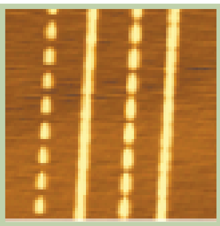
ULTRA-HIGH-DENSITY DATA STORAGE

Innovative, inexpensive, efficient, and increasingly compact storage technologies promise practically unlimited capacity and instant access to data anytime, anywhere.



ATOMIC-FORCE MICROSCOPE SCAN OF A RECORDED BIT ON A DISK'S PHASE CHANGE MATERIAL COATING, SIROS TECHNOLOGIES, SAN JOSE, CA

DIGITAL DATA STORAGE IS THE LIFELINE OF THE INFORMATION REVOLUTION. THE METAPHORICAL PAPERLESS OFFICE WOULD NOT EVEN BE AN OPTION WITHOUT UBIQUITOUS INEXPENSIVE DIGITAL STORAGE. NOW, DIGITAL DISPLAYS, FAST COMMUNICATION SYSTEMS, LARGE STORAGE REPOSITORIES, AND POWERFUL PROCESSORS ARE POISED TO FURTHER DIMINISH OUR DEPENDENCE ON TRADITIONAL PHYSICAL MEDIA, MOST NOTABLY PAPER, AND POINT THE WAY TOWARD VAST AMOUNTS OF ONBOARD AND readily available data and access from practically any electronic device and appliance by practically any computer user or consumer worldwide. That's why we focus this special section on the extraordinary ultra-high-density storage technologies emerging today (or that are just around the corner) and their often-invisible contribution to the future of distributed information networks and appliances.

Digital data storage is one of the great technological success stories of the past century. Invented by IBM researchers almost 50 years ago, it has facilitated information technology, allowing it to flourish. Without it, the kind of information systems we know today wouldn't have been feasible in the first place. Computers, automobiles, electronic consumer devices, aircraft, boats, all kinds of engines, and practically any electronic device or appliance require local data storage to enable them to carry out crucial processor functions. For example, microprocessors controlling fuel injection systems require knowledge about the engines they're attached to, as well as the environment and the specific functions that need to be executed.

Access to and the application of that knowledge is possible only if it is stored in digital format. For optimal performance, such data is ideally kept in solid-state memory devices located close to the processor; in other cases, storage devices might be some distance away on a network, accessible by geographically distributed processors. Integration of processors and memory is especially important, as it allows faster and more capable systems to be devel-

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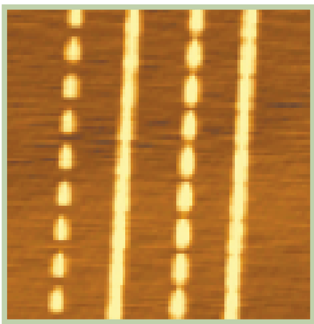
oped and provides a greater range of performance options.

Development of digital data storage devices has also received enormous attention from engineers over the past 50 years. Initially, data in digital form was stored in refrigerator-size ferroelectric devices consuming enormous amounts of power and requiring dedicated teams of human technicians to function. More recently, in contrast, IBM introduced a removable disk drive the size of a quarter, selling for about $350 retail, designed for use in PCs and a variety of consumer electronic products and capable of storing 1GB of data (in terms of information capacity, close to the *Encyclopedia Britannica*). As part of a digital camera, such a magnetic drive could record and store thousands of high-resolution digital images.

Along with the ever-shrinking dimensions of these devices, the march of performance improvement in magnetic recording has likewise been phenomenal. Over the past 10 years, for example, data storage capacity has increased at least 60% per year, and more recently 80%–100% per year, while cost has remained the same or been reduced. What technological and business factors have made this price/performance improvement curve possible? The main ones are: mass production, low-cost manufacturing, higher yields, larger volumes, and shrinking electronics; a steady flow of innovations in mechanics, magnetic materials, manufacturing technology, system integration; and new designs for flying heads and signal-processing chip sets.

In its simplest form, a magnetic disk drive consists of a tiny head—only a few millimeters across—flying over a rotating magnetic disk. By pulsing an electric current through the head, a low-power magnetic field is created that can be used to flip magnetic domains from one orientation to another. By using the same head to sense the orientation of the magnetic moment, along with sophisticated digital processing techniques to assure dependable operation, bits are stored as 0s or 1s; a 0 corresponds to one orientation of the magnetic domain, a 1 to the opposite orientation. As the bits become smaller, the head has to fly ever closer to the disk surface. For faster data-access times—from when a command was given by the processor to get the data, to the time it was actually accessed—the disk has to spin ever faster.

Rotating disks in state-of-the-art devices spin at more than 10,000rpm, and their heads fly 25nm or less above disk surfaces packing 60Gb of data per square inch of surface. While reading this data more than 10,000 times, a device has to be so well-designed, it tolerates only a single bit error to ensure the kind of performance a typical user has come to expect; anything less and the device is not commercially viable. This is awesome performance. Especially when you consider that all the information an average person might read or learn in a lifetime can be stored on a disk drive costing no more than a few hundred dollars and that fits comfortably in a shirt pocket.



WHAT MAKES THE PRICE/PERFORMANCE IMPROVEMENT CURVE POSSIBLE? IN PART, A STEADY FLOW OF INNOVATIONS IN MECHANICS, MAGNETIC MATERIALS, MANUFACTURING TECHNOLOGY, AND SYSTEM INTEGRATION, ALONG WITH NEW DESIGNS FOR FLYING HEADS AND SIGNAL-PROCESSING CHIP SETS.

Magnetic storage devices represent the bar against which the performance of all data storage devices is measured. In practically all the information systems we're familiar with today, data is stored in a number of different devices, organized in a hierarchical fashion called the "data storage pyramid" by storage-device engineers. At the top of the pyramid are the solid-state memories, the fastest and costliest devices. Providing relatively less performance and lower cost, magnetic storage is prominent at the level below solid-state memories. At the level below magnetic storage are near-line devices, including inexpensive and relatively low-performance tape and removable disks. Below that, at the pyramid's lowest level, off-line storage is provided by optical discs and tape jukebox devices in which media are found and placed in drives via robot servo mechanisms.

This classical representation of the data storage hierarchy has recently undergone considerable modification as a result of our increasing reliance on the Internet and the flood of portable consumer appliances designed to communicate through it. A likely future scenario may therefore play out in the following way: The Internet makes it possible to network all kinds of information systems, in turn making possible distributed computing and storage silos. Servers containing powerful computing technology and storage banks are connected to provide access to users anywhere, anytime. That access is provided through a variety of methods, including wireless communication, optical fiber, copper wire, and communication satellites, as well as a spectrum of devices, from mobile telephones, personal digital assistants, and intelligent consumer products, to computers and workstations.

For each such device, the storage requirements are and will be different. Portable appliances will most likely continue to rely on solid-state memory, while servers and PCs incorporate mainly magnetic storage devices with tape and optical media for backup and restore functions. Distribution of data and programs will occur largely over the Internet, which will ultimately supersede CDs as the preferred medium for distributing data and software for consumers and vendors alike. New applications, inspired largely by multimedia applications, will continue to drive consumer, corporate, and scientific demand for storage at unprecedented levels.

Even though more and more of our information will be stored digitally, paper—the historical storage medium of choice—will remain the most popular medium for displaying documents, primarily due to its low cost and convenient format. But as soon as the next decade, new digital thin-display media could challenge paper's role, fueling even greater demand for digital data storage.

It is not surprising that to exploit this burgeoning demand for storage, new technologies are being researched and developed at a furious pace. For portable appliances, solid-state, high-performance yet compact devices are needed. Rotating disk drives require new media and continued improvement in capacity and performance. All storage devices need to be inexpensive and easy to maintain, networked through intricate systems that allow remote control, sharing of content and processing power, and device management. For example, storage area networks (SANs) and network attached storage (NAS) systems incorporate sophisticated software layers for ready installation and maintenance, as well as reduced cost of ownership.

This history, design innovation, and shear business opportunity prompted us to invite leading scientists and engineers to describe their visions of the promising future of ultra-high-density digital data storage. Garth Gibson and Rodney Van Meter describe how SANs and NAS reduce the cost of ownership of disk drives. Intelligent software allows devices to be attached to networks and shared by multiple authorized users. Moreover, SANs and NAS are on a merger trajectory, with potentially enormous benefits to the entire data storage field, from the terabyte-consuming enterprise data warehouse to the casual home PC user.

To accommodate ever-increasing volumes of data, scientists and engineers are constantly investigating new ideas and methods for data storage. Volume holographic storage changes the storage paradigm by recording information *inside* a medium, not merely on its surface. As a result, enormous storage capacities—hundreds of gigabytes per disk—and phenomenal data rates—more than 6Gb/s—have already been achieved in the laboratory. Such performance is the equivelent of reading the *Encyclopedia Britannica* from cover to cover in roughly a second. Sergei Orlov explores this 3D storage world as a potential follow-on approach to blue-laser DVD technology as it reaches its inherent capacity and performance limits later this decade.

Magneto-optical (MO) recording is a hybrid storage method using an optical stylus for writing and reading to and from a medium having both magnetic and optical properties. MO enjoys great popularity in Japan but is less widely used in the U.S. and Europe, for no obvious reason. Still, it has enormous potential worldwide as a recording technology for achieving great data densities and fast data transfer rates, competitive with magnetic recording. MO technology's intrinsic physical properties provide a stable environment for the smallest bits, down to sizes at which magnetic media become unstable. Potentially, MO technology provides a means for overcoming the thermal instability of nanoscale magnetic bits, a phenomenon commonly referred to as the "paramagnetic effect" by storage engineers. Terry McDaniel provides intriguing insight into how the technology is being developed and the role it might be expected to play in future storage devices and associated products.

CD-ROM and DVD-ROM are the most popular optical removable storage technologies today worldwide in PCs, servers, and consumer electronics (140 million units sold in 1999). Drives and media are inexpensive and reliable. Philips Electronics and Sony originated CD-ROM technology 20 years ago and have since maintained their leadership roles in the development of new media and drives. The original ROM distribution media are now complemented by recordable and read/write media. Henk van Houten and Wouter Leibbrandt have a keen understanding of the technology and its future place in the storage hierarchy, providing here a highly informed glimpse of what the technology will likely bring to consumer electronics, as well as to computer storage.

One clear trend in today's storage market is that devices are getting ever smaller, lighter, and more efficient for portable applications. Electronic silicon-based manufacturing and processing have brought a fascinating array of new devices in shrinking physical dimensions. It is no coincidence that engineers are leveraging these manufacturing techniques for wholly new purposes besides electronics. For example, research and development of microelectromechanical systems (MEMS) have already yielded a variety of intriguing devices, including electric motors on the head of a pin, pumps the size of a dime, mirrors smaller than a human hair, and probes that can detect atomic dimensions. MEMS technology promises to revolutionize storage too. L. Richard Carley, Gregory G. Ganger, and David F. Nagle describe a future world of smart (miniature) appliances and intelligent portable devices.

If all of this sounds utopian, remember that the storage world has a remarkable record of innovation, churning out increasing performance at ever-reduced cost. This inherently self-destructive market in which only the fittest companies—and technologies—survive seems to welcome new disruptive technologies that routinely refresh corporate life cycles. If the past is any indicator, future storage capacity will not only be astounding but inexpensive, compact, and pervasive too. C

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