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## The Future of Data Storage Technologies



*International Technology Research Institute*  
*World Technology (WTEC) Division*



**NIST**

WTEC Panel Report on

# The Future of Data Storage Technologies

Sadik C. Esener<sup>p5</sup> , Panel Co-Chair

Mark H. Kryder<sup>p6</sup> , Panel Co-Chair

William D. Doyle<sup>p6</sup>

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David A. Thompson<sup>p8</sup>

June 1999

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## APPENDIX A. PROFESSIONAL EXPERIENCE OF PANELISTS

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## APPENDIX A. PROFESSIONAL EXPERIENCE OF PANELISTS

**Name: Sadik C. Esener (Co-Chair)**

Address: Department of Electrical and Computer Engineering (0407)

[http://itri.loyola.edu/hdmem/a\\_01.htm](http://itri.loyola.edu/hdmem/a_01.htm)

University of California, San Diego  
9500 Gilman Drive  
La Jolla, CA 92093-0407

Sadik C. Esener is a Professor in the Electrical and Computer Engineering Department at the University of California, San Diego, where he leads the Optoelectronic Computing Group and is the Director of the joint DARPA/Industry/University consortium on Free-Space Optical Interconnects. He received his PhD in electrical and computer engineering from UCSD in 1987 where he also was an assistant professor from 1986 to 1991. In 1991, he became an associate professor, and in 1996, professor. His current research at UCSD is in the area of optical interconnect devices and systems. Professor Esener is also actively involved in research on optical data storage and has co-pioneered the development of parallel read-out 3D optical storage systems based on two-photon absorption. He is the co-founder and President of Call/Recall, Inc., a San Diego-based company developing multilayer optical data storage systems and media. He holds 6 patents, and has over 100 publications, and several book chapters. He is a member of IEEE, OSA, and SPIE. Professor Esener received a certificate of recognition from NASA in March 1987 for his pioneering work on optically addressed random access memories.

**Name: Mark H. Kryder (Co-Chair)**

Address: Carnegie Mellon University  
Data Storage Systems Center  
Roberts Engineering Hall, Room 348  
Pittsburgh, PA 15213-3890

Mark H. Kryder is the Stephen J. Jatras University Professor of Electrical and Computer Engineering and Director of the Data Storage Systems Center at Carnegie Mellon University. He received his PhD in electrical engineering and physics from the California Institute of Technology in 1970, where he also was a research associate from 1969 to 1971. From 1971 to 1973 he was a visiting scientist at the University of Regensburg, W. Germany. From 1973 to 1978 he was a research staff member and manager of exploratory magnetic bubble device technology at the IBM T.J. Watson Research Center. Since 1978, he has been at Carnegie Mellon University where he founded first the industrially funded Magnetics Technology Center and then the NSF/industrially funded Data Storage Systems Center. He has over 300 publications and 16 patents. His current research is in the area of ultrahigh density magnetic and optical recording technologies. Professor Kryder is a member of the National Academy of Engineering, a Fellow of the IEEE, a member of the American Physical Society, the Materials Research Society and the Optical Society of America.

**Name: William D. Doyle**

Address: University of Alabama  
Box 870209  
Tuscaloosa, AL 35487-0209

William Doyle received BS and MS degrees from Boston College in 1957 and 1959, and a PhD

degree in physics from Temple University in 1964. He joined Franklin Institute Laboratories in 1959, focusing on thin magnetic films for information storage. He has continued this work throughout his career at Univac (1964-1979), Motorola (1979-1984), and Kodak (1984-1990) where he had both scientific and management responsibilities. In 1970-1971, he was a Senior Visiting Fellow at the University of York, England. Since 1990, he has served as Director of the Materials for Information Technology (MINT) Center and holds the MINT Chair in the Physics Department. He is an IEEE Fellow, has authored more than 50 papers on storage materials, and was an IEEE Magnetics Society Distinguished Lecturer in 1982 and 1995. In 1993, he received the IEEE Magnetics Society Achievement Award and was President of the Society from 1987-1988.

**Name: Marvin Keshner**

Address: Hewlett-Packard Laboratories  
1501 Page Mill Road  
Palo Alto, CA 94304-1126

Dr. Keshner has three degrees, BS, MS and PhD, in electrical engineering and computer science-all from MIT in Cambridge, Mass. His areas of focus were solid state physics, communications theory, medical electronics, and analog circuit design.

Between his Masters and PhD programs, Dr. Keshner was the lead engineer at the medical electronics lab, located at the Boston City Hospital, and part of the Harvard Medical School teaching and research program.

Dr. Keshner joined Hewlett-Packard Laboratories in 1979 to work on the development of the thin film disk for magnetic disk storage devices. Since then, he has worked on magnetic and optical storage devices and also on architectures for achieving high performance from the storage in computer systems.

Currently, Dr. Keshner is the director of the Information Storage Technology Laboratory at HP Labs in Palo Alto, California. His team is currently working on magnetic tape, optical and various advanced storage projects.

**Name: Masud Mansuripur**

Address: University of Arizona, Optical Science Center  
1630 East University Blvd.  
Tucson, AZ 85721

Dr. Masud Mansuripur is a professor of optical sciences at the University of Arizona in Tucson. He received his BS degree at Arya-Mehr University of Technology (1977) and two MS degrees at Stanford University (1978 and 1980, respectively). Dr. Mansuripur also did his PhD at Stanford (1981).

Dr. Mansuripur's areas of research have included magneto-optical disk data storage, information

theory, micromagnetic simulations, optics of birefringent media, and the theory of diffraction. He is the author of *Introduction to Information Theory*, (Prentice-Hall, 1987) and *The Physical Principles of Magneto-Optical Recording* (Cambridge University Press, 1995). In addition, he has published over 100 papers in scientific journals and has given numerous technical presentations at international conferences and industrial laboratories.

### **Name: David A. Thompson**

Address: International Business Machines Corporation  
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David A. Thompson received his BS, MS, and PhD degrees in Electrical Engineering from the Carnegie Institute of Technology, Pittsburgh, Pa., in 1962, 1963, and 1966, respectively. In 1965, he became an Assistant Professor of Electrical Engineering at C.I.T., now Carnegie Mellon University. His research activities there were primarily in the fields of magnetic thin films and microwaves. From 1968 to 1987 he was at the IBM Thomas J. Watson Research Center, Yorktown Heights, New York. There his work was concerned with magnetic memory, magnetic recording, and magnetic transducers. He became an IBM Fellow in 1980, and was named Director of the Compact Storage Laboratory in December 1985. He moved to Almaden Research Center in 1987 to assume responsibilities as Director of Magnetic Recording Institute as well as Director of Compact Storage Laboratory. These two programs merged in 1991, to form the Advanced Magnetic Recording Laboratory (AMRL). He is presently head of AMRL. Dr. Thompson is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), and a member of Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and the IEEE Magnetics Society. He has served terms as President, Vice President, and Secretary-Treasurer of the IEEE Magnetics Society. He served four three-year terms on the Administrative Committee of the IEEE Magnetics Society, is often a member of the Program Committee of the Intermag Conference, was Program Co-Chairman of the Intermag '86 Conference and of the Intermag '78 Conference in Florence, Italy, and has served as Reviews Editor of the *IEEE Transactions on Magnetics*. He was Conference Chairman of the first TMRC (The Magnetic Recording Conference) in 1990. Dr. Thompson has been member of the Technical Advisory Board of the Magnetics Technology Centre (National University of Singapore) since its inception. He was elected a member of the (U.S.) National Academy of Engineering in 1988. In April 1992 he received the IEEE Cledo Brunetti Award, "for pioneering work in miniature magnetic devices for data storage..." In 1993 he received the National Inventor of the Year Award from the New York (Patent Lawyers) Association. He is currently a Master Inventor of the IBM Corporation. In 1996, he was inducted into the Silicon Valley Engineering Hall of Fame.




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June 1999

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## **Foreword**

# **FOREWORD**

Timely information on scientific and engineering developments occurring in laboratories around the world provides a critical input to maintaining the economic and technological strength of the United States. Moreover, sharing this information quickly with other countries can greatly enhance the productivity of scientists and engineers. These are some of the reasons why the National Science Foundation (NSF) has been involved in funding science and technology assessments comparing the United States and foreign countries since the early 1980s. A substantial number of these studies have been conducted by the World Technology Evaluation Center (WTEC) Division, managed by Loyola College through a cooperative agreement with the National Science Foundation.

The purpose of the WTEC activity is to assess research and development efforts in other countries in specific areas of technology, to compare these efforts and their results to U.S. research in the same areas, and to identify opportunities for international collaboration in precompetitive research.

Many U.S. organizations support substantial data gathering and analysis efforts focusing on nations such as Japan. But often the results of these studies are not widely available. At the same time, government and privately sponsored studies that are in the public domain tend to be "input" studies. They enumerate inputs to the research and development process, such as monetary expenditures, personnel data, and facilities, but do not provide an assessment of the quality or quantity of the outputs obtained. Studies of the outputs of the research and development process are more difficult to

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perform because they require a subjective analysis performed by individuals who are experts in the relevant scientific and technical fields. The NSF staff includes professionals with expertise in a wide range of disciplines. These individuals provide the expertise needed to assemble panels of experts who can perform competent, unbiased reviews of research and development activities. Specific technologies such as telecommunications, biotechnology, and nanotechnology are selected for study by government agencies that have an interest in obtaining the results of an assessment and are able to contribute to its funding. A typical WTEC assessment is sponsored by several agencies.

In the first few years of this activity, most of the studies focused on Japan, reflecting interest in that nation's growing economic prowess. The program was then called JTEC (Japanese Technology Evaluation Center). Beginning in 1990, we began to broaden the geographic focus of the studies. As interest in the European Community (now the European Union) grew, we added Europe as an area of study. With the breakup of the former Soviet Union, we began organizing visits to previously restricted research sites opening up there. Most recently, studies have begun to focus also on emerging science and technology capabilities in Asian countries such as the People's Republic of China.

In the past several years, we also have begun to substantially expand our efforts to disseminate information. Attendance at WTEC workshops (in which panels present preliminary findings) has increased, especially industry participation. Representatives of U.S. industry now routinely number 50% or more of the total attendance, with a broad cross-section of government and academic representatives making up the remainder. Publications by WTEC panel members based on our studies have increased, as have the number of presentations by panelists at professional society meetings.

The WTEC program will continue to evolve in response to changing conditions. New global information networks and electronic information management systems provide opportunities to improve both the content and timeliness of WTEC reports. We are now disseminating the results of WTEC studies via the Internet. Twenty-six of the most recent WTEC final reports are now available on the World Wide Web (<http://itri.loyola.edu><sup>9</sup>) or via anonymous FTP ([ftp.wtec.loyola.edu/pub/](ftp:wtec.loyola.edu/pub/)<sup>10</sup>). Viewgraphs from several recent workshops are also on the Web server.

As we seek to refine the WTEC activity, improving the methodology and enhancing the impact, program organizers and participants will continue to operate from the same basic premise that has been behind the program from its inception, i.e., that improved awareness of international developments can significantly enhance the scope and effectiveness of international collaboration and thus benefit the United States and all its international partners in collaborative research and development efforts.

Paul J. Herer  
National Science Foundation



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## Executive Summary

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## EXECUTIVE SUMMARY

This report reviews the status of Japanese high-density data storage technology, manufacturing and R&D in comparison to that in the United States. It covers various optical data storage technologies, magnetic hard disk drives, and magnetic tape drives. Information sources used in the study include literature review, visits to 15 relevant sites in Japan, a review of the draft reports by panelists, site visit hosts, and study sponsors. The report also includes information obtained from presentations from U.S. panelists and Japanese counterparts given at a workshop that took place in Tokyo prior to the site visits.

The panel found that Japan clearly leads in optical data storage and magnetic tape drives, the United States and Japan are competitive in magnetic hard disk drives, and researchers in both countries are clearly aware of future challenges in data storage technologies for the next decade. Both the United States and Japan put significant emphasis on long-range alternative data storage techniques.

There are clear possibilities for Japan to surpass the United States in the hard disk drive segment and opportunities for the United States to catch up in optical data storage. Japanese government funding in data storage in general appears to far outstrip comparable government funding in the United States. In optical data storage, with Japan being in a comfortable leading position, most R&D funding is derived

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from industrial sources, although new large government programs in this area are being started. However, there is substantial present government and industrial support for R&D in magnetic hard disk drives where Japan trails the United States.

## **MISSION AND PROCEDURE**

The purpose of this WTEC panel study of high-density data storage in Japan was to investigate and report on the current status of Japanese data storage technologies compared to that in the United States. In particular, the panel's mission was to assess status and directions of Japanese R&D in high-density data storage technologies, and to contrast them with approaches taken by the United States.

To meet this goal, the panel researched the professional literature of both countries, visited numerous companies and government organizations in Japan, attended workshops on emerging technologies in the United States, and organized a workshop in Japan with participants including academic researchers. This report is a synthesis of the panel's findings reached by identifying general directions that transcend institutional boundaries.

The WTEC panel focused its investigations on four main areas:

1. optical data storage technology
2. magnetic hard disk technology
3. magnetic tape technology
4. emerging long-term data storage technology alternatives

The organizations chosen for site visits have established a leadership role in some important aspect of data storage technology. In all, the panelists visited 15 Japanese institutions including five companies and one government organization involved in optical data storage only, four companies focused on magnetic data storage only, and five companies that are heavily involved in both magnetic and optical data storage.

## **OPTICAL DATA STORAGE**

The recent economic recession in Japan that affected most areas of heavy investment seems not to have altered the strong commitment of the Japanese industry to optical data storage technologies, especially to technologies aimed at multimedia applications. Significant investments are clearly being made at each company that the panel visited to enable the insertion of novel concepts into new products to be launched over the next five years.

In Japan, the present focus for optical storage is to exploit its advantages to gain market segments that are not well served by magnetic hard disks. Over the next five years this market segment will grow into revenues of about \$20 billion per year. About two-thirds of present revenues are derived from magnetic hard drives. Optical storage offers a low-cost, reliable, and removable medium with excellent robustness and archival lifetime. A key targeted market is to replace magnetic tape for video

camcorders and VCRs. Additional applications include storing digital photographs, recording movies and other video materials, and multimedia presentations for home and business.

Over the last 15 years and especially since the early nineties, Japanese companies have heavily invested in optical data storage to the point that now the Japanese industry enjoys a comfortable lead in this area. This lead is not only in the manufacturing and R&D of conventional optical disk media and disk drive systems, but also in the manufacturing of the enabling optoelectronic components such as CD lasers. The success of the CD and new DVD family of products has resulted in a 20% annual revenue growth rate in recent years, enabling the Japanese optical storage industry to contribute significantly towards the support of the optoelectronics component industry in Japan.

It is clear that the infrastructure for manufacturing and R&D in optical data storage differs strikingly between the United States and Japan. Indeed, many big and very big companies, such as Sony, Hitachi, Matsushita, Fujitsu, Toshiba and Canon, dominate the landscape in Japan. Even more importantly, some of these companies are also involved in magnetic hard disk drive storage systems, providing their company policy makers a global outlook on opportunities in data storage. At all the sites visited, the panel sensed a very strong support, awareness and commitment from the upper management to current and future development of optical data storage technology.

In addition, there exist extensive teaming arrangements among these institutions, as well as with smaller companies, providing a formidable R&D and volume manufacturing capability (e.g., the Advanced Storage Magneto Optical (ASMO) consortium). However, these teaming arrangements also lead to competition and different standards that delay the acceptance of optical storage products by the consumer. At the same time, the creation of standards by clusters of Japanese companies makes the penetration of conventional optical data storage by U.S. enterprises nearly impossible. Cross-licensing arrangements make the matter worse.

Japan seems to be extremely well positioned to lead the manufacturing of optical data storage products over the next five years. Within this time frame a clear technology roadmap exists to push the effective areal densities of present DVD-type products up to 50 Gb/in<sup>2</sup>, targeting multimedia applications. Magneto-optical (MO) disk technology, recently re-strengthened by the ASMO alliance, is claimed to be able to surpass phase change media (e.g., DVD-RAM) capabilities within the same time frame for these applications, while becoming more and more competitive in performance with magnetic hard disk drives. With the limitations of conventional longitudinal magnetic recording in sight, it is becoming increasingly difficult to dismiss MO technology as a potential threat to the U.S. magnetic hard drive industry.

In addition, significant investment is being made towards mastering technologies to support DVD-ROM needs. To this end, a well-thought-out roadmap that leverages on microfabrication techniques (e.g., e-beam lithography) is in place to push the limits of mastering techniques to areal densities exceeding 100 Gb/in<sup>2</sup>. Finally, for emerging alternative optical storage technologies, Japanese companies seem to put a significant emphasis on probe storage that may provide Tb/in<sup>2</sup> areal densities for certain applications requiring small size and low power. Japanese universities and research organizations work mostly in partnership with industry on advanced concepts that can be incrementally integrated into present approaches.

In contrast to the heavy investment from the industry itself, the panel learned that over recent years, there has been only limited Japanese government support for optical data storage. This small support was mostly directed towards R&D organizations and universities perhaps because of the leading position Japanese industry has enjoyed in this area. However, the panel members also learned that this coming year, a large government supported R&D program is being planned, targeting the Japanese optical data storage industry and aimed at longer term R&D. Increasingly, the Optoelectronics Industry and Technology Development Association (OITDA) seems to play a coordinating role in seeking such government funding and generating technology roadmaps in Japan.

The optical storage manufacturing effort in the United States is limited to the Hewlett Packard Company, which produces CD and DVD products, and a small company, Pinnacle, which addresses niche markets in removable storage. In addition, a few entrepreneurial companies (e.g., Terastor, Quanta, Maxoptics, Calimetrix, Call/Recall Inc., Holoplex...) each carrying on R&D in distinct revolutionary approaches, aim at 100 Gb/in<sup>2</sup> areal densities and beyond. Also, IBM continues its long term R&D in optical storage and develops a considerable amount of intellectual property. Furthermore, there are a large number of manufacturers of optical libraries that serve niche markets. These U.S. producers of optical libraries assemble Asia-made CD drives in their systems but leverage on proprietary know-how in support software and networking.

At the present time, the entrepreneurial companies are isolated and lack large-scale manufacturing capabilities necessary to launch consumer products and may therefore be ultimately dependent on Japan's formidable OE and disk media industry. However, recent acquisitions of optical storage companies by U.S. magnetic storage manufacturers and recent U.S. venture capital interest in this area seem to signal perhaps the beginning of a trend towards the reorganization of the data storage industry in the United States for gaining better overall competitiveness.

Some U.S. universities still play an important role in conventional optical storage for both Japan and the United States since a significant amount of know-how on optical disk heads and metrology still exists at these institutions. Because little U.S. government funding is available in this area, some of this effort is sponsored by the smaller U.S. companies, but most support comes from Japanese institutions.

However, in addition to IBM, significant know-how and intellectual property reside in U.S. universities and small U.S. R&D companies on several unconventional long-term optical data storage approaches that promise data densities approaching Tb/in<sup>2</sup>. These include near field and solid immersion lens approaches, volumetric (multi-layer and holographic) storage, and probe storage techniques. In addition, in recent years, under government funding, the United States has gained an advantage on certain potentially enabling technologies such as vertical cavity lasers (VCLs), array optics, and MEMS. These powerful technologies may impact or become affected by optical data storage. VCLs and optical arrays may enable high data rate optical drives by exploiting parallelism. Micro machining can find a high volume application in either the disk drive industry or for probe storage. The United States has a slight lead in research, but a high volume application and the investment it draws could quickly evaporate that lead. Japan can easily take the lead in these areas away from the United States with its process development strength.

It is the panel's overall assessment, as summarized in Table ES.1<sup>p20</sup>, that Japan clearly leads in all major technical areas of optical data storage with the exception of certain R&D areas and certain products serving niche markets. Japan is out ahead in optical recording, but is struggling for a business model in which many companies become profitable rather than the two or three that attempt to control the standard. There is a necessity for the required copy protection solution as part of the removable optical storage standards. Due to the large U.S. market size and powerful U.S.-based content providers, opportunities do exist for U.S. companies to generate and arbitrate such solutions.

Opportunities do also exist for the United States to re-enter the optical data storage market via new technologies. Solid immersion lens based approaches appear promising in the short term. For the longer term and significant gain in market share, volumetric parallel accessible storage systems like holographic and two-photon multi-layer recording techniques appear most promising. The key issue is an inexpensive yet reliable write once material or preferably an erasable volumetric material. With the information explosion on the net, searching for desired data becomes a critical factor. Development of suitable hardware that exploits parallel readout to facilitate content-based data search may point to a potential opportunity. In addition, investing in micro-mechanics for micro-actuators as well as for probe storage and creating a new infrastructure in the United States to support future data storage approaches certainly appears compelling at this time.

Table ES.1

Optical Data Storage Technologies: Comparison of State of the Art in Japan and the United States

| Technology                         | Japan  |       |
|------------------------------------|--------|-------|
|                                    | Status | Trend |
| Conventional optical disks - Heads | +      | ↑     |
| - Mastering                        | +      | ↑     |
| - Media                            | +      | ↑     |
| - Channels                         | +      | ↑     |
| - Servos                           | +      | ↑     |
| - Drive integration                | +      | ↑     |
|                                    |        | ⇒     |

|                                                                        |   |   |
|------------------------------------------------------------------------|---|---|
| - Library integration                                                  | - |   |
| ROM media                                                              | = | ↑ |
| Emerging non-conventional near-field optical disk technologies - Heads | - | ↑ |
| - Mastering                                                            | + | ↑ |
| - Media                                                                | + | ↑ |
| - Channels                                                             | - | ↓ |
| - Servos                                                               | - | ↓ |
| - Systems integration                                                  | - | ↓ |
| - Head-disk interface                                                  | - | ↓ |
| Probe storage - writing and reading                                    | = | ⇒ |
| - Media                                                                | = | ⇒ |
| - Processing                                                           | + | ⇒ |
| Holographic R&D                                                        | - | ↓ |
| 2-Photon multi-layer disk R&D                                          | - | ↓ |
| Supporting technologies - MEMS                                         | - | ↑ |
| - Passive micro-optic assemblies                                       | + | ↑ |

|                         |                        |   |                    |
|-------------------------|------------------------|---|--------------------|
|                         |                        |   |                    |
| - Advanced micro-optics |                        | - | ↓                  |
| - Mastering lasers      |                        | = | ⇒                  |
| - Optical media testers |                        | = | ↓                  |
| Key                     |                        |   |                    |
| +                       | Ahead of United States | ↑ | Gaining ground     |
| =                       | Two countries even     | ↓ | Losing ground      |
| -                       | Behind United States   | ⇒ | No change in trend |

However, we should point out that except for low cost, personal, removable storage, which will be a sizable market over the next five years (\$20 billion/year in revenues), optical storage will not be the dominant technology for storage. Magnetic disk drives will be. The United States should not lose this technology and its future investment base.

## MAGNETIC STORAGE

In spite of the recent economic difficulties in Japan, it was found that Japanese companies are gaining strength both technologically and marketwise in the area of magnetic data storage. For the past three years U.S. company market shares have decreased as a percentage of total, while Japanese company market shares have increased. Furthermore, although U.S. companies still account for over 75% of magnetic hard disk drive sales, a much larger percentage of the components used in those drives are made in Japan.

It was found that the Japanese government, companies and universities were making major commitments to research on advanced magnetic and other data storage. Twenty-one Japanese companies in the magnetic data storage area are funding the Storage Research Consortium (SRC), which currently supports 34 Japanese universities working toward demonstrating 20 Gb/in<sup>2</sup> on a magnetic hard disk. Major funding of university research in this area by Japanese companies is a relatively new phenomenon and was originally announced as a direct response to the success of the United States in creating centers for research on magnetic data storage at universities such as Carnegie Mellon University, the University of California at San Diego and Stanford University. In addition, the Japanese government is providing ¥5 billion in funding to six industrial firms to develop 40 Gb/in<sup>2</sup>

magnetic recording technology by funding the Association of Super-Advanced Electronics Technologies (ASET) program through MITI. The SRC and ASET programs are coupled through the leadership of the six industrial firms and researchers, which are part of both programs.

Japanese companies were clearly aware of the long-term research issues such as barriers to increased storage density caused by thermal instabilities and had relatively large research programs addressing them. By comparison, with the exception of IBM, most U.S. companies are working only upon the next generation or two (1-3 years) of product and are relying upon their involvement in the National Storage Industry Consortium or U.S. universities to deal with longer term (5-10 year) issues.

It was the judgment of the panel that, in the area of magnetic disk drives, Japan was either gaining ground on the United States or maintaining parity in all areas of the technology. This is shown in Table ES.2<sup>23</sup>, which shows the panel's judgment of the status of Japanese technology compared to that of U.S. companies. It was judged that Japanese technology in the critical areas of heads, head-disk interface and track following are already equal to those in the United States, and that the Japanese are gaining on their U.S. counterparts in the area of disk media. Without the advanced research done by IBM in the United States, the Japanese would clearly be judged to be ahead in several of these areas.

Table ES.2

Magnetic Disk Drives: Japan Compared to the United States

| Component              | Status   | Trend                |
|------------------------|----------|----------------------|
| Magnetic Heads         | Parity   | Pulling Ahead        |
| Magnetic Media         | Trailing | Gaining              |
| Channel Electronics    | Trailing | Maintaining Position |
| Head-Disk Interface    | Parity   | Maintaining Position |
| Track Following Servos | Parity   | Pulling Ahead        |
| System Integration     | Trailing | Gaining              |

Another strength of the Japanese is that they have major programs in technologies such as perpendicular recording and probe recording. Advocates of perpendicular recording argue that it may be able to achieve 5-10 times higher density than conventional longitudinal recording, before thermal instabilities, which are expected to limit the density of conventional longitudinal magnetic disk drives, become a problem. Probe recording on various media types has been shown to have potential of storing information at densities several orders of magnitude higher than possible with longitudinal magnetic recording. Canon showed the WTEC team probe recording of 10 nm sized spots on Langmuir-Blodgett type media. Most U.S. disk drive companies have no activities in either perpendicular or probe recording.

In the area of magnetic tape drives, the Japanese have a critical advantage in that they are the only source of high-performance recording tape. This leaves U.S. magnetic tape drive manufacturers critically dependent upon Japanese companies for tape media and is a serious threat to the development of future high-performance tape drive products. To develop advanced tape drives, it is necessary that all the components be developed together and integrated. Currently, as Table ES.2<sup>p23</sup> shows, U.S. companies are considered to have the lead in magnetic heads, servos, signal processing and systems integration of tape drives for data storage, but if U.S. tape drive manufacturers are unable to obtain advanced tape media samples in the future, this lead could disappear very quickly, because U.S. drive development will have to wait until suitable tape becomes commercially available, which could be long after competitors have developed their products. This situation is particularly perplexing, since advanced media development, including media substrates and head-media interface, are seen as the primary roadblocks to future progress in the technology. This problem is not easily solved as there is currently only one viable tape media supplier in the United States, and it is not licensed for the double-coat technology, which was developed by Fuji in Japan and which is currently the favored approach to making high-performance tape media.

## **FUTURE MARKETS**

Advances in data storage technology are critical to computer technology; however, advances in data storage technology have been so rapid over the past several decades that it has been taken for granted by the computer industry. Areal density on magnetic hard disk drives has advanced over 2 million times since the first disk drive, the RAMAC, was introduced by IBM in 1957, and this has dramatically reduced cost of data storage. In the last ten years alone, the average price per megabyte of information stored on disk has dropped from \$12 to less than \$0.1 as shown in Fig. ES.1<sup>p25</sup>, which plots past and projected future cost per megabyte of disk storage and total worldwide disk drive sales revenue from 1988 to 2000. This has fueled good growth in the data storage industry, but, with the advent of computer networks, the demand for data storage is increasing and the industry is projected to grow at an even more rapid pace in the future. The fact that an increasing portion of the components of disk drives are being made in Japan, the recently instituted cooperative university-industry-government cooperative research programs in Japan, and the strength of the Japanese companies in long-term research on magnetic data storage compared to those in the United States suggest that Japanese companies will assume a larger portion of this future market. Indeed, Japan has gained a larger percentage of the market for disk drives each of the last three years. The United States needs to make a larger commitment to long-term research in this area and should consider working cooperatively with Japan in areas where both sides bring something to the program.

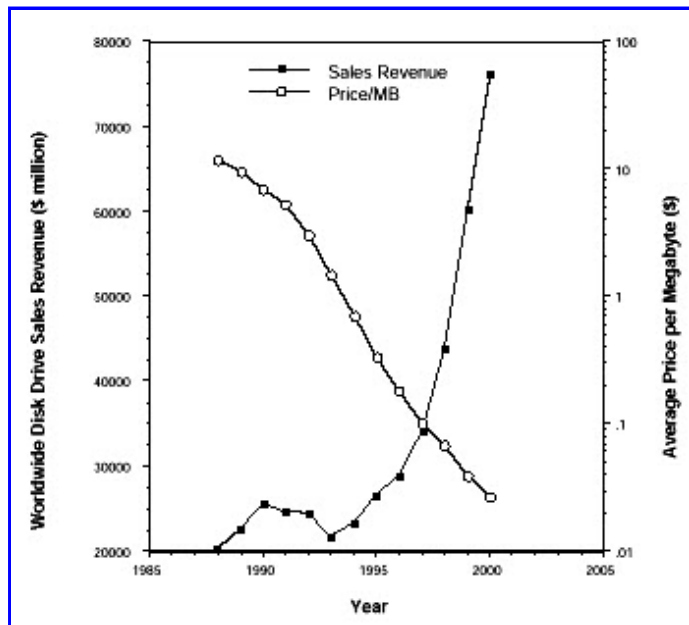


Fig. ES.1. Trends in disk drive sales and cost per megabyte.



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## 1: Optical Recording Technology And Applications

# CHAPTER 1

## INTRODUCTION-OPTICAL STORAGE

[Sadik C. Esener<sup>p5</sup>](#)

## OPTICAL RECORDING TECHNOLOGY AND APPLICATIONS

Optical storage systems consist of a drive unit and a storage medium in a rotating disk form. In general the disks are pre-formatted using grooves and lands (tracks) to enable the positioning of an optical pick-up and recording head to access the information on the disk. Under the influence of a focused laser beam emanating from the optical head, information is recorded on the media as a change in the material characteristics, often using a thermally induced effect. To record a bit, a small spot is generated on the media modulating the phase, intensity, polarization, or reflectivity of a readout optical beam which is subsequently detected by a detector in the optical head. The disk media and the

[http://itri.loyola.edu/hdmem/01\\_01.htm](http://itri.loyola.edu/hdmem/01_01.htm)

pick-up head are rotated and positioned through drive motors and servo systems controlling the position of the head with respect to data tracks on the disk. Additional peripheral electronics are used for control and data acquisition and encoding/decoding. Such a system is illustrated in Fig. 1.1<sup>26</sup>.

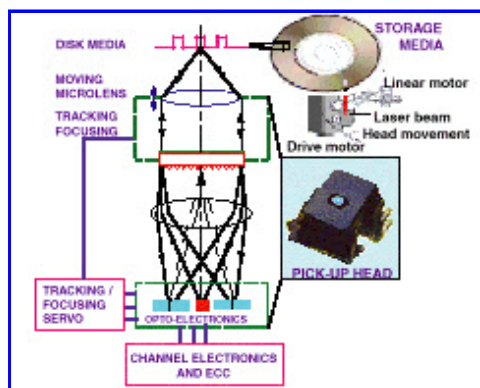


Fig. 1.1. Key components of an optical disk system.

As for all storage systems, the storage capacity, data transfer rate, access time, and cost characterize optical disks systems. The *storage capacity* is a direct function of the spot size (the minimum dimensions of a stored bit) and the geometrical dimensions of the media. A good metric that measures the efficiency in using the storage area is the areal density ( $\text{Gb/in}^2$ ). The areal density is governed by the resolution of the media and by the numerical aperture of the optics and the wavelength of the laser in the optical head used for recording and read-out. The areal density can be limited by how well one can position the head over the tracks. The track density (tracks/in) is used as a metric for this characteristic. In addition the areal density can be limited by how close the optical transitions can be spaced. This is measured by the linear bit density (bits/in).

The *data transfer* rate is critical in applications where long data streams must be stored or retrieved such as in image storage or back-up applications. The linear density, the rotational speed of the drive, and the number of pickup heads determine data rate. It is often limited by the optical power available, the speed of the pick-up head servo controllers, and the tolerance of the media to high centrifugal forces.

The *access time* is a critical parameter in computing applications such as transaction processing and represents how fast a data location can be accessed on the disk. It is mostly governed by the latency of the head movements and is proportional to the weight of the pick-up head and the rotation speed of the disk.

Finally, the *cost* of a drive, consisting of the drive cost and the media cost, strongly depends on the number of units produced, the automation techniques used during assembly, and component and overall system yields.

Optical storage offers a reliable and removable storage medium with excellent robustness and archival lifetime and with very low cost. A key difference between optical recording and magnetic recording is the ease with which the optical media can be made removable. Both optical recording and readout can be performed with a head positioned relatively far away from the storage medium, unlike magnetic

hard drive heads. This allows the medium to be removable and effectively eliminates head crashes, increasing reliability. In addition, during recording, optical radiation is used as a focused thermal source allowing the use of more stable materials suitable for archival lifetimes. On the other hand, the remote optical head is heavier and leads to slower access times when compared to hard disk drives.

Consequently optical storage has remained limited to market segments requiring removability and reliability that are not well served by magnetic hard disks. Typical applications involve archival storage, including software distribution, storing digital photographs and medical imaging, information appliances including recording movies, other video materials, and multimedia presentations at home and business, and online databases including video servers. More recently the magnetic tape market for video camcorders and VCRs has also been targeted.

These types of applications, while benefiting from random access capabilities of disk systems, are less sensitive to access time requirements but require low cost and high capacity removable storage. The compact disk (CD) format and more recently the digital video disk (DVD) format based on phase change media are designed to best satisfy these requirements. By thermally heating at different rates, a laser beam can record bits of information by locally changing the reflectivity of the medium. With the CD and DVD formats, the information is recorded in a spiral while the disk turns at a constant linear velocity, thus maximizing data capacity at the expense of transfer rate. The original CD format used a 12 cm standard disk which offers a typical capacity of 650 MB with a seek time (access time) in the order of 300 ms and data rate of about 100 kbps. Approximately a decade later, the DVD format offers 4.7 GB capacity, 10 Mb/s data rate and 100 ms access time by using a smaller spot size (from a shorter wavelength laser and a higher numerical aperture lens), faster rotation speeds, higher power lasers, more powerful error correction codes, and faster servo systems. Because the head is not flying on the media, one head is also capable of recording and reading multiple storage layers, thus increasing the capacity to 9.4 GB in a two-layer DVD-ROM disk.

Magneto-optic (MO) storage systems record data by thermally heating (with the laser spot) the media under the influence of a magnetic field. Data are recorded by re-orienting magnetic domains within the heated spot. During readout the polarization of the laser beam is modulated by the orientation state of the magnetic domains. Until recently, all systems using magneto optic media used a *standard format* to shorten the access times (at the expense of capacity) and approach hard disk like speed performance with a removable media. With standard formatted systems the disk turns at a constant angular velocity and data are recorded on concentric tracks as in magnetic hard drives. While reading the inner or outer tracks the speed of rotation remains constant, allowing for faster access times. However, this format results in constant number of bits per track, limited by the number of bits that can be supported by the most inner track, and wastes valuable real estate on the outer tracks. To eliminate this waste, a "banded" format is now used where tracks of similar length are grouped in bands, allowing the outer bands to support much larger number of bits than the inner bands. This, however, requires different channel codes for the different bands to achieve similar bit error rates over the bands. Today, removable MO systems provide 640 MB capacity with 3.5 inch diameter disks with speed performance comparable to hard drives. The WTEC team members learned during the visits that in the near future certain MO disk drive products might adopt the DVD format and become contenders for the video market as a VCR replacement.

In contrast to non-removable systems, for removable storage, yearly increases in performance are not necessarily desirable. This is because removable storage systems and media are tightly constrained by standards that are established for compatibility purposes. Removable storage manufacturers instead introduce products at an entry capacity and performance point that is desirable for a particular data type. Thus, the optical storage market is essentially driven by applications rather than by progress made in technology. Therefore, projections made on optical storage critically depend on application roadmaps such as the one shown in Fig. 1.2<sup>28</sup>.

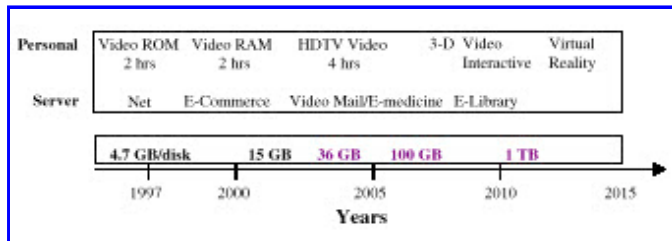


Fig. 1.2. Potential evolution of application requirements for removable storage (information gathered from OITDA and surveys performed by Call/Recall, Inc. and USC).

Over the next decade with the emergence of the Internet, a new and important class of applications referred to as server-based applications will emerge. While personal applications will define future removable storage standards, server-based applications will significantly boost the size of the optical and magnetic disk storage market.

Many server-based applications, such as electronic commerce, medicine, and libraries, among others, require modest access times (<10 ms) but very large storage capacities and appreciable data transfer rates, as shown in Fig. 1.3<sup>29</sup>. These applications, because of their very large capacity requirements, will initially be constructed as RAID or disk library systems based on commodity personal computer drives. Drive and database maintenance costs will be among deciding factors for various technology solutions.

With the DVD ROM standard it is possible to distribute one two-hour video movie per disk. Soon the DVD RAM standard will enable consumers to record a two-hour long video per disk. An important jump in performance will be needed slightly after the turn of the millennium to address HDTV applications requiring 15 GB capacities per movie. Most of WTEC's hosts indicated that the technology was in already place to address HDTV quality video. There are also serious considerations by both the phase change and MO manufacturers to use 30-40 GB disks as VCR replacements, perhaps shortly before the year 2005. Guessing the type of applications that may drive optical storage technologies beyond 2005 is certainly speculative at this point in time. It is, however, plausible that 3D interactive video in some form of virtual reality application might become a driver for higher capacities within the next decade, pushing capacity requirements beyond 0.1 TB to 1 TB per disk. Several MO disk drive manufacturers also point out that the performance gap between magnetic hard drives and MO drives has shrunk to a point where MO drives might be considered for general computing applications. This will depend on the capacity and cost performance that hard disk drives offer in the future.

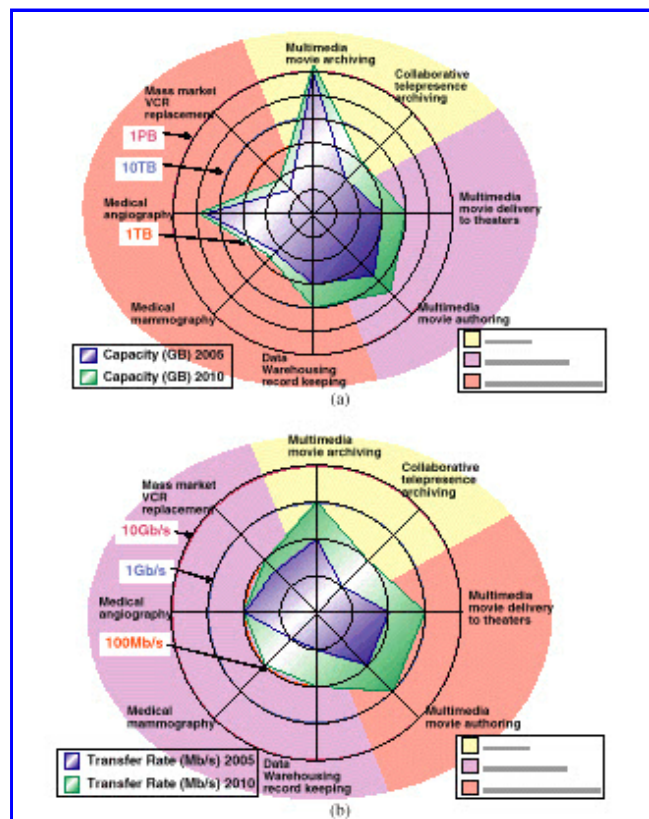


Fig. 1.3. (a) Capacity and (b) data rate requirements imposed by various applications by the years 2005 and 2010 (information gathered from OITDA and surveys performed by Call/Recall, Inc. and USC).

A different, yet critical, category of applications concerns portable and handheld devices that place more importance on system volume and power dissipation considerations. Typical applications here include compact storage systems for camcorders, personal digital assistants and communicators. Within the next decade, these applications will require about 50 GB capacity and reasonably fast access times (microseconds) and transfer rates (100 Mb/s) within very small volumes and with power dissipations of less than a few milliwatts. Miniaturized hard disk drives, solid state disks, probe storage, and even single electron DRAM chips might serve this category of applications in the future. At this point it is doubtful that conventional optical storage technologies can address the needs of this market segment.

It was the strong belief of our Japanese hosts in general that the performance of data storage systems during the next decade will not be limited by a lack of applications pull but will rather be constrained by the capabilities of technologies in hand.



## OPTICAL STORAGE MARKET

The growth of the disk storage market, which includes drives and media, has been driven over the last decade by the PC revolution. Over the next decade, it is expected to expand even faster, fueled by the multimedia revolution and Internet specific applications.

The volume of the disk storage market exceeded \$36 billion in 1996 with the hard disk segment at \$30 billion, and the optical disk segment at \$6 billion. As can be noticed from Fig. 1.4a<sup>p31</sup>, the market share of the optical disk drives has been growing recently at 20% per year, faster than the hard disk drive market, as a result of the successful CD technology. These figures do not include revenues from media sales that may add additional \$30 billion/year revenues to the optical disk segment.

Disk drive revenues were expected to exceed \$50 billion/year in 1998 (Disk Trend) due to server applications driving increased sales of hard disk drives and from multimedia applications driving increased DVD sales.

Although Japan has a significant market share in the hard disk drive segment where the United States currently leads, the United States has only 1.5% market share in optical storage products where Japan leads. As described in Fig. 1.4b<sup>p31</sup>, the number of U.S. optical storage manufacturers has dropped significantly since the late eighties, while the number of Asian, and especially Japanese, manufacturers has increased dramatically. Several reasons can account for this disparity, including the slow acceptance of optical storage products and short-term strategies of the U.S. industry in the eighties, the focused interest of the U.S. industry on magnetic hard disk drives, and the economic recession in the United States in the late eighties. Another important reason is that optical storage manufacturing in Japan is backed up by a formidable optoelectronic industry that can manufacture CD related components at very low costs. Consequently, the Hewlett-Packard Company remains the only U.S. manufacturer with a profitable optical storage business, largely due to its considerable strength in optoelectronic component manufacturing.

CD-ROM products have clearly been generating the largest revenues (\$4.6 billion/year in 1996) within the optical storage market since most PCs are shipped equipped with CD drives. Only two manufacturers are left in this area in the United States, while Japan has 14; however, it is striking that there are 36 optical library system assemblers in the United States compared to 18 in Japan. The optical library segment had \$514 million sales in 1996 and is only growing at 4.5% a year. These U.S. producers of optical libraries assemble Asian-made CD drives in their systems but leverage on proprietary know-how in support software and networking. Presently these U.S. firms are relegated to the role of assemblers. However, with advanced MO drives and upcoming Internet-specific applications, there might be a brighter future in this area.

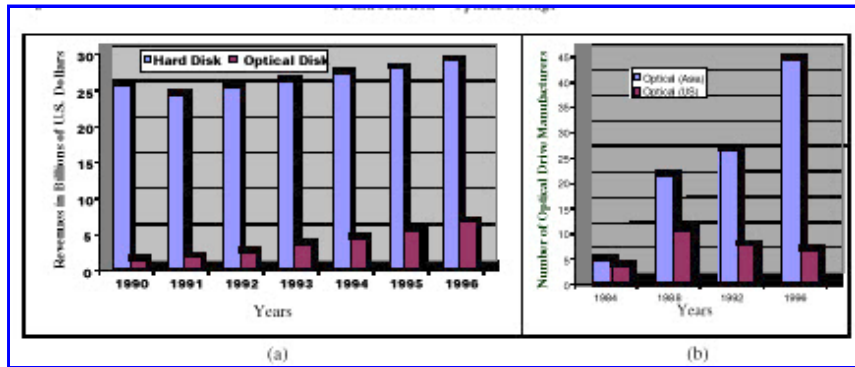


Fig. 1.4. (a) A comparison of worldwide hard disk drive and optical disk storage revenues and (b) disparity in the number of U. S. and Asian optical drive manufacturers (Disk Trend).

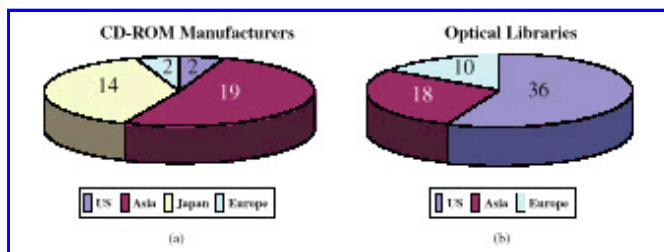


Fig. 1.5. (a) Distribution of CD-ROM and (b) optical library manufacturers.

In the U. S. removable media market, optical data storage products have been experiencing stiff competition from magnetic removable storage products such as IOMEGA's ZIP drive and SyQuest's SyJet drive products. Because the U.S. magnetic removable media manufacturers ventured into the removable market without negotiating compatibility standards, they have beaten the optical storage products to the market and gained considerable market shares. In Asia and Japan, however, magnetic removable products have only a negligible market share. The situation is reversed because in Asia the consumers appear to be more concerned with product compatibility. As can be observed from Fig. 1.6<sup>31</sup>, optical storage products possess more than 90% of the recordable removable storage market in Japan. MO disk drives have the largest market share at 85%, with 1.7 million drives and 17 million media units sold per year. It should be pointed out that more recently, CD-recordable (CD-R) products have been gaining significant market share in the United States as well.

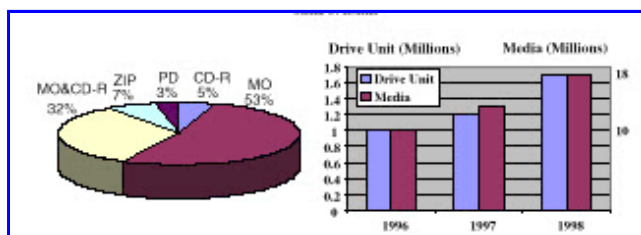


Fig. 1.6. Respective removable media market share distribution in Japan in 1997 (Fujitsu).

In summary, CD-ROM products are at the end of their product life cycle and are being replaced by DVD-ROM products that are starting to ship in quantity. CD-R shipments are up and CD-RW is

moving in a big way. DVD-RAM products should come in soon. With a price drop in MO drives, there has been an upsurge in demand in Asia, but MO products still encounter stiff competition from magnetic removable drives in the U.S. market.



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## SUMMARY OF TECHNOLOGY STATUS

### SUMMARY OF TECHNOLOGY STATUS

Japanese manufacturers are convinced that over the next decade new emerging applications will pull the performance of optical storage systems and that evolving conventional optical storage technologies (DVD and MO) are capable of satisfying these demands for at least another seven to eight years (Fig. 1.7p<sup>33</sup> ).

During the period of the WTEC site visits, PC manufacturers were heavily involved in the advanced R&D of 4.7 GB DVD-RAM products. The panel learned that PC manufacturers may combine higher NA optics with shorter wavelength blue lasers and single carrier independent pit edge recording (developed by SONY) together with radial direction partial response (RPR) encoding technique to achieve 15 GB capacity double layer disks required for the HDTV standard. Matsushita Electric Company (MEI) will be introducing a frequency doubled blue laser in some of its products within 1999. The panel also learned that MEI was experimenting with more transparent PC media layers that enable four-layer disks to be used in higher capacity products. In addition, various mastering techniques including UV laser, SIL lens, e-beam, and probe mastering are being developed to extend the effective areal density of DVD-ROM products to 50 Gb/in<sup>2</sup> as described in Fig. 1.8p<sup>33</sup> .

All PC manufacturers seem to put highest priority, and therefore significant effort, into achieving backward and forward compatibility within a product line, and also on compatibility between different product lines within the DVD family.

In recent years, MO R&D activity has been revived through the ASMO consortium.

MO drive manufacturers now believe that the MO technology can be extended to 5.2 GB capacity in the near future, and then to 10.4 GB on a 5.25" double-sided disk using 680 nm wavelength and a lens with an NA of 0.55. Beyond that, they plan to rely on one of the magnetic super-resolution (MSR) techniques, either Magnetic Amplifying Magneto Optical Systems (MAMMOS) from Hitachi-Maxell or Domain Wall Displacement Detection (DWDD) from Canon, in addition to magnetic field modulation, to enable further capacity increases. By 2002 they may be able to achieve areal densities approaching 20 Gb/in<sup>2</sup> by combining one of the MSR techniques with the use of a blue laser and

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larger NA optics. By adopting a format similar to DVD, MO researchers at Fujitsu are contemplating 36 GB capacity disc systems as VCR replacements. Finally, they envision using SIL lenses and parallel heads to extend the areal density and data rate of MO products to exceed 100 Gb/in<sup>2</sup> and 1 Gb/s respectively.

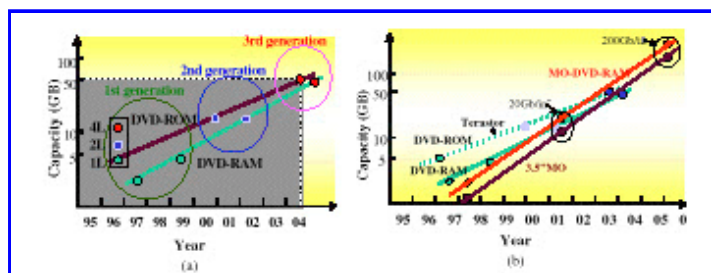


Fig. 1.7. Example roadmaps describing performance potentials of (a) phase change media (Hitachi) and (b) MO media based systems (Fujitsu).

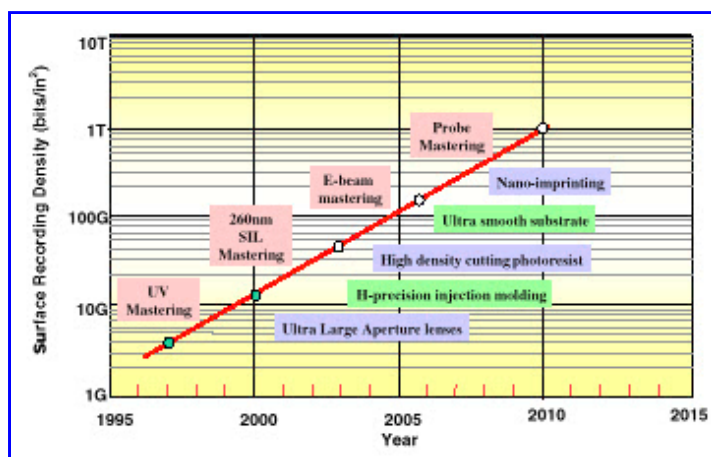


Fig. 1.8. A potential roadmap for mastering technology (OITDA).



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## LONG TERM OUTLOOK

### LONG TERM OUTLOOK

Many novel technologies are being pursued in parallel towards accomplishing higher capacities per disk and higher data transfer rates. Several unconventional long-term optical data storage techniques promise data densities greater than 100 Gb/in<sup>2</sup> and perhaps even exceeding Tb/in<sup>2</sup>. These include near field and solid immersion lens approaches, volumetric (multi-layer and holographic) storage, and

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probe storage techniques.

A solid immersion lens approach using MO media pursued by Terastor in the United States promises at least 100 Gb/in<sup>2</sup> areal density. This technique relies on flying a small optical lens about 50 nm above the storage medium to achieve spot sizes smaller than the diffraction limit of light. Since the head is now lighter, this type of technology may lead to access times comparable with hard drives. Several Japanese companies are intrigued by the approach and are involved in Terastor's activities. Similar objectives are pursued by Quinta, a Seagate Company, where increasing amounts of optical technologies including optical fibers and fiber switches are used to reduce the size and weight of the head, which is non-flying ("far-field"), but still placed quite near to the disk medium.

Multi-layer (multi-value) storage is pursued both in Japan and the United States. In Japan the effort concentrates on increasing the number of storage layers in a PC based DVD disk. Some researchers also envision adapting multi-layer recording to MO media by simultaneously reading and computing the data on several layers. Both approaches, however, have limited scalability in the number of layers. In the United States, Call/Recall, Inc. is using a fluorescent disk medium to record and read hundreds of layers. Also in the United States, significant effort is being put into developing holographic storage, aiming for areal densities exceeding 100 Gb/in<sup>2</sup>. Companies both in the United States and Japan are exploring the use of parallel heads to speed up data transfer rates. Finally, both in Japan and in the United States, optically assisted probe techniques are being explored to achieve areal densities beyond a Tb/in<sup>2</sup>. Fig. 1.9<sup>p35</sup> summarizes the author's projections for long-term trends in optical storage.

In summary, a fast growing removable data storage market governed by optical storage has resulted from substantial progress that has been made in optical disk storage techniques. These advances have come through a combination of laser wavelength reduction, increases in the objective lens numerical aperture, better ISI and cross-talk management, and coding improvements under the constant pull of new applications. Undoubtedly, emerging applications will pull optical storage techniques to reach new performance levels. There is room for advances in storage capacity, as transitions to blue lasers, near-field optical recording, and multi-layer systems will occur.

To further report and analyze Japan's potential role in this developing important market, in the following chapters, we present in more depth the status of optical storage in Japan from a business oriented perspective, and a review of the technologies being developed for the near as well as longer terms.

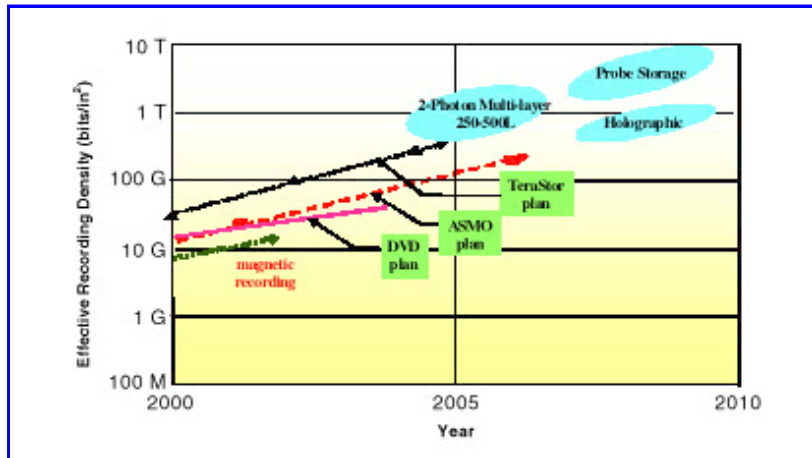


Fig. 1.9. Alternative optical storage technologies and their potential impact (speculative personal projections from the author).



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## 2: Introduction

# CHAPTER 2

## INTRODUCTION-MAGNETIC RECORDING TECHNOLOGY

[Mark H. Kryder<sup>p6</sup>](#)

### INTRODUCTION

A schematic of a magnetic recording system is illustrated in Fig. 2.1<sup>p36</sup>. The magnetic recording medium consists of a magnetic coating on some form of substrate. (The substrate is not shown.) In the case of magnetic tape, the substrate is a flexible medium, such as Mylar, whereas in a magnetic disk drive it is typically an aluminum alloy or glass. To record and play back the information one or more magnetic recording heads are used. The recording head consists of a high-permeability magnetic core with a narrow gap cut into it and a few turns of conductor wound around it. When current flows through the conductor, magnetic flux flows through the magnetic core, emanates from the core at the gap and penetrates the magnetic medium, causing it to be magnetized to the right or the left. Binary data are encoded in the form of transitions (ones) or the absence thereof (zeroes) in the magnetization

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in coincidence with a clock, which is synchronized with the disk or tape motion. A similar recording head is used to sense the magnetic flux emanating from the recorded transitions in the medium during read back. In order to achieve high recording density it is imperative that the head be very close to the medium. Spacings of the order of 50 nm are used in today's disk drives. Highly sophisticated signal processing electronics are used to encode binary ones and zeroes into the write current waveforms and also to convert the waveforms sensed by the read head back into digital data. An actuator is used to servo-position the head relative to the media for accessing the desired track of data.

The rotation rates of magnetic disk drives today range from 3,600 to 10,800 rpm. With high performance actuators, it is possible to access a track on a disk in a couple of milliseconds. Hence, total access time to a random sector on the disk is only a few milliseconds, and disks provide relatively fast access to data.

Magnetic tape drives on the other hand, record data linearly over the length of the tape. Average access time is the length of time it takes to transport half the length of tape over the head and is typically many seconds. Although tape has a relatively long access time, since it is very thin and can be wound upon itself, it offers an extremely high volumetric storage density and low cost.

A relatively new technology in both disk and tape drives is magnetoresistive (MR) head technology. Previously, inductive heads, which sensed the time rate of change of magnetic flux in the head core, were used. However, inductive heads have limited sensitivity, and the amplitude of the read back signal depends upon the relative head-medium velocity. Magnetoresistive heads, on the other hand, are considerably more sensitive than inductive read heads, and since they directly detect the amount of flux flowing through the head core, the signal amplitude is independent of the head-medium velocity. Recently, IBM and Japanese manufacturers Yamaha and TDK have introduced giant magnetoresistive (GMR) head technology. GMR heads offer yet higher sensitivity than conventional MR heads.

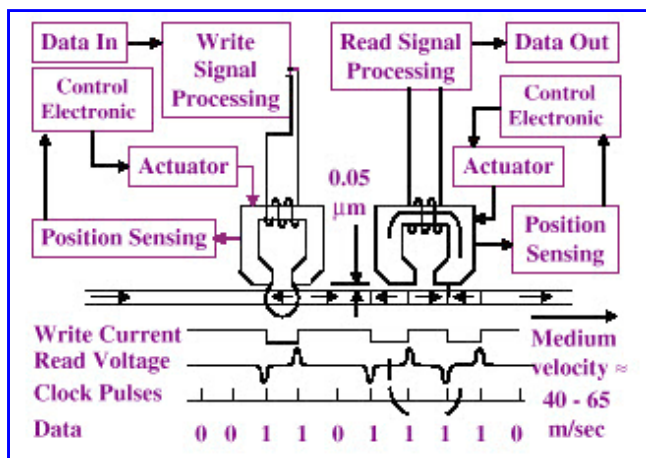


Fig. 2.1. A schematic diagram of a magnetic recording system.



## MAGNETIC DISK DRIVE APPLICATIONS AND MARKETS

Magnetic disk drives have been the primary means of storing information on computers since 1957 when IBM introduced the RAMAC, the first disk drive. As opposed to semiconductor random access memory, magnetic disk drives provide long-term storage of information in the absence of electrical power; i.e., they *provide non-volatile* storage. Because of the disk format and the relatively short access time, which disks provide to data, they are used extensively for online storage of information.

Although sometimes taken for granted because of its long history of continual advancement, magnetic disk drives have been critical to the information technology revolution we have been experiencing. The software programs which companies such as Microsoft have been introducing would not be useable if large capacity, high performance disk drives were not available. Moreover the trend toward the storage of more graphical information including video would not be possible without the large data storage capacity and low cost of magnetic disk drives. Indeed, the growth of the Internet and computer networking in general would not be possible without the higher capacities of disk drives and the lower cost of storing information that they make possible. Magnetic disk drive sales are currently over \$30 billion per year, but, as was illustrated in Fig. ES.1p<sup>25</sup>, are projected to grow to over \$75 billion in 2000. This growth is expected to come largely from the more widespread use of computer networks to access data warehouses of information and to store it locally for future use.

U.S. companies have been the major producers of disk drives, as illustrated in Fig. 2.2p<sup>37</sup>; however, the U.S. share of the market has been declining over the past three years. The majority of non-U.S. manufactured drives are from Japan. As will be made clear below in the section on magnetic disk drives, although the majority of drives are manufactured by U.S. companies, Japanese companies are making an increasingly large number of the components used in those drives and have increased their market share steadily over the past three years.

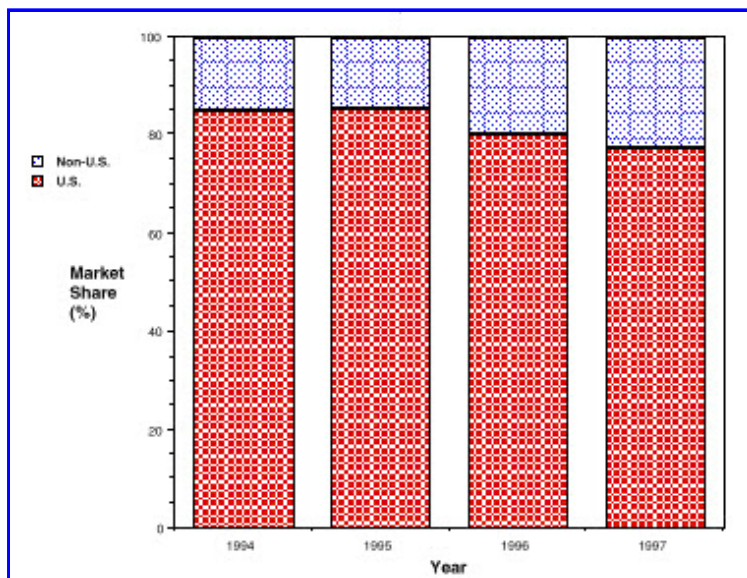


Fig. 2.2. A bar graph showing the market share of non-U.S. and U.S. manufacturers of disk drives (Disk/Trend).



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## MAGNETIC DISK DRIVE TECHNOLOGY STATUS

# MAGNETIC DISK DRIVE TECHNOLOGY STATUS

About a decade ago, the areal storage density on magnetic disk drives was advancing at a pace of about 25% per year. At that time semiconductor dynamic random access memory was advancing at a pace of about 40% per year, and many semiconductor proponents argued that the time would come when semiconductor devices offered a higher storage density and lower cost than magnetic disk storage. These proponents argued that with their faster access time, semiconductor devices would replace disk drives. In 1991, however, the magnetic disk drive industry responded by advancing the rate of progress in areal density to 60% per year, as illustrated in Fig. 2.3<sup>38</sup>. With the recent announcement of recording at 10 Gb/in<sup>2</sup> density by IBM, it is now believed that this rate of progress can be sustained at least into the next millenium. Hence, rather than converging toward the areal density of magnetic disk drives, the areal density of semiconductor memory devices is falling further behind that of magnetic disk drives, and it no longer appears likely that semiconductor memory devices will be a significant threat to magnetic storage.

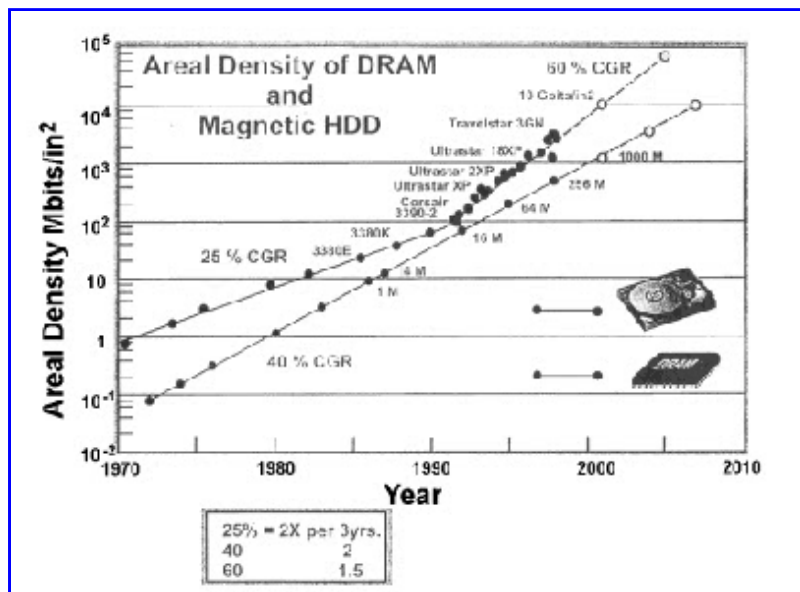


Fig. 2.3. Areal density of magnetic hard disk drives and of dynamic random access memories as a function of the year of shipment (IBM).

In spite of the current rapid pace of advancement in disk drive technology, there are some obstacles to progress on the future horizon. Since 1957 when IBM introduced the first disk drive, the RAMAC, the

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areal density of magnetic disk recording has been increased over 2 million times by linear scaling of dimensions of the head, medium and head-medium spacing, while the sensitivity of read heads has been increased. While doing this, it has been necessary to reduce the size of the magnetic particles of which the medium is made in order to maintain the signal to noise ratio of the system. This is because the signal to noise ratio scales approximately with the number of magnetic particles contained within a bit. If this trend is continued, it is inevitable that the particle size will become so small that the magnetic energy of a particle,  $K_U V$ , (where  $K_U$  is the magnetic anisotropy energy holding the magnetization in its orientation and  $V$  is the volume of the particle) will decrease to values that approach thermal energy given by  $K_B T$  (where  $K_B$  is Boltzmann's constant and  $T$  is the absolute temperature). When this occurs, thermal energy alone may cause magnetic recordings to become unstable.

Although this thermal instability problem appears at first glance to be a problem in the magnetic recording medium, in reality part of the limitation comes from the magnetic recording head. Magnetic materials that have higher values of magnetic anisotropy energy  $K_U$  exist; however, they require higher fields for recording than can be produced with existing recording heads. Before the field produced by the head is made large enough to write on the medium, the magnetic material from which the head is made saturates.

Modeling has indicated that if magnetic recording continues to be scaled linearly, this thermal instability limit will be reached at about  $36 \text{ Gb/in}^2$ , or a factor of nine higher than the highest density disk drive made today. At the 60%/year growth rate, this density would be reached in about five years. However, modeling performed by a group of researchers working with the National Storage Industry Consortium (NSIC) has recently shown that, if the bit cell is not scaled linearly but decreased in track width more than in bit length, a density of  $100 \text{ Gb/in}^2$  may be achievable. Ultimately, however, thermal instabilities will become a problem, and means to circumvent this limitation must be found.

One possible means of extending magnetic recording density beyond what can be achieved using longitudinal magnetic recording is to use perpendicular magnetic recording. As illustrated in Fig. 2.4p<sup>40</sup>, in perpendicular magnetic recording, the medium is magnetized perpendicularly to the film plane, rather than in the plane. If a high permeability magnetic underlayer is placed under the perpendicularly magnetized thin film medium, then an image of the magnetic head pole is produced in the underlayer. Consequently, the perpendicular medium is effectively in the gap of the recording head, where the field is larger than the fringing field produced at a longitudinal medium by a longitudinal magnetic recording head. With this larger record field it is possible to record on media with higher  $K_U$  and, consequently, smaller grain size  $V$  and smaller bit sizes. Advocates of perpendicular recording argue that, because of these higher record fields and the fact the media may be made thicker, perpendicular recording can achieve considerably higher densities without suffering from thermal instabilities than longitudinal recording can. Japanese companies and universities have long been proponents of perpendicular magnetic recording and have considerably more experience with it than we have in the United States.

Another possible means to circumvent the thermal stability problem of conventional longitudinal magnetic recording is to use some form of thermally assisted recording process. If the temperature of

high  $K_U$  media is raised, then a smaller field is adequate for recording. If the media are kept near room temperature for storage and readout, but raised in temperature during recording it may be possible to use media with intrinsically higher  $K_U$  (and, consequently, improved thermal stability) while still being able to record on them. Dr. Miura of Fujitsu Laboratories, the Storage Research Consortium (SRC) and ASET suggested such an approach may have merit during this WTEC team's Japan trip.

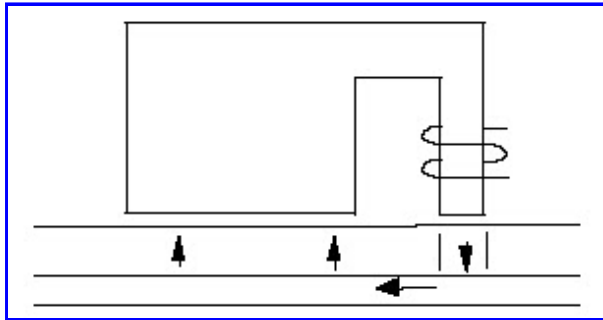


Figure 2.4. A schematic diagram of a perpendicular magnetic recording medium with a soft underlayer and a single pole head.



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## MAGNETIC TAPE DRIVE APPLICATIONS AND MARKETS

In spite of their relatively long access time, magnetic tape drives offer many advantages over magnetic disk drives for specific applications. Since the tape is extremely thin (a few microns) and is wound upon itself, it offers extremely high volumetric density of storage. Moreover, tape is relatively inexpensive and may be removed from the drive. With these features, digital magnetic tape drives are used in a wide variety of applications, but the extent of the usage depends upon the size of the computer system. This is illustrated in Fig. 2.5<sup>p41</sup> where the various applications for digital magnetic tape are shown across the top, and the computer systems they are used in are shown down the side. This figure clearly illustrates that the largest number of tape applications are in large computer systems and that magnetic tape serves a large variety of needs.

The markets for various digital tape drives are shown in Table 2.1<sup>p41</sup>. Compact tape drives are small form factor drives, which are typically used for disk backup on personal computers as well as on a

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network. Performance tape drives are high-end tape products used predominantly for large computer systems. Tape libraries are automated media changing subsystems comprised of multiple tape drives, shelves or racks to contain media, and mechanisms to move media between drives and storage shelves. Summed together the total digital tape drive market was about \$4.6 billion in 1996.

The market share of non-U.S. and U.S. manufacturers of the various classes of tape drives are also shown in Table 2.1<sup>41</sup>. As in the case of disk drives, U.S. companies sell the majority of digital magnetic tape drives used for data storage and most of the non-U.S. manufacturers are Japanese. Although Japanese companies have only a small fraction of the market for magnetic tape drives for data storage, they dominate the analog audio- and videotape drive businesses. Moreover, they are the dominant manufacturers of magnetic tape media.

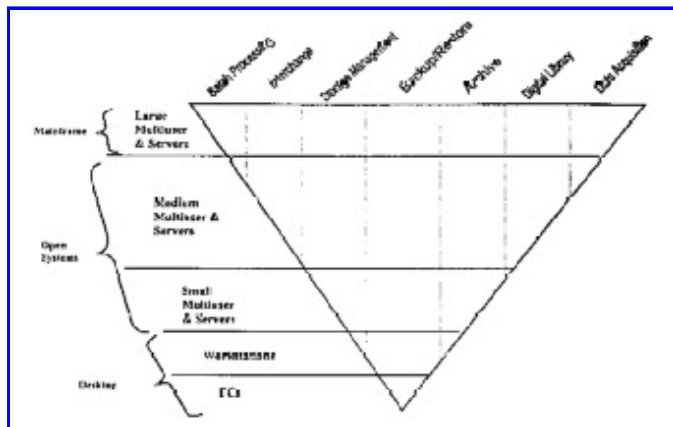


Fig. 2.5. User application segments for magnetic tape. The inverted triangle shows the tape applications (across the top) and the systems use of these applications down the side. The presence of an application with a particular system shows the importance of tape storage in that environment. (Reprinted with permission of the National Storage Industry Consortium.)

Table 2.1  
1996 Revenues from Tape Drive Sales

|                         | U.S. Mfrs.   |      | Non-U.S. Mfrs. |      | Worldwide |
|-------------------------|--------------|------|----------------|------|-----------|
|                         | (\$ million) | %    | (\$ million)   | %    |           |
| Compact Tape Devices    | 1,559.8      | 81.6 | 350.6          | 18.4 | 1,910.4   |
| Performance Tape Drives | 988.1        | 75.6 | 318.7          | 24.4 | 1,306.8   |
|                         |              |      |                |      |           |

|                |         |      |       |      |         |
|----------------|---------|------|-------|------|---------|
| Tape Libraries | 1,196.5 | 85.0 | 211.3 | 15.0 | 1,407.7 |
| TOTAL          | 3,744.3 | 81.0 | 880.6 | 19.0 | 4,624.9 |

Source: Freeman Reports



**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

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## MAGNETIC TAPE DRIVE TECHNOLOGY STATUS

The fact that tape is removable carries with it a few burdens. Purchasers of tape systems expect to be able to play their tapes on future tape storage systems, at least for a generation or two of tape drives. Thus, it is necessary for the tape drive manufacturer to not only increase the performance of future tape drive systems, but to simultaneously provide the capability of playing back tapes recorded on previous generation systems. This places very significant constraints upon the tape drive designer and has resulted in a slower rate of advance of the technology compared to disk drives. Consequently, the areal density on magnetic tape is considerably less than on magnetic disks, and thermal instabilities in the media are not looming as a short-term problem.

Rather, the problem for magnetic tape is to increase areal density at a sufficiently rapid rate to keep the cost of storage on tape well below that of magnetic disks. Until recently this was not a concern, because the cost of information storage on tape has been 10 to 100 times lower than on magnetic disks. Indeed, until recently, the major push in magnetic tape recording systems has been to improve performance (data rate and access time), rather than density. Now, however, as shown in Fig. 2.6<sup>43</sup>, because the cost of storage on magnetic disk drives is coming down at a more rapid pace than that of tape drives, the cost advantage of tape is becoming smaller. If this trend continues, the time will come when tape users decide to move applications to disks. Thus, tape is now in the position that disk drives were with respect to semiconductor memory before 1991, when the disk drive industry increased the areal density growth rate to 60%/year. For magnetic tape to continue to enjoy a significant market share, it must increase areal density at a more rapid pace than it has in the recent past.

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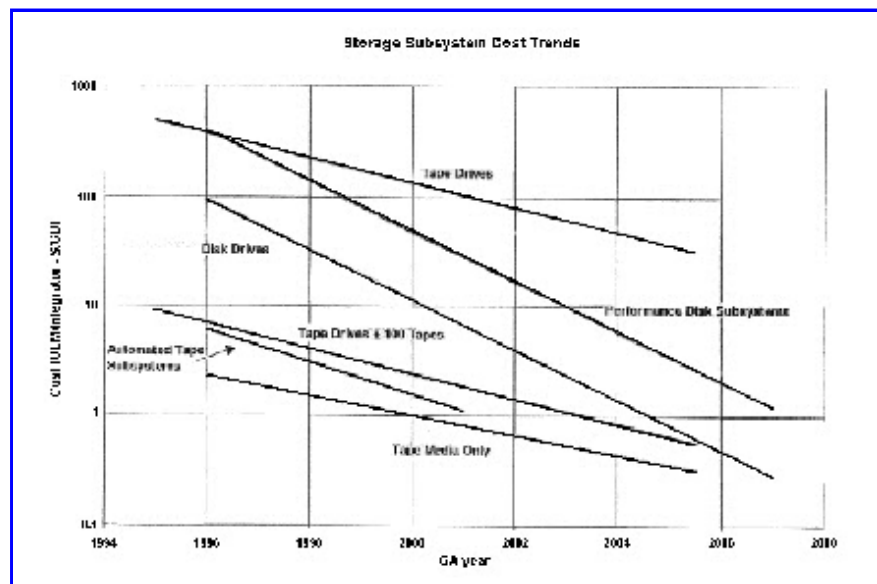


Figure 2.6. The cost in \$/GB of storage as a function of the year of general availability for various storage technologies.



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## 3: Introduction

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## CHAPTER 3

# MAGNETIC DISK TECHNOLOGIES

David A. Thompson<sup>p8</sup>

## INTRODUCTION

Magnetic hard disk technology is the undisputed leader for online storage applications, i.e., for storing data inexpensively, but in such a way as to be available within a time period less than human response times. Although the time delay for the first data bit to become available is thousands of times longer than for semiconductor memory, the data (when it does arrive) streams from the disk at tens of megabytes per second. The cost of hard disk storage is a few cents per megabyte, which is several orders of magnitude less than for semiconductor memory.

Tape storage is cheaper than disk storage, but its access time is much longer. It is possible to configure optical storage for online applications, but such a system is inferior to hard disk storage in every respect: cost, data rate, access time, etc. Only by moving to a library configuration or a data interchange application, which both utilize the removability of optical media at the expense of access time and mechanical complexity, does optical storage find a successful niche in which it can compete. There is at this time no technology that appears to have a chance of displacing hard disk storage in the next 10 years.

One major difference between hard disk and interchange media like tape and disk is the effect that standards and the need for backward compatibility have on the rate of technological progress. Hard disk standards involve external attributes of the drive only: physical size, power, cooling, and the data bus protocol and connector. There is no need for the customer to know what technology is being used to store and retrieve data within the box.

The situation with interchange media is different. The customer is vitally interested in his ability to read old formats and share media with other customers. There is also a benefit from utilizing standards from the audio and video entertainment industries. As a result, almost all of the tape media progress is spill-over from the much larger entertainment market, and many of the optical storage standards are based on compatibility with audio or video players.

This difference is also reflected in the nationality of the companies that manufacture disk drives. As recently as 1997, U.S.-based companies produced about 80% of the revenues and an even greater fraction of the hard disk drive (HDD) units sold. This is just the opposite of the situation in tape and optical storage, where Japanese and other Asian companies dominate the business for both entertainment and for computer storage devices (see Fig. 3.1<sup>p45</sup> and Tables 3.1<sup>p45</sup> -3.3<sup>p46</sup> ).

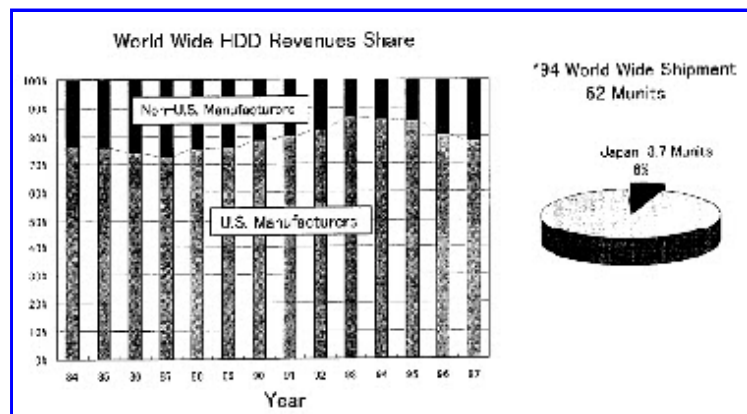


Fig. 3.1. U.S. and non-U.S. HDD market share per year (ASET/SRC, Miura, March 1998).

From this data, one might expect that Japan is not a center of HDD technology. This impression is completely false! Consider the following observations:

- The most profitable and fastest growing segment of the HDD business is the 2.5-inch laptop drive. It is also the portion of the business where areal density leadership is most important, since size and power consumption are more important in this application than is price per MB. All of the current 2.5-inch drives are designed in Japan. (This includes IBM's Fujisawa Laboratory.)
- According to Mark Geenen of TrendFocus (in a lecture on June 23, 1998), the fastest growing companies in the HDD business and in the components business (heads, disks) are Japanese. Hitachi and Fujitsu are especially strong in their base technologies, and TDK, Alps, and Yamaha are greatly increasing their market share in the head business. A shakeout due to overcapacity in the disk business will favor well-financed companies, which include some of the Japanese companies. Overall, it appears that Japan's share of the HDD business is poised to greatly increase in the next few years.
- The approach of the superparamagnetic limit may put an extra emphasis on technological means to change the evolutionary approach. The panel saw in this study that the larger Japanese companies have a strong advanced technology position in devices, materials, and recording physics.

Other examples of a rising Japanese presence can be seen by a few months of press clippings (Table 3.4<sup>p46</sup>), by the order in which companies have brought magneto resistive (MR) heads to the marketplace (Table 3.5<sup>p47</sup>), and in the areal density being shipped as of May 1997 (Table 3.6<sup>p48</sup>).

Table 3.1  
Share of HDD Market by National Origin, 1995

|             | United States | Japan   | Other | U.S. Share (%) |
|-------------|---------------|---------|-------|----------------|
| HDD Revenue | \$22,722      | \$3,610 | \$250 | 85.5           |

### 3: Introduction

|                        |      |     |   |      |
|------------------------|------|-----|---|------|
| (\$ million)           |      |     |   |      |
| HDD Units<br>(million) | 79.5 | 8.4 | 2 | 88.4 |

Source: Gourevitch et al. 1997

Table 3.2  
Location of HDD Final Assembly, 1995 (% of units)

| United States | Southeast Asia | Japan | Other-Asia | Europe | Total |
|---------------|----------------|-------|------------|--------|-------|
| 4.6           | 64.2           | 15.5  | 5.7        | 10.0   | 100   |

Source: Gourevitch et al. 1997

Table 3.3  
Geographic Distribution of the Wage Bill (%)

|                  | United States | Japan | S.E. Asia | Europe | Other |
|------------------|---------------|-------|-----------|--------|-------|
| Percent of Total | 42.2          | 23.9  | 12.9      | 6.2    | 14.8  |

Source: Gourevitch et al. 1997

Table 3.4  
Recent Headlines-Typical Press Clippings

| Date    | Headline                                             |
|---------|------------------------------------------------------|
| 5/18/98 | Hitachi to Begin Mass-producing GMR Heads            |
| 5/13/98 | Hitachi Announces a 6.48 GB GMR Mobile HDD           |
| 5/12/98 | Toshiba Formally Announces a 6.4 GB GMR Mobile Drive |

### 3: Introduction

|         |                                                                     |
|---------|---------------------------------------------------------------------|
| 4/18/98 | HITACHI Announces 3.5", Half-High, 12000 rpm 9.1 GB Hard Disk Drive |
| 4/15/98 | Fujitsu Introduces Three New Mobile Hard Drives                     |
| 3/06/98 | Integral files for Bankruptcy                                       |
| 2/27/98 | HITACHI Reveals New HDAs                                            |
| 2/04/98 | Mitsumi Electric to Enter the Magneto-Resistive (MR) Head Race      |
| 2/03/98 | Fujitsu to Incorporate GMR Head Technology in Disk Drives           |
| 1/23/98 | HITACHI Announces 12,000 rpm High-End hard Disk Drive               |
| 1/22/98 | Seagate Exits the Mobile HDD Business                               |
| 1/20/98 | Hitachi Announces New 2.5" Mobile Hard Disk Drives                  |
| 5/13/98 | Hitachi Metals to Sample GMR Heads in February                      |

The connection between the HDD industry and the Japanese universities has been weak for many years, but the recent establishment of the Storage Research Consortium (SRC) has begun the process of building the sort of ties in Japan that exist in the United States and Singapore.

**Table 3.5**

#### **Introduction of MR Heads by Company**

| Company | Month (or Quarter) | Year |
|---------|--------------------|------|
|         |                    |      |

### 3: Introduction

|                    |          |      |
|--------------------|----------|------|
| IBM                | May      | 1991 |
| Fujitsu            | February | 1994 |
| Seagate            | 1Q       | 1994 |
| Hitachi            | June     | 1994 |
| Quantum            | October  | 1994 |
| Hewlett<br>Packard | 4Q       | 1995 |
| NEC                | 1Q       | 1996 |
| Micropolis         | December | 1996 |
| Maxtor             | 4Q       | 1996 |

Source: Disk/Trend Report as reported by ASET

Table 3.6

Current Areal Density by  
Company

| Company | Areal<br>Density<br>(Mb/in <sup>2</sup> ) |
|---------|-------------------------------------------|
| IBM     | 2,638.0                                   |
| Hitachi | 2,013.0                                   |
| Quantum | 1,646.0                                   |
|         |                                           |

### 3: Introduction

|            |         |
|------------|---------|
| Toshiba    | 1,308.0 |
| Fujitsu    | 1,300.0 |
| Maxtor     | 1,193.0 |
| Seagate    | 1,108.0 |
| JTS        | 1,008.0 |
| Micropolis | 959.2   |
| Samsung    | 884.0   |



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### LONG TERM STRATEGIES

## LONG TERM STRATEGIES

A major purpose of this study was to discover how the strategic outlook for HDD technology differs in Japan from that elsewhere. The short answer is: it doesn't. This is due to several factors: the technology lead is still with the United States, and the physics challenges ahead are recognized to be the same by leaders in both countries. For example, the areal density targets from ASET/SRC are very similar to those of NSIC (Figs. 3.2p<sup>50</sup> and 3.3p<sup>50</sup> ).

These challenges include the superparamagnetic effect, the need for increasing read head sensitivity, the need to scale head-to-disk spacing with the linear density, the need to follow extremely narrow data tracks, and the need to switch magnetic materials at increasing speeds. They are the same challenges faced around the world, but the Japanese bring certain special skills to the search for solutions. These include special understanding of magnetic materials and national strengths in micromechatronics. The latter was seen in the number of different proposals that we saw for two-stage actuators that will be necessary for the rapidly increasing track densities that will be seen in the next

[http://itri.loyola.edu/hdmem/03\\_02.htm](http://itri.loyola.edu/hdmem/03_02.htm)

few years. For example, Fig. 3.4<sup>p50</sup> and Fig. 3.5<sup>p51</sup> show some of the widely differing approaches being pursued.

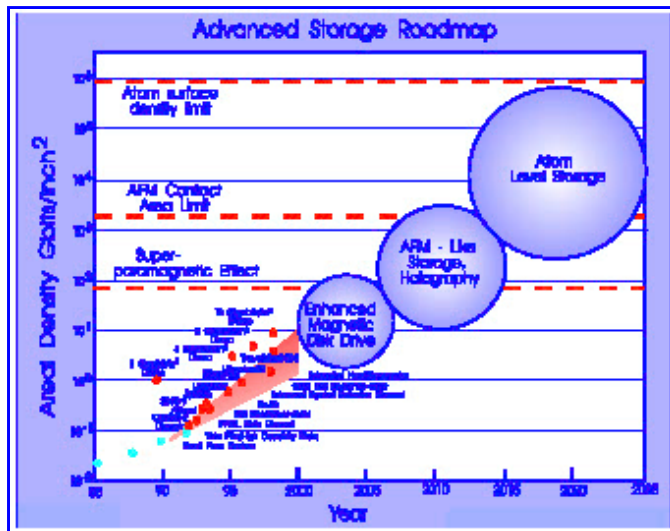


Fig. 3.2. Roadmap (IBM).

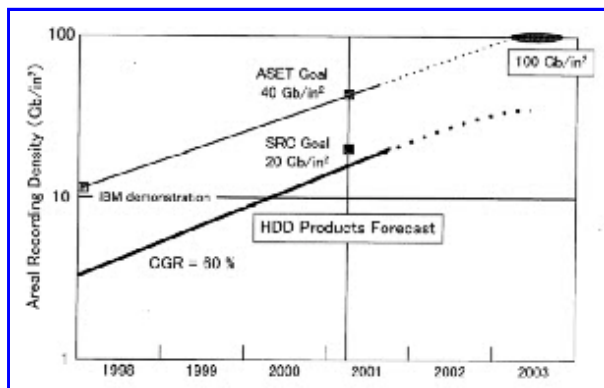


Fig. 3.3. ASET/SRC areal density projection (Miura, March 1998).

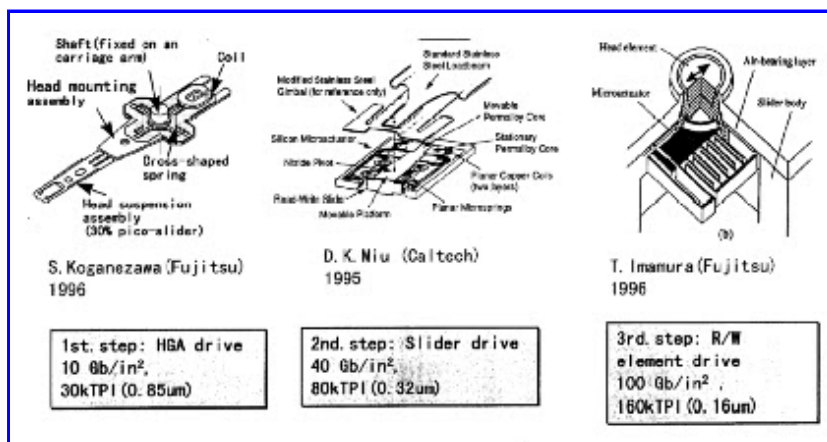


Fig. 3.4. Possible microactuator designs (Miura, March 1998).

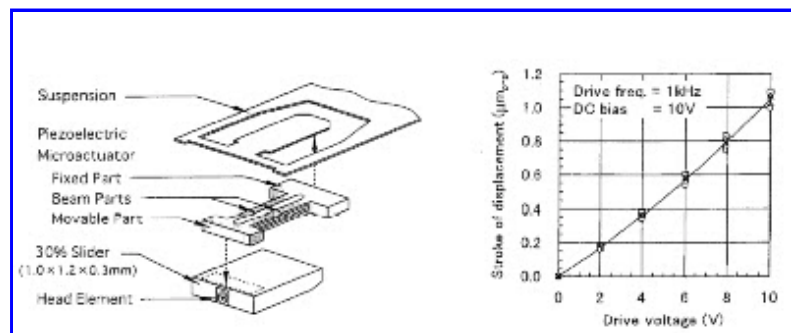


Fig. 3.5. TDK microactuator (described at TMRC, August 1998).

The ASET presentation at the March 1998 WTEC workshop in Tokyo contains a succinct summary of some of the materials work that the panel saw. Japan's leadership in magnetic materials predates the disk drive business and reflects its prowess in solid state physics, in high tech fabrication methods, and the benefits of being the leader in magnetic recording for audio and video applications. Figs. 3.6<sup>51</sup> through 3.8<sup>52</sup> show a portion of that summary.

An alternative form of magnetic recording called "perpendicular recording" has been an almost exclusively Japanese domain for 20 years (Fig. 3.9<sup>53</sup>). Until recently it had no particular advantages over conventional recording, but as one begins to see superparamagnetic effects limiting areal density, perpendicular media hold the promise of being more stable than longitudinal media for the same number of grains per bit. This is primarily because perpendicular media are thicker for the same areal density than longitudinal media (which allows more stored energy per grain); because the demagnetizing fields in perpendicular recording favor high bit densities (the opposite of the longitudinal case); and because the strength of the field from the write head can be stronger for perpendicular recording. If this turns out to be true, then Japan has a substantial lead in gaining experience with this technology.

| High Bs Materials, High ρ Materials                              |                                            |                          |           |
|------------------------------------------------------------------|--------------------------------------------|--------------------------|-----------|
| Plating High Bs                                                  | FeCoNi                                     | 1.9 – 2.4 T              |           |
| High ρ                                                           | NiFe                                       | ~ 160 μΩ                 |           |
| Granular Nano-Crystal                                            | Co/Fe/Al <sub>2</sub> O <sub>3</sub>       | 1.9 T                    | 100 μΩ cm |
| High sensitive, Stable, Spin-Valve materials for Narrow gap Head |                                            |                          |           |
|                                                                  |                                            | $\Delta \rho / \rho > 2$ |           |
| Antiferro magnetic materials                                     | MnPt, PdPtMn, IrMn, NiMn, RuRhMn, CrMnPt   |                          |           |
| Structure Ferromagnetic pinned layer,                            | NiFe/Cu/Co/Ru/Co/CrMnPt                    |                          |           |
| Bias compensation layer,                                         | NiFe/PdPtMn/CoFeB/Cu/CoFeB/NiFe/Ta/NiFe    |                          |           |
| New bias,                                                        | IrMn/CoFe/Cu/CoFe/NiFe/CoZrNb              |                          |           |
| Specular Refraction,                                             | NiO/α-Fe <sub>2</sub> O <sub>3</sub> /NiFe |                          |           |
|                                                                  | MgO/NiCoFe/Cu/Co/Cu/Ag                     |                          |           |
| Vertical GMR,                                                    | aCoMnB/Co/Cu/Co/CoO or IrMn                |                          |           |
|                                                                  | Cr/[NiFe/CuNi]n/NiFeCr n=3                 |                          |           |

Fig. 3.6. Storage materials (Y. Miura, WTEC workshop, March 1998).

| ASET/SRC                                  | Media Technology                                        |
|-------------------------------------------|---------------------------------------------------------|
| Media Noise                               |                                                         |
| Underlayer                                | CrTiB/CrMo (Hitachi)                                    |
| Fine Grain/Size Distribution              | CoCrPt/Cr/TiB (Hitachi)                                 |
|                                           | CoCrPtTaNb/CrMo (Fujitsu)                               |
| Ultra-High Vacuum Process                 | CoCrTa/Cr (Tohoku-u)                                    |
| Orientation                               | Resonant interaction of grains (Toyota Tech. Institute) |
| Thermal Stability of Magnetization        |                                                         |
| Micromagnetic simulation                  | Nihon-u, U of Electro. Commu.                           |
| Decay in head signal, Decay in MFM signal | (Hitachi, Toyota Tech. Institute)                       |
| Decay in SQUID                            | (Fujitsu)                                               |
| Keepers layer                             |                                                         |
| Microstructure measurement                |                                                         |
| MFM analysis                              | Magnetic clusters vs. S/Nmedia (Akita-u, Tohoku-u)      |
| Spin Polarized STM                        | Hokkaido-u, ETL, Toshiba, Fujitsu                       |

Fig. 3.7. ASET/SCR storage issues (Y. Miura, WTEC workshop, March 1998).

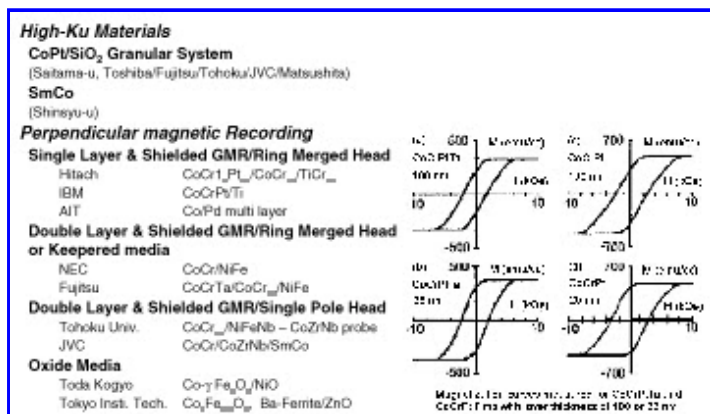


Fig. 3.8. Storage media materials and efficiencies.

Auxiliary facing-pole driven type (1) 1975 Flexible media (Tohoku Univ.)

Auxiliary back-pole driven type (2) 1984 Flexible media (Sony)

Auxiliary back-pole driven type 1991 Hard media (Tohoku Univ.)

Micro Flexhead (3) 1991 Hard media (Censtor)

Ring/MR merged thin film head (4) 1997 Hard media (IBM Japan)

Film conductor driven type head (4) 1997 Hard media (Tohoku Univ.)

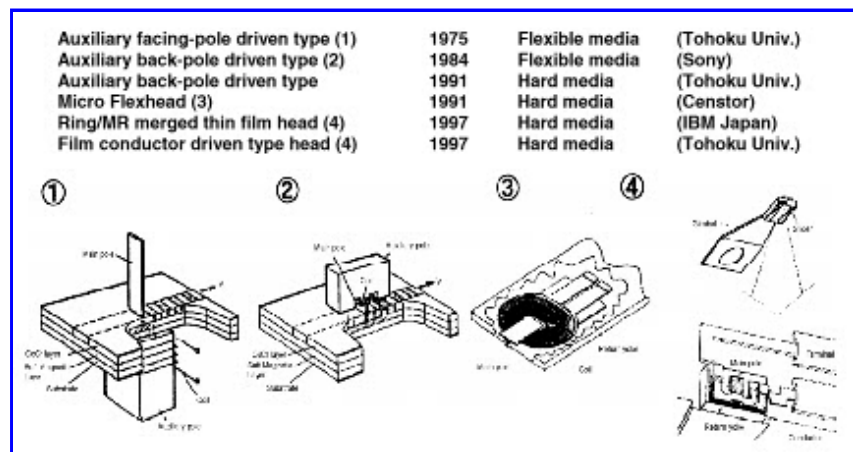


Figure 3.9. Perpendicular magnetic recording with a single-pole head (Nakamura, Tohoku Univ., 1998).



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## CONCLUSIONS

### CONCLUSIONS

Japan's minority position in the HDD business is much stronger than it may appear. The Japanese have a strong presence at the leading edge of technology, which is presently found in 2.5-inch drives. They are building momentum in the components business. They have special skills that may be crucial when the evolutionary path that the industry has been following needs to change because of superparamagnetism or other obstacles.

The vision of the future that the WTEC team found in Japan is the same as we have here in the United States. Hard disk drives will continue to dominate online storage for at least the next 10 years. Simple scaling has driven the technology for 40 years. In that time, the MR head represents the only change in the physics of how a disk drive operates. But 10 years from now, other significant changes in technology will be necessary; simple scaling of the storage medium will not be possible. At that time, the leading companies will have had to grapple with a number of technical challenges, for which the Japanese are well prepared.



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[http://itri.loyola.edu/hdmem/03\\_03.htm](http://itri.loyola.edu/hdmem/03_03.htm)

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Gourevitch, Peter, et al. 1997. WHO IS US? The nationality of production in the hard disk industry. Report 97-01, UCSD, March (See <http://www-irps.ucsd.edu/~sloan/papers/whoisus.htm/#toc21>).

Miura, Y., 1998. Presentation at the U.S. - Japan Workshop on Future Data Storage Technologies, Tokyo, Japan, March 9.




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#### 4: Background

## CHAPTER 4

## MAGNETIC TAPE STORAGE

[William D. Doyle](#)<sup>6</sup>

### BACKGROUND

The information contained in this report originates from three principle sources: (1) participation in the recent tape technology roadmap program conducted by the National Storage Industry Consortium (NSIC)<sup>1p55</sup>, (2) WTEC-sponsored visits to several Japanese companies including Sony, Fuji Film and Matsushita, which have a particular interest in magnetic tape, (3) contacts with JVC in Japan and Quantegy and Imation in the United States.

Magnetic tape is the oldest technology in the current storage hierarchy. It has dominated program storage and data backup in large computer systems for about 50 years, the audio market (Philips cassette) for 20 years (until the development of the CD) and the video market (VHS) for 20 years. However, the latter is threatened in the future by optical DVD. The reason for the longevity of tape in data storage is simply that it has provided the lowest cost solution for the required performance. Heads and media developed for the consumer market were incorporated into storage systems with relatively small additional effort and, because of the volume and price sensitivity of the consumer market, at relatively low cost.

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The cost per gigabyte of various actual and projected storage technologies is shown as a function of time in Fig. 4.1<sup>p56</sup>. Traditionally, tape enjoyed a cost advantage relative to disk of two orders of magnitude, but, as the cost trend shows, this has narrowed rapidly to an order of magnitude in 1998 with a projected crossover point in less than 10 years. This is happening primarily because of the extraordinary 60%/year rate of increase in disk storage density resulting in similar decreases in cost. Tape is threatened, not by optical technology, but by disk technology unless it can sharply increase storage density at a rate comparable to disks.

Tape is a removable medium, and, consequently advances are hindered by the requirement for interchangeability, backward compatibility and agreement on specifications. There are also many formats with different tape widths and cartridge designs, which defocus development efforts. Fortunately, the major market in the future will be large and medium size systems where the number of formats is limited. The previous demand for small, low cost tape systems for data back-up in PCs, which was served by several formats, will be satisfied by optical disk or even extra hard drives. Despite these hurdles, rapid progress must be achieved, and the technology barriers to achieving it are highlighted here. Particular attention is paid to the relative strengths of Japan and the United States. We will see that Japan is in a position to control improvements in future tape systems.

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<sup>1p54</sup> NSIC. The National Storage Industry Consortium (NSIC)'s Tape Technology Roadmap is available from NSIC, 9888 Carroll Center Road, Suite 115, San Diego, CA 92126-4580.



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#### FUTURE TAPE TECHNOLOGY

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## FUTURE TAPE TECHNOLOGY

NSIC's targets for the years 2002 and 2007 are listed in Table 4.1<sup>p56</sup> along with actual specifications for existing products as of 1997. The assumption is that multi-track magnetoresistive thin film heads will be used in both linear and helical formats to achieve the required density and data rates.

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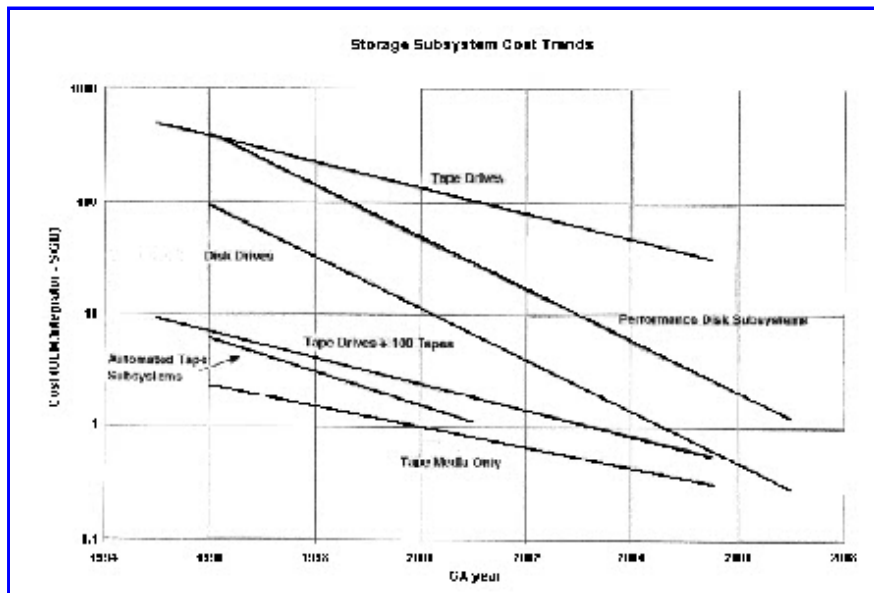


Fig. 4.1. Storage subsystem cost trends.

Table 4.1  
Tape Density Projections

| Year | Linear Bit Density (kbpi) |         | Track Density (tpi) |         |         | Volumetric Density Terabytes/in <sup>3</sup> |
|------|---------------------------|---------|---------------------|---------|---------|----------------------------------------------|
|      | Linear                    | Helical | Linear              | Helical | Helical |                                              |
| 1997 | 100.00                    | 120.00  | 750                 | 2,800   | -       | <0.2                                         |
| 2002 | 200.00                    | 200.00  | 6,000               | 6,000   | 6,000   | 0.9                                          |
|      | (25 dB @ 100 kcfi)        |         |                     |         |         |                                              |
| 2007 | 300.00                    | 300.00  | 20,000              | --      | 20,000  | 4.7                                          |

Source: NSIC, May 1998. Used by permission.

Further, by 2007, both formats will have the same volumetric density of ~5 terabytes/in<sup>3</sup>. Clearly, the projections show that most of the improvement, particularly in longitudinal recorders, will come from significantly increased track density. The increases in linear density are not inconsistent with the historical data although there has been a flattening-off since approximately 1995. It is also required

that the tape thickness be reduced to about 4  $\mu\text{m}$  while still maintaining sufficient mechanical properties to be transported reliably.

The various components of a tape storage system are shown in Table 4.2<sup>p57</sup> with an indication of the relative position of the United States and Japan. Head technology and system electronics will be derived from hard disk drive (HDD) development but new media, improved head/tape tribological properties, reliable tape transports and new systems must come from the tape industry.

Table 4.2  
Requirements for 4.7 Terabyte/in<sup>3</sup>

| Requirements                                                                                                                                                                                                                                                            | World Leader                                                                                                           |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| From HDD Development <ul style="list-style-type: none"> <li>• Multi-track GMR heads in both linear and helical systems to achieve media noise-limited SNR (Sony, Yamaha)*</li> <li>• Electronics including EPR4 channel combined with (O,K) codes</li> </ul>            | <ul style="list-style-type: none"> <li>• U.S./Japan</li> <li>• U.S.</li> </ul>                                         |
| From Tape Development <ul style="list-style-type: none"> <li>• New media (Fuji Film)*</li> <li>• Head-media tribology (Sony)*</li> <li>• Fundamental understanding of tape mechanics and transport (Sony)*</li> <li>• System development (Sony, Matsushita)*</li> </ul> | <ul style="list-style-type: none"> <li>• Japan</li> <li>• Japan</li> <li>• U.S./Japan</li> <li>• U.S./Japan</li> </ul> |

\*WTEC Visits



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## HEAD TECHNOLOGY

### HEAD TECHNOLOGY

Enormous improvement in read heads for HDDs has been realized by the introduction of magneto resistive (MR) heads in 1991 by IBM and later many others, and more recently in 1998 by the

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introduction of GMR heads by IBM followed closely by Hitachi. IBM, for many years, also used multi-track MR sensors in a complex head structure for some tape systems, and recently the quarter inch format adopted multi-track MR thin film heads for advanced products.

Developers of future tape systems will rely primarily on progress in HDD heads for the design and manufacture of GMR heads. At the present time, IBM is the world leader with Hitachi a close second. At the present time, the only independent GMR head supplier is Yamaha, known in the United States primarily for its musical instruments. It has been suggested that Yamaha obtained at least some of the basic technology for GMR from another Japanese company.

There is an enormous effort in GMR both in Japan and the United States with sufficient manufacturing resources in both countries. The capabilities would be rated as equal.




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## ELECTRONICS

Tape systems will also derive the channel design and read/write electronics from HDDs, incorporating them into more complex chips required for multi-channel recording. Because of its present lead in HDDs, the United States has a significant advantage.




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div.c39 {text-align: center} span.c38 {font-family: Symbol} p.c37 {font-family: Times; font-size: 60%} p.c36 {font-weight: bold} caption.c35 {font-weight: bold}

## NEW MEDIA

For high-density storage, the leading candidates are acicular metal particle (MP) tape and metal evaporated tape ME (Fig. 4.2<sup>p59</sup>). Because of the process difficulties manufacturers experienced in

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making particulate tape coatings thinner than  $\sim 2 \mu\text{m}$ , ME appeared in the early 1990s to have a significant advantage. However, the revolutionary use by Fuji Film of co-cast multi-layer technology derived from photographic film processing to produce magnetic layers  $< 200 \text{ nm}$  thick swung the advantage back to particulate tape. It was felt to be cheaper to produce, because of the relatively faster coating speeds, and more durable. Barium ferrite particles have also been considered for many sound scientific reasons, but the performance of MP and its availability have dampened interest in barium ferrite. However, Fuji Film has provided double-coat barium ferrite tapes for specific applications (e.g., ARKIVAL Technology Corp., Nashua, NH) where the environmental reliability is a dominant issue.

|                                                                                                  |                    |                      |
|--------------------------------------------------------------------------------------------------|--------------------|----------------------|
| Fuji "Double Coat" MP<br>Coercivity $> 2200 \text{ Oe}$<br>Particle Length $\geq 100 \text{ nm}$ | Lubricant          |                      |
|                                                                                                  | Magnetic Pigment   | $< 200 \text{ nm}$   |
|                                                                                                  | Smoother Layer     | $< 3 \mu\text{m}$    |
|                                                                                                  | Substrate          | $6 - 14 \mu\text{m}$ |
| Metal Evaporated (ME)<br>Coercivity $> 2200 \text{ Oe}$<br>Particle Length $< 50 \text{ nm}$     | Back Coating       | $\sim 1 \mu\text{m}$ |
|                                                                                                  | Lubricant          |                      |
|                                                                                                  | Hard Overcoat      | $< 50 \text{ nm}$    |
|                                                                                                  | ME Magnetic Film   | $< 200 \text{ nm}$   |
| Fuji "Double Coat" MP<br>Coercivity $> 2200 \text{ Oe}$<br>Particle Length $\geq 100 \text{ nm}$ | Substrate (Aramid) | $6 - 14 \mu\text{m}$ |
|                                                                                                  | Back Coating       | $\sim 1 \mu\text{m}$ |
|                                                                                                  | Lubricant          |                      |
|                                                                                                  | Hard Overcoat      | $< 50 \text{ nm}$    |
| Metal Evaporated (ME)<br>Coercivity $> 2200 \text{ Oe}$<br>Particle Length $< 50 \text{ nm}$     | ME Magnetic Film   | $< 200 \text{ nm}$   |
|                                                                                                  | Substrate (Aramid) | $6 - 14 \mu\text{m}$ |
|                                                                                                  | Back Coating       | $\sim 1 \mu\text{m}$ |
|                                                                                                  | Lubricant          |                      |

Fig. 4.2. High performance tape media.

ME has been dogged by repeated reports of low thresholds for wear and corrosion. However, in the panel's visit to Sony, panelists were told that the problem had been solved. Japanese manufacturers seem to have targeted ME for future DV consumer applications. Sony is installing an ME production line in its Dothan, AL plant and JVC has switched its focus in Japan to ME. At the present time, no ME tape is manufactured in the United States, and there is no indication that either Quantegy or Imation have any plans to do so.

In the United States, the only manufacturers of MP tape are Quantegy and Imation. However, the only supplier of the very thin "double coat" MP tape is Fuji Photo Film. Sony has licensed the technology but only for a new 200 MB floppy product. Imation researchers feel confident that they have the technology in place and will be a supplier of tape cartridges to specific formats when a market demand is evident. Fuji has an extensive patent portfolio surrounding the "double coat" process that restricts other manufacturers like Quantegy. Clearly, if the only supplier of the highest performance MP tape is Japanese, U.S. system designers will be at a severe disadvantage.

To achieve 300 kbpi with particulate tape, particles  $< 50 \text{ nm}$  in length must be available. Commercial tapes with  $100 \text{ nm}$  MP particles are available, and experimental tapes with  $80 \text{ nm}$  particles have been

tested. However, although SEM images of 50 nm particles have been shown by Toda, no data on the particle characteristic has been published. All of the major particle suppliers are Japanese including the former U.S. companies Pfizer and Hercules, which were acquired by Japanese manufacturers. Thus, U.S. tape manufacturers do not have a domestic supplier of advanced magnetic particles.

The progress proposed in Table 4.3<sup>60</sup> will require improved substrate materials which are thinner, stronger mechanically and more dimensionally stable. At the present time, there are products using PET (polyethylene terephthalate), PEN (polyethylene naphthalate) and PA (polyamid). PET dominates low performance particulate tapes; PEN, which is stiffer, is used in several advanced products both for MP and ME; PA, which is even stiffer, is used in the SONY microcassette at a thickness of only 2.5  $\mu\text{m}$ . However, the cost of PET is half that of PEN and a tenth that of PA. Both PET and PEN are manufactured in very high volume for other commercial applications, which results in lower cost for the tape market. If an entirely new, more exotic material is discovered, it will be difficult for the industry to afford the development and manufacturing costs if significant commercial applications cannot be identified. The major substrate manufacturers are Toray and Teijin, both Japanese. There is no supplier in the United States of high-quality tape substrate materials.

Table 4.3  
Thinner Substrates

| High End MP         | Now        | +5 Years | +10 Years    |
|---------------------|------------|----------|--------------|
| Substrate Material  | PET/PEN/PA | PEN/PA   | PA or better |
| Substrate Thickness | 14 m m     | 5-6 m m  | 4-5 m m      |
| Total Thickness     | 18 m m     | 8-9 m m  | 6-7 m m      |
|                     |            |          |              |
| Mid-Low Range MP    | Now        | +5 Years | +10 Years    |
| Substrate Material  | PET/PEN/PA | PEN/PA   | PA or better |
| Substrate Thickness | 4.5 m m    | 3-4 m m  | 2-3 m m      |

|                 |       |         |         |
|-----------------|-------|---------|---------|
| Total Thickness | 7 m m | 4-5 m m | 3-4 m m |
|-----------------|-------|---------|---------|

PET = polyethylene terephthalate \$PET = 1/2 \$PEN = 1/10 \$PA

PEN = polyethylene naphthalate

PA = polyamid (aramid)

The data rate capacity product in a multi-track recorder is limited by the dimensional stability of the tape, dominated by the substrate. Present materials which experience several mechanisms of instability have an overall quality figure of ~1000 PPM. In a new material with the quality figure reduced to 500, the gain could be translated into a 2X increase in capacity or data rate or some combination of both. This is easily seen by examination of Fig. 4.3<sup>p62</sup>, which depicts the situation when a previously written pattern is read with a multi-track head. Assume the media has expanded so that the outermost channels of the multi-track head are off-track but at the limit of detectability. Only the track width and the head span matter. If the substrate was replaced by a medium with twice the stability (half the distortion), either the track width could be halved and the number of tracks on the tape doubled (2X capacity) or the head span and therefore the number of channels could be doubled (2X data rate).

The industry faces a major challenge in the development of improved but cost-effective substrate materials. The clear necessity to increase cost effectiveness conflicts with the expected higher costs of new materials.



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## HEAD-MEDIA INTERFACE

### HEAD-MEDIA INTERFACE

The most serious challenge to achieving the target densities (Table 4.1<sup>p56</sup>) is reduced head-media spacing. The effective head to media spacing must be reduced from the present value of 80-100 nm to <30 nm. This includes head gap erosion, media roughness and air entrapment at high tape to head speeds. No obvious solution to these requirements has been identified.

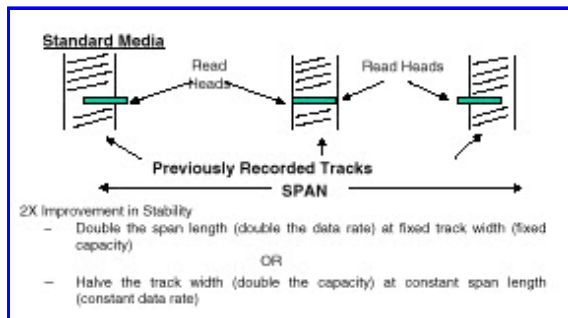
Thin film heads expose a variety of soft and hard materials to the abrasive tape surface. Highly desirable would be a thin (<10 nm) head overcoat which was highly wear resistant. Thicker overcoats are now used in ME tapes to reduce wear and corrosion. Sony is the world's leader in this area and presumably would have knowledge of the efficiency of head overcoats as well. Several U.S. companies, including IBM, Seagate and StorageTek, make tape heads and presumably are studying

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this problem.

Peak media roughness, not the average roughness, limits the spacing between the head and media. It is now about 20 nm and must be reduced by improved processing to <10 nm.

Traditionally, tape heads were made with long throat heights, which wore away during use. This is one reason VCRs eventually fail. Thin film heads have very short throat heights (<1.5  $\mu\text{m}$ ) so a more creative solution must be found. The head slider used in an HDD is a very sophisticated, aerodynamic form designed to keep the head "flying" close to the media surface. Similar analysis must be employed to minimize the flying height of the head over the tape at high tape-head speeds. The United States is in a strong position in this area because of its leadership in HDDs.



### 2X Improvement in Stability

- Double the span length (double the data rate) at fixed track width (fixed capacity)

OR

- Halve the track width (double the capacity) at constant span length (constant data rate)

Fig. 4.3. Substrate stability-capacity/data rate trade-offs.



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### CRITICAL ISSUES

## CRITICAL ISSUES

1. Can the United States develop a domestic source for advanced tape media? Unless this occurs,

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system designers will be limited by the availability of experimental tapes from non-U.S. suppliers and may be forced to adopt particular formats supported by the present U.S. manufacturers. Reduction in the number of formats would be better for users but not necessarily as profitable for the manufacturers and would certainly constrain innovation. The recent agreement between IBM, Seagate and Hewlett-Packard to develop a new linear open format is a very positive step. This area is an excellent opportunity for an ATP (DOC/NIST) award.

2. Is it practical with traditional media and heads to achieve a spacing of 30 nm? This is the most difficult technical problem limiting storage density. Novel materials work is required and should be a focus area for NSF.
3. Does the industry have the resources to fund the development of new substrate materials? Probably not is the answer. An industry-wide materials research program supported by both the United States and Japan would have a major impact.
4. Will the cost of new substrate materials prevent their widespread use? The substrate is a very large fraction of media cost. A factor of 10 higher cost for PA clearly has limited its application. Remembering that tape exists because of its relatively low cost, the industry faces a critical dilemma which may make it difficult to achieve the density target (Table 4.1<sup>p56</sup>) proposed by NSIC.

1 NSIC. The National Storage Industry Consortium (NSIC)'s Tape Technology Roadmap is available from NSIC, 9888 Carroll Center Road, Suite 115, San Diego, CA 92126-4580.



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## 5: Introduction

# CHAPTER 5

## R&D ACTIVITIES IN OPTICAL DATA STORAGE MEDIA

**Masud Mansuripur<sup>P7</sup>**

## INTRODUCTION

During the first week of April 1998, the WTEC panel on future data storage technologies visited the Research and Development Department of Nikon Corporation at Shinagawa-ku in Tokyo, the Corporate Research and Development Laboratory of Pioneer Corporation in Tokyo, and the Hypermedia Research Center, Optical Recording Technology Laboratory, of Sanyo Corporation in Gifu prefecture. What follows is a summary of the observations made during these visits and a fairly

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detailed description of the conversations with scientists, engineers, and technical managers with whom the panel met. To put these visits in perspective, the first part of the report gives an overview of the field of optical data storage. All the technical terms are defined, and the various methods and technologies of relevance to optical data storage are reviewed.



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### AN OVERVIEW OF THE FIELD OF OPTICAL DISK DATA STORAGE

## AN OVERVIEW OF THE FIELD OF OPTICAL DISK DATA STORAGE

Our need for storage is explosive; fueled by multimedia requirement for text, images, video and audio, storage requirements are growing at an exponential rate and are expected to exceed  $10^{20}$  bits (12 exabytes) in the year 2000. With an increasing amount of information being generated or captured electronically, a large fraction, perhaps as much as 40%, will be stored digitally. To meet this need, the hierarchy of on-line, near-line and off-line storage systems will be composed of many diverse technologies: magnetic disk drives, magnetic tape drives and tape libraries, optical disk drives and optical libraries. The mix of these sub-systems will be very application-specific so as to optimize the performance and cost of the overall system.

An optical storage system is a particularly attractive component of this hierarchy because it provides data access times that are an intermediate solution between a hard disk drive and a tape drive. Access time is the time, including latency, required to start retrieving a random block of data and typically ranges from less than 10 msec for a hard disk drive, to 30-50 msec for an optical disk drive, and several seconds for a tape drive. It becomes an important link in the chain as data are staged up and down between cpu, memory, and storage.

Perhaps the most enabling feature of optical storage is the removability of the storage medium. With separations of a few millimeters between the recording surface and the optical 'head', and with active servos for focusing and tracking, the medium can be removed and replaced with relatively loose tolerances. The infamous *head crashes* often experienced in hard disk drives do not occur in optical drives. Data reliability and removability are further enhanced by using the 1.2 mm transparent disk substrate as a protective cover to keep contamination away from the recording surface. (The recently announced digital versatile disk or DVD will have a substrate thickness of only 0.6 mm.)

Removability has created a whole new industry in CD-audio. CD-ROMs have enhanced the efficiency of distribution and use of software, games, and video. These read-only disks containing 680 MB of information can be mass replicated by injection molding in a few seconds for less than 10¢ each, and

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they are virtually indestructible. One-day express mail of 125 CDs is an effective data rate of 1.0 MB/s.

At the other end of the spectrum, phase change and magneto-optical disks are used in WORM (write-once-read-many) and read/write/erase systems where a single disk can contain almost 5 GB. Using robotics, storage libraries can be assembled with capacities of a terabyte with access to any disk in under 5 seconds.

This review will discuss the fundamentals of optical storage, the components that comprise a system, and the emerging technologies that will allow increased performance, higher storage capacities, and lower cost.

Several international conferences on optical data storage are held each year, and the proceedings of these conferences are a good source of information concerning the latest developments in this field. References (JSAP 1995; OSA 1996; MORIS 1996) provide some information about these conference proceedings and/or digests. There are also several published books in this area, to which the readers are referred for an in-depth coverage of the various subjects (Bouwhius et al. 1985; Marchant 1990; Mansuripur 1995; McDaniel & Vitoria 1997).

Optical data storage research in the United States dates back to the late 1950s and early 1960s when Bell Labs, IBM, 3M, and Honeywell, among others, developed several key concepts and technologies for optical recording. Several important patents were filed in those early days, which eventually became the property of Disco Vision Associates (DVA), a California-based company with ties to Pioneer of Japan. In recent years, several large U.S. companies (IBM, Eastman Kodak, 3M) have withdrawn from the field of optical storage, either dismantling or selling off their manufacturing facilities in the United States. At the same time a few small companies (MaxOptix, MOST, Laser Byte, Pinnacle Micro), which had carved a niche market for themselves by bringing innovative designs or assembled products to the market, have either failed or are struggling to survive. About 2.5 years ago two startup companies (Quinta and TeraStor) began in California, with the express goal of marrying optical and magnetic recording technologies. Although the promised products of Quinta and TeraStor have not yet materialized in the market, their approach has created a resurgence of interest in the field, especially among the hard drive manufacturers, who see this as a potential threat, as well as an opportunity to overcome the dreaded "superparamagnetic problem."

## **Recording and Readout of Information on Optical Disks**

An optical disk is a plastic (or glass) substrate with one or more thin-film layers coated upon its surface(s). The information may be prerecorded on the surface of the substrate by the disk manufacturer, or it may be recorded on one or more of the thin film layers by the user. Typical diameters of presently available optical disks are as follows:

- 12 cm, as in compact disk audio (CD), compact disk read-only memory (CD-ROM), compact disc recordable (CD-R), and digital versatile disk (DVD)
- 2.5", as in digital audio mini disk (MD)
- 3.5", as in magneto-optical (MO) removable storage devices

- 5.25", as in both magneto-optical and phase-change (PC) rewritable disks
- 12" and 14", such as the write-once-read-many (WORM) media manufactured by Kodak and other companies for high volume storage applications

In the case of read-only media the information is pressed onto the substrate by injection molding of plastics, or by embossing of a layer of photopolymer coated on a glass substrate (Bouwhuis et al. 1985; Marchant 1990). The substrate is then coated with a thin metal layer (e.g., aluminum) to enhance its reflectivity. In other types of optical disks, some information, such as format marks and grooves, may be stamped onto the substrate itself, but then the substrate is coated with a storage layer that can be modified later by the user during recording of information. Typical storage layers are dye-polymer films for write-once applications, tellurium alloys for ablative recording (also write-once), GeSbTe for phase-change rewritable media, and TbFeCo magnetic films for magneto-optical disks (also rewritable) (Marchant 1990; Mansuripur 1995; McDaniel & Victora 1997).

CD technology was developed jointly by Philips of the Netherlands and Sony of Japan in the late 1970s and early 1980s, then introduced to the market in 1983 as the hugely successful compact audio disk. Today most of the research and advanced development work in DVD (the successor to CD) and future generations of read-only media takes place in Japan. Sony, Matsushita, Pioneer, Toshiba, Sharp, and NEC are some of the leading Japanese companies in this area. The MiniDisc (MD) was pioneered by Sony, and despite a sluggish early start, has become a very successful product in Japan. The major players in the field of magneto-optical data storage are Sony, Fujitsu, Hitachi Maxell, Mitsubishi, Nikon, and Sanyo. In phase-change optical recording, the leaders are Matsushita, Toshiba, and NEC, recently joined by Sony. Many other companies are involved in the development of components (lasers, miniature optics, actuators, detectors, substrates, spindle motors, etc.) as well as mastering machines and test equipment for optical recording products. These include some of the major multinational corporations as well as smaller firms.

In a typical disk the storage layer is sandwiched between two dielectric layers, and the stack is capped with a reflector layer (e.g., aluminum or gold), and protected with a lacquer layer. The dielectric layers and the reflective layer perform several tasks: protecting the storage layer, creating an optically tuned structure that has optimized reflectivity and/or absorptivity, allowing the tailoring of the thermal properties of the disk for rapid cooling and reduction of thermal cross-talk during writing, and so on (Mansuripur 1995; McDonald and Victora 1997).

Fig. 5.1<sup>p67</sup> is a schematic diagram showing the basic elements of an optical disk drive. The laser is usually a semiconductor laser diode, whose beam is collimated by a well-corrected lens and directed towards an objective lens through a beam-splitter. The objective lens focuses the beam onto the disk and collects the reflected light. This reflected light is directed (at the beam-splitter) towards the detectors, which produce a data readout signal as well as servo signals for automatic focusing and tracking. The functions and properties of the various elements of this system will be described in some detail in the following sections.

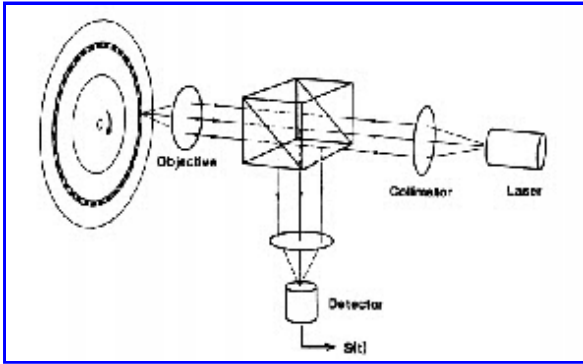


Fig. 5.1. Basic configuration of an optical disk system.

## The Light Source

All optical recording technologies rely on lasers as their source of light. The lasers used in optical disk and tape data storage are semiconductor laser diodes of the shortest possible wavelength that can provide sufficient optical power for read/write/erase operations over a period of several thousand hours. Presently the shortest wavelength available in moderate power lasers (around 50 mW) is in the neighborhood of 680 nm; these lasers are being used in CD-R, MO, and PC products. For CD and DVD applications where writing is not a concern, low power lasers (e.g.,  $\approx 5$  mW) which emit at 630 nm and 650 nm are being considered. The emphasis on short wavelength lasers for optical recording applications is due to the fact that shorter wavelengths can be focused to smaller spots at the diffraction limit. All things being equal, the diameter of a focused spot scales with its wavelength: a reduction of the wavelength by a factor of 2, for example, will result in a reduction of the focused spot diameter by the same factor and, consequently, a fourfold increase in the data storage density can be realized.

The wavelengths of optical data storage have continuously shrunk during the past 15 years; starting at 830 nm, they are now down to 630 nm, and there is every indication that they will continue to shrink in the foreseeable future. Nichia Chemicals Corporation of Japan recently announced that 50 mW blue lasers operating in the wavelength range of 370 nm to 420 nm would be available before the end of 1998. Several other Japanese companies (e.g., Sony, Matsushita, Pioneer) have demonstrated the feasibility of small, inexpensive, second harmonic generation (SHG) green and blue lasers for use in optical disk drives.

What is needed for optical data storage is compact and inexpensive laser diodes that can be incorporated into small, low-cost drives. The power requirement from such lasers is several milliwatts for read-only media and several tens of milliwatts for recordable media. The lasers should be capable of direct modulation (e.g., by modulating the electrical current input to the laser), otherwise the cost and the size of external modulators may become prohibitive. Spatial coherence and single transverse-mode operation is a requirement, because the beam must be focused to diffraction limit. (In this context vertical cavity surface emitting laser diodes (VCSELs) as well as arrays of such lasers need to be improved, since, at high powers, these lasers tend to operate in high-order modes.) Low-noise operation is very important, especially in applications such as magneto-optical readout, where signal-to-noise ratio is at a premium.

Although operation of laser diodes in several longitudinal modes is presently acceptable, for future devices it may be important to add operation in a single, stable, longitudinal mode to all their other desirable characteristics. Mode hopping, wavelength shifts of several nanometers with temperature fluctuations and with operating current, manufacturing variability of the wavelength from batch to batch, etc., are so severe that, at the present time, it is not possible to consider the use of diffractive lenses either for the collimator or for the objective lens. These high numerical aperture (NA), diffraction-limited lenses are still produced by molding of glass elements. In the future, when microminiaturization becomes a necessity and lenslet arrays begin to appear in commercial products, operation of the laser in a single, stable, longitudinal mode may be required.

Practically all semiconductor diode lasers used in optical storage products come from Japan. Hitachi, Sharp, and Toshiba are the leading producers of semiconductor lasers, and Nichia Chemicals is in a position to dominate the market in the area of GaN-based short-wavelength (green/blue/ultraviolet) lasers. In the United States there are pockets of excellence and know-how both in the industry and among the universities. Spectra Diode Laboratory (SDL), OptoPower and Ortel are manufacturers of specialty laser diodes in this country. Lucent Technologies and Motorola, among others, have significant programs in laser diode arrays and VCSELs. But, by and large, the major source for inexpensive laser diodes is outside the United States.

## The Objective Lens

Presently disk and tape optical recording systems use molded glass lenses for focusing the laser beam to a diffraction-limited spot (see Fig. 5.2<sup>p68</sup>). These lenses consist of two aspheric surfaces on a single piece of glass, have fairly large numerical apertures (in the range of 0.4 to 0.6), and are essentially free from aberrations. The numerical aperture of a lens is defined as  $NA = \sin \theta$ , where  $\theta$  is the half-angle subtended by the focused cone of light at its apex. A 0.5 NA lens, for example, will have a focused cone whose full angle is  $60^\circ$ . The diameter of the focused spot is of the order of  $\lambda_0/NA$ , where  $\lambda_0$  is the vacuum wavelength of the laser beam. It is thus clear that higher numerical apertures are desirable if smaller spots (and therefore higher recording densities) are to be attained. Unfortunately, the depth of focus of an objective lens is proportional  $\lambda_0/NA^2$ , which means that the higher the NA, the smaller will be the depth of focus. It thus becomes difficult to work with high NA lenses and maintain focus with the desired accuracy in an optical disk drive.

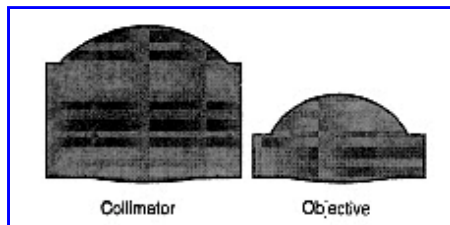


Fig. 5.2. Single-element aspheric lenses used in optical disk drives.

But a small depth of focus is not the main reason why the present optical drives operate at moderate numerical apertures. The more important reason has to do with the fact that the laser beam is almost invariably focused onto the storage medium through the disk substrate. The disk substrate, being a

slab of plastic or glass, has a thickness of 1.2 mm (DVD substrates are only half as thick, or 0.6 mm). When a beam of light is focused through such a substrate it will develop an aberration, known as coma, as soon as the substrate becomes tilted relative to the optical axis of the objective lens. Even a  $1^\circ$  tilt produces unacceptably large values of coma in practice. The magnitude of coma is proportional to  $NA^3$ , and therefore, higher NA lenses exhibit more sensitivity to disk tilt. Another aberration, caused by the variability of the substrate's thickness from disk to disk, is spherical aberration. This aberration, which scales with the fourth power of NA, is another limiting factor for the numerical aperture. In the future, manufacturers will move toward higher numerical apertures by adopting one or more of the following strategies:

- use thinner substrates or avoid focusing through the substrate altogether
- make the substrates as flat and as uniform as possible
- develop servo mechanisms whereby the tilt and thickness variations of the disk are automatically sensed and corrected for in the optical path

As was mentioned earlier, the use of smaller lenses is always desirable in optical storage technology, particularly if lens arrays are being considered for parallel accessing of multiple tracks in a system. In this respect, gradient-index (GRIN) lenses, holographic optical elements (HOEs), and binary diffractive optical (BDO) lenses are all being considered for future generations of optical storage devices. In the United States, the Florida-based Geltec, Inc. is a major innovator as well as manufacturer of molded glass optics. Many Japanese companies (e.g., Sony) make their own molded glass or plastic lenses for use in optical disk drives. NEC is particularly strong in design and implementation of holographic optical elements (HOEs). Nippon Sheet Glass (NSG) is a major manufacturer of GRIN lenses and other micro-optical elements.

With the rapid changes taking place in the optical recording industry, as exemplified by the convergence of magnetic and optical technologies in the recently announced Quinta and TeraStor products, there will be strong demand for innovative micro-optical elements. In order to stack multiple platters within one drive, it is imperative to reduce the size of the optical head; this can be achieved only if the sizes of the collimator, objective lens, polarizers, beam-shaping optics, etc., are substantially reduced below their current values. With companies like Geltec in the lead, the United States is currently in a good position to take advantage of this window of opportunity. But the Japanese technology is also advancing rapidly, and the U.S. lead may soon evaporate.

## Automatic Focusing

A typical optical disk has a plastic substrate that is not perfectly flat, but is slightly warped. Also, when mounted in a drive, small tilts of the axis could cause vertical motions of the disk surface during operation. It is not unusual to find vertical movements as much as  $\pm 100 \mu\text{m}$  during the operation of an optical disk. A typical objective lens has a numerical aperture of 0.5 or higher, and therefore, the focused beam has a depth of focus of a fraction of  $\lambda_0/NA^2$ , which is only a fraction of a micron. The focused spot must remain within the depth of focus while the disk rotates at speeds of several thousand rpm and wobbles in and out of focus by as much as  $\pm 100 \mu\text{m}$  in each revolution. Needless to say, without an autofocus mechanism to maintain the disk continually in focus, the operation of an

optical disk drive is unthinkable.

In practice the objective lens is mounted in a voice coil actuator (bandwidth = several kHz), and a feedback mechanism is used to drive the lens towards and away from the disk in such a way as to maintain focus at all times. The signal needed for this feedback mechanism is derived from the light that is reflected from the disk itself. Fig. 5.3<sup>p70</sup> shows a diagram of the astigmatic focus-error detection system used in many practical devices these days. The light reflected from the disk and collected by the objective lens is either convergent or divergent, depending on whether the disk is further away from best focus or closer to the lens than the plane of best focus. This returned beam goes through an astigmatic lens, which normally focuses the incident beam to a symmetric spot halfway between its focal planes. A quad detector placed at this plane (also called the plane of least confusion) then receives equal amounts of light on its four quadrants. When the disk is out of focus, however, the astigmat creates an elongated spot on the detector. Depending on the sign of defocus, this elongated spot may preferentially illuminate quadrants 1 and 3 or quadrants 2 and 4 of the detector. Therefore, the combination signal  $(S_1 + S_3) - (S_2 + S_4)$  provides a bipolar focus-error signal, which is fed back to the voice coil for maintaining focus automatically.

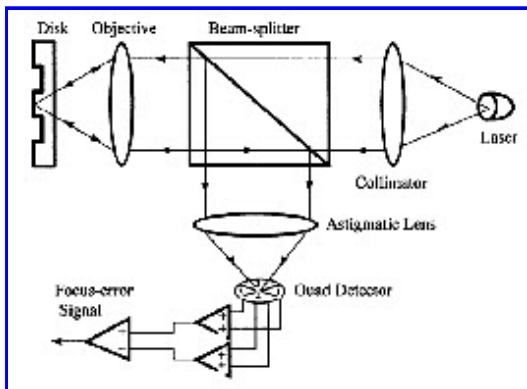


Fig. 5.3. Astigmatic focus-error detection system.

Servo design and manufacture has a stronghold in Japan, but other East Asian nations such as Taiwan, South Korea, and Singapore have recently made significant contributions to this area. Sony, Fujitsu, NEC, Pioneer, Sharp, Toshiba, and Samsung Electronics of Korea have a mature base for miniaturized servo-control technologies. As a result, they are in a strong position to develop faster components for future generation optical drives. It is perhaps safe to declare the art of miniaturization of small mechanical devices (e.g., servo motors and actuators) dead in the United States. However, silicon-based micro-electromechanical devices (MEMS) are finding their way into the field of optical storage, and U.S. industry and universities are quite strong in this field. Once again the U.S. position is open to challenge from the Japanese and other East Asians, since they recognize the significance of this field and are moving quickly to close the gap.

## Automatic Track-Following

The information on an optical disk is recorded either around a series of concentric circular tracks or on a continuous spiral. Manufacturing errors and disk eccentricities caused by mounting errors, thermal expansion of the substrate, etc., will cause a given track to wobble in and out of position as

the disk spins. Typically, a given track might be as much as  $\pm 100\text{ }\mu\text{m}$  away from its intended position at any given time. The focused spot, of course, is only about  $1\text{ }\mu\text{m}$  across and cannot be at the right place at all times. An automatic tracking scheme is therefore desired. Given the mechanical rotation rates of the disks, the frequency response of the actuator needed for track following does not have to cover more than a few kHz, and a voice coil is usually sufficient for the purpose. The feedback signal, for controlling the position of the objective lens within the tracking coil, is again provided by the return beam itself. Several mechanisms have been proposed and have been put to use in commercial devices. Three of these schemes are mentioned here.

The push-pull tracking mechanism relies on the presence of either grooves or a trackful of data on the media. In the case of CD and CD-ROM, the data are prestamped along a spiral on the substrate, and the sequence of marks along the spiral comprises a sort of discontinuous groove structure. The discontinuity is irrelevant to the operation of the tracking servo, however, because it is at a much higher frequency than the tracking servo is designed to follow. Writable media such as CD-R, MO and PC require a tracking mechanism distinct from the data pattern, because prior to the recording of data, the write head must be able to follow the track before it can record anything. Once the data are recorded, the system will have a choice to follow the original tracking mechanism or to follow the recorded data pattern. Continuous grooves are a popular form of preexisting tracks on optical media (see Fig. 5.4a<sup>p72</sup>). A typical groove is a fraction of a micron wide (say,  $0.4\text{ }\mu\text{m}$ ) and one-eighth of a wavelength ( $\lambda/8$ ) deep. As long as the focused beam is centered on a track, diffraction of light from the adjacent grooves will be symmetric. The symmetry of the reflected beam, as sensed by a split detector in the return path, would produce a zero error signal (see Fig. 5.5p<sup>72</sup>). However, when the focused spot moves away from the center of the track, an asymmetry develops in the intensity pattern at the split detector. The bipolar signal thus generated from the difference signal is sufficient to return the focused spot to the center of the track.

In read-only media, the three-beam method of tracking has been extremely popular. The laser beam is divided into three beams, one of which follows the track under consideration, while the other two are focused on adjacent tracks, immediately before and after the desired track. Any movement of the central track away from its desired position will cause an increase in the signal from one of the outriggers and, simultaneously, a decrease in the signal from the other outrigger. A comparison of the two outrigger signals provides sufficient information for the track-following servo.

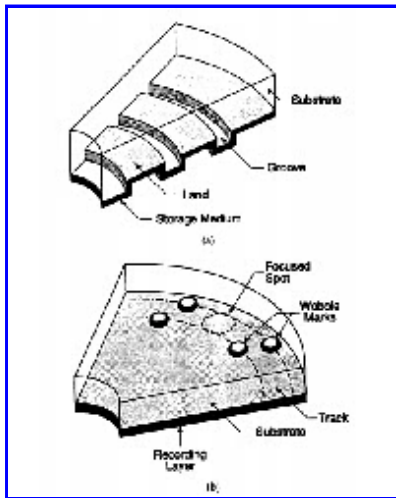


Fig. 5.4. Recordable optical disks: pregrooved media (a) and sampled-servo media (b).

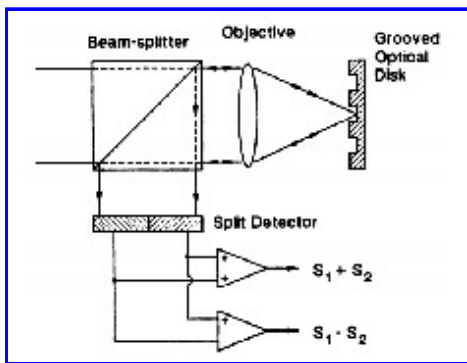


Fig. 5.5. Track-error signal generated by push-pull method.

In yet another possible tracking scheme, the so-called sampled servo scheme, a set of discrete pairs of marks is placed on the media at regular intervals (see Fig. 5.4b<sup>72</sup>). Since these marks are slightly offset from the track center in opposite directions, the reflected light first indicates the arrival of one and then the other of these wobble marks. Depending on the position of the spot on the track, one of these two pulses of reflected light may be stronger than the other, thus indicating the direction of track error.

Much of what was said about servo actuators in the previous section applies to tracking servos and controllers as well. Advances in track following will probably occur in the area of micro-electromechanical devices (MEMS). Tracking actuators are also needed for future generations of hard disk drives, and a convergence of ideas and techniques used in optical and magnetic recording fields is quite likely here. The United States is a powerhouse in hard disk-related technologies with companies such as IBM, Seagate, Quantum, Read-Rite, etc. working feverishly to develop tracking schemes for disk drives. In Japan, Sony, Hitachi, Fujitsu, Pioneer, NEC, and several other companies are quite strong in this field.

Another related subject is the issue of tracking strategies beyond those that are already known and described above. For example, Polaroid Corporation has introduced a new concept that goes beyond the standard sample-servo format and is flexible enough to allow the drive manufacturer to select any

one of a number of possible values for the track-pitch. Such innovations will pave the way for future generations of optical disk drives which use advanced techniques (such as near-field optics) and may not be compatible with the older methods of tracking.

## Disk Substrates

Polycarbonate is a fairly strong, inexpensive, moldable plastic that is currently the material of choice in optical disk fabrication. The pattern of pits and grooves is readily impressed onto the surface of this substrate during injection molding. The transparency of polycarbonate at red and near-infrared wavelengths allows the focused beam of light to reach the storage layer through the substrate, an important factor for removable disks, since focusing through the substrate will keep dust, fingerprints, and scratches on the front facet of the disk well out of focus. Thermal and mechanical properties of polycarbonate are acceptable for present day needs, and its multitude of applications outside the field of optical storage has brought its price down to almost negligible values.

On the negative side, polycarbonate is a birefringent plastic and affects the polarization state of the beam as it travels through the substrate. Substrate birefringence is particularly troublesome in MO data storage, where the readout signal is embedded in the polarization state of the return beam. If one denotes the refractive indices of the substrate along the radial, azimuthal, and vertical directions by  $n_r$ ,  $n_\phi$ , and  $n_z$ , then in-plane birefringence implies that  $n_r \neq n_\phi$  and vertical birefringence implies that  $n_r \neq n_z$ . Careful balancing techniques applied during substrate manufacture have made it possible to reduce the in-plane birefringence to negligible values, but the remnant vertical birefringence and the fact that in-plane birefringence may return at elevated temperatures have kept alive the search for better materials. For example, amorphous polyolephin, which is essentially free from birefringence, has been shown to be an excellent substrate material. Its high price (because of its low volume of applications in other areas), however, has so far been an impediment to its use in optical data storage.

Transparency of plastics will become an issue in the future when very short wavelength lasers become available. Also, if disk flatness happens to be an issue, and recent trends toward flying optical heads and near-field recording indicate that it might be, then glass and aluminum substrates may be more suitable alternatives for these applications. Already several Japanese manufacturers have started R&D programs to develop glass substrates for optical disk applications. Characteristics that are deemed desirable for glass to become an acceptable substrate material are low cost, flatness, hardness, low stress birefringence, and the ability to be patterned with grooves and preformat marks.

In the United States, General Electric Co. is a leading manufacturer of polycarbonate. Other chemical companies (such as Hoechst-Celanese) are also knowledgeable about plastic substrate materials, although they do not seem to have an active development program for optical recording applications. Until recently Eastman Kodak and 3M manufactured their own polycarbonate disk substrates, but these operations have now come to an end. In Japan the work on polycarbonate substrates in many companies has been ongoing for almost two decades, and the level of expertise in this field is quite staggering. Sony, Fujitsu, Pioneer, Mitsubishi, Hitachi-Maxell, NEC, and Nikon, among others, have refined the art and science of substrate manufacturing to the point that they can now routinely fabricate high quality, rigid, low-birefringence substrates for optical disks.

## Magneto-Optical Recording and Readout

Presently all commercially available MO disks are based on an amorphous terbium-iron-cobalt [ $\text{Tb}_x(\text{Fe}_y\text{Co}_{1-y})_{1-x}$ ] magnetic alloy. Typical compositions have a value of  $x \approx 0.2$  and  $y \approx 0.9$ . This material belongs to a class of materials known as the rare earth-transition metal alloys. (Terbium is a rare earth element, while iron and cobalt both are transition metals.) The TbFeCo alloy has several interesting properties as described below (Mansuripur 1990).

- In thin-film form, amorphous TbFeCo is magnetized perpendicular to the plane of the film, as shown in Fig. 5.6<sup>p74</sup>. Magnetic recording uses media that are in-plane magnetized (i.e., hard disks and floppy disks). Perpendicular recording is superior, however, because individual magnetic domains recorded on the storage layer are oriented with their north poles next to their neighbor's south poles and vice versa. This is an energetically more favorable configuration than the head-to-head domains of magnetic recording, and the recorded marks, therefore, are more stable.

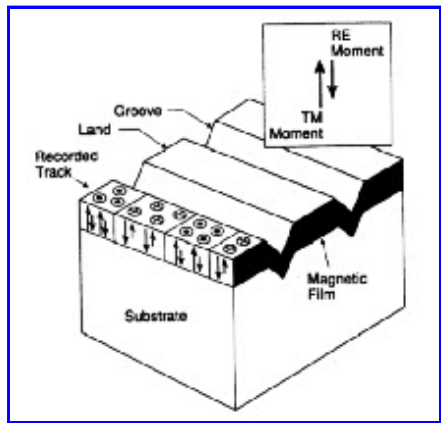


Fig. 5.6. Small section of a simplified magneto-optical disk.

- The media of conventional magnetic recording are ferromagnetic. Being composed of one magnetic species, they have a very strong magnetization, which of course is needed during readout: the stray magnetic field, leaking out of the disk or tape surface, provides the readout head with information about the local state of magnetization. Large magnetic moment translates into a large demagnetizing field within the medium, which tends to destabilize the recorded marks. Magneto-optical recording, on the other hand, uses ferrimagnetic alloys. In the case of TbFeCo alloy, for instance, the magnetization of the Tb subnetwork is oriented opposite to that of the FeCo subnetwork. As a result, the net magnetization is very small, and the destabilizing effects of the demagnetizing field are negligible. Readout of MO media is not hampered by the ferrimagnetic nature of the material, because the laser beam used for information retrieval interacts mainly with the FeCo subnetwork. (The magnetic electrons of the Tb ion, being the 4f electrons, are shielded by the higher-lying orbits and are, therefore, not accessible to the red laser beam.)
- At room temperature, the media of MO recording exhibit a large coercivity (of the order of several kilo Oersteds). The coercivity drops, however, with the increasing of temperature, and at the Curie point, where the ferrimagnetic phase undergoes a transition to the paramagnetic, the

coercivity becomes zero. For typical MO media the Curie point is around 300°C. The reduction of coercivity with increasing temperature is used to advantage in MO recording. The writing and erasure of data on MO media rely on the heat generated by a focused laser beam to raise the material's temperature to the vicinity of its Curie point. A small externally applied magnetic field (around 100 Oe or so) can then decide the direction of magnetization of the heated spot after the laser has been turned off and the material has cooled down. Writing of the information can be achieved by a continuous-wave (CW) laser beam and a modulated magnetic field. This method is known as the magnetic field modulation recording scheme. Alternatively, one can start with an erased track, apply a reverse-magnetizing DC magnetic field to the region of interest, and modulate the laser power to record the information along the track. This is known as the laser power modulation recording (or light intensity modulation-LIM) scheme. The laser power modulation scheme does not allow direct overwrite of the pre-existing data on the track (unless a more complex media structure is employed, as discussed below in the section on exchange-coupled magnetic multi-layers). The data must therefore be erased during one revolution of the disk, and recorded in a subsequent revolution. Erasure is very similar to writing, in that it uses the heat generated from the laser beam and requires assistance from an externally applied magnetic field to decide the direction of magnetization after cool down. Since erasure is applied to an entire sector (and not to individual bits within that sector), it is sufficient to leave the laser beam on continuously (i.e., CW operation) and to apply a DC magnetic field in the desired direction.

- The MO media rotate the polarization vector of the incident beam upon reflection. This is known as the polar magneto-optical Kerr effect. The sense of polarization rotation is dependent on the state of magnetization of the medium. Thus, when the magnetization is pointing up, for example, the polarization rotation is clockwise, whereas down-magnetized domains rotate the polarization counterclockwise. The polar Kerr effect provides the mechanism for readout in MO disk data storage. Typical materials used today impart about 0.5° of polarization rotation to the linearly polarized incident light. But, given the extremely low levels of noise in these media, the small Kerr signal nonetheless provides a sufficient signal-to-noise ratio for reliable readout. Readout and writing in optical disk drives are typically carried out with the same laser. To avoid obliteration of the recorded data, the power of the read beam must be substantially below that of the write beam. Also readout is carried out in CW, whereas writing is generally done in pulsed mode. To reduce the laser noise in readout, it is customary to apply a very high frequency modulation (several hundred MHz) to the laser driver. This high-frequency modulation is well outside the range of recording frequencies and does not affect the readout of data, but it forces the laser to operate in all its various longitudinal modes simultaneously, becoming temporally incoherent but, at the same time, less noisy.
- The media of MO recording are amorphous. Lack of crystallinity in these media makes their reflectivity extremely uniform, thereby reducing the fluctuations of the read signal. This amounts to very low levels of noise in readout, which ultimately helps increase the data storage densities. (In general, the larger the available signal-to-noise ratio from a given medium, the higher will be the achievable packing densities in that medium.) To be sure, noise from the MO medium is not the only noise in readout, but it is the dominant one. The other sources of readout noise are the thermal noise of the electronic circuitry, the shot noise of photodetection, and the laser noise. The method of MO readout is a differential method, whereby the signal is split between two photodetectors and the outputs of the two are then subtracted from each other to yield the final

signal. The subtraction eliminates many of the common mode sources of noise, but of the noises that remain at the end, the media noise is still the dominant component.

The only U.S. firm that could manufacture MO disks until recently was 3M, but that program seems to have come to an end. With the recent excitement generated by Quinta and TeraStor corporations, it is likely that some hard disk manufacturers in the United States might have started their own internal research and development activities, but, to this author's knowledge, no one is making commercial-quality MO disks in the United States. In Japan there are powerhouses such as Sony, Hitachi-Maxell, Maxell-Nikon Optical (MNO), Mitsubishi Chemicals, TDK, and several other firms, which have extremely good products on the market. These companies are also in a good position to address the future needs of drive manufacturers, whether these manufacturers demand conventional disks for through-substrate applications, or front-surface disks for near-field applications. The manufacturing processes, as well as the quality of thin magnetic and dielectric films and the substrates, are continually improving in Japan, making it virtually impossible to compete with the low cost and high quality of their MO products.

## Phase-Change Media and the Mechanism of Recording

Presently the medium of choice for erasable phase-change recording is a  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  alloy, which is affectionately referred to as the GST material (Ohara, Akahira and Ishida 1996). This alloy is sputter-deposited on a plastic substrate, with an undercoat and an overcoat of  $\text{ZnS-SiO}_2$  dielectric layers. The stack is then capped with an aluminum alloy layer for making an antireflection structure. The quadrilayer stack is also effective as a rapid cooling structure, thanks to the heat-sinking properties of the aluminum layer. The as-deposited GST alloy is amorphous. However, each disk is annealed at the factory to transform the recording layer into its polycrystalline state. The recording process turns small regions of the GST medium into amorphous marks, by raising the local temperature above the melting point and allowing a rapid cool down quenching. The reflectivity of the amorphous mark is different from that of the polycrystalline background and, therefore, a signal is developed during readout. Erasure is achieved by using a laser pulse of an intermediate power level (i.e., between the read and write powers). If sufficient time is allowed for the laser beam to dwell on the amorphous mark, the mark will become crystalline once again (annealing). This process is compatible with direct overwrite and is therefore preferable to MO recording, where direct overwrite is harder to achieve.

In the United States, Energy Conversion Devices (ECD), Inc. of Troy, Michigan is the technology leader in the field of phase-change optical media. ECD also owns some of the basic patents on PC materials. In Japan Matsushita Electric Co. is the leader, with Hitachi, Toshiba, and a few other companies close behind. There is significant activity also in S. Korea, Taiwan, and Singapore. The challenge for PC media manufacturers in the next few years is to improve the media in order to increase the recording speed and cyclability. The PC drives are not very different from MO and CD-R drives; therefore, advances in optical components that benefit other areas of optical recording will benefit the PC drives as well. In the area of drives, however, there is currently no U.S. presence, and all commercial products come out of Japan. There are indications, however, that some of the U.S. firms may be gearing up to jump into the fray and produce their own drives. There are certain

methods of recording and readout in the near-field that are particularly suited to PC (as opposed to MO) media. It is advisable, therefore, that we in the United States should devote some of our resources to investigating the combination of media and read/write/erase systems in the near future, as we pursue greater densities and higher data rates.

Comparing PC and MO technologies, one can find several advantages and disadvantages for each. PC drives are simpler than MO drives, because they do not need magnets to create external magnetic fields, and also because there is no need for sensitive polarization-detecting optics in PC readout. The read signal is very strong for PC media, so much so that despite the rather large component of media noise of PC, the SNR is still somewhat larger than that of MO media. On the other hand, repeated melting, crystallization, and amorphization of PC media results in material segregation, stress buildup, micro-crack formation, etc. These factors tend to reduce data reliability and cyclability of the PC media. MO disks are guaranteed to sustain over  $10^6$  read/write/erase cycles and can probably do better than that in practice, but the corresponding figure for PC media is typically one to two orders of magnitude lower. The maximum temperature reached in MO media during recording and erasure is typically around  $300^\circ\text{C}$ , as opposed to  $600^\circ\text{C}$  in PC media. The lower temperatures and the fact that magnetization reversal does not produce material fatigue account for the longer life and better cyclability of the MO media. Writing and erasure in MO media can be very fast, fundamentally because spin flips occur on a sub-nanosecond time scale. In contrast, although amorphization in PC media can be very rapid, crystallization is a rather slow process: the atoms must be kept at elevated temperatures long enough to move around and find their place within the crystal lattice. As a result, in principle high data rates are achievable with MO media, but there may be barriers to achieving them in PC media. On the other hand, PC media are directly overwritable, but MO media can be overwritten either with magnetic field modulation (which is a rather slow process) or by using exchange-coupled magnetic multi-layers (which are more difficult to manufacture than the conventional single-magnetic-layer disks).

## Solid Immersion Lens

A new approach to optical disk data storage involves the use of near-field optics in general and the solid immersion lens (SIL) in particular (Kino 1994). The SIL approach requires that a part of the objective lens fly over the surface of the storage medium, as shown in Fig. 5.7p78. The hemispherical glass of refractive index  $n$  receives the rays of light at normal incidence to its surface. These rays come to focus at the center of the hemisphere and form a diffraction-limited spot that is smaller by a factor of  $n$  compared to what would have been in the absence of the SIL. (This is a well-known fact in microscopy, where oil immersion objectives have been in use for many years.) A typical glass hemisphere having  $n = 2$  will reduce the diameter of the focused spot by a factor of 2, thus increasing the recording density fourfold. To ensure that the smaller spot size does indeed increase the resolution of the system, the bottom of the hemisphere must either be in contact with the active layer of the disk or fly extremely closely to it. For a disk spinning at several thousand rpm, it is possible to keep the SIL at a distance of less than 100 nm above the disk surface.

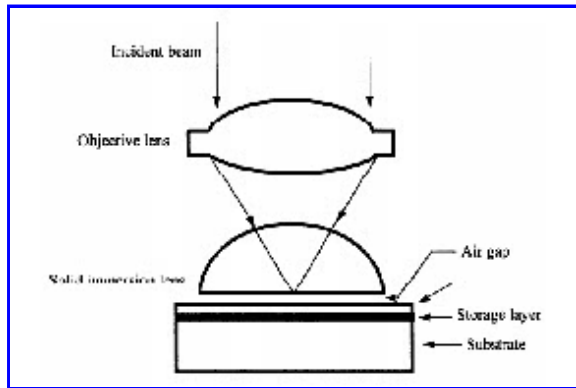


Fig. 5.7. Solid immersion lens.

The rays of light that are incident at large angles at the bottom of the hemisphere would have been reflected by total internal reflection, except for the fact that light can tunnel through and jump across gaps that are small compared to one wavelength. This tunneling mechanism is known as frustrated total internal reflection, and its presence qualifies the application of SIL in optical data storage as a near-field technique. The price one will have to pay for the increased storage density and data rate afforded by the SIL is the necessity to permanently enclose the disk within the drive, thereby making it non-removable. (The possibility of maintaining removability in an SIL system has been suggested, but it remains to be demonstrated in a practical setting.) The United States is currently in a leading position in this field, with companies like TeraStor pursuing a commercial product vigorously. There was substantial interest and curiosity on the part of WTEC's Japanese hosts in this subject, as evidenced by the numerous questions that they asked WTEC panelists about the technical and business aspects of the TeraStor approach. Although the Japanese seem to be playing catch-up at this point, it will not be long before they can make flying optical heads using SIL or some such technique. After all, many of the components that TeraStor is using in its experimental drive come from Japan, and it is only a matter of time before the Japanese engineers learn how to put these items together and build a complete system. Sony already has a working system with a variant of the solid immersion lens, one that is not working in the near-field yet, but can provide insight into the subtleties of SIL-based systems. Perhaps what makes the SIL concept so attractive to the Japanese industry is its ability to bridge the gap between optical and magnetic recording technologies. Traditionally, hard disk drives have been the domain of American companies, whereas Japan has been strong in optical recording. The SIL has the potential to marry these two technologies, thus giving the Japanese industry an opening to capture at least a fraction of the hard disk market.

## Land-Groove Recording

It has been found that by making the land and groove of equal width, and by recording the information on both lands and grooves, it is possible to eliminate (or at least substantially attenuate) the cross-talk arising from the pattern of marks recorded on adjacent tracks (Fukumoto, Masuhara and Aratani 1994). Fig. 5.8a<sup>p79</sup> shows a typical pattern of recorded data on both lands and grooves. It turns out that for a particular groove depth (typically around  $\lambda/6$ ) the cross-talk from adjacent tracks reaches a minimum. Fig. 5.8b<sup>p80</sup> shows the computed cross-talk signal obtained from a theoretical model based on scalar diffraction theory. These results are in excellent agreement with the experimental data, indicating that cross-talk cancellation is a direct consequence of diffraction from

the grooved surface and interference among the various diffracted orders.

Land-groove recording works well in phase-change media, and, in fact, this is where it was originally discovered. For MO systems, the birefringence of the substrate creates certain problems; specifically, the presence of in-plane birefringence will make the optimum groove depth for land reading different from that for groove reading. To overcome this problem either better substrates (with smaller in-plane birefringence) should be developed, or a servo system must be deployed to automatically correct the effects of birefringence. So far, the laboratory results of land-groove recording on MO disks have been very encouraging, and there is little doubt that this technique will play a major role in future generations of both PC and MO devices.

The Japanese engineers are quite comfortable with land-groove recording at this point. Major contributions in this area have come from Matsushita, NEC, and Sony, but just about every company in Japan and South Korea seems to have developed laboratory versions of the land-groove disk and studied its properties (Figs. 5.8a<sup>p79</sup>, 5.8b<sup>p80</sup>). To this author's knowledge, however, no one in the United States has made any contributions to this field. Land-groove recording will be an important aspect of high-density recording in the near future, and deserves more attention.

## Exchange-Coupled Magnetic Multi-layers

Figure 5.9a<sup>p80</sup> shows a diagram of an exchange-coupled magnetic trilayer. In this system the top and bottom layers have perpendicular magnetic anisotropy, while the intermediate layer is an in-plane magnetized layer. The function of the intermediate layer is to ease the transition from the top to the bottom layer. The top and bottom layers typically have different compositions, magnetic moments, thicknesses, coercivities, etc. By exchange-coupling these two layers together, it is possible to lock their magnetic behavior to one another, so that switching one layer would make the other layer either more likely or less likely to switch (Mansuripur 1995; McDaniel and Victora 1997). When the two layers are magnetized in opposite directions, a domain wall develops between them (going through the intermediate layer, of course). This domain wall, which has energy associated with it, makes the collapse of a domain formed in either of the layers much more likely; in other words, it makes a domain such as that in Fig. 5.9b<sup>p80</sup> less stable and more susceptible to external disturbances, compared to a domain that goes through the entire thickness of the magnetic stack. Using exchange-coupled magnetic multi-layers, engineers have created media designs with many useful and novel capabilities.

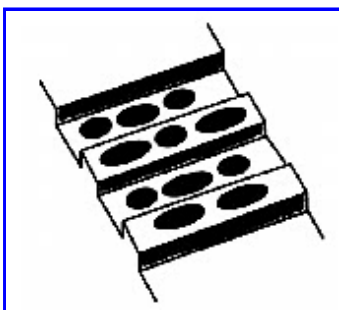


Fig. 5.8a. Typical pattern of land-groove recording.

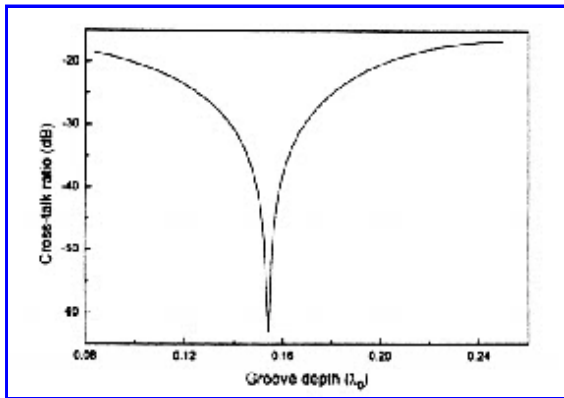


Fig. 5.8b. Cross-talk signal from a model based on scalar diffraction theory.

One such structure allows light-intensity modulation direct overwrite (LIMDOW) in magneto-optical disks. In these media the recorded domains, being of the type shown in Fig 5.9b<sup>p80</sup>, collapse under a focused laser beam of moderate power. Low-power beams that are used for readout do not disturb the recorded domains, and high-power beams create domains that go through the entire thickness of the stack; only moderate-power beams are capable of erasing a pre-existing mark. Thus by switching the laser power between moderate and high levels, one can create a desired pattern of domains irrespective of what data have been previously recorded in that location.

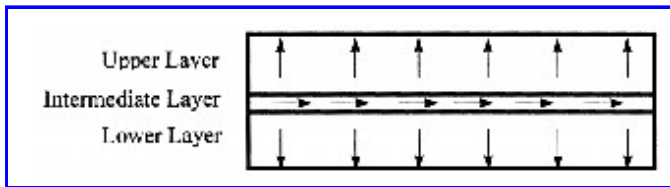


Fig. 5.9a. Exchange-coupled magnetic trilayer.

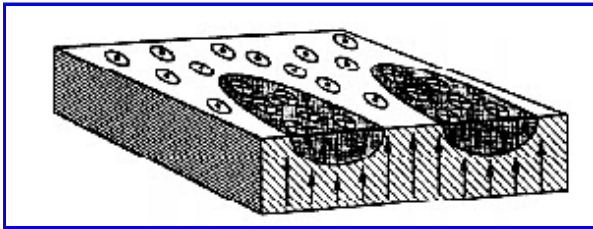


Fig. 5.9b. Cross-sectional view of magnetic domains in an exchange-coupled magnetic multi-layer.

Another magnetic multi-layer structure enables high resolution readout based on the concept of magnetic super resolution (MSR) (Kaneko and Nakaoki 1996). In this scheme the recorded data is kept in a storage layer; then, during readout, the recorded marks are presented to the read beam one at a time. This is achieved by selective copying of the marks (i.e., magnetic domains) to the read layer using the temperature induced in that layer by the focused laser spot. The essential features of MSR are shown in Fig 5.10<sup>p81</sup>. The two schemes shown in this figure are known as front aperture detection (FAD) and rear aperture detection (RAD). In Fig. 5.10a<sup>p81</sup> the laser beam heats up the read layer, temporarily erasing the domains within the heated region. The mark in the front aperture region is then detected. In Fig. 5.10b<sup>p81</sup> the rear aperture area, which is heated up, yields to the storage layer and accepts its magnetic state, thus receiving the domains and exposing them to the read beam. The

advantage of MSR is that, since it presents the domains one at a time to the read beam, it does not suffer from intersymbol interference and cross-track cross-talk. More important perhaps is the fact that the minimum mark length that is readable in an MSR system is shorter than any that are readable in conventional systems. There is a lower limit, known as optical cutoff, to the mark lengths in conventional optical recording. MSR can overcome this limit and read below the optical cutoff.

More recent work in magnetic multi-layers has involved layers that are separated by thin, non-magnetic dielectric films. The coupling between the various magnetic layers in these structures is no longer mediated by exchange, but it is by means of magneto-static forces, whereby the stray magnetic field from one layer acts on the magnetization of another layer. For example, one proposed MSR technique, referred to as central aperture detection (CAD), has an in-plane-magnetized read layer which is separated from the perpendicularly magnetized storage layer by a thin dielectric film. During readout, the laser beam raises the temperature of the in-plane layer, making it possible for the stray magnetic field from a recorded domain (which resides within the storage layer below) to align the local magnetization of the readout layer with its own (perpendicular) direction of magnetization. A variation on this theme is the newly proposed concept of magnetic amplifying magneto-optical system (MAMMOS). Here, after copying the recorded mark to the readout layer, an external magnetic field is used to expand the copied domain, thereby amplifying the readout signal. Clearly, coupled magnetic multi-layers open the door to many new possibilities, and we expect to see many of these innovations in future generations of MO products.

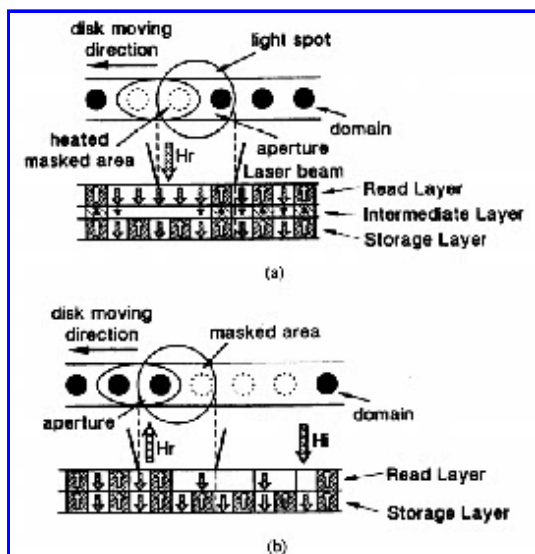


Fig. 5.10. Exchange-coupled magnetic multi-layer used in magnetic super resolution (MSR) as seen in front aperture (a) and rear aperture (b).

Exchange-coupled magnetic multi-layers are the exclusive domain of the Japanese industry. The original concepts of DOW and MSR were developed by Nikon and Sony, and many contributions were made later by a host of other Japanese companies. Essentially nothing novel has been contributed to this field by the U.S. industry. Hitachi Maxell and MNO (Maxell Nikon Optical) are proficient in the manufacture of exchange-coupled magnetic disks. The future seems to belong to MSR and MAMMOS and their derivatives. Unfortunately, the United States seems to have been left behind in this area, and unless something is done to change the situation drastically, we are bound to

be "followers."

## Stacked Optical Disks and Double-Layer DVD

Magnetic drive manufacturers generally use a stack of several magnetic disks to achieve the desired storage capacity within the small volume of a hard drive. The small size and the low cost of magnetic heads allows them to use a separate head for each disk surface without compromising the overall size and price of the drive. In contrast, optical heads are very expensive and rather bulky. To achieve volumetric data storage with optical disks, designers have sought methods that rely on a single head for accessing multiple platters. In 1994 IBM researchers demonstrated a system that could read through a stack of six CD surfaces using a single optical head (Rubin et al. 1994). Their system was very similar to a conventional CD player, except that they had taken special care to correct the spherical aberrations that result when the beam of light is focused through a substrate at different depths. The IBM stack consisted of three thin glass disks (thickness  $\approx 300\text{ }\mu\text{m}$ ) on both surfaces of which the data pits had been embossed. Unlike standard CDs, these disks were not metallized because the focused laser beam had to pass through several such layers before reaching the desired surface. A bare glass surface reflects about 4% of the incident light, and this was apparently sufficient to enable the detection system to retrieve the data and to play back, with high fidelity, the recorded audio and video signals.

Technically, the method described above is straightforward and requires only that the objective lens be corrected for focusing through different thicknesses of the substrate. The separation between adjacent surfaces must be large enough to reduce cross-talk from the data marks recorded on neighboring surfaces. With a 0.5 NA objective lens, a separation of 40 or 50 microns is typically enough to assure acceptable levels of cross-talk from these other surfaces.

In the case of writable media, recording and readout of information on multiple platters is more difficult, primarily because storage layers absorb a significant amount of the laser light. (In their 1994 demonstration, IBM researchers also described a four-layer WORM disk and a two layer MO disk.) Recently double-layer MO and PC disks have been proposed and demonstrated in several industrial laboratories around the world. Again the separation between recording layers has been kept at about 40 microns to reduce cross-talk, and the laser beam has been strong enough to write on the second layer even after half of its power has been absorbed by the first layer. (The power density at the first layer is reduced by a factor of almost 2000; hence, no writing occurs at that layer.) Since focusing through an additional 40 microns of plastic is well within the range of tolerance of typical objective lenses, correction for spherical aberration has not been necessary in these double-layer systems.

Stacked optical disks have obvious advantages in terms of volumetric capacity, but the technological barriers for rewritable media are substantial. Japan is currently in a leading position in this area, with a clear shot at double-layer DVD. Matsushita, Sony, Toshiba, and Pioneer are the leaders, but there is significant know-how in other companies as well.



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## REPORTS OF VISITS TO INDUSTRIAL LABORATORIES IN JAPAN

## REPORTS OF VISITS TO INDUSTRIAL LABORATORIES IN JAPAN

### Nikon Corporation

Nikon's involvement with optical storage media is through a joint venture with Hitachi-Maxell, called MNO (Maxell-Nikon Optical). This company, which is nearly three years old, manufactures and markets exchange-coupled magnetic multi-layer MO disks capable of direct overwrite (DOW). Both 3.5" and 5.25" disks are produced by MNO. The high-end product is currently the 4X, 5.25" DOW disk with 2.6 GB capacity (double-sided). The 8X, ISO format disk was expected to be introduced into the market later in 1998 by Sony Corporation. The DOW version of the 8X, 5.25" MO disk will follow the non-DOW disk. (The ISO has almost finished specifying the 8X 5.25" DOW disk and has finished specifying the DOW 4X 5.25" and the DOW 5X 3.5".)

The current price of the DOW disks in Japan is approximately 50% higher than the non-DOW disk. For example the 3.5" DOW disk can be purchased for ¥2,400, whereas the non-DOW disks cost about ¥1,600. Despite this price difference, the general consensus at Nikon was that the overwrite capability is important to the user, and they believed that a large fraction of the users will prefer the DOW disks.

As far as compatibility with drives is concerned, all 640 MB drives for the 3.5" disks and all 4X drives for the 5.25" disks can handle the DOW disks as well as the ISO standard non-DOW disks. WTEC hosts also stated that all future-generation drives for MO will be compatible with the DOW disks.

The market for MO drives is still small, but most Japanese scientists/engineers with whom this author talked seem to think that there is a bright future in this field. In 1996 there were nearly 1 million 3.5" MO drives sold worldwide, and the number was close to 930,000 units in 1997. By far the largest share of the market (i.e, percentage of users) was in Japan. There does not seem to be a large market for the Zip drives in Japan, although the panel was told that Fuji film is now making Zip media, and NEC has been licensed to manufacture Zip drives. According to the WTEC panel's hosts at Nikon, Japanese consumers think very highly of optical technologies, perhaps because of the superior performance of CD audio and its resounding success in the market place. Any technology that uses lasers is likely to attract the attention of the Japanese consumers. As for MO technology, the panel was told that the shelves in Akihabara are full of MO disks these days.

No one at the meeting knew the exact size of the market for MO disks, but our panelists' guess (based on the number of drives sold last year) was that there is probably demand for 10 to 20 million 3.5" disks this year. Given that several manufacturers in Japan produce these disks, hosts were asked if this

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type of a market was suitable for their company to be involved with. The answer was a strong yes, with the comment that 10, 20, 30, 40 million disks per year is certainly a good enough market for Japanese disk makers to pursue.

There was some talk about the Windows 98 operating system and that this version of Windows will allow bootup from removable media. Also the fact that Win '98 will accept ATAPI interface (instead of SCSI) was considered a boost for MO drives in the near future. Fujitsu, for example, is already making 3.5" MO drives with ATAPI interface; Fujitsu has also announced 1.2 GB 3.5" (one-sided) MO drives, and reportedly has plans for Dragon I and II drives, which will accept both 3.5" MO disks and CD-ROMs.

Nikon researchers apparently are not involved in phase-change media development. The only information they provided on this type of media was based on their personal knowledge of the R&D efforts in Japan. They said that in April 1998 Hitachi and Panasonic would ship DVD-RAM disks and drives. These are 2.6 GB/side, 5.2 GB (double sided) 120 mm diameter disks. Sony's DVD+R/W is expected to have around 3.5 GB capacity, and Pioneer's DVD-RW will be about 3.4 GB capacity. The latter is expected to be introduced in 1999.

The participants had some reservations about the future of CD-R type media (CD-recordable, DVD-recordable, WORM-type media). They felt that with the mastering equipment makers' effort to develop a new method of mastering of CD and DVD, stamping as few as 100 disks will be cheaper than recording them individually on the CD-R type media. Of course CD-R will continue to serve a special niche market, but more and more people will gravitate toward the ROM type media on the one-hand and toward the rewritable media on the other hand.

WTEC's hosts stated that there are essentially two types of markets for MO disks and drives in the near future: (a) personal computer/consumer/portable applications, and (b) infrastructure applications such as servers and mainframes. From now on, they said, the 3.5" and 5.25" disks will move in different directions, partly because of differences in removability requirements and partly because of the price targets that manufacturers feel they can set for each product.

For portable applications it was felt that SyQuest and Jazz drives are not suitable because they can be dropped only about 40 cm or so. The same concern applies to the magnetic field modulation (MFM) method, which contains a flying head. The LIMDOW (light intensity modulation direct overwrite) technology, on the other hand, does not use a flying head and is therefore more suitable for portable applications. Technologies which use the magnetic field modulation technique are probably more suited for infrastructure applications (e.g., servers and mainframes) as well as for low-end consumer applications such as the MiniDisc.

The participants felt certain that the optical ROM format will be around in 20 years and beyond. They mentioned that semiconductor memories should be watched closely in the next few years. New semiconductor technologies such as one-electron DRAM might be able to compete with optical RAM storage products. The need of optical storage devices for some sort of mechanical actuator to access the data might be considered to be a drawback for this technology, when the recording densities would be much higher in the very distant future. The participants also felt certain that the optical RAM

format will be around in 20 years and beyond.

## **Pioneer Corporation's R&D Laboratory**

In the field of optical disk data storage, Pioneer is a manufacturer of CD-ROM, DVD-ROM and DVD-R media. Presently it is engaged to establish the DVD-RAM version 1.0 and 2.0 (2.6 GB and 4.7 GB) specifications in DVD Forum working group 5, but Pioneer's main focus is developing the 4.7 GB DVD-RW disc and drive as well as the next generation 15 GB DVD-RW disc and drive.

Pioneer researchers are engaged in a number of research activities at the leading edge of modern optical technology. For example, they are developing blue lasers for various applications using both the technique of second harmonic generation (SHG) and direct fabrication of blue semiconductor lasers based on III-V materials (GaN-based system). They are also active in developing new display technologies based on a class of organic electroluminescent materials. At the time of this visit the R&D laboratories employed a total of 165 researchers.

In the area of optical data storage, Pioneer's research seems to be focused on DVD-ROM and rewritable DVD systems. The company has an in-house mastering facility for producing high-density disks for research and development purposes. Pioneer researchers mentioned their plans to bring out the 15 GB DVD-ROM by the year 2001. This system, which is intended for high definition TV (HDTV), will use low-power blue lasers, and will employ actively controlled liquid crystal (LC) elements for aberration correction and for tilt servoing. The use of 410 nm blue laser and a 0.6 NA objective lens will allow a capacity of only 9 GB on a 12 cm platter. To get to 15 GB, Pioneer researchers plan to use a number of advanced techniques, including 2D equalizer, cross-talk canceller, adaptive tangential equalizer, and Viterbi decoder.

In its prototype 15 GB DVD-ROM system, Pioneer uses a three-beam cross-talk canceller, which also provides the feedback signal to the radial tilt correcting servo based on a LC element. Although in principle this liquid crystal element can also do automatic correction for the tangential tilt, in practice the speed of switching the LC is not sufficient for high-speed applications. The tangential tilt correction is therefore done by electronic equalization. The details of this equalizer (which they referred to as "super equalizer") were not discussed, because Pioneer is applying for a patent on this technology.

To produce the 15 GB master for second-generation DVD-ROM, Pioneer researchers used a photo-bleachable dye layer on top of the photoresist. Only the central region of the focused spot is strong enough to bleach the dye layer and, therefore, expose the photoresist layer below. In this way, the researchers could achieve super-resolution and create well-defined pits. They estimated that the use of the photo-bleachable layer had improved their cutting resolution by about 20%. Their mastering machine used a 0.9 NA lens and a 351 nm laser, and created DVD masters with a track pitch of 0.37 microns and minimum mark length (3 T) of 0.25 microns.

In the area of rewritable DVD the researchers mentioned Pioneer's DVD-R/W format based on rewritable phase-change media, with a limited number of write/erase cycles (around 1,000). This product is intended for the consumer market (as opposed to computer market), for which the limited

cyclability is acceptable. Compatibility with DVD-ROM was highly emphasized. The material of choice for DVD-R/W is InAgSb, which is the same material used in CD-R/W. The researchers said that they have confirmed a jitter value of less than 7% in this material at 4.7 GB capacity and over 100 times cyclability, which is better than what DVD-RAM can claim at the moment. Pioneer researchers hoped to develop the 4.7 GB DVD-R/W before the end of 1998. They maintained that of all the issues facing rewritable DVD, probably the copy protection issue is the most significant stumbling block.

Pioneer researchers gave the WTEC team a tour of their laboratories, where the panel saw the various technologies developed for the second generation DVD-ROM and DVD-RW. In particular, panelists saw the improvement of the read signal due to the LC-based tilt servo, and the improvement of the eye-pattern by the so-called "super equalizer."

As for life after 2001, Pioneer researchers showed us preliminary examples of techniques that will be used in the 50 GB DVD-ROM. Unless some new technologies are developed in the next few years, it seems likely that electron beam lithography will have to be depended upon to create 50 GB master disks.

Pioneer Laboratories has done research on both magneto-optical and phase-change media in the past, but researchers seem determined to move towards phase-change technology in their consumer-oriented strategy. The researchers who talked to the WTEC panel maintained that advanced storage magneto-optical disk (ASMO, a.k.a. MO7) seems to have the support of the disk manufacturers but not the support of drive manufacturers in Japan. They also seemed to think that there are certain problems with the development of the ASMO technology, especially as related to the thin disk.

## **Sanyo Corporation's Hypermedia Research Center**

One group some of the panelists visited is involved only in magneto-optical (MO) recording research, although Sanyo manufactures CD, CD-ROM, MiniDisc, pickups, and lasers for the optical data storage market. Advanced storage magneto-optics (ASMO) technology seems to be one focus of research at Sanyo. The current plans call for the 6 GB ASMO disk on a 12 cm platter (single-sided), followed by the second-generation disk at 12 GB using the MAMMOS technology, and leading up to the 30 GB disk in the third generation.

According to the Sanyo researchers, magnetic-field modulation (MFM) recording is attractive because it offers the possibility of recording domains as small as 0.1 microns in diameter. Although the minimum required data rate is currently around 4 Mb/s, the researchers foresee the potential of 50 Mb/s data rates in the next 2-3 years using the MFM technique. They also believe that in the near future access times will reach below the current value of 60 msec.

The substrate thickness for ASMO disks is 0.6 mm in the data area (1.2 mm in the central hub area). The tilt of the disk is not considered a serious concern here because MFM recording and the technique of magnetic super resolution (MSR) readout used in ASMO disks are not tilt-sensitive. Therefore high-numerical aperture objectives can be used in conjunction with the 0.6 mm substrate without much concern for tilt-induced coma. The preferred mode of MSR seems to be CAD-MSR. The

GdFeCo layer used as the readout layer has a large Kerr signal, even at short (blue) wavelengths. As for future-generation devices using blue laser diodes, Sanyo researchers mentioned that they had researched superlattice materials such as PtCo, but they also felt confident that, using the MAMMOS technology, TbFeCo and GdFeCo media would offer sufficient sensitivity and acceptable levels of signal to noise ratio (SNR) at short wavelengths.

It was mentioned that the density of MO media is limited only by the width of magnetic domain walls in amorphous RE-TM alloys (on the order of 10-20 nm), and that data transfer rates are limited perhaps by the 10 psec time constant for magnetization reversal in these media.

Concerning the competition between hard disk drives (HDDs) and optical disk drives (ODD), hosts at Sanyo felt that both technologies will coexist in the future. While HDDs are superior in terms of cost-performance and data rate, ODDs have the advantage of removability and mass-reproducibility. It was mentioned that the rapid growth and the pace of change in HDD technologies is perhaps the reason why the Japanese companies are not leading in this area. Slow decision-making processes were blamed for the slow pace of change in Japan. The Sanyo researchers emphasized that while the hard disk drives are made in the United States, many parts and components come from Japan. The focus of magnetic recording in Japan seems to be on magnetic tapes for VCRs.

Sanyo researchers felt that the MO technology is superior to phase-change (PC), even in terms of compatibility with DVD-ROM. The wollaston prism, for example, costs under a dollar in large quantities, and silicon photodiodes are very cheap; in fact the split detectors needed in MO drives are about the same price as the single-detectors used in PC drives. Some versions of MAMMOS operate without a magnetic field whatsoever. So all the talk of MO being more expensive than PC, they contend, is unrealistic.

It was mentioned that the growth path for LIMDOW technology is through MSR and blue lasers, although the researchers felt that the commercialization of high-power blue lasers before the end of 1998 was not likely. They also emphasized the importance of the partial response maximum likelihood (PRML) technique for high-density recording. As for the use of liquid crystal (LC) devices in optical disk drives, they mentioned that Sanyo currently uses LCs in its DVD-ROM drives to achieve compatibility with CD-ROMs, but they said that the cost of these elements must come down before their use becomes widespread.



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## SUMMARY

Optical storage has made significant progress since its first introduction as laser videodisc in the late 1970s. Granted, its growth has not been on the explosive 60% per year slope that magnetic storage has enjoyed over the last few years, but then it should not be expected to do so. Removability, backward compatibility and interchangeability carry with them a demanding burden, called *standards*, that must be developed and agreed to by the entire industry. The customers demand this as they do not want a repeat of the VHS/Betamax situation a few years ago. In contrast, the only standard imposed on the magnetic storage industry is the interface; the media and recording technology are captive within the drive, thus permitting tremendous freedom and competition.

Progress has been substantial, however, with CD technology jumping from 680 MB to 4.7 GB with the introduction of DVD. Removable 3.5" magneto-optical (MO) has steadily grown from 128 MB to 640 MB, and 5.25" MO now contains 4.6 GB on a single platter. These advances have come through a combination of laser wavelength reduction, increases in the objective lens numerical aperture, better ISI and cross-talk management, and coding improvements. There is room for even greater advances in storage capacity as we make the transition to blue lasers, near-field optical recording, and multi-layer systems. Increases in storage capacities of 50 to 100 fold are not unreasonable to expect in the next 5 to 10 years.




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## 6: Introduction

# CHAPTER 6

## STATUS OF OPTICAL STORAGE IN JAPAN

**[Marvin Keshner](#)**<sup>P7</sup>

## INTRODUCTION

Companies in Japan have made strong investments in optical storage both recently and over the past

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15 years. With few exceptions, such as Philips in the Netherlands, the dominant players in optical storage are in Japan. Many of the U.S. optical storage companies are out of the business. Some are choosing to buy optical storage drives from outside of the United States, to add firmware and/or software and then to market the products under their name. The United States also has several optical library companies that buy optical drives and incorporate them into their libraries.

Recently, there has been renewed investment in the United States in optical recording. Representatives of many storage companies believe that magnetic recording technology is approaching some fundamental limits in areal density. As a result, several start up companies, backed with funding from many of the magnetic disk drive companies, are developing products to replace magnetic storage for some segments of the market. Included are Terastor, Quinta, Digital Papyrus and others.

Meanwhile, in Japan, the focus for optical storage is not to compete with magnetic disk drives, but rather to exploit the advantages of optical storage to serve market segments that are not well served by hard disks. Specifically, optical storage offers a reliable, removable medium with excellent robustness, archival lifetime, and low cost per GB. The targeted markets are replacing tape for video camcorders and replacing tape for time shifting TV programs (VCR replacement). Also targeted are the markets for storing digital photographs, for recording movies and other video material over the Internet, and for multimedia presentations at home and for business.



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## STANDARDS AND COMPATIBILITY

### STANDARDS AND COMPATIBILITY

Optical recording in Japan is focused on the benefits to the customer offered by a removable, low-cost medium. Customers want a recording medium that has a standard format, allowing it to be exchanged with a friend and played easily on anyone's system. Without a strong standard format, customers would not be able to move information from one system to another. A key benefit of the removable medium would be lost.

Over time, as improvements are made in recording technology, customers want to be able to read older versions of the technology in the newer players (backwards compatibility). They also want to be able to write (in a new writer) an older version that can be played in an older player. Naturally, it becomes more and more difficult to meet these requirements for compatibility over many generations of the technology. Most companies attempt to provide compatibility for at least 3 or 4 generations.

Over the past 15 years, Philips and Sony have controlled the standard for the CD family of optical products. These companies have maintained a strong standard with excellent compatibility among

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new and old generations. On the other hand, for the family of magneto-optical products, the process of agreeing upon a single standard format for the industry has been difficult and slow. The slowness of this process is one of the factors that has made it difficult for the magneto-optical industry to match the 60% per year growth in areal density that has supported the magnetic hard disk industry.

For video optical disks, including the various versions of erasable DVD, the standard setting process has been difficult. The optical industry in Japan is quite fragmented with several competing groups of companies allied around incompatible technologies and/or format standards. The DVD (digital video disk) consortium has selected phase change material for its erasable disks. Although consortium members have agreed upon a single standard for the DVD-ROM, there are two competing standards for the erasable format, DVD-RAM and DVD+RW. In addition, there are several companies with large investments in magneto-optical technology (MO) for erasable optical disks. These companies are hoping to show that MO is a superior technology and that it should be used instead of phase change for creating an erasable DVD optical disk.

The difficult business environment for optical disk manufacturers underlies the difficulty in achieving an industry-wide standard agreement for video disks. For compact disk (CD) technology, the two companies who control the standard, Sony and Philips, are making good profits, while almost all of the other manufacturers are losing money. Hence, many companies believe that the only way to have a profitable business in optical video disks will be to control the standard. Then, the few companies that control the standard will make money by licensing the patents that are included in the definition of the standard format. Also, they will be able to limit the number of low cost competitors by keeping the licensing fees high. (This approach is in contrast to several of the standard setting groups in the tape area, where the licensing fees are minimal and companies compete for profits based on product quality and on added value beyond the standard format, e.g., DDS and Linear Tape Open.)




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## ROADMAPS FOR OPTICAL STORAGE

### ROADMAPS FOR OPTICAL STORAGE

The roadmaps derive from customer requirements and tend to be independent of the choice of technology by which they are implemented. Nevertheless, the different camps (DVD-RAM, DVD+RW and MO) have slightly different roadmaps. Today, we have read-only products with 0.65 GB (CD-ROM) and 4.7 GB (DVD-ROM). We will also have writable and erasable products with 0.65 GB (CD-RW), 2.6 GB (DVD-RAM), 3.0 GB (DVD+RW) and 2.6 GB (per side) (5.25" MO). Many companies take the position that 4.7 GB will be an important capacity for camcorders and maybe for replacing VCRs. The next capacity point is targeted to be in the 10-20 GB range. This capacity will certainly be large enough to replace VCRs for recording standard definition TV. Finally, many

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companies are talking about a capacity point in the 30-40 GB range for recording 4-6 hours of HDTV.



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## PHASE CHANGE OPTICAL RECORDING

### PHASE CHANGE OPTICAL RECORDING

Many technology roadmaps are possible for phase change optical recording (See for example Fig. 6.1<sup>p92</sup>). However, many companies are emphasizing the necessity for strong compatibility among at least three generations (under 3.5 GB, about 4.7 GB and about 15 GB). Compatibility would make it difficult to change the thickness of the substrate, to change the penetration depth to the recording layer or to use very high NA lenses ( $>0.65$ ). Since all the roadmaps use a blue laser for the 15 GB generation, compatibility also requires that the disks designed for red lasers must be readable with blue. Toshiba presented results demonstrating that this is possible.

There is close to a consensus that a red laser will be used for the 4.7 GB generation, but the margins are very thin. Similarly, the expectation is that a single recording layer with a blue laser and 0.65 NA will be sufficient for achieving about 15 GB, but again the margins are thin. Alternate plans would include using 2 layers for the 15 GB generation and 4 layers for 30 GB. Matsushita has a two-layer, erasable disk working in its lab. However, some companies, for example, Sony, have completely incompatible proposals. Sony presented an open eye pattern for data recorded at a capacity of 12 GB using a 515 nm laser, NA = 0.85, and a thin substrate with 0.1  $\mu\text{m}$  depth to the recording layer. The panel also saw proposals using partial response maximum likelihood (PRML), optical super resolution, a thermal management buffer layer to improve the writing, and cross track cancellation to allow for higher track density.

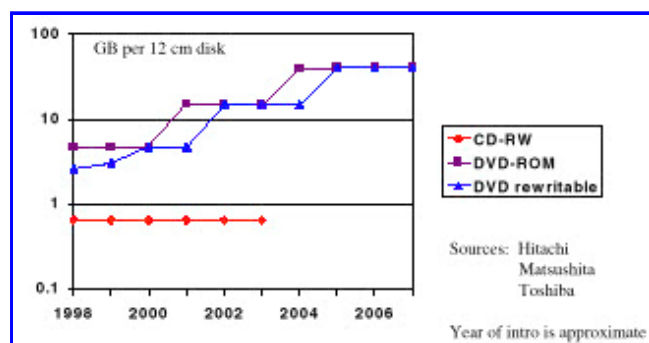


Fig. 6.1. Roadmap for phase change disks.



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## MAGNETO-OPTIC RECORDING

## MAGNETO-OPTIC RECORDING

Products that use magneto-optic (MO) recording technology have been available since 1989. The leading manufacturers are Fujitsu, Sony, Konica and Olympus. Capacities started at 0.325 GB per side for a 5.25" disk and are about to become 2.6 GB. The 5.25" drives have a low volume market for archival storage, especially within automated libraries. The 3.5" disk drives have achieved a moderate volume market at just under one million drives per year. Most of the sales for 3.5" drives are in Japan with little acceptance in either Europe or the United States. Finally, the Sony minidisk for recording music has been on the market for many years, but is recently starting to gain acceptance and achieve significant volumes.

MO technology has several advantages over phase change. It offers more rewrite cycles, longer archival lifetime and faster write and erase times. In addition, magnetic field modulation allows bits to be written that are shorter than the optical spot size (up to 5x). Finally, various super resolution techniques have been demonstrated to extend the areal density towards 100 Gb/in<sup>2</sup>.

MO also has several disadvantages compared with phase change. Magnetic field modulation requires a flying head and close spacing between the head and the medium. This requires a clean surface and careful control of the environment. It may impair the reliability, if the disk is removable. If optical modulation is used, then MO and phase change can only write bits that are about the size of the optical spot. Finally, MO senses a 1% change in the polarization of the reflected light. Although the signal to noise is adequate, the polarization sensing optics are a little more complicated than the optics for phase change signal detection.

The MO companies have formed the Advanced Storage MO group (ASMO) to create a standard to challenge phase change. They have selected a 12 cm disk that is compatible with the DVD standard. They are planning to achieve a single-sided capacity of 6 GB using magnetic field modulation. They hope to offer faster access time (30 msec vs. 180 msec) and higher transfer rates (3 Mb/s vs. 1.4 Mb/s) than the phase change can offer. Even though the phase change optics are a little more complicated, and even though higher performance usually requires more costly components, the ASMO companies hope to be able to offer these advantages at the same price that can be achieved with phase change.

Recently TeraStor, a startup company in the United States, introduced a major breakthrough in magneto-optic technology. It is using an immersion lens that focuses the light inside of a high-index medium rather than through a significant air gap. As a result, TeraStor's optical spot size is 2-3 times smaller in diameter and areal density is 4-9 times greater than previously possible. TeraStor must use a flying optical head with a very small air gap (much smaller than a wavelength of light) between the head and the disk. Key issues are the reliability of the wear layers on the head and disk, plus the

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control of the environment to avoid a buildup of contaminants on the head or the disk. Whether a head-disk system can be developed to be reliable for removable medium is also a key issue. If not, then the immersion lens might be used for non-removable disks that would compete with magnetic disk drives.



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## WHICH TECHNOLOGY WILL WIN?

Some companies take the position that MO technology will win because of performance, almost unlimited erasability and the ability to achieve higher areal density (Fujitsu). Others view low cost as the most important criterion and maintain that phase change disks allow for a simpler and lower cost drive design (Matsushita, Hitachi and Toshiba). Finally, some are hedging their bets (Sony). It is also possible that the technologies will be positioned to go after different markets. For example, phase change might win in the low cost, high volume market for camcorders and VCRs, where cost is key and for which moderate level of erasability and performance are acceptable. MO might win in the archival storage market, where cost is less of an issue and performance and lots of erase cycles are critical. The immersion lens version of MO might be particularly successful in libraries, where high capacity is key and where the environment can be controlled to improve the reliability of the head to disk interface.



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## IS 45 GB PER SIDE GOOD ENOUGH?

The hard disk industry has increased the capacity of non-removable disk drives every year. For removable storage, yearly increases are not desirable. It is more important to offer a capacity point that is usable for the desired applications and then hold that capacity point while increasing the installed base and lowering the price. CDs were designed to store more than 1 hour of music. Their capacity has been unchanged for 15 years. Floppy disks first increased in capacity from 0.25 to 0.5 to

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1 MB, then stopped increasing. For text files, 1 MB was sufficient. Although improvements to 2 MB, 10 MB and then 40 MB have been offered over the last 10 years, none of them have been successful. Only recently, as the applications have shifted from text files to image files has there been an unmet need for higher capacity. Currently, there are several contenders to meet this need: super floppy disks at 100-200 MB, removable hard disks at 1 GB and erasable CDs at .65 GB.

For video disks, depending on the compression algorithms, 2 hours of HDTV will require somewhere around 15 GB. An erasable disk with a capacity of 30 GB or more would be able to record more than 4 hours with HDTV quality and more than 12 hours with standard definition TV quality. Industry representatives believe that these capacity points will be long-lived standards with wide acceptance for both consumer and computer applications. Both phase change and magneto-optic technology should be able to achieve capacities of 30 GB or more on a 12 cm disk.




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## BEYOND VIDEO DISKS AND BEYOND 100 GB PER DISK

Although video disks will not need to require capacities much beyond 30 GB, most people believe that future computer applications will continue to utilize as much capacity as can be made available at a reasonable price. Furthermore, video disks have only modest requirements for transfer rate (under about 5 MB per second). But, in the year 2005, desktop computers will be expecting transfer rates of 40-80 MB per second, and backbone networks will be operating at better than 1 GB per second.

Neither phase change or magneto-optic technologies are likely to extend their capacities beyond 100 GB per disk (Fig. 6.2<sup>p96</sup>). Neither is likely to achieve transfer rates in excess of 40 MB per second without using parallel optical pickups at significantly higher drive costs.

For capacities well above 100 GB on a 12 cm disk, one must look for an optical technology that utilizes the volume of the disk and not just the surface. There are two candidates currently in the research community: two photon and holographic. Whereas phase change materials may be possible with sufficient transparency to allow for 2-4 layers, two photon materials are completely transparent except at the intersection of two light beams. Thus, hundreds or maybe thousands of layers are possible. Capacities could be more than 1 TB per disk. Holographic recording also utilizes the volume. Light is imaged coherently by the selected hologram and incoherently by all of the others. It could also achieve more than 1 TB per disk. The key issue for both is the development of suitable materials. For commercial applications, an erasable material is preferred. However, a very inexpensive write-once material could also be a commercial success. The WTEC panelists saw little work on either of these technologies in Japan. Most of the work is in the United States.

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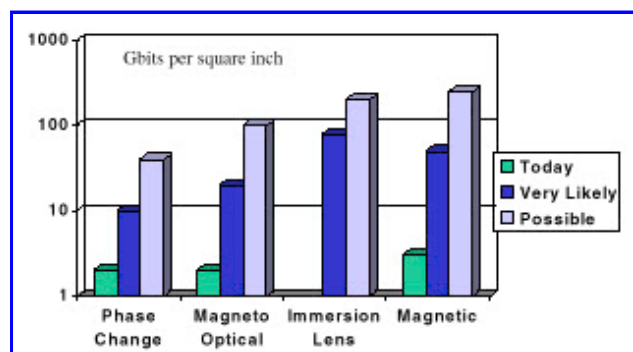


Fig. 6.2. Areal density vs. technology.

Probe storage is another new technology that is being pursued by many companies in Japan and a few companies and universities in the United States. The panel saw programs at Cannon, Toshiba, Hitachi, Matsushita and others in Japan. Carnegie Mellon University, IBM and HP have programs in the United States. Probe storage offers the potential of really high areal densities, perhaps as high as 10 Tb/in<sup>2</sup>. In addition, it also holds the promise of small size devices that will operate at low power. Representatives of several companies mentioned that they see probe storage for portable applications such as camcorders. Chapter 7 of this report covers some of these longer-term options in more detail.



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## 7: Introduction

# CHAPTER 7

## ALTERNATIVE STORAGE TECHNOLOGIES

**Sadik Esener<sup>p5</sup>** and **Mark Kryder<sup>p6</sup>**

## INTRODUCTION

Over the last decade, areal storage densities of secondary storage systems have increased by at least 2 orders of magnitude due to the insatiable thirst exhibited by computing applications for higher capacity, faster access, higher data transfer rate and very low cost data storage systems. This extraordinary increase in areal data densities has been primarily achieved by decreasing the bit dimensions further and further. For high-performance systems, areal density remains the critical factor because mechanical and electrical constraints dictate that low cost, fast and accurate data

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sensing can only be achieved over short distances.

A key unknown for the future of the data storage business over the next decade is how far the applications pull will increase the areal densities. If the application pull continues, an equally important issue is whether reducing the bit size of conventional storage systems will remain the economically viable solution to increase areal densities or whether new technologies will be needed.

From the previous chapters, it has become clear that the areal density of conventional data storage systems will encounter certain physical or engineering limits within the next decade. For example, the diffraction limit of light puts a limit on the practical spot size in optical disc systems; the thermo-magnetic limit sets up a maximum areal density for longitudinal magnetic recording used in present-day hard drives.

In view of these limits it is expected that new, more unconventional technological solutions may become necessary. These solutions may entail the further increase of the areal density by surpassing the presently perceived limits, using, for example, near-field optics or perpendicular magnetic recording. The solutions may also take advantage of additional available degrees of freedom such as those provided by volumetric storage techniques. For example, holographic and two-photon optical storage approaches enable data to be recorded in the volume of a medium rather than just its surface, thereby achieving much greater volumetric densities and data locality.

The solutions may also be derived from significantly different technology platforms that may lead to new types of data storage systems. For example, micro-electro mechanical systems (MEMS) technology can enable probe storage techniques to achieve 100X better areal densities than those projected for conventional technologies. In a more distant future, biologically inspired nano-structures may be envisioned to play important roles in storage systems as well. Finally, solutions may result from indirect impact of new technology platforms. For example, the advent of low cost vertical cavity surface emitting laser arrays and of micro-mechanical actuators may significantly affect the cost and design of pick-up heads enabling fast access parallel recording and readout.

This chapter will review the possible evolution paths for alternative data storage technologies over the second part of the next decade. Along with this review we will attempt to address issues critical for devising a long term strategy for U.S. data storage systems and related component manufacturers including the following:

- emerging applications that cannot be addressed with conventional storage technologies, with the potential of opening up new markets and initiating new profitable business areas
- relative strengths and weaknesses of new emerging technology platforms with respect to emerging applications
- relative strengths and emphasis placed by the United States and Japanese R&D institutions in developing alternative storage technologies



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## LONG RANGE APPLICATIONS PULL

### LONG RANGE APPLICATIONS PULL

In addition to the required capacity, applications of secondary data storage systems can be broadly characterized in terms of required access time, data transfer rates, and allowed volume and power dissipation. For example, most general computing applications, such as transaction processing, require both fast access and data rate and are well served by hard disk drives. The hard disk industry has increased the capacity of non-removable disk drives every year to satisfy the demands of the PC industry. Unless major changes occur over the next decade in the personal computer market, present application pull is expected to continue both in terms of capacity and access time requirements. Most people believe that future computer applications will continue to utilize as much capacity as can be made available at a reasonable price.

On the other hand image file storage (still images as well as video) applications require very low cost, high capacity storage media combined with fast data transfer rates. These applications are less sensitive to access times. Presently, removable storage devices including "digital versatile disks" satisfy these requirements and serve this category of applications.

In contrast to non-removable systems, for removable storage, yearly increases in performance are not necessarily desirable. This is because removable storage is tightly coupled with standards that are established for compatibility purposes. Removable storage manufacturers offer a capacity entry point that is usable for the desired applications. As indicated in Fig. 7.1<sup>p98</sup>, during the next decade it is expected that video applications will drive the removable storage consumer market. HDTV quality video disks, depending on the compression algorithms, will require about 15 GB for 2 hours of video. An erasable disk with a capacity of 36 GB or more would be able to store more than 4 hours with HDTV quality and more than 12 hours with standard definition TV quality and could be used as video-tape replacement. With upcoming personal level consumer applications such as video-mail, 3D video and server applications including electronic medicine and electronic digital libraries, removable storage applications could use capacities exceeding a terabyte per platter. Typically this class of applications will require about 1 Gb/s data transfer rates but moderate access times.

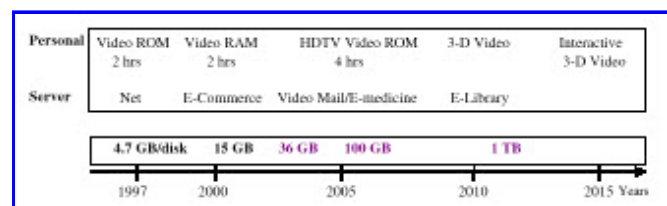


Fig. 7.1. Potential evolution of application requirements for removable storage.

A third category of applications concerns portable and handheld devices that place more importance on volume and power dissipation considerations. Typical applications include compact storage

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systems for camcorders, personal digital assistants and communicators. Within the next decade, these applications will require about 50 GB capacity and reasonably fast access times (microseconds) and transfer rates (100 Mb/s) within very small volumes with power dissipations not exceeding a few milliwatts. Miniaturized disk drives, solid state disks or probe storage may serve this category of applications in the future.

It was the strong belief of this panel's Japanese hosts in general that the performance of data storage systems during the next decade will not be limited by a lack of applications pull but will rather be constrained by the capabilities of technologies in hand.

In the previous chapter, projections were made for areal densities that could be possible with more conventional technologies. As can be seen from Fig. 7.2<sup>p99</sup>, it will be increasingly difficult to exceed 100 Gb/in<sup>2</sup> or 100 GB/disk (12 cm diameter) with conventional techniques. Based on roadmaps derived from the panel's visit in Japan, presented in earlier chapters, a window of opportunity is expected to open by 2005 for alternative storage technologies. Thus, it is important to study the potential performance characteristics of new emerging technologies and understand their application potentials.

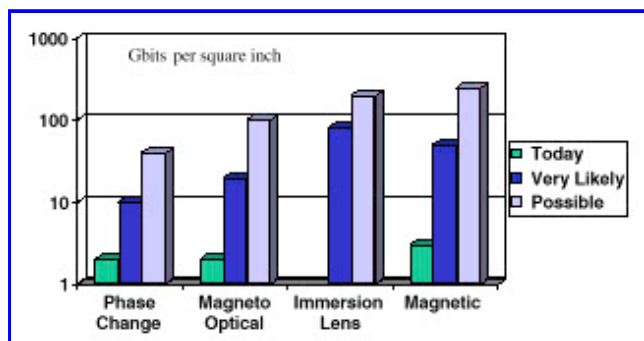


Fig. 7.2. Estimates for possible areal densities that may be reached by various conventional techniques.



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## LONG TERM TECHNOLOGY PUSH

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## LONG TERM TECHNOLOGY PUSH

New approaches to storage can be classified in terms of the degrees of freedom they utilize as shown in Fig. 7.3<sup>p100</sup>. One possible degree of freedom that is being considered for future data storage

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systems is recording multiple values per spot. A typical method that uses this degree of freedom is pit depth recording. Assuming a material that provides 16 distinct pit depths and enough signal separation for detection, this approach may result in a 4x improvement in areal density over conventional methods. However, the dynamic range available from the storage materials limits the impact of this approach.

A powerful direction for increasing the areal density that has driven progress in data storage traditionally is to decrease the bit size. Storage technologies that record and read from the surface of a medium are constrained to this degree of freedom. These technologies include magnetic, near-field optics, and probe storage. Depending on the technology in hand, bit sizes can be reduced significantly, providing a potential for up to 1000x improvement over conventional approaches. However, reliability, servo systems and mostly cost issues may impose practical engineering limits in the future.

In addition, optics can be used to record and retrieve information from the volume of a transparent storage medium. This is an important degree of freedom for optical storage if it can be harnessed at low cost. Although multi-layer phase change disks have been demonstrated and produced (2 layers), and methods are being investigated for magneto-optics to take advantage of this degree of freedom, this approach is not truly scalable for conventional optical storage media. Indeed, optical power considerations as well as aberrations and interlayer crosstalk limit the scalability in the third dimension to less than 16 layers in conventional optical storage. However, two methods--two-photon recording and holographic storage--promise to fully exploit this degree of freedom by providing potential areal densities in the order of Tb/in<sup>2</sup> and possibly at low costs. Currently, suitable materials and peripheral optoelectronic devices are still in development.

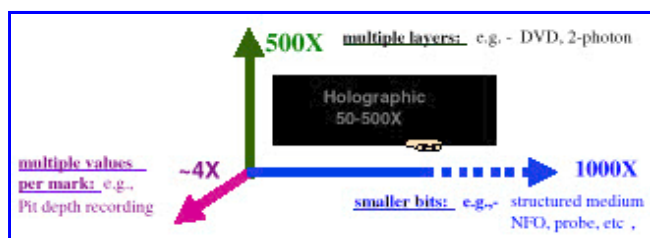


Fig. 7.3. New degrees of freedom in data storage.

Finally, the advances made in optoelectronic device arrays and MEMS may enable data to be accessed in parallel. This may lead to a significant increase in data transfer rates enabling applications such as content addressed data mining to become practical.

## Advanced Magnetic Storage

As noted earlier in the introduction, longitudinal magnetic recording, which has been increased in areal density by approximately 2.5 million times since 1957, is predicted to exhibit superparamagnetic thermal instabilities in the recordings when the density reaches 36 Gb/in<sup>2</sup>, which is less than one order of magnitude higher than the areal density on current disk drives. Some of the Japanese researchers the WTEC team visited predicted that conventional longitudinal magnetic recording may be limited to even lower densities, such as 20 Gb/in<sup>2</sup>, because of grain size variations in the media. Although a

change in the bit aspect ratio from about 20:1 to the order of 4:1 or 6:1 has been predicted to make it possible to achieve densities of the order of 100 Gbit/in<sup>2</sup>, it is inevitable that the technology must change if the rapid 60% per year increase in areal density, which has been the trend for the past seven years, is to continue to much higher densities.

Various new magnetic storage technologies are being explored to circumvent the barriers that these superparamagnetic effects impose. Alternative magnetic storage technologies that the WTEC team saw being investigated in Japan included perpendicular magnetic recording, thermally or optically assisted magnetic recording and patterned media recording. These technologies, the advantages they may offer and the work being done on them, are discussed in the following sections.

### Perpendicular Magnetic Recording

One possible means of extending magnetic recording density beyond what can be achieved using longitudinal magnetic recording is to use perpendicular magnetic recording. The medium is magnetized perpendicular to the film plane, rather than in the plane.

As a result of the perpendicular orientation of the magnetization in the medium, a recorded transition does not contain large magnetostatic charge as it does in a longitudinal medium. Instead, magnetostatic charge is mostly at the bottom and top surfaces of the medium. Consequently, whereas in longitudinal magnetic recording the demagnetizing fields tend to increase with recording density and reduce the thermal stability of the recordings, in perpendicular magnetic recording the demagnetizing fields tend to decrease with the recording density, possibly enabling higher densities to be recorded, if the code used for recording prevents long strings of zeros (no transitions) from being recorded in the medium.

Moreover, many Japanese researchers argue that thicker media may be used in perpendicular magnetic recording. Since grains typically extend through the medium thickness, by using a thicker medium, the grain volume, and therefore the stability of the medium against superparamagnetism, is enhanced.

Finally, with perpendicular magnetic recording, it is, in principle, possible to fabricate the medium on a high permeability magnetic underlayer. This causes an image of the main pole of the recording head to be formed in the underlayer, so that the medium is effectively in the gap of the head. Whereas with conventional longitudinal magnetic recording, the recording is done with the fringing field from the head, with perpendicular recording using a high permeability magnetic underlayer, the perpendicular medium is effectively placed in the gap of the head. This enables much higher write fields from the recording head, which in turn enable much higher anisotropy (and therefore more thermally stable) magnetic materials to be recorded.

Exactly how large the advantage of perpendicular recording is with regard to extending the recording density beyond what can be achieved with longitudinal recording is not yet clear; however, most researchers do admit that it probably does offer some advantage. Although U.S. companies worked on perpendicular magnetic recording in the early 1980s, there has not been much activity since; whereas in Japan there has been a continuous effort since the late 1970s, and it is clear that the Japanese are considerably more knowledgeable about the technology than U.S. researchers in the field. Thus, the

U.S. magnetic disk drive industry is at some risk with regard to finding itself behind its Japanese competitors if a switch to perpendicular magnetic recording comes when the superparamagnetic limits of longitudinal recording have been reached.

### Thermally Assisted Magnetic Recording

As noted in the introduction, superparamagnetic thermal instability occurs in a medium when the magnetic anisotropy energy  $K_U V$  of a grain of the medium becomes sufficiently small that thermal energy  $K_B T$  may cause the magnetization to switch. Hence, to increase the thermal stability of the medium, it is necessary to increase the magnetic anisotropy energy density  $K_U$ . However, if the magnetic anisotropy becomes too large, it may become impossible to produce the field necessary to record on the medium with available magnetic recording head materials.

One way to overcome this barrier is to use thermally assisted magnetic recording.

Heating a magnetic material generally causes the magnetic anisotropy energy density  $K_U$  to decrease. Hence, the idea of thermally assisted magnetic recording is to use thermal energy to lower the  $K_U$  of a medium sufficiently that it may be written with available magnetic recording head materials and then to cool the medium back to ambient conditions, so that the thermal stability of the large  $K_U$  material is achieved.

Continuously exchange coupled perpendicularly oriented magnetic media like that used for magneto-optic recording may be written in this manner, and recent work has shown that domains as small as 20 nm are stable for times in excess of 10 years in such media.

Thermally assisted magnetic recording is commonly used in magneto-optic recording, where a focused laser beam is used to heat the medium; however, magneto-optic recording uses the Kerr (or Faraday) magneto-optic effects for readout of the recorded information. Since the magneto-optic effects are relatively small, it is difficult to achieve high signal-to-noise ratio when reading out by this technique, and the bandwidth of magneto-optic disk drives is typically restricted to smaller values than magnetic disk drives.

It was suggested by Dr. Miura of Fujitsu Laboratories (during his presentation to WTEC of the research being carried out by the Storage Research Consortium and ASET) that an approach using optically assisted writing and magnetic readout may have merit to overcome both of these limitations.

### Patterned Media Magnetic Recording

Yet another method of overcoming the barrier to increasing the areal density of magnetic recording imposed by superparamagnetic effects is to use patterned or structured media.

In conventional magnetic recording, to achieve an acceptable signal-to-noise ratio, it is necessary that there be of the order of 100 grains in the volume of a bit cell. This is because the transitions tend to follow the grain boundaries, and therefore have a significant variance in their position relative to

where they were intended to be written. By making the grain size smaller with respect to the bit cell dimensions, the variance is reduced.

The idea of patterned or structured media recording is to pattern or structure the media in such a way that the medium consists of small islands of magnetic material in a regular array on a planar surface, presumably with small variance in the location of the bit cells. Ideally, for a rotating disk medium the array would be circumferential, which would be difficult to produce except lithographically, but other symmetries are possible, and self structured arrays are an alternative. Advocates of this approach argue that, in such a structure, it would be possible to have the entire bit cell be magnetically coupled or even a single grain. Thus, a 100-fold increase in areal density could be achieved before superparamagnetic effects set in. Assuming a density of 100 Gb/in<sup>2</sup> is possible with longitudinal or perpendicular magnetic recording, this suggests that densities approaching 10 Tb/in<sup>2</sup> could be achieved in patterned or structured media recording. If achievable in practical devices, this would enable several orders of magnitude density gain and a couple more decades of growth in the areal density of magnetic storage.

Although there was some mention of patterned media recording by some of the companies the WTEC team visited in Japan, panelists were not shown any work on it.

## Probe Storage

One of the novel optical storage technologies that may have a major impact in the next millennium is probe storage (Fig. 7.4<sup>103</sup>). A large majority of the Japanese companies visited were investing significant R&D efforts towards developing practical probe storage systems. This area is also actively investigated in U.S. institutions.

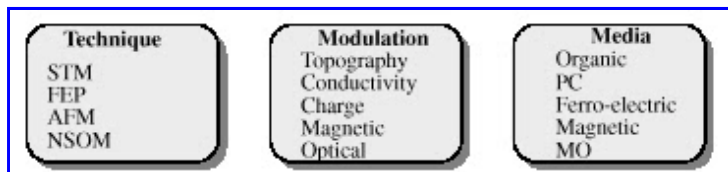


Fig. 7.4. Probe storage: a combination of sensing and modulation techniques that can be used with a variety of media for ultra high areal densities.

Probe storage techniques can generally be broken down into those that use a scanning tunneling microscope (STM), field emission probe (FEP), an atomic force microscope (AFM), and near field scanning optical microscope (NSOM). These techniques can employ a variety of modulation techniques including topographic (mechanical), charge, magnetic, conductivity and optical modulation. They have been used and demonstrated with a large variety of materials including organic, ferro-electric, magneto-optic, magnetic and phase change media.

The scanning tunneling microscope takes advantage of the tunneling current that occurs across the gap between two conductors when they are held very close together (on the order of angstroms) (Eigler and Schweizer 1990). With current flow, atoms may be deposited onto a substrate. With an STM it is actually possible to manipulate a single atom, making the approach the highest density storage device

demonstrated to date. However, most engineering efforts today concentrate on larger bit sizes (i.e., 10-20 nm size bits, giving a data density of over 1 Tb/in<sup>2</sup>).

The main drawback to the STM is its slow data rate. Although individual bits may be recorded and read very quickly (using a voltage pulse of less than a nanosecond), the scanning of the STM probe is very slow. The height of the probe tip must be held very constant or else it will lose the tunneling current or crash into the substrate. Therefore scanning speeds are limited by the servo actuating speeds. Data rates as fast as 100 kb/s have been demonstrated (Mamin et. al 1995).

Materials have been developed for read/write/erase applications using STM which undergo phase change (which changes their electrical conductivity); however, these materials may suffer from fatigue and slow recording times (Sato and Tsukamoto 1993).

The atomic force microscope employs a cantilevered tip that is scanned across a sample. In this case the tip is usually in contact with the sample surface. Features on the surface of the sample cause deflections of the tip that can be detected optically by monitoring the back surface of the tip with a laser and split photodiode detector.

Write once read only memory (WORM) writing with an AFM may be achieved using a thermo-mechanical process. The position of the AFM tip is placed concurrent with the focal point of a laser. When a pulse is sent out from the laser it locally heats the area around the tip causing the tip to sink into the polymer substrate creating a pit. Using this technique, pits as small as 100 nm have been recorded giving a recording density of roughly 30 Gb/in<sup>2</sup>. The recording speed for that experiment was 200 kb/s and readout was up to 1.25 Mb/s.

It may also be possible to produce inexpensive ROM replicas readable by an AFM. Disc "masters" have been fabricated using e-beam lithography (Terris et al. 1996). The masters have then been used to replicate data in a photo-polymer. Features as small as 50 nm have been successfully replicated.

Read/write/erase AFM storage has been done in a number of different materials including charge trapping materials such as nitride-oxide-semiconductor (NOS) layers (Fujiwara, Kojima and Seto 1996) and also phase change materials the same those being used in optical discs (Kado and Tohda 1995). The smallest bits that have been recorded are on the order of 75 nm giving a recording density of over 100 Gb/in<sup>2</sup>. Readout rates of 30 kb/s have been achieved, but predicted rates of up to 10 Mb/s may be possible.

The major obstacle for AFM storage is tip wear. The tip is slowly worn down as it drags across the sample, reducing the resolution of the readout.

Near-field optical recording includes any technology that allows one to surpass the areal density limit imposed by the diffraction of light in optical data storage. Near field scanning optical microscopy (NSOM) combats the effects of diffraction on the optical spot size by placing the pick up heads very near (about 50 nm above) the media. A near-field probe can produce spots as small as 40 nm in diameter and conceptually can achieve areal densities in the order of 100 Gb/in<sup>2</sup>. The problem is that the probe must be near contact with the medium, making it difficult to prevent head crashes and

support removable media.

One of the original near-field recording techniques was through the use of a tapered fiber (Betzig et al. 1992). The tip of a fiber, which is smaller than the wavelength of the recording light, is positioned within 10 nm of the sample. Using magneto-optic materials, bits as small as 60 nm have been recorded and read out. The tapered fiber approach suffers from very low optical efficiency.

STM, AFM and NSOM can all provide ultra high areal densities. However, the total area available for storage restricts the capacity per device (chip). Assuming a scan area of  $1\text{cm}^2$ , 30 nm effective spot size yields a total capacity of 10 GB only. Yet using parallel access and MEMS technology, relatively fast access can be achieved. Considering the low power nature of these approaches, we expect this type of probe storage to have a potential market for applications that require portability.

Perhaps a more scalable approach, in terms of capacity per device, is the use of a solid immersion lens (SIL) (Terris et. al 1994; Terris, Mamin and Rugar 1996; Ichimura, Hayashi and Kino 1997). The SIL reduces the actual spot size by both refracting the rays at the sphere surface and by having an increased index of refraction (up to  $n = 2$ ) within the lens. However, this small spot size can only exist within the SIL; therefore, the evanescent wave from the bottom surface of the lens must be used for recording. This means that the SIL must be held within 100 nm or less of the recording surface. Maintaining such a distance over a rapidly spinning disc is possible using a technique borrowed from hard disk storage: the flying head. The flying head floats on a cushion of air above the disc and is able to hold the head in very close proximity to the disc without crashing. SILs have been fabricated with equivalent numerical aperture of up to 1.8. Using 780 nm wavelength, recording spot sizes on the order of 320 nm have been achieved, giving recording densities on the order of  $3\text{ Gb/in}^2$ . Using the flying head, data rates of up to 3 Mb/s were achieved, and data rates of up to 15 Mb/s may be possible.

During the WTEC panel's visit to Japan, panelists saw significant progress in various areas of probe storage. This includes hybrid STM/AFM systems, automated Langmuir-Blodgett film deposition systems, new organic polymers (Fig. 7.5<sup>p105</sup>), record breaking small recorded spots (Fig. 7.6<sup>p106</sup> and Fig. 7.7<sup>p106</sup>), and probe fabrication techniques (Fig. 7.8<sup>p106</sup>) that can lead to low cost manufacturable systems. Dr. Ohta at Matsushita perhaps best underlined the expectations of Japanese researchers in probe storage by stating that, "phase change media welcomes probe storage."

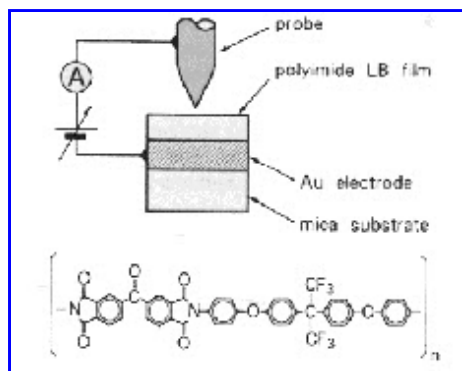


Fig. 7.5. Recording by STM/AFM probe in organic LB films (Yano et al. 1996).

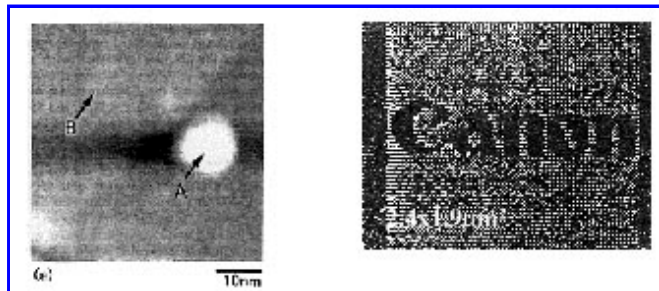


Fig. 7.6. Probe storage at Canon: (a) record breaking spot sizes were achieved using organic LB films over an area as large as 4 micron square (Yano et al. 1996).

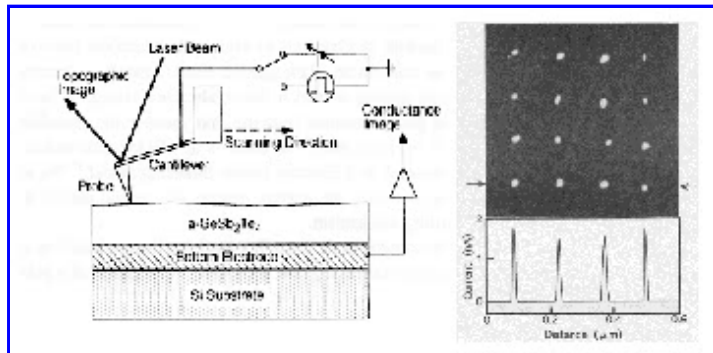


Fig. 7.7. Probe storage at Matsushita: record breaking erasable spots of 10 nm diameter have been recorded in phase change media using STM (Kado and Tohda 1995).

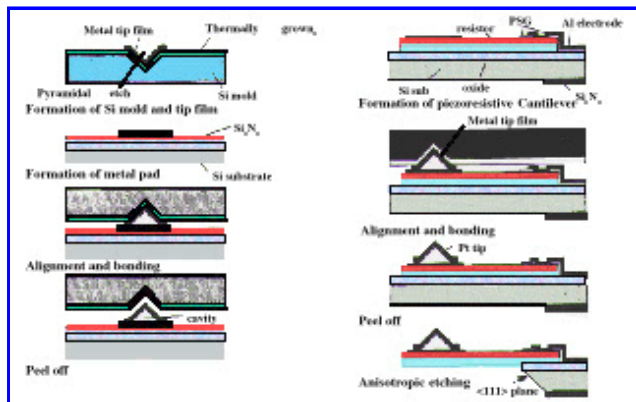


Fig. 7.8. Manufacturing process for low-cost fabrication of probe tips and their integration with the actuators (Yagi et al. 1997).

Research work in the United States is equally active with IBM's efforts in atom herding and thermo-mechanical recording depicted in Fig. 7.9p<sup>107</sup> (Terris et al. 1996). Most of the work in the United States emphasizes demonstration of parallel access probe storage techniques using FEP techniques (e.g., work carried out at Hewlett Packard) as well as MEMS techniques that utilize phase change, ferro-electric and magnetic media (e.g., work carried out at Cornell (Miller, Turner and MacDonald 1997) and Carnegie Mellon).

Near field optical storage using the SIL techniques is being investigated both in Japan and in the United States. Terastor, a start-up company in the United States, is working towards

commercialization of a magneto-optic disk system that utilizes an SIL lens. Several Japanese drive manufacturers are involved with Terastor's activities and are pursuing separate R&D efforts as well. Institutions involved in this direction include NAIR, Hitachi, Fujitsu, and Toshiba.

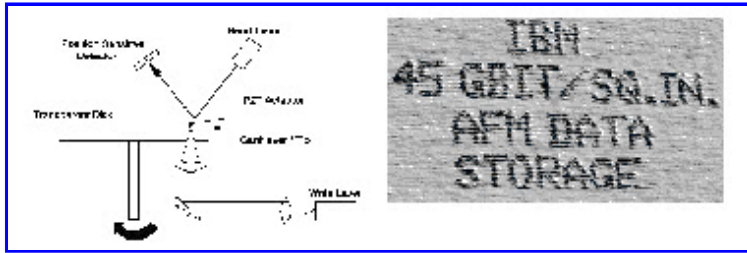


Fig. 7.9. Thermo-mechanical recording at IBM using rotating plastic disk using an atomic force microscope tip. At selected locations, electrical current was pulsed through the tip causing the tip to be heated. The heat from the tip softens the substrate and the pressure from the tip causes an indentation to be formed. Marks smaller than 0.1 micron can be written in this manner (Mamin et al. 1995).

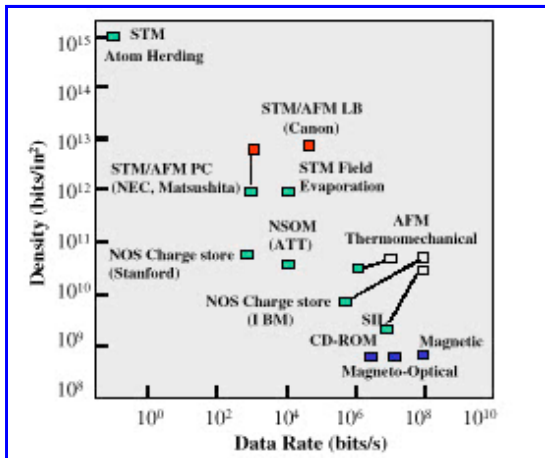


Fig. 7.10. Classification and demonstrated performance of probe storage and comparison with present storage techniques. Recent results from Canon and Matsushita have been added to the figure (Modified after IBM) (Mamin et al. 1995).

## The Third Dimension in Optical Storage

Several approaches to 3D optical storage are being actively investigated both in the United States and Japan. These include the extension of present disk systems based on PC and MO media to a layered format, and 3D layered disk systems recorded by two photon absorption and read by fluorescence and volume holographic storage, where data are recorded in a distributed fashion in the volume. In addition, more futuristic approaches are being investigated to utilize the wavelength as the third dimension.

### Multi-Layer Recording

Layered 3D optical storage is a natural extension of present optical disk systems with a potential to increase the media capacity without significantly affecting the cost of the drives. In this case, the volumetric density ( $\text{Mb/in}^3$ ) rather than the areal density is the relevant figure of merit. However, in order to be able to compare layered disks with conventional disks we will use the effective areal density as the figure of merit. This figure corresponds to the number of bits that can be accessed from one side of a disk divided by the top surface area of the disk. This figure must, however, be used with caution and should be applied to volumetric disks with thickness not significantly larger than conventional disks.

Multi-layer recording extends the effective areal recording density and capacity per disk. It therefore enables the penetration of new markets with technologies in hand and eliminates pick-up head duplication. Since data can be made more local to the pick-up head a larger amount of data can be accessed faster. In addition, when the number of layers can be made large, as in the case of two-photon recording, the approach can relax constraints in other dimensions, providing significant cost saving. For example, for larger effective areal density, a multi-layer disk system may use larger spot size and use low cost, lower numerical aperture optics and servo systems.

However, there are also limitations to the third dimension. These include higher optical power requirements depending on the transparency of the material, dealing with aberrations and inter-layer crosstalk while imaging through the volume, extra costs associated with focusing and tracking in three dimensions, and smaller signal levels requiring more complex signal processing and error correction schemes.

### Multi Layer Phase Change

In the United States, IBM researchers have shown that the addressing of four to 16 active layers with a single optical head is possible. The number of layers were clearly limited by interlayer crosstalk considerations and the capabilities of the dynamic focusing lens addressing the data in the third dimension. In IBM experiments, several conventional CD-ROM disks were stacked together, each with one active layer.

During discussions with Matsushita representatives, the WTEC panelists learned that a four-layer DVD RAM is also possible by using more transparent recording layers in PC medium. The panelists also noted Hitachi's roadmap for PC disks shown in Fig. 7.11<sup>p108</sup> (Asthana 1994). Chapter 1 of this report covers multi-layer DVD-RAM approaches. Thus the panel expects to see over the next few years two and four layer DVD-RAM systems. However, most researchers believe that a practical limit to the maximum number of layers in PC media would perhaps be 8 layers considering recording power requirements and crosstalk limitations.

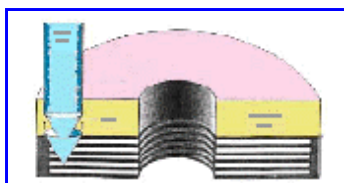


Fig. 7.11. Multi-layer optical disk stack (IBM).

## Multi-Layer MO

The success of double layer DVD-ROM has attracted interest in whether it is possible to use multiple layers with the MO media. A possible approach is shown in Fig. 7.12<sup>p109</sup> (Nakagawa et al. 1997). The disk medium consists of two active TbFeCo MO layers, one modified by the presence of an additional PtCo layer. Thus the characteristics of the two recording layers are slightly different in terms of required power and wavelength. This difference is exploited by wavelength selective thermo-magnetic recording to selectively record onto each layer using two different lasers of different wavelengths. During readout the effect of the two layers on the polarization state of the readout beam is additive on the polarization state of a read-out beam. However, since the total Kerr rotation angle of two reflected waves of two different wavelengths is dependent on the linear combination of the retardation imposed by each layer, by detecting each wave independently it is possible to calculate the state of the recorded bits in each layer. This requires the solution of a linear system of two equations with two unknowns (the bit states) in real time, a rather straightforward operation with present capabilities of electronics.

It is possible in theory to extend this approach to more than two layers using more than two wavelengths. However, the number of lasers, optical components and receiver circuits as well as the head mass grow with growing number of layers. Nevertheless, this approach can significantly benefit from technologies being developed for wavelength division multiplexing (WDM) communication over fiber optic networks and may fuel their manufacturability further. This type of forward-looking R&D in Japan demonstrates the importance attributed to multi-layer recording approaches.

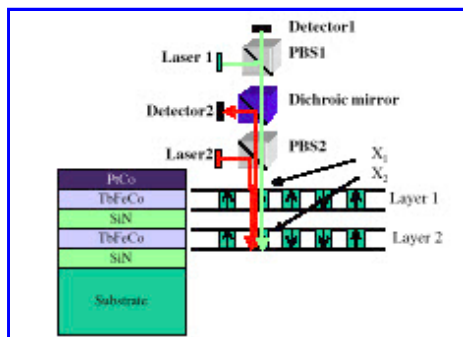


Fig. 7.12. University of Tokyo and Hitachi Maxell Ltd.'s approach to double layer MO disk recording and readout.

## Two-Photon Recording: Extending Multi-Layer Recording to More than a Hundred Layers

The two-photon recording approach used by Call/Recall, Inc. in the United States relies on recording bits in a volume by using two-photon absorption (Hunter et al. 1990). As described in Fig. 7.13<sup>p110</sup>, a spot is written in the volume of a molded organic polymer only in locations where two beams with sufficient photon energies, one carrying the information and the other specifying the location, intersect temporally and spatially. The recorded bits are then read by fluorescence when excited by single photons absorbed within the written spot volume.

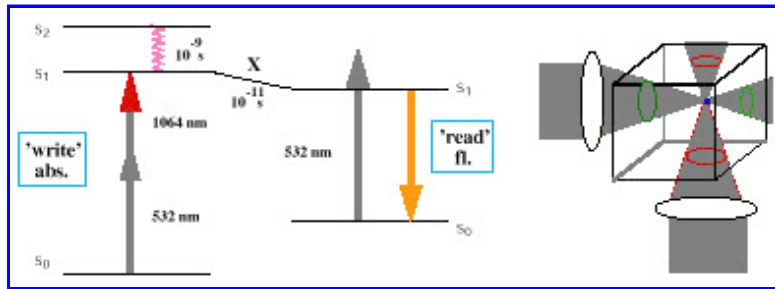


Fig. 7.13. Principle of two-photon recording in 3D (Call/Recall, Inc.).

Using this method, multiple layer ROM disk recording, and readout with a portable unit, have been demonstrated as shown in Fig. 7.14<sup>p110</sup>. The results indicate no crosstalk between layers spaced as close as 30  $\mu\text{m}$  and excellent stability of the written bits at room temperature. The spot size is limited by the recording wavelengths through diffraction as well as by the sensitivity and integration time of the read-out detector used. The approach promises low cost, ultra high effective areal density (1-100 Tb/in<sup>2</sup>) removable disk media with thousands of layers for image and video applications. In addition to the extremely large volumetric densities achievable with this monolithic 3D disk approach, the stored data can be accessed in parallel leading to high data transfer rates suitable for content-based search operations.

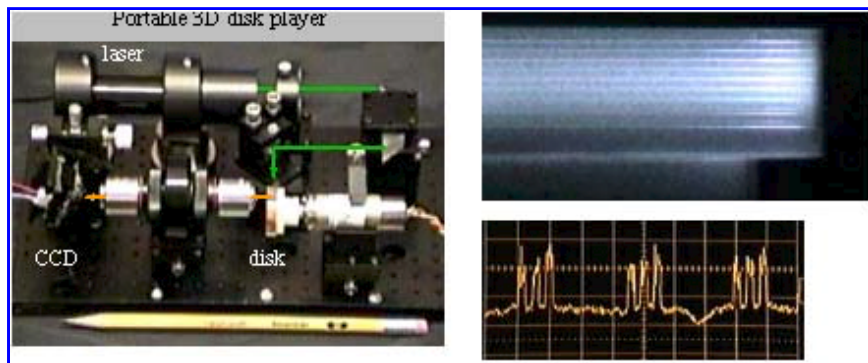


Fig. 7.14. Multi-layer 3D ROM disk reader on the left; side view of a disk showing many recorded layers; and the oscilloscope trace related to detected bit stream with the disk rotating at 5,000 rpm (Call/Recall, Inc.).

However, several issues remain to be resolved. So far only small (1.5 inch diameter) disks have been demonstrated. Although insensitive to media shrinkage, the approach is affected by surface quality and volumetric homogeneity of the media. The cost of short pulse-high intensity lasers required for two-photon recording is still too high to consider their use in a consumer product. Finally, materials capable of writing and erasing without fatigue are yet to be demonstrated for addressing a larger span of applications.

The potential impact of layered 3D optical disks on the capacity per disk can be much greater than the impact of, for example, blue lasers. This is because the capacity is directly proportional to the number of layers. Assuming relaxed areal densities, 3D disks provide the potential for realizing disks with 100 GB to 1 TB capacities before 2005 as shown in Fig. 7.15<sup>p111</sup>. In addition to Call/Recall, Inc., two-photon recording is also being investigated at the Jet Propulsion Laboratory in the United States

and at Osaka University in Japan (Toriumi, Hermann and Kawata 1997). At this point in time, two-photon recording appears to be a potential contender for future removable ultra-high capacity optical disk storage.

### Holographic Storage

In bit-oriented memories if any portion of the storage media is damaged or blocked, the data stored in that region is lost. This is not the case for holographic storage, where the information about each stored bit is distributed throughout a large region. If a portion of the holographic storage media is damaged or blocked, instead of causing catastrophic loss of some of the data, all of the data are partially degraded. For common types of damage, such as surface dust or smudges, holograms are remarkably robust. This has generated interest in holographic data storage, and despite the more complex optical systems, high cost media, and sources with good spatial coherence required, there has been continued research in the field since the early 1960s (Solymar and Cooke 1981).

Holograms are created by recording the interference pattern of two optical wavefronts. The storage media can record the fringes as index and/or amplitude modulation. When the recording is illuminated by one of the wavefronts (the reference beam), the other wavefront (the object beam) is reproduced.

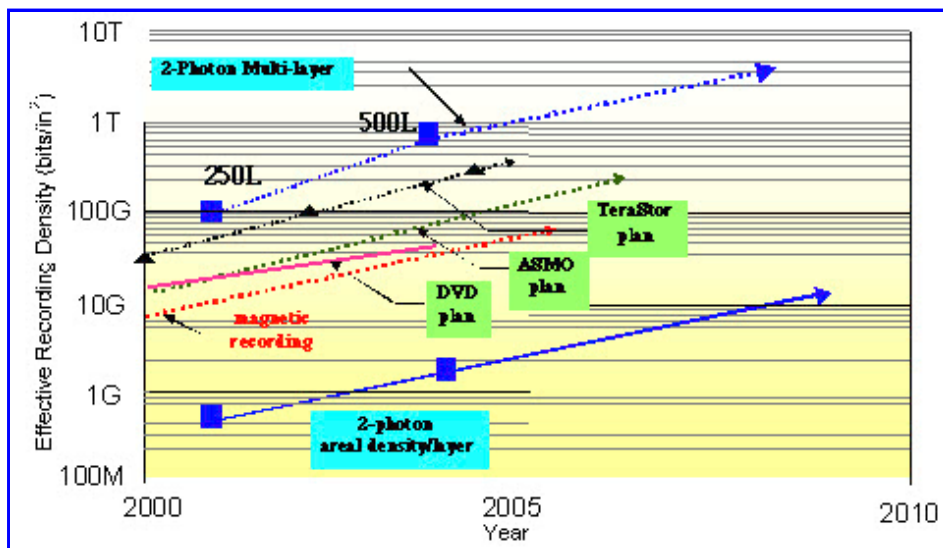


Fig. 7.15. Potential impact of 3D multi-layer optical storage and its comparison with conventional data storage and new emerging techniques such as SIL (compiled from data obtained from TeraStor Web site, OITDA storage roadmap and Call/Recall, Inc. internal reports).

Since the diffraction efficiency of amplitude holograms is limited to 6-7%, and the efficiency of volume amplitude holograms is limited to 33%, volume phase holograms with their diffraction efficiency approaching 100% are best suited for storage applications. In addition, the Bragg selectivity of volume holograms allows the volume multiplexing (by angle or wavelength or combination) of many pages of data with small crosstalk between the pages.

Photorefractive crystals (PRC) and photo-polymers are typically used in demonstration experiments both for non-moving and volumetric disk type applications. These materials are recorded at room

temperature, and the inorganic PRCs offer high photocyclicity. Using PRCs, 10,000 images were successfully stored and retrieved (Mok and Stoll 1992). More recently, hero experiments have demonstrated effective areal densities in excess of 64 Gb/in<sup>2</sup>.

The main drawback of the approach with PRCs is the high cost of materials, the decrease in diffraction efficiency with increasing number of multiplexed holograms and read-out cycles, and the relatively small and slow changes in the index of refraction. To circumvent these problems, significant progress has been made in terms of using recording schedules to improve the uniformity of the recorded data, fixing procedures to permanently store data in PRCs, and new recording geometries to minimize crosstalk. In addition, more recently, photorefractive polymers that exhibit large index of refraction changes under very large electric fields have been demonstrated.

Holographic storage as a read only archival memory can also use polymers such as those available from DuPont and Polaroid. In this case, the shrinkage of the polymer after recording and over time results in a shift in readout wavelength, as well as in increased crosstalk and loss of resolution. Very recently encouraging results on reduced shrinkage materials have been announced.

Holographic storage allows for massively parallel read-write operations. To take advantage of this capability, researchers are considering the potential benefits of using holographic storage as a means for fast access storage using non-moving media. In this case, holographic storage may compete with DRAM banks, solid state disks and probe storage to fill the "access time gap" that exists between the primary and secondary storage. Also for this type of application, in the United States a new start-up company, Templex Technology Inc., is investigating the potentials of using optical beam to record and read "persistent spectral hole burning" materials using the wavelength as the third dimension (see for example <http://www.templex.com><sup>68</sup>). Because of the very low temperatures required for this technology, interest in Japan in PSHB only exists within certain university research groups.

Most of the above mentioned progress in holographic storage has been achieved in the United States where the National Storage Industry Consortium carries out a research program with the participation of several U.S. corporations and universities to develop holographic storage media and systems. Key players in the United States include Holoplex, Inc., Optitek Corp., IBM, Rockwell International, Lucent, and Polaroid.

In Japan there is a lesser degree of interest in holographic storage although several university laboratories, NAIR and NTT are involved with it at the fundamental research level. Several Japanese managers remain skeptical, however, about the practicality of the approach.

## Parallel Access

With the strong demand for capacity for removable systems comes an equally strong demand for high data rates. This demand originates from the wish to quickly transfer large image and video files to direct memory and from the desire to perform fast content based search and image processing with this type of file. The conventional method to increase data rates in a disk system is to increase the rotation speed and to increase the linear bit density. Present rotation speeds are already high and are limited by media integrity and servo speeds. The linear density increases as the square root of the

areal density and therefore falls short of satisfying the emerging needs of content-based database search.

Based on progress made in different areas of optoelectronics, newer technologies exploiting the parallel access capabilities of optical storage are emerging to satisfy these new requirements. In Japan, short term and long term approaches to parallel data access on optical disks are under investigation. For example, Fujitsu is investigating the use of laser and detector arrays to access data in parallel from an MO disk as shown in Fig. 7.16<sup>p113</sup>.

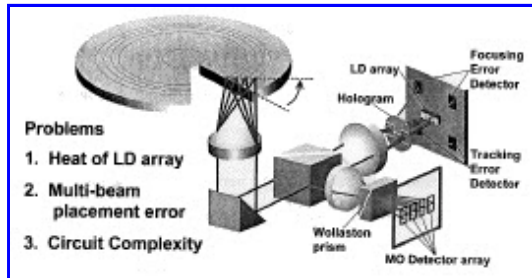


Fig. 7.16. Multi-beam optical head investigated at Fujitsu.

Issues including heat extraction from laser diode arrays, multi-beam positioning errors, packaging and signal processing circuit complexity for post processing are being investigated.

A more futuristic approach being explored at the University of Tokai by Prof. Goto and his group is shown in Fig. 7.17<sup>p113</sup>. This approach involves the use of VCSEL arrays flying directly above an optical disk medium using a near field geometry. The laser is used to both record and directly detect the presence of a bit based on the optical signal that is fed back into the laser. In order to achieve high data rates, massively parallel access through VCSEL array is contemplated as described in Fig. 7.18<sup>p114</sup>.

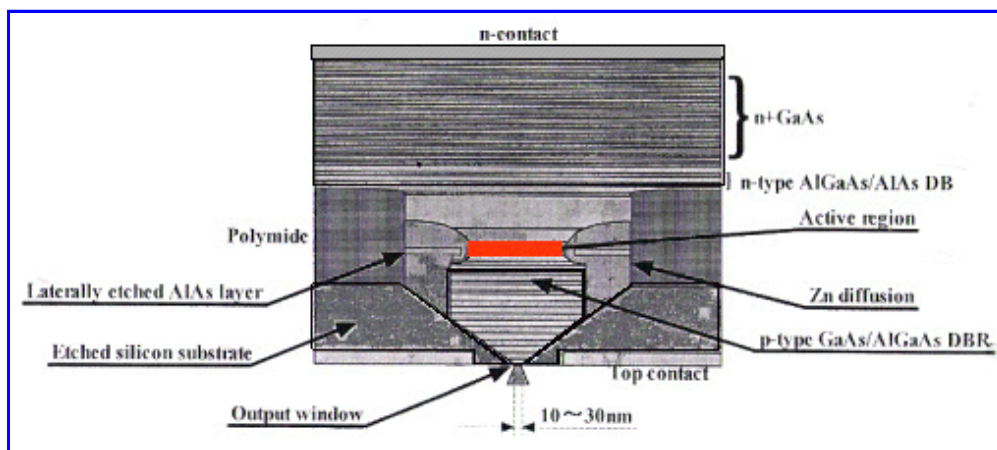


Fig. 7.17. Use of a VCSEL for recording and readout in a near field optics geometry.

In the United States, Quinta, Inc., recently acquired by Seagate, Inc., a manufacturer of magnetic hard drives, has been developing a method to access several optical disk surfaces in parallel using optical fibers. The fibers are used for distributing the laser power to the head and back to the receivers for

readout, and a novel optoelectronic switch is used to selectively access data on various plates. Also in the United States, Call/Recall, Inc., jointly with Hewlett Packard Company and Optical Micro Machines, is investigating the use of VCSEL arrays and MEMS to facilitate parallel access to multi-layer disks. In addition, R&D on massively parallel accessing of holographic data storage systems is also underway as described earlier.

It is believed that parallel access is a viable method to increase the data transfer rate of optical and probe storage systems. The issue is rather when the necessary components that can enable massively parallel data transfer may provide a favorable cost entry point to market such systems.

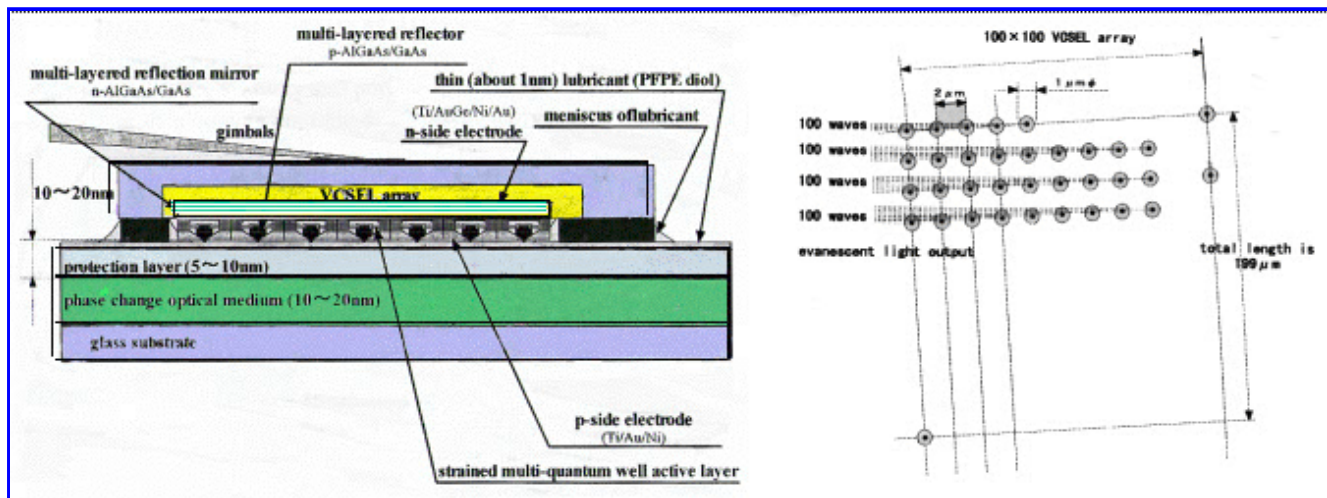


Fig. 7.18. Schematic of a VCSEL array access with a massively parallel near field optics architecture to optical disks promising TB capacities and Tb/s data transfer.

## Mastering and Replication Technologies

One of the key areas in optical data storage for ROM type applications is the high fidelity replication process. In this area of R&D significant investments are being made by Japan's key CD-ROM and DVD-ROM manufacturers. The mastering effort ranges development of SIL lenses and large area electron beam lithography to the development of ultra short wavelength lasers and probe mastering techniques. Supporting technologies including high precision injection molding and ultra smooth polishing techniques are being developed as well. A potential roadmap derived from OITDA's roadmap for mastering and replication is shown in Fig. 7.19<sup>p115</sup>. At this point in time, we do not know of a development effort of this magnitude in this area in the United States.

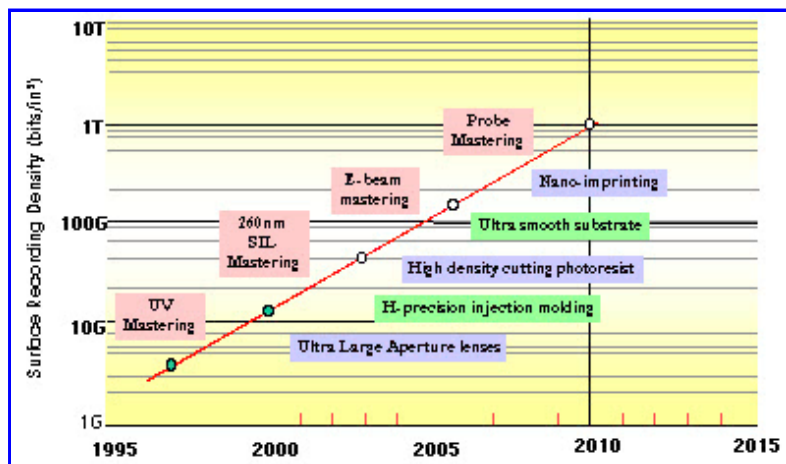


Fig. 7.19. Roadmap for mastering and replication (compiled based on data available from OITDA, discussions during Sony site visit and various private discussions).



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[http://itri.loyola.edu/hdmem/07\\_03.htm](http://itri.loyola.edu/hdmem/07_03.htm)

## TECHNOLOGY COMPARISON

### TECHNOLOGY COMPARISON

From the above discussion, it is clear that significant R&D activity is in place both in the United States and Japan to develop alternative storage techniques to address windows of opportunity that may present themselves in the second part of the next decade as shown in Fig. 7.20<sup>116</sup>.

At this point it appears that magnetic perpendicular recording and structured media are well placed to take hard disk drives well into the next decade, satisfying general purpose computing requirements. It is possible that with these technologies 200 GB capacity hard disk drives will be available within the next decade.

In terms of replacing conventional removable optical disk storage for video-type applications, the United States seems to put more emphasis in its R&D effort into SIL lens approaches with Terastor and into true volumetric storage development with holographic storage and two-photon recording technologies. Most Japanese effort in this area seems to be focused on improving conventional optical disk technologies where the Japanese have a strong lead. Both countries are investigating the merits of thermo-mechanical recording on moving polymer disks, perhaps for mastering purposes.

Both countries seem to be pursuing parallel accessing techniques for optical storage, relying on progress made in optoelectronic array devices as well as MEMS actuators.

[http://itri.loyola.edu/hdmem/07\\_04.htm](http://itri.loyola.edu/hdmem/07_04.htm)

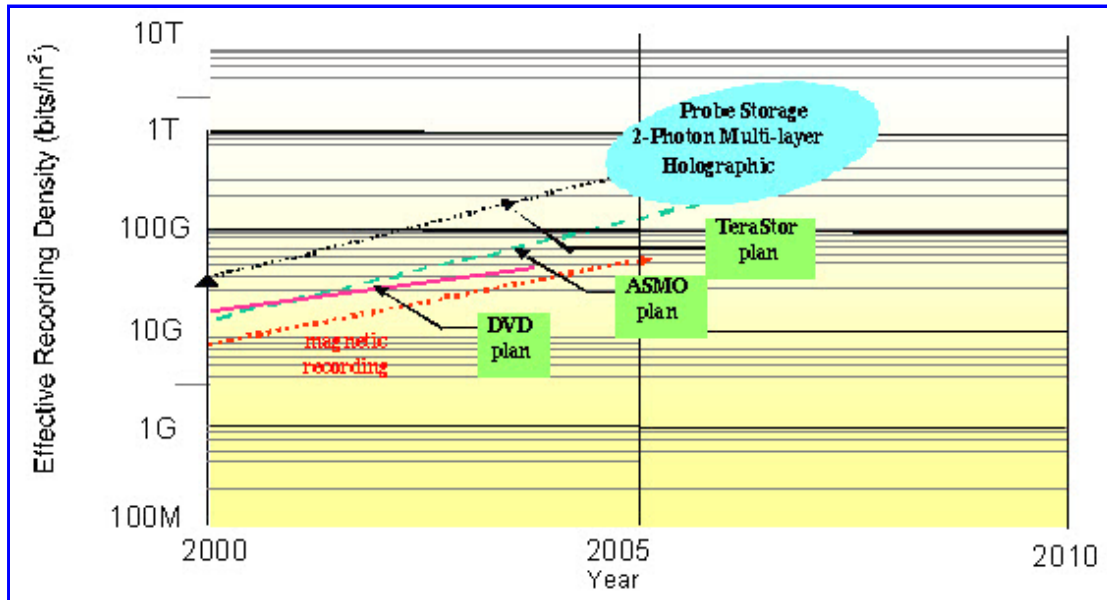


Fig. 7.20. Possible roadmap for alternative technologies (derived from various data obtained from TeraStor Web site, OITDA storage roadmap, private communications with Holoplex researchers and Call/Recall, Inc. internal reports).

Both Japan and the United States are strongly involved in the development of various probe storage techniques. The Japanese effort seems to lead in materials and system development. The United States seems to have a slight lead in terms of development of parallel access probe storage, possibly because of its present lead in MEMS development. Fig. 7.21<sup>p116</sup> shows the possible evolution of storage capacities in several systems. Unlike in the United States, metrology and mastering technology is an area of high investment in Japan with significant ongoing research in large area e-beam, deep UV laser development, and probe mastering.

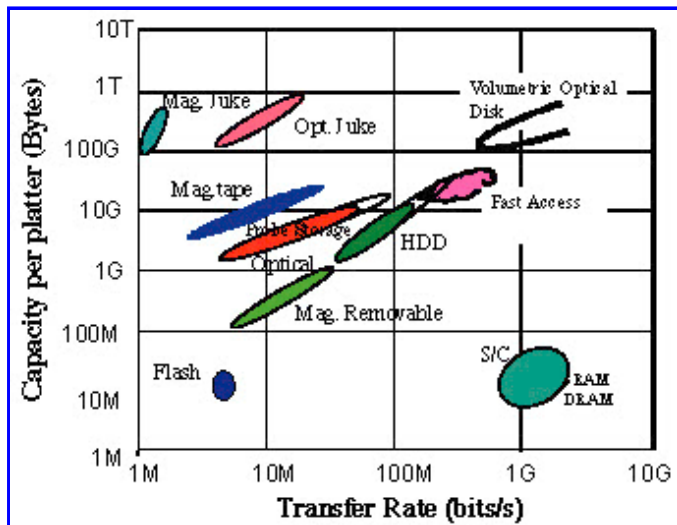


Fig. 7.21. Potential evolution of capacity vs. transfer rate and comparison with conventional techniques (Call/Recall 1997 storage survey).



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[http://itri.loyola.edu/hdmem/07\\_04.htm](http://itri.loyola.edu/hdmem/07_04.htm)

## CONCLUSION

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## CONCLUSION

As described in Table 7.1<sup>117</sup>, several emerging technologies are well placed to capture new markets from conventional storage technologies by the second half of the next decade.

Table 7.1  
Emerging Technologies and Applications

| Technology                      | Applications                | Performance                   |
|---------------------------------|-----------------------------|-------------------------------|
| Structured magnetic media       | General purpose, computing  | 200 GB, ms access             |
| SIL lens near-field MO disks    |                             |                               |
| Volumetric disks                | Advanced video, removable   | 200 GB-1 TB, 1 Gb/s data rate |
| Thermo-mechanical probe (disks) | Mastering                   | 1 TB and more, Mb/s data rate |
| Probe storage (chips)           | Portable video applications | 10 GB, ms access, 100 Mb/s    |

For the longer term and significant gain in market share, removable volumetric parallel accessible storage systems such as holographic and/or two-photon approaches appear attractive. The key issue for holographic storage is the development of an inexpensive, reliable write-once material. Two-photon recording can benefit from the development of a higher sensitivity write-once material and preferably from an erasable material. These technologies are especially important since they can drive the low-cost manufacturing of optoelectronic and MEMS device arrays that can be critical for many other applications areas.

Probe storage is clearly an important area for future investment, particularly for very small or very low power storage devices. It has the potential of capturing a new market segment, that of portable digital video equipment.

[http://itri.loyola.edu/hdmem/07\\_05.htm](http://itri.loyola.edu/hdmem/07_05.htm)

## CONCLUSION

Japan seems to be clearly ahead in developing metrology, mastering and replication technologies. The United States must invest in these critical areas since they serve many other manufacturing areas as well.

Micro-machining can find a high-volume application in the disk drive industry and probe storage. The United States has a slight lead in research, but a high-volume application and the investment it draws could quickly evaporate that lead. Japan can easily take the lead in micro-machining away from the United States with its process development strength.



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[http://itri.loyola.edu/hdmem/07\\_05.htm](http://itri.loyola.edu/hdmem/07_05.htm)

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[http://itri.loyola.edu/hdmem/07\\_06.htm](http://itri.loyola.edu/hdmem/07_06.htm)

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## APPENDICES

### APPENDIX B. PROFESSIONAL EXPERIENCE OF OTHER TEAM MEMBERS

**Name: Ms. Stella Lin**

Address: P.O. Box 11082  
Arlington, VA 22102

Ms. Lin is an associate of EnSTec Consulting Services, Inc. She speaks fluent Japanese, Chinese, Taiwanese and Spanish. She has an MS degree in accounting and extensive experience as a financial specialist. She is skilled at handling logistics and business transactions, developing briefing materials, and facilitating travel arrangements and appointments.

**Name: Christopher McClintick**

Address: ITRI/WTEC  
Ocher House  
Loyola College  
4501 N. Charles St.  
Baltimore, MD 21210

Dr. Christopher McClintick is Head of Publications for ITRI/WTEC. He is responsible for editing and preparing reports for publication and develops policy analysis on selected studies. Dr. McClintick also teaches in Loyola College's Department of Modern Languages and Literatures.

Dr. McClintick has been a writer and editor for weekly and daily newspapers, a legislative assistant to former Speaker of the U.S. House of Representatives Thomas S. Foley, and has taught at Vanderbilt University, where he received his PhD. He was awarded BA and MA degrees from Whitman College and the University of Washington, respectively.

**Name: Mr. Hiroshi Morishita**

Address: HMI Corporation  
Matsudo Paresu 1002  
35-2 Koyama  
Matsudo 271, JAPAN

Hiroshi Morishita, President, HMI Corporation, specializes in ultra-micro manipulation technology for MEMS (microelectromechanical systems). He founded HMI Corporation in 1991 to commercialize his ultra-micro manipulator system. He extended his interest and business to the field

of archaeological excavating and to the new robot manipulator system to help bed-ridden persons. In 1994, he became a consultant to WTEC panel members concerning their study tours in Japan. He graduated from the University of Tokyo (BA, MA, mechanical engineering), and is in the final stage of preparing his doctoral thesis. He was a visiting researcher in the Mechanical Engineering Department in 1992 and 1993 and at RCAST (the Research Center for Advanced Science and Technology) at the University of Tokyo in 1994 and 1995.

**Name: Kent B. Rochford**

Address: National Institute of Standards and Technology  
Optoelectronics Division, M/S 815  
325 Broadway  
Boulder, CO 80303-3328

Kent Rochford received his PhD from the Optical Sciences Center at the University of Arizona in 1990. He is Project Leader of the Fiber Optics Sensors Project in NIST's Optoelectronics Division. His research at NIST has centered on polarimetric optical fiber sensor systems. Dr. Rochford has developed magneto-optic current and field sensors, polarization instrumentation, and led the project's development of a calibration standard for optical retardance. A recent research focus has been the measurement of optical disc substrate birefringence.

**Name: Gerald J. Whitman**

Address: P.O. Box 11082  
Arlington, VA 22102

Mr. Whitman is President of EnSTec Consulting Services, Inc., established to facilitate international cooperation in scientific research, technology development, and environmental conservation. He is an engineer with broad experience in international science, environmental, nuclear energy and space programs. A former Foreign Service officer, he recently returned from Japan, where he served as Minister-Counselor for Environment, Science, and Technology at the U.S. Embassy in Tokyo.




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[http://itri.loyola.edu/hdmem/b\\_01.htm](http://itri.loyola.edu/hdmem/b_01.htm)

**Appendix C.: Canon Research Center**

## APPENDIX C. SITE REPORTS

Site: **Canon Research Center**

[http://itri.loyola.edu/hdmem/c\\_01.htm](http://itri.loyola.edu/hdmem/c_01.htm)

**Advanced MM Device Division**  
**R&D Headquarters**  
**5-1 Morinosato-Wakamiya**  
**Atsugi, Kanagawa 243-01, Japan**  
<http://www.canon.co.jp/75>

Date Visited: 13 March 1998

WTEC: M. Kryder (report author), M. Keshner

Hosts:

- Mr. Kiyoshi Takimoto, General Manager, Advanced MM Device Div.
- Mr. Koji Yano, Advanced MM Device Div.
- H. Yoshida, Manager, Memory Research Department, Memory Research Div., Products Technology Research Center

## BACKGROUND

Canon is a major corporation with over 75,000 employees and sales of over \$22 billion in 1996. Its products include a large number of image-based systems including copiers, facsimile machines, image scanners, projectors, cameras, printers, displays, camcorders, lenses, binoculars, medical imaging systems, and photolithographic systems for the semiconductor industry.

The Canon Research Center carries out projects in biotechnology, optical technology, electron beam technology, advanced materials and nanometer technology.

## DISCUSSION

Mr. Takimoto presented an overview of the work on probe recording technology at the Canon Research Center. He explained that the work on probe recording has been carried out by the groups working on advanced materials and on nanometer technology. There are approximately 10 people from the advanced materials area and 20 from the nanometer technology area who are involved.

The Advanced Materials Group discovered the "switching memory" phenomenon of Langmuir Blodgett (LB) films. LB films are ultra-thin films composed of organic mono-layers on a substrate. Canon researchers found that when electrical current is applied to a certain type of LB film between a gold and aluminum layers, it displays a change in electrical resistance. This work was described in an article by Sakai et al. (1988).

The Nanometer Technology Group is now exploring the use of these LB films as a medium for probe recording using a scanning probe microscope. Researchers showed the WTEC team data indicating that a micromachined Pt-Rh probe could be used to repeatably write 10 nm spots on such media. The write time was quoted as being less than 1 microsecond and the read time as being less than 10

microseconds. The researchers reported that reproducibility of the recording and readback process was greater than 104. Although the LB materials had been shown to be rewritable in a metal/LB/metal configuration, they reported that using the SPM, it was only write once. The researchers were trying to understand the reason they had not been able to achieve rewritability.

They also reported that others had found a similar conductance change phenomenon in GeSbTe thin films, but said that these materials were rougher than the LB films, which had a peak-to-valley roughness of less than 1 nm.

The Canon researchers indicated that they were interested in developing these ultra-high density memory devices for server applications and for use in camcorders, which could record HDTV quality images.

They indicated they were not currently working on near-field optical probe storage, but said they were following the development of that technology.

H. Yoshida also described work on "domain wall displacement detection" (DWDD), which was first presented at the MORIS/ISOM Conference in Yamagata, Japan, Oct. 1997. This technology enables one to read out marks smaller than the diffraction limit of optical resolution from a magneto-optical disk, and appears to be a very promising technology for extending the density of magneto-optical recording technology. This work was done at the Products Technology Research Center, rather than the Canon Research Center.

## LAB TOUR

Canon researchers took the WTEC team to the laboratory where they showed an LB film coating apparatus of a very clever design and on which they could continuously coat A4 size sheets. They asserted this was the only system that could do continuous coating.

The researchers then exhibited the playback of an array of 10 nm sized spots recorded on their media. They also showed panel members SEM images of a probe array containing eight Pt probe tips. They had developed a very repeatable process for making the probes, which were very clean in appearance. In operation these probes were run in contact with the media, but the load was very light and there was no detectable wear of either the medium or the probe itself.

## SUMMARY

Canon has about 30 people working on MEMS-based probe recording on a Langmuir-Blodgett film. The researchers are able to selectively write 10 nm sized spots in arrays and play them back very repeatably. They appear to have excellent MEMS processing capabilities and have also developed a continuous coating apparatus for Langmuir-Blodgett films. Canon researchers have interest in applying these very advanced storage technologies to video cameras and server applications. Currently the technology is write-once, but they are working to make it rewritable.

In the Products Technology Research Center, Canon also has an active research group working on magneto-optical recording. Recently this group reported on a new method of high-density recording called "domain wall displacement detection." This technology appears to be very promising for achieving densities beyond the diffraction limit and appears competitive with the best of the magnetic super resolution techniques.

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Site: **Fujitsu Ltd.**  
**Fujitsu Laboratories, Ltd.**  
**(HDD presentations)**  
**10-1 Morinosato-wakamiya, Atsugi**  
**Kanagawa 243-01, Japan**  
<http://www.fujitsu.co.jp/index-e.html><sup>76</sup>

Date Visited: 11 March 1998

WTEC:

- D. Thompson (report author)
- W. Doyle
- M. Kryder
- C. McClintick
- G. Whitman

Hosts:

- Dr. Koichi Ogawa, General Manager, Optical Disk Products
- Dr. Yoshimasa Miura, General Manager, Technology Research
- Dr. Takashi Uchiyama, General Manager, M Project Group
- Mr. Yukihiro Uematsu, Director, File Memory Laboratory File Technology Division, Storage Products Group
- Dr. Mitsumasa Oshiki, Dir., Magnetic Disk Laboratory, Peripheral Systems Laboratory
- Dr. Kazuo Kobayashi, Research Fellow, Peripheral Systems Laboratories

## BACKGROUND

Fujitsu Limited is an electronics and computer powerhouse, with over \$35 billion in annual sales. Two thirds of that is in information processing. Fujitsu's storage device sales total about \$2.2 billion annually, including hard disk drives (HDDs), magneto-optical drives and libraries, and tape drives. Fujitsu's HDD market share has been increasing. It could exceed 10% this year, with a production rate of about 1.5 million drives per month.

Fujitsu Laboratories has about 1,500 employees. Within that organization, the Peripheral Systems Lab contains the Magnetic Disks Lab at Atsugi, the Optical Disk Media Lab at Akashi, and the M Project Group (MO drive) at Akashi. In the Storage Products Group, the File Memory Lab has about 60 people. Many of these transferred from Fujitsu Laboratories a few years ago in order to accelerate the conversion to magnetoresistive (MR) and spin valve heads and disks. In addition, the research group is in the process of restaffing its hard disk projects.

In the current struggle between MO and phase change optical technologies, Fujitsu is a champion for magneto-optics.

## DISCUSSION

After an introduction by Dr. Ogawa, and a storage business plan presentation by Dr. Miura, the panel heard Mr. Uematsu present Fujitsu's HDD technology roadmap. In response to the panel's interest in the application of perpendicular recording to actual products, the members saw previously unpublished photographs of a 1.8 inch prototype drive intended for a PCMCIA slot in a laptop computer. This work was performed circa 1992 at 200 Mb/in<sup>2</sup>, and used a Censtor-style in-contact inductive head. It had a steel case for magnetic shielding, and had full LSI inside the enclosure. The WTEC panel had numerous questions about outgassing, magnetic shielding, popcorn noise in the head and soft underlayer, frictional effects on the tracking servo, and so forth. The project was abandoned for business reasons (the 1.8 inch market never materialized), and because the technical problems were not entirely solved.

Fujitsu's technology roadmap for longitudinal recording projected the following growth curve:

|      |                        |
|------|------------------------|
| 1998 | 3.6 Gb/in <sup>2</sup> |
| 1999 | 6.2                    |
| 2000 | 10                     |
| 2001 | 15                     |
| 2002 | 25                     |

The bit cell aspect ratio during this period evolves from about 20x today to about 10x by 2002. A switch to perpendicular recording is considered unlikely before the end of this period. Along the way, the head will evolve from a conventional spin valve, which the company was scheduled to ship in 1998, to an adjacent soft layer spin valve called BCL-type in the year 2001, and possibly a spin tunneling head by 2003. Fujitsu managers expect CoCrPtTa alloys to suffice for the media through 2001, then expect to use a CoPt-SiO<sub>2</sub> granular composite longitudinal medium with a soft keeper.

The Fujitsu hosts expect the media grain size to go from 13 nm at the time of this visit at 2 Gb/in<sup>2</sup> to 11 nm at 40 Gb/in<sup>2</sup>. This deviation from simple scaling is driven by the superparamagnetic effect, and is accompanied by a major decrease in the grain size standard deviation. Even with this improvement, however, the media signal-to-noise ratio at 40 Gb/in<sup>2</sup> would be expected to be much below today's levels, and to be a challenge to the channel and ECC people. The panel did not hear about coding or ECC, but Fujitsu's roadmap shows decision feedback equalization by the year 2000, and a new technique being sought for the year 2004.

The trend towards lower bit cell ratio will accelerate the need for precision and bandwidth in the actuators. Fujitsu anticipates an evolution that includes piggyback actuators by the year 2000. The company's present design, a magnetic actuator in the middle of the suspension, achieves a 3.3 kHz bandwidth, 0.27 ms settling time, and a 500 G shock resistance. Fujitsu managers estimate a \$2 to \$3 additional cost per head for this design, but feel that a \$1 cost is necessary for future success. For this

reason, they expect piezoelectric or MEMS designs to ultimately prevail. They discussed a conceptual design from UC Berkeley of a rotary electrostatic MEMS actuator mounted at the slider/suspension interface. This design would possess a half micron stroke for 50 volt excitation, but Fujitsu's design goal is one micron stroke and a reduced voltage. And, of course, the device must have enhanced shock resistance and a \$1 cost.

Another aspect of high track densities that Fujitsu researchers are studying is the problem of servo pattern accuracy for sector servo drives. Rather than dealing with timing jitter and erase band size, they have chosen to pursue a photolithographic patterned media technique that they call ESPAR. This involves pre-etching the (silicon) substrate before depositing a 75 nm CoCrPtTa magnetic servo layer. This is then lapped flat, and the data layer of 17 nm is deposited.

WTEC panelists were excited by this display of high track density technology, and asked if this might accelerate the trend towards a ratio of linear to track density of less than 10:1. The answer was that confidence in the data rate capability, as well as an extrapolated linear density of 630 kb/in at 40 Gb/in<sup>2</sup> at a magnetic spacing of 20 nm (to mid-plane of the storage layer), and an expected shield-to-shield spacing in spin valve sensors of only 90 nm, all lead Fujitsu managers to believe that advances in linear density will keep pace with advances in track density, at least until 40 Gb/in<sup>2</sup> is reached.

Fujitsu researchers do not favor load/unload technology, and therefore need an anti-stiction technique for very flat sliders and disks. This is accomplished by a patterned slider having four very small (0.09 mm<sup>2</sup> area) pads and by using only 2 nm of lubricant. On a very smooth disk, this results in an order of magnitude decrease in stiction force.

Dr. Kobayashi gave a fascinating presentation on his spin tunneling sensors. These could replace spin valves by as early as 2003. His junctions use permalloy magnetic layers, faced with 3.3 nm of Co, a dielectric gap of about 1.3 nm of Al-Al<sub>2</sub>O<sub>3</sub>, and the necessary bias and pinning layers. He achieves up to 24% MR ratio with either natural oxidation or plasma oxidation in oxygen of the aluminum, but the required time drops from 500 hours to 60 seconds. There is also an unusual behavior after annealing of his tunnel junction samples, which contain an NiMn pinning layer. The MR ratio of the junction increases with annealing temperatures up to 300°C, where the 24% value is observed. Other issues being pursued with these junctions are the high impedance for very small devices, and the voltage dependence of the MR ratio. Future work will examine half-metallic ferromagnets to increase spin polarization, and double barrier resonant tunneling.

Dr. Oshiki showed the panel an interesting experimental project on spin polarized scanning tunneling microscopy. The basic physics involves polarized photo emission of electrons from single crystal cleaved GaAs tips, using circularly polarized light to stimulate the emission. Previous work has required a transparent subject, since transmitted light was used to stimulate electrons polarized perpendicularly to the surface of the sample. This new technique uses illumination from the side, and can therefore be used with metallic samples. Preliminary data show about a 10% contrast for domains in an NiFe sample. In addition to microscopy, this technique could be used for data readout--if were not for the fact that it requires UHV conditions and a half-day bake-out to get a clean enough tip for operation.

The final presentation of the HDD portion of the program was a talk by Dr. Oshiki on the merits of grazing angle X-ray reflectivity apparatus for analysis of spin valve layered structures. Compared to ordinary X-ray fluorescence, the technique is more sensitive and more accurate. Fujitsu is working with an equipment manufacturer to make such a tool commercially, for the purpose of calibrating production XRF equipment on a more frequent and convenient basis. Comments at lunch included the general feeling at Fujitsu that holographic memory was not practical with present media (the company abandoned it about five years ago); that the probe storage group favored a multiplexed tip approach (Fujitsu already had four tips working simultaneously); and that multilayer optical media were a better approach to volumetric storage than either holography or ultra-high density surface recording methods.

## LAB TOURS

The WTEC team toured the periphery of several clean rooms containing systems for advanced materials research in both media and head materials. Fujitsu has produced experimental media ranging from conventional alloys to ultra-high energy  $\text{Sm}_2\text{Co}_{17}$  and  $\text{Sm}_2\text{Fe}_{12}$  that no conventional head could write. Experimental head materials for advanced spin valves and tunnel junctions are also produced in those laboratories. The team saw an extensive characterization and analysis area, including glancing angle X-ray equipment and a marvelous transmission electron microscope (TEM) adapted for sensitive magnetic imaging.

## SUMMARY

Fujitsu is actively pursuing high-density HDD technology, magneto-optical storage, and probe storage. The company is well connected with ASET and SRC, and has leading-edge efforts in all three areas.




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[http://itri.loyola.edu/hdmem/c\\_02.htm](http://itri.loyola.edu/hdmem/c_02.htm)

p.c28 {font-family: Times; font-size: 60%} sup.c27 {font-family: Times; font-size: 80%} div.c26 {text-align: center} li.c25 {font-family: Times; font-size: 60%} span.c24 {font-family: Times; font-size: 60%} p.c23 {font-weight: bold}

**Site: Fujitsu Ltd.  
Fujitsu Laboratories Ltd.  
(optical storage presentations)  
Peripheral Systems Lab., Atsugi Facilities**

[http://itri.loyola.edu/hdmem/c\\_03.htm](http://itri.loyola.edu/hdmem/c_03.htm)

**10-1 Morinosato-wakamiya, Atsugi**  
**Kanagawa 243-01, Japan**  
<http://www.fujitsu.co.jp/index-e.html><sup>76</sup>

Date Visited: 11 March 1998

WTEC:

- S. Esener (report author)
- W. Doyle
- M. Keshner
- M. Kryder
- M. Mansuripur
- D. Thompson

Hosts:

- Dr. Seiya Ogawa, Sr. Vice President and General Mgr., Peripheral Systems Laboratories
- Dr. Yoshimasa Miura, General Manager, Technology Research
- Dr. Koichi Ogawa, General Manager, Optical Disk Product, Storage Product Group
- Dr. Takashi Uchiyama, General Manager, M Project Group
- Dr. Mitsumasa Oshiki, Dir., Magnetic Disk Laboratory, Peripheral Systems Laboratory
- Dr. Keiji Shono, Director, Optical Disk Medial Lab.
- Mr. Yukihiro Uematsu, Director, File Memory Laboratory File Technology Division, Storage Products Group
- Mr. Tetsuo Koezuka, Senior Researcher, M Project Group
- Dr. Kazuo Kobayashi, Research Fellow, Peripheral Systems Laboratories

## BACKGROUND

Fujitsu, Ltd. was established in 1935. It employs 46,795 employees in Japan and 165,056 worldwide. Its capitalization is about two billion dollars, and consolidated sales in 1996 exceeded \$35 billion. Main product categories include computer and information processing systems (66%), telecommunication systems (19%), electronic devices (11.4%) and other operations (3.6%).

Fujitsu Laboratories was created in 1962 through the merger of R&D sections previously managed by separate technical divisions. In 1968, Fujitsu Laboratories, Ltd. was spun off as a wholly owned subsidiary of Fujitsu, Ltd. It has facilities in Kawasaki, Akashi, Atsugi, Numazu, Makuhari, and California. It employs 1,500 employees and is capitalized at \$50 million. In 1993, Fujitsu Laboratories, Ltd. was reorganized by field rather than location and now conducts R&D into core multimedia technologies in a wide range of fields including telecommunications, information processing, multimedia systems and devices, personal systems, semiconductors, peripherals and terminals, and materials. The research is undertaken at the following seven laboratories:

- Multimedia Systems Laboratories: develops information and communications infrastructures and multimedia processing technologies
- Personal Systems Laboratories: develops personal information systems and devices for home and office
- Peripheral Systems Laboratories: develops easy-to-use computer peripherals, as well as reliable sensing and control technologies
- Network Systems Laboratories
- Electron Devices and Materials Laboratories
- Materials and Materials Engineering Laboratories
- System LSI Development Laboratories

There are also a number of project groups working across these boundary lines.

The Peripheral Systems Laboratories develops magnetic and magneto-optical disks, input/output devices (e.g., scanners, plasma display panels, data compression), inspection and manufacturing technologies and mechatronics. The Peripheral Systems Lab employs 250 researchers and another 1,000 employees in Thailand for mass manufacturing. One hundred fifty researchers are involved in MO research.

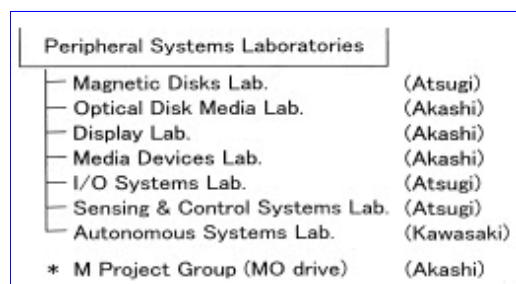


Fig. C.1. Peripheral Systems Laboratories.

Storage systems are being developed jointly at Fujitsu Storage Products Group and Fujitsu Laboratories, Ltd., Peripheral Systems Laboratories, as described in [Table C.1<sup>p130</sup>](#) below.

**Table C.1**  
**Organizational Chart**

| Fujitsu Storage Products Group                                                                                                                                                                                                    | Fujitsu Laboratories, Ltd.                                                                                                                                                                                                      |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• Storage Technology Labs.               <ul style="list-style-type: none"> <li>○ File Memory Lab.</li> <li>○ HDI Eng. Department</li> <li>○ Development Department</li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>• M Project Group</li> <li>• Peripheral Systems Lab.               <ul style="list-style-type: none"> <li>○ Magnetic Disk Lab.</li> <li>○ Optical Disk Media Lab.</li> </ul> </li> </ul> |

- |                                                                                                                                                                                                 |  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
| <ul style="list-style-type: none"> <li>• Storage Component Division</li> <li>• HDD Division</li> <li>• Optical Disk System Division</li> <li>• Int. Eng. &amp; Mfg. Support Division</li> </ul> |  |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|

Fujitsu is concentrating on producing drives; however, it has the capability of producing several thousand media units that are used for testing purposes. The recording media group performs sputtering, R/W testing and other measurements. The substrate group performs mastering, patterned HDD, injection molding and substrate testing.

## DISCUSSION

### Comparison with Other Storage Products

MO appears to be central to Fujitsu, Ltd.'s plans for multimedia storage systems, and management perceives 3.5" magneto-optical disks as "the personal files of the multimedia era." This disk format is expected to carry information from office to home or onto portable PCs and for information sharing. In 1995, the number of drive units (230 MB/disk) shipped reached about 800,000 units/year, roughly a 3x increase from 1992 (128 MB/disk). Present shipments (640 MB/disk) average around 1.5 million units/year and Fujitsu researchers estimate future shipments to exceed 5 million units/year shortly beyond 2000. Indeed, in Japan MO drives have 52% of drive market share for removable media and 32% of users have both MO and CD-R drives. CD-R only (4.8%), PD (3.2%) and Zip (6.3%) have relatively small market shares.

An interesting item that opened the discussions was the difference between the Japanese market and the U.S. market for removable storage where the roles of the Zip drive and MO are reversed. Discussions centered on cost per drive, backward compatibility, time to market, and product quality. Also resistance to foreign products in both countries by end users was brought up among possible reasons.

Dr. Ogawa then compared the performance of MO with HDDs and noted that the performance gap between these two technologies has practically disappeared. Indeed, under certain conditions MO can be faster than HDDs in writing but HDDs have a slight advantage in read operations. The reduction in the gap is attributed to "light intensity modulation and direct over write" (LIMDOW) technique that uses over write and an ultra cache to speed up data transfer rates up to 5 Mb/s (asynch) and 10 Mb/s (synch). With a rotation speed of 4300 rpm typical MO seek times are on the order of 28 ms. This performance is sufficient for MPEG II coded motion picture.

Indeed, Fujitsu managers see the following advantages in MO:

- unrivaled capacity that can be easily scaled up to 18 GB or more (presently 6-7 GB)
- reliability of MO media; claimed better reliability than CD-ROM and PC; MO achieves 10 M RWE operations while PC is 10 K and RW DVD 1 K cycles
- CD/DVD compatibility (r) one medium, many applications
- HDD-like performance (r) possibility for jukebox video server

## Next Generation Products

Next generation 3.5" MO products will have a 1.3 GB capacity and will be followed by 3 GB products. The aim of Fujitsu is to produce one medium for a full hierarchy of personal applications. To this end the company is participating in the Advanced Storage MO (ASMO) Alliance for a 6 GB MO disk for MPEG II motion picture storage that uses DVD format. Fujitsu, Olympus, Sharp, Imation, Sanyo and Hitachi-Maxell are among participants in ASMO. Magnetically-induced super-resolution (MSR), which was proposed some time ago, is one of the key features being used in ASMO. It utilizes the fact that the beam spot is hot in the center and cooler at the periphery. A magnetic film domain is formed on top of the MO recording layer, and operates as a magnetic mask depending on temperature differences. When multiple recording marks are located within a beam spot, a single mark alone can be shown through a "window" in the mask. This prevents interference between read signals. Thus ASMO will provide MO disks offering about 5 Gb/in<sup>2</sup> surface recording density. The standards were decided on in the summer of 1997 and production was scheduled to begin as early as late 1998.

## Aiming at 70 Gb/in<sup>2</sup>

To boost the surface recording density to over 10 Gb/in<sup>2</sup>, however, even MSR is unstable. When the MSR mask is made larger, resolution rises, but at the same time the signal/noise (S/N) ratio degrades. The ratio of light reflected from the mask increases, adding to the noise in the read signal. With a 680 nm laser diode, the top end of surface recording density using MSR is thought to be about 7 Gb/in<sup>2</sup>.

To increase the performance of MO systems Fujitsu counts on progress to be made on three different fronts. On the magnetic front the company is considering the use of magnetically induced super-resolution (MSR), magnetic field modulation, magnetic amplifying magneto-optical system (MAMMOS) from Hitachi-Maxell or domain wall displacement detection (DWDD) from Canon. On the optical side, the use of shorter wavelength laser diodes, larger NA lenses, solid immersion lenses (SIL), and near-field optics are the subject of current studies. Finally, various approaches grouped under multi-value recording are being evaluated. These include multi-edge (SCIPER), multi-layer and parallel recording using multiple wavelengths.

The magnetic amplifying magneto-optical system (MAMMOS) jointly developed by Hitachi Maxell, Ltd and Sanyo Electric Co, Ltd. applies the concepts of MSR in reverse. Instead of masking inside the beam spot, the tiny recording mark in the recording layer is enlarged to read. Because most of the reflected light contains signal, S/N degradation is minimized. With a 680 nm light source it is possible to reach 20 Gb/in<sup>2</sup>, and in the future blue-purple light source could achieve 70 Gb/in<sup>2</sup>. With a surface

recording density of 20 Gb/in<sup>2</sup>, the same 120 mm diameter disk as is currently used for digital video disk (DVD) would hold 30 GB of data per side. This storage capacity is sufficient to hold 10 hours of compressed motion video data, with images of standard television broadcast quality. A capacity of 90 GB would be provided at 60 Gb/in<sup>2</sup>. However, Fujitsu researchers pointed out difficulties associated with production since synchronization with the magnetic field is difficult with the MAMMOS technique. It was suggested that perhaps DWDD technique might be more promising. However, a 30 GB product was suggested as a desirable capacity for video-MO systems for media to be shared between TV and PCs in a post-VCR era. Data transfer rates of 30 Mb/s would be required. A possible roadmap suggested by Dr. Ogawa is provided in Table C.2<sup>p133</sup>.

**Table C.2**  
**Possible Roadmap**

|                                            | Present<br>(1997) | 5 Years<br>(2002)          | 10 Years Later<br>(2007)     |
|--------------------------------------------|-------------------|----------------------------|------------------------------|
| Recording Density<br>(Gb/in <sup>2</sup> ) | 1.17              | 20                         | 200                          |
| Capacity 3.5 inch (GB)                     | 0.64              | 15                         | 150                          |
| 120 mm *GB)                                | 2.6               | 36                         | 360                          |
|                                            | (DVD-RAM)         |                            |                              |
| Transfer Speed (Mb/s)                      | 20                | 50~100                     | 100~300                      |
| Seek Times (ms)                            | 30                | 10~20                      | 5~10                         |
| Optical Systems                            | 680 nm<br>NA 0.55 | 410 nm<br>Large NA<br>lens | 205 nm<br>SIL                |
| Media                                      |                   | Magnetic<br>Expansion      | Multi-value &<br>Multi-layer |

## Video MO

Video MO with 36 GB capacity and 30 Mb/s speed can be used both for TV and PC applications. For PC applications it will hold 5 hours HTTPV, will be capable of multi-TV channel recording or could be used as a personal video server. It would have direct link to peripherals through a IEEE 1394. On the PC side, for content management the video MO would enable easy video stream editing. It would be capable of fast index search, multi-TV channel, summary scene and fast feed playing.

## Speculative Research Directions

It was pointed out that it was the proper time to start research for 0.1-1 Tb/in<sup>2</sup> areal density storage products. For example certain applications such as camcorders require 100 Gb/in<sup>2</sup> densities and at those densities mechanical positioning is crucial. Therefore piezoelectric and MEMS actuators are important directions to look at. Near field optics (NFO) is also a promising direction, and Fujitsu is working with the University of Tokyo for simulation of the physics. More importantly, Fujitsu is pursuing research for parallel addressing of MO drives using VCSEL arrays (Multi Beam Optical Head Project) jointly with Prof. K. Goto's group at Tokai University.

## LAB VISIT

The WTEC team was shown an apparatus that was capable of packaging at high speeds laser diodes and photodetectors with 5 micron and 0.5 $\mu$ m alignment accuracy by using robotic vision techniques. This machine would be capable of producing integrated optical heads and also can be applied to fiber optic products.

## OTHER DISCUSSION

- It was pointed out that PC was challenged at 20 GB per platter and needed blue laser to go beyond 10 Gb/in<sup>2</sup>. However, MO could increase capacity without necessarily relying on new components because of the added degree of freedom that is derived from magnetic control.
- MO drives are cheaper since they require one extra component (for polarization sensing) that costs \$1 extra, while PC requires more laser power for recording, resulting in an increase in cost of \$4.
- Interaction between the HDD and MO communities: Dr. Ogawa pointed out that the two communities learn from each other. These interactions include adoption of filed modulated mag head, front illumination and optical RAID concepts that were borrowed from the HDD community. Removable magnetic disks, pre-grooved media, and laser-assisted magnetic recording may be used in HDDs. In most cases, however, there is a necessity to fuse magnetic and optical techniques. Japanese companies that are producing both HDD and optical products may be at an advantage.



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**Published: June 1999; WTEC Hyper-Librarian<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_03.htm](http://itri.loyola.edu/hdmem/c_03.htm)

Site: **Fuji Electric Co., Ltd.**  
**4-18-1, Tsukana Matsumoto**  
**Nagano 390, Japan**  
<http://www.fujielectric.co.jp/><sup>78</sup>

Date Visited: 13 March 1998

WTEC: W. Doyle (report author)

Hosts:

- Mr. Toshihiko Nakamura, Staff Genl. Mgr., Computer Peripherals & Component Div.
- Dr. Takabumi Fumoto, Peripherals Technical Center, Fremont, CA, Manager, R&D, Disk Group
- Mr. Akihiro Otsuki, Deputy General Manager, R&D, Disk Group
- Mr. H. Yamazaki, Staff General Manager, R&D, Disk Group
- Mr. N. Takahashi, Manager, R&D, Disk Group

## CORPORATE DESCRIPTION

Fuji Electric, a relatively unknown company in the United States, is a worldwide supplier of equipment and components for electronic and power applications. It was the parent of Fujitsu, which was spun-off in the late 1930s. The net revenue in 1997 was \$5.7 billion, generated by 12,900 employees. About 9% is accounted for by the Disk Division located in Matsumoto near Nagano. Disks are produced at Matsumoto, at two factories in Yamanashi near Shirane and at a new site in Malaysia with a total of 19 production lines. The R&D laboratory for storage, located in Matsumoto, has about 100 researchers and participates in the SRC program. A broad product line supplies disks to all major markets.

## OVERVIEW

Fuji Electric is a major supplier of hard disks, with a strong research effort focused on media for 20 Gb/in<sup>2</sup> (SRC) and 40 Gb/in<sup>2</sup> (ASET) demonstrations by 2001. Strong interactive discussions showed that Fuji management clearly recognizes the importance of superparamagnetic effects and is directing a major effort to optimize performance and thermal effects at high density. Fuji managers are also considering potential alternatives such as perpendicular recording, SIL, near-field and MO which they feel will be required beyond 40 Gb/in<sup>2</sup>. No discussion of probe based storage occurred. Fuji Electric is not a producer of optical media.

[http://itri.loyola.edu/hdmem/c\\_04.htm](http://itri.loyola.edu/hdmem/c_04.htm)

W. Doyle gave a 30 minute presentation on high speed switching in thin film media based on his invited paper at the 1998 Joint Conference. Dr. Fumoto gave an extensive review of future storage technologies based on projects in SRC and ASET. Both presentations were highly interactive.

## R&D ACTIVITIES

### Conventional Media (Fumoto)

The widely heralded technology demonstrations by IBM and Fujitsu have been followed in the last few years by products in less than 3 years. Demonstrations of 20-40 Gb/in<sup>2</sup> in 2000 will require new media with higher coercivity, lower noise limit, and no greater sensitivity to thermal decay than today's low  $M_t$  media, which already show severe problems at both short and long times.

In work done in collaboration with J. Judy, University of Minnesota, the recorded signal decay decreased rapidly below a grain size of 10 nm but appeared independent of recording density up to 150 KFCI. CoCrPtTa was found to be superior to CoCrTa, consistent with the higher anisotropy  $K$  in the Pt films. Based on simulation results, a target specification is  $K \cong 2 \times 10^6$  ergs/cc,  $M_s = 460$  emu/cc,  $M_R = 320$  emu/cc, with a grain diameter of 9 nm and a magnetic spacing  $< 15$  nm, which will give a predicted relaxation time of  $10^8$  secs ( $\sim 3$  years). To obtain sufficient SNR, the grain interaction must be reduced which can be correlated to higher  $H_C/H_k$  ratios. The grain size must be reduced and a narrower distribution of grain sizes achieved. Fuji managers believe that an important advance was the reduction of gaseous impurities by two orders of magnitude, which resulted in an increase in HC from 2,200 Oe to 3,000 Oe. Impressive lattice images in (110) CoCrTa on (200) Cr showed tri-crystal symmetry. No specific explanation for the increased coercivity was offered. Results on these materials were published in 1995 and 1996. Some work on granular media showed very high viscosity, which has discouraged further work in this area.

It was suggested that a 20 Gb/in<sup>2</sup> demonstration at slow disk rotation speeds would be announced by a Japanese company in the near future.

### Head Media Interface

Present disks with mechanical/chemical texture and an  $R_a = 1$  nm with a flying height of 16 nm have survived 400 K passes. Future disks will have an  $R_a = 0.3$  nm with a flying height of 10 nm.

### Perpendicular Recording

Simulations predict that the limit set by thermal effects for longitudinal recording will be  $\sim 20$  Gb/in<sup>2</sup> but that the limit for perpendicular may be  $> 40$  Gb/in<sup>2</sup>. However, no indication of a significant perpendicular media program was given and the hosts expressed interest in a collaboration through NSIC. The main problems associated with perpendicular recording, including the absence of an erase

band, increased spacing loss, domain noise in a soft underlayer, and head-induced data erase, were clearly recognized and may explain Fuji's present research posture.

## Future Technologies

An evaluation of possible future technologies including SIL technology (Terastor), optically assisted Winchester (Quinta), near-field MO and MAMMOS (magnetic amplifying magneto-optical system) being considered as future alternatives was presented. The most likely candidate was judged to be MAMMOS, allowing 60 Gb/in<sup>2</sup> on removable media, although the access time would be a problem. No discussion of probe storage occurred.

## CONCLUSION

Fuji Electric is a highly competitive supplier of rigid disks with a clear awareness of the challenges faced by the media at densities >10 Gb/in<sup>2</sup>. As alternate technologies evolve, it should be expected that Fuji will continue to play a significant role.



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[http://itri.loyola.edu/hdmem/c\\_04.htm](http://itri.loyola.edu/hdmem/c_04.htm)

sup.c22 {font-family: Times; font-size: 80%} p.c21 {font-family: Times; font-size: 60%; text-align: center} div.c20 {text-align: center} sup.c19 {font-size: 60%} span.c18 {font-family: Times; font-size: 60%} p.c17 {font-family: Times; font-size: 60%} p.c16 {font-weight: bold; text-align: center} td.c15 {font-weight: bold} a.c14 {font-weight: bold}

Site: **Fujifilm Company, Ltd.**  
**Odawara Factory**  
**Recording Media Product Division**  
**2-12-1 Oogi-cho, Odawara**  
**Kanagawa, Japan**  
<http://www.fujifilm.co.jp/><sup>79</sup>

Date Visited: 11 March 1998

WTEC:

- S. Esener (report author)
- H. Morishita

[http://itri.loyola.edu/hdmem/c\\_05.htm](http://itri.loyola.edu/hdmem/c_05.htm)

#### Hosts:

- Mr. Akira Kashiwagi, General Manager, R&D Center, Recording Media Product Division
- Dr. Hiroo Inaba, Senior Research Staff
- Mr. Shinji Saitoh, Manager
- Mr. Makoto Nagao, Research Associate
- Mr. Kouichi Maski, Research Associate

## BACKGROUND

Fujifilm Company was established in 1934; it has about a 65 year history. The Odawara factory was constructed in 1937. The first research on magnetic recording media was started about 45 years ago. At that time, tape for quadraplex video systems developed by the Ampex Company was one of the main targets. Later, Fujifilm developed and marketed many kinds of tapes, including audio, video, and computer media. In 1988, the first product for the VHS market was developed, using simultaneous dual coating technology. Fujifilm also developed metal particulate media technology in parallel with this coating technology. In 1992, Fujifilm succeeded in developing ATOMM tape, which has a non-magnetic under layer and a high- performance and super thin magnetic overcoat. Presently in Fujifilm's R&D laboratory almost all kinds of new flexible magnetic recording media are under development. Fujifilm claims to have a good reputation as the best flexible magnetic media manufacturer. The recording media product division employs 1,000 people. The R&D section employs 200 researchers, including R&D for CD-R. Fujifilm has 20% of the Japanese VHS market and is the main supplier of DLTs. Fujifilm buys the metal particulates and base films from outside vendors.

## DISCUSSION

Dr. Inaba gave an in-depth presentation on present status and future directions of tape media at Fujifilm. Key points he addressed included the following: choice and preparation of magnetic powder, with a comparison of MP and barium ferrite; the substrate material; the coating and slitting processes; and issues in reducing spacing.

Over the last decade, Fujifilm has maintained a continuous increase in coercivity of MP using first FeNi and later Fe-Co powders. Coercivities at the range of 2,300 Oe can now be obtained. At the same time the switching field distribution has dropped significantly to about SFD=0.2. In addition particle volumes have been greatly reduced to about  $10^{-5} \mu\text{m}^3$ . Presently each powder grain consists of only a few domains and the objective remains that of obtaining single domain particles. The advances in MP are summarized in Table C.3p<sup>139</sup>.

On the other hand, Dr. Inaba and his team see certain advantages in barium ferrite. It exhibits interesting properties including higher coercivity or smaller magnetization suitable for MR heads, good noise performance (fine grain) exceeding MP noise performance by 6 dB, good stability derived from its oxide nature and durability. The key limitations of barium ferrite are considered to be lack of reliable suppliers, the requirements for MR heads, and assymetrical signal waveform requiring

different signal processing techniques.

Table C.3  
Advances in MP

|                                 | Unit                | Advanced MP | HI8 MP | 8 mm Tape |
|---------------------------------|---------------------|-------------|--------|-----------|
| Coercivity                      | kA/m                | 190         | 142    | 121       |
|                                 | Oe                  | 2,410       | 1,800  | 1,520     |
| Saturation Magnetization        | Am <sup>2</sup> /kg | 153         | 131    | 121       |
| Co Content                      | Atm%                | 30          | 10     | 0         |
| Particle Length                 | nm                  | 93          | 102    | 148       |
| Particle Length Distribution    | %                   | 29          | 38     | 53        |
| Content of Single Crystal Metal | %                   | 31.5        | 24.7   | 22        |

In the area of substrates, Dr. Inaba's roadmap includes transitioning from PET --> PEN --> aramid within the next decade. He also points out the PBO material manufactured by Toyobo that provides the biggest stiffness with very large isotropic modulus (4,000/4,000). He expects that by increasing the availability of aramid produced by Toray and Asahi-Kasei, it should be possible to reach substrate thickness of about 3  $\mu\text{m}$  within five years and perhaps down to 2  $\mu\text{m}$  over the next decade.

Using an accurate coating process such as the DWT die coater, Fujifilm has been able to reduce the thickness of the substrate from 0.4  $\mu\text{m}$  to 0.2  $\mu\text{m}$  with a significant reduction in defect densities. Dr. Inaba pointed out that coating thicknesses less than 0.1  $\mu\text{m}$  are now within reach. Defect densities have been reduced by controlling dust particles but also by improving monitoring techniques such as improved optical defect sensors.

In order to improve track linearity, accurate slitting is required. Fuji researchers seem to have put an early emphasis on this aspect, trying out laser-assisted slitting. But because a certain texture is required for reducing wear and tear they continue to use shear cutting methods.

To reach smoother surface quality, Fuji researchers put emphasis on the formulation using special lubricants. In order to reduce real area of contact to decrease friction, yet to achieve less separation between the head and tape (for more resolution) several aspects are being investigated:

- designing surface texture by trial and error
- use of more lubricants without plasticization
- use of hard and compliant surface

Using these techniques Dr. Inaba and his team project a roadmap for the next 10 years, as shown in Table C.4<sup>140</sup>.

Table C.4  
10 Year Projections

| DVC/LP                               | Now   | Aggressive |           | Conservative |           |
|--------------------------------------|-------|------------|-----------|--------------|-----------|
|                                      |       | + 5 Years  | +10 Years | +5 Years     | +10 Years |
| Tape Thickness                       | 7     | 4.5        | 3         | 4.5          | 3         |
| Wavelength                           | 0.49  | 0.3        | 0.2       | 0.4          | 0.3       |
| Track Pitch                          | 6.67  | 3          | 1.5       | 5            | 3         |
| Linear Density (kbp <sub>i</sub> )   | 103   | 169        | 253       | 127          | 169       |
| Track Density (tpi)                  | 3,800 | 8,400      | 17,000    | 5,060        | 8,400     |
| Areal Density (Mb/in <sup>2</sup> )  | 390   | 1400       | 4300      | 640          | 1400      |
| Volume Density (Tb/in <sup>3</sup> ) | 1.4   | 7.9        | 36.3      | 3.6          | 11.8      |

## OTHER DISCUSSION

### Disk and Optical Tape Media vs. Magnetic Tape

Fujifilm researchers did not perceive optical tape as a major competitor since sensitivity to dust, difficulty in precise tracking and lack of critical mass are expected to restrict the applicability of optical tape. Also they perceive tape technologies and disk technologies as being aimed at different markets and applications: tape media for professional markets that cannot use compression and disks for consumer use. In addition, the researchers perceive the volumetric density and low cost advantage of tapes as an essential point for the future success of tape media (Fig. C.2<sup>141</sup>).

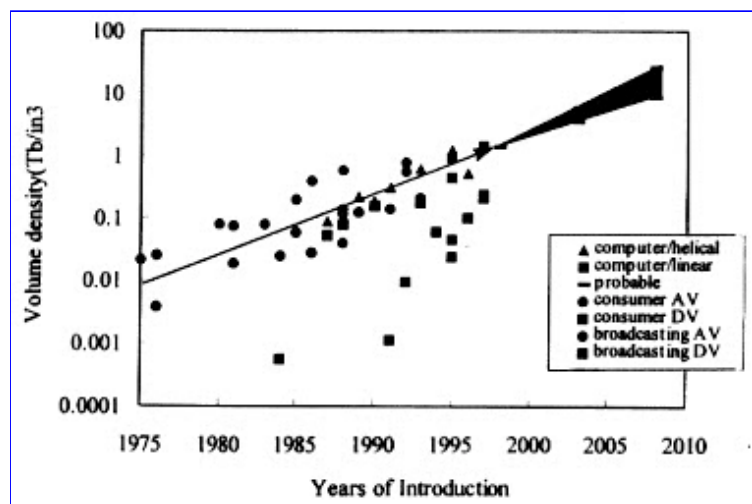


Fig. C.2. Projection for volumetric density.



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[http://itri.loyola.edu/hdmem/c\\_05.htm](http://itri.loyola.edu/hdmem/c_05.htm)

#### Appendix C: Pioneer Corporation

Site: Pioneer Corporation  
Corporate R&D Laboratory  
6-1-1 Fujimi, Tsurugashima  
Saitama 350-02, Japan  
<http://www.pioneer.co.jp/index2-e.html><sup>81</sup>

Date Visited: 30 March 1998

WTEC:

[http://itri.loyola.edu/hdmem/c\\_12.htm](http://itri.loyola.edu/hdmem/c_12.htm)

- M. Mansuripur (report author)
- H. Morishita

Hosts:

- Mr. Fumihiko Yokogawa, General Manager of the Optical Disc Systems Department
- Mr. Takashi Kato, Coordinator of Laboratory Management and Planning Section
- Dr. Hiroshi Ito, Senior Assistant Manager

## BACKGROUND

In the field of optical disk data storage, Pioneer is a manufacturer of CD-ROM, DVD-ROM and DVD-R media. Presently it is engaged to establish the DVD-RAM version 1.0 and 2.0 (2.6 GB and 4.7 GB) specifications in the DVD Forum working group 5, but its main focus is developing a 4.7 GB DVD-RW disc and drive as well as next generation 15 GB DVD-RW disc and drive.

## R&D ACTIVITIES

Pioneer laboratories are engaged in a number of research activities at the leading edge of modern optical technology. For example, they are developing blue lasers for various applications using both the technique of second harmonic generation (SHG) and direct fabrication of blue semiconductor lasers based on III-V materials (GaN-based system). They are also active in developing new display technologies based on a class of organic electroluminescent materials. At the time of this visit their R&D laboratories employed a total of 165 researchers.

In the area of optical data storage, Pioneer's research seems to be focused on DVD-ROM and rewritable DVD systems. Pioneer has an in-house mastering facility for producing high-density disks for research and development purposes. The hosts mentioned their plans to bring out the 15 GB DVD-ROM by the year 2001. This system, which is intended for high definition TV (HDTV), will use low-power blue lasers, and will employ actively controlled liquid crystal (LC) elements for aberration correction and for tilt servoing. The use of a 410 nm blue laser and a 0.6 NA objective lens will allow a capacity of only 9 GB on a 12 cm platter. To get to 15 GB, Pioneer researchers plan to use a number of advanced techniques, including 2D equalizer, cross-talk canceller, adaptive tangential equalizer, and Viterbi decoder.

Pioneer's prototype 15 GB DVD-ROM system uses a three-beam cross-talk canceller, which also provides the feedback signal to the radial tilt correcting servo based on an LC element. Although in principle this liquid crystal element can also do automatic correction for the tangential tilt, in practice the speed of switching the LC is not sufficient for high-speed applications. The tangential tilt correction is therefore done by electronic equalization. The details of this equalizer (which the hosts referred to as "super equalizer") were not discussed because Pioneer is applying for a patent on this technology.

To produce the 15 GB master for second-generation DVD-ROM, Pioneer researchers used a

photo-bleachable dye layer on top of the photoresist. Only the central region of the focused spot is strong enough to bleach the dye layer and, therefore, expose the photoresist layer below. In this way, the researchers could achieve super-resolution and create well-defined pits. They estimated that the use of the photo-bleachable layer had improved their cutting resolution by about 20%. Their mastering machine used a 0.9 NA lens and a 351 nm laser, and created DVD masters with a track pitch of 0.37 microns and minimum mark length (3T) of 0.25 microns.

In the area of rewritable DVD the hosts mentioned Pioneer's DVD-R/W format based on rewritable phase-change media, with a limited number of write/erase cycles (around 1,000). This product is intended for the consumer market (as opposed to the computer market), for which the limited cyclability is acceptable. Compatibility with DVD-ROM was highly emphasized. Pioneer researchers' material of choice for DVD-R/W is InAgSb, which is the same material used in CD-R/W. They said that they have confirmed a jitter value of less than 7% in this material at 4.7 GB capacity and over 100 times cyclability, which is better than what DVD-RAM can claim at the moment. Pioneer researchers hoped to develop the 4.7 GB DVD-R/W before the end of 1998. They maintained that of all the issues facing rewritable DVD, probably the copy protection issue is the most significant stumbling block.

Pioneer researchers gave the WTEC team a tour of their laboratories, where they showed the various technologies developed for the second generation DVD-ROM and DVD-RW. In particular, team members saw the improvement of the read signal due to the LC-based tilt servo, and the improvement of the eye-pattern by the so-called "super equalizer."

As for life after 2001, Pioneer researchers showed the WTEC team preliminary examples of techniques that will be used in the 50 GB DVD-ROM. Unless some new technologies are developed in the next few years, it seems likely that electron beam lithography will be needed to create 50 GB master disks.

Pioneer researchers have investigated both magneto-optical and phase-change media in the past but seem determined to move towards phase-change technology in their consumer-oriented strategy. They maintained that the "advanced storage magneto-optical disk" (ASMO, a.k.a., MO7) seems to have the support of the disk manufacturers but not the support of drive manufacturers in Japan. They also seemed to think that there are certain problems with the development of the ASMO technology, especially as related to the thin disk.



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sup.c13 {font-size: 80%} span.c12 {font-family: Symbol} span.c11 {font-family: Times; font-size: 60%} p.c10 {font-weight: bold; text-align: center} td.c9 {font-weight: bold} div.c8 {text-align: center} p.c7 {font-family: Times; font-size: 60%} p.c6 {font-weight: bold} a.c5 {font-weight: bold} span.c4 {font-size: 80%} p.c3 {font-size: 80%}

Site: **Hitachi Central Research Laboratory (HCRL)**

**(magnetic storage presentations)**

**1-280 Higashi-koigakubo**

**Kokubunji, Tokyo 185, Japan**

<http://koigakubo.hitachi.co.jp/82>

Date Visited: 12 March 1998

WTEC:

- M.H. Kryder (report author)
- W.D. Doyle
- D.T. Thompson

Hosts:

- Dr. Ryo Imura, Mgr., Information Storage Research Department
- Dr. Takashi Yamaguchi, Sr. Researcher, Mechanical Engineering Research Laboratory
- Mr. Hishashi Takano, Sr. Researcher, Information Storage Research Dept.
- Mr. Yoshihiro Hamakawa, Sr. Researcher, Information Storage Research Dept.
- Dr. Masaaki Futamoto, Chief Researcher, Information Storage Research Dept.
- Mr. Hirofumi Sukeda, Senior Researcher, Information Storage Research Dept.
- Dr. Sumio Hosaka, Sr. Researcher, Hitachi Advanced Research Laboratory

## BACKGROUND

Hitachi, Ltd. has seven corporate laboratories, whose responsibilities and research fields change in response to market and social needs. Dr. Ryo Imura presented an overview of these laboratories. These research laboratories and the approximate number of personnel at each are as follows:

|                                            |                                                                |
|--------------------------------------------|----------------------------------------------------------------|
| Hitachi Central Research Laboratory        | 1000 (approximately 820 of these are technical research staff) |
| Hitachi Research Laboratory                | 1050                                                           |
| Mechanical Engineering Research Laboratory | 550                                                            |

|                                            |     |
|--------------------------------------------|-----|
| Production Engineering Research Laboratory | 480 |
| Systems Development Laboratory             | 490 |
| Design Center                              | 170 |
| Advanced Research Laboratory               | 140 |

Hitachi Central Research Laboratory concentrates its R&D efforts in the fields of information and media, electronic devices and medical electronics. Michiharu Nakamura, General Manager of the Central Research Laboratory states that the lab's aim is to develop a new industrial frontier through endeavors in research that extend from the development of new scientific technologies to their practical application. He states that the researchers put a special emphasis on the creation of new technological trends and the speedy transfer of new technology to commercial products.

Within the Central Research Laboratory, the Information Storage Research Department has approximately 30 people working on optical recording and about 70 people working on magnetic recording. Within the magnetic recording area, there are groups working on magnetic recording heads, magnetic simulation, magnetic recording media and read/write electronics (where work on channels is done). Work on servos and actuators is done in the Mechanical Engineering Research Laboratory. Within the optical recording area, there are groups working on magnetic super-resolution magneto-optic recording, DVD-RAM, optical heads and optical media.

## DISCUSSION

Dr. T. Yamaguchi made a presentation on future track-following and servo technology for magnetic disk drives. He presented a track misregistration (TMR) budget for a 10 Gb/in<sup>2</sup> disk drive (Table C.5<sup>145</sup>):

Table C.5  
TMR Budget for 10 Gb/in<sup>2</sup> Disk

|                  |                        |
|------------------|------------------------|
| Track density    | 31,600 tracks per inch |
| Track pitch (Tp) | 0.8 micron             |
|                  |                        |

|                              |              |
|------------------------------|--------------|
| Non-repeatable runout (NRRO) | 0.096 micron |
| Synchronization              | 0.084 micron |
| Settling                     | 0.08 micron  |
| TMR                          | 15% of $T_p$ |
| Position error at write      | 12% of $T_p$ |
| Position error at read       | 14% of $T_p$ |

Dr. Yamaguchi also described work in which researchers were putting an accelerometer on the head suspension and using the signal from it as a feedback to actively suppress resonances in the suspension. He indicated the lab was doing work on dual stage actuators, and that there was work on voice coil microactuators, piezoelectric actuators and MEMS-type actuators. He indicated that the piezoelectric approach was currently favored and that he considered the MEMS-based actuator to be further away from practical implementation.

Mr. Takano presented a roadmap for hard disk drives and projected the following for hard disk drives at 40 and 100 Gbit/in<sup>2</sup> (Table C.6<sup>146</sup>):

Table C.6  
Disk Drive Roadmap

|                               | 40<br>Gb/in <sup>2</sup> | 100<br>Gb/in <sup>2</sup> |
|-------------------------------|--------------------------|---------------------------|
| Track density (ktpi)          | 75                       | 140                       |
| Linear density (kbpj)         | 530                      | 707                       |
| Erase band width<br>(microns) | 0.06                     | 0.03                      |

|                                     |      |      |
|-------------------------------------|------|------|
|                                     |      |      |
| TMR (microns)                       | 0.03 | 0.02 |
| Tolerance (D Tw)<br>(microns)       | 0.04 | 0.02 |
| Write track width<br>(Tw) (microns) | 0.27 | 0.14 |
| Read track width<br>(TR) (microns)  | 0.24 | 0.12 |

He also presented simulations of recording at 100 Gb/in<sup>2</sup> using both perpendicular and longitudinal recording. The perpendicular recording system used a ring head and a single layer medium without a soft underlayer. The work indicates that one can use a thicker medium in perpendicular recording than in longitudinal; the researchers assumed a 7 nm medium thickness in longitudinal recording and a 30 nm medium thickness in perpendicular recording. Other parameters of the systems were as shown in Table C.7<sup>147</sup>.

The simulations indicated that the transitions were considerably better defined in the case of perpendicular recording; although, in the case of perpendicular recording, regions where there were no transitions became noisy because they tended to self-demagnetize. The researchers also showed simulations that indicated that exchange coupling between grains tended to improve the definition of the transitions in the perpendicular recording case.

Table C.7

Simulations of 100 Gb/in<sup>2</sup> Disk: Longitudinal vs. Perpendicular Recording

|                                             | Longit.             | Perp.                  |
|---------------------------------------------|---------------------|------------------------|
| Grain size (nm)                             | 7                   | 6                      |
| Thickness of magnetic layer (nm)            | 7                   | 30                     |
| Anisotropy constant, Ku (J/m <sup>3</sup> ) | 3 x 10 <sup>5</sup> | 0.75 x 10 <sup>5</sup> |
| Exchange coupling between                   | 0                   |                        |

|                                                       |       |                     |
|-------------------------------------------------------|-------|---------------------|
| grains, A (J/m)                                       |       | $1 \times 10^{-13}$ |
| Saturation flux density (Tesla)                       | 0.816 | 0.478               |
| Gap length (microns)                                  | 0.1   | 0.1                 |
| Write track width (TW) (microns)                      | 0.14  | 0.14                |
| Coercive force of media (Oe)                          | 4,500 | 3,400               |
| Saturation flux density x media thickness, Brt (Gm m) | 45    | 104                 |
| Fly height (nm)                                       | 10    | 10                  |

Hitachi is one of several companies working on 40 Gb/in<sup>2</sup> recording density under the MITI-sponsored ASET program, and is responsible for work on media and on advanced heads. Hitachi is working on a spin-valve head design that is to have a sensitivity of 1,560 (V/(m. Hitachi engineers have demonstrated CoFe spin-valve sensors with a magnetoresistance ((R/R) of 7% using a 10 nm thick IrMn exchange bias layer. Simulations indicate that one can obtain more output using designs in which the track width is defined by the lead structure, rather than the self-aligned abutted permanent magnet structure.

Dr. M. Futamoto presented work on the effects of superparamagnetism on both longitudinal and perpendicular media. He indicated that thermal stability was considerably better in perpendicular media, because of the larger media thickness. He also indicated that if the perpendicular remanent squareness could be increased to 1, the tendency for perpendicular media to demagnetize was greatly reduced. He projected his personal description of a roadmap for future magnetic recording technology. He indicated that he expected longitudinal recording to use Co-alloy media like those in current products up to 20-40 Gb/in<sup>2</sup> and that to extend the density to 100 Gb/in<sup>2</sup>, new media such as SmCo, CoPt or FePt would be required. He suggested that, alternatively, perpendicular recording could begin using a thin film ring head, and a single- layer Co-alloy medium. Later generations could use, first, advanced thin film ring heads with continuously exchange-coupled amorphous media like those used for magneto-optic media, single pole heads with double-layer polycrystalline media and, ultimately, single pole heads with continuously exchange-coupled amorphous media on a soft underlayer. He indicated that such perpendicular recording approaches would lead to 3-4 times higher linear density and 3-5 times higher track density than possible with longitudinal recording, resulting in densities in the 200-400 Gb/in<sup>2</sup> range.

## SUMMARY

The presentations in the magnetic recording area at Hitachi Central Research Laboratory indicated that the researchers are working very hard on advanced magnetic recording technologies. Company researchers are working on advanced actuator and track following technologies for very high track densities, and have, to our knowledge, the most active industrial research effort in the world on perpendicular magnetic recording. Their simulations and experimental data indicate that perpendicular recording can use media that are 3-4 times thicker than longitudinal media at an equivalent density and that such media, consequently have superior thermal stability at high recording densities where superparamagnetic effects are a problem in longitudinal recording. The hosts also indicated that continuously exchange coupled perpendicular media may offer superior signal to noise ratio and thermal stability.



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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_07.htm](http://itri.loyola.edu/hdmem/c_07.htm)

## Appendix C: Matsushita Electric Industrial Co., Ltd.

Site: **Matsushita Electric Industrial Co., Ltd.**  
**Optical Disk Systems Development Center (ODSC)**  
**3-1-1, Yagumo Nakamachi, Moriguchi City**  
**Osaka, 570-8501, Japan**  
<http://www.mei.co.jp/panasonic-e.html><sup>83</sup>

Date Visited 13 March 1998

WTEC:

- K. Rochford (report author)
- S. Esener
- H. Morishita

Hosts:

- Dr. Takeo Ohta, General Manager, Optical Disk Systems Development Center
- Dr. Kazuo Yokoyama, Chief Research Engineer, Central Research Laboratories
- Dr. Hiroyuki Hasegawa, Staff Engineer, AVC Products Development Laboratory
- Dr. Tatsuaki Ishida, Engineer, AVC Products Development Laboratory

## BACKGROUND

[http://itri.loyola.edu/hdmem/c\\_08.htm](http://itri.loyola.edu/hdmem/c_08.htm)

Matsushita Electric Industrial Co., Ltd. (MEI), the number two consumer electronics company in Japan, is the leader of a group of more than 200 affiliates that serve business, industry, and consumer markets. It is best known for products that are marketed under the National, Panasonic, Quasar and Technics brands. FY 97 revenue of \$61.0 billion was reported.

MEI has been a leader in optical storage, having released one of the first PD-compatible rewritable systems in 1995, and undertook a leading role in the development of DVD. The 21/2-hour meeting with the WTEC team consisted of three talks by MEI engineers with about 45 minutes for discussion between presentations.

## DISCUSSION

Dr. Ohta began with a talk describing rewritable optical discs using phase change technology (which MEI has worked with since 1972). In comparison with magneto-optic recording, phase change (PC) has many advantages, including signals that are 20 times larger than MO (normalized for reflectivity), wide wavelength response (large signals over at least 430 to 830 nm), a simpler read and write optical system, and easier compatibility with DVD and CD read-only discs. PC media has a 50-year stability and can be overwritten more than 1 million times.

A key issue for near term DVD-RAM includes optimized thermal designs for higher sensitivity. Also, the need for unified DVD-RAM standards was described. A single standard is needed to maximize viability of the format.

During discussion, it was expected that recording densities of 120 mm diameter discs will reach 11 Gb/in<sup>2</sup> using 0.6 NA optics if a blue (425 nm) laser is available. MEI recently announced an SHG laser that provides 26 mW at 425 nm, and that should cost only 10% more than a comparable laser diode. If a blue laser is not available, solid immersion lens (SIL) technology can be used to read high data densities; improving density using the same NA is desired, though, since more generations of discs will remain compatible.

Formats will migrate from 4.7 GB discs to double layer 8.5 GB, and then to 15 GB discs for HDTV recording. Single layer recording may achieve 20 GB or more by using higher NA, media superresolution, and thinner substrates. Beyond that, multilayer stacks, possibly up to 4 layers, can increase disc capacity.

Dr. Ohta's concluding remark that "phase-change welcomes nanometer memory technologies" was exemplified by Dr. Yokoyama's presentation on AFM recording. Marks of 10 nm diameter (~1 Tb/in<sup>2</sup>) with up to 100 times conductivity increases were recorded in GST films using 3 V pulses for 5 ms from a conductive AFM tip. Data are read with the AFM tip at 0.5 V with a few nA of current, and marks could be erased by reversing the pulsed voltage. Data rate is limited by the decreasing reliability of writing as pulse duration decreases but approached 1 kb/s in the demonstration.

Dr. Ishida described a high density magnetic tape recording system based on obliquely oriented metal evaporated tapes. His research goal is a 1 Gb/in<sup>2</sup> product by the year 2000, using 5 ktpi track density

and 200 kfrpi linear recording density. A demonstration of 1 Gb/in<sup>2</sup> recording with 50 dB carrier-to-noise (by using an MIG type inductive head) was described.

The obliquely oriented Co-O tapes show potential beyond several Gb/in<sup>2</sup>, but signal-to-noise challenges remain. Applying more sensitive magneto-resistive heads in (helical scanning) removable tape systems requires significant innovation since they cannot survive contact recording. Furthermore, tape - head spacing for contact recording will be larger than HDD fly heights because of the relatively large separations that tape systems must accommodate (~30 nm protrusion height, 10 nm protective layer, [20 nm head recess] and ~ 20 nm for adhering impurities ["brown stain"]). Ultimately, if MR heads are used, tape properties must be re-optimized, and this work is underway. Tracking is also an issue; for higher density, tape thicknesses of 5 µm are predicted, and expansion of polymer tapes (due to temperature or humidity) may cause excessive skew angle.

## SUMMARY

MEI is committed to rewritable discs based on phase change media. The resurgence of magneto-optical recording is considered to be an academic pursuit and not a viable path. The organization has a clear roadmap for disc products up to 15 GB or so, and company researchers believe multilayer technologies can push rewritable disc capacity to 80 GB.



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[http://itri.loyola.edu/hdmem/c\\_08.htm](http://itri.loyola.edu/hdmem/c_08.htm)

Site: **National Institute for Advanced Interdisciplinary Research (NAIR)**  
**1-1-4 Higashi**  
**Tsukuba, Ibaraki 305, Japan**  
[http://www.nair.go.jp/nair\\_e.html](http://www.nair.go.jp/nair_e.html)<sup>84</sup>

Date Visited 10 March 1998

WTEC:

- K. Rochford (report author)
- M. Keshner
- S. Lin
- G. Whitman

Hosts:

[http://itri.loyola.edu/hdmem/c\\_09.htm](http://itri.loyola.edu/hdmem/c_09.htm)

- Dr. Nobufumi Atoda, Supervising Researcher, Optical Memory Group
- Dr. Junji Tominaga, Chief of Research
- Mr. Hisao Osawa (Nikon, OE Group)
- Mr. Akira Sato (Minolta, Optics Tech. Div.)
- Mr. Yuzo Yamakawa, Director, Device Research Division, Pioneer Electronic Corporation

## BACKGROUND

NAIR was founded in 1993 as part of MITI's Agency of Industrial Science and Technology (AIST) to pursue interdisciplinary research in fundamental and frontier areas of industrial science. The government-funded research is collaborative, and includes industrial, academic, and government participants. Management is based on four principles: extensive openness, flexibility and mobility of staffing, international collaboration, and objective evaluation of research progress. Though NAIR does retain permanent research staff, term employees drawn from government, industrial, and academic organizations, as well as foreign guest researchers, make up the majority of research staff.

The four major research areas are divided into the following groups: Atom Technology, Cluster Science, Bionic Design, and Optical Memory. The Optical Memory Group had an FY 98 budget of ¥160 million and 13 researchers (4 NAIR staff, 2 assigned from other AIST institutes, 3 assigned from universities, 3 industrial researchers, and one foreign post-doc). The group began its research program in April 1997 after completion of a one-year feasibility study.

The Optical Memory Group's objective is to develop a technological basis for ultra-high density data storage using near-field optics. The research program is five-fold: (1) explore near-field recording principles; (2) explore suitable recording materials; (3) develop fabrication techniques for various probe types; (4) reduce feature size while improving dimensional accuracy and enhancing power throughput; and (5) evaluate dynamic signal detection. To address these issues, the group is divided into two projects, with one focusing on optical system design and another working on recording media design.

## DISCUSSION

A prepared presentation by Dr. Atoda described several issues facing media selection. First, media must record and erase without significant deformation to reduce the possibility of head crashes. Second, the low optical power provided by near-field probes suggests that thermally assisted recording is desirable. Finally, clear recording thresholds are needed to obtain good edge definition. These issues make current organic write-once media less attractive than phase change or magneto-optic materials.

Early work has looked at the behavior of phase change (PC) materials. A test bed using a classical microscope head has been built for making 200 nm diameter marks on PC materials to test near-field readout. One demonstration showed that near-field readout modulation doesn't significantly degrade for dielectric cover layers as thick as 20 to 30 nm.

The researchers have observed a 5% reduction in volume due to writing (amorphous to crystalline) in SiN/GST/SiN sandwich structures. Study of the sandwich indicates that GST crystallization begins at the dielectric interface and is initially confined to within 15 nm of the interface. This suggests the possibility of two layers of recording if the GST film is thicker than 30 nm.

Another area of research involves array write/read. Researchers have produced and characterized 200 nm diameter holes in Si wafers; these appear useful as masks that could be placed over a laser beam to produce a two-dimensional array of probes. Ball lenses inserted over the holes have improved the optical throughput by up to two orders of magnitude. One result of this work might be a flying head array with integrated laser and detector. NAIR researchers estimate that near-field probe data throughput is limited (by optical power considerations) to 10 to 100 kb/s; a read/write array could increase this to 10 Mb/s, so array technology is important for near-field systems.

When WTEC's hosts were asked to name the single most difficult aspect of this project, tracking was the quick reply. Reduction of track pitch raises trade-offs between tracking accuracy and the dynamic range needed to accommodate track noise, wobble, etc. The registration of read/write arrays to tracks becomes more difficult with decreasing track width, and may require challenging array fabrication tolerances or array agility to accommodate compatibility among systems. For optical storage in general, the development of short wavelength lasers was considered a key area.

Though this is a long-term research project, there was discussion about the market forces that affect commercialization, and concern was expressed about the profitability of the storage industry. Because prices fall as participants introduce competing products, it's important to have a product that is resistant to these pressures. One approach is to introduce products early in the market cycle and benefit from this higher profit period. Near-field recording is very challenging, however, and the hosts estimated that five years would be needed for prototype development, and as much as 20 years for a commercial product.

## SUMMARY

Developing a near-field optical storage system is an ambitious undertaking that presents many challenges, and the NAIR team, though in early stages of research, clearly recognizes this and harbors no illusions. It is an interdisciplinary problem, however, and may benefit from the flexible staffing approach used at NAIR; as problems are solved and new issues become important, the group can draw from many sources to enlist researchers with expertise in the current problems.



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Site: **Nikon Corporation**  
**Research and Development Department**  
**Information Storage Products Division**  
**1-6-3 Nishi-ohi, Shinagawa-ku**  
**Tokyo 140, Japan**  
[http://www.nikon.co.jp/main/index\\_e.htm](http://www.nikon.co.jp/main/index_e.htm)<sup>85</sup>

Date Visited: 30 March 1998

WTEC:

- M. Mansuripur
- H. Morishita

Hosts:

- Dr. Jun Saito, Manager, Optomechatronics R&D Department
- Dr. Hiroshi Ooki, Senior Manager
- Mr. Katsura Otaki, R&D Department

Nikon's involvement with optical storage media is through a joint venture with Hitachi-Maxell, called MNO (Maxell-Nikon Optical). This company, which is nearly three years old, manufactures and markets exchange-coupled magnetic multilayer MO disks capable of direct overwrite (DOW). Both 3.5" and 5.25" disks are produced by MNO. Nikon's high-end product is currently the 4X, 5.25" DOW disk with 2.6 GB capacity (double-sided). The 8X, ISO format disk was expected to be introduced into the market later in 1998 by Sony Corporation. The DOW version of the 8X, 5.25" MO disk will follow the non-DOW disk. (At the time of this visit, the ISO was almost finished specifying the 8X 5.25" DOW disk, and had finished specifying the DOW 4X 5.25" and the DOW 5X 3.5".)

As of the date of this visit, the price of DOW disks in Japan was approximately 50% higher than the non-DOW disk. For example, the 3.5" DOW disk could be purchased for ¥2,400, whereas the non-DOW disks cost about ¥1,600. Despite this price difference, the general consensus at Nikon was that the overwrite capability is important to the user, and the hosts believed that a large fraction of the users will prefer the DOW disks.

As far as compatibility with drives is concerned, all 640 MB drives for the 3.5" disks and all 4X drives for the 5.25" disks can handle the DOW disks as well as the ISO standard non-DOW disks. The hosts also stated that all future-generation drives for MO will be compatible with the DOW disks.

The market for MO drives is still small, but most of the Japanese scientists/engineers this WTEC team met seemed to think that there is a bright future in this field. In 1996 there were nearly 1 million 3.5" MO drives sold worldwide, and the number was close to 930,000 units in 1997.

By far the largest share of the market (i.e, percentage of users) was in Japan. There does not seem to be a large market for the Zip drives in Japan, although Fuji film is now making Zip media, and NEC

has been licensed to manufacture Zip drives. According to WTEC's hosts at Nikon, the Japanese consumers think very highly of optical technologies, perhaps because of the superior performance of CD audio and its resounding success in the market place. Any technology that uses lasers is likely to attract the attention of Japanese consumers. As for MO technology, the hosts indicated that the shelves in Akihabara were full of MO disks.

No one at the meeting knew the exact size of the market for MO disks, but the guess (based on the number of drives sold in 1997) was that there was probably demand for 10 to 20 million 3.5" disks in 1998. Given that several manufacturers in Japan produce these disks, hosts were asked if this type of a market was suitable for their company to be involved with. The answer was a strong yes, with the comment that 10, 20, 30, 40 million disks per year is certainly a good enough market for Japanese disk makers to pursue.

There was some talk about the Windows 98 operating system and that this version of Windows will allow bootup from removable media. Also the fact that Win'98 will accept ATAPI interface (instead of SCSI) was considered a boost for MO drives in the near future. Fujitsu, for example, is already making 3.5" MO drives with ATAPI interface; Fujitsu has also announced 1.2 GB 3.5" (one-sided) MO drives, and reportedly has plans for Dragon I and II drives, which will accept both 3.5" MO disks and CD-ROM.

Nikon apparently is not involved in phase-change media development. The only information the hosts provided on this type of media was based on their personal knowledge of the R&D efforts in Japan. They said that in April 1998 Hitachi and Panasonic were expected to ship DVD-RAM disks and drives. These are 2.6 GB/side, 5.2 GB (double sided) 120 mm diameter disks. Sony's DVD+R/W is expected to have around 3.5 GB capacity, and Pioneer's DVD-RW will be about 3.4 GB capacity. The latter is expected to be introduced in 1999.

The participants had some reservations about the future of CD-R type media (CD-Recordable, DVD-Recordable, WORM-type media). They felt that with the mastering equipment makers' effort to develop a new method of mastering of CD and DVD, stamping as few as 100 disks will be cheaper than recording them individually on the CD-R type media. Of course CD-R will continue to serve a special niche market, but more and more people will gravitate toward the ROM type media on the one-hand and toward the rewritable media on the other hand.

It was stated that there will be essentially two types of markets for MO disks and drives in the near future: (a) personal computer/consumer/portable applications, and (b) infrastructure applications such as servers and mainframes. From now on, the 3.5" and 5.25" disks will move in different directions, partly because of differences in removability requirements, and partly because of the price targets that manufacturers feel they can set for each product.

For portable applications it was felt that SyQuest and Jazz drives are not suitable because they can be dropped only about 40 cm or so. The same concern applies to the magnetic field modulation (MFM) method, which contains a flying head. The LIMDOW (light intensity modulation direct overwrite) technology, on the other hand, does not use a flying head and is therefore more suitable for portable applications. Technologies that use the magnetic field modulation technique are probably more suited

for infrastructure applications (e.g., servers and mainframes) as well as for low-end consumer applications such as the MiniDisc.

The participants felt certain that the optical ROM format will be around in 20 years and beyond. They mentioned that semiconductor memories should be watched closely in the next few years. New semiconductor technologies such as one-electron DRAM might be able to compete with optical RAM storage products. The need of optical storage devices for some sort of mechanical actuator to access the data might be considered to be a drawback for this technology, when the recording densities would be much higher in the very distant future. The participants also felt certain that the optical RAM format will be around in 20 years and beyond.



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[http://itri.loyola.edu/hdmem/c\\_10.htm](http://itri.loyola.edu/hdmem/c_10.htm)

Site: **Olympus Technology Research Institute**  
**2951 Ishikawa-cho, Hachioji-shi**  
**Tokyo 192, Japan**  
<http://www.olympus.co.jp/><sup>86</sup>

Date Visited: 11 March 1998

WTEC:

- M. Keshner (report author)
- S. Lin
- K. Rochford

Hosts:

- Mr. Masakawa, General Manager, OMA Business Dept.
- Mr. Matsubayashi, Manager, Sr. Eng., OMA Business Dept.

## BACKGROUND

Olympus has a significant business in magneto-optic disk drives, both 3.5" and 5.25". Olympus, Fujitsu and Konica are the only manufacturers in the world for the 3.5" MO drives. These products are very popular in Japan with volumes of about 1 million units per year, but have not really been adopted in volume in other parts of the world as yet. Olympus is also working with TeraStor in the United States on an MO drive that uses a solid immersion lens to reduce the optical spot size by 2x, and

[http://itri.loyola.edu/hdmem/c\\_11.htm](http://itri.loyola.edu/hdmem/c_11.htm)

thereby increase the capacity by 4x over conventional techniques. Olympus is one of many partners in the TerraStor group, and it is designing and manufacturing the upstream optical head assembly.

## DISCUSSION

Olympus managers believe that MO drive technology can be extended. Their current plans are for 5.2 GB and then 10.4 GB capacities on a 5.25" double-sided disk. Beyond that, they believe that one of the magnetic super-resolution techniques, plus magnetic field modulation, will enable the capacities to be as high as 50-100 GB per disk.

The hosts mentioned several technology issues that must be addressed, such as the sensitivity of MO materials to 410 nm laser light and, of course, signal to noise at the very high densities. However, the biggest issue was that of standards and drive volumes. They believe that drives based on MO technology can be just as inexpensive to manufacture as drives based on phase change technology--given the same unit volumes. Today, the MO drives have received good acceptance in Japan for the high volume consumer product market and good acceptance throughout the world for the higher performance professional product market. However, recently, phase change drives such as the CD-RW have started selling well all over the world. The key question is, which will become the accepted standard and, thereby, achieve the high unit volumes? Many of the component costs, such as optics and lasers, are highly volume sensitive.

The hosts also discussed the likely market success of the TeraStor approach. Again, the big concern was volume. The TeraStor drives may become a fixed disk drive rather than one with removable medium because of the possible wear and contamination issues. Then, the key question is how will its costs and volumes compare with magnetic fixed disk drives and which will win? Here also, high volume is needed to bring down the manufacturing costs, and the market might not support both technologies with the necessary high volumes.

## SUMMARY

Olympus is currently one of the major players in magneto optical drive technology development and product manufacturing. Management takes the position that MO technology can meet the requirements of the marketplace, but only if it becomes the accepted standard and can enjoy the high manufacturing volumes that will enable drive manufacturers to achieve low prices. The next few years may be a turning point when one or the other technology becomes dominant for removable optical disk recording.



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Site: **Yamaha Corporation**  
**Thin Film Head Division**  
**203 Matsunokijima, Toyooka-mura, Iwata-gun**  
**Shizuoka 438-0192, Japan**  
<http://www.yamaha.co.jp/english/index.html><sup>87</sup>

Date Visited: 10 March 1998

WTEC:

- W. Doyle (report author)
- M. Kryder
- D. Thompson

Hosts:

- Mr. Kenji Suzuki, Manager, R&D Planning Division
- Mr. Atsushi Toyoda, General Manager, TFH Division
- Mr. Masataka Nishimura, General Manager (sales and marketing), TFH Division
- Mr. Tokuo Mimori, Assistant Manager, R&D Planning
- Mr. Kiyohiko Ito, retired technical leader (initiated the TFH program and now serves as a consultant)

## CORPORATE DESCRIPTION

Yamaha is widely known for the manufacture of musical instruments from pianos to synthesizers but less well known for its electronic components, which were developed to support electronic instruments. In 1997 revenue was ~\$4 billion, generated by 8,800 employees at several sites worldwide. Yamaha surprised the industry in 1991 by bringing TFH and, later, MR and GMR heads to the market before many other companies. In 1997, Yamaha produced 80 million MR heads. Although Yamaha has extensive experience in LSI, and previously, in 1984, made an aborted attempt at perpendicular heads, the company was not known to have competence in magnetic materials and recording systems. It is possible that a major Japanese customer such as NTT is collaborating with Yamaha. Head fabrication is done at the Shizuoka plant.

## OVERVIEW

Yamaha has a clear focus to maintain its leadership and be the major non-captive supplier of advanced GMR sensors. Yamaha managers are well aware of the approaching supraparamagnetic limit and have developed a clear technology roadmap that includes two generations of SIL followed by near-field optical recording. Because they also manufacture CD optical heads, they are confident about their ability to manufacture future optical heads. For now, however, the focus is production of TFHs.

## ROADMAP

Yamaha's technology roadmap includes GMR heads, advanced GMR heads, dual stage actuators, and sliders shrinking to the "femtoslider" level and beyond. The superparamagnetic effect in media has not affected the company's plans as yet, since it does not make media. In anticipation of higher coercivities and narrower track widths in the future, Yamaha researchers have experimented with sputtered high moment pole tip materials, but did not have them in production at the time of this visit.

## THIN FILM HEAD BUSINESS

Although a market leader, Yamaha hosts indicated that they felt squeezed by system integrators to lower prices unrealistically.

## THIN FILM HEAD PROCESSING

Three-inch square  $\text{Al}_2\text{O}_3$ -TiC substrates are obtained from two sources, and the heads are fabricated using a relatively conventional process. Magnetic pole materials are plated, and the GMR is sputtered. Nikon I-line steppers are used to define features with critical dimensions, and focused ion beam etching is used for pole trimming. The wafer size is quite small by industry standards, which now can be up to 6", but Yamaha managers do not believe this is as important as achieving high yield. Re-tooling for larger wafers would require substantial new capital investments. Smaller sliders allowing many more heads per wafer have improved productivity.

Yamaha makes its own integrated suspensions, which allows it to produce advanced prototypes. Yamaha researchers have considered silicon chips placed on the suspension and the possibility of their producing SIL flying optical heads, but have no projects to report as yet.

## UNIVERSITY RELATIONS

Yamaha managers indicated that they did not believe it is necessary for them to establish collaborations with any Japanese university. Yamaha does not participate in ASET.

## FACILITIES TOUR

The highlight of this visit was the extensive, informative tour led by Mr. Ito of the wafer fabrication area. Most of the equipment, astonishingly, was custom designed and is maintained by Yamaha. Although this was common in the IC industry 25 years ago, most manufacturers of ICs and TFHs use commercially available equipment, often supported by service contracts. The equipment was obviously carefully designed for maximum automation, efficient integration and maximum use of space. The fab area is one large Class 1000 clean room (ceiling filters and floor exhausts) estimated to be 40,000-50,000 ft<sup>2</sup>. All operations, including substrate polishing, are carried out in long parallel

rows. Overall, it appeared comparable in size to those of major U.S. manufacturers, such as Seagate Technology.

## FUTURE TECHNOLOGIES

Yamaha is primarily focused on GMR TFHs for longitudinal recording. No interest was expressed in heads for perpendicular recording, partially due to the memory of the earlier failure of the market to develop in 1984. It would appear that Yamaha will depend on obtaining new technologies from more research-oriented customers. No evidence of a significant R&D effort was obtained in this visit.



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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_19.htm](http://itri.loyola.edu/hdmem/c_19.htm)

## Appendix C: Sony Headquarters

Site: **Sony Headquarters**  
(magnetic storage presentations)  
**Corporate R&D Strategy Department**  
**6-7-35 Kitashinagawa, Shinagawa-ku**  
**Tokyo 141-0001, Japan**  
<http://www.sony.co.jp><sup>88</sup>

Date Visited: 10 March 1998

WTEC:

- W. Doyle (report author)
- M. Kryder
- D. Thompson

Hosts:

- Ms. Chie Iwakiri, Corporate R&D Strategy Department
- Dr. Jun Takayama, Research Fellow, Research Center
- Mr. Tadashi Ozue, Senior Research Scientist, Research Center
- Mr. Seiichi Onodera, Senior Engineer, Recording Media
- Mr. Teiiche Miyauchi, Manager, Research Center
- Mr. Takahiro Kawana, Manager, R&D Department, Recording Media

## CORPORATE DESCRIPTION

[http://itri.loyola.edu/hdmem/c\\_14.htm](http://itri.loyola.edu/hdmem/c_14.htm)

Sony is a world leader in electronics and entertainment with 163,000 employees that in 1997 generated \$45.7 billion in revenue (29% in the United States), and \$1.1 billion in net income. Traditionally, Sony has been a leader in audio and video products and now has a new focus in digital and network technologies. Sony is a leading player in magnetic tape technology for data storage, participating in several formats including QIC, TRAVAN, DDS 19 mm and 8 mm. The R&D budget is \$30 million, with some magnetics R&D carried out at the Yokohama Research Lab, but the major effort is in the Sendai location.

## RESEARCH AND DEVELOPMENT

### High Data Rate Tape Recorder (Takayama)

Dr. Takayama pointed out that a data rate of 1.2 Gb/s is required for HDTV broadcast applications which will be compressed to 50 Mb/s for home use. He described two existing products:

1. A 1" open reel recorder which achieves 1 Gb/s user data rate using 18  $\mu\text{m}$  thick, 1,500 Oe MP tape with 8 record, 8 reproduce and 2 erase conventional inductive heads on a  $355^\circ$  scanner. Track pitch is 37  $\mu\text{m}$  and the shortest recorded wavelength (2 bits) is 0.69  $\mu\text{m}$  (48 Mb/in<sup>2</sup>) with a head/tape speed of 51 m/sec.
2. A 19 mm cassette recorder which achieves 512/400/256 Mb/s using 16/13  $\mu\text{m}$  thickness 850 Oe oxide media with 16 record and 16 reproduce heads to compensate for the smaller wrap angle of 180. The track pitch is 45  $\mu\text{m}$ , and the shortest recorded wavelength is 0.9  $\mu\text{m}$  (30 Mb/in<sup>2</sup>) with a head/tape speed of 40/31/20 m/sec. To push the user data rate and density to 1 Gb/s and 60 Mb/in<sup>2</sup>, double the number of heads to 32 each for record and reproduce, and halve the track pitch to 23  $\mu\text{m}$ . Increasing the writing speed was felt to be more difficult. To further increase the user data rate to 2.0 Gb/s, the media will be changed to 1,500 Oe MP with a track pitch of 23  $\mu\text{m}$  and a shortest recorded wavelength of 0.45  $\mu\text{m}$  (120 Mb/in<sup>2</sup>). Doubling the number of heads again to 64 each for record and reproduce was considered impractical.

An alternative considered was a multi-track linear serpentine system using the same media at 6 m/sec. This would require 100 channels/head for read/write/read and was felt to be impractical both because of expected low yield of the head and the need for 600 head connections.

The conclusion would seem to be that multiple heads in a helical system is a more attractive solution for data rates in this range.

### MR Heads in Helical Tape Systems (Ozue)

Mr. Ozue showed that in 1991 the areal density of HDDs exceeded tape storage for the first time at 100 Mb/in<sup>2</sup> and has continued to increase at a faster pace. To remain competitive, the rate of areal density increase in tape must parallel HDDs and reach 1 Gb/in<sup>2</sup> in 2000. To accomplish this, Sony plans to continue to focus on helical systems but to adopt all the significant advances in HDD including thin film media, thin film record, MR/GMR reproduce heads, PRML or other advanced

signal channels, and in-contact recording. An experimental system was described using a SAL/AMR reproduce head with NiZn ferrite shields, track width of 17 nm, azimuth of 25° on 100 nm thick, 1,500 Oe Co-O evaporated tape with a DLC overcoat,  $M_t = 2.6 \text{ memu/cm}^2$ , and a squareness of 0.8. It realized 12 dB more signal at a wavelength of 0.5  $\mu\text{m}$  (141 Mb/in<sup>2</sup>) than an inductive head. Sony hosts were optimistic that the target of 1 Gb/in<sup>2</sup> in 2000 would be achieved.

Wear of thin film heads and media is a major concern in the industry. Mr. Ozue said, however, at a wavelength of 0.5  $\mu\text{m}$  no signal loss was detected after 1,000 reads. The total magnetic spacing is 50 nm. The head is apparently designed with a deep throat height similar to ferrite heads, which is expected to accommodate some head wear. How this affects performance was not discussed.

## Tape Media Technology (Onodera)

Mr. Onodera summarized recent advances in both MP and ME tape. Sony is using 80 nm MP particles in 100 nm thick coatings and experimenting with 60 nm particles. Dispersion is the major technical challenge to achieve low media noise. A 200 MB floppy was expected to be announced the end of the summer (1998). Sony researchers believe the reliability problem associated in the past with ME has been solved using a DLC overcoat. Helical systems require recording only in one direction, so only a single angle-of-incidence layer is needed. However, Mr. Onodera speculated that two layers might be used to reduce noise. The cost differential between MP and ME will be narrowed as the reduced moment needed for MR heads can be achieved with thinner films, resulting in higher web throughput.

## ASET Research Program (Miyauchi)

The ASET program is sponsoring work at Sony on a vertical GMR head, which was reviewed by T. Miyauchi. A comparison through simulation of horizontal and vertical heads including the bottom conductor height revealed several important points. The output for both types depends on the flux decay length  $\lambda_B$ , which defines the length of the sensor over which the field from the media is effective. This is particularly important for vertical heads where  $\lambda_B$  depends on  $\mu_e^{1/2}$  where  $\mu_e = 4\pi M_s/H_e$  is the effective permeability in the sensor,  $M_s$  is the saturation magnetization of the sensor and  $H_e$  is the effective anisotropy field including the induced anisotropy and the bias field from the permanent magnet stabilization field. For a gap length of 0.13  $\mu\text{m}$ ,  $\lambda_B = 0.55 \mu\text{m}$  for  $\mu_e = 1,000$  and decreases to 0.28  $\mu\text{m}$  for  $\mu_e = 250$ . The gap length is consistent with a linear density of 700 kbp, which at 57 ktpi will achieve 40 Gb/in<sup>2</sup>. The analysis showed that when the vertical height of a horizontal sensor  $h < 2\lambda_B$ , the output is independent of  $h$ . In the vertical case, when  $h > 2\lambda_B$ , the output is independent of  $W$ , the sensor width. The latter is considered a significant advantage for vertical heads as track widths are decreased below 1  $\mu\text{m}$ . If  $2\lambda_B > W$ , the output from a vertical head will exceed the output from a horizontal head.

The output from an experimental device using an NiFeCr/(NiFe/CuNi)<sub>n</sub>/NiFe/Cr multilayer with  $W = 2.0 \mu\text{m}$  and a sensor length of 8  $\mu\text{m}$ , gave good agreement with the model below 3 mA ( $25 \times 10^6$

A/cm<sup>2</sup>) where the output was ~6 mV. Above 3 mA, Joule heating dominated the behavior, which could be improved by heat sinking. The characteristic dependence of output on an applied field was shown for another device with  $W=0.5\text{ }\mu\text{m}$  and sensor length= $2\text{ }\mu\text{m}$ . It gave a full width-half max of 16.8 Oe with a sensitivity of 215  $\mu\text{V/Oe}$ . To produce these devices, Sony used an inductively coupled plasma magnetron sputtering system capable of simultaneous deposition from six 2" targets onto 4" substrates. Vertical stripes down to 0-1  $\mu\text{m}$  have been fabricated with electron beam lithography and ion beam etching. Future vertical devices include three GMR layers with both outside layers pinned with adjacent antiferromagnetic layers and an abutted hard magnet for domain stabilization.

## FUTURE TECHNOLOGIES

There was no discussion of future storage systems due to a shortage of time.



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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_14.htm](http://itri.loyola.edu/hdmem/c_14.htm)

Site: Sony Corporation  
(optical storage presentations)  
Research and Development Center  
6-7-35 Kitashinagawa, Shinagawa-ku  
Tokyo 141-0001, Japan  
<http://www.sony.co.jp/><sup>88</sup>

Date Visited: 10 March 1998

WTEC:

- M. Keshner (report author)
- S. Esener
- K. Rochford

Hosts:

- Mr. Masahiko Kaneko, Mgr. Adv. Development Lab
- Dr. Shigeo Kubota, General Mgr. and Chief Scientist, Research Center

## BACKGROUND

[http://itri.loyola.edu/hdmem/c\\_15.htm](http://itri.loyola.edu/hdmem/c_15.htm)

Sony is an electronics and entertainment company with more than \$46 billion in sales. Roughly 78% of the sales are from electronics, and 22% are from movies and music. In the electronics business, about 14% are VCRs, 18% are audio products, 18% are television sets, and 27% are other. Movie production accounts for 10% of sales, and music, 8%. For the year ending in April of 1997, Sony had a profit of \$3 billion and spent about \$2 billion on R&D. One-third of the \$2 billion was spent on advanced R&D and two-thirds were spent on product design. The Corporate Research Center has several divisions:

- Research Center-devices and materials
- Advanced Development-optical disk, magnetic recording and new concepts
- Media Processing
- Information Technology
- Advanced Production
- Next Century-development of the "robot pet"
- Platform Software Development

The Sony Corporation has 163,000 employees worldwide and is divided into several companies:

- Displays
- Home Audio Visual
- Personal Audio Visual
- Information Technology (PCs)
- Personal & Mobile (auto products and cellular phones)
- Broadcast and Professional
- Digital Network Solutions
- Semiconductor
- Computer Peripherals
- Recording Media and Energy

## DISCUSSION

The entire WTEC team attended an overview presentation of the Sony Corporation and the Sony Research and Development Center. Then the group was split for presentations on magnetic recording and on optical recording. (See previous [Sony site report](#)<sup>160</sup> in this appendix, for magnetic storage discussions.)

Mr. Kaneko from the Optical Media Lab, within the Advanced Development Lab, presented Sony's ideas for high capacity. He presented ideas for extending both phase change and magneto optic technologies to achieve 15-20 Gb/in<sup>2</sup> or about 20-30 GB on a DVD disk. They included the following:

1. Phase change recording, using a thin substrate (0.1 mm  $\pm$  3  $\mu$ m), a high NA lens (0.85), Using a PR (121) ML read channel, a (1,7) code and land & groove recording, with a 635 nm laser, they showed excellent eye patterns at 8 GB per disk. With a 515 nm laser, they could achieve 12 GB

per disk. Writing power was 5 mW at 3.4 meters per second. With 2-4 layers, and a 410 nm laser, capacities of 35-70 GB are possible.

2. Magneto optic recording, using a 650 nm laser, NA=0.6 and land & groove recording, with an NRZI code, a CAD disk to reduce crosstalk and magnetic field modulation. Readout requires a super-resolution technique, either magnetic amplifying magneto-optical system (MAMMOS) from Hitachi-Maxell or domain wall displacement detection (DWDD) from Canon.

Sony managers also presented their ideas for a very high capacity ROM optical disk. The technology is called "single carrier independent pit edge recording" (SCIPER). It is designed for a blue laser (410 nm) and uses the following ideas:

- SCIPER stores data by modulating the position of the leading and trailing pit edges in very small discrete steps. Mark centers are precisely every 0.38  $\mu\text{m}$ . The mark size to the left of the bit center varies to encode 4 bits (16 sizes), with a maximum of 0.16  $\mu\text{m}$  in steps of 0.01  $\mu\text{m}$ . The mark size to the right encodes another 4 bits.
- SCIPER will be combined with radial direction partial response (RPR) encoding, where data are read out simultaneously from two adjacent tracks. The crosstalk between two adjacent tracks is removed by pre-coding. Track pitch is 1/2 roughly 0.45 microns. Hence, the optical spot always sees two tracks at once. The signal from the first track is read separately. Then, for all subsequent tracks, one of the track signals is subtracted from the combined signal. The use of a 2D code is envisioned to minimize crosstalk between tracks that are read simultaneously.
- Using SCIPER together with RPR to improve the track density can extend the areal density up to 100 Gb/in<sup>2</sup> or about 150 GB per disk. Please note that this is a ROM technology. Excellent signal-to-noise ratios will be required. The key will be extremely precise mastering technology with better than 7 nm resolution.

In the final presentation, Dr. Kubota discussed Sony's advanced mastering technology. It uses quadrupling of a YAG laser to achieve a wavelength of 266 nm. The non-linear crystal is a Czochralski grown beta barium borate. The cutoff wavelength is about 193 nm. Scattering at 213 nm is less than 2%. The power in the green laser is 0.45 watts and the output power at 266 nm is about 100 mW. Lifetime is more than 1,000 hours at this power in a shoe box sized device.

## SUMMARY

Sony has made major investments in optical disk recording, both erasable and read only. The company is not publicly committed, as yet, to either phase change or magneto-optic technology for its product roadmap. Managers feel that both technologies can lead to products in the 15-30 GB range. They have shown the feasibility for a ROM product with over 100 GB capacity per disk.




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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

Site: **Sanyo Corporation**  
**Hypermedia Research Center**  
**Optical Recording Technology**  
**180, Ohmori, Anpachi-cho**  
**Anpachi-gun, Gifu 503-01, Japan**  
<http://www.sanyo.co.jp/><sup>89</sup>

Date Visited: 3 April 1998

WTEC: M. Mansuripur (report author)

Hosts:

- Dr. Satoshi Sumi, Manager, Optical Recording Technology Lab.
- Dr. Minoru Kume, Principal Specialist, Recording Media Dept.

## BACKGROUND

This group is involved only in magneto-optical (MO) recording research, although Sanyo manufactures CD, CD-ROM, MiniDisc, pickups, and lasers for the optical data storage market. Advanced storage magneto-optics (ASMO) technology seems to be one focus of research at Sanyo. The current plans call for the 6 GB ASMO disk on a 12 cm platter (single-sided), followed by the second-generation disk at 12 GB using the MAMMOS technology, and leading up to the 30 GB disk in the third generation.

According to the Sanyo researchers, magnetic-field modulation (MFM) recording is attractive because it offers the possibility of recording domains as small as 0.1 microns in diameter. Although the minimum required data rate is currently around 4 Mb/s, they foresee the potential of 50 Mb/s data rates in the next 2-3 years using the MFM technique. They also believe that in the near future access times will reach below the current value of 60 msec.

## R&D ACTIVITIES

The substrate thickness for ASMO disks is 0.6 mm in the data area (1.2 mm in the central hub area). The tilt of the disk is not considered a serious concern here because MFM recording and the technique of magnetic super resolution (MSR) readout used in ASMO disks are not tilt-sensitive. Therefore high-numerical aperture objectives can be used in conjunction with the 0.6 mm substrate without much concern for tilt-induced coma. The preferred mode of MSR seems to be CAD-MSR. The GdFeCo layer used as the readout layer has a large Kerr signal, even at short (blue) wavelengths. As for future-generation devices using blue laser diodes, the Sanyo researchers mentioned that they had researched superlattice materials such as PtCo, but they also felt confident that, using the MAMMOS technology, TbFeCo and GdFeCo media would offer sufficient sensitivity and acceptable levels of signal-to-noise ratio (SNR) at short wavelengths.

It was mentioned that the density of MO media is limited only by the width of magnetic domain walls in amorphous RE-TM alloys (on the order of 10-20 nm), and that data transfer rates are limited perhaps by the 10 psec time constant for magnetization reversal in these media.

Concerning the competition between hard disk drives (HDD) and optical disk drives (ODD), the hosts expressed the view that both technologies will coexist in the future. While HDD is superior in terms of cost-performance and data rate, ODD has the advantage of removability and mass-reproducibility. It was mentioned that the rapid growth and the pace of change in HDD technologies is perhaps the reason why the Japanese companies are not leading in this area. Slow decisionmaking processes were blamed for the slow pace of change in Japan. The hosts emphasized that while the hard disk drives are made in the United States, many parts and components come from Japan. The focus of magnetic recording in Japan seems to be on magnetic tapes for VCRs.

The Sanyo researchers felt that the MO technology is superior to phase-change (PC), even in terms of compatibility with DVD-ROM. The wollaston prism, for example, costs under a dollar in large quantities, and silicon photodiodes are very cheap; in fact the split detectors needed in MO drives are about the same price as the single-detectors used in PC drives. Some versions of MAMMOS operate without a magnetic field whatsoever. So all the talk of MO being more expensive than PC, they contend, is unrealistic.

It was mentioned that the growth path for LIMDOW technology is through MSR and blue lasers, although the researchers felt that the commercialization of high-power blue lasers before the end of 1998 was not likely. They also emphasized the importance of the PRML technique for high-density recording. As for the use of liquid crystal (LC) devices in optical disk drives, they mentioned that Sanyo currently uses LCs in its DVD-ROM drives to achieve compatibility with CD-ROMs, but they said that the cost of these elements must come down before their use becomes widespread.



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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_13.htm](http://itri.loyola.edu/hdmem/c_13.htm)

Site: **Toshiba Corporation**  
**(optical storage presentations)**  
**Research and Development Center**  
**1 Komukai Toshiba-cho, Saiwai-ku**  
**Kawasaki 210-8582, Japan**  
<http://www.toshiba.co.jp/><sup>90</sup>

Date Visited: 12 March 1998

[http://itri.loyola.edu/hdmem/c\\_17.htm](http://itri.loyola.edu/hdmem/c_17.htm)

WTEC Attendees:

- K. Rochford (report author)
- W. Doyle
- S. Esener
- M. Keshner
- M. Kryder
- S. Lin
- C. McClintick
- H. Morishita
- D. Thompson

Hosts:

- Mr. Haruo Nakatsuka, VP, Chief Research Dir., R&D Center
- Dr. Riichi Kato, Chief Specialist, Research Planning
- Dr. Nobuyuki Toyoda, General Manager, Materials and Devices Research Labs
- Mr. Setsuo Yamamoto, Group Mgr., Research Administration
- Dr. Yasuo Ikawa, Group Manager, Research Planning
- Mr. Masashi Sahashi, Project Manager, Magnetic Head Development Lab
- Dr. Kozo Sato, Senior Manager, Advanced Research Lab
- Mr. Katsutaro Ichihara, Sr. Research Scientist, Research Lab III
- Dr. Koichiro Inomata, Senior Chief Fellow
- Dr. Kenji Sano, Senior Research Scientist, Research Lab V
- Dr. Tatsuo Fujiwara, Fellow, Toshiba Research Consulting Corp.
- Dr. Hideyuki Nishizawa, Research Scientist, Research Lab III
- Mr. Hiromichi Kobori, Sr. Research Scientist, Research Lab IV
- Dr. Yuji Kubota, Sr. Mgr., Hard Disk Drive Technology Dept.
- Mr. Yoichiro Tanaka, Group Manager, Hard Disk Drive Technology Dept.
- Mr. Yoshinori Fujimori, Chief Specialist, Research Administration
- Dr. Katsuyuki Naito, Senior Research Scientist, Advanced Research Lab

## BACKGROUND

Toshiba is a large producer of computing and communications systems, electronic devices, consumer electronics, household appliances, and power generation and distribution equipment. With 186,000 employees, Toshiba had net sales for FY 97 (ending 3/31/97) of nearly \$44 billion, and about \$2.7 billion was allocated for research and development (6.1% of net sales).

Toshiba's R&D is organized into Corporate Laboratories for long range research (5 + years), Development Laboratories for medium term research (3-5 years), and Business Group Engineering Departments for short range (< 3 years) work. The Research and Development Center, one of two corporate laboratory centers, employs about 1,300 scientists and engineers (~13% PhD, ~61% MS) divided among 9 laboratories.

Toshiba has been very active in optical data storage, and was a founding member of the DVD alliance (and developer of the Super Density format before the DVD consolidation).

## DISCUSSION

The 31/2 hour meeting included summaries of Monday's workshop presentations from the WTEC panelists and five presentations from Toshiba scientists, two of which discussed optical storage. Before the presentations, the panel was treated to a demonstration of high-definition video recorded on HD-DVD (a 15 GB 120 mm disc).

Dr. Naito's talk on "novel optical memory functions using organic dot structures" described work to find a high density recording material applicable to near-field scanning microscopy. Dr. Naito described a method based on photoluminescence, motivated in part by his comment that conventional materials have low contrast (1% for magneto-optic and 10% for phase change). He has prepared 10 ~ 100 nm diameter organic dots by vacuum evaporation and read the photoluminescence from each island with an NSOM probe. To record, a gold-coated AFM tip held at a voltage injects charge into the organic islands. If charge isn't injected, the maximum luminescence is observed. Injecting holes into the island, however, quenches the luminescence, and minimal light is detected by the NSOM probe. The quenched state is stable for at least 9 hours. In addition, the amount of injected charge can be varied by the tip voltage and the quenching of photoluminescence controlled, raising the possibility of multilevel recording.

The diameter and thickness of the islands can be somewhat controlled. The spatial distribution of dots is not well controlled, however, and work is underway to improve dot placement.

Mr. Kobori presented a talk on the "future prospects of DVD technology." For replicated DVD, he predicts that a 30 GB disc will be available by 2001 and will double in capacity to 60 GB by 2006. Toshiba demonstrated 15 GB using a green SHG source last year, and is working on 30 GB using a blue laser. For DVD-RAM, based on phase change media, 9.4 GB will be available next year, and 30 GB should arrive by 2005. The intent is to increase density through media and system changes rather than increasing NA. Systems using blue lasers and PRML will be introduced in 2001, and media superresolution will be used in 2005.

Key technologies for the 30 GB HD-DVD include blue (410 nm) laser and PRML. The smallest mark length is 0.2  $\mu\text{m}$ , and the track pitch is 0.4  $\mu\text{m}$ . Track pitch deviation must be (5 nm, requiring mastering improvements such as short-wavelength lasers (260 to 350 nm), improved resists, better servo control, and possibly superresolution technology. A future format, UD-DVD, would hold 50 to 60 GB, use a 0.2  $\mu\text{m}$  track pitch (with 2.5 nm maximum deviation) and 0.1  $\mu\text{m}$  minimum mark length. Mastering will require electron beam sources or possibly SIL methods.

Toshiba is doing little or no magneto-optic work and is not involved in the ASMO format. MO is considered to be too wavelength sensitive and not a good material for blue laser recording.

## SUMMARY

Toshiba has a well developed roadmap for increasing DVD capacity and performance. The plan includes holding the numerical aperture to 0.6 for cross-compatibility, while pushing other aspects of the system and media to gain improvements. Phase change material is considered to be the best choice for RAM discs.



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**Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>**

[http://itri.loyola.edu/hdmem/c\\_17.htm](http://itri.loyola.edu/hdmem/c_17.htm)

Site: **Toshiba Corporation**  
**(magnetic storage presentations)**  
**Research and Development Center**  
**1 Komukai, Toshiba-cho**  
**Saiwai-ku, Kawasaki 210-8582, Japan**  
<http://www.toshiba.co.jp/><sup>90</sup>

Date Visited: 12 March 1998

WTEC:

- D. Thompson (report author)
- W. Doyle
- S. Esener
- M. Keshner
- M. Kryder
- S. Lin
- C. McClintick
- H. Morishita
- K. Rochford
- G. Whitman

Hosts:

- Mr. Haruo Nakatsuka, VP, Chief Research Dir, R&D Center
- Dr. Riichi Kato, Chief Specialist, Research Planning
- Dr. Nobuyuki Toyoda, General Mgr, Materials and Devices Research Labs
- Mr. Setsuo Yamamoto, Group Manager, Research Administration
- Dr. Yasuo Ikawa, Group Manager, Research Planning
- Mr. Masashi Sahashi, Project Manager, Magnetic Head Development Lab
- Dr. Kozo Sato, Senior Manager, Advanced Research Lab

[http://itri.loyola.edu/hdmem/c\\_18.htm](http://itri.loyola.edu/hdmem/c_18.htm)

- Mr. Katsutaro Ichihara, Sr. Research Scientist, Research Lab III
- Dr. Koichiro Inomata, Senior Chief Fellow
- Dr. Kenji Sano, Senior Research Scientist, Research Lab V
- Dr. Tatsuo Fujiwara, Fellow, Toshiba Research Consulting Corp.
- Dr. Hideyuki Nishizawa, Research Scientist, Research Lab III
- Mr. Hiromichi Kobori, Sr. Research Scientist, Research Lab IV
- Dr. Yuji Kubota, Sr. Manager, Hard Disk Drive Technology Dept.
- Mr. Yoichiro Tanaka, Group Manager, Hard Disk Drive Technology Dept.
- Mr. Yoshinori Fujimori, Chief Specialist, Research Administration
- Dr. Katsuyuki Naito, Senior Research Scientist, Advanced Research Lab

## BACKGROUND

Toshiba is a diversified company with more than \$44 billion in sales. More than half of that is in the information/communications systems and electronic devices segment. In the computer marketplace, it is especially strong in laptop computers, where it is the industry leader. Toshiba has a major market share in liquid crystal displays, 2.5 inch HDDs, and optical storage devices for the portable market.

Toshiba R&D Center is a world-class facility, with more than a thousand researchers. It is just one of 15 Toshiba labs worldwide.

## DISCUSSION

After an overview presentation by Mr. Nakatsuka, and a series of summary presentations by the U.S. panelists, the panel received presentations on spin-dependent tunneling, contact recording head technology, and GMR head technology. The spin-dependent tunneling work by Dr. K. Inomata is aimed at increasing head sensitivity by increasing the delta R and at improving reliability by reducing the likelihood of pinhole shorts. To this end, Toshiba researchers use a double gap resonant tunneling geometry. The results are very impressive, though the impedance of 10,000 ohms for a one square micron device is still too high for high data rate applications.

The contact recording work by Dr. Y. Kubota is aimed at producing a head/disk interface with less than 10 nm spacing, which will be needed for ultra-high density magnetic recording. The approach is conceptually related to the Tripad technology developed by Readrite Corporation. It remains to be seen whether the resulting low contact pressure will allow an acceptable wear rate and lifetime. It may turn out that this interface is practical for low speed applications only.

The third Toshiba talk by, M. Sahashi, was on a suite of technology improvements that allow the company to make a high performance, high output bottom type spin valve using <111> oriented IrMn antiferromagnetic pinning layers and CoFe/Cu/CoFe GMR layers. This shows that Toshiba is at the leading edge in spin valve design and materials. Detailed discussion of this topic does not fit the five to 15 year pre-competitive charter of this study, but the WTEC panelists found it impressive.

## LAB TOURS

The panel received a visually stunning demonstration of high resolution DVD technology at the Toshiba Science Institute Theater.

## SUMMARY

Toshiba maintains one of Japan's strongest research organizations in advanced data storage. In the magnetic recording area, its roadmap seems to correspond to that in the United States, with the possible exception of an earlier approach to contact recording than is expected here. Toshiba's work on spin tunneling has the potential of very large efficiencies, but cannot be fully evaluated at high data rates until a method of lowering the impedance is found, or until a high impedance amplifier can be incorporated into the sensor itself.



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*Published: June 1999; [WTEC Hyper-Librarian](#)<sup>5</sup>*

[http://litri.loyola.edu/hdmem/c\\_18.htm](http://litri.loyola.edu/hdmem/c_18.htm)

Site: **TDK Corporation**  
**Chikumagawa #2 Technical Center**  
**Data Storage Components Business Group**  
**543 Otai, Saku, Nagano, Japan**  
<http://www.tdk.co.jp/tetop01/index.htm><sup>91</sup>

Date Visited: 13 March 1998

WTEC:

- D. Thompson (report author)
- G. Whitman

Hosts:

- Dr. Joichiro Ezaki, Executive Director, Gen. Mgr., Data Storage Components Group
- Dr. Isamu Sato, General Manager, Storage Device Group, Advanced Products Development
- Dr. Mikio Matsuzaki, Head, Products Division No. 1, Data Storage Components Group
- Dr. Haruyuki Morita, Manager, Thin Film Head Development, Data Storage Components Group
- Dr. Satoru Araki, Assoc. Mgr., Advanced Materials R&D Dept., Data Storage Group
- Dr. Cheung Chi Yue, Raymond, Section Manager, Tribology and Mechanical Design

[http://litri.loyola.edu/hdmem/c\\_16.htm](http://litri.loyola.edu/hdmem/c_16.htm)

- Dept., SAE Magnetics (H.K.), Ltd.

## BACKGROUND

TDK is a \$6 billion per year company, of which about one-fourth is in data storage components. Product development is performed at the Nagano facilities, but advanced projects aimed at technologies more than three years in the future are also conducted at the corporate R&D center in Chiba.

TDK's reputation and income in the storage business are based on its optical storage media and its thin film recording heads. This visit dealt only with heads. TDK has been shipping MR heads since 1994 and was planning spin valve head production for 1998. At the time of this WTEC visit, the company was capable of producing about 50 million heads per year.

## DISCUSSION

Dr. Ezaki presented TDK's long-term technical strategy. In terms of basic head technology, spin valves are expected to continue beyond 20 Gb/in<sup>2</sup>, followed by some sort of tunneling GMR devices. Since TDK does not make media, it is spared the need to deal immediately with the superparamagnetic effect, but it is prepared to design heads for either perpendicular or longitudinal media, patterned or not. In the very long term, beyond 200 Gb/in<sup>2</sup>, TDK managers anticipate replacing magnetic recording with something else, such as holographic storage or probe storage.

Dr. Ezaki observed that the current rapid pace of advances in HDD areal density is having a chilling effect on alternative technologies. For example, ferroelectric RAM, which was being pursued at TDK as an alternative to disk storage, has been de-emphasized at TDK in recent years for this reason. Probe storage was also discussed, but the data rate problems of this technology remain a key inhibitor. No specific programs in these areas were presented.

TDK's primary advanced technology thrust at this time is aimed at improving read head sensitivity and write head bandwidth, and at addressing the problems of the ultra-high track densities that will soon be needed. The first topic does not fit this WTEC study's charter of pre-competitive technologies, and was not pursued, but dual-stage actuators were discussed. TDK's strength in ceramics and integrated suspension design leads naturally to a piezoelectric actuator approach. Its first attempt uses a small laminated PZT bender bonded between the slider and the suspension. TDK researchers can achieve a one micron displacement for a 10 volt swing, with a first resonance at 20 kHz. This is a very impressive result, and could be extremely important to the industry. The principal negative is the additional disk-to-disk spacing required. Other details not addressed include the necessary scheme for carrying conductive leads from the suspension to the head.

Another important project involves placing a silicon chip near the head end of the suspension, to eliminate transmission line effects in writing. TDK researchers were able to minimize non-linear transition shift to beyond 400 Mtps in this manner.

The discussion then turned to modeling of the magnetic recording process. The WTEC panel saw presentations of a number of papers that have been or will be published in this area. Of particular interest to this study were discussions of the comparative results on longitudinal and perpendicular recording, and on GMR head sensitivity during scaling to very narrow tracks.

## SUMMARY

It appears that TDK managers agree with the U.S. panelists on the important strategic issues, and have a good program for addressing the head/suspension problems of the next ten years, provided that magnetic recording continues to prevail. The WTEC team did not review GMR heads in detail but did see impressive work on a PZT dual-stage actuator and high bandwidth chip-on-suspension technology.

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*Piezoelectric piggy-back microactuator for hard disk drive.* Submitted to APMRC '98



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[http://itri.loyola.edu/hdmem/c\\_16.htm](http://itri.loyola.edu/hdmem/c_16.htm)

Site: **Hitachi Central Research Laboratory (HCRL)**  
(optical storage presentations)  
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Kokubunji, Tokyo 185, Japan  
<http://koigakubo.hitachi.co.jp/82>

Date Visited: 12 March 1998

WTEC:

- S. Esener (report author)
- W. Doyle
- M. Keshner
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- M. Mansuripur
- D. Thompson

Hosts:

[http://itri.loyola.edu/hdmem/c\\_06.htm](http://itri.loyola.edu/hdmem/c_06.htm)

- Dr. Ryo Imura, Department Manager, Information Storage Research Dept.
- Dr. Takashi Yamaguchi, Senior Researcher, 2nd Dept., Hitachi Mechanical Engineering Research Lab.
- Mr. Hishashi Takano, Senior Researcher, Information Storage Research Dept.
- Mr. Yoshihiro Hamakawa, Senior Researcher, Information Storage Research Dept.
- Dr. Masaaki Futamoto, Chief Research Scientist, Information Storage Research Dept.
- Akira Arimoto, Chief Researcher, Electron Devices Research Department
- Dr. Kazuetsu Yoshida, Senior Researcher, Information Storage Research Dept.
- Dr. Sumio Hosaka, Senior Research Scientist, Advanced Research Laboratory
- Mr. Hirofumi Sukeda, Senior Researcher, Optical Disc Storage Research Center, Information Storage Research Dept. & Image & Information Media Systems Div.
- Mr. Takeshi Maeda, Chief Researcher, Information Storage Research Dept.
- Mr. Shigeru Nakamura, Senior Researcher, Optical Disc Storage Research Center, Information Storage Research Dept.
- Mr. Yuko Nakamura, Engineer, Research Cooperation Center, Planning Office

## BACKGROUND AND ORGANIZATION

### Background

The main business of Hitachi, Ltd. and its subsidiaries is a combination of electrical, electronics and information systems. Hitachi is active in information and electronics (mainframes to microcomputers, magnetic and optical disks, telecommunication, medical electronics and chip making), power systems (nuclear and thermal power plant, transmission systems, pollution control equipment), industrial systems, transportation systems (elevators escalators, automotive), and consumer products (air conditioners, refrigerators, TV, VCR, video camera).

The Hitachi Central Research Laboratory (HCRL) was established in 1942 by Mr. N. Odaira, founder of Hitachi, Ltd. for "creating new basic technologies for the coming 10 to 20 years, as well as pursuing development work for today's business." HCRL is active in information and media, electronic devices, and medical electronics. Hitachi pursues joint development partnerships and alliances with other companies and universities in Japan and overseas to make use of R&D resources.

### Hitachi R&D Organization

Seven corporate research laboratories are directly attached to the president's office. These labs are the following:

- Central Res. Lab for Information and Electronics
- Hitachi Res. Lab for Power & Industrial Systems
- Mechanical Res. Lab for Mechatronics
- Production Eng. Res. Lab for Processing
- Systems Development Lab
- Design Center for Industrial Design

- Advanced Research Lab for Fundamental Science

In addition, R&D for product development is also carried out under the business groups. Hitachi also funds research facilities throughout North America, Europe and Asia.

## HCRL Organization

Research in HCRL is carried out in 13 departments. These include the following:

1. Advanced Technology Research
2. Electron Devices Research
3. ULSI Research
4. System LSI Research
5. Information Storage Research
6. Optoelectronics Research
7. Processor Systems Research
8. Network Systems
9. Communication Systems Research
10. Multimedia Systems Research
11. Medical Systems Research
12. Strategic Projects
13. Administration

## DISCUSSIONS

Dr. Yamaguchi described HCRL's effort in developing positioning technologies for 10 Gb/in<sup>2</sup> areal densities with  $t_{pi}=31.6$  K and  $T_p=0.8$   $\mu$ m. HCRL's present work aims at  $TW/TWR=0.63/0.50$ , with a settling of 0.08  $\mu$ m, non-repeatable runout (NRRO) = 0.096 (m and max TMP = 15%Tp. He noted that presently the dominant disturbances are of mechanical origin and the key is to increase the servo bandwidth. Present crossover frequency of 500 Hz produces an NRRO of 0.183  $\mu$ m. Future systems are aimed at 1 kHz with NRRO of 0.132 (m. At higher bandwidths the detection noise becomes dominant.

Several directions are being pursued to increase servo bandwidth including dedicated servos, multi-sensing and multi-stage approaches. Presently, for multi-sensing, sensors and accelerometers are placed at different locations on the actuator arm. In the future two stage actuators are being contemplated. However, this increases the number of servo systems. Piezoelectric actuators are considered to be promising, while the reliability of MEMS actuators remains a concern.

Mr. Sukeda discussed the future directions envisioned for optical data storage at HCRL. He indicated that the next generation of DVD would be aimed at satisfying the needs of HDTV, requiring 15 GB capacity for two hours video stream and approximately three times faster data rate than current DVD performance. HCRL does carry on research on both PC and MO media and on probe storage for the

future. During the visit, the discussion centered on PC media and probe storage.

The technologies that HCRL is developing for PCs include adaptive recording control to improve signal-to-noise ratios (for product insertion in 1999) of 4.7 GB DVDs and super resolution and blue laser recording (for product insertion in 2001) for 15 GB DVDs.

Adaptive recording control relies on contrast enhancement and thermal engineering of the media for more homogeneous absorption of heat and better reflectivity. To this end a thermal buffer layer and a contrast enhancement layer are introduced into the media as shown in Figure C.3<sup>177</sup>. This optimized media design should allow for 4.7 GB capacity per layer.

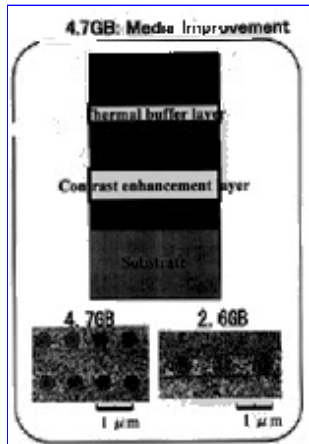


Fig. C.3. Improvement of SNR (~1999).

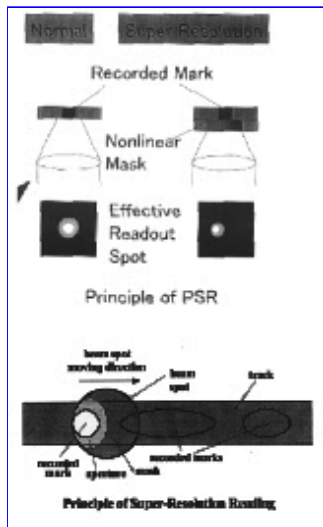


Fig. C.4. Super Resolution (~2001).

To keep backward compatibility, for the near future, increasing the NA of the optical system is not envisioned. Instead, media PSR is being investigated for 15 GB products. The principle of super-resolution (PSR) for PC media is based on affecting the intensity profile of the spot to be recorded by introducing a non-linear phase mask as described in Figure C.4<sup>177</sup>. A more conventional technique that was first studied was to introduce a photoreactive organic film to produce the mask.

However, because of the limited cycle ability of this film, HCRL researchers have developed a new oxide glass film, 200 nm thick, that contains Si, Na, Ca, Co, and O (proprietary composition). This film produces a very large index change ( $n \sim 0.5$ ) as a function of temperature ( $dn/dT$ ). The persistence of the change in the index is less than the time it takes for one disk rotation, and no damage is observed during reading and recording. However, 30% more laser power is required. Future efforts will be concentrated on improving recording sensitivity.

The structure of the new disk media is shown in Figure C.5<sup>178</sup>. It was also noted that blue lasers may be more important for PC media. But for next generation products, because of back compatibility considerations, the time is not considered ripe for introducing blue lasers in a product.

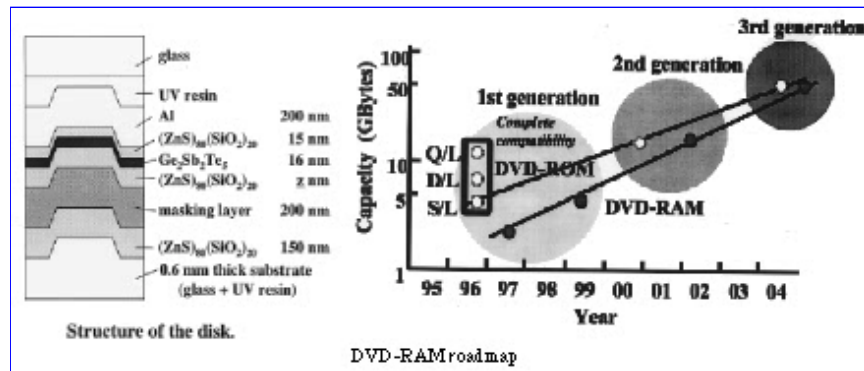


Fig. C.5. Cross-section of a PC disk with phase mask layer (L.) and HCRL roadmap for DVD products (R.).

Dr. Hosaka described HCRL's effort in probe storage to reach areal densities in the  $0.1\text{--}1\text{ Tb/in}^2$  range with 1 Mb/s data rate for ROM application. Both phase change and plastic media that can be deformed under heat are being studied using AFM pit recording. Using 15 mW from an SNOM probe and a 30 nm GeSbTe layer  $200\text{ Gb/in}^2$  densities have been demonstrated. Using a plastic deformation approach with a heated AFM tip, pits separated by 10 nm have demonstrated the feasibility of  $1\text{ Tb/in}^2$  densities. Read out is carried out with a probe oscillating at 2.3 MHz with a rotation speed approaching mm/s. For faster readout the oscillation frequency needs to be increased using a shorter and stiffer probe. Using this method with  $25\text{ nm} \times 12\text{ nm}$  pits separated by 20 nm on a disk rotating at 100 rpm, HCRL researchers have achieved a 1.25 Mb/s data rate. However, at this point reading from the same location with good repetition appears difficult. The WTEC team learned that Canon, Epson, Sharp and Matsushita are also involved in probe storage with their own approaches.

## OTHER DISCUSSIONS

HCRL researchers believe that PC can address many high performance applications with areal densities on the order of  $20\text{ Gb/in}^2$ . The main issue is to keep media compatibility for different applications. The researchers feel that the future of PC beyond  $20\text{ Gb/in}^2$  is not clear but point out that MO should be able to reach  $100\text{ Gb/in}^2$  densities because of an extra degree of freedom introduced by the magnetic field.



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[http://itri.loyola.edu/hdmem/c\\_06.htm](http://itri.loyola.edu/hdmem/c_06.htm)

## APPENDIX D. GLOSSARY

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AFM

atomic force microscope

ASMO

Advanced Storage Magneto-Optical Disk Group (also called MO7)

B/b

Byte/bit (example: GB = gigabyte, Gb = gigabit)

BDO

binary diffractive lenses

CAD

central aperture detection

CD

compact disk

CD-R

compact disk recordable

CD-ROM

compact disk read only memory

CPU

computer processor unit

CW

continuous wave (laser beam)

DAT

digital audio tape

DDS

digital data storage

DLT

digital linear tape

DOW

direct overwrite

DRAM

dynamic random access memory

DVD

digital video disk

DWDD

domain wall displacement detection

[http://itri.loyola.edu/hdmem/d\\_01.htm](http://itri.loyola.edu/hdmem/d_01.htm)

|          |                                             |
|----------|---------------------------------------------|
| DVD-RAM  | DVD random access memory                    |
| DVD-ROM  | DVD read only memory                        |
| DVD + RW | DVD + read write                            |
| FAD      | front aperture detection                    |
| FEP      | field emission probe                        |
| GMR      | giant magnetoresistive (head technology)    |
| GRIN     | gradient index lenses                       |
| HDD      | hard disk drive                             |
| HDTV     | high definition television                  |
| HOE      | holographic optical element                 |
| LC       | liquid crystal                              |
| LIM      | light intensity modulation                  |
| LIMDOW   | light intensity modulation direct overwrite |
| MAMMOS   | magnetic amplifying magneto optical system  |
| Mb/s     | megabit per second                          |
| MB/s     | megabyte per second                         |
| MD       | mini disk                                   |
| MFM      | magnetic field modulation                   |
| MEMS     | micro-electro mechanical systems            |
| MO       | magneto-optic                               |
| MP       | metal particle (tape)                       |
| MR       | magnetoresistive                            |
| MSR      |                                             |

|        |                                                                                                                                |
|--------|--------------------------------------------------------------------------------------------------------------------------------|
|        | magnetic super resolution                                                                                                      |
| NA     | numerical aperture ( $NA = \sin \theta$ , where $\theta$ is the half-angle subtended by the focused cone of light at its apex) |
| NAIR   | National Institute for Advanced Interdisciplinary Research (Japan)                                                             |
| NFO    | near field optics                                                                                                              |
| NRRO   | non-repeatable runout                                                                                                          |
| NSIC   | National Storage Industry Consortium (U.S.)                                                                                    |
| NSOM   | near field scanning optical microscope                                                                                         |
| NTT    | Nippon Telegraph and Telephone Corporation (Japan)                                                                             |
| ODD    | optical disk drives                                                                                                            |
| OITDA  | Optoelectronics Industry and Technology Development Association (Japan)                                                        |
| PA     | polyamid                                                                                                                       |
| PC     | phase change                                                                                                                   |
| PEN    | polyethylene naphthalate                                                                                                       |
| PET    | polyethylene terephthalate                                                                                                     |
| PRML   | partial response maximum likelihood                                                                                            |
| PRC    | photorefractive crystals                                                                                                       |
| RAD    | rear aperture detection                                                                                                        |
| RAID   | redundant array of independent disks                                                                                           |
| RAM    | random access memory                                                                                                           |
| ROM    | read only memory                                                                                                               |
| RPR    | radial direction partial response (Sony)                                                                                       |
| RW     | read/write                                                                                                                     |
| SCIPER |                                                                                                                                |

|       |                                                      |
|-------|------------------------------------------------------|
|       | single carrier independent pit edge recording (Sony) |
| SHG   | second harmonic generation                           |
| SIL   | solid immersion lens                                 |
| SRC   | Storage Research Consortium (Japan)                  |
| STM   | scanning tunneling microscope                        |
| TEM   | transmission electron microscope                     |
| VCSEL | vertical cavity surface emitting laser diodes        |
| WDM   | wave division multiplexing                           |
| WORM  | write once read many                                 |




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 [69] [http://itri.loyola.edu/hdmem/fh07\\_16.gif](http://itri.loyola.edu/hdmem/fh07_16.gif)  
 [70] [http://itri.loyola.edu/hdmem/fh07\\_17.gif](http://itri.loyola.edu/hdmem/fh07_17.gif)  
 [71] [http://itri.loyola.edu/hdmem/fh07\\_18.gif](http://itri.loyola.edu/hdmem/fh07_18.gif)  
 [72] [http://itri.loyola.edu/hdmem/fh07\\_19.gif](http://itri.loyola.edu/hdmem/fh07_19.gif)  
 [73] [http://itri.loyola.edu/hdmem/fh07\\_20.gif](http://itri.loyola.edu/hdmem/fh07_20.gif)  
 [74] [http://itri.loyola.edu/hdmem/fh07\\_21.gif](http://itri.loyola.edu/hdmem/fh07_21.gif)  
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 [76] <http://www.fujitsu.co.jp/index-e.html>  
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