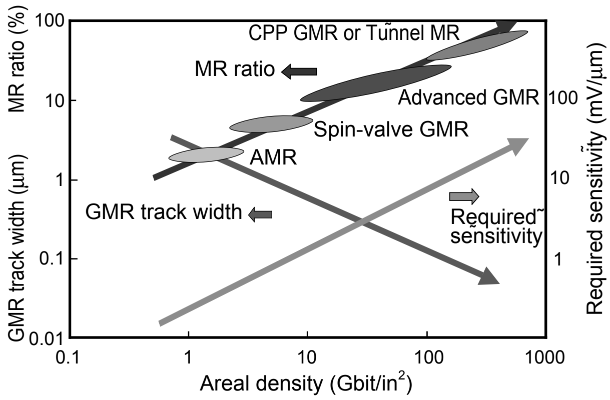
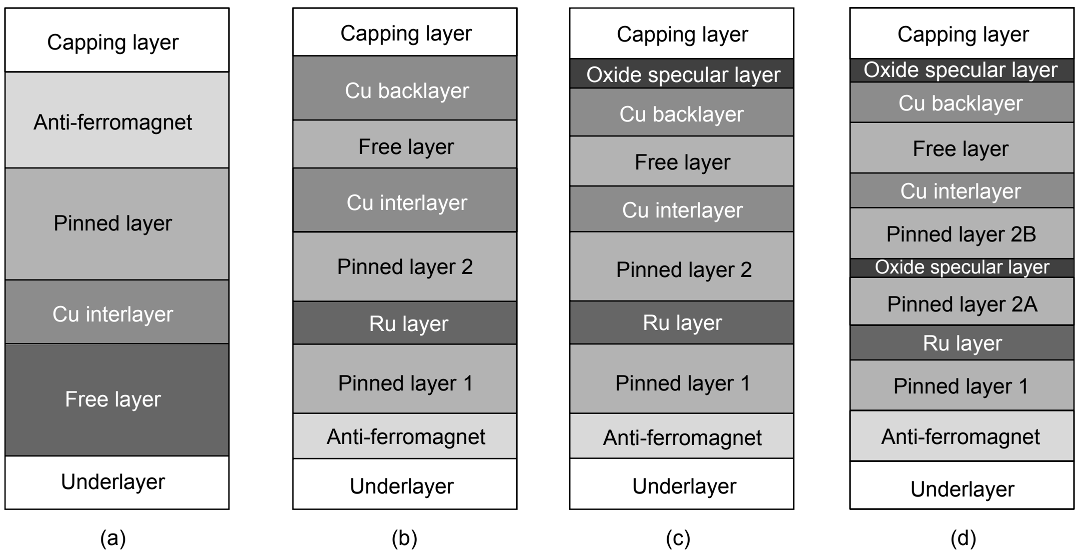


Figure 15
Technology roadmap for giant magnetoresistive heads.

and anti-ferromagnetic layer when the thicknesses of the free, Cu, and pinned layers are significantly reduced in conventional spin-valve films. In a specular spin-valve film, a specular reflection layer of oxide, which is placed between the free layer and the capping layer or between the pinned layers, can suppress this scattering loss and increase the rate of GMR change. This effect occurs because electrons are reflected several times at the interfaces between the free layer, Cu interlayer, and pinned layer, which is similar to the behavior seen in a super-lattice GMR multilayer.[16]

It is well known that Tunnel-MR elements with a ferromagnetic metal-insulator-ferromagnetic metal structure can have an MR ratio of over 40%, which is larger than that of SV elements.[17] Therefore, the Tunnel-MR could be a candidate reading head for future HDDs. Fujitsu has developed a spin-valve-like Tunnel-MR element that has a 40% MR ratio and high sensitivity at low-intensity magnetic fields thanks to the performance of its $CoFe_{26}$ layers. This element,



(a) Top type spin-valve, (b) bottom type synthetic ferrimagnet spin-valve,
(c) bottom type single specular spin-valve, and (d) bottom type double specular spin-valve.

Figure 16
Evolution of spin-valve GMR head element.

however, has a large junction resistance (RA > 1kΩ μm^2), which limits the channel bandwidth and leads to greater Johnson noise. Also, because tunneling GMRs use a quantum effect, the shot noise needs to be examined.

There are two current-flow configurations for a GMR element. One is current in plane (CIP) mode, and the other is current perpendicular to plane (CPP) mode (**Figure 17**). The conventional SV GMR head is used in the CIP mode, and the Tunnel-MR is used in the CPP mode. If we assume that the power consumption in the sensor and therefore its temperature remain constant, the output voltage of the CPP head is roughly inversely proportional to the square root of the sensor size (area). The CPP-GMR head, therefore, exhibits a higher output voltage as the sensor size becomes smaller. In this sense, the CPP-GMR head is a preferable structure for ultra-high-density recording.

Fujitsu has been studying a novel CPP type spin-valve element as an alternative candidate to the Tunnel-MR.[18] SV GMR heads having an oxide layer show a moderate resistance. CPP heads with a moderate RA have several advantages. They have a higher output voltage, better signal to noise ratio, more immunity to the magnetic field of the sense current, and a narrower effective sensor width. In the prospective areal density of around 100 to 300 Gbit/in^2, however, the amplitude of the output voltage is still insufficient. Some modification is indispensable to utilize CPP-SV heads for more than 100 Gbit/in^2 recording.

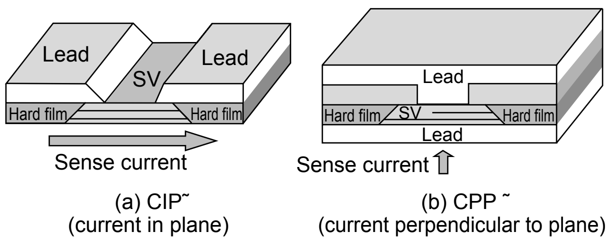


Figure 17
Giant MR sensor configurations.

Because of the rapid increase of the track density, a narrower write track width is required. In addition, a stronger writing field is required as the coercivity of media increases in order to achieve a higher recording density. The challenge is to suppress side erasure while maintaining sufficient writing capability. One solution is to reduce the flying height. However, this is not practical when the head disk interface is considered. Moreover, an increase in the data transfer rate (i.e., writing frequency) particularly needs to be considered for enterprise model HDDs. It is very difficult, but very important, to optimize the design of write heads.

To write data on a medium with a high coercivity, the pole tip materials of the inductive write elements must have an ultra-high magnetic saturation induction Bs.[19] It is well known that sputtered Fe-M-(N and/or O) (M = no addition, Al, Ta, Zr, Rh, etc.) and electroplated CoNiFe films show soft magnetic properties but have Bs from only 1.8 to 2 T. Accordingly, Fujitsu has developed soft magnetic FeCoAlO films with high Bs of 2.4 T.

5.2 Magnetic recording media

Because the MR/GMR head has a low impedance-noise and a higher output, the media design concept has changed from achieving higher output to achieving lower noise. In the granular media design, low noise is achieved not only by using a small magnetic grain size, but also by reducing the magnetic exchange interactions between grains. Grain size reduction however leads to an unstable magnetization state due to thermal fluctuation. This is a well-known superparamagnetic effect of magnetic particles. Lu and Charap have concluded that, due to the superparamagnetic effect, the areal density of magnetic recording is limited to around 40 Gbit/in^2.[14]

Fujitsu has been striving to overcome the superparamagnetic limit with various methods, for example, by using an antiferromagnetic underlayer, soft keeper layer, and crystal orientation. Now, Fujitsu has developed the synthetic ferrimagnetic media (SFM) technology, which will extend the limit of longitudinal recording up to 300 Gbit/in^2.[5),20)] **Figure 18** shows (a) a conventional medium with a single memory layer, (b) an SFM (anti-ferro-coupled medium) with double magnetic layers separated by a thin Ru layer, and (c) an SFM with three magnetic layers. The SFM is an example application of the results of multilayer physics research.

SFM technology exploits quantum effects to overcome superparamagnetic effects in magnetic layers. Each magnetic grain in an SFM consists of anti-parallel spin orientations, which make it possible to reduce the effective memory layer thickness without reducing the magnetization switching volume. Fujitsu has demonstrated a 106 Gbit/in^2 recording density with this SFM in combination with a high-sensitivity, double specular SV head.[4)]

Figure 19 shows the bit length of Fujitsu's HDD products versus the medium parameter δMr/Hc, where δ is the medium's thickness, Mr is the residual magnetization, and Hc is the coercivity. In order to achieve high-density longitudinal recording (i.e., a high-resolution magnetization reversal), we must realize a small δMr/Hc value. SFM provides a small δMr/Hc value without increasing the coercivity significantly. This is why Fujitsu has stated that longitudinal recording should be applicable up to 300 Gbit/in^2 or more.

5.3 Head-disk interface

The head-to-media separation has reached 10 nm for commercial products. An ultra smooth surface treatment technique is key for achieving such a fine separation. The stiction free slider (SFS) has small contact pads on the air bearing surface (ABS) to avoid stiction during contact start stop (CSS) mode.[21)] Fujitsu has been using this type of slider since 1993.

To reduce the magnetic spacing, we have to reduce not only the overcoat carbon films on the slider ABS and disk surface, but also reduce the pole tip recession. At the products stage, chemical vapor deposition (CVD) is replacing sputtering deposition because of the superior hardness and good step coverage of CVD films. Fujitsu has been developing a filtered cathodic arc (FCA) carbon process, which enables us to achieve an ultra thin overcoat film of less than 3 nm.

5.4 Signal processing

Fujitsu has achieved a 735 Mb/s internal data transfer for high-performance production HDDs. High-speed writing becomes increasingly difficult because problems such as RCL resonance, eddy current problems in the head core materials, impedance matching of interconnections, and the dynamic coercivity issue of media become much more significant. To maintain a small non-linear transition shift (NLTS), a sharp write field gradi-

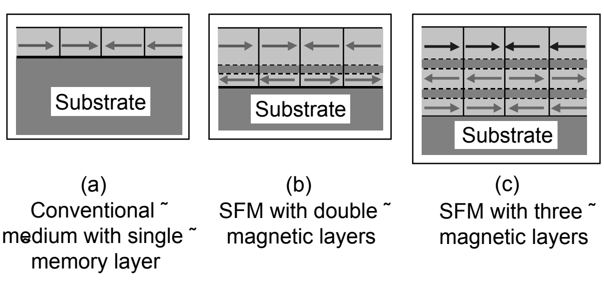


Figure 18
Synthetic ferrimagnetic media (SFM) structure.

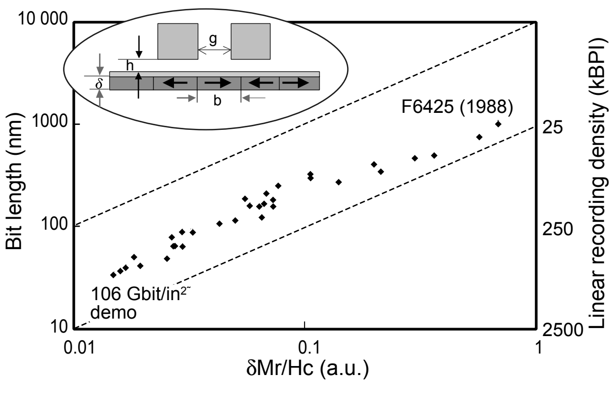


Figure 19
Bit length of Fujitsu's products versus medium parameter δMr/Hc.

ent must be maintained around medium coercivity. Fujitsu has provided instruments to measure the write current and the write field response at a resolution of 5 GHz.[22] The write/read IC chip mounted on a suspension will be a main candidate for future high-speed writing, but heat dissipation will be an issue.

5.5 Mechanisms and their control

In 3.5-inch form factor high-performance HDDs, the rotational speed of the spindle motor has reached 15 krpm and is expected to go even higher.[2] This high rotational speed causes a large windage disturbance and disk flutter, which are serious obstacles to achieving higher track densities. Fujitsu's research group has solved this issue by directly simulating airflow with the Navier-Stokes equation. Recent advanced high-speed processors and large storages have enabled us to perform this simulation by either a differential method or a finite element method.[23]

Another requirement for achieving a higher track density is a wider servo bandwidth. For the single actuator system, the servo bandwidth is limited by the mechanical resonances of the carriage, coil, and ball bearing pivot. Some types of microactuators have been proposed as possible ways to attain a wider servo bandwidth. Current research on microactuator design can be divided into three types: driving a complete head suspension assembly, driving only a slider, and driving a tiny head element only.[24] Because the head suspension driving microactuators are easy to manufacture, they are expected to be used in HDDs in the near future, in spite of their very limited mechanical characteristics compared with the slider and/or head element driving types.

To realize an ultra high track density, it is essential to reduce the track misregistration (TMR). Therefore, it is necessary to reduce the amount of repeatable position errors (RPEs), improve the accuracy of position signals of servo track writers (STWs), and also reduce the amount of non-repeatable position errors (NRPEs) with fluid dynamic bearings and/or piggyback actuators. On the other hand, the number of STWs on our production lines must be increased at an annual rate of at least 50% to compensate for the time required to write servo patterns for the extra data tracks. Manufacturers are forced to make an enormous investment every year to secure sufficient facilities, including clean room areas. As a result, there is a strong requirement for a low-priced STW that can write quickly and efficiently. Fujitsu has been developing effective, low-cost STW systems with high-precision writing performances.[25]

Generally, the mechanical performance improves as the microactuator is brought closer to the head. Therefore, an MEMS-based microactuator is considered to be the ultimate technology for very high track densities. Fujitsu has developed a piezoelectric microactuator for dual-stage actuator systems that uses the shear mode of piezoelectric elements to drive the head suspension assembly.

Ball bearings are used in HDD motors. As the recording density of HDDs increases, however, the effect of the non-repeatable run-out (NRRO) caused by bearing vibrations becomes an unavoidable problem in positioning control of magnetic heads. Also, there is a demand for motors that make less acoustic noise and have improved shock resistance. To solve these problems, fluid dynamic bearings (FDBs) have been used instead of ball bearings.[3]

5.6 Perpendicular magnetic recording

We used to study perpendicular magnetic recording (PMR) for 1.8-inch disk drives with contact microflex inductive head technology,[26] but we froze the project in 1994 because of the difficulty of wear issues. However, after the prediction of a superparamagnetic limit for longitudinal recording, PMR research came back into the limelight.[27] The most promising characteristic of PMR is the excellent writability of single-pole heads combined with perpendicular media with a soft magnetic underlayer. The medium noise, however, is higher than we expected. Fujitsu has been studying a novel TbFeCo amorphous material approach for PMR with an FeC soft underlayer in favor of the conventional Co/Pd multilayer systems.[28] Despite the difficulties, PMR is a very attractive technology for achieving a terabit density per square inch.[29]

5.7 Lithography limit

Because of the rapid progress in recording density, the dimensions of head elements have entered the sub-quarter-micron domain (Figure 15). Head dimensions are shrinking faster than the semiconductor roadmap.[30] Now, photolithography with 248 nm KrF UV light has become indispensable for head fabrication. How to overcome the semiconductor technology limit is currently an important issue. However, solutions, for example, electron beam lithography combined with photolithography, are expected.

The magnetic recording density of commercial hard disk drives has been increased 18 million times since the first HDD was introduced to the world, and now SF media technology has overcome the latest superparamagnetic limit.[31] Because of SF media technology, we now believe that Fujitsu can provide key technologies for longitudinal magnetic recording at up to 300 Gbit/in^2 (**Figure 20**). HDDs have the technological potential to store

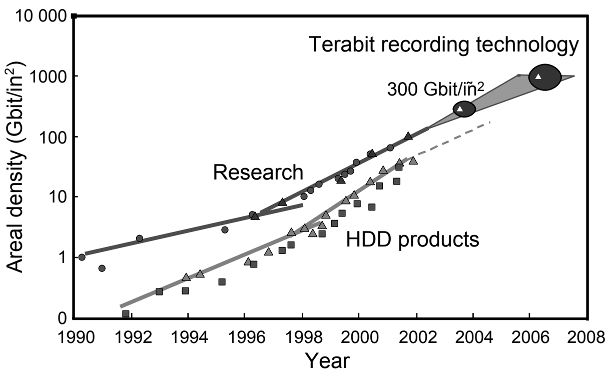


Figure 20
The future of magnetic recording.

10 times as much data than was stored in 2001, which is estimated to be around 5 EB.

The subject of what will come after longitudinal recording is outside the scope of this paper, but it is certain that new breakthroughs will push the limit even higher. Some promising candidates are perpendicular recording, patterned media, the integration of magnetic recording with optical recording, and nano-probe technology.

6. Conclusions

How much unique information is produced in a year? In 2000, almost 5000 PB (5 EB) of original data was created and transmitted, and around the world there is a stock of about 100 EB of information. Most of this information is stored on magnetic and optical media; however, it is recorded as analog information, for example, as video and audio recordings. The information stock will expand rapidly in the future due to the progress of broadband networks. It is estimated that it will be around 160 EB in 2005 and around 260 EB in 2010.

Information storage will change the structure of society and will occupy a major position in the social infrastructure. Processors, networks, and information storage, which are the key components of the broadband era, will form a huge network computer.

HDDs have gone beyond various technological limits that have been predicted and now have 18 million times the magnetic recording density of the world's first HDD. Fujitsu has overcome the so-called physical limit of magnetic recording by elegant breakthrough technologies. Fujitsu will provide HDD products, focusing on the enterprise segment, the mobile segment, and emerging non-PC applications with advanced magnetic recording technologies.

The HDD industry has the technological potential to supply at least 10 times as much storage capacity than is currently available. In 2000 alone, worldwide shipment of HDDs was enough to store 3 EB of information. The total amount of HDD capacity that will be supplied in 2005 is expected to be 33 EB. And the figure for 2010 is expected to be 170 EB. Currently, the HDD storage system is the only system that can be used to store the bulk of the worldwide information stock.

References

1) I. Sanaka: Fujitsu's Approach to Information Storage Device & Systems. *FUJITSU Sci. Tech. J.*, **31**, 1, p.1-5 (1995).
2) K. Aruga: 3.5-inch High-Performance Disk Drives for Enterprise Applications: AL-7 Series. *FUJITSU Sci. Tech. J.*, **37**, 2, p.126-139 (2001).
3) A. Makita: 2.5-inch Hard Disk Drives for Mobile Applications: Hornet-15L. *FUJITSU Sci. Tech. J.*, **37**, 2, p.140-144 (2001).
4) J. Hong, J. Kane, J. Hashimoto, M. Yamagishi, K. Noma, and H. Kanai: Spin-Valve Heads with Specularly Reflective Oxide Layers for over 100Gb/in^2. IEEE TMRC2001 A4, Minneapolis, August 2001.
5) B. R. Acharya, A. Ajan, E. N. Abarra, A. Inomata, D. Hasegawa, and I. Okamoto: Synthetic Ferrimagnetic Media: Role of the Magnetic Anisotropy of the Stabilization Layer. Joint European Magnetism Symposia, (Sa-B3-05) Grenoble, France, 1st, September 2001.
6) Gordon Bell: A Personal Digital Store. *Communication of the ACM*, **44**, p.86-91 (2001).
7) Richard Comerford: Magnetic Storage: The medium that wouldn't die. *IEEE Spectrum*, **37**, p.36-39 (2000).
8) Robert H'obbes' Zakon: Internet Timeline v5.4.
http://www.zakon.org/robert/internet/timeline/
9) Jack Cole: Tutorial - Emerging Standards Impacting Storage System Architectures, 18th IEEE-9th NASA Storage System Symposium, San Diego, April 2001.
http://storageconference.org/2001/presentations.html
10) SNIA Storage Networking Industry Association: Shared Storage Model - A framework for describing storage architectures, SNIA Technical Council, June 2001.
http://www.snia.org/English/Resources/SNCP/SNCP_FS.html
11) How Much Information? School of Information Management and Systems, University of California, Berkeley.
http://www.sims.berkeley.edu/research/projects/how-much-info/
12) US Census Bureau, Statistical Abstract of the United States, 1999, Washington D. C. 1999.
http://www.census.gov/prod/www/statistical-abstract-us.html
13) L. D. Stevens: Magnetic Recording, The First 100 Years, Chapter 18, Edited by E. D. Daniel, C. D. Mee, and M. H. Clark, *IEEE Press*, p.270-299, 1998.
14) P.-L. Lu and S. H. Charap: Thermal instability at 10 Gbit/in^2 magnetic recording. *IEEE Trans. Magn.*, **30**, p.4230-4232 (1994).
15) R. E. Fontana, Jr., S. A. McDonald, H. A. A. Santini, and C. Tsang: Process Considerations for Critical Features in High Density Areal Density Thin Film Magnetoresistive Heads: A Review. *IEEE Trans. Magn.*, **35**, p.806-811 (1999).
16) H. Kanai, K. Noma, and J. Hong: Advanced Spin-Valve GMR Head. *FUJITSU Sci. Tech. J.*, **37**, 2, p.174-182 (2001).
17) H. Kikuchi, M. Sato, and K. Kobayashi: Low-Resistance Ferromagnetic Tunnel Junction. *FUJITSU Sci. Tech. J.*, **37**, 2, p.183-191 (2001).
18) K. Nagasaka, Y. Seyama, R. Kondo, H. Oshima, Y. Shimizu, and A. Tanaka: CPP Operational Mode of GMR Head. *FUJITSU Sci. Tech. J.*, **37**, 2, p.192-200 (2001).
19) I. Tagawa, S. Ikeda, and Y. Uehara: High-Performance Write Head Design and Materials. *FUJITSU Sci. Tech. J.*, **37**. 2, p.164-173 (2001).
20) E. N. Abarra, B. R. Acharya, A. Inomata,

A. Ajan, and I. Okamoto: Synthetic Ferrimagnetic Media. *FUJITSU Sci. Tech. J.*, **37**, 2, p.145-154 (2001).
21) T. Yamamoto, Y. Kasamatsu, and H. Hyodo: Advanced Stiction-Free Slider and DLC Overcoat. *FUJITSU Sci. Tech. J.*, **37**, 2, p.201-211 (2001).
22) S. Wakana, T. Nagai, Y. Sakata, and H. Sekiguchi: Wide-Bandwidth Scanning Kerr Microscope for Measurement of Write Head Dynamics. *FUJITSU Sci. Tech. J.*, **37**, 2, p.236-242 (2001).
23) M. Tatewaki, N. Tsuda, and T. Maruyama: A Numerical Simulation of Unsteady Airflow in HDDs. *FUJITSU Sci. Tech. J.*, **37**, 2, p.227-235 (2001).
24) S. Koganezawa and T. Hara: Development of Shear-Mode Piezoelectric Microactuator for Precise Head Positioning. *FUJITSU Sci. Tech. J.*, **37**, 2, p.212-219 (2001).
25) Y. Uematsu and M. Fukushi: Servo Track Writing Technology. *FUJITSU Sci. Tech. J.*, **37**, 2, p.220-226 (2001).
26) W. Cane, A. Payne, M. Baldwinson, and M. Hempstead: Challenges in the Practical Implementation of Perpendicular Magnetic Recording. *IEEE Trans Magn.*, **MAG-32**, p.97-103 (1996).
27) H. Takano, Y. Nishida, M. Futamoto, H. Aoi, and Y. Nakamura: Possibilities of 40Gb/in^2 Perpendicular Recording. Intermag2000 AD06, Toronto, Canada, April 2000.
28) K. Matsumoto: Perpendicular Magnetic Recording Using Magneto-Optical Media. *FUJITSU Sci. Tech. J.*, **37**. 2, p.155-163 (2001).
29) R. Wood: The Feasibility of Magnetic Recording at 1 Terabit per Square Inch. *IEEE Trans Magn*, **36**, p.36-42 (2000).
30) SEMATEC: International Technology Roadmap for Semiconductors (ITRS). *http://public.itrs.net/Files/2000UpdateFinal/2kUdFinal.htm*
31) E. N. Abarra, A. Inomata, H. Sato, I. Okamoto, and Y. Mizoshita: Longitudinal Magnetic Recording Media with Thermal Stabilization Layers. Intermag2000 AA06, Toronto, Canada, 2000. *J. Appl. Phys. Lett.*, **77**, p.2581-2583 (2000).

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