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The State of an Emerging Technology and a Look at What Lies Ahead

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Data Storage: Pushing the Physical Limits

Executive Summary

The gap between data storage research and the market has never been smaller.

In the next five years, data storage technology is likely to advance along the familiar course of electronic memory chips, magnetic disk drives and CD-like removable media. Meanwhile, research in materials science and nanotechnology is paving the way for future storage media with huge capacities.

Patterned media, which should be ready for applications in five years, is likely to bridge the gap between today's magnetic disks and future technologies.

There are several new media that could be ready for practical application in five to ten years:

- Arrays of nanowires
- Patterns of electric charges or magnetic particles stamped into thin films of plastic
- Holograms
- Single or small groups of molecules, including carbon nanotubes

Superfast microelectromechanical systems (MEMS) storage devices that use thousands of read/write heads, each positioned over a small area of recording media, could also be ready within the five to ten year time frame.

The future storage media with the potential to store the most data per square inch is the atom. A prototype from the University of Wisconsin records bits as the presence or absence of individual atoms, and has a capacity of 250 terabits per square inch, enough to store 10 DVDs worth of data on a pinhead. Practical applications however, are one to two decades away.

What to Look For

Disk drives:

Patterned media
Terabit-per-square-inch patterned media
Very large, extraordinary or ballistic magnetoresistance

Optical devices:

Twenty gigabytes on a CD-size disk via blue lasers
Practical near-field technology
Practical holographic technology

Memory devices:

Molecular layers
Nanowire transistors
Bits in single carbon nanotubes
Bits in single molecules

Alternative devices:

Microelectromechanical systems (MEMS)
Bits in single atoms
Multiple bits in the quantum states of an atom

Smaller bits

Nobel laureate Gerd Binnig is making a data storage device out of a thousand microscopes. The chip-size system will be able to hold many gigabytes of data, enough to let a credit-card-size digital camera store thousands of pictures.

Hans Coufal is working out the kinks in a system for storing massive amounts of data in small pieces of glass or plastic. The method stores pages of data as holograms that can be retrieved all at once, making it much faster than today's disk drive technology.

These are among dozens of data storage projects being pursued by just one organization — IBM Research.

In today's technological society data storage is ubiquitous, and the weight of the installed manufacturing base is pushing much of the research toward improving existing technologies. There is also tremendous incentive for coming up with radically better alternatives.

The stakes are high. The business community is accustomed to bit densities doubling every 12 to 18 months, and, according to IBM Research, the gap between research and the market has never been smaller.
(www.almaden.ibm.com/st/disciplines/storage/)

The bottom line in data storage research is making bits smaller so storage devices can hold more data. There are three approaches:

- Pushing the limits of today's technologies to make smaller bits
- Using new technologies to produce smaller bits for today's devices
- Making entirely new devices

Basic and applied research, particularly in materials science and nanotechnology, is paving the way for storage media with huge capacities. Some researchers have made great progress toward new types of devices, like microelectromechanical systems (MEMS). And the relentless drive for ever-smaller bits has pushed chemists and physicists rather than electrical engineers to the vanguard of data storage research.

This report assesses the state of data storage research and maps out the many roads ahead.

- The first section examines strategies for advancing today's magnetic storage technologies, focusing on efforts to make small magnetic domains stable.

- The second section covers emerging storage media made possible by nanotechnology.

- The third section looks at ways to locate, write data to and read data from incredibly shrinking bits, and details the devices being considered for these difficult jobs.

- The fourth section examines optical and holographic storage technologies and the hurdles researchers are struggling to overcome.

- The fifth section details initiatives aimed at storing bits in individual atoms and molecules, and looks at the ways the bottom-up approach to storage technology is being integrated with traditional, top-down manufacturing.

How It Works

Today's technology

The technology used to to read a bit stored on today's production magnetic disks is based on magnetoresistance, the change in the way a material conducts electricity in the presence of a magnetic field. The read head of a disk drive is a probe containing an electric circuit. The probe floats just above the surface of the disk, and when it encounters a tiny magnetic field produced by a bit recorded on a tiny portion of the disk, the resistance of the probe's circuit decreases. The type of bit — a 1 or a 0 — is determined by measuring the change in resistance.

In order to sense the smaller magnetic fields of smaller bits, read heads have to be more sensitive. Probes with greater magnetoresistance are able to sense weaker magnetic fields. Disk drives use giant magnetoresistance probes, which undergo a 100-percent decrease in resistance when they encounters a magnetic field.

Giant magnetoresistance occurs when two thin layers of magnetic material with opposite magnetizations are separated by a thin film of non-magnetic material. The giant magnetoresistance device changes resistance based on electrons' spins. Electrons spin in one of two directions, up or down, which correspond to the North and South poles of a magnetic field.

When a current of electrons attempts to pass through the layers, electrons spinning in one direction are blocked by one of the magnetic layers, and electrons spinning in the other direction are blocked by the other layer. In the presence of a magnetic field, the magnetization of the layer with the opposite orientation reverses. This brings the two layers into alignment, and the layers together block only electrons of one spin.

Very large, extraordinary, ballistic

There are several candidate technologies for more sensitive magnetoresistance: very large, extraordinary and ballistic magnetoresistance.

Very large magnetoresistance was discovered by researchers at Johns Hopkins University. The effect is produced in nanowires and single-crystal thin films of bismuth. Devices that use very large magnetoresistance undergo a 250-percent change in resistance at room temperature in the presence of a magnetic field, and so are more sensitive than those that use giant magnetoresistance.

Extraordinary magnetoresistance was found by NEC Laboratories America and is produced by sandwiching a thin layer of highly conducting metal like gold between layers of nonmagnetic semiconducting materials. Devices that use extra-ordinary magnetoresistance undergo as much as a

Enduring magnetism

There's a limit to how small the magnetic bits in conven- tional disk drives can be and that limit is on the horizon. The superparamagnetic limit is the smallest a bit can be and remain stable. Any smaller and heat from the environment can cause enough of the magnetic domains that make up the bit to fall out of alignment that the bit is erased. Researchers estimate that the bit-size limit is 50 to 75 nanometers, which is one-fifth to one-tenth the size of the bits in today's disks. A nanometer is about the length of 10 hydrogen atoms.

Unlike related transistor size limits facing the computer chip industry, however, the impending end of today's disk drive technology is not keeping researchers awake at night. Recent history has shown that scientists have been able to come up with strategies for pushing back the superparamagnetic limit, including reorienting magnetic bits from parallel to perpendicular to the disk surface. And the decade remaining before conventional bits are truly tapped out should leave plenty of time for replacement technologies to mature.

Meanwhile, patterned media is likely to bridge the gap between today's magnetic disks and future technologies. Today's disks are made from thin films of magnetic material, and bits can be written anywhere on their surfaces. Dividing the disk material into tiny, physically isolated areas produces bits that remain stable at much smaller sizes.

Media patterned by the same lithographic methods used to etch the transistors in computer chips could push capacities beyond a terabit — one trillion bits — per square inch, the next major benchmark in data storage research. Less traditional technologies like nanowire arrays hold promise for producing patterned media with even higher densities. A terabit is 125 gigabytes, which is the total capacity of today's higher-capacity disk drives. These disks hold 50 billion bits per square inch.

Today's CD ROMs hold 650 megabytes and DVDs hold 4.7 gigabytes. At a terabit-per-square-inch, a CD/DVD-size disk would hold 1,750 gigabytes, which is about 370 times the capacity of a DVD. Such a disk would pack 22 times the information held by a whole DVD into an area the size of a postage stamp.

The 18 million books in the Library of Congress' collection, given an average of 300 250-word pages, would require 6.75 terabytes of storage space. The library's book collection could be stored on just under four CD/DVD-size disks that store a terabit per square inch.

Such a disk would need to have one bit every 25 nanometers. Twenty-five nanometers is at the edge of today's lithography, but it is well within reach of materials processing technologies.

The main challenges to using patterned media are finding inexpensive ways to produce it and adapting the apparatus that reads and writes bits — the read/write head — to work with it. IBM researchers have developed a stamping technique that patterns a disk surface all at once, a method that could make patterned media economical. The second problem poses a tricky engineering challenge because the read/write head has to access minuscule, quickly-moving bits.

550 percent change in resistance when sensing magnetic fields similar to those of bits on disks.

Ballistic magnetoresistance, discovered by researchers at the Laboratory of Small Systems Physics and Nanotechnology in Spain and extended by researchers at the State University of New York at Buffalo, is produced at the junction of two nanowires. Because the junction is only a few hundred atoms wide, electrons flow straight through rather than bouncing from side to side the way electrons flow through larger wires. The change in resistance is greater than 3,000 percent, and the small size of the sensor makes it possible to read tiny, closely-packed bits.

MEMS

One technology that promises to store more information than disk drives is microelectromechanical systems. MEMS have electrostatic actuators — electrically-driven springs and levers — that can move components like storage media and read/write heads tiny, precise distances. The three principal MEMS storage projects — at IBM Research, Carnegie Mellon University and Hewlett-Packard Laboratories — use similar mechanics: arrays of thousands of microscopic tips positioned above rectangular sections of storage media that move short distances laterally and longitudinally relative to the tips. The three approaches record information differently.

The IBM device records bits by heating the tips to melt tiny pits in a plastic storage medium, similar to burning a CD. The presence of a pit represents a 1 and the absence a 0. The device reads bits by sensing changes in temperature. When a tip moves across the surface and falls into a pit, more of the tip is in contact with the surface, which causes it to dissipate heat more quickly.

The CMU device is comparable to a magnetic disk drive. Each tip is a miniature read/write head and the surface is magnetic. An actuator and sensor on each tip keeps the tip a precise distance above the surface to accommodate microscopic variations in surface height.

The HP device fires a beam of electrons from each tip into the surface. The researchers are exploring several ways to record bits using electron beams, including storing tiny electric charges in the surface and eventually using the beams to trigger individual molecular switches.

Near-field optics

Another technology that could take storage to new densities is near-field optics, which uses light to read and write bits similar to but much smaller than those of conventional optical storage devices like CD and DVD drives. Lenses and apertures can focus light beams only so far, limiting how narrow a light beam

Patterns can also be formed in a material as the material is created, and such methods could ultimately lead to smaller patterns and cheaper manufacturing processes. Disk manufacturer Seagate Technology is betting on this approach with a material that contains ordered arrays of iron-platinum particles. The material won't require that read/write heads sync up with preformed bits, but does call for a new writing technology that uses lasers to heat the material.

Patterned media and ordered materials probably won't be ready for practical application for at least five years.

Nanotech makes media

In recent years, scientists have been able to manipulate matter at the nano and even atomic scale. This has led to a flurry of experimental materials patterned on the nanoscale. These materials combine attributes of perpendicular and patterned media.

One promising avenue is arrays of nanowires. Nanowires are metal, semiconductor or conductive polymer wires that range from a few to a few hundred nanometers in diameter and 10 to several thousand nanometers long.

Several chemistry-based manufacturing processes yield ordered, vertical arrays of nanowires. Metal and semiconductor nanowires can be formed by condensing vapors of metal or metal oxides into holes in a plastic film or onto certain types of crystal surfaces. Nanowires embedded in a plastic film could store bits of information, either magnetically or by electric charge.

Chemists have been able to grow polymer nanowires by getting ring-shaped polymer molecules to stack up and by causing branched polymer molecules to spiral into tubes. It is tricky but possible to use these for data storage; one possibility is embedding infinitesimal specks of metal or semiconductor in the microscopic plastic tubes. A NASA-led team has done something similar by genetically engineering a protein from a bacteria to form arrays of nanoscale tubes and then coaxing microscopic specks of gold onto the ends of the tubes.

A few nanowire-based media methods under development could be ready for mass production within one or two years and most within five years. But media is only part of the data storage story.

Reading, writing and addressing

Using these emerging high-density media and increasing the density of today's magnetic media, both require higher-resolution read/write capabilities.

For magnetic media, this means read heads that are more sensitive than today's technology. Read heads sense the state of a bit's tiny magnetic field via magnetoresistance — the effect of a magnetic field on a material's resistance to electric current. There is a small menagerie of magnetoresistances: giant, very large, extraordinary and ballistic. (See How It Works: Today's technology)

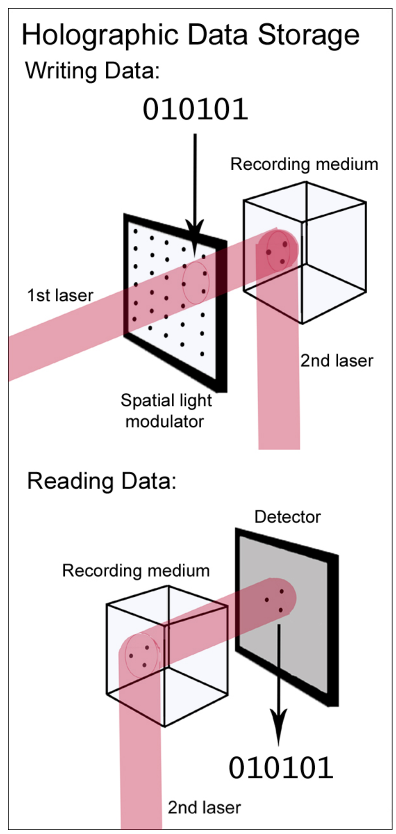
Engineers are likely to be able to scale down today's giant magnetoresistance technology to handle smaller bits, but it will probably tap out well before terabit-per-square-inch densities arrive.

can be relative to its wavelength. But if a lens or aperture is nearly in contact with a recording surface, light shined through the lens or aperture is confined to a very small area and so can record and read very small bits. Near-field optics has the potential to pack more than a terabit per square inch.

A common near-field optical device is the solid-immersion lens, which is a nearly spherical piece of transparent material with a high refractive index. The refractive index determines the angle at which light waves bend as they pass from one medium to another, and is responsible for the familiar bent-drinking-straw illusion. The spherical shape of the lens bends the light beams inward, concentrating them in a smaller area than would be possible with an ordinary lens.

Holographic storage

Holographic storage devices have the potential to both hold much more data than magnetic technologies and access it much faster. Holograms are made by bouncing a laser beam off an object and having a second laser beam intersect the reflected light. The laser beams interfere with each other, producing a unique pattern of bright and dark areas that can be captured in storage media like light-sensitive plastics or glass composites. The resulting hologram can be illuminated by shining the second laser beam on the media at the same angle as when the hologram was recorded.



Data is stored holographically by shining a laser beam through a two-dimensional display, usually a liquid crystal display, containing a series of light and dark spots that represent 1s and 0s. Data holograms are two-dimensional pages rather than three-dimensional representations of objects. These holographic pages can be stacked by slightly varying

Two technologies positioned to succeed giant magnetoresistance are the semiconductor-based extraordinary magnetoresistance technology developed by NEC Research and the nanowire-based ballistic magnetoresistance developed by researchers at the State University of New York at Buffalo.

The NEC technology could be ready for practical application in the next year or two, and the SUNY Buffalo technology in three to five years.

Micromechanics

A radical alternative, derived in part from a type of microscope, could replace disk drives altogether with a simpler mechanism manufactured the same way as computer chips. Microelectromechanical systems (MEMS) storage devices turn the concept of a disk drive on its head; instead of one read/write head hovering above a rapidly rotating disk, thousands of read/write heads are positioned above or below a rectangular piece of recording media.

The read/write head array moves short distances forward, back, and side to side over the recording media to allow each read/write head to access its own small portion of the media. A MEMS device under development at Carnegie Mellon University uses magnetic disk drive recording technology; the most advanced MEMS storage project, IBM's Millipede, melts microscopic pits into a plastic surface similar to the way CDs are recorded. (See How It Works: MEMS)

MEMS storage devices are likely to come to market able to hold more than a terabit per square inch; the Millipede prototype currently makes 10-nanometer diameter pits. And the aggregate data throughput of the read/write heads will make the devices faster than today's disk drives. One question is the durability of the read/write heads.

MEMS storage devices also raise the possibility of an entire computer system — processor, memory and data storage — on a chip. In five to ten years, cell phones and even wristwatches could have the capabilities of today's computers.

IBM's Millipede could find its way into products within three years, but it is likely to take more than five years before other MEMS storage devices are ready for practical application.

Another alternative storage technology stamps microscopic patterns of electric charges or magnetic particles into thin films of plastic. The stamps are made using standard lithography, which is a slow and expensive way to record data, but once a stamp is made it can rapidly produce many read-only copies.

Stamp-based data storage could be ready within a few years, but it's not clear that it offers a compelling alternative to other technologies.

Hazy optics

Optical storage technologies have always been long on potential — lasers are fast and holograms are information-dense — but short on impact. Optical technologies play a major role in archival storage, and CDs/DVDs have become the removable media of choice, but the angle of the second laser beam. The thicker the storage medium, the more pages of data it can hold.

Molecular switches

Storing a bit in a single molecule is about as small as you can get. Certain molecules can be used to store data because they can be switched back and forth between two stable states that can represent the 1s and 0s of digital data. One of these is rotaxane, which contains a thin, thread-like section with a ring that moves freely around it. The ends of the thread section are thicker, preventing the ring from slipping off. Researchers have found ways to move the ring from one end of the thread to the other and the ring will stay where it is placed.

A bit can also be stored in a molecule by changing the molecule's resistance. Some molecules can be made to change their electrical resistances by using a chemical reaction to add or remove electrons or applying a voltage to change the molecule's shape. Researchers have shown that it is possible to read such a bit by applying a low voltage in order to measure the molecule's resistance.

Who to Watch

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magnetic technologies are likely to remain the mainstays of core memory and data storage applications for years.

Nevertheless, researchers the world over are plugging away at problems that have held back optical storage technologies; the resources devoted to the research could position optical technologies for an expanded role in data storage. In the meantime, advancements are improving the capacity and performance of removable media.

There are three ways to cram more data onto optical disks: make smaller bits, put multiple layers on each disk, and make each mark count for more than one bit. Most research efforts focus on bit size.

The bit size of optical disks like DVDs is mainly limited by the wavelength of the light produced by the lasers that record bits. DVD lasers have a wavelength of 650 nanometers and are focused through a lens to produce 400-nanometer marks in the media. Blue lasers have wavelengths of around 400 nanometers and are poised to increase storage capacities by four or five times, but more significant improvements will require other approaches.

For years, researchers have used near-field optics to produce marks smaller than 100 nanometers. The technology involves shining light through tiny holes or refractive materials placed closer to the recording media than the wavelength of the light. The main challenge is getting read/write heads that are nearly touching the media to work at high speeds. (See How It Works: Near-field optics)

Using multiple layers allows researchers to avoid having to make smaller marks, but requires more complicated control mechanisms, like lasers with variable depth of focus or an additional, intersecting laser beam that allows the device to determine which layer to write to or read from.

Some researchers are exploring ways of storing multiple bits per spot. The typical approach is to have the recording laser burn pits of different depths. Sixteen possible pit depths will allow each spot to hold four bits of data, quadrupling a disk's storage capacity. Other approaches include recording and sensing different colors. A lot of basic research is still required to determine the potential reliability and performance of these technologies, but it's likely they could be developed quickly if they prove worthwhile.

Holographic storage, meanwhile, could be the sleeper of data storage technology. The technology has been kicking around laboratories for years, and the requirements for applying it practically are well understood. (See How It Works: Holo graphic storage)

Though early holographic storage research results engendered unrealistic expectations, time has brought solutions to many of the problems that have held the technology back. And continued investment by large corporations including IBM and Lucent Technologies makes the technology a good, if still long-term, bet.

Researchers have recently demonstrated holographic data densities as high as 250 gigabits per square inch, and the technology has the potential for much higher densities. It is also potentially much faster than magnetic technologies because whole pages of data can be retrieved at once.

Improved and lower-cost laser diodes, photodetectors, and liquid crystal displays have brought the components of holographic storage within range of practical applications. One of the principal remaining challenges is coming up

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with reliable, cost-effective media. The media has to be lightweight, durable and resistant to even small distortions, which can degrade stored holograms.

Holographic data storage is likely to become practical in five to ten years. Holographic write-once applications are likely to be developed before holographic random-access memory.

Building blocks of substance

Bits are already measured in nanometers, and it is only a matter of time before bits are stored in individual atoms or molecules, yielding phenomenal storage capacities. Chemists have been concocting molecules that are bistable, meaning they can be switched between two states and kept in one state until switched to the other. One state can represent 1 and the other 0, allowing a bit to be stored in a single molecule.
(See How It Works: Molecular switches)

The following research centers are at the forefront of molecular memory research:

- Hewlett-Packard Laboratories
- Pennsylvania State University
- Rice University
- University of California at Los Angeles
- Yale University

Relative Scale:

A row of 10 hydrogen atoms is one nanometer long.
An E. coli bacterium is 1,000 nanometers, or one micron, wide.
A human hair is about 75 microns in diameter.

Bit Sizes:

Near-field optics can produce bits smaller than 100 nanometers.
Today's magnetic disk drive bits are as small as 30 by 250 nanometers.
The bits on a DVD are 400 nanometers long.
The bits on a CD are slightly less than 1 micron long.

The next challenge to using individual or small numbers of molecules for data storage is integrating the molecules with traditional electronics. To date, molecular electronic systems have either been produced in isolation or formed as layers within traditional, lithographically formed devices. Researchers are working to attach molecules to specific positions on chip surfaces, and are working to attach gold nanoparticles to the ends of molecules to make the molecules easier to switch electrically.

Hewlett-Packard Laboratories has developed a molecular memory prototype that has about one thousand switchable molecules at each junction of a set of crossed nanowires. The nanowires connect to standard integrated circuits, and a novel scheme involving gold nanoparticles randomly sprinkled on the nanowires makes each junction addressable. The prototype holds about 10 times as much data as an equal area of a standard memory chip.

In addition to carefully designed molecules, chemists have been working with carbon nanotubes. Research teams from around the world are exploring how to coax the rolled-up sheets of carbon atoms to form memory chips. Individual nanotubes, which can be smaller than one nanometer in diameter, could be used as cells in nonvolatile memory chips. Cells consist of a transistor for reading and writing bits and a capacitor for storing a bit. Nanotubes can be used as transistors, and deliberately formed defects, attached gold dots or attached organic molecules can store electric charges. Researchers are still working out means of controlling how and where nanotubes form, however.

There's also been a lot of progress in recent months in making transistors and diodes out of individual nanowires. Researchers at Harvard University, the University of California at Berkeley, and Lund University in Sweden have been making nanowires from layers of different materials. The Harvard researchers have made prototype field-effect transistors, which could be used in memory chips. These projects will be detailed in the March, 2003 Alternative Computer Chips *Making the Future* report.

Molecular and nanotube storage devices could be used in practical applications in five to ten years. Nanowire devices could be ready within five years because they are produced by many of the same processes used in chip fabrication.

Sub-pinhead DVDs

Researchers at the University of Wisconsin have developed a prototype storage device that records bits as the presence or absence of individual atoms on a crystal surface. The prototype has a capacity of 250 terabits per square inch, enough to store 10 DVDs worth of data on a pinhead.

Though atomic-scale data storage is still decades away, the Wisconsin researchers have begun to chart the territory. They have determined some of the physical limits and found that the technology is feasible. Significantly, their prototype works at room temperature.

Limits and opportunities

In the next five years, data storage technology is likely to advance along the familiar course of electronic memory chips, magnetic disk drives and CD-like removable media. But once these technologies begin to reach their physical limits, a wide range of alternative technologies will be poised to move into the mainstream. IBM Research, for example, is pursuing many options, including technologies based on a patterned stamps, microelectromechanical systems, nanowires and holograms.

Data storage research is the epitome of applied science, and the bleeding edge of the technology is drawing closer to the frontiers of basic chemistry, electrical engineering, materials science and physics. In order to provide the technological underpinnings of the coming era of protein-folding databases, massive data mining and missions to Mars, anything that looks like 1s and 0s to scientists as they peer through their microscopes is fair game.

Recent Key Developments

Advances in storage media:

- A method for making magnetic bits using a stamp (Stamp Corrals Tiny Bits, page 9)
- A technique for making virtual boundaries for magnetic bits (Defects Boost Disk Capacity, page 10)
- A technique for fencing in magnetic bits (Bound Bits Could Bring Bigger Disks, page 12)
- A way to embed vertical nanowires in a thin film (Tiny Wires Store More, page 13)
- A material whose magnetic and electric fields are aligned (Aligned Fields Could Speed Storage, page 15)

Advances in storage technologies:

- A read head that will sense tinier bits (Disks Set to Go Ballistic, page 16)
- A method for stamping tiny electric charges onto a plastic disk (Rubber Stamp Leaves Electronic Mark, page 17)
- A MEMS storage device prototype with 1,000 read/write heads (Mechanical Data Storage Goes Massively Parallel, page 18)
- A one-terabit-per-square-inch prototype MEMS storage device developed by IBM Research in June
- A tiny read/write head for a MEMS storage device (Disk-on-a-Chip Takes Shape, page 19)

Advances in memory technologies:

- A method for storing tiny charges in nanotubes (Oxygen Makes Nanotube Memory, page 21)
- A prototype nanowire memory chip that uses only 1,000 molecules per bit (Molecule Chip Demoed, page 22)
- A method for addressing a memory chip made of nanowires (HP Maps Molecular Memory, page 23)
- A memory element made of crossed nanotubes (Bendable Nanotubes Store Bits, page 25)

Advances in optical storage:

- A prototype 1-gigabyte, 3-centimeter optical disc that uses a blue laser developed by Philips Research in June
- A method for writing data five 5 millimeters deep in glass developed by ERATO and Tokyo Institute of Technology in August
- A material that can be recorded to using one type of light and read via another (Light-Sensitive Memory Does Not Fade, page 26)
- A material that stores high-resolution holograms (Glass Mix Sharpens Holograms, page 26)
- A method for increasing hologram resolution (Holographic Technique Stresses Interference, page 28)
- A recording scheme that stores more than one bit per dimple (Color Deepens Data Storage, page 28)

Advances from the frontiers of science:

- A way to store a 1,000-bit image in a liquid crystal molecule (Molecule Stores Picture, page 30)
- A method to store bits using the positions of individual atoms (Ultimate Memory Demoed, page 31)
- A method for using small numbers of silver atoms as optical bits (Silver Shines and Red and Green, page 32)
- A molecular switch that could serve as a memory element (Molecule Makes Mini Memory, page 33)
- Using a 1,000-molecule element to hold a bit for 15 minutes (Molecules Make Short-Term Memory, page 35)
- Genetically engineering a protein to form arrays of microscopic bits of metal (Altered Protein Orders Metal Bits, page 36)

Stamp Corrals Tiny Bits

By Kimberly Patch, Technology Research News
October 16/23, 2002

The way disk drives store information in a computer is fairly straightforward—microscopic areas of magnetic material represent 1s or 0s depending on their magnetic orientations. The smaller these magnetic areas, or bits, the more 1s and 0s fit on a disk.

One way to get more information on a disk is to make bits smaller. Disk drive manufacturers have managed to double the capacity of drives every year for the past five years, largely by shrinking bits. The laws of physics, however, are closing in. Today's densest prototype disk drives contain 100 gigabits, or billion bits per square inch; it looks like bits will not hold their magnetic orientations reliably beyond 200 gigabits per square inch.

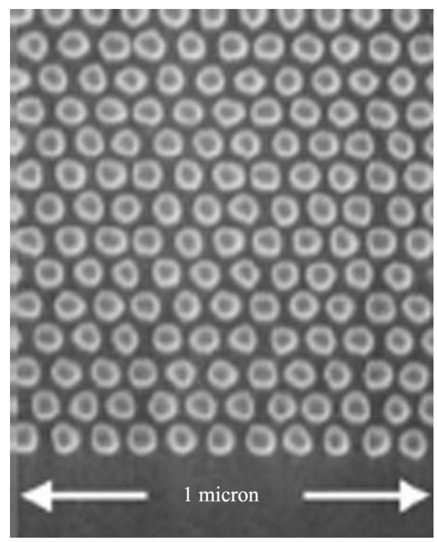
This is because heat causes the magnetic grains that make up a bit to randomly flip their orientations; when a bit contains too few grains of material, enough grains can ran-domly flip that it becomes unclear whether the bit represents a 1 or a 0. "If the grains are made much smaller... the energy re-quired to flip their magnet-ization can be so low that the magnetization would be ther-mally unstable," said Gary McClelland, a research staff member at IBM's Almaden research center.

The surfaces of today's standard disk drives are thin films of magnetic material, and individual bits are defined only by the actions of the recording head. It has been known for years that patterning, or physically isolating the magnetic material in each bit is one way to keep small numbers of grains aligned. It takes extra work, however, to make specific patterns on the disks. Existing techniques are an estimated two to four orders of magnitude more expensive than today's disk manufacturing processes, said Robert White, a professor of electrical engineering and materials science at Stanford University and founder of the school's Center for Research on Information Storage Materials.

McClelland and his Almaden colleagues have found a way to stamp magnetic material onto a disk, and the method shows promise as a relatively inexpensive way to pattern media.

The researchers used beams of electrons to etch a master stamp, then spread a thin film of liquid polymer, or plastic, on a silicon oxide wafer. They pressed the stamp into the polymer using 290 pounds per square inch of pressure for a full minute, and at the same time hardened the polymer with ultraviolet light. The researchers then pressed the mirror image into a second layer of polymer on a wafer to form an exact replica of the stamp in plastic.

The process left a pattern of 28-nanometer-high polymer pillars. The researchers used a beam of electrically charged fluoride atoms to carve the polymer pattern into the underlying silicon oxide, then added several layers of magnetic film over the silicon oxide pillars.



Source: IBM Research

This master stamp is used for patterning magnetic media, which allows for smaller bits.

One key to the process was making the stamp flexible. "By using a flexible stamp, we can accommodate the small but inevitable surface roughness and curvature present in glass disk substrates," said McClelland.

The tricky part of the process was finding the right mix of adhesion and release layers, McClelland said. The problem is one familiar anyone who's struggled to remove a recalcitrant cupcake from a tin—the polymer had to stick to the glass surface, but not to the stamp. The design the researchers came up with enabled the polymer "to adhere to the glass substrate, but also allowed the stamp to separate easily," from the finished surface, McClelland said.

The researchers have managed to put together a process that many people have been talking about for a long time, said Stanford University's White. "It is significant that this comes out of IBM, [which] has the potential to utilize it," he said.

The Almaden technique is somewhat unusual because the magnetic layer was added at the end of the process, said White. "It isn't obvious that this would work," he said.

Although the idea of using imprint lithography has been around for about five years, and the use of flexible plates is also not unique, the researchers have managed to stamp out a relatively large area, which is also an important step, he said. "Because you can't use a step-and-repeat technique with this kind of resolution, you have to do it all in one slam dunk," he said.

The technique is also relatively simple, and thus potentially inexpensive, said White. "It's not dirt cheap, but it is a step toward an inexpensive way of making patterned media," he said. "Once you have the master you can make large numbers of copies."

The areal density of the researcher's prototype is 74 gigabits per square inch, which is about twice the density of existing commercial drives, said McClelland. It is feasible, however, to make patterns as dense as 500 gigabits per square inch using the technique, he said.

This type of technique could eventually push disk drive density as high as 2,000 gigabits, or 2 terabits per square inch, said White. Meanwhile, existing non-patterned media is likely to top out at 200 gigabits per square inch, he said.

The researchers are working on stamping out smaller bits, and also on using a standard disk substrate instead of the silicon oxide surface they used in their prototype, according to McClelland. Another step is figuring out how to write and read the bits at the high speeds today's disk drives require. "The major additional complication is the need to synchronize data writing and reading... as the disk rotates at high speeds," McClellan said.

Once the disk substrate is patterned by imprinting, the disk can probably be coated and finished using existing manufacturing processes, said McClelland.

It is premature to speculate about when any particular density-enhancing technology will be adopted by disk drive manufacturers, said McClelland. However, "if our research continues on its successful path, we expect that patterned media could be considered for adoption in about five years," he said.

Meanwhile, IBM rival Seagate is betting on a different horse. Instead of imposing a pattern on disk media, they're working on processes that will automatically build a pattern from the ground up. "Seagate is more actively pursuing self-ordered magnetic arrays as a means to achieving bit-patterned media," said Mark Kryder, a professor of electrical and computer engineering at Carnegie Mellon University, and Seagate's senior vice president of research.

Seagate's technology, dubbed heat assisted magnetic recording, combines self-ordered arrays of iron-platinum particles, which are very stable, with a technique that calls for heating the media with a laser beam to make it possible to write data to them. The technique could eventually lead to storage densities as high as 50 terabits per square inch, according to Seagate. Seagate's effort is partly funded by the U.S. Department of Commerce.

McClelland's research colleagues were Mark W. Hart, Charles T. Rettner, Margaret E. Best, Kenneth R. Carter, and Bruce D. Terris. They published the research in the August 19, 2002 issue of *Applied Physics Letters*. The research was funded by IBM.

Timeline: 5 years
Funding: Corporate
TRN Categories: Data Storage Technology; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Nanoscale Patterning of Magnetic Islands by Imprint Lithography Using a Flexible Mold," *Applied Physics Letters*, August 19, 2002.

TRN

Defects Boost Disc Capacity

By Kimberly Patch and Eric Smalley, Technology Research News
April 18, 2001

The solution to a major nuisance in the field of superconductivity could also prove useful in the quest to make higher capacity data storage media.

Microscopic vortices form in superconductor material when the material is in a magnetic field. These tiny magnetic tornadoes hinder the flow of electrons, which reduces the superconductor's efficiency. Introducing vertical defects into the superconductor material pins these vortices in place, which minimizes their effect.

A team at IBM Research has applied this pinning technique to magneto-optical recording media. By corralling the tiny magnetic fields that constitute bits, the researchers reduced the size of a viable bit, allowing more information to be stored on a disc.

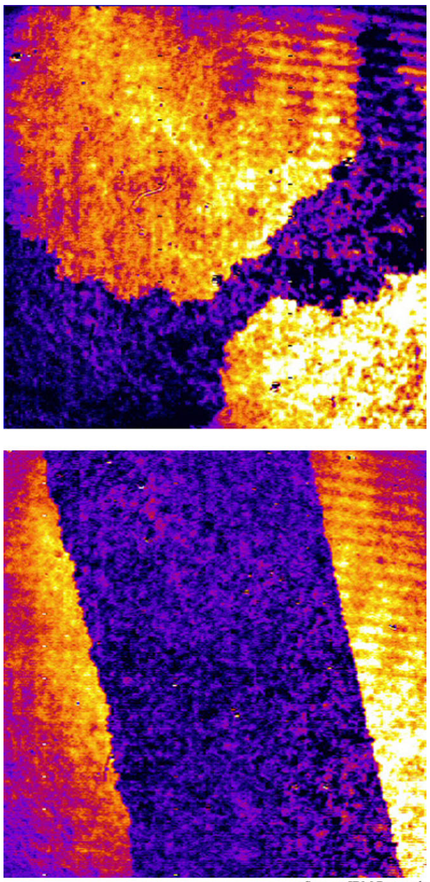
If the technology can be scaled up, it could lead to data storage densities on the order of one terabit per square inch, said Lia Krusin-Elbaum, a research staff member at IBM Research. One terabit per square inch translates to a standard-size compact disc that could hold 23 terabits of data, which is enough to store 687 two-hour movies.

In magneto-optical recording, which is used in rewritable compact discs, the heating action of the recording laser changes the orientation of a disc's magnetic field. The data is read by shining a polarized laser beam on the disc. The polarization of the light that bounces back indicates whether the domain, or bit, hit by the laser is oriented up or down. Ones and zeros are represented by the two types of polarized light.

If the domains are too small they interfere with each other and they also become more susceptible to small increases in temperature, which can reverse their magnetic fields. Orienting the domains perpendicularly helps to a point, but researchers still face these problems when they try to further reduce the size of the domains.

One way around the problem is to pattern the media by setting up boundaries to contain each domain, or by embedding periodically spaced particles or nanowires, one per bit, in the material. But patterned media is more difficult to produce than ordinary media, and patterned media would require yet-to-be-developed recording technology that can be positioned precisely over the domains.

The IBM technique attempts to combine the best of both approaches by producing tightly confined, perpendicularly-oriented domains, but in unpatterned media. The technique "uses continuous films, [is] relatively easy to prepare, and it does not require nanometer-scale patterning or fabrication," said Krusin-Elbaum.



Source: IBM Research

The top image shows the irregular walls of a magnetic domain formed in media without linear defects. The bottom image shows the smooth walls of a magnetic domain formed in media with a linear defect.

The record-ing medium consists of a 0.7-nanometer layer of cobalt sand-wiched between 3-nanometer and 2-nanometer layers of plati-num. The re-searchers make vertical, linear defects, or up-ward folds in the cobalt layer. The defects produce strain in the material around them, and domains that form in the areas of strain take on the shape and orientation of the defect.

A domain in media without defects is analogous to a strand of cooked spaghetti wriggling side to side. The effect of the defects is analogous to confining the spaghetti inside a straw. The result is the domains are 10 times narrower and so can be packed together 100 times more densely.

The strain induced by each defect extends hundreds of microns around the defect, said Krusin-Elbaum. In the IBM experiments, the average domain formed perpendicularly as far as 300 microns from the defect.

This means relatively few defects would be needed to prepare each CD, she said. For example, if the strain from each defect was effective for an area 300 microns in diameter, about 160,000 defects would be required to prepare a CD-size disc. Those defects would support more than 23 trillion domains.

Other researchers are working on improving the storage capacity of a rewritable CD to 100 gigabits per square inch, said Krusin-Elbaum. "Introducing linear defects may push this density into [the] terabit per square inch range," she said.

"This is nice work and potentially very useful," said Phillip N. First, a physics professor at the Georgia Institute of Technology. "Because the density of imposed defects would be much less than the bit density, this new work could provide a relatively simple path to media densities [on the order of] 1 terabit per square inch for perpendicular magnetic recording," he said.

There are, however, "many other technological hurdles to be overcome in reading and writing the data," he added.

One of those hurdles is the wavelength of light. Magneto-optical disks are read using light, and lightwaves cannot distinguish features smaller than a wavelength. Three hundred or 400 nanometers is the shortest wavelength researchers have been able to use so far. "That takes you into the ultraviolet," said Robert White, a professor of electrical engineering and materials science and engineering at Stanford University and director of the university's Center for Research on Information Storage Materials.

Even 100-nanometer domains, which would require 100-nanometer-wavelength light or smaller, only yield 65 gigabits per square inch, said White.

There are tricks to increasing storage capacity, like overlapping the round bit areas and reading the edge of the crescent that's showing, he added. If the defects act to smooth the edges of the crescents, that may help. "But it's not obvious to me that this is going to take us to the terabit [range]," he added.

So far the researchers have tested domains formed by individually-produced defects. The researchers' next step is to make media containing more than a single defect, said Krusin-Elbaum. The researchers hope to demonstrate the feasibility of their technique in the next couple of years and to put it to use in the next 5 years, she said.

Krusin-Elbaum's research colleagues were Takasada Shibauchi, Bernell Argyle, Lynne Gignac and Dieter Weller. They published the research in the March 22, 2001 issue of the journal *Nature*. The research was funded by IBM.

Timeline: 5 years
Funding: Corporate
TRN Categories: Materials Science and Engineering; Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Stable ultrahigh-density magneto-optical recordings using introduced linear defects," *Nature*, March 22, 2001

Bound Bits Could Bring Bigger Disks

By Kimberly Patch, Technology Research News
February 28, 2001

Despite the constant speed and capacity improvements to magnetic computer disks, the basic technology behind them has stayed largely the same for the past 40 years.

In order for the capacity improvements to continue, the bits that store digital information must continue to shrink. The practice of shrinking bits, however, is expected to run up against the laws of physics within the next few years.

Although it is still too early to tell how these problems will be solved, researchers from IBM's Almaden Research Center have moved one approach a step forward by reading and writing to patterned media, which uses a single magnetic domain to represent a bit.

This is in contrast to the hundred or so magnetic grains, or domains that make up each bit on today's thin-film media. The average magnetic pole direction of its grains determines whether the bit represents a one or a zero. Below that many grains per bit, the signal to noise ratio is too low to be sure of the average magnetic pole direction of the bit. This is because the grains do not point in exactly the same direc-tion, or even always hold their positions. The grains that change randomly or point less directly contribute noise to the signal from the majority of the bits pointing in the correct direction.

The problem with cramming more bits onto conventional media is once the grains of material shrink below certain size, larger numbers of grains become unstable and will flip their magnetic poles randomly due to changes in temperature.

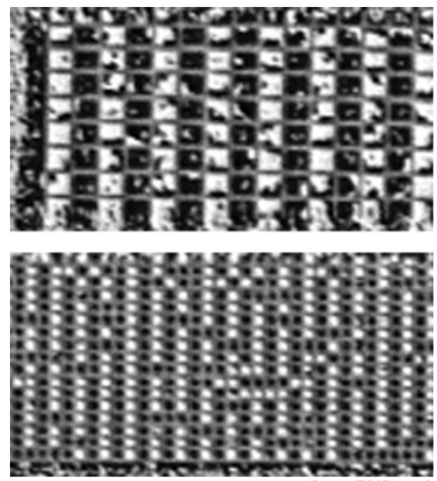
This is one reason it's a bad idea to leave a floppy disk in a hot car—over time enough heat will randomly flip enough grains that the bits will become unreadable.

Conventional wisdom says the most bits that can be crammed onto a square inch of disk space using today's thin film technology will be around 100 million, or 100 gigabits. This is five times the state-of-the-art 20 gigabits per inch, but disk space traditionally doubles every year, meaning grain size could come into play in as soon as three years. Today's grain sizes are about 15 nanometers, or the size of 150 carbon atoms in a row.

Patterned media isolates bits physically by, for instance, carving a ditch around a small square, which leaves a magnetic island. The grains in this small, isolated group are coupled magnetically and so change poles in lockstep, are very stable, and can function as a bit.

Because grain size is not relevant in patterned media, this type of media could store much more information before running into the grain size limitations facing today's technology.

Researchers from IBM's Almaden Research Center have demonstrated a patterned media with single domain islands 80 nanometers across, which translates to a density of 100 gigabits per square inch. "We've taken a magnetic film and used a focused ion beam to carve it up into small islands," said Bruce Terris, manager of exploratory magnetic media and phenomena at Almaden. "The islands are small enough that each island is a single domain. And then we used a magnetic recording head to read and write to those islands," he said.



Source: IBM Research

These two pictures show a magnetic film etched into square islands. The squares appear ragged in the top picture because each island contains several magnetic domains that flip independently. In the bottom picture, however, the islands are small enough that the grains of material act magnetically as one bit.

Patterned media has its own challenges, however, and most of them involve changing the disk design that has worked well for 40 years.

For instance, the thin films on conventional disks are like blank slates that can be written on starting at any point. With patterned media, however, information must be written precisely on the islands that make up the bits. It's a more complicated engineering problem to write within the lines. "The writing will need to be more precise because you have to have the write... head synchronized to those islands," said Terris.

Another challenge is tracking. Bits line up around a disk, and the read head must stay on the correct track to read bits in the correct order. It will be more difficult to write and read on the narrower tracks of patterned media, said Terris. "You need a mechanical servo system that will keep the head on track in those dimensions," he said.

Although the researchers' 80-nanometer islands are only five times smaller than today's conventional bits, they are much more than five times narrower. This is because patterned bits are generally square, while conventional bits are 10 to 15 times wider than they are long, with the wide side perpendicular to the edge of the disk, making for a relatively wide track for the read and write heads to follow, said Terris.

The researchers read and wrote information to the islands using sensors that were in direct contact with the bits. In order to make this type of technology viable, they would have to use read and write heads that fly above the disk without touching it. To work with patterned media, the disk heads would have to fly closer to the disk than today's state-of-the-art media, said Terris. "The heights would probably be on the order of 10 nanometers or lower," in contrast to be 20 to 30 nanometer range of today's disks, he said.

Perhaps the biggest challenge, however, is making the islands small enough to make it worth it to invent a whole new technology around them.

In principle, it is possible to use lithography to make 12.5-nanometer islands, which would make a disk density of 1,000 gigabits, or one terrabit per square inch, said Terris. "But that is extremely challenging, and to do that in a manufacturing way is still a problem to be solved," he said.

The research is a step toward making patterned media practical, but the field "is in its infancy [and] there are a couple of really difficult hurdles," said Caroline Ross, an associate professor of material science at the Massachusetts Institute of Technology. "I think probably the major [IBM] contribution is they've shown they can read and write bits" onto the islands, she said.

The big challenge is making the patterned bits small enough; the second problem is you have to be able to do this cheaply over a very large area like the area of hard disk, said Ross. The lithography methods used in semiconductor manufacturing, for instance, won't make small enough structures, she said.

The ion beam method the IBM researchers used is only good for research purposes. "It's very slow and costly. So you need a way to pattern full disks with 50-nanometer features in a cost-effective manner," said Terris. According to both Terris and Ross, it's not yet apparent what could work effectively.

It is also a possibility that today's disk technology could be pushed further than conventional wisdom says is possible. "There will be a limit to conventional media but it's a question of where the limit really is," said Ross. "People originally thought maybe it was 10 gigabits per square inch and then they said 50 and now they say 100. It's always very hard to put numbers on those predictions because people seem to find a way around them," she said.

It will be at least three years before patterned media technology could be technically viable, said Terris.

Terris' research colleagues were Jens Lohau, Andreas Moser, Charles T. Rettner, and Margaret E. Best of IBM's Almaden Research Center. They published the research in the February 12, 2001 issue of Advanced Physics Letters. The research was funded by IBM, the Department of Energy (DOE) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: > 3 years
Funding: Corporate, Government
TRN Categories: Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Writing and Reading Perpendicular Magnetic Recording Media Patterned by a Focused Ion Beam," *Applied Physics Letters*, February 12, 2001.

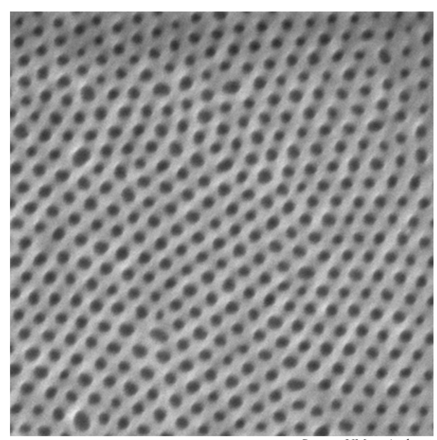
TRN

Tiny Wires Store More

By Eric Smalley, Technology Research News
December 20/27, 2000

It's impossible to say how many angels can dance on the head of a pin, but the music they're dancing to is another matter. A pinhead-sized section of magnetic storage media made from millions of microscopic wires could hold three and half CDs worth of music.

Researchers at the University of Massachusetts at Amherst and IBM Research have developed a process that yields metal wires 14 nanometers in diameter arrayed vertically on a surface. The process solves half the problem of producing disk drives that have much higher capacities.



Source: UMass Amherst

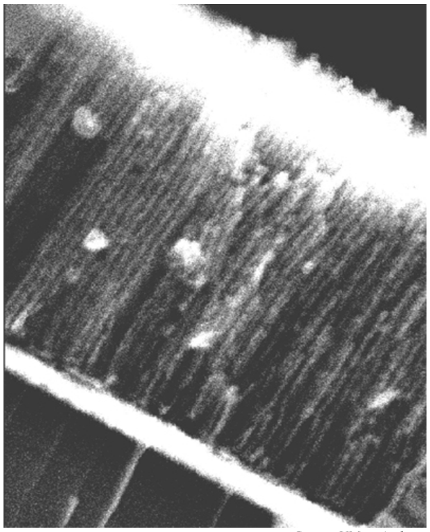
These holes, each 14 nanometers in diameter, can be filled with metal to make an array of nanowires.

The other half of the problem is de-veloping a read-write head sen-sitive enough to make use of the media. If the technology to read from and write to an individual nano-wire is worked out, the ensuing drives would hold 1.2 terabits per square inch, said Mark Tuominen, an associate professor of physics at the

University of Massachusetts at Amherst. “That’s about 25 DVD-quality movies on a surface the size of a quarter.”

Such disks would hold 24 times more than today’s state-of-the-art magnetic disk drives, which store up to 50 gigabytes per square inch.

“That’s a staggering result,” said Michael E. McHenry, a professor of material science and engineering at Carnegie Mellon University. “The next big goal in data storage is going to be this terabit-per-square-inch recording density.”



Source: UMass Amherst

Cobalt nanowires fixed to a silicon substrate look like bristles on a brush. The magnetic orientation of each wire could represent a bit.

The process uses many standard chip-making tech-niques, includ-ing spreading a thin film of material over a silicon substrate. The film in this case is a heated mix of polysty-rene and polymethyl-methacrylate (PMMA) in which PMMA forms 14-nano-meter-diameter cylinders.

“We use an electric field to orient the cylinders so they stand stick straight, like soldiers standing side by side, perpendicular to the surface,” said Tuominen. The cylinders are evenly spaced about 24 nanometers apart.

The researchers cool the film to harden it, and then use ultraviolet radiation to break down the PMMA cylinders. “Wherever the cylinders were, now there’s a pore from the surface to the substrate,” he said.

The film is then immersed in a solution containing tiny particles of metal that fill the pores when an electric current is applied. The result is an orderly array of metal nanowires.

“Having these things periodically arranged over a large length scale is very important. You have to know where to go looking for [a] particular piece of information,” said McHenry.

Making the bits perpendicular to the surface is important for fitting a lot of information in a small area. The bits in disk drive media today are parallel to the surface. The problem is researchers can’t simply shrink the bits. Below about 50 nanometers, the magnetic particle that constitutes a bit has to be longer than it is wide or else it becomes superparamagnetic.

If a particle is superparamagnetic, thermal energy from the environment can change its magnetic orientation, meaning the bits become unstable and can flip. Orienting the bits perpendicular to the surface allows researchers to keep them large enough to be stable while fitting more of them in the same surface area, said Tuominen.

Another important part of the project was to develop a process that can easily scale up for mass production, Tuominen said. “It was important to make arrays [that were] spun cast onto a surface,” similar to the way light-resistant material is applied to put on silicon surfaces in chip making, he said. “This is quite straightforward and adaptable to industrial processes.”

The researchers have used the process to make cobalt, copper, gold and cobalt-copper nanowires. They used a similar process to make silicon oxide pillars. Silicon oxide is an insulator and structural element in computer chips and other silicon devices.

The researchers have also used electron beam patterning to make nanowire arrays on specific portions of a surface, Tuominen said. “You can arbitrarily pattern the array quite easily.”

Now the researchers are working on making smaller nanowires. “[We’ve] made pores as small as five nanometers, but that’s still a work in process,” Tuominen said.

The arrays could also be used to produce high-density memory. “The underlying physics... is not completely established... but there is some promise to possibly use these for a type of MRAM. Many hurdles have to be overcome before that’s a reality,” said Tuominen. Magnetic Random Access Memory, which uses magnetism rather than electric charges to store bits, and is likely to be the next generation of computer memory. MRAM will be faster and more dense than today’s memory and will retain data after the computer is turned off.

Because the process is compatible with existing manufacturing techniques, it could be adopted in less than a year, said Tuominen.

Tuominen’s research colleagues were Thomas Thurn-Albrecht, Jörg Schotter, Gerd A. Kästle, Nathan Emley and Thomas P. Russell of UMass Amherst, and Takasada Shibauchi, Lia Krusin-Elbaum, Kathryn Guarini and Charles T. Black of IBM Research. They published the research in the December 15, 2000 issue of *Science*. It was funded by the National Science Foundation and the Department of Energy.

Timeline: <1 year
Funding: Government
TRN Categories: Semiconductors and Materials; Data Storage Technology
Story Type: News
Related Elements: Technical paper, “Ultrahigh-Density Nanowire Arrays Grown in Self-Assembled Diblock Copolymer Templates,” *Science*, December 15, 2000

TRN

Aligned Fields Could Speed Storage

By Kimberly Patch, Technology Research News
January 1/8, 2003

Atoms are like tiny magnets, with poles that repel each other. The opposite ends of atoms also have opposite electrical charges. When the atoms or molecules within a material line up, the material as a whole has magnetic or electric poles.

Today's electronic devices use just one of the two orientations. Magnetic computer disks, for instance, represent the ones and zeros of digital information using the magnetic orientations of tiny areas, or bits, of a material, while computer memory chips only use electric orientations.

This could change. Researchers from three institutes in Germany and Russia have found a material whose electric and magnetic domains line up together. The work could bring together the currently separate fields of magnetic and electronic data storage, which would give both methods more flexibility.

The researchers discovered the phenomenon after finding it was possible to image the magnetic and electric domains of a material at the same time by bouncing light waves off the materials, then making an image of the way both the magnetic and electric fields of the material changed the light waves' phases. "It works similar to holography," said Manfred Fiebig, a scientist at Dortmund University and at the Max-Born Institute in Germany. It "allows us to tell the difference between the very similar electric and magnetic domains in our... samples and image them as bright and dark areas," he said.

The results showed that the magnetic and electric domains in the material yttrium manganese oxide lined up. "The surprising result was the discovery of the very strong [alignment] of electric and magnetic domains," said Fiebig. This is something that had not been observed before, he said.

Materials like these may eventually make it possible to write data to a device using one method and read it using another, said Fiebig. It could, for instance, enable faster methods of storing information on magneto-optical disks by changing the magnetization using electrical properties, he said.

Coupled magnetic and electric devices could also find applications in spintronics, said Fiebig. Spintronics uses the magnetic orientations of electrons to control the flow of electric current. The electric writing and magnetic reading could be used in these devices, he said.

The method required that the measurements take place at a very low temperature, which meant devising a way to rotate the sample inside a cryostat—"a high-end thermos bottle with windows," said Fiebig. And to image the electric properties of the material, the researchers had to make the measurements while the material was in the electric field. To apply this field, the researchers used transparent electrodes that did not interfere with the lasers.

Properties of pieces of material as small as one nanometer can be measured this way. A nanometer is a millionth of a millimeter, or the span of 10 hydrogen atoms.

Practical developments will require finding new compounds that show the linked properties at higher temperatures, Fiebig added. "The key question is the development of other ferroelectromagnetic materials which are more favorable for technical applications, meaning higher magnetic ordering temperatures, [and] easy control of the magnetic and electric state," he said.

The research is intriguing, said Anthony Bland, a professor of physics at the University of Cambridge in England. The effects "may be useful in as yet unforeseen ways," he said.

Finding uses for this type of material is a long way off, however, Bland said. First, similar materials that can be used at higher temperatures would have to be found. "These experiments were conducted at very low temperatures whereas real devices will require a room-temperature operation. This is likely to be a very challenging materials problem," he said.

In addition, the method is very unlike the general body of current research on materials for uses like storage. Eventual applications would be based on a new methodology which is not yet proven, he said.

The researchers are working to show control of the electric state of the material using its magnetic field and control of the magnetic state of material using its electric field, Fiebig said. They are also working on a theoretical explanation of the mechanism involved, he said.

The researchers are also looking to expand the imaging method to clarify unknown magnetic and crystallographic structures as an alternative to the classical diffraction techniques involving neutrons, x-rays, and electrons, Fiebig said.

Fiebig's research colleagues were Thomas Lottermoser and Dietmar Froehlich at Dortmund University in Germany, and Alexander V. Goltsev and Roman V. Pisarev from the Ioffe Physical Technical Institute of the Russian Academy of Sciences. They published the research in the October 24, 2002 issue of *Nature*. The research was funded by the German research Council (DFG) and the Russian Foundation for Basic Research.

Timeline: 10 years
Funding: Government
TRN Categories: Data Storage Technology; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Observation of Coupled Magnetic and Electric Domains," *Nature*, October 24, 2002.

1Disks Set to Go Ballistic

By Eric Smalley, Technology Research News
July 24/31, 2002

One of the challenges to cramming more information onto computer hard drives is making a sensor sensitive enough to measure the presence or absence of a magnetic field in a microscopic bit of material.

Reading a bit means sensing if its magnetic field affects the flow of electrons through an electric circuit. If the magnetic field is strong enough to change a sensor's electron flow, the bit represents a 1, if not, it is a 0. The smaller the bit, the smaller its magnetic field, and the harder it is to sense the difference between a 1 and a 0.

Researchers from the State University of New York at Buffalo have used an effect dubbed ballistic magnetoresistance to make a tiny prototype sensor that is 15 times as sensitive as the giant magnetoresistance sensors used in today's disk drives. The T-shaped sensor consists of a pair of wires connected by only a few hundred atoms.

Source: SUNY Buffalo

The contact between these wires is only a few hundred atoms wide. The tight squeeze keeps electrons from scattering, allowing the sensor to read the minuscule bits that future, super high-capacity disk drives will depend on.

Because the sensor is very small as well as sensitive, it could be used to read tiny, closely packed bits. "Due to the nanoscale of the sensor, bit size can be reduced to... terabit-per-square-inch densities," said Harsh Deep Chopra, an associate professor of materials science and engineering at SUNY Buffalo. A terabit is 125 gigabytes, and a DVD holds 4 gigabytes. A CD-sized magnetic disk with such small bits could hold 1,800 gigabytes, or about 450 DVDs worth of information.

The key to making sensors that can read smaller bits is increasing the magnetoresistance of the sensor, or read head, used to distinguish the magnetic states of the bits. The higher a material's magnetoresistance, the greater the difference in the number of electrons flowing through it when it is surrounded by a magnetic field versus when it is not. If the difference is significant, it can be used to distinguish weak magnetic fields like those of very small bits that represent 1's from bits that have no magnetic field and represent 0's.

Ballistic magnetoresistance produces a greater difference between 1 and 0 signals and other types of magnetoresistance, but the challenges to using it in disk drives is that it works best with either very strong magnetic fields or extremely low temperatures. Strong magnetic fields can't be used with small bits, and a low-temperature requirement makes for impractical devices.

The Buffalo researchers got around these potential restrictions when they discovered that the right size and shape of the contact point in the tiny wires of a sensor increases the ballistic magnetoresistance effect to the point where it can be used with weak magnetic fields at room temperature.

The researchers' ballistic sensor consists of two nickel wires 125 microns in diameter connected to form a T. A micron is a thousandth of a millimeter, and a human hair is about 75 microns thick. The researchers sharpened the end of one wire at the T junction to a 40-nanometer point to make an extremely small contact between the two wires. A nanometer is one thousandth of a micron, or about the length of 10 hydrogen atoms in a row.

When the sensor is in a magnetic field, the magnetic orientations of its electrodes align, making current flow more easily.

In addition, electrons flow even more easily through the sensor because of its small size. As electrons flow through materials like metal, they ordinarily scatter, bouncing in different directions. An electrical current arises when the average of all the movement is a flow in one direction. In wires only a few nanometers wide, however, the scattering stops and electrons flow straight through, or ballistically. The sensor allows electrons to flow this way because the contact surface at the T junction between the electrodes is only a few hundred atoms

In the absence of a magnetic field, the magnetic orientations of the electrodes in the researchers' sensor are opposite, which increases the device's resistance to electrical currents.

The sensor's small size also gives it an an advantage where resistance is concerned. Electrons have spin, which is similar to a magnet's North and South poles. If an electron's spin is aligned with the magnetic orientation of an electrode, it can pass through. If not, it is blocked. If the contact between the sensor's electrodes were larger, a few electrons would reorient their spins and pass through, reducing the resistance. But because the contact is so small, the electrons don't have time to reorient, which gives the device a higher resistance.

The combination of ballistic electron flow in the presence of a magnetic field and greater resistance in the absence of a magnetic field means a greater difference in electron flow than is possible with today's giant magnetoresistance devices. This makes for a more sensitive sensor.

In low magnetic fields at room temperature, the electrical resistance of the researchers' sensor is 33 times greater than when no magnetic field is present, allowing the sensor to read bits so small that one trillion of them could fit in a square inch, according to Chopra. Previous ballistic magnetoresistance experiments have yielded increases in resistance of as much as seven times. The giant magnetoresistance used in today's disk drives doubles electrical resistance.

Making practical storage devices that use ballistic magnetoresistance should be fairly straightforward because it is similar to giant magnetoresistance, said Chopra. Giant magnetoresistance devices use two thin layers of magnetic material separated by an even thinner non-magnetic layer. Because the magnetic layers have opposite magnetic orientations, passing a current of electrons through both layers is difficult: one layer blocks electrons that have one spin orientation while the other layer blocks electrons of the other orientation. Adding a magnetic field causes the magnetic orientations of the two layers to align and so block electrons of only one spin orientation.

"The good news is that the effect is like giant magnetoresistance except it is... huge and it comes packed in a sensor size that is atomic scale," said Chopra. More work needs to be done to closely control the stronger ballistic effect and assess its long-term stability, he added.

The device's strong effect at room temperature and in small magnetic fields makes it "potentially very interesting" for data storage technology, said Caroline Ross, a professor of materials science and engineering at the Massachusetts Institute of Technology. "We still need to understand exactly the mechanism for the effect," she said.

The tiny contact point between the wires forces the boundary of the magnetic field to be very narrow, effectively blocking electrons, said Ross. "Hence this phenomenon is a direct result of the small size of the contact," she said.

The ballistic magnetoresistance the researchers produced could be used in practical applications in 4 to 6 years, said Chopra.

Chopra's research colleague was Susan Hua. They published the research in the July 1, 2002 issue of the journal Physical Review B. The research was funded by the National Science Foundation (NSF) and the Department of Energy (DOE).

Timeline: 4-6 years
Funding: Government
TRN Categories: Data Storage Technology; Materials Science and Engineering; Physics
Story Type: News
Related Elements: Technical paper, "Ballistic magnetoresistance over 3000% in Ni nanocontacts at room temperature," Physical Review B, July 1, 2002

Rubber Stamp Leaves Electronic Mark

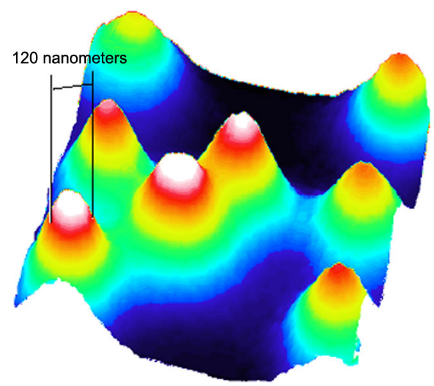
By Eric Smalley, Technology Research News
March 21, 2001

Proving that old technologies can contribute to contemporary research, a pair of Harvard University researchers has fashioned a high capacity data storage device based on a rubber stamp.

The researchers' electric microcontact printing system can transfer electric charge from the stamp to a thin film of plastic, and can also be used to transfer vanishingly small particles to a surface in the same way photocopiers transfer toner to paper.

The system stamps electric charge into a film of plastic to store about a CD's worth of data in an area 1 centimeter square.

The system can also stamp tiny amounts of particles, including magnetic particles, onto a surface in patterns with features as small as 120 nanometers. Applying particles to sur-faces can be used for for high-resolution printing, mag-netic data stor-age and posi-tioning mole-cules on bio-logical and chemical sens-ors and testers.



Source: Harvard University

The hills represent areas with trapped electric charge. Harvard researchers have been able to pattern charge with features as small as 120 nanometers.

"The organization of small particles and molecules is a difficult task in nanotechnology," said Heiko O. Jacobs, a postdoctoral researcher in the department of chemistry at Harvard University.

The researchers used photolithography and electron beam lithography to etch patterns on a piece of semiconductor, which then served as a mold for a liquid polymer, said Jacobs. Curing the polymer yielded the rubber stamp. The researchers coated the 5-millimeter-thick stamp with an 80-nanometer gold film.

To write a pattern of charge, the researchers placed the stamp on a negatively-conducting silicon wafer covered with an 80-nanometer film of polymethylmethacrylate (PMMA), which is a plastic that holds electric charge. They applied an electric current to the gold plate of the stamp, which was drawn through the PMMA film to the silicon wafer. The result was an electric charge injected into the areas of the PMMA film in contact with the stamp.

Today's disk drives use the magnetic orientation of microscopic particles to represent bits, but electric charge can also be used to represent bits, said Jacobs. If the charged areas can be made small enough, the technology could become a reasonable alternative to magnetic storage.

A big drawback to previous charge-based data storage technologies has been the difficulty of copying data stored in electric charges. "In charge-based data storage, a rapid replication of data [was] not possible; it took days to pattern data on an area of 1 square inch," said Jacobs. "Electric microcontact printing provides a way to replicate data patterns for charge-based data storage from a master."

The system can transfer a pattern of charge that represents five gigabits of data to the plastic film in about 20 seconds. Five gigabits is 625 megabytes.

Electrets, which are materials that retain electric charges, also have useful optical properties. Electrets can be used to shorten a light wavelength from, for example, red to blue, Jacobs said. Wavelength converters are an essential component of optical telecommunications equipment.

The novelty of electric microcontact printing is not the physics involved, but the demonstration of nanoscale patterned charge transfer, said Aime S. DeReggi, a physicist at the National Institute of Standards and Technology. "It would have some very interesting applications in nanotechnology. The question is how long does the memory remain," he said. "What factors effect longevity? For example, does humidity effect [it]?"

Electric microcontact printing could be used in practical applications in five years, said Jacobs.

Jacobs' research colleague was George M. Whitesides. They published the research in the March 2, 2001 issue of *Science*. The research was funded by the Swiss National Science Foundation, the German Research Foundation (DFG) and the Defense Advanced Research Project Agency (DARPA).

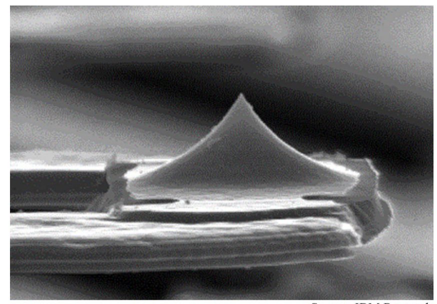
Timeline: 5 years
Funding: Government
TRN Categories: Data Storage Technology; Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Submicrometer Patterning of Charge in Thin-Film Electrets," *Science*, March 2, 2001

Mechanical Data Storage Goes Massively Parallel

By Eric Smalley, Technology Research News
December 6, 2000

IBM's Millipede project is finally living up to its name. The latest protype in the project, which aims to use microelectromechanical systems as data storage devices, sports more than one thousand read-write heads.

Researchers at IBM's Zürich laboratory have demonstrated a three-millimeter-square device that uses an array of 32 by 32 atomic force microscope probe tips to read and write data by sensing and making tiny indentations on a surface.



Source: IBM Research

The sharks-tooth-shaped object is a tip used to read and write data in IBM's microelectro-mechanical data storage system. The tip can make holes as small as 20 nanometers.

Millipede's highly parallel nature makes it potentially very fast. The tips are small enough that the device will be able to store more data per square inch than today's mag touch format picture position netic media. It is small, uses little power and should be cheap to produce because it is a microelectromechanical system (MEMS). MEMS are essentially com-puter chips with moving parts.

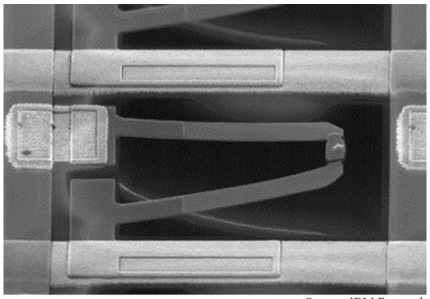
MEMS devices could provide large amounts of data storage capacity for systems ranging from computers to cell phones to household appli-ances, especially if magnetic data storage technol-ogies eventually bump up against the laws of physics.

"Magnetic storage is prog-ressing at such a rate that it makes it difficult to compete with it using other tech-nologies," said Cal Quate, a professor of electrical engi-neering at Stanford Uni-versity. "I think that the Millipede [tech-nology] has the best chance if the magnetic systems run out of steam."

Tiny actuators, which are electrically or magnetically controlled springs, move the device's storage medium laterally and longitudinally relative to the tips. The movement is enough to give each tip its own section of the surface to operate on. Other actuators gently press the surface against the tips.

To write a "1" in the binary language of computers, the device sends a small electrical current into a tip, which heats it up enough to melt a small indentation in the surface. A "0" is represented by the unaltered surface. The device reads a bit by sensing the change in electrical potential in a tip caused by changes in temperature. When a tip is in an indentation, more of the tip is in contact with the surface so heat dissipates more quickly. The whole device can be erased by heating the entire surface.

The Millipede protype has achieved data densities of 100 to 200 gigabits per square inch, several times higher than the current state-of-the-art in magnetic storage devices, said Gerd K. Binnig, an IBM Fellow at IBM Research in Switzerland.



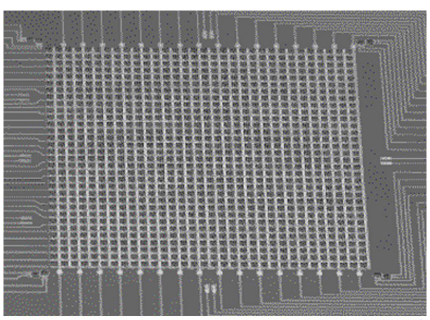
Source: IBM Research

The tip is mounted on this flexible arm, or cantilever. The tip is the small, upside-down, V-shaped object to the right.

The indentations in the 1,024-tip device are 80 nanometers apart, and the researchers have demonstrated spacings as small as 40 nanometers with individually operated tips, he said. A nanometer is one millionth of a millimeter.

The spacings are determined in part by the storage medium. The current protype uses a thin film of the polymer polymethylmethacrylate, though the researchers have indications that other polymers might give better results, Binnig said. "In the past we did not play with different polymers. In the future we will," he said.

The storage density is also dependent on how the system reads bits. The researchers have tested a coding scheme in which indentations are so close that adjacent bits run together, forming trenches. The device determines the number of bits by sensing the length of the trench, said Binnig. IBM has not settled on a coding scheme for the device, he said.



Source: IBM Research

This shows 1,024 cantilever-mounted tips arranged in a 32 by 32 grid. The device is three millimeters square and can hold more than three gigabytes of data.

The current Millipede prototype is far slower at transferring data than magnetic media, though it has the potential to outstrip it considerably, said Binnig. "Today's data rate is just limited by the current laboratory hardware implementation," he said.

The 32 by 32 array can transfer data from a processor to the storage medium or vice versa at one megabit per second, Binnig said. Current magnetic disks transfer data at rates up to 20 megabits per second, and arrays of disk drives can go higher.

"Much higher data rates will be achieved by truly parallel reading [and] writing of all tips simultaneously," said Binnig. "This requires integrated electronics which we will have [at the] end of next year."

Each Millipede tip has a data transfer rate of about 100 kilobits per second. When the array operates in parallel, it should have a data transfer rate of about 400 megabits per second. Future versions of the Millipede device could have as many as one million tips, which would have a collective data transfer rate of 100 gigabits per second, said Binnig.

"The Millipede [technology] is very well done and many of the aspects that held it back in the past have been overcome. The tips are uniform. They have high writing speed [and] high throughput," said Quate.

IBM plans to use the technology in commercial products in three to five years, said Binnig.

Binnig's colleagues were M. I. Lutwyche, M. Despont, U. Drechsler, U. Dürig, W. Häberle, H. Rothuizen, R. Stutz, R. Widmer and Peter Vettiger. They published their work in the November 13, 2000 issue of *Applied Physics Letters*.

Timeline: 3-5 years
Funding: Corporate
TRN Categories: MicroElectricMechanical Systems (MEMS); Data Storage Technology
Story Type: News
Related Elements: Technical paper "Highly parallel data storage system based on scanning probe arrays," *Applied Physics Letters*, November 13, 2000

Disk-on-a-Chip Takes Shape

By Eric Smalley, Technology Research News
October 25/November 1, 2000

Cheaper, faster mass data storage could arrive sooner rather than later thanks to an advance that bridges the gap between disk drive technology and microelectromechanical systems (MEMS).

Researchers at Carnegie Mellon University have built a mechanism that controls read/write tips for a MEMS data storage device. MEMS are tiny mechanical devices made from silicon chips.

These storage devices can be made using largely the same materials and techniques as those used to produce computer memory and processor chips, making them potentially much cheaper than today's disk drives.

Storage MEMS also open the possibility of building an entire computer system on a single silicon chip, said L. Richard Carley, a professor of electrical and computer engineering at CMU. "In the long run you could build really low-cost embedded systems that are incredibly intelligent because they would have 5 [to] 10 gigabytes of mass storage coupled with a lot of processing power," he said.

The CMU device uses magnetic disk drive media fixed to the underside of an 8mm by 8mm silicon plate. The plate is attached to a larger piece of silicon by tiny actuators, or motors, that move the plate side to side and back and forth. The plate is placed on top of another that contains an array of 6,400 microscopic tips. Each tip will have its own actuator that moves it up and down.

The researchers have built and demonstrated a tip actuator and tip. Their next step is putting a magnetic read/write head on the tip, said Carley.

The tips will serve as the equivalent of a disk drive's read/write head, though instead of scanning the entire surface of a disk each tip will scan only a portion of the plate. Data will be written and read across all of the tips at once.

One of the biggest challenges to making a magnetic MEMS storage device was devising a means ofcontrolling the distance between each tip and the surface of the storage media. The 8mm silicon plate is not perfectly flat at the nanometer scale, making the distance to the plate potentially different for each tip.

"We're actually building a little sensor that senses how far away the tip is, an actuator that pulls it up and a feedback loop that ... holds it at 30 nanometers spacing" said Carley. "So we have an active servo loop in every one of those 6,400 tips."

The large number of tips in the array makes the MEMS device poten-tially faster than disk drives. "The aggregate data rate can be really high even though the individual tip data rates are relatively low," said Carley. "Even at 100 kilobits per second, if I have 6,000 tips I'm running 600 megabits per second."

Individual disk drives have data rates up to about 20 Mbps, though arrays of disk drives can have much higher aggregate data rates.

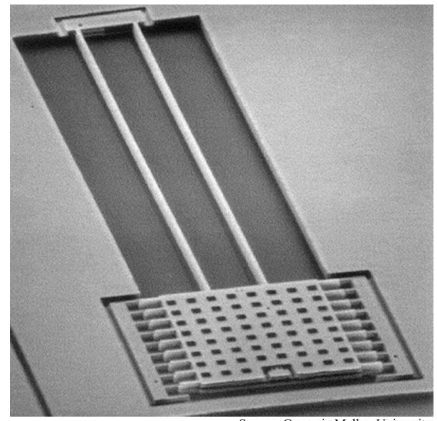
Access time, or how long it takes to get any particular piece of data, is another important measure of data storage performance. "We can get very short access times because the [plate] only moves 100 microns. We can get [down] to the hundreds of microseconds instead of the multiple milliseconds that you get from a disk drive," said Carley.

The position of the plate can be controlled to within a few nanometers, making it possible to use bits that are as small as a few tens of nanometers square, said Carley. A nanometer is one millionth of a millimeter. Today, bits on the the most dense disk drives are about 50 nanometers long, though they will likely be a small as 25 nanometers within five years, he said.

Bits on disk drives are about 20 times wider than they are long because the tracks on the disks have to accommodate the microscopic flaws in their mechanical components that prevent the disks from achieving perfectly circular spins, said Carley. The bits on MEMS magnetic storage devices will be only as wide as they are long, so many more will fit on the same area, he said.

At 50 nanometers per bit, CMU's 8mm-square plate would have a capacity of 2 GB, Carley said. With 25 nanometer bits the capacity would be 8 GB, he said. These devices could also be an order of magnitude cheaper per bit than memory chips, Carley said.

There are several other MEMS data storage research projects underway, including efforts at Cornell University, Hewlett-Packard and IBM. Those efforts use media that is more akin to rewritable CDs.



Source: Carnegie Mellon University

This scanning electron microscope image shows an actuator that moves a probe tip up and down. The probe tip is the small rectangle set on the near edge of the larger, waffle-shaped rectangle. CMU researchers plan to use an array of 6,400 of these actuators and tips to read and write data in a storage device built on a chip.

"There are many imposing research challenges to making [MEMS data storage] happen. But if it works... you can envision non-volatile data storage ... at a fraction of the size, weight and power budget of existing disk drives, even the impressive 1-inch disk drive from IBM," said Albert P. Pisano, professor of mechanical engineering and electrical engineering and computer sciences at the University of California in Berkeley. Pisano is also a former DARPA program manager responsible for funding the CMU effort.

The CMU researchers should have prototypes of their data storage devices in two to three years, said Carley. The devices could be used for specialty applications within five years, and could be used in general commercial applications in 8 to 10 years, he said.

Carley's colleagues were James A. Bain, Gary K. Fetter, David W. Greve, David F. Guillou, Michael S. C. Lu, Tamal Mukherjee, Suresh Santhanam, Seungook Min, Greg Ganger and David Nagle of CMU, and Leon Abelmann of the University of Twente in the Netherlands.

They published their work in the May 1, 2000 issue of the Journal of Applied Physics. Another technical paper is scheduled to be published in an upcoming issue of the IEEE Transactions on Magnetics.

The CMU research was funded by DARPA. Ongoing research to develop systems based on the technology will be funded by NASA.

Timeline: <5 years, 8-10 years
Funding: Government
TRN Categories: Microelectromechanical Systems (MEMS); Data Storage Technology
Story Type: News
Related Elements: Technical papers "System Design Consideration for MEMS-Actuated Magnetic-Probe-Based Mass Storage," accepted for IEEE Transactions on Magnetics; "Single-chip computers with microelectromechanical systems-based magnetic memory," Journal of Applied Physics, May 1, 2000

TRN

Oxygen Makes Nanotube Memory

By Eric Smalley, Technology Research News
November 27/December 4, 2002

Carbon nanotubes have been used to make experimental transistors, chemical sensors and memory devices that are far smaller than anything available today. But moving from experimental prototypes to practical devices requires overcoming a large hurdle: controlling the way nanotubes grow.

Nanotubes tend to form as mixes of two types—semiconducting and metallic—with semiconducting the more technologically desirable. In April, 2001, IBM researchers announced they could weed out metallic nanotubes by sending enough current through a batch of nanotubes to burn up the metallic tubes but not enough to damage the semiconducting ones.

Researchers at the Max Planck Institute in Germany have come up with an alternative method of producing all-semiconducting bundles that, in addition, prepares the microscopic tubes for use in memory devices. The technique allows researchers to oxidize bundles of a few nanotubes or individual nanotubes that measure as small as 2 nanometers in diameter. A nanometer is one millionth of a millimeter, and a line of 20 hydrogen atoms spans two nanometers.

Oxidizing a bundle of nanotubes converts metallic ones to semiconducting, said Marko Burghard, a scientist at the Max Planck Institute for Solid State Research in Germany. Assemble the oxidized bundles into larger arrays and they could be "key building blocks for low-cost memories with ultra-high storage densities," he said.

The process could theoretically produce memory devices that hold one trillion bits per square centimeter, said Burghard. A trillion bits is about 31 DVDs worth of data.

The researchers hit on the process after finding that about half of nanotube bundles left in open air for several months had changed from metallic to semiconducting. This happened because oxygen atoms in the air combined with the carbon atoms in the metallic nanotubes to form a nonmetallic oxide.

The researchers were able to induce the effect by heating the nanotubes in air or treating them with oxygen plasma. A plasma is a gas whose atoms are ionized, meaning they have more or fewer electrons than normal and so can conduct electricity.

The researchers took advantage of a consequence of the oxidation process to make prototype memory devices from the oxidized tubes. The devices use a single oxidized nanotube or bundle of oxidized nanotubes as the semiconducting channel of a transistor. Data is represented by tiny electric charges of one or a few electrons stored in a defect on the surface of a nanotube produced by the oxidation. The defects are tiny clumps of amorphous, or jumbled, carbon attached to the otherwise orderly, crystalline nanotubes.

By sending three volts of electricity through the nanotubes, the researchers stored a charge in a surface defect. In electronic memory, the presence of a charge generally represents a 1 and the absence of a charge a 0. To read the 1s and 0s, the researchers sent a small current through the nanotubes to measure their conductivity. Nanotubes that harbor a stored charge are about 1,000 times more conductive than those without a charge.

Charge storage memory devices based on nanotubes were first developed several years ago; research teams at the University of Maryland and the University of Pennsylvania have recently developed experimental devices.

The Max Planck Institute memory device, however, is able to store charges longer than the other devices, said Burghard. The Maryland researchers reported a charge storage time of 1.4 hours, and the Pennsylvania researchers 16 hours. The Max Planck device is able to store charges for more than 12 days, Burghard said. Stored charge memory devices can be used as nonvolatile computer memory, which retains its data when the power is off.

The research is important work, said Vincent Crespi, an assistant professor of physics at Pennsylvania State University. "It enables a memory device to be implemented within a single nanotube plus three contacts," he said. "The charge trap seems to come along for free."

The researchers will need precise, reproducible control over the character of the charge trap before the device can be used in practical applications, Crespi added.

The researchers plan to study further the oxidation process and the nature of the charge storage defects, said Burghard. Another goal is to search for better, more controllable chemical modifications of the nanotubes, "for example, by electrochemically attaching appropriate chemical residues or small metal clusters, which could then be used for charge storage," he said.

The researchers' nanotube memory element could be used in practical applications in five to ten years, said Burghard.

Burghard's research colleagues were Jingbiao Cui, Roman Sordan and Klaus Kern. They published the research in the October 21, 2002 issue of the journal *Applied Physics Letters*. The research was funded by the Max Planck Society.

Timeline: 5-10 years
Funding: Private
TRN Categories: Nanotechnology; Data Storage Technology; Materials Science and Engineering; Chemistry
Story Type: News Related Elements: Technical paper, "Carbon nanotube memory devices of high charge storage stability," *Applied Physics Letters*, October 21, 2002

TRN

Molecule Chip Demoed

By Eric Smalley, Technology Research News
September 18/25, 2002

Researchers at Hewlett-Packard's HP Labs have made a working, 64-bit memory device that uses as few as a thousand molecules to store each bit of information, and they have come up with a process for mass-producing the molecular memory chip.

The researchers' prototype holds 10 times the data of a comparably-sized segment of a silicon memory chip. Ultimately, the molecular technology could pack 100 billion bits into a square centimeter of chip space, which is about 1,000 times what today's chips hold, according to Philip Kuekes, a computer architect at HP Labs.

The researchers have also made simple molecular logic circuits, and the technology could eventually be used to make entire computer processors, according to Kuekes.

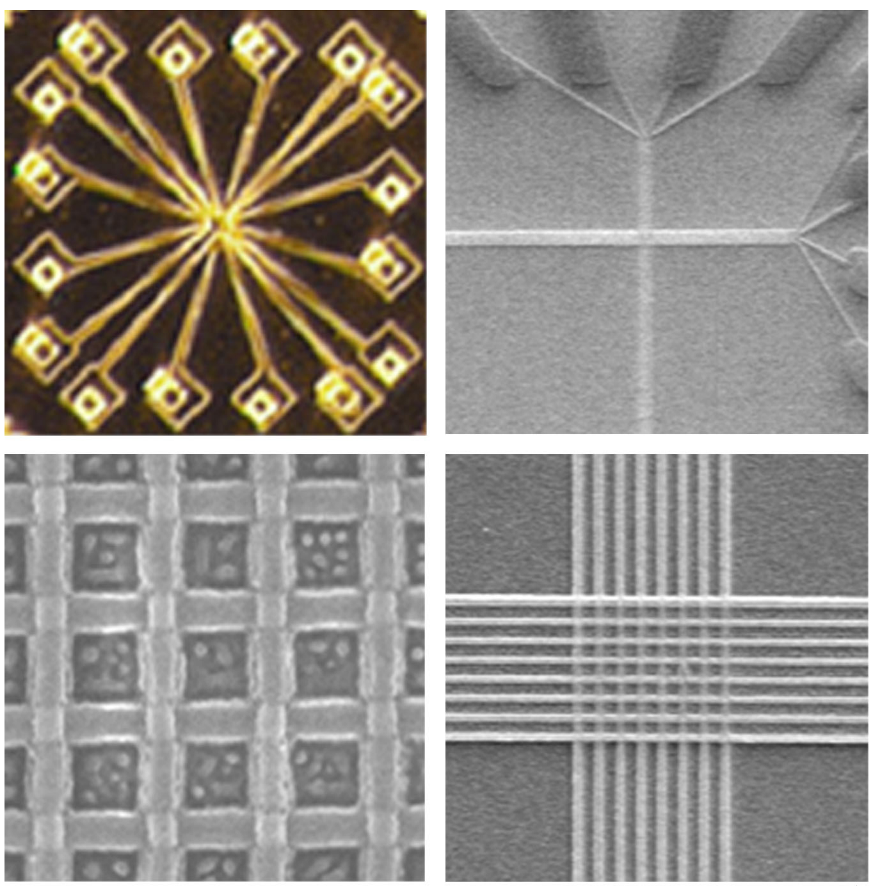
HP's molecular technology could enable manufacturers to continue to make smaller chip components when silicon technology reaches its size limits in about 10 years, said Kuekes. Silicon computer chips have doubled in performance about every 18 months for the past 30 years, a phenomenon known as Moore's Law, because manufacturers have been able to make transistors and other components smaller. The photolithography processes used to make those components are likely to hit physical limits in about a decade.

The molecular memory device consists of two sets of eight parallel wires arranged perpendicularly, one set on top of the other, to form 64 junctions. Each wire is 40 nanometers in diameter, or about 130 atoms across. Between the sets of wires is a layer of material only one molecule thick. "There's only about a thousand molecules in between two of those wires," said Kuekes.

Previous research has demonstrated electronic switches made from single molecules. HP's 1,000-molecule switches, however, are contained in a memory chip made in a scalable, relatively inexpensive manufacturing process. Theoretically, only a single molecule is needed to store each bit in the HP device.

The molecules act as minuscule electronic switches. Sending a pulse of electricity from one wire to another through the layer of molecules changes the molecules' resistance to the flow of electricity. These higher and lower resistance states can represent the ones and zeros of digital information.

A computer would write data to the memory by sending electrical pulses to specific junctions to change the resist-ance of the molecules there. The computer could then read the memory by using weaker electrical pulses that don't change the mole-cules' resistance but pass through a junction if the resistance is low and do not if it is high. The memory is nonvolatile, meaning it retains data even when the power has been turned off.



Source: HP Labs

The top left image shows the one millimeter square array of electrodes that connect HP Labs' molecular memory device to the outside world. The top right image shows the electrodes connected to the device's much smaller grid of nanowires. The bottom right image shows the grid, and the bottom left is a close-up of the nanowires. Each wire is 40 millionths of a millimeter wide, and each junction contains 1,000 molecules that act as an electrical switch that stores a bit.

The molecular memory prototype contains a logic device and mem-ory in a single, integrated circuit, said Kuekes. “We were able to build very simple logic [circuit], a de-multiplexer, which is used to address a mem-ory,” he said. A de-multiplexer chan-nels signals from the memory de-vice’s wires through a smaller number of larger wires that connect the device to the outside world.

The molecular memory architec-ture could even-tually be used to build more com- plicated logic cir-cuits like those used to manipulate data in computer processors, according to Kuekes.

Perhaps more important than the prototype is the nanoimprint lithography process used to make it. “With this one manufacturing technology [we will] at some point be able to reinvent the integrated circuit, and build all the memory functions and logic functions that people are familiar with today,” said Kuekes.

Nanoimprint lithography is a microscopic stamping technique that can inexpensively make many of the memory devices at a time, said Kuekes. The researchers made 625 of the prototype memory devices at once.

To make the stamp, the researchers carved a microscopic pattern of 625 sets of eight parallel 40-nanometer ridges on a block of silicon using an electron beam. Electron beams can be focused more narrowly, and so carve smaller patterns, than the laser beams used to make today’s computer chips. “While it’s fairly expensive and difficult to make a master, once you’ve got the master you can print out a large number of copies,” said Kuekes.

The researchers pressed the stamp into a layer of plastic to make sets of eight parallel trenches, which they filled with platinum to make wires. Then they spread a layer of molecular switches on top of the wires. Next they deposited another layer of plastic, pressed the stamp into it perpendicularly to the first set of wires, and filled those trenches to make the second set wires. Last, they chemically removed the plastic, leaving the crossed wires sandwiching the molecular switches.

The HP prototype is a significant development, said Deepak Srivastava, a senior scientist and task leader at NASA Ames Research Center. “All the contributing technologies are scalable.” The process could be used in commercial manufacturing plants within the next few years, he said.

High-density memories are likely to be among the first commercialized products to result from nanotechnology research, Srivastava added.

The researchers plan to make a memory device within three years that can store 16,000 bits in a 128-by-128 array of wires, said Kuekes. “We expect... to be both increasing the number of wires and decreasing the pitch between the wires,” he said. Decreasing the pitch, or space, between the wires would allow the researchers to fit more wires, and therefore more junctions, in the same space.

The technique could be used to make useful memory devices in five to ten years, said Kuekes. It will take at least ten years of development before technique can be used to make other types of computer chips, he said.

Kuekes’ research colleagues were R. Stanley Williams, Yong Chen, Douglas Ohlberg, Xuema Li, Duncan Stewart, Tan Ha, Gun-Young Jung and Hylke Wiersma. Williams presented the research at a symposium marking the 175th anniversary of the Royal Institute of Technology of Sweden. The research was funded by the Defense Advanced Research Projects Agency (DARPA) and Hewlett-Packard.

Timeline: 5-10 years
Funding: Government, Corporate
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Integrated Circuits; Data Storage Technology; Nanotechnology
Story Type: News
Related Elements: None

HP Maps Molecular Memory

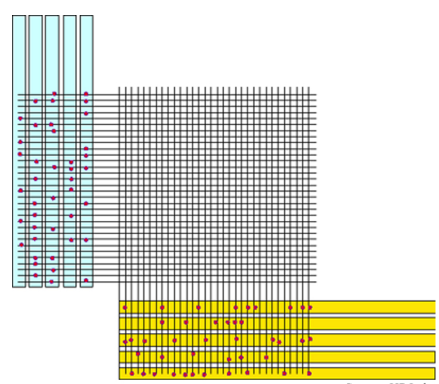
By Eric Smalley, Technology Research News
July 18, 2001

Building electronic components like computer memory out of individual molecules would yield extraordinarily powerful and cheap computers. But figuring out how to mass-produce the devices is a tremendous challenge.

Assuming the devices can be built, another monumental challenge remains: how do you talk to them? The wires in today’s semiconductor devices are about 100 times too large to fit molecular devices.

Researchers at Hewlett-Packard Company have found a random chemical process that bridges the gap.

The researchers’ proposed molecular memory unit is a grid of tiny wires, each about two nanometers in diameter. A nanometer, which is one millionth of a millimeter, is about 10 carbon atoms long. A single molecule at each junction of the nanowires is an electrically activated switch whose on and off states rep-resent the ones and zeros of computing. On one side the tiny wires extend past the grid.

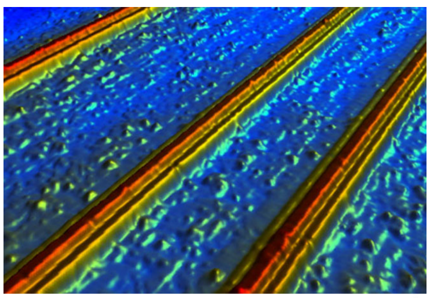

Source: HP Labs

The red dots in this diagram of a molecular memory array represent gold nanoparticles that connect nanowires, represented by the black lines, to larger wires, represented by the blue and yellow bars. The random distribution of the gold nanoparticles gives each nanowire a unique address.

To connect the memory unit to the outside world, the researchers plan to randomly sprinkle nanometer-size gold particles on the sections of the nanowires that extend past the grid and then lay down a set of larger wires on the gold particles at right angles to the nanowires. This second set of wires, each about 200 nanometers in diameter, is large enough to make a connection to the macroscopic world.

By using the right concentration of gold particles, the researchers can ensure that half of the junctions between the larger wires and nanowires hold individual particles. “There’s a purely random, 50-50 chance that a nanowire is connected to a big wire by a dot,” said Philip Kuekes, a computer architect and senior scientist at HP Labs.

Some of the junctions the larger wires make with a single nanowire will have con-nections and others won’t. For instance, a nano-wire connected randomly to 10 larger wires might have con-nections at the first, second, fourth, seventh and ninth, but not the third, fifth, sixth, eighth and tenth larger wires. If a connection represents a one hand no connection a zero, this particular string of junctions would represent the binary number 1101001010. “So there’s a random binary number. That’s a unique address for the nanowire,” said Kuekes.



Source: HP Labs

These parallel wires are about 10 atoms wide and the spaces between them about 50 of nanowires are slated to serve as the foundations of Hewlett-Packard's molecular memory devices.

In order to read or write to a memory array of nanowire junctions, you have to be able to identify each junction, which holds one bit of data. The binary numbers of the two nanowires that intersect at a junction combine to make a unique address for the junction.

If it were possible to assign addresses directly to the nanowires, 10 larger wires would be sufficient to name 1,000 nanowires because 2^{10} is 1,024. But because the addresses are assigned randomly, many of them are duplicated. Increasing the size of the addresses by adding more larger wires reduces the number of duplicated addresses, said Kuekes.

The trick is finding the balance between getting as few duplicated addresses as possible and keeping the number of larger wires manageable. The HP researchers found that four times the log of the number of nanowires is optimal, said Kuekes. The log of a number is how many times you have to multiply 10 to get the number. For example, the log of 1,000 is three because 103 equals 1,000. By this formula, 12 larger wires can address 1,000 nanowires, 16 can address 50,000 nanowires, 23 can address 500,000 nanowires, 24 can address a million nanowires and 36 can address a billion nanowires.

To find all the unique nanowire addresses, the HP researchers came up with a computer algorithm that measures electrical resistance as the larger wires are switched on and off. Because each nanowire crosses a unique sequence of larger wires, it has a unique electrical signature. The process essentially builds a map of the nanowire grid, said Kuekes.

Figuring out how to exchange information between molecular scale devices and conventional electronic devices is perhaps the most fundamental molecular electronics problem, said Tom Jackson, a professor of electrical engineering at Pennsylvania State University. “The HP [proposal] points in that direction,” he said. “It’s significant [but] there are limitations to it.”

One problem is that simply connecting the nanowires to the larger wires with gold nanoparticles would yield fixed connections that could not be turned on and off, making it impossible to electrically identify each nanowire, Jackson said. To get around this problem, the HP proposal calls for adding a molecular switch similar to those in the memory unit to each of the nanowire-larger wire junctions linked by a gold nanoparticle.

Putting a molecular switch on each nanoparticle and then forming connections between the nanowires and larger wires without crushing the molecular switches is a major but not insurmountable challenge, Jackson said.

Researchers at Hewlett-Packard and the University of California at Los Angeles are beginning a four-year project to build a 16 kilobit memory device using the molecular memory technology, said Kuekes.

The researchers’ ultimate goal is to pack 100 gigabits, or 100 billion bits, into one square centimeter of chip space using the molecular memory technology, he said. That’s at least 1,000 times more than is possible using standard semiconductor technology, he said.

The molecular memory addressing system could be used in practical devices in five to ten years, according to Kuekes. Beginning in five years the technology could be used in niche products that require very low-power, very high-density memory, he said. The molecular memory technology should match the data capacity of standard semiconductor memory in nine or 10 years, he added.

Kuekes’ research colleague was Stan Williams of Hewlett-Packard. They received a United States patent for their research on July 3, 2001. The research was funded by the Defense Advanced Research Projects Agency (DARPA) and Hewlett-Packard. Their ongoing work is also funded by DARPA and HP.

Timeline: 5-10 years
Funding: Government, Corporate
TRN Categories: Biological, Chemical, DNA and Molecular Computing;

Integrated Circuits
Story Type: News
Related Elements: United States patent, "Demultiplexer for a molecular wire crossbar network," number 6,256,767, July 3, 2001

Bendable Nanotubes Store Bits

By Eric Smalley, Technology Research News
July 12, 2000

One of the first steps to building blazingly fast, dirt cheap and vanishingly small molecular computers is figuring out how the devices would hold data.

Carbon nanotubes have looked like ready-made microscopic wires to researchers for long time, and the idea of building memory arrays from perpendicular strands of them is nothing new. One of the challenges, however, has been figuring out how to control the junctions where the wires cross in order to create the on and off states necessary for binary computing. Most approaches have focused on inserting spring-like molecules between the crossed nanotube wires.

A different approach that uses the mechanical properties of carbon nanotubes has paid off for researchers at Harvard University who have built a tiny memory device that could be a predecessor to the building blocks of tomorrow's molecular computers.

The Harvard team coaxed the nanotubes into making and breaking the connections on their own. Carbon nanotubes come in two forms: semiconducting and metallic. Metallic nanotubes will bend toward a perpendicular semiconducting nanotube when electrically charged. When a metallic nanotube is one to two nanometers away from a semiconducting nanotube, the electrical resistance at the junction is low, creating an on state. When the nanotubes are apart the resistance is much higher, creating an off state.

"The clever thing is it combines both electronic and mechanical properties of single-wall nanotubes," said Yue Wu, an associate professor in the physics and astronomy department at the University of North Carolina, Chapel Hill. "It gives people hope to make large [memory] arrays. It—to a certain extent—has demonstrated experimentally that this can be done."

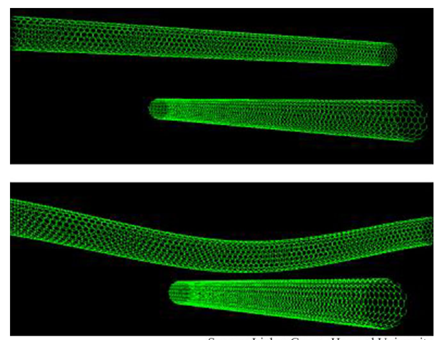
Because carbon nanotubes are so small, little more than a nanometer in diameter, memory arrays built from them could house 1012 cross-wire elements per square centimeter. That would be 10,000 to 30,000 times more dense than today's Dynamic Random Access Memory (DRAM) memory chips, said Charles M. Lieber, professor of chemistry at Harvard and leader of the team that developed the nanotube technique.

"It's much higher density than… will ever be attainable with silicon [wafer] technology," he said. In principle these memory arrays could also be 1,000 to 10,000 times faster than today's memory chips, he added.

Perhaps as significant as the scale of Harvard's nanotube memory device is its ability to remain in either the on or off state without a continuous electrical charge. Most computer memory today only works when the computer is on because it needs to be continuously refreshed. Non-volatile silicon wafer memory exists, but it is much less dense than standard computer memory.

Carbon nanotube arrays could also be used to build computer processors. "We think in the longer term actually making a computer almost entirely based on this type of architecture is a possibility," Lieber said. "They certainly offer the promise of a lot more power. [And realizing] the potential of the assembly approaches that we and other people are using it's going to be low cost."

However, there are several hurdles to overcome before anyone is going to be able to produce memory modules from carbon nanotubes.



Source: Lieber Group, Harvard University

The upper diagram depicts the off state and the lower diagram depicts the on state of the nanotube memory device.

"The distance between the crossed wires has to be controlled fairly precisely, from one to two nanometers," Wu said. "You have to come up with a way that you can assemble many, many of these cross-wires. To make this pattern of nanotubes with precise control of distance— that's going to be the difficulty. The other diffi-culty right now [is] when people grow nanotubes, we all grow spaghetti. How to grow straight tubes, that's also something people need to work on."

In addition, there is not yet a reliable way to produce separate sets of metallic and semiconducting nanotubes. The Harvard team is working on a way around this problem by using silicon wires for the semiconducting portion of the array, Lieber said. However, this will not produce the same density as a purely nanotube array, he said.

A silicon wire-carbon nanotube hybrid memory array could become commercially viable in about two years, according to Lieber. Barring an earlier breakthrough of being able to build separate semiconducting and metallic nanotubes, purely nanotube memory arrays are five to 10 years away, he said.

The research was funded by the Defense Advanced Research Projects Agency and the Office of Naval Research.

The Harvard team reported on their findings in a paper in the July 7 issue of the journal *Science*.

Timeline: > 2 years; > 5 years
Funding: Government
TRN Categories: Nanotechnology; Data Storage Technology; Integrated Circuits
Story Type: News
Related Elements: Technical paper "Carbon Nanotube-Based Nonvolatile Random Access Memory for Molecular Computing," *Science*, July 7, 2000

Light-sensitive Memory Doesn't Fade

By Eric Smalley, Technology Research News
July 4/11, 2001

Optical data storage devices have the potential to surpass magnetic disk drives in capacity, but the necessary technology is in its infancy and faces several hurdles. One problem is figuring out how to use light to read data stored in light-sensitive material without altering the data.

A team of researchers in Japan has addressed the problem with a recording medium that can be read more than a million times without damaging data.

The researchers designed the material for near-field recording systems, which use extremely narrow beams of light to record bits. The narrow beams are produced by shining light through a tiny hole and a lens, both positioned extremely close to the surface of the recording medium.

"Information recording is achieved as the reversible—that is, rewritable—photoreaction of the photochromic molecules" in the medium, said Tsuyoshi Tsujioka, a principal researcher at Sanyo Electric Company's New Materials Research Center. Photochromic materials change color when they are exposed to light.

Ordinarily, data is read by shining low intensity light on the material and measuring the change in how it absorbs the light. But each exposure to low-intensity light produces the same reaction as the recording operation, only to a lesser degree.

"Repeated irradiation... for information readout destroys the information," said Tsujioka.

The researchers got around the problem by using a different color, or wavelength, of light to read data. Data is written with red light and read with infrared light. The infrared light does not trigger the photochromic reaction but does induce a electric current in the medium.

Instead of measuring a change in light absorption, the researcher's system senses the difference in current through areas of the material that have been altered by the recording lightwaves.

"The recording density of probe memory systems such as near-field memory is... related to the size of the probe apex," said Tsujioka. "Our goal [is] one bit stored by one molecule."

If that proves possible, the storage system could hold 100 terabits of data per square inch, said Tsujioka. That density would be enough to store about half a million high-resolution photographs in an area the size of a pinhead.

The nondestructive readout method could be ready for use in practical applications in five to ten years, said Tsujioka.

Tsujioka's research colleagues were Yuji Hamada and Kenichi Shibata Sanyo Electric Company, and Akira Taniguchi and Takashi Fuyuki of the Nara Institute of Science and Technology in Japan. They published the research in the April 16, 2001 issue of the journal *Applied Physics Letters*. The research was funded by Sanyo.

Timeline: 5-10 years
Funding: Corporate
TRN Categories: Materials Science and Engineering; Data Storage
Technology
Story Type: News
Related Elements: Technical paper, "Nondestructive readout of photochromic optical memory using photocurrent detection," *Applied Physics Letters*, April 16, 2001

Glass Mix Sharpens Holograms

By Ted Smalley Bowen, Technology Research News
April 11, 2001

The concept of storing information as holograms has been around for decades, but the lack of a suitably thick and stable material for storing holograms has hindered its development.

Given the right material, however, holograms could store more than 20 times as much information per square inch as standard magnetic or optical media. The data could be retrieved faster, as well.

A pair of researchers from Canada and Spain have made a glass composite that is a good candidate for the job. It can be made at least a millimeter thick, resists distortion, and has the optical properties needed to store holograms, according to the researchers.

The modified silica "makes holographic storage a more viable alternative to today's storage media including CD-ROMs and DVDs," said Pavel Cheben, a senior member of the research staff at Optenia, Inc.

A holographic disc of the material the size of a standard CD, for instance, can hold nearly a terabit of data, or about 20 times as much per square inch as a single-layer DVD, he said. This translates to about one billion pages of double spaced text or one million high-resolution photographs.

Such high data densities are possible with holographic storage because individual pages of data can literally be stored in the same space.

To store data holographically, a spatial light modulator first converts the ones and zeros of digital data into a string of light and dark areas and displays them on its screen. A laser beam is then split into an object beam and a reference beam. The object beam is shined through the screen, picking up the light and dark areas of the binary image as part of its wave pattern.

When the reference beam converges with the object beam on a light-sensitive storage material, the two streams of light interfere with each other, creating a pattern of light and dark areas that is captured in the material.

Light interference occurs when the peaks and troughs of two lightwaves meet. Where a pair of peaks or troughs line up they reinforce each other and and the light becomes brighter. Where a peak and a trough line up, they cancel each other out and the light becomes dimmer.

Subsequent pages of data can be recorded as holograms in the same space by slightly varying the angle of the reference beam, essentially creating a three-dimensional space stack of two-dimensional page images. The thicker the storage medium, the more pages of data it can contain.

Because a whole page of data is stored in each image, the whole page can be retrieved at once. This makes data retrieval times much faster than those possible with current storage media, which retrieve information serially, one bit at a time.

Demonstrated data retrieval times from holographic images are as fast as one gigabyte per second, which is more than 400 times faster than today's 2.4-megabyte-per-second, 16-times CD-ROMs, according to Glenn Sincerbox, a professor of optical sciences at the University of Arizona.

To produce the material, the researchers used a sturdier, inorganic glass base in place of the organic polymers used in previous experiments. They made the photosensitive glass composite by adding a photoinitiator and an acrylic to a porous silica.

The researchers mixed the components, then cast them in Teflon vials. The results were one-millimeter-thick slabs of optical-grade glass composite.

The photoinitiator triggers polymerization, or hardening, of the acrylic in the areas of the composite hit by light, in particular the light parts of the interference pattern from the laser beams.

During polymerization, individual molecules link up with each other. Because the silica is porous, molecules of the liquid acrylic are drawn from the dark areas to the light areas by the polymerization process. The result is a much higher concentration of the acrylic in the areas exposed to light.

The acrylic has a higher refractive index than the surrounding glass, meaning it deflects light at a sharper angle. Data is retrieved from a holographic storage medium by shining a laser beam through it at the angle of the reference beam when that particular page of data was stored. The positioning of the acrylic makes the light refract into the original pattern.

The large difference between the refractive index of the glass base and that of the acrylic gives the material a strong refractive index modulation, which allows it to store data pages at resolutions as high as 1,024-by-1,024-pixels, said Cheben. It also means an area of the material a little over a millimeter square could potentially hold as many as 1,000 pages, he said.

"The stronger the refractive index modulation is, the more efficient holographic imprinting is... more holograms can be recorded and retrieved with higher signal strength, which ultimately results in a higher storage density and less noisy readout," he said.

The photoinitiator the researchers used made the medium more sensitive to blue and green light, which is more efficient than colors at the other end of the spectrum. "High photosensitivity means that less light power is needed to record a hologram, or, using the same light power... a shorter time. Sensitivity in blue and green is preferred because [they have] shorter wavelengths than red light, and data storage density increases with decreasing wavelength," Cheben said.

The researchers have stored plane wave grating images in the material for six months, according to Cheben. Plane wave gratings are prism-like devices used to separate individual colors from light, a process that produces simple patterns on surfaces. The researchers' next step is testing the material with actual data, he said.

The initial tests showed "excellent holographic properties of the glass including dynamic range, light sensitivity, shrinkage, and scattering," Cheben said. The tests with actual data should show the same, he said.

The medium's optical quality and stability so far are promising, said Sincerbox.

One trade-off, however, results from the researchers' use of a relatively low concentration of the photoinitiator to ensure uniform light absorption throughout the glass. The low concentration means a correspondingly low number of holograms can be superimposed, said Sincerbox. Holographic storage can theoretically store 2,000 to 5,000 pages in one area, Sincerbox said.

Commercial implementations of memory devices made from the composite could be feasible in two or three years, according to Cheben.

Cheben worked on the holographic storage project while with the Canadian National Research Council. His research colleague was Maria Calvo of Complutense University in Madrid.

The researchers described the work in the March 12, 2001 edition of the journal *Applied Physics Letters*. The research was funded by Complutense University.

Timeline: 2-3 years
Funding: University
TRN Categories: Data Storage Technology
Story Type: News
Related Elements: Technical paper: "A photopolymerizable glass with diffraction efficiency near 100% for holographic storage," *Applied Physics Letters*, March 12, 2001.

TRN

Holographic Technique Stresses Interference

By Eric Smalley, Technology Research News
April 11, 2001

Getting a sharp image is important in holographic data storage, but it's hard to achieve because holograms are created by the subtle interference patterns of two intersecting laser beams.

A team of researchers from China has added a twist to a holographic data storage system developed at the California Institute of Technology that promises to increase the system's diffraction efficiency, allowing for higher resolution recordings.

The technique uses a usually unwanted form of interference to reinforce the recorded images.

Data holograms are made when a pattern representing the data is put into a laser beam. When the beam comes together with a second laser beam on a recording medium, the interference pattern they create is captured in the medium. A hologram is read by shining a laser on the medium at the same angle as the second recording laser. This reproduces the original data pattern.

The Caltech system uses lithium niobium oxide suffused with particles of iron and manganese as its recording medium. The system first records, then fixes a hologram to make it permanent.

When the second beam bounces off the data pattern captured in the medium during both recording and fixing, it reproduces the pattern in the same manner as data is read out. The researchers noticed that when the beam hit this inadvertently read out pattern, it created a new interference pattern that was a copy of the original pattern. This echo pattern was also captured in the recording medium.

Depending on the orientation of the recording medium's crystals, the new pattern was either in phase or 180° out of phase with the original pattern, said De'an Liu, a graduate student at the Shanghai Institute of Optics and Fine Mechanics.

If the new pattern is in phase it reinforces the original pattern and if it is out of phase it weakens the original pattern, he said. "The superposition of the recorded and the new [patterns effects] diffraction efficiency, accordingly called self-enhancement or self-depletion effect," said Liu.

A hologram that has a higher diffraction efficiency can store more data because it's pattern is more sharply defined, which means it can fit more bits into a given area.

The researchers measured the diffraction efficiency for the four possible combinations of the effect: self-enhanced recording and self-enhanced fixing, self-enhanced recording and self-depleted fixing, self-depleted recording and self-enhanced fixing, and self-depleted recording and self-depleted fixing.

"The results show that the combination of self-enhanced recording and self-enhanced fixing has the highest diffraction efficiency, and it is twice as large as the lowest one from the combination of self-depleted recording and self-depleted fixing," said Liu.

The self-enhanced holographic storage technique could be used in practical systems in two to three years, he said.

Liu's research colleagues were Liren Liu, Youwen Liu and Changhe Zhou. They published the research in the November 6, 2000 issue of *Applied Physics Letters*. The research was funded by the National Natural Science Foundation of China and the Chinese Academy of Sciences.

Timeline: 2-3 years
Funding: Government
TRN Categories: Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Self-enhanced nonvolatile holographic storage in LiNbO3:Fe:Mn crystals," Applied physics Letters, November 6, 2000

TRN

Color Deepens Data Storage

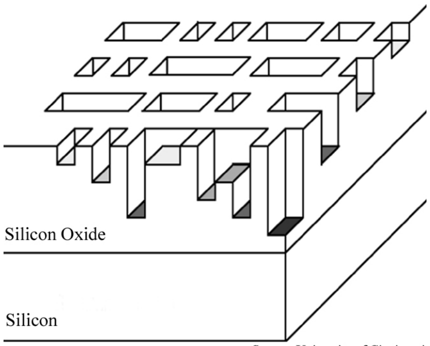
By Kimberly Patch, Technology Research News
January 31, 2001

Computers have always stored information using different physical states, like the opposite poles of a magnet, to represent the ones and zeros of the binary number system.

Efforts to store more information in magnetic media are focused on cramming more magnets into the same space rather than increasing the complexity of the information because magnets only have two poles.

Being able to store more than two possible meanings in one physical area, however, is another way to cram more information into a small space.

With this in mind, a team of researchers the University of Cincinnati is using the different colors of light reflected from tiny holes in a thin film of silicon dioxide to gain many different colors that can be used to encode bits. The color of the reflected light depends on the depth of the hole. Like magnetic media, each bit stillhas two states, but "at every location I can have multiple bits," said Andrew Steckl, a professor of solid-state microelectronics and director of the Nanoelec-tronics Labor-atory at the University of Cincinnati.



Source: University of Cincinnati

This diagram shows stepped holes in a thin film storage medium. Each hole depth produces a different light interference pattern, resulting in a different color.

The scheme is a write-once, read-many (WORM) method, mean-ing media using it cannot be erased and re-written.

The researchers have produced a prototype of their thin-film media that uses 16 distinct colors, but the method is scalable to many more, said Steckl. "There is virtually no limit to the number of colors that can be produced. It is solely dependent on the detector design and the detector's capability to distinguish colors in different saturation and hue level," Steckl said.

Using the 16-color prototype, the researchers have written more than five gigabytes of information on a square inch of film, which is about double the density of today's DVD disks. In theory, this type of storage media could use more colors to harbor two terabytes per square inch, according to Steckl.

To make the storage devices, the researchers added an 800-nanometer thick silicon dioxide film to a silicon wafer. To write information onto the film, they added holes of 15 different depths using focused ion beam micromilling. Individual holes, or pixels, measured half a micron to two microns in diameter and 50 to just under 800 nanometers deep. The absence of a hole added a 16th color. The researchers controlled the depth of each hole by varying the number of gallium ions shot at the film.

Holes of a specific depth reflect white light, which is a mix of all colors, with a particular interference pattern, yielding light of a certain wavelength or color. Sixteen hole depths produce 16 different colors.

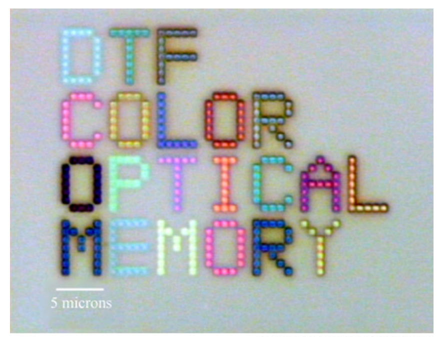
Each hole can hold four bits of information because each color represents a four-bit number. This is because it takes four binary digits to write 16 different numbers, starting with 0000 and ending with 1111. "Four bits makes all the possible parameters," of the 16 states, said Steckl.

In a similar manner, four different hole depths would hold two bits of information, because there are four binary possibilities using two binary digits: 00, 01, 10 and 11. Following this pattern, eight different parameters would hold three bits of information, 36 parameters five bits, 64 parameters six bits, 128 parameters seven bits and 256 parameters eight bits.

The researchers were able to make the holes at a speed of 310 microns per second, meaning the devices are not fast in terms of writing information.

Once written, however the color information can potentially be read faster than binary storage media. Using an array of detectors, or read heads, the amount of information read equals the transfer speed of the read device multiplied by the color bit depth, said Steckl.

The film memory devices are also sturdy. Silicon dioxide is a strong material, making it difficult to alter and potentially very long-lasting, said Steckl. "The robustness of this material makes it [a good candidate] for data storage in harsh environments such as high-temperature or radiation. It may store data [for] centuries," said Steckl. It's also potentially useful for secure applications like smartcards because it is so difficult to alter, he added.



Source: University of Cincinnati

These colored letters are formed by holes in the thin film storage media. The colored pixels can also be used to store 4-bit digital data.

In addition to providing archival computer storage, the tiny points of color could be used to form words or symbols, said Steckl. "A machine that is trained to optical character recognition or a human could excerpt information very quickly," through symbols or words spelled out using the colors, Steckl said.

The researchers can also increase the number of hole depths to gain more colors and therefore more bits, and decrease the size of the holes to cram more infor-mation per square inch, said Steckl. "Right now we have 16 levels, and each level is about 50 nanometers [from the next.] By improving the minimum step distance we can go from four bits per pixel to eight bits per pixel. And then by making the hole itself smaller you can also increase the density significantly," Steckl said.

The researchers next step is to make a working prototype of a drive that can read the optical film.

The memory device is a clever and potentially useful device for writing permanent information and reading it out with reflected light, said Robert Dickson, an assistant professor of chemistry at the Georgia Institute. "It provides a very nice demonstration of how, by using color, [you can] potentially write more than one bit of information per data point."

Practical applications for the thin film optical scheme could be developed in three to five years, said Steckl.

Steckl's research colleague was C.J. Chi of the University of Cincinnati. They published the research in the January 5, 2001 issue of *Science*. The research was funded by Department of Defense (DOD).

Timeline: 3-5 years
Funding: Government
TRN Categories: Semiconductors and Materials; Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Digital Thin-Film Color Optical Memory," *Applied Physics Letters*, January 8, 2001.

Molecule Stores Picture

By Kimberly Patch, Technology Research News
November 27/December 4, 2002

All hydrogen atoms are not necessarily alike—they can contain different amounts of energy, which gives them different spins. The spin of a particle is like a top turning either clockwise or counterclockwise.

As a result, identical molecules that contain the same atoms in the same order can still be distinguishable because their atoms can have different spins.

Researchers from the University of Oklahoma have found a way use the spins of 19 hydrogen atoms contained in a liquid crystal molecule to briefly store and read 1,024 bits representing a 32-by-32-pixel black and white pattern, a method they have termed "molecular photography".

The researchers had previously used liquid crystal molecules to briefly store, then read out the sentence "the quick brown fox jumps over the lazy dog," according to Bing M. Fung, a professor of chemistry at the University of Oklahoma. Each hydrogen atom, with its two spin states, can represent one bit of information.

In theory, 19 hydrogen atoms with two spin states each can store nearly 219, or about half a million, bits of information, said Fung. A group of five bits can represent 25, or 32 bits of information, which is enough to distinguish among the letters of the alphabet.

The researchers used nuclear magnetic resonance, or radio waves—the same process that underlies medical magnetic resonance imaging (MRI) technology—to change the spin states of the hydrogen atoms contained in a sample of trillions of molecules of liquid crystal. Nuclear magnetic resonance machines use radio waves and magnetic fields to image substances like soft tissue. The bits representing the image were coded into a single electromagnetic pulse that contained 1,024 distinct frequencies near the 400 megahertz, or million-cycle-per-second frequency of FM radio.

The researchers put the sample in a nuclear magnetic resonance spectrometer, which provided a very strong magnetic field. "In a high magnetic field, the hydrogen nuclei can absorb radio frequency energy," said Fung. "Different spin states can absorb tiny differences in energy even though they are in the same molecule, he said.

When the researchers stopped the pulse, the spins that absorbed energy released it, and the spectrometer picked up the released energy, giving the researchers a picture of the frequencies contained in, and thus the information coded in, the pulse, said Fung.

The researchers were able to store as many as 1,024 frequencies in the 19 hydrogen atoms, but the resolution of the spectograph is best when there are fewer than about 300 frequencies, said Fung. When there were more than 300 frequencies, the researchers had to read the pattern one row at the time. "The peaks overlap so we had to break them down into two dimensions," he said.

The researchers do not know exactly how the hydrogen atoms absorbing and storing energy in spin states, said Fung. "I think each of the frequencies [affects] more than one spin state. Maybe a bunch of spin states absorb one frequency, another bunch of spin states absorb another," he said.

The technique may eventually make it easier to store and process information within molecules, said Fung. "We're developing some fundamental concepts and techniques [toward using] molecules to store and process information in a practical way, but I cannot tell you right now what it will end up to be," he said.

There is an inherent advantage in storing and processing information in molecules, said Fung. "You want to go down to smaller and smaller sizes so that you can put a lot of information in a very small device," he said.

In addition, when a device becomes as small as a few dozen molecules, the physical rules that govern the material's behavior change, and there may be advantages to the new rules, Fung said. "When the device becomes smaller, the normal physics rules break down and the quantum behavior dominates," he said. "We have to study smaller systems to understand how they work."

Even though the researchers are storing information in the spins of individual atoms, the process is not quantum computing because the spins are not correlated, said Fung. The technique falls between classical and quantum information processing, he said. Quantum computer schemes use attributes like spins of particles to compute, but require entangled, or linked particles.

The research could have interesting applications, said Noel Clark, a physics professor at the University of Colorado. "I've never heard of anyone encoding this many bits in the spin-coupled system of a single molecule," he said.

Such large collections of coherently interacting spins may be useful if the method can eventually be used to store different spins in different molecules, he said. “It’s not, in the form presented here, a potential method for bulk data storage [because] it probes many molecules in parallel, each of which are doing the same thing,” he said.

It’s hard to say when the method could be used practically, said Fung. “It’s really, really hard to use molecules to store and process information. It won’t be next year, but it won’t be decades either,” he said.

The researchers are currently trying to find solid materials that will store information in a similar way. “Liquid crystal [has] mechanical properties like a liquid so it cannot be easily miniaturized,” said Fung. “So we’re working on solids, but unfortunately solids can’t store that much information,” he said. The researchers are working with special types of solids that have more motion in order to find solids that can store more, he said.

Fung’s research colleagues Anatoly K. Khitrin and Vladimir L. Ermakov. They published the research in the October 15, 2002 issue of the Journal of Chemical Physics. The research was funded by the National Science Foundation (NSF).

Timeline: 2-10 years
Funding: Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Chemistry; Data Storage Technology
Story Type: News
Related Elements: Technical paper, “Nuclear Magnetic Resonance Molecular Photography,” Journal of Chemical Physics, October 15, 2002; technical paper, “Information Storage Using a Cluster of Dipolar-Coupled Spins,” Chemical Physics Letters, July 3, 2002.

TRN

Ultimate Memory Demoed

By Kimberly Patch, Technology Research News
August 7/14, 2002

The ultimate in miniaturization is the atom—there are 10 million billion of them in a single grain of salt.

The scientist Richard Feynman suggested several decades ago that it would be possible to use single atoms to store bits of data. Researchers from the University of Wisconsin at Madison have taken a large step toward making the idea a reality with a prototype that uses single silicon atoms to represent the 1s and 0s of computing.

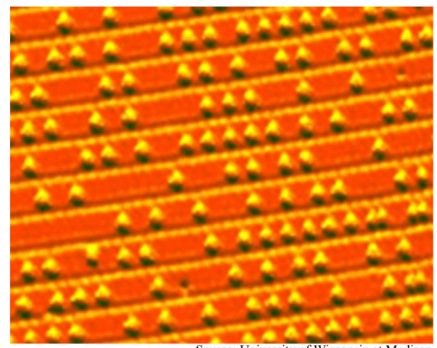
Practical atomic-scale memory would increase the amount of information that could be stored per square inch of recording material by several thousand times.

The researchers realized they had hit upon a mechanism for atomic memory when they discovered that scattering gold atoms on a silicon wafer caused the silicon atoms to assemble into tracks exactly five atoms wide. The pattern resembled the microstructure of a CD.

Making the tracks turned out to be relatively easy. “We can actually get atoms to assemble themselves... precisely, without any type of lithography,” said Himpsel. “It is actually quite simple, and my graduate students make the surfaces routinely now,” he said.

The breakthrough that made the prototype possible was working out a practical way to write data into the memory, Himpsel said. “In general, it is difficult to work with an individual atom in a controlled way, without affecting neighboring atoms,” he said.

The researchers initially tried to write information to the memory by moving atoms along the tracks. “That works well at very low temperatures with loosely-bound atoms, but not at room temperature where we wanted the memory to operate,” said Himpsel. Eventually, “instead of moving them, we [picked] up the atoms,” using a scanning tunneling microscope, he said.



Source: University of Wisconsin at Madison

The dots in this image are gold atoms on a silicon surface that is arranged in tracks five atoms wide. The gold atoms represents 1s and the places where gold atoms are missing represent 0s.

The researchers found that the optimum spacing for each bit is a four-atom section of track. This makes the bit spacing 1.5 nanometers along the tracks and 1.7 nanometers between tracks, which amounts to a data storage density of 250 trillion bits per square inch. This is equivalent to storing the contents of 7,800 DVDs in one square inch of material. A nanometer is one millionth of a millimeter.

The researchers formatted the memory by depositing extra silicon atoms onto the tracks to make every bit a 1, then wrote data by removing atoms to represent 0s.

To read the data, they scanned along the tracks looking for the presence or absence of the extra atoms.

The approach bridges two broad camps of work on data storage, said Himpsel. “One group of researchers manipulates atoms with great precision at very low temperature,” he said. The other group improves existing memory devices, which use thousands of atoms per bit. “We attempt to bridge the gap between the two camps by sticking to the atomic density limit, but... obtaining realistic numbers for the ultimate performance limits of a memory, such as speed, error rate, and stability” at room temperature, he said.

The researcher's prototype resembles the way nature stores data in DNA, said Himpsel. The memory structure self-assembles into the tracks. In addition, "the density and readout speed of DNA [is] quite similar to our silicon memory," he said. While DNA uses 32 atoms to store one bit using one of four base molecules, the researcher's silicon memory uses 20 atoms including the atoms between the individual atoms that store the bits, said Himpsel.

The prototype is clever, said Phillip First, an associate professor of physics at the Georgia Institute of technology.

Writing atomic bits is impractically slow at present, but the work is a realistic analysis of bit stability, which is good, recording density, which is high, and readout speed, said First. It is "a very impressive demonstration of the practical limits of two-dimensional data storage using single-atom bits," he said.

Although the prototype is very slow at reading data compared with readout speeds of mag-netic disks, the researcher's work shows that this can be improved, said First. The fundamental limit of readout speeds has to do with signal-to-noise ratio, and the researchers showed that this limit is substantially higher than the speed they were able to achieve with the current prototype. If the researcher's storage media were combined with microelectromechanical systems that allowed for parallel data readout from the memory, "the ultimate data rate could be comparable to magnetic disks," according to First.

The researchers intend to boost the readout speed next, said Himpsel. "An immediate next step is the use of fast scanning electronics to speed up the readout to its theoretical limit, which is 100,000 times faster than our simple electronics allowed," he said.

Because the readout speed decreases as the bit size gets smaller, when practical atomic storage devices are eventually made, scientists are likely to strike a balance between storage density and performance that falls short of the 20-atoms per bit density the researchers have proven is possible, said Himpsel. "Somewhere on the way to the atomic limit is an optimum combination of density and speed."

The researchers are also working on finding the optimum coding and signal filtering methods for the memory in order to cut down on the error rate, Himpsel said. Using more than a single atom per bit could also reduce error rates.

And the researchers eventually need to tackle the as yet unsolved problem of making the memory work outside of a vacuum, said Himpsel.

Although the research shows that it is possible to store bits of data in single atoms, there is a lot of work to be done before the technology could be made practical, said Himpsel. It will take "decades," he said. "I will be retired by the time we have atomic-scale memory in use."

This type of memory may eventually become useful for storing vast amounts of data, but because the stability of each bit of information depends on one or a few atoms, it likely to be used for applications where a small number of errors can be tolerated. "I would not want to trust my bank account to a memory where a single atom could wipe out my savings," said Himpsel. "However, for pattern recognition—face or handwriting recognition—it is not critical that all the pixels are stored perfectly," he said.

Himpsel's research colleagues were Roland Bennewitz of the University of Wisconsin at Madison and the University of Basel in Switzerland, and Jason Crain, Armen Kirakosian, Jia-Ling Lin, Jessica McChesney and Dmitri Petrovykh of the University of Wisconsin at Madison. They published the research in the July 4, 2002 issue of the journal Nanotechnology. The research was funded by the National Science Foundation.

Timeline: > 20 years
Funding: Government
TRN Categories: Data Storage Technology; Nanotechnology; Physics
Story Type: News
Related Elements: Technical paper, "Atomic Scale Memory at a Silicon Surface," Nanotechnology, July 4, 2002.

TRN

Silver Shines Red and Green

By Kimberly Patch, Technology Research News
February 14, 2001

Silver, in very small quantities, can act rather like a traffic light, a trait that could be used to store bits of information.

Researchers from the Georgia Institute of Technology are using the florescence characteristics of tiny clusters of silver atoms to gain red, green and shades of yellow that can be controlled, or rewritten, with a laser.

The researchers have figured out how to photochemically create very small clusters of silver atoms that emit light at room temperature. They've demonstrated a binary data storage prototype that simply uses light and the absence of light to store information.

The scheme has the potential to go beyond binary storage because the clusters can emit both red and green light, and clusters that emit both colors at nearly the same time produce mixes of the two colors that look yellow, said Robert Dickson, an assistant professor of chemistry at the Georgia Institute of Technology.

This is because as an organic molecule gains double bonds, the wavelengths of light it absorbs shift. As more silver atoms join a cluster, forming double bonds, "you get a shift to longer wavelengths. Different sizes and also potentially different geometries of a given cluster size will give different emission colors," said Dickson.

This scheme can potentially store a lot of information in a small space because it uses multiple colors and because the clusters, made up of only a few silver atoms, are so small.

The number of possible colors this scheme could produce depends on how many distinct mixes of yellow can be detected, said Dickson. "You could use it as a high-density data storage medium using shades of different colors to store more than one bit of information per data point," he said.

For instance, if a certain point has the potential to be one of four colors, those four colors could represent all the possible combinations of two bits: 00, 01, 10, and 11. In a similar manner, eight colors could store three bits of information and 16 colors four bits of information.

The tiny clusters could also eventually be used as biological labels whose florescence could be turned on and off with a laser, said Dickson. The clusters could be attached to certain types of cells, for example, which could then be tracked as they move through the body. "It's very early on. [The results show] potential for data storage [and] for potentially interesting biological labels that can turn on at a certain time," he said.

The researchers create the clusters by irradiating silver oxide, which changes it into clusters of a few silver atoms each plus silver peroxide. When blue light is shown on these silver nanoparticles, they fluoresce. Fluorescence occurs when an atom absorbs energy from light, which moves one of the atom's electrons to a higher energy level. When the electron relaxes back to a lower energy level, the atom releases the excess energy in the form of a photon.

The scheme can be used to rewrite information. "It allows you to generate florescence only in the areas that you've pre-illuminated, so you can write images to our samples," said Dickson.

The researchers are currently working on better controlling the florescence. "We are nailing down the mechanism for how these clusters change size and are produced... by doing very fundamental photophysical studies—florescence absorption type measurements," said Dickson. Those studies are a precursor to designing materials optimized for data storage. "You want nice, properly sensitized particles that... will give us the behavior we want," he said.

A silver florescence data storage mechanism could be produced within a decade, said Dickson. Biological labeling using this method would likely take longer because it involves figuring out how to attach the clusters to proteins and put them inside living cells, said Dickson.

Dickson's research colleagues were Lynn A. Peyser, Amy E. Vinson and Andrew P. Bartko of Georgia Tech. They published the research in the January 8, 2001 issue of *Applied Physics Letters*. The research was funded by Georgia Tech.

Timeline: 10 years
Funding: University
TRN Categories: Semiconductors and Materials; Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Photo Activated Florescence from Individual Silver Nanoclusters," *Science*, January 5, 2001.

TRN

Molecule Makes Mini Memory

By Chhavi Sachdev, Technology Research News
August 15, 2001

If you're reading this on a computer, these words are stored in memory that is made of transistors and capacitors, and grouped into chips that measure an inch or so. The most common type of memory, dynamic random access memory (DRAM), needs to be refreshed thousands of times per second to prevent the words from fading away.

Researchers at Pennsylvania State University and Rice University are working on computer memory that looks and works very differently. They have demonstrated that they can change the electrical conductance of a single molecule to use it as a switch to perform the same function as a transistor.

"We have demonstrated that single molecules can switch. So switching and memory could be scaled to the single molecule level - one million times smaller than the smallest transistor," said James Tour, a professor of chemistry at Rice University.

Memory made from molecular switches would require little power and hold information for hours at a stretch, according to the researchers.

In the past, scientists have demonstrated switching in bundles of thousands of molecules. The Penn State and Rice researchers were able to attain switching in a single phenylene ethynylene oligomer molecule by changing the spatial arrangement of its atoms and thereby its conductance, said Paul Weiss, an assistant professor of chemistry at Pennsylvania State University. "The specific conformational changes are not known," he said. "It might be [a change in] tilt or an internal motion."

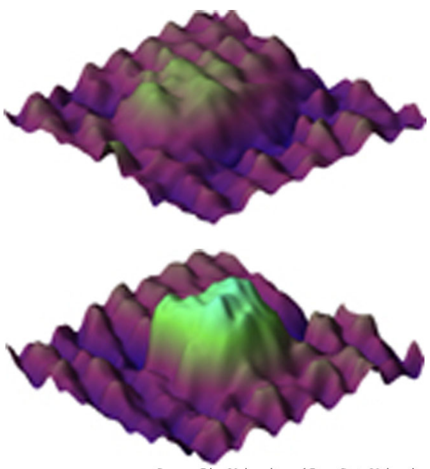
The molecules, which are two nanometers long and half a nanometer across, can retain the change for as long as 26 hours. "If we made memory out of these switches, the persistence time determines how often we need to refresh memory," said Weiss. "The persistence time in a state prior to switching ranges from fractions of seconds up to tens of hours-depending largely upon the tightness of the environment around them," he said.

The researchers demonstrated the molecules' switching ability by anchoring them in a matrix of a alkanethiol layer on a gold substrate, then passing a current through them.

"[We] add an electron by applying a voltage, and the switch turns on - it is in a conductive state," said Tour. Removing the electron makes the molecule non-conductive, which is the off position.

Like soldiers standing at attention in a crowd, when the switches are on they appear to become taller and straighter than their neighbors in the matrix. When the switches are off they are at ease.

The researchers found that molecules packed in a tight matrix stayed in the on position longer than those in a loosely packed, poorly ordered matrix. "Conformation can affect the switch hold time in the on state," he said. Think of the molecules as marbles. If you don't confine them, the slightest thing makes them wobble around. Put them in a box, they settle in and don't move.



Source: Rice University and Penn State University

These colored scanning tunneling microscope images show a molecular switch that could eventually be used in computer memory devices. The top image shows the molecule switched off and the bottom image shows it switched on.

The researchers got the idea to use the molecules as switches from an experiment five years ago that involved positioning a related series of molecules under a Scanning Tunneling Microscope (STM), said Weiss. Just as in the later experiment, one end of the oligomers was bound to a gold electrode through a sulfur atom. "They are prevented from lying flat on the gold by the alkanethiolate matrix," he said. The molecules stand off the surface in a tilted, but ordered way, he said.

"Our idea was to hook up metal crystal as one electrode and the tip of our STM as the other electrode, [but] it turned out to be a little more complicated," said Weiss. "When we mixed those two molecules together on the surface, not only did the molecules we wanted to study not stand up, but the other molecules [did not remain] in any sort of ordered array," he said. To rectify the mess, one of the researchers used defects in the matrix as places to insert and anchor the molecules.

"In the intervening five years, we've gotten very good at controlling the type of defect, the size of the defect and the number of defects," said Weiss. By controlling the defects, the researchers can manipulate the number of molecules that will be in the field of view of the STM, he said.

A central issue is the precise gap between the tip of the STM and the molecule, said Weiss. "We've learned how to interpret the contribution of that gap quantitatively [by observing] how the current decreases when we pull the tip away," he said Weiss. "We were able to tell the difference between supplying an electron to them, by which I mean running a current, or simply applying an electric field." By backing the STM tip off just enough, the researchers have been able to "apply a voltage between the tip and the underlying metal electrode and show that just with that electric field we are able to make the molecules switch," he said.

The researchers are not yet sure exactly how the switching process works. It could be that the changes within the molecule affect how the molecule conducts current. Electron paths, or orbitals, might no longer extend over the full length of the molecule as they did, but become localized in its middle instead, said Weiss.

Another possibility has to do with contacts. A working hy-pothesis is that a tilt of the entire molecule would change how the electrons of the molecule con-nect with the underlying metal to cause the large conduct-ance change, said Weiss. "The molecule is not [completely] static… It is able to rotate internal bonds freely on the time scale on which we see switching," said Weiss.

The process is reversible. "The molecules can go back and forth many times between different states, which is important in having memory which you can write over… and using these things for logic," said Weiss.

The work is clever, said Mike Ward, Professor of Inorganic Chemistry at the University of Bristol in England. "The combination of demonstrating a remarkable switching [and] memory effect… demonstrating what causes it, and [showing] that in principle it is feasible on the single-molecule scale make this a piece of science…at the forefront of current work into molecular electronics," he said.

The work shows clearly that the switching process is associated with some sort of structural or orientational change of the molecules, Ward said. The alternative possibility that the switching process is related to the gain or loss of an electron can be ruled out, he said. "This effect would not be influenced by the tightness of the packing around the… molecules."

The researchers are currently making variations of the molecules in order to pinpoint what features drive the switching. "We are looking at molecules with different backbones, …changing the environment around the molecules, and developing a careful way of turning them on," said Weiss.

The researchers' main goal is making primitive logic and addressable devices like memory from these molecules, said Tour. Eventually, they would like to make devices that meld silicon and molecules, said Weiss.

"This is not a technology that will one day overturn silicon dominance. It's more likely that some of these molecules will be used in some hybrid system where you take advantage of integrating molecular functions with some other properties" for activities like sensing, said Weiss. Biological and chemical sensors could, for instance, pick up changes in current and resistance.

Weiss and Tour's colleagues were Zachary Donhauser, Brent Mantooth, Kevin Kelly, Lloyd Bumm, Jason Monnell, Josh Stapleton, and David Allara at Penn State and David Price and Adam Rawlett at Rice University. The research was funded by the Army Research Office, the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), the Office of Naval Research (ONR), and Zyvex.

Timeline: 2-3 years
Funding: Corporate; Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing
Story Type: News
Related Elements: Technical paper, "Conductance Switching in Single Molecules Through Conformational Changes," *Science*, June 22, 2001.

Molecules Make Short-Term Memory

By Eric Smalley, Technology Research News
June 27, 2001

Short of using quantum effects, the ultimate computer memory would store each bit in a single molecule. Memory devices made from one or even a relatively few molecules have the potential to hold hundreds of times more data than today's semiconductor memories.

There are two challenges to using molecules as memory: finding a molecular mechanism that can be reliably switched on and off, and making a device that can read and write to individual molecules.

While the second challenge is likely to remain unsolved for a long time, researchers are beginning to crack the first. Finding suitable molecular mechanisms could also yield useful devices short of full-blown molecular memory.

Researchers at Yale University and Rice University have developed a prototype that could lead to cheap, high density, nonvolatile memory. The device consists of a one-molecule-thick film, or monolayer, 30 to 50 nanometers in diameter that connects two metal electrical contacts.

A positive electric pulse changes the conductivity of the molecules from low to high, which constitutes writing one bit. A smaller positive pulse measures the conductivity of the molecules to read whether there is a bit but does not erase it. A negative pulse returns the molecules to their low conductivity state, erasing the bit.

"It has resettable conductivity states: on or off corresponds to different resistances, and the states are resettable reproducibly," said Mark A. Reed, a professor of engineering and applied science at Yale University.

The molecules don't remain in the high conductivity state for long, however. They hold the information for about 10 to 15 minutes, far shorter than magnetic nonvolatile memory, which theoretically holds data infinitely. "These self assembled monolayer devices have yet to be infinite, but 10 to 15 minutes might be of sufficient interest," said Reed.

The molecular mechanism requires no more than one molecule, which opens the possibility of eventually producing single-molecule memory devices. However, "this is very, very challenging and may not be the best application goal to chase," said Reed. "I don't envision single-molecule memory cells," he said.

But the device, which uses about 1,000 molecules, doesn't have to be scaled all the way down to one molecule to yield memory that is far cheaper and higher capacity than today's semiconductor devices.

"It strikes me as an impressive and important piece of work," said Mike Ward, a chemistry reader at the University of Bristol. "It is very easy to find molecules which undergo a change in response to a stimulus of some sort, but often the change reverses as soon as the stimulus is removed."

It's too soon to gauge how long it will take before practical applications for the molecular device can be developed, said Reed.

Reed's research colleagues were Jia Chen, now at IBM, and Adam M. Rawlett, David W. Price and James M. Tour of Rice University. They published the research in the June 4, 2001 issue of the journal *Applied Physics Letters*. The research was funded by the Defense Advanced Research Project Agency (DARPA) and the Semiconductor Research Corporation.

Timeline: Unknown
Funding: Government, Corporate
TRN Categories: Biological, Chemical, DNA and Molecular Computing
Story Type: News
Related Elements: Technical paper, "A Molecular Random Access Memory Cell," *Applied Physics Letters*, June 4, 2001

Altered Protein Orders Metal Bits

By Eric Smalley, Technology Research News
January 1/8, 2003

Genetic engineering usually means experimental drugs, altered food crops and the specter of a new race of superhumans.

Researchers from NASA, the SETI Institute and Argonne National Laboratory have genetically modified a bacteria that lives in geothermal hot springs in order to make a microscopic scaffolding that produces a high-tech material.

The altered bacteria gene produces a protein that automatically constructs orderly arrays of microscopic bits of gold or zinc. The microscopic bits of metal can serve as quantum dots, which trap one or a few electrons, and can be used in electronics.

Nanoscale arrays of quantum dots could be used to make data storage devices that hold enormous amounts of information; quantum computers that use quantum dots to compute, and materials that channel light waves in optical computers and communications devices.

The technique uses biotechnology and chemistry in place of conventional chipmaking processes. "The concept of using self-assembling biomolecules for materials science is not new," said Andrew McMillan, a research scientist at NASA's Ames Research Center. What is new is "we engineered [specific functions] into a protein that self-assembles into flat crystals," he said.

Certain portions of the protein bind to certain metals. When the protein tubes arrange themselves in a lattice,or crystal-like, structure, the result is uniform placement of nanoscale bits of metal, said McMillan.

The researchers used a protein from Sulfolobus shibatae, an extremophile organism that can grow in temperatures as hot as 85 degrees Celsius. The bacteria's ability to withstand high temperatures means the protein, called chaperonin, is particularly stable.

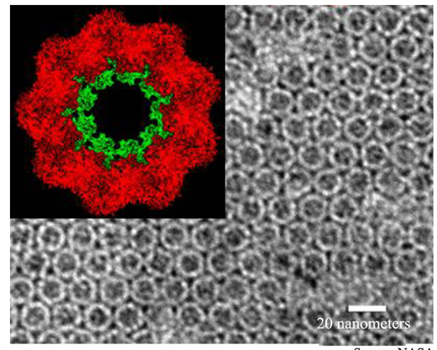
Chaperonins are essential proteins that exist in nearly all organisms, said McMillan. Their predominant function is thought to be facilitating protein folding inside cells, he said. Proteins fold to change shape at the molecular level, which allows them to carry out specific life processes.

Chaperonins are made of 14, 16 or 18 protein subunits arranged in a pair of stacked rings. "Our work takes advantage of the... characteristic barrel shape," said McMillan. The rings are 16 to 18 nanometers high by 15 to 17 nanometers in diameter. A nanometer is about the width of 10 hydrogen atoms.

The researchers used one of the three types of proteins that make up the chaperonin subunits. They altered the Sulfolobus genes to produce a protein with a slightly different structure, then inserted the altered genes into common E. coli bacteria, which manufactured large amounts of the modified protein. They heated the E. coli to 85 degrees Celsius to destroy the E. coli and its own proteins, leaving behind the engineered Sulfolobus protein.

The researchers engineered two variants of the protein. To get one variant, they removed a portion of the gene that causes bits of protein to partially block the openings at the ends of the chaperonin. The partially blocked variant had an opening of 3 nanometers and the unblocked variant had an opening of 9 nanometers.

They also mutated the genetic code of both variants to produce cysteine residues on the chaperonins' openings. Cysteine, an amino acid, acts like glue to bind a bit of gold or zinc to each opening like sticking a ball to the end of a tube.



Source: NASA

The red ring represents a genetically modified protein. The black and white microscope image shows an array of the rings.

The modified chaper-onins did not lose their inherent stability or ability to self-assemble, said McMillan. "We were able to alter the protein without destroying its ability to form interesting structures," he said.

The researchers crystallized the altered chaperonins into flat, hexagonally packed templates, said McMillan. These chaperonin crystals arranged 5-nanometer quantum dots into arrays when the researchers used the variant with the 3-nanometer opening, while the the 9-nanometer chaperonin arranged 10-nanometer quantum dots.

The researchers' work expands the rapidly growing field of using biomolecules as nanoscale scaffolding to organize inorganic nanocrystals, said Shuguang Zhang, a principal research scientist and associate director of the Center for Biomedical Engineering at the Massachusetts Institute of Technology. The researchers used a well-understood protein complex that can assemble itself into useful structures, he said.

Proteins are particularly useful because researchers can modify their structures in precise locations without significantly altering their folding behavior, said Zhang. "This tailor-made approach will have tremendous impact on the growth of nanotechnology and nanobiotechnology," he said. "However, much effort is still needed to reduce the high cost of production and [improve the] stability of proteins in their complexes," said Zhang.

"I think the basic idea is neat, but the end result was not all that impressive," said Gerard Wong, an assistant professor of materials science and engineering at the University of Illinois at Urbana Champaign. "You have to compare what they wind up making with what people have already accomplished using block copolymer lithography and other competing technologies," he said.

Block copolymer lithography uses ultraviolet light to alter the structure of a mix of two polymers so that they form thin plastic films with closely packed arrays of nanoscale holes. The films can serve as templates for making data storage media or optical materials.

Protein-guided nanostructures could be used in practical applications in two to five years, said Jonathan D. Trent, a research scientist at NASA Ames Research Center. Sony Corporation and Matsushita Electric Industrial Co., Ltd. are pursuing protein-based techniques for manufacturing memory, he noted.

The researchers' next step is to see what other kinds of particles they can array using their protein scaffolding, said McMillan. "We hope to build on this model of self-assembling and see what we can push it to do," he said.

One challenge to using the technique for practical applications is determining whether and how to remove the protein templates, which could contaminate devices, after the arrays are formed, said McMillan.

McMillan and Trent's research colleagues were Chad D. Paavola of NASA's Ames Research Center, Jeanie Howard and Suzanne L. Chan of the SETI Institute, and Nestor J. Zaluzec of Argonne National Laboratory. They published the research in the November 25, 2002 issue of the journal *Nature* Materials. The research was funded by NASA, the U.S. Department of Energy (DoE) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 2-5 years
Funding: Government
TRN Categories: Biotechnology, Materials Science and Engineering, Nanotechnology
Story Type: News
Related Elements: Technical paper, "Ordered Nanoparticle Arrays Formed on Engineered Chaperonin Protein Templates," *Nature* Materials, November 25, 2002

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