Leading the Way in Storage

By Bruce Schechter and Michael Ross

IBM innovations in the technology of magnetic hard-disk drives have driven up storage density at a phenomenal rate, now approaching 60 percent per year.

In Brief:

The development and evolution of hard-disk drives is one of the outstanding technological success stories of the past 40 years. It is also one in which IBM has played the roles of both pioneer and leader. Almost every major advance - from the first commercial drive to the latest head design - originated in IBM's laboratories, and the company remains the technological leader in the data storage industry. Today, IBM scientists continue to explore new technologies to enable ever-denser, faster and more reliable disk-drive products, as well as a variety of future technologies that may one day lead to entirely new kinds of storage devices.

On September 13, 1956, IBM unveiled the RAMAC®, a new device to store the world's rapidly increasing flood of digital information. The size of a refrigerator, the RAMAC contained a stack of 50 spinning platters, each two feet in diameter and coated with a paint chock-full of magnetic iron oxide particles.

In a data storage world dominated by paper and magnetic tape and punch cards, RAMAC was the world's first commercial hard-disk drive. While its total capacity was only 5 megabytes, its "random access" mechanism that could move the head to any track on any disk in a second or less gave it a performance edge over larger-capacity magnetic tape drives. That pioneering disk drive quickly became the most cost-effective way to store large amounts of computer data that had to be accessed frequently. It also sparked the growth of IBM's West Coast research, development and manufacturing facilities. Today, the hard-disk drive industry is a $46 billion business, served by more than 100 companies.

In the four decades since RAMAC's debut, improvements in all aspects of disk-drive technologies have yielded a millionfold increase in the amount of information that can be stored in a given area of disk surface, a 3,000-fold speedup in the amount of data a drive can read and write in a second, and a more than 500,000-fold decrease in the inflation-adjusted cost of storing each bit of data. Nearly all of the technical innovations that made this progress possible originated from within IBM. And today this rapid pace of innovation and improvement is actually accelerating.

For the first 35 years after the RAMAC's introduction, the "areal density" - the number of discrete bits of information that can be squeezed onto a square inch of disk real estate - increased at a brisk average of about 20 percent a year. But since 1991, when IBM introduced a number of advanced features, the annual areal density improvement has doubled to a phenomenal 60 percent. In the first half of 1997, IBM introduced a thin disk drive for laptop computers with the current world-record areal density (2.6 gigabits per square inch). Last year, IBM scientists also demonstrated storage densities of 5 gigabits per square inch and the experimental microfile, a functional hard drive the size of a domino tile that would hold 250 megabytes at next year's product areal densities.

Such progress involves continual technological innovation in every aspect of the disk drive and reflects the success of IBM's data storage research and technology transfer to the product developers. These areas include; the magnetic materials and lubricants coating the disks; the heads, that read and write the individual bits; the aerodynamic "sliders" that permit the head to fly very close to the disk; the codes specifying the optimal sequencing of 1s and 0s; and the precision mechanical systems, electronics and software that enable and control the entire process.

While it would be a mistake to lose sight of the critical importance of improving each element of the disk drive, advances in head technology have come to epitomize the dramatic evolution in the technology. Any discussion of head technology ultimately focuses primarily on the size of the magnetic bit, a tiny, elongated region of magnetized material on the surface of the disk. Typically come 15 to 20 times wider than it is long, each bit has a particular magnetic orientation - left or right - that can be used to encode binary information. The major recurring theme of disk drive innovation over the years is to reduce the size of a bit.

Sensitivity Counts

The original RAMAC had a single pair of heads, each consisting of wire wrapped around a magnetic core. By running a pattern of electrical pulses through the wire, the head created a corresponding pattern of magnetic fields that magnetized bits on a circular track directly below on the spinning disk. To read back the data, the head was placed above the track. As the bits spun beneath the head, the sweep of their magnetic fields generated opposing voltages in the head. Today's disk drives use the same general design. Since the detectable signal from a bit decreases as the bit gets smaller, a "scaling" approach to increased density requires reducing the read/write head's dimensions while increasing its sensitivity.

In 1969, IBM Fellows David Thompson and Lubomyr Romankiw, then both at the Thomas J. Watson Research Center, invented a method for making the wire coils by the same photolithographic thin-film techniques used to make semiconductor chips. That method led to very small and sensitive read heads that IBM first used in products in 1979 and are still used today in many of the disk drives made by IBM's competitors.

"As revolutionary as the thin-film head was," says IBM Fellow Ching Tsang, "we knew that it would eventually run out of steam. So we were already trying to learn how to make dramatically more sensitive read-element sensors that exploited the magnetoresistive properties of some materials." The electrical resistivity of a magnetoresistive (MR) material changes according to the strength and orientation of the magnetic field it experiences.

The incentive to try this approach was substantial: MR read elments were expected to be three to five times more sensitive than inductive designs while performing just as well with the smaller-diameter disks that were becoming popular. They would also permit the inductive coil to be designed solely for writing data. MR sensors had already been used in the low-density, low-data-rate applications such as badge readers and magnetic tape players. But for years, scientists trying to make MR heads for the much more demanding disk-drive environment encountered severe problems with nonlinearity and noise. Tsang and colleagues solved those problems in the mid-1980s and designed the world's first practical disk-drive head with an MR read element.

After devising the daunting improvements needed to mass produce the required very thin films - an example of Research's many contributions to IBM's manufacturing capabilities - IBM introduced the first hard disk drive with an MR head in 1991, and set an industry record for areal density in the process. A rapid series of ever-denser IBM products followed and continues today.

Because the MR effect depends on the volume of the sensor, scientists know that an MR head's sensitivity decreases as its dimensions shrink. A density of 5 gigabytes per inch is thought to be close to the limit of MR technology. Fortunately, a related technology, giant magnetoresistive (GMR) sensing - another field that IBM pioneered - can provide much more sensitivity for a given size head.

GMR sensors consist of multiple layers of materials, some of them only a few atoms thick. The GMR effect depends upon the unusual and extraordinarily sensitive way in which current flows through these layers in the presence of a magnetic field. The most useful GMR sensor design for disk drives is known as a spin valve and resulted from an exceptionally broad and rapidly productive research effort at the Almaden Research Center in San Jose, Calif. "Spin valves should start appearing in commercial products soon, as areal densities approach 5 gigabits per square inch," says Currie Munce, who holds the dual positions of director of Storage Systems and Technology at Almaden and director of Advanced Technology for IBM's Storage Systems Division (SSD), which develops and manufactures data storage products.

Beyond heads

To detect smaller bits accurately, disk-drive designers also have to fly the head closer to the disk. But moving closer is not so simple when the head is already flying only a few millionths of an inch from the disk. "There is some very challenging, almost mystical, science going on where the head and disk nearly meet," says Thompson, who now heads the Advanced Magnetics

Research Laboratory joint program between Research and SSD.

Because various contaminants or irregularities in the disk surface can suddenly become potential obstacles, higher-density drives require myriad improvements, such as smoother and cleaner disks, more effective lubrication, new aerodynamic designs for the "slider" and more precise mechanisms for positioning the head over the ever-narrower data tracks.

While enabling higher areal densities, smooth disks also promote the potentially severe problem of "stiction": the head sticking to the disk so tightly after the drive is turned off that the unit cannot be restarted. Two of the latest products feature a recently designed ramp structure near the disk's outer edge where the head can be parked without touching the disk. Extensive research also enabled designers to use this "load/unload" structure to increase a disk drive's power efficiency and resting shock tolerance without adding to their critical thickness - all important factors for use in mobile computers.

Innovative disk formatting also permits drives with MR heads to have better performance and increased data storage capacity beyond that due just to areal density. The new formats store data-location information in the drive's electronics rather than on the disk.

While most of IBM's data storage research is conducted at Almaden, groups throughout the division make significant contributions: For example, servo writing, mechanical shock tolerance and metal plating technologies from Watson; servo optimization from the Tokyo Research Lab, and pioneering signal processing research from the Zurich Research Lab.

"None of these achievements would have been possible without the close collaboration by the scientists and engineers within both Research and the SSD product-development groups," says Munce. "And by enhancing our teamwork, we are introducing new technologies into products faster than ever before, keeping IBM as the technology leader in this increasingly competitive business."

IBM's leadership has bottom-line benefits, too. Just a few years after beginning to sell disk drives to other computer companies, SSD has become one of the top two suppliers in the highly profitable mobile and server market segments, according to the industry analyst firm International Data Corp. More than half of IBM's 1996 disk-drive revenue came from sales to other companies.

Is the end in sight?

The steady improvement in hard drive technology since day one is apt to raise the question: How long can progress continue? Are there any intractable limits that threaten to prevent future advances?

This is actually a very old question that was first answered "yes" - quite prematurely, it turned out- in the mid-1970s when the director of IBM's San Jose Research Center, Almaden's predecessor, predicted that magnetic areal density would top out before 1980 at 2 million bits per square inch. Since then, others have also forecast the end of magnetic improvements within the foreseeable futures of their times.

"Those perceived barriers of the past two decades were all determined by engineering challenges, such as making some element thin or precisely enough or positioning the head accurately enough," recalls Thompson, "and they always seemed to be about five years off. But with a lot of hard and creative work, the needed improvements were made to extend areal density."

Today, however, disk-drive designers are approaching a limit determined by fundamental physics, not engineering ingenuity. As the volume of magnetic material within a single bit shrinks to increase areal density, there comes a point beyond which random jiggling of the electron spins due to temperature is likely to cause the direction of a bit's magnetization to undergo spontaneous reversals within the expected lifetime of the disk drive. "This superparamagnetic limit will eventually limit the progress we can achieve by simply scaling down existing technology," says Thompson.

Scientists find it difficult to estimate just when the superparamagnetic limit will be reached, because it depends on many factors, including specific properties of the particular materials being used. But most agree that the limit will be encountered at densities of somewhere between 40 to 100 gigabits per square inch - about 20 to 50 times greater than those available today. Such a density limit to magnetic storage, however, need not spell the end of all progress in hard-disk drives any more than highway speed limits or internal combustion engines hindered improvements in automobiles.

Exploring Alternate Approaches

Along with the ongoing efforts to create next-generation magnetic-disk-drive technology, Research teams are exploring various approaches to find complementary and possible follow-on technologies. The more promising technologies likely to achieve substantially higher storage densities and product-level performance include those based on holography (see "Looking into a Crystal Cube") and molecular-scale devices (see "Probe-based Storage"), as well as other novel techniques, such as scanning interferometric apertureless microscopy.

"It is very difficult to predict which new technologies will prove both technically and commercially successful. We choose to direct our efforts toward strategic areas which will enable us to identify the winning technologies early and develop a leading position in moving them to market," says John Best, director of the Almaden Research Center and Research Division vice president for storage. "The successful ones are usually those that best meet customers' needs."

In the world of storage, success means enabling users to reliably store and manage a seemingly endless amount of data as effortlessly as possible, whether it be in a commercial data warehouse, a home computer, or a portable computer on the road.

"Customers' demand for data storage has always appeared insatiable to us in the business," says Best. "But with the advent of the Internet, digital libraries, networked computing and the plummeting cost of storing a bit of data, I think the general public is suddenly aware of that, too. Millions of users are now buying disk-drive capacities in gigabytes, a word I suspect most hadn't even imagined a few years ago. We'll soon be seeing terabytes in the home and petabyte installations in businesses."

Dreaming of the future

There is more at stake, however, than simply keeping up with demand. As drives become smaller, cheaper and more capacious, new applications will become feasible. Thompson points to the Microfile, which could find initial use in digital cameras, to store many more images more economically than solid-state "flash" memory, as well as in other applications such as pagers, cell phones and personal digital assistants.

Surely sometime in the next century, it will become commonplace for people to wear a variety of electronic devices, all communicating with each other and demanding more storage (see "The Body Electric"). Thompson envisions one such device that might solve a widely shared problem. "I hate the fact that I can't remember everything: where my car keys are, what you told me on the phone the other day and what my boss said to me this morning," he says.

The solution: a "digital diary" that would combine wearable cameras and microphones with future storage devices. "If data densities improve in the next 40 years as much as they have in the last 40, then my compact digital diary could record everything I heard, said or saw in the course of a day," says Thompson. Later, the device could download the day's information into a home computer for sorting, filing and long-term storage. Combined with a voice-activated user interface and connected into a person's wearable personal area network, a digital diary could identify that oh-so-familiar face at a party or show you where you left your car keys.

"And what stockbroker, doctor, lawyer, journalist or scientist would not want a perfect memory," Thompson asks, "especially if their competitors all had them?"

The digital diary may only be a dream today, but that has been the origin of many technologies that are shaping our lives. The important thing is that research projects that could make that diary a reality - as well as the next generations of industry-leading data-storage products - are already under way.

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More Information:

Looking into a Crystal Cube

Probe-based Storage

Looking into a Crystal Cube

"Storing data as holograms has intrigued scientists for decades. In the early 1960s, former Almaden Research Center scientist Glenn Sincerbox helped IBM develop the world's first working holographic data storage system - a write-once system using photographic film, for the U.S. Air Force. Today, IBM participates in two industry/university/government consortia that aim to demonstrate holographic storage technologies by the turn of the century.

A traditional hologram is produced when a beam of laser light, the reference beam, interferes with another beam reflected from the object to be recorded. The pattern of interference is captured by photographic film, a light-sensitive crystal or some other optical material. Illuminating this pattern by the reference beam reproduces a three-dimensional image of the object.

"Each viewing angle gives you a different view of the same object," explains Almaden researcher Hans Coufal. "Holographic data storage works in exactly the same way. But for every angle, instead of having another view of the object, we have a completely different page of information." Up to 10,000 pages have been stored in a single cube of recording material one centimeter on a side. Each page contains one megabit of information, which means that the cube can store about 10 gigabits.

Holographic recording has the advantage of being inherently parallel. It reads and stores an entire page at a time. The technology permits data rates of up to one gigabit (or 125 megabytes) per second, making it ideal for storing image data. Another advantage of holographic storage, largely untapped, lies in its use as associative memory. Just as illuminating a hologram with a reference beam recovers the stored information, illuminating it with a pattern of information will reproduce the corresponding reference beam and angle, which immediately identifies the page on which the information is stored. In other words, holographic memories can be searched extremely fast for data patterns. "This would allow database searches using physics rather than software," Coufal says.

Probe-based Storage

In 1989, IBM Fellow Don Eigler at Almaden demonstrated perhaps the ultimate in data storage, when he and a colleague rearranged 35 xenon atoms on a nickel surface with a scanning tunneling microscope (STM) to spell out the letters IBM. This corresponds to a storage density of about a million gigabits per square inch, some 500,000 times that of today's densest drives. But it required a temperature of near absolute zero and several hours to create the pattern.

However, other storage schemes based on scanning probe techniques could lead to practical devices. In particular, the atomic force microscope (AFM), invented by IBM Fellow and Nobel laureate Gerd Binnig of the Zurich Research Laboratory, has potential as a tool for high-density storage. Both Dan Rugar at Almaden and Binnig and Peter Vettiger at Zurich lead teams that are exploring AFM-based storage techniques.

Using micromachining techniques, Almaden researchers have fabricated tiny silicon cantilevers 10 microns long - one-tenth the diameter of a human hair - and 0.3 micron thick with an even smaller silicon probe tip (0.008 micron in diameter, about 10,000 times smaller than the cross-section of a human hair). The tip rests on a rotating plastic disk. To store data, heat from an electric pulse through the tip momentarily softens the surface of the plastic, and the slight force that the tip exerts on the plastic pokes a tiny depression. As the tip is pulled across a pit on playback, its dip into the pit is detected.

"This is essentially a very tiny high-tech phonograph," Rugar explains. "We can reliably read and write data at a density of 64 gigabits per square inch - 100 times that of a CD-ROM - and have developed the basics for a read-only system holding CD's worth of data on a disk the size of a penny (20 mm diameter).

The system's 10-megabit-per-second data rate is comparable to that of a 8x CD-ROM. Last year the Almaden scientists tested small arrays of tips aimed at increasing the overall data rate futher.

The Zurich team's approach, called Millipede, aims to increase the AFM storage data rate into the gigabit-per-second range by employing thousands, or even millions, of cantilevers scanning "en bloc" and operating in parallel over a static substrate. Besides plastic, the group is exploring the use of other organic materials as storage media. In addition to reading and writing thermomechanically, the team is investigating a scheme to erase data in small storage fields by locally heating the medium so that it reflows and restores the surface to its prerecorded state.

Late last year, using methods similar to very large-scale integration chip-making, the Zurich team fabricated the first fully functional two-dimensional array. It consisted of 25 cantilevers in a 5-by-5 array with integrated tip heating and bit sensing. According to Vettiger, the group manager, the researchers plan to operate a 1,000-cantilever array by the end of this year. Their goal is to store 1 terabit (or 125 gigabytes) on a 3.5-cm-square (1.4-inch-square) surface, which is about the equivalent of 200 hours of compressed video.