MASS DATA STORAGE

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Thomas M. Coughlin, Chair Roger Hoyt, IBM, Co-Chair

EXECUTIVE SUMMARY

The mass data storage industry is progressing at a somewhat slower pace of technology development than in the late 1990s and early 2000s. The industry continues to operate in a challenging business environment. While much advanced development and some component manufacturing will remain in North America, competitive pressures to maintain profitability have required this U.S. initiated industry to locate over 90% of its volume manufacturing and assembly outside North America. In addition, much of the component technology development as well as disk drive company ownership are now outside of North America, especially with the rate of consolidation such as the sale of IBM's disk drive division to Hitachi. Independent component suppliers for key components such as heads and disks have shrunk significantly with developments such as Read Rite becoming the in-house head manufacturing division of Western Digital.

Current areal densities of announced disk products now exceed 15.5 Gb/cm^2 (100 Gb/in^2). Recent technical advances suggest storage areal densities over the next decade may attain or even surpass 155 Gb/cm^2 (1000 Gb/in^2). Other critical enablers for mass storage's continued advances in capacity and performance are perpendicular recording, heat assisted magnetic recording, availability of micro-electromechanical systems (MEMS) technology, smaller disk drive form factors, and a broad set of new consumer and appliance applications for mass storage data products.

Digital tape storage will likely continue to play a vital role in the storage hierarchy, but not without substantial changes to tape subsystem architectures. The sequential access of tape will limit the applications to which it can be put. However, for archival applications tape has a long history and competing disk-based technologies will have to develop considerable field experience before many IT managers will trust their archived data on them. Technical advances in capacity per cartridge and performance (data transfer rate) will continue.

Optical storage is a diverse and growing family of products for audio-video publication and recording, software and database distribution, and data backup and archiving. No storage technology provides more low-cost, application-specific solutions for consumer electronics. The 2003 ex-factory revenue for optical storage drives and media is almost $25 billion. Over the past 30 years, optical storage has also offered the IT market solutions ranging from 3.5" MO and 5.25" MO to 12" and 14" WORM, both stand-alone and optical disk library resident. In 1982, a family of 120mm disk read-only products was launched, starting with CD-DA. DVD followed in 1995.

Today, third generation "blue laser" products with more than 20 GB capacity per storage layer are just entering the market. These products form the consumer electronics core of the optical storage business. Holographic memories systems are also poised for shipment within the next 12

months. Optical storage highlighted in the roadmap period 2005-2015 has the potential to reach capacity levels of 200 GB for both read-only (replicated) and recordable/rewritable (WO/RW) media on multilayer 120mm diameter disks. UDO (Ultra Density Optical) technology using WO and RW 130mm phase change disks could reach a capacity of 240 GB before 2015.

Although the future of optical storage appears assured for at least the next 10 years, the technology has reached a critical plateau. The wavelength limit (405 nm) of laser diodes in the conventional optical domain (400-700 nm) has been reached, as have the practical limits of objective lens numerical aperture (0.85) and rotation speed (about 10,000 rpm). New technologies and materials that provide super resolution and low-noise operation at UV wavelengths will be required to drive the future of "optical" (using an extended definition) storage beyond the projections of the current roadmap.

A number of alternative approaches to today's established data storage technologies will develop over the next decade. These include magnetic random access memory (MRAM), probe-based, molecular, fluorescent multilayer optical, near-field optical and 3-D holographic storage components and systems. The impact on the design and performance of MEMS and nanotechnology on data storage is expected to be significant.

North America will continue to support innovation and development and continue driving advances in mass data storage technology. This includes not only industrial development, but also activities in government and academic labs as well as industry associations and consortia, and support of the supplier infrastructure.

INTRODUCTION

From the computer industry's first use of digital magnetic recording for system level storage in 1955, the worldwide information processing industry has grown to rely heavily on magnetic mass data storage. The industry is large, with total annual revenue in excess of $50 billion and shipped volumes of rigid disk drives of about 262 million units in 2003 (**Figure 1**). Many industries, such as banking, retailing, insurance, travel, etc., depend on the rapid and reliable access to customers' data records in their day-to-day operation. **Figure 2** shows the expected growth in information storage requirements over the next few years. Between 2004 and 2007 we can expect at least a four-fold increase in the amount of digital stored data (both original data and copies). Much of this data storage capacity is made possible by magnetic mass storage technology. The broad spectrum of technologies used includes floppy and rigid disks, tape, flash memory, and a number of read-only, write-once, and read-write optical storage approaches. **Figure 3** shows the storage system hierarchy where different data storage systems are compared regarding cost, capacity, and data access time.

Figure 1. World Wide Disk Drive Production vs. Application
(Source: Coughlin Associates, 2004)

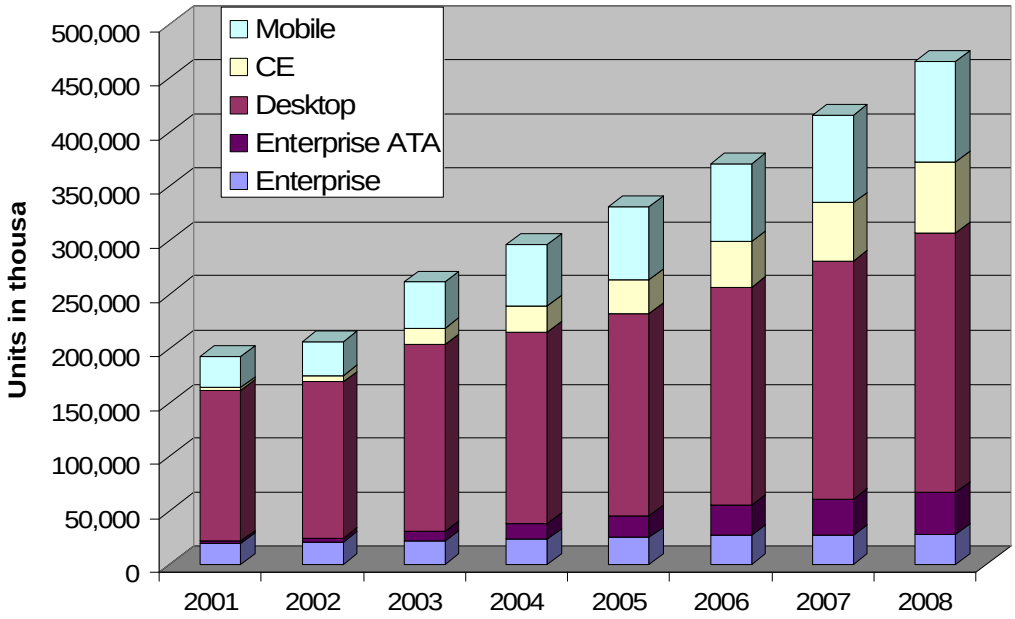


Figure 2. Expected Growth in Information Storage Requirements

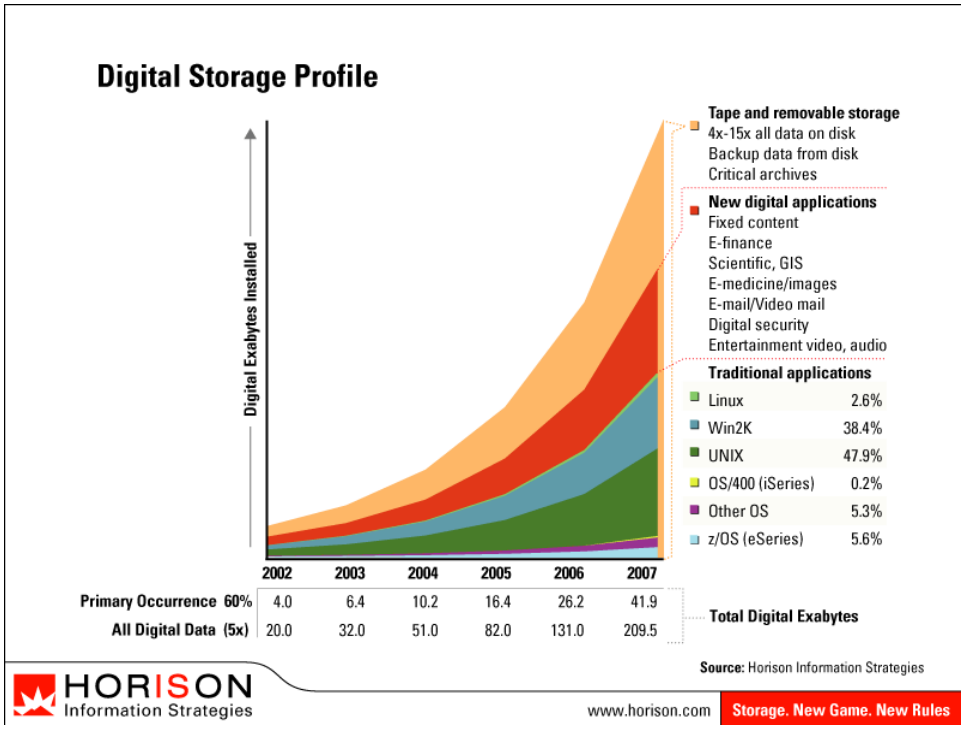
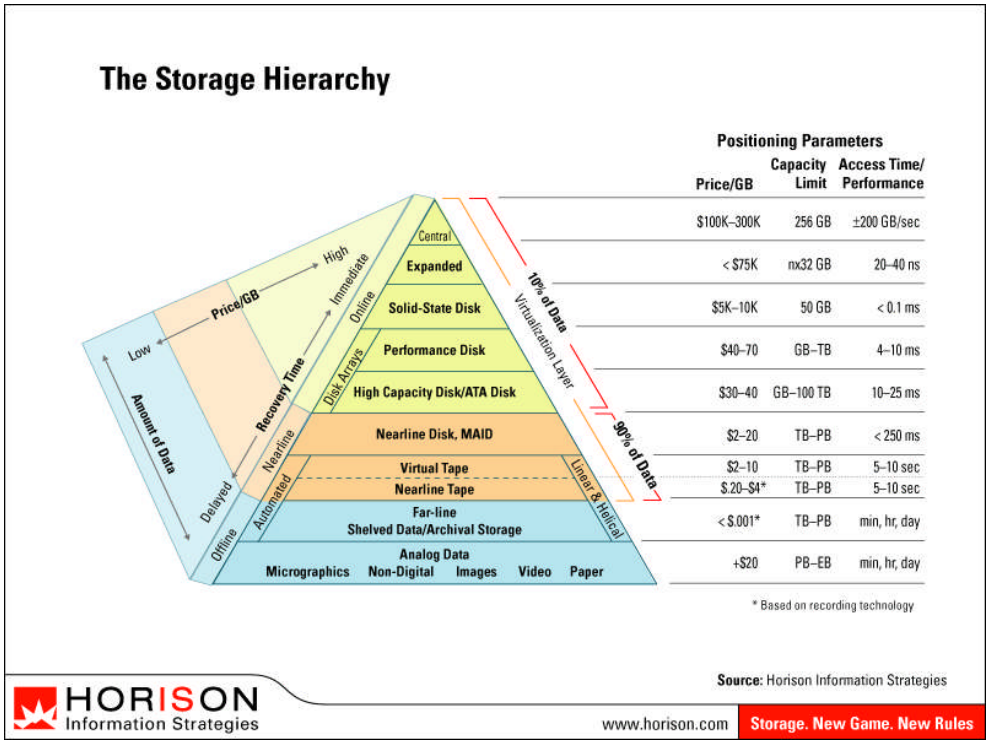


Figure 3. Data Storage Hierarchy



Application platforms span the entire range from high performance mainframe, servers, workstations, and desktop personal computers, to mobile laptop and even hand-held or wearable units. The largest growth areas in data storage are mobile, network storage, and new consumer applications such as MP3 and video players. Network storage is primarily used in centralized server based storage for the large databases critical for corporations' critical assets. Personal computer data storage will remain the largest storage application for some time to come but will not fuel expected storage growth like it has in the past. As shown in **Figure 1** we expect that the majority of growth in the future will come from consumer applications, mobile computer drives, and network storage. **Figure 1** also show that disk drives with the ATA or SATA interface are expected to play a more and more dominant role in the network storage or "enterprise" markets.

From being almost entirely U.S. based, the magnetic storage industry has, over the past 23 years, truly become globalized (compare **Figure 4** and **Figure 5**). This has included entry of foreign-based companies into the market, foreign acquisition of some U.S. manufacturers, and movement offshore of substantial manufacturing assembly facilities by all U.S.-based companies. This movement of manufacturing outside North America has been driven by competitive pressures to decrease costs, improve efficiency, and to locate close to emerging markets. It is also possible, with the sale of IBM's disk drive business to Hitachi as well as further mergers and exits in the drive and components industry that we may start to see erosion of the North American technology base. In the past technology such as development and shipment of recording heads with giant magnetoresistance (GMR) based read elements, advanced low noise thin film disk media and advanced partial response maximum likelihood (PRML) digital data detection

channels have had the majority of development in the U.S It remains to be seen whether this will continue to be the case. These and other advances have been key enablers to increasing areal density, capacity, and performance.

Figure 4. Assembly Locations, Desktop Drives, All OEM Firms, 1981

Figure 5. Assembly Locations, Desktop Drives, All OEM Firms, 2004

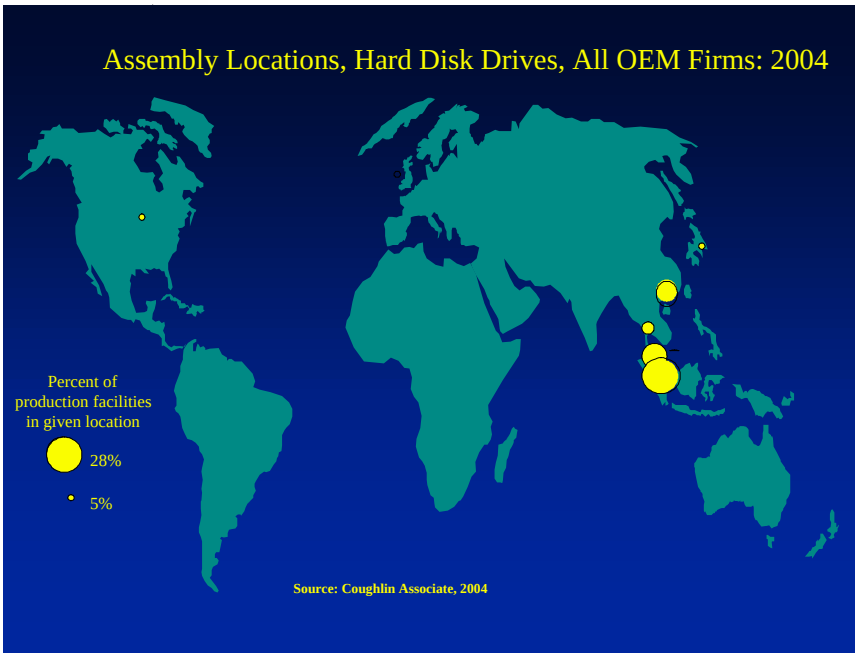


Figure 6 shows broad expectations of the development of magnetic recording technology over the next few years indicating major developments in production heads and media used in disk

drives. Synthetic antiferromagnetic (or antiferromagnetic) (SAF) media extends the thermal stability of longitudinal recording.

Because of the competitiveness of this industry there has been considerable consolidation of the drive and sub-component supplier base except in the very small form factor disk drives. As of mid-2004 there are only a handful of significant disk drive suppliers: Seagate, Maxtor, Western Digital, Fujitsu, Samsung, Toshiba, and Hitachi. With Hitachi's purchase of IBM's disk drive business the majority of disk drive producers are Asian-based, although the majority of disk drives are still produced by North American-based companies Seagate, Maxtor, and Western Digital. Note that 2003 saw the rise of two new small form factor disk drive companies. One of these is U.S. (Cornice) and the other based in China (GS MagicStor). These companies manufactured primarily 1.0-inch disk drives by 2004.

Magnetic mass storage technology advances have enabled the migration of disk units to 3.5-inch and smaller diameter form factors. The 3.5-inch and 2.5-inch form factors are present in all segments of the market: server, desktop, and mobile. The introduction of a 1-inch form factor in 1997 pointed the way to future configurations of the disk drives. Toshiba announced that they will make a 0.85-inch disk drive by the end of 2004. There are signs that 2.5-inch form factor disk drives may start to displace 3.5-inch drives for many applications due to the increasing areal recording density, limited data storage requirements for many applications, as well as constraints on available space in consumer electronics devices. **Figure 7** shows projections for disk drive form factors in coming years. Over the next several years there will be a significant trend towards smaller form factor disk drives for many applications.

Figure 6. Projected Areal Densities and Recording Technologies
Production Hard Disk Drives (Source: Coughlin Associates)

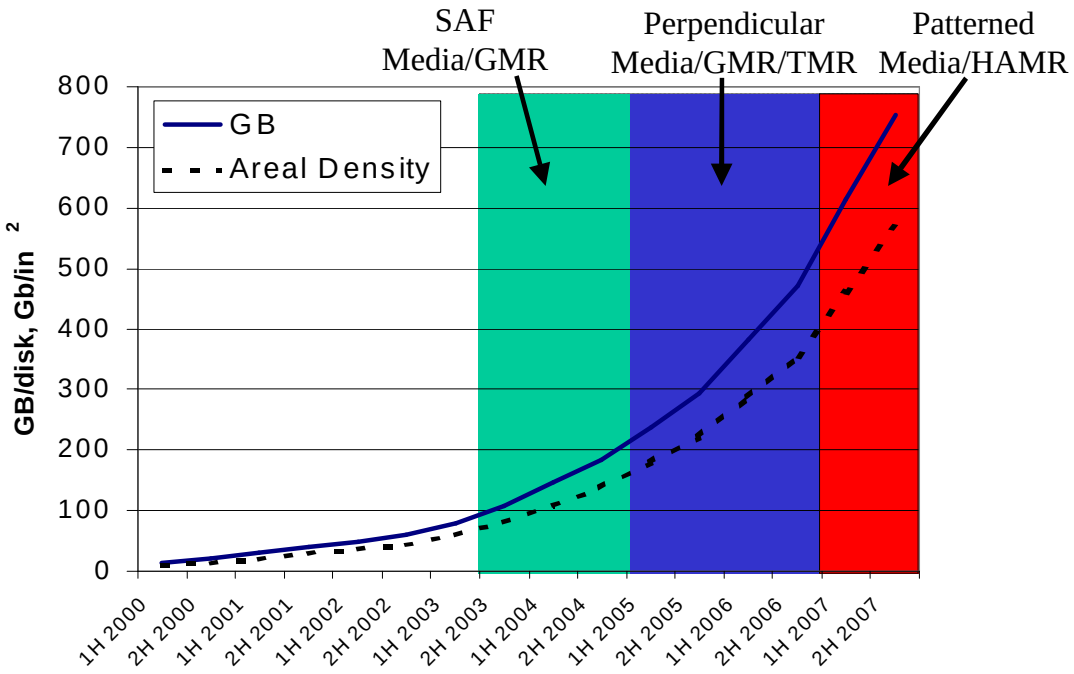
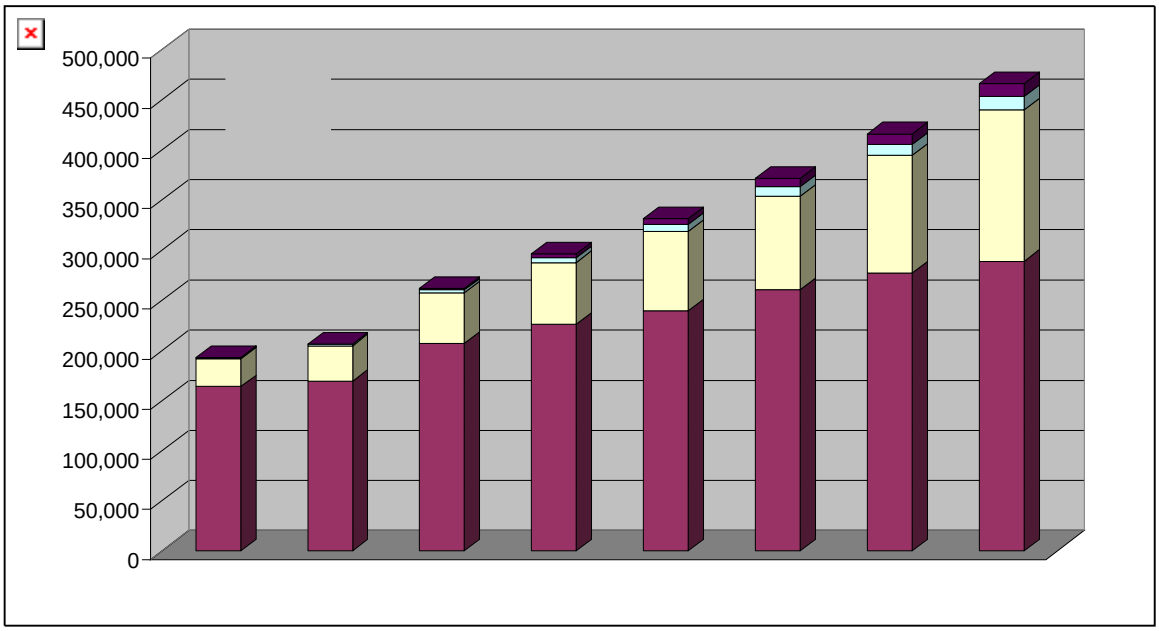


Figure 7. Projected Trends in Disk Drive Form Factors
(Source: Coughlin Associates)



A key factor in the increased capacity of the smaller drive units is the increase in areal density of stored information on a disk's surface. This has grown at an impressive 60% compound annual growth rate historically and accelerated to greater than 100% rate in the late 1990s and early 2000s. We expect that the long term trend will be between 40-60% compound annual growth, similar to the historical growth rate and also similar to that of semiconductor transistor density growth. The bit cell length corresponding to an areal density of 12.3 Gb/cm^2 (80 Gb/in^2) is much smaller than the minimum line width of current semiconductor products. Furthermore, track widths less than 50 nm are anticipated in the next decade, and sensor film thickness in advanced magnetoresistive read heads is already down to a few nanometers. Insulating layer thicknesses for future tunneling magneto-resistive junction (TMR) heads will be less than 1 nm.

A particular technical challenge will be making magnetic recording heads with track width dimensions that are smaller than the minimum feature size of the optical lithographic equipment used in the semiconductor industry. An additional constraint is balancing magnetic media thermal stability with signal to noise ratio (SNR). Electron Beam lithography is capable of supporting 50 nm track widths.

Often leveraging from magnetic disk's rapid technology advances, tape drives have increased in capacity and data rate, and are physically smaller--many tape drive product offerings are now in the 5.25-inch and 3.5-inch form factors. Automated tape libraries have become commonplace and have enabled a new class of storage access performance, falling between that of disk and manual tape.

Optical storage is provides very diverse choices of storage technologies. It includes read-only (RO), write-once (WO), and rewritable (RW) media and media removability. It enables consumer electronics (CE) products with high market appeal, ranking only after magnetic disk

drive penetration in the storage suites of PCs and workstations, and can be used for image and document capture, near-line storage, AV (audio-video) editing, and archiving in professional and enterprise applications. Attempts to find profitable market niches for optical storage over the past 40 years have led to a wide spectrum of technologies and disk sizes and types, competing with one another for a broad range of applications. However, very few optical storage products succeeded in being mass storage that achieved mass markets. Only highly standardized[1] products have achieved significant market penetration.

From about 1965 to 1987,[2] many people expected that rewritable optical storage would challenge and eventually displace magnetic storage. The extraordinary improvement in price/performance from 1987 to today made magnetic hard disk drives (HDDs) the dominant (general purpose) mass storage technology. Higher cost and lower throughput (data transfer rates and access times) make it impossible for optical storage to displace magnetic storage from its market segments. As a result, optical storage has evolved solutions that emphasize its strengths: (1) standardized, removable replicated media, (2) write-once (recordable), removable, crash-proof, and archival (long life) media, and (3) near-line storage using an optical disk library (ODL; also, "jukebox").

Optical storage for CE (personal entertainment) storage, on the other hand, was conceived for specific consumer applications (primarily, digital audio and video in the forms of read-only and recordable/rewritable CD and DVD media). Strict media standards permit specific applications to be implemented by means of signal processing, logical and applications level software, and packaging; for example, DVD-Video is a CE application of DVD-ROM (a computer storage technology), not a new format. Recall that a CD-DA replicated in 1982 can still be played today, more than 20 years later. The same will likely be true for SDTV (standard definition television) DVD disks and successors.

The successful introductions of CD-DA in 1982, CD-ROM in 1984, and DVD in 1995 ensured that almost all optical storage development resources would be focused on optical storage for CE and PC/Workstation applications. Computer data optical storage applications declined rapidly in the 1990s due both to the incredible achievements of magnetic disk storage and an unacceptably slow improvement in price/performance of optical storage systems. Today, only Fujitsu's highly reliable 3.5"/86mm ISO MO (magneto-optical) disk product line (offering 0.64, 1.3 and 2.4 GB media capacities) survives and prospers. The robust 5.25"/130mm ISO MO (magneto-optical) disk product line (offering 5.2 and 9.1 GB media capacities) has reached the end of its technology life, and is slowly being phased out of production. Plasmon's 30 GB UDO (Ultra Density Optical) 5.25"/130mm phase change product line was first shipped in late 2003. Although it's too early to speculate on reliability and market acceptance, UDO is generally acknowledged to be the successor to both 5.25" MO and 12" WORM storage.

Capacity and throughput for optical storage will continue to improve, although more slowly than for magnetic storage. Optical disk capacity increases not continuously, as is the case for

[1] Both public (for example, ISO and ECMA) and proprietary (for example, Sony/Philips "books" and the DVD Forum) standards have been promulgated.

[2] In 1987 Maxtor introduced a 780 MB FH magnetic disk drive. For the first time, the number of magnetic disk surfaces per spindle trumped the track density advantage of optical disk media. Consequently, magnetic disk drives would thereafter have the greater "box" capacity, an advantage likely to last for the indefinite future given the rate of disk drive areal density growth.

magnetic disk and tape, but in distinct leaps (for example, 650 MB CD to 4.7 GB DVD). Moreover, optical media are removable, which in itself mandates more conservative capacity targets. Throughput for optical storage devices, as defined by data rate and access time, is well behind that of magnetic disk drives. However, for the mainstream CE applications of optical disk hardware and media (CD and DVD), this has little consequence. The media and supporting drives are designed for specific applications (music and video playback being the best known). And even for PC/workstation applications, few would argue that installing a 50 MB program from a CD-ROM disk is inferior to installing it from a set of 3.5" floppy disks, even though the CD-ROM reader sustained data rate is less than 20% of the typical desktop hard disk drive. Optical drives and media designed for generic computer data storage (for example, 3.5" and 5.25" MO) aim to satisfy a higher performance standard.

The technology of optical storage has advanced significantly over the past 10 years. Optics, laser diodes, servo controls, media manufacturing quality, coding, and read/write channels have all improved greatly. An important example is the "blue" laser diode. In the early 1990s operation outside the laboratory of GaN-based blue laser diodes was not thought feasible. However, by 1995 Japanese chemical company Nichia (Tokushima, Japan) demonstrated the first stable devices. By 2001, the company was sampling 405 nm, 5 mW laser diode kits for $5,000. Today, 405 nm 30 mW laser diodes sell for less than $50 OEM. Laser diodes with pulsed output power of 200 mW and CW (continuous wave) output power of 100 mW are also available. Moreover, operating life now exceeds 10,000 hours. Blue laser diodes are the focus of and the driving technology behind the optical storage products profiled in near-term and future product roadmaps.

The market and applications profiles for optical storage can be defined by four primary segments (this definition is intended to be broadly inclusive):

- ***Segment 1***: Consumer Electronics (CE) – This segment includes, for example, CD-DA, DVD-Video, DVD+/–R, DVD+/–RW, DVD-RAM, MiniDisc, and BD/HD DVD.
- ***Segment 2***: PC/Workstation – This segment includes all non-application specific CD/DVD storage and 3.5" MO (5.25" MO is sometimes used for archival storage in medical image processing workstations and similar applications, but the volume is very low).
- ***Segment 3***: Professional (including departmental) – This segment includes 5.25" MO and UDO and Sony's Professional Disc for DATA (both are "blue laser" technologies); 3.5" MO is sometimes used by this segment, but penetration is relatively low.
- ***Segment 4***: Data Center (enterprise) – This segment also includes 5.25" MO and UDO and Sony's Professional Disc for DATA, but with a much greater emphasis on optical disk library (ODL) solutions.

Some overlap exists. The status and roadmap tables will help clarify principal market segments in terms of type of optical storage.

Consumer electronics (segment 1), primarily audio-video (AV), digital image capture, and gaming applications, is, and will likely continue to be, the largest and fastest growing segment for optical storage use. The advent of high-definition TV (HDTV) will make the evolving Blu-ray Disc (BD) and its successor optical technologies essential for both consumer and professional (for example, non-linear editing and movie/TV program production) AV

applications. Other professional applications will include law, medical, and government offices. PC/workstation applications will continue to be a major market for multifunction optical storage drives that integrate total CD and DVD functionality (and later, BD) into a single unit. Optical storage data center application opportunities will continue to decline[3], but will be necessary when reliable, near-line and archival storage for large databases are required (these are primarily optical disk library + WO[4] optical media applications).

Manufacturing of hardware and media is, and will continue to be, entirely dominated by Asian companies (Japan, Korea and Taiwan/China, in particular). North American-based companies will mainly play the essential role of product and system integrators for value-added applications.

Non-volatile semiconductor memory has established itself for many consumer and industrial applications. It is the digital storage medium of choice for handheld devices such as digital cameras and USB drives.

New storage technologies continue to make advances. MRAM products first appeared in the market in 2004. A few laboratories are developing probe-based storage as well as new chip level storage technologies using various advanced materials and electronics systems.

CONTRIBUTORS

Chair—T. M. Coughlin, Coughlin Associates (www.tomcoughlin.com)
Co-Chair— R. F. Hoyt, Hitachi Global Storage Technology

S. Adamson, Asymtek
J. M. Daughton, Nonvolatile Electronics (NVE)
S. Naberhuis, Hewlett-Packard
P. Frank, Information Storage Industry Consortium (INSIC)
R. B. Goldfarb, National Institute of Standards and Technology (NIST)
J. Handy, Semico
G. Hughes, University of California at San Diego (UCSD)
M. Johnson, Naval Research Laboratory
F. Moore, Horison Information Strategies
R. Rottmayer, Seagate Technology
S. Wang, Stanford University
R. G. Zech, Advanced Enterprises (ADVENT) Group

[3] Legal requirements may mandate the use of WO media for the foreseeable future; this is a small, but profitable, niche for WO optical media, such as Plasmon's UDO and high-quality DVD+/–R disks.
[4] WO and WORM (Write-Once/Read-Mostly) are synonymous.