TRN's
Making the Future report
The State of an Emerging Technology and a Look at What Lies Ahead

Report Number 11 February, 2004

Nanomechanics and Nanoelectronics: Molecule-Size Machines

Executive Summary

Nanotechnology research is aimed at building minuscule machines and electronics and constructing materials molecule-by-molecule.

The technology promises to open the way to faster and lower-power electronics, jewelry-size computers, data storage densities in the realm of several terabits per square centimeter, ultrahigh-bandwidth communications devices, microscopic transmitters and receivers, new types of devices like handheld biological sensors, and inexpensive manufacturing processes.

Near-term nanotech developments will make materials tougher and lubricants slipperier. Longer-term research is largely focused on developing the basic building blocks of nanoscale technology — components that are hundreds of times smaller than a red blood cell.

Nanoelectronics researchers are working to develop tiny transistors, memory devices, switches, wires, light emitters and networks. Nanomechanics researchers are working to develop ratchets, actuators, motors, shuttles, springs, pistons and bearings.

There are two approaches to building both types of devices: the top-down method of today's microelectronics manufacturing and the bottom-up techniques of biology, chemistry and materials engineering. Raw materials include inorganic matter like metals and semiconductors, molecules like polymers and carbon nanotubes, and biological molecules like DNA and proteins.

Carbon nanotubes and nanowires are especially promising because they can be exceedingly small, assembled chemically, and have the potential to be grown in place and en mass. Carbon nanotubes are also very strong mechanically.

DNA is the star player in the biological molecule arena because the molecules can be programmed to self-assemble into many shapes and patterns, including templates for assembling other materials.

Nanotechnology is a catchall term for the work of many disciplines that have extended to the nanoscale, and the work is becoming increasingly interdisciplinary. There are many health, environmental and social issues left to address, but there appears to be no fundamental technological barrier to building nanoscale devices. It will be at least a decade before the more imaginative applications of nanotechnology come within reach.

What to Look For

Nanotube electronics:

Carbon nanotubes sensors
Hybrid nanotube-silicon chips
Carbon nanotube logic circuits
Mass production of nanoelectronics

Nanowire electronics:

Nanowire memory chips
Nanowire LEDs and lasers
Nanowire processor chips
Nanowire-based computers
Nanocomputers

Molecular electronics:

Hybrid semiconductor/organic memory chips
DNA-assembled logic circuits
Hybrid DNA-nanotube devices
Ultrahigh density molecular memory
Molecular logic circuits

Nanomechanics:

Nano mechanical sensors
Nano mechanical logic devices
Molecular materials/drug assemblers
Free-moving nanoscale machines

Race to the bottom

Given the hype surrounding nanotechnology, an uninformed person could be forgiven for thinking that it won't be long before microscopic submarines patrol his body and hordes of minuscule robots assemble anything he asks for.

In general, nanotechnology research is aimed at building minuscule machines and electronics and constructing materials molecule-by-molecule. But near-term nanotech developments are more likely to make materials tougher and lubricants slipperier than produce blood-based submarines. The work could just as easily be labeled chemistry and materials engineering.

The longer-term research that promises to eventually narrow the gap between nanotech hype and reality is largely focused on developing the basic building blocks of nanoscale technology — transistors, LEDs, ratchets and motors that are hundreds of times smaller than a red blood cell.

These research efforts fall into the two broad categories of nanoelectronics and nanomechanics.

Nanoelectronics research is aimed at developing a wide range of electronic devices at tiny scales:

- Transistors
- Memory
- Switches
- Wires
- Light emitters
- Networks

Nanomechanics research is aimed at developing all manner of microscopic machines:

- Ratchets
- Actuators
- Motors
- Shuttles
- Springs
- Pistons
- Bearings

On both fronts, researchers are making devices using three types of materials: inorganic matter like metals and semiconductors, molecules like polymers and carbon nanotubes, and biological molecules like DNA and proteins.

Nanodevices made from inorganic matter have analogs in the world we see, like the switches and diodes of everyday electronic devices, but they have to be constructed, and, given the size scale, putting together even a simple device is tricky and time-consuming.

Molecules are ready-made components and they naturally self-assemble. Their electrical properties, however, are generally more difficult to tune than those of the inorganic semiconductor materials usually used in electronics.

Carbon nanotubes are a bit of an anomaly. The rolled-up sheets of carbon atoms occur naturally in soot, have a relatively complicated shape, and have very useful electrical and mechanical properties. They are also fairly easy to grow en masse.

How It Works

The physics of the very small

The laws of physics behave differently at very small scales. At the nanoscale, electrons travel more quickly through wires, transistors can mete out electrons one at a time, objects stick to each other, light can bend matter, and the right mix of DNA can get molecules dancing.

Going ballistic

Researchers have made semiconductor nanowires as narrow as a few nanometers, gold nanowires about half a nanometer wide, and carbon nanotubes just six atoms across. The structures can be used as electrical wires, but with a key advantage over ordinary wires.

Though electrons travel from point to point at the speed of light, they rarely travel through metal and semiconductor crystals in a straight line. Electrons scatter in all directions as they bounce off a wire's boundaries and impurities.

At the nanoscale, wires have negligible impurities and closely spaced walls, leading electrons to travel more or less straight through, or ballistically. The result is electron transit times that are hundreds of times faster than for ordinary wires.

One at a time

Transistors that are small enough can take advantage of quantum effects to control the flow of electricity at the rate of one electron at a time. Ordinary transistors have a semiconductor channel, source and drain electrodes that move electrons into and out of the channel, and a gate electrode that changes the channel's electrical conductance in order to control the flow of electricity through the device.

Single-electron transistors contain a tiny reservoir, or island, rather than a channel. The island can hold a set number of electrons at a time, and barriers, or junctions, between the electrodes and the island block electrons from moving on or off the island. When a voltage is applied to the transistor's gate electrode, the junctions' resistance to the electrons is weakened but not removed entirely.

The exact position of an electron, like that of all quantum particles, is a matter of probability. Physicists describe electrons as clouds, and an electron has a certain probability of being at any given point in its cloud. Electron clouds fluctuate, and if an electron's cloud extends beyond a barrier that would otherwise block the electron, at some point the probability of the electron being at a point beyond the barrier is high enough that the electron

Two worlds

The nanoscale is much smaller than the merely microscopic; there's lots of room when it comes to small.

The transistors used to power today's computers, which are among the smallest manufactured components, are on the order of 100 nanometers, which is nearly 1,000 times smaller than you can see, but still 1,000 times bigger than a hydrogen atom.

Carbon nanotubes can be smaller than one nanometer in diameter, which is 10 times wider than a hydrogen atom, 1,000 times narrower than an E. coli bacterium and more than 50,000 times narrower than a human hair. A nanometer is one millionth of a millimeter.

The advantages of smaller

There are several advantages to being able to produce devices that are so tiny.

On the electronics side, the smaller the device, the faster it works, simply because it takes less time for the electrons that carry electrical signals to travel over short distances and thinner wires. Researchers from the Tokyo Institute of Technology have shown that electrons move through gold wires as small as 0.6 nanometers in diameter at nearly 100th the speed of light — many times faster than through bulkier wires. (See "Atomic Scale Wires Speed Electrons", page 30.)

Smaller bits — or areas that hold the 1s and 0s of computer information — lead to computer media that packs more information into smaller spaces. Memory devices based on nanotubes, nanowires and molecules could eventually store single bits in areas as small as a few nanometers, leading to storage densities of several terabits per square centimeter. A terabit is 1,000 gigabits, or 125 gigabytes, which would hold the contents of 26 DVDs.

Nanoelectronics could also open the way to many new types of devices, including very low-power computers, jewelry-size computers, tiny sensors scattered throughout the environment, and microscopic transmitters and receivers. Nanoelectronics could perhaps even extend radio frequency identification tags to the nano realm, allowing tags to be mixed into substances like paint and printer ink.

On the mechanical side, smaller means faster. The most common form of microelectromechanical and nanoelectromechanical device is the resonator, which simply vibrates. Tiny resonators vibrate at extremely high rates at the nanoscale — billions of times a second.

Vibrations are useful in two broad areas: sensors and transmitters. Resonator-based sensors can be used to sense forces, like acceleration, as well as substances like biomolecules and chemicals. Fast vibrations make for extremely sensitive sensors, including devices that can detect the presence of individual molecules. It also makes for high-bandwidth communications devices.

simply appears there. The phenomenon, quantum tunneling, is widely used in electronics.

Because the negatively-charged electrons repel each other, adding an electron through tunneling when the island is at its maximum capacity forces another off. This forms a sort of turnstile that assures that electrons will pass through the transistor one at a time.

Come closer, but not too close

At the nanoscale, the force of attraction between molecules — the van der Waals force — becomes a major player. It draws molecules close together, but it also keeps them from coming into contact. This makes it possible to stick carbon nanotubes together while also allowing the inner tubes of multiwall carbon nanotubes to slide telescope-style without any friction.

Dipole molecules are electrically unbalanced, meaning their constituent atoms are configured so that the distribution of electrons makes one end of the molecule electrically positive and the other negative. Dipole molecules are infinitesimal magnets, and the force of attraction between them is very strong.

The van der Waals force is the sum of the electrostatic attraction and repulsion between individual electrically balanced, or neutral, molecules. The positive and negative charges within neutral molecules, while balanced on average, vary over time because the distribution of electrons fluctuates. For the brief instant that a molecule's electron distribution is uneven, the molecule becomes a dipole.

The distribution of electrons also shifts in response to the electrons of nearby molecules. A neutral molecule that is momentarily a dipole can induce a nearby molecule to also become a dipole because like charges repel each other and unlike charges attract each other. The two molecules' electron distributions become synchronized and the molecules are drawn together. The effect also applies to large numbers of molecules.

Neutral molecules are drawn together until their electron clouds nearly meet. Beyond that point the van der Waals force becomes repulsive because the negatively-charged electron clouds repel each other.

Sunburned shape shifters

The right kind of light, usually ultraviolet, causes certain molecules to change shape. In bulk, the molecules form rubber-like materials that visibly contract and expand under alternating light conditions.

Researchers have recently demonstrated the effect in individual polymer molecules. Polymers are long and chain-like. The shape-changing polymers

Arrays of millions of nanoelectromechanical devices could also be used to make electromechanical logic and memory devices for computers.

The challenges of smaller

Though researchers have become adept at making technologically useful nanoscale devices like wires, transistors and light-emitting diodes, there are two significant challenges to making these devices commercially viable. The first challenge is finding ways to precisely position and interconnect thousands of tiny devices. The second is figuring out how to connect these arrays to larger microelectronic circuits.

There are two approaches to building nanoelectronic and nanomechanical devices: the top-down method of today's microelectronics manufacturing and the bottom-up techniques of biology, chemistry and materials engineering.

The advantages of the top-down approach are precision and integration with existing microelectronics. However, today's mass production photolithography chipmaking techniques have yet to scale down to device feature sizes below 100 nanometers. And the techniques that enable smaller features — ion and electron beam etching — are too expensive for mass production.

The bottom-up approach — directing devices to self-assemble from extremely small components, including carbon nanotubes, nanowires and molecules — has the potential to be extremely inexpensive because the devices largely build themselves. Researchers are still getting a handle on how to make such devices form exactly where they are needed.

Electronics

Many research efforts are focused on using nanotechnology to replace today's chipmaking techniques. Nanoelectronics holds the promise of fantastically powerful and fantastically small electronic devices. Researchers are exploring four types of nanoelectronic components:

- Carbon nanotubes
- Semiconductor nanowires
- Polymers and other organic molecules
- DNA and other biological molecules

Nanotube electronics

Researchers are busily making devices from the versatile component nature has handed them in the nanotube, including field-effect transistors, memory cells and biological and chemical sensors. Nanotube transistors are so small that they can designed to reliably forward a single electron at a time. Single-electron transistors can be used as exquisitely sensitive electric charge sensors, and researchers have begun to devise logic schemes based on the transistors.

have side groups, which are collections of atoms that attach to the side of the chain. One or more of the side groups can be shifted from one side of the chain to the other. Photon energy of the right wavelength changes the molecule's chemical bonds, causing the shift, and light of a different wavelength shifts the side group back.

When the side groups are all on one side of the molecule, known as the trans configuration, the molecule is relatively straight. When the side groups are on alternating sides of the molecule, the cis configuration, the molecule is bent, and therefore shorter. This light-induced shape change produces a mechanical force that can be harnessed to do work.

Dancing DNA

DNA strands contain four types of bases — adenine, cytosine, guanine and thymine — attached to a sugar-phosphate backbone. Adenine combines with thymine, and cytosine combines with guanine, which pulls matching pairs of strands into biological DNA's familiar double helix.

These complementary bases sequences can also be chemically programmed to pull DNA strands into a variety of other shapes, and even cause individual strands to fold in on themselves. Researchers have found ways to cycle DNA through a series of shape changes to form molecular motors.

DNA motors typically consist of a motor strand or set of strands that undergoes the shape change, fuel strands that the induce the shape change, and control or removal strands that reverse the work of the fuel strands.

Who to Watch

Nanoelectronic Devices

Phaedon Avouris, IBM Research
Yorktown Heights, New York
www.research.ibm.com/nanoscience/

Marko Burghard, Max-Planck-Institute for Solid State Research
Stuttgart, Germany
www.mpi-stuttgart.mpg.de/kern/

Hongjie Dai, Stanford University
Stanford, California
www.stanford.edu/dept/chemistry/faculty/dai/group/

Cees Dekker, Delft University of Technology
Delft, The Netherlands
www.mb.tn.tudelft.nl/user/dekker/index.html

James Ellenbogen, The Mitre Corporation
Bedford, Massachusetts
www.mitre.org/research/nanotech/index.html

Charles Lieber, Harvard University
Cambridge, Massachusetts
cmliris.harvard.edu/

One reason nanotubes are so popular is their very desirable electronic properties. There are three basic types of materials in terms of electronics: insulators block the flow of electrons, conductors allow electricity to flow, and semiconductors slow the flow down, allowing it to be controlled. Depending on its structure, a nanotube is either a conductor or a semiconductor.

Carbon nanotubes have high carrier mobilities, meaning they carry electricity efficiently. Nanotubes also readily bond to biomolecules, including DNA. Sensors made from carbon nanotubes can detect DNA that belongs to specific types of pathogens.

Some research teams are working to control nanotube growth. Carbon nanotubes ordinarily form in a jumble, though researchers have developed methods of growing nanotubes in densely packed arrays. Using them as components of electronic devices, however, requires growing individual nanotubes in precise locations and orientations.

Researchers at Stanford University have developed a method of using electric fields to direct a nanotube to grow between two points, and have demonstrated the technique by growing a carbon nanotube between an electrode and a cantilever in a microelectromechanical system. In January 2004, the researchers teamed up with scientists at the University of California at Berkeley to add silicon circuits to the mix. They demonstrated the method by building a chip with hundreds of nanotube transistors connected to thousands of silicon transistors. (See “Nanotubes tied to silicon circuit,” page 12.)

Researchers from the Max Planck Institute in Germany is paving the way to using nanotubes in combination with DNA. They used a computer simulation to show that it is possible to insert DNA into nanotubes. (See “Study Shows DNA Will Fill Tubes,” page 12.)

Researchers from the National Aeronautics and Space Administration (NASA) have found a way to grow webs of connected carbon nanotubes that could eventually form networks with many connections, similar to the human brain. (See “Nanotube Web Could Mimic Brain”, page 14.)

Another team of researchers at the Max Planck Institute in Germany have come up with a method of oxidizing carbon nanotubes to make them all semiconducting, and using the oxidized nanotubes as memory storage elements. (See “Oxygen Makes Nanotube Memory”, page 15.)

Researchers from Lund University in Sweden and the University of Copenhagen in Denmark have used carbon nanotubes as electronic leads to connect a circuit and a gold nanoparticle to form a single-electron transistor. (See “Spot of Gold Makes Tiny Transistor”, page 16.)

Researchers at Delft University in the Netherlands have made logic circuits using transistors made from nanotubes. (See “Tiny Tubes Make Logic Circuits”, page 17.)

IBM researchers have found that it is possible to weed out metal nanotubes from semiconducting tubes by passing enough electricity through the usual mix of both types to destroy just the metal ones. (See “Jolts Yield Nanotube Transistors”, page 19.)

Paul McEuen, Cornell University
Ithaca, New York
www.lassp.cornell.edu/lassp_data/mceuen/homepage/welcome.html

Hongkun Park, Harvard University
Cambridge, Massachusetts
www.people.fas.harvard.edu/~hpark/

Daniel Ralph, Cornell University
Ithaca, New York
www.lassp.cornell.edu/lassp_data/ralph.html

Lars Samuelson, Lund University
Lund, Sweden
www.ftf.lth.se/FTF/Person/SamuelsonL/Default.html

Peidong Yang, University of California at Berkeley
Berkeley, California
www.cchem.berkeley.edu/~pdygrp/main.html

Molecular Electronics

James Heath, University of California at Los Angeles
Los Angeles, California
www.chem.ucla.edu/dept/Faculty/heath/

David Janes, Purdue University
West Lafayette, Indiana
dynamo.ecn.purdue.edu/~janes/

Mark Ratner, Northwestern University
Evanston, Illinois
www.chem.northwestern.edu/faculty/professor?professor_id=910

Mark Reed, Yale
New Haven, Connecticut
www.eng.yale.edu/reedlab/

Jorge Seminario
University of South Carolina
www.cosm.sc.edu/~jorgemgr

James Tour, Rice University
Houston, Texas
www.jmtour.com

R. Stanley Williams, Hewlett-Packard Laboratories
Palo Alto, California
http://www.hpl.hp.com/research/qsr/people/Stan_Williams

Nano and Molecular Mechanics

Takuzo Aida, University of Tokyo
Tokyo, Japan
macro.chem.t.u-tokyo.ac.jp/Aida.html

Fred Brouwer, University of Amsterdam
Amsterdam, the Netherlands
www.chem.uva.nl

Michael Roukes, California Institute of Technology
Pasadena, California
www.cmp.caltech.edu/~roukes/roukes.html

Alex Zettl, University of California at Berkeley
Berkeley, California
www.physics.berkeley.edu/research/zettl/welcome.html

Nanotubes could be used for simple electronic applications like sensors within five years, and for more complicated electronics in five to ten years.

Biomolecular Mechanics

Carlo Montemagno, UCLA
Los Angeles, California
www.cnsi.ucla.edu/faculty/montemagno_c.html

Nadrian Seeman, New York University
New York, New York
seemanlab4.chem.nyu.edu/homepage.html

Viola Vogel
University of Washington
www.nano.washington.edu/

Bernard Yurke, Lucent Technologies' Bell Laboratories
Murray Hill, New Jersey
www.bell-labs.com/org/physicalsciences/profiles/yurke.html

Nanowire electronics

Researchers are also working to find uses for nanowires, which, like nanotubes, can be exceedingly small, assembled chemically, and have the potential to be grown in place and en mass. Researchers have made field effect transistors and light-emitting diodes from semiconductor nanowires.

Researchers are also beginning to integrate arrays of nanowires and larger microelectronic circuits. The key to connecting the minuscule to the merely microscopic is finding ways of accessing specific nanowire junctions using a relatively small number of larger wires. Research teams at Harvard University and at Hewlett-Packard Laboratories have accomplished this by means of addressing techniques that chemically modify selected nanowire junctions and randomly assign unique identification numbers to each nanowire, respectively. (See "Chemicals map nanowire arrays," page 21 and "HP maps molecular memory," page 25.)

Several research teams have developed techniques for making segmented nanowires that are as small as five nanometers in diameter and made from different materials, paving the way for making diodes and transistors on single nanowires. (See "Tiny Wires Turn Chips Inside Out", page 24.)

Harvard researchers have devised a layering technique and used it to make a nanowire transistor 50 nanometers in diameter, which is several times smaller than those used in today's computer chips. The combination of layering and segmenting allows researchers to control nanowire composition along the length and width of the wire. (See "Coax Goes Nano", page 22.)

Nanowires are usually grown from semiconductors like silicon, silicon germanium, gallium arsenide, gallium phosphide, indium arsenide, and indium phosphide. The properties of these semiconductors are well known from their use in traditional electronics. Nanowires can also be made from metal and polymers.

Researchers from the University of Tokyo have devised a way to make titanium nanowires using an intentionally flawed sapphire. The method promises to make nanowires in bulk, and the sapphire-nanowire combination has the potential to be a ready-made electrical network. (See "Crystal Cracks Nurture Nanowires", page 29.)

Researchers from the University of Pennsylvania have found a way to make blocks of trillions of insulated nanowires that measure 10 nanometers in diameter by chemically combining conductive molecules with branched polymers to form a thin plastic film. (See "Chemists Brew Tiny Wires", page 29.)

Nanowire electronics could be used as sensors within two years and for more complicated electronics in five to ten years.

Nano light emitters

Researchers are also working to make minuscule light-emitting devices, including nanotube and nanowire transistors and diodes. Such devices are useful for telecommunications. Light also has the potential to be used for communications among chip components.

Tiny light-emitting diodes could also be developed into single-photon sources, which are a key component of quantum cryptography schemes. Quantum cryptography has the potential to provide perfect security. (See TRN's Making the Future report titled Quantum Cryptography: Potentially Perfect Security.)

IBM Research scientists have found a way to make nanotubes emit 1.5 micron light, which is an infrared wavelength widely used in telecommunications. (See "Nanotube Shines Telecom Light ", page 14.)

A group of researchers from Switzerland have modified a method used to make lasers from semiconductor chip material in order to form a light-emitting diode that measures 600 nanometers across and emits light at the 1.3 micron range commonly used in long-distance telecommunications.

And Harvard researchers have shown that it's possible to make light-emitting diodes by crossing two types of nanowires. The researchers' prototypes emit red and infrared light in the 700- to 900-nanometer range. The method can potentially produce diodes that emit the entire range of visible light. (See "Crossed Nano Wires Make Lilliputian LEDs", page 27.)

It may be a decade before nanotube light-emitters become practical, but nanowire light-emitting diodes could find practical application in two to five years.

Molecular electronics

Many research efforts are aimed at using nature's ready-made parts — usually in the form of simple molecules — to construct electronic devices. The challenges include finding durable molecules and coming up with ways to connect individual or small numbers of molecules to electrodes.

Researchers at the University of California at Riverside and North Carolina State University have synthesized a ring-shaped molecule that stores electrical charge. The presence and absence of charge can represent the 1s and 0s of computer information. The molecule can survive the high temperatures involved in chipmaking processes and can withstand being switched trillions of times. (See "Hardy molecule makes memory," page 32.)

Researchers from Osaka Kyoiku University have found a way to store information in a single molecule. The molecular memory is potentially compatible with existing electronics, works at room temperature, and has the potential to use very little power. (See "Molecular Memory Is Electric", page 32.)

Hewlett-Packard Laboratories researchers have developed a scheme for making simple molecular toggles that are comparable to ordinary light switches. Switches are a key component of electronics, which use on and off signals to represent the 1s and 0s of computer information. (See "Molecule Toggle Makes Nano Logic", page 33.)

Researchers from Cornell and Harvard have found ways to coax individual molecules to act as transistors, which allow more or less electrical current through depending on the strength of the surrounding electrical field. The molecular transistors are as short as 1 nanometer. (See "Mixes Make Tiniest Transistors", page 34.)

Practical molecular electronics applications are 10 to 20 years away.

The stuff of life

Among the most intriguing possibilities for mass production of nanoscale electronics are biological molecules, especially DNA, because billions of years of evolution have honed their self-assembly capabilities. DNA molecules can be coaxed to interconnect into many shapes and patterns. The challenge is finding ways to improve their otherwise weak electronic properties.

Researchers typically approach the problem by causing DNA to self-assemble into a template that can be coated with another material, or by combining DNA with nano materials like carbon nanotubes or metal atoms before causing DNA to self-assemble into a nanostructure.

Researchers from the Technion-Israel Institute of Technology have devised a DNA template self-assembly process that makes transistors in a test tube from a mix of DNA, carbon nanotubes, silver, gold and four types of protein molecules. (See "DNA Assembles Nanotube Transistor", page 12.)

Duke University researchers have demonstrated a way to coax DNA to form nine-strand tiles that then self-assemble into waffled ribbons. The researchers made a protein detector and a template for precisely-formed silver nanowires from the tiles. (See "DNA Forms Nano Waffles", page 28.)

Tokyo University researchers have coaxed modified DNA molecules to form stacks of single metal ions. (See "Artificial DNA Stacks Metal Atoms", page 33.)

Practical applications of DNA-based electronics are five to ten years away.

Mechanics

Molecules and nanotubes can also be used to construct two types of minuscule mechanics: arrays of nanoscale mechanical components for larger devices and stand-alone nanoscale devices.

An array of thousands of nanoscale cantilevers, for example, could enable chemical and biological sensors capable of detecting a wide range of substances.

Stand-alone nanomachines are a much longer-range prospect. Possibilities include combining nanoelectronics and nanomechanics to make nanoscale factory robots for making structures and materials that require more complicated fabrication processes than natural self-assembly forces alone can provide.

Researchers are working with four basic components to produce nanomechanical devices:

- Carbon nanotubes
- Molecules

- Light-driven molecules
- Biological molecules

Nanotube mechanics

In addition to desirable electrical properties, nanotubes have almost fantastic mechanical properties. They are stronger than steel by weight but also very flexible and resilient. Because they are so small, the interactions of nanotubes with each other and other objects in their environment are dominated by atomic forces, in particular the Van der Waals force. The upshot is that individual nanotubes experience little friction. (See How It Works, page 2.)

There are two basic types of nanotubes: singlewall and multiwall. A singlewall nanotube is a simple tube. A multiwall nanotube is a group of nested nanotubes. Researchers have also figured out how to grow nanotube-like structures that are pointed and that are shaped like curved horns.

Researchers have found uses for nanotubes in many types of mechanical devices:

- Springs, which can store and release energy
- Oscillators, which vibrate many times per second and act as precision timers and sensors
- Bearings, which facilitate movable parts in devices like motors

Researchers from the University of California at Berkeley and Lawrence Berkeley National Laboratory have demonstrated a nanoelectromechanical rotor that uses a multi-walled carbon nanotube as its axis. By controlling electrical current through nearby electrodes, the researchers were able to control the orientation and rate of spin of a 300-nanometer gold plate fixed to a 40-nanometer-diameter nanotube. The device could eventually be used for optical switching, pumping and flow detection in microfluidics and as a transmitter.

Researchers from the University of North Carolina at Chapel Hill have positioned tiny paddles on top of the nanotube as handles, then twisted the nanotube like a toy airplane propeller to make it act like a tiny spring. (See “Twisted Nanotubes Have Spring”, page 37.)

Researchers from the University of California at Riverside and Tsinghua University in China have calculated that a multiwall nanotube can act as an extremely sensitive oscillator that could vibrate more than a billion times a second. (See “Nudged Nested Nanotubes May Oscillate”, page 37.)

And researchers from the University of California at Berkeley have shown that is possible to use multiwall nanotubes as bearings. Key to the method was figuring out a way to electrically peel away the ends of the nanotube to expose the concentric tubes. (See “Nanotubes Make Microscopic Bearings”, page 38.)

Carbon nanotube-based nanomechanical devices could be used practically in about five years.

Molecular mechanics

Many molecules readily change shape, and researchers have found ways to control the changes to, for example, make a molecule rapidly switch back and forth — movement that can be harnessed to do mechanical work. The keys to carrying this out are finding ways to power the process and control the results.

Researchers have used molecules to make a variety of nanomechanical devices:

- Rotors
- Propellers
- Ratchets
- Motors

A researcher from the Max Planck Institute in Germany has devised a scheme to use the electromagnetic interactions between charged particles to drive a molecular ratchet mechanism. (See “Natural Force Drives Molecular Ratchet”, page 39.)

Researchers from the University of Leipzig in Germany have proposed a way to mechanically control liquid crystal molecules, despite their slippery nature. (See “Linked Liquid Crystals Move Matter”, page 40.)

Several research efforts are devoted to making molecular motors that could power nanoscale devices and act as electromechanical switches for devices like computer memory.

University of Tokyo researchers have constructed a rotary motor from a pair of ring-shaped molecules and a single metal ion that acts as a bearing. The rate of rotation depends on the number of electrons in the rings. Multiple motors can be combined into columns.

Simple mechanical devices made from molecules could become practical within two years. More complicated structures are a decade or more away.

Light-driven molecular mechanics

One way to power nanomechanical devices is to use the energy of photons.

Over the years, researchers have made polymer materials that expand and contract in response to specific wavelengths of light. In May 2002, researchers at Ludwig-Maximilians University and the Max Planck Institute for Biochemistry in Germany synthesized a single polymer molecule that can be expanded and contracted optically. The molecule could eventually be used as a valve, pump or motor in nanoscale devices.

Researchers from the University of Washington have built a transport system that consists of a nanoscale motor that powers microscopic shuttles around microtubule tracks. The shuttles and tracks are made from kinesin and microtubules, which are proteins that form structural and communications networks in living cells. An ultraviolet light beam acts to free the molecular fuel needed to power the motor. (See “Molecular Shuttle Gains Light Throttle “, page 42.)

Tel Aviv University researchers have built a tiny transport system powered by a spring-like photosensitive molecule over a surface that contains depressions. (See “The Little Light-Sensitive Molecule That Could “, page 45.)

An international research group has devised a way to power a molecular piston using light to create a negative charge at one end of the molecule. This forces a bead-like portion of the molecule to slide from one end to the other. (See “Light Powers Molecular Piston “, page 43.)

And an accidental discovery at the Kyushu University in Japan may lead to a type of actuator that could power nanoscale devices. The researchers found that ultraviolet light forces a certain type of crystal to rearrange its chemical bonds, shrinking the material. (See “Crystal Changes Shape in Ultraviolet Light”, page 44.)

Practical mechanical applications for molecular devices are about five years away.

Relative Scale

An electron is 100 billion times smaller than a hydrogen atom.

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.

Biomolecular mechanics

Three and a half billion years of evolution has produced many molecules useful to life. Most of these molecules are much more complicated than those currently used in prototype molecular devices.

Researchers are tapping biological molecules to make molecular machines. The key player is DNA, which contains the code or blueprints needed to produce all of life’s proteins; DNA molecules can be constructed in the lab in an even larger variety.

Researchers are also tapping proteins, which are made up of one or more long chains of carbon, hydrogen, oxygen, nitrogen and sometimes sulfur atoms, and coil or fold into a huge variety of three-dimensional shapes useful for living processes.

Key to DNA’s usefulness is that it self-replicates in order to propagate living organisms. Its ability to replicate and its ability to manipulate other molecules makes it especially important in the drive to make molecular-scale machines.

At least three separate research teams have recently constructed motors using DNA and RNA. The more advanced versions run continuously. The motors exert between 15 and 60 trillionths of a Newton of force. (See “DNA Motor Keeps Cranking”, page 46; “RNA Forms Nanomotor”, page 47.) One Newton accelerates a one kilogram mass at a rate of one meter per second per second.

Cornell researchers have connected a tiny metal propeller to a biomolecular motor from a bacterium. The device exerts about 120 trillionths of a Newton of force. (See “Biomotor Powers Propeller”, page 49.)

Other researchers are tapping proteins. In addition to the light-driven motor, University of Washington researchers are using kinesin and microtubules to record the nooks and crannies of objects otherwise too small to image. (See “Cell Parts Paint Pictures”, page 47.) Microtubules, at 24 nanometers thick, are about 3,000 times narrower than a human hair.

Biomolecular mechanical devices could find practical use in five to ten years.

Combined forces

Nanotechnology is a buzzword that implies an entirely new branch of science. In reality, the term is a catchall for the work of many disciplines that have extended to the nanoscale.

Nanotechnologists are chemists, physicists, electrical engineers and mechanical engineers, and the field draws on a wide range of skills and experiences. What the electrical engineer can't etch out of silicon, the chemist might be able to synthesize in a test tube. And what the physicist makes of carbon nanotubes could be the critical component of a microscopic machine built by the mechanical engineer.

As researchers move beyond basic exploration of the nanoscale and attempt to build nanomechanical and nanoelectronic devices, the work is becoming increasingly interdisciplinary. It is not uncommon for projects to combine semiconductor fabrication, carbon nanotube growth and molecular synthesis. Familiar devices formed of known materials can be made smaller, faster and cheaper by harnessing natural forces like molecular self-assembly.

No small matter

Though there are many health, environmental and social issues left to address, there appears to be no fundamental technological barrier to building nanoscale devices. There is, however, at least a decade of hard work ahead before any of the more imaginative applications of nanotechnology come within reach. In the meantime, nanoelectronic and nanomechanical devices are likely to begin transforming the inner workings of everyday machines like computers.

Recent Key Developments

Advances in carbon nanotube electronics:

- A method of integrating carbon nanotube transistors with silicon transistors, (Nanotubes Tied to Silicon Circuit, page 12)
- A carbon nanotube transistor assembled by DNA molecules (DNA Assembles Nanotube Transistor, page 12)
- A model that shows that single strands of DNA can be slid into carbon nanotubes (Study Shows DNA Will Fill Tubes, page 14)
- A nanotube transistor that emits telecommunications-frequency light (Nanotube Shines Telecom Light, page 14)
- A method of making mesh networks of carbon nanotubes that could be used as neural networks (Nanotube Web Could Mimic Brain, page 14)
- A method of making memory chips using carbon nanotubes (Oxygen Makes Nanotube Memory, page 15)
- Self-assembled networks of carbon nanotube ropes, University of California at Los Angeles, Imperial College of Science, Technology & Medicine in England, and California Institute of Technology, January 2002
- A single-electron transistor made from a gold nanoparticle and carbon nanotubes, (Spot of Gold Makes Tiny Transistor, page 16)
- Logic circuits consisting of carbon nanotube transistors, (Tiny Tubes Make Logic Circuits, page 17)
- Transistors made from bent carbon nanotubes, (Nanotube Kinks Control Current, page 18)
- Transistors made from electrically-modified multiwalled carbon nanotubes, (Jolts Yield Nanotube Transistors, page 19)

Advances in nanowire electronics:

- A method of addressing specific transistors in a nanowire memory array, (Chemicals Map Nanowires, page 21)
- An electrically-driven laser made from a single cadmium sulfide nanowire, Harvard University, January 2003
- A nanowire resonant tunneling diode, Lund University in Sweden, December 2002
- A laser formed from a quantum wire, University of Tokyo in Japan and Lucent Technologies' Bell Laboratories, December 2002

- A method of making nanoscale coaxial cable that can also be used to make nanoscale transistors (Coax Goes Nano, page 22)
- A design for nanoscale metal antennas, Princeton University and Purdue University, March 2002
- A method of making nanowire devices from alternating layers of semiconductor materials (Tiny Wires Turn Chips Inside Out, page 24)
- A method of addressing specific junctions in a nanowire memory array, (HP Maps Molecular Memory, page 25)
- A light-emitting diode formed from the intersection of two nanowires (Crossed Nanowires Make Lilliputian LEDs, page 27)

Advances in nanowire fabrication:

- A method of making nanoscale waffled ribbons and sheets out of DNA molecules (DNA forms nano waffles, page 28)
- A method of forming titanium nanowires embedded in sapphire chips (Crystal Cracks Nurture Nanowires, page 29)
- Insulated nanowires consisting of boron nitride nanotubes filled with carbon buckyballs, University of California at Berkeley, April 2003
- Self-assembled nanowires made from a yeast protein and gold nanoparticles, Whitehead Institute for Biomedical Research, March 2003
- A method of forming arrays of polymer nanowires (Chemists Brew Tiny Wires, page 29)
- Nanowires formed from four intertwined strands of guanine, University of Modena in Italy, March 2002
- Sub-nanometer gold nanowires (Atomic Scale Wires Speed Electrons, page 30)
- Three-nanometer gold-palladium nanowires (Tiny Metal Wires Chart Nanoelectronics, page 31)

Advances in molecular electronics:

- A molecular switch that can withstand microchip processing, (Hardy Molecule Makes Memory, page 32)
- A room-temperature electric memory cell made from a single molecule (Molecular Memory Is Electric, page 32)
- A method of stacking metal ions inside artificial DNA (Artificial DNA Stacks Metal Atoms, page 33)
- A design for a molecular toggle switch (Molecule Toggle Makes Nano Logic, page 33)
- A measurement of the electrical conductance of a single hydrogen molecule, Leiden University in the Netherlands, October 2002
- A diode made from a single molecule, University of Chicago, October 2002
- Two types of transistors made from single molecules (Mixes Make Tiniest Transistors, page 34)
- A molecule that bonds to gold at both ends (Molecule Connects Contacts, page 35)
- A single-molecule electrical switch (Switch Narrows Molecular-Macroscopic Gap, page 36)

Advances in nanotube mechanics:

- An electrically-driven nano rotor with a carbon nanotube axle, University of California at Berkeley and Lawrence Berkeley National Laboratory, July 2003
- A spring made from a compressed carbon nanotube (Twisted Nanotubes Have Spring, page 37)
- A model that shows that inner tubes of a multiwall carbon nanotube could slide back and forth continuously (Nudged Nested Nanotubes May Oscillate, page 37)
- A nanoscale bearing made from a multiwall carbon nanotube (Nanotubes Make Microscopic Bearings, page 38)

Advances in molecular mechanics:

- A design for a molecular ratchet using undirected energy, Ibaraki University and University of Tokyo in Japan, April 2003
- A molecular ratchet driven by particle-level electromagnetism (Natural Forces Drives Molecular Ratchet, page 39)
- A nanoscale actuator made by linking liquid crystal and polymer molecules (Linked Liquid Crystals Move Matter, page 40)
- A two-speed molecular rotary motor (Molecular Motor Shifts Speeds, page 41)

Advances in light-driven molecular mechanics:

- A molecule-porous silicon mix with pores that open and close, National Institute of Advanced Industrial Science and Technology in Japan, January 2003
- A single polymer molecule that can be contracted and expanded by different wavelengths of light, Ludwig-Maximillians University in Germany, Max Planck Institute for Biochemistry in Germany and Case Western Reserve University, May 2002
- A molecular shuttle whose fuel is released by ultraviolet light (Molecular Shuttle Gains Light Throttle, page 42)
- A molecular ring-and-rod-shaped piston that is driven by light (Light Powers Molecular Piston, page 43)
- A crystal that expands and contracts under ultraviolet light (Crystal Changes Shape in Ultraviolet Light, page 44)
- A design for a light-driven molecular shuttle (The Little Light-sensitive Molecule That Could, page 45)

Advances in biomolecular mechanics:

- A DNA motor that runs continuously (DNA Motor Keeps Cranking, page 46)
- A DNA axle turned by an RNA motor (RNA Forms Nanomotor, page 47)
- A microscopic-terrain mapping system based on a cell protein and microtubules (Cell Parts Paint Picture, page 47)
- A DNA rotary motor (Morphing DNA Makes Motor, page 48)
- A nanoscale metal propeller turned by a biomolecular chemical motor (Biomotor Powers Propeller, page 49)

Carbon Nanotube Electronics

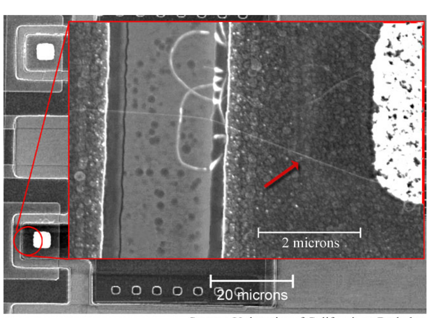
Nanotubes Tied to Silicon Circuit

Technology Research News, January 28/February 4, 2004

Many research teams are working to make electronics that include carbon nanotubes — rolled-up sheets of carbon atoms that have useful electrical properties and that can be as narrow as the span of four hydrogen atoms.

Researchers from the University of California at Berkeley and Stanford University have fabricated a circuit that combines carbon nanotube transistors and traditional silicon transistors on one computer chip. Connecting minuscule nanotube transistors to traditional silicon transistors enables the atomic-scale electronics to communicate with existing electronic equipment.

Such integrated nanotube-silicon circuits could enable super-sensitive sensors that distinguish among thousands of chemical or biological agents and ultra-high-density memory chips that store 100 times the information of today's state-of-the-art memory chips, according to the researchers.



Source: University of California at Berkeley

The close-up (inset) of this silicon chip shows an integrated carbon nanotube.

The researchers grew carbon nanotubes on portions of a silicon chip that contained connections made from molybdenum, a metal able to withstand the high temperatures needed to grow the nanotubes. The prototype chip contains thousands of silicon transistors and hundreds of nanotube transistors.

The silicon transistors were configured in an 11-level binary tree that allowed for individual access to all the nanotube transistors using only 22 input signals.

The researchers' chip is designed to rapidly evaluate the electrical properties of large numbers of nanotubes, which will help researchers optimize nanotube growth processes. It can be used for that purpose now. More broadly practical carbon nanotube-silicon transistor chips could be built in five to ten years, according to the researchers.

The work appeared in the January, 2004 issue of *Nano Letters*.

TRN

DNA Assembles Nanotube Transistor

By Kimberly Patch, Technology Research News
November 20, 2003

Nanotechnology is all about making machines and materials molecule-by-molecule. Such precision promises to enable microscopic machines, faster electronics, and materials that harbor new properties.

Because it is difficult and tedious to manually put atoms and molecules in place, researchers are looking for ways to cause materials to self-assemble. Self-assembly is an especially attractive concept because it has the potential to be quick, relatively easy, and very inexpensive.

One way to make things assemble automatically is to coax nature's self-assembly molecule — DNA — to assemble into templates that can in turn cause other molecules to line up in all the right places.

Researchers from the Technion-Israel Institute of Technology have brought the idea a large step forward by demonstrating a DNA-template self-assembly process that makes transistors in a test tube using an assortment of raw ingredients: carbon nanotubes, silver, gold, and four types of protein molecules.

The process could eventually be used to make many types of materials, molecular machines and electronics, and even entire computers.

DNA is made up of four bases — adenine, cytosine, guanine and thymine — attached to a sugar-phosphate backbone. In cells, two strands of DNA zip together into the familiar double helix when their bases line up — adenine connects to thymine and cytosine to guanine — and sequences of bases act as templates to build proteins. Nanotubes are rolled-up sheets of carbon atoms that form naturally in soot and can be smaller than one nanometer in diameter, or 75,000 times narrower than a human hair.

Researchers have been able to make artificial DNA molecules that have tailor-made sequences of bases for some time. The key to using this type of DNA as a template for tiny components and new materials is finding ways to connect nonbiological materials like metal and carbon nanotubes to specific sequences of DNA bases. "Combining DNA, proteins, metal particles and carbon nanotubes and a test tube is not easy since these materials are alien to each other," said Erez Braun, a professor of physics at the Technicon-Israel Institute of Technology.

The researchers accomplished this by co-opting the natural antibody process. Antibodies connect to specific proteins that make up the outside cell walls of pathogens like bacteria in order to capture and dispose of the bacteria.

The researchers' process self-assembles a transistor in several steps. First, the researchers coax a long double strand of DNA and a short single strand to position the nanotube.

The short single strand is coated with a protein from an E. coli bacteria that connects to a target span of 500 bases on the double strand. The span measures about 250 nanometers, or 250 millionths of a millimeter. An antibody to the bacteria protein then binds to the protein, followed by a second antibody that binds to the first one. Finally, a carbon nanotube that has been coated with a second type of protein binds to the second antibody, connecting the nanotube along the target sequence of the double strand of DNA.

The DNA-nanotube assembly is then stretched out on a silicon wafer, where the E. coli protein carries out a second job as a resist, or shield.

When a solution of silver is mixed with the DNA, silver molecules attach only to those segments of DNA that are unprotected by the protein. This sets up the second step of the wire-building process. When the researchers add suspended gold particles and electrify the solution, gold deposits around the silver clusters to form gold wires on both sides of the nanotube.

These gold wires are the source and drain electrodes of a transistor. The nanotube forms the transistor's semiconducting channel, and the silicon surface acts as a gate electrode, which controls the flow of current running through the device to turn it on or off.

"We harnessed a basic biological process... responsible for mixing genes in cells... to create sequence-specific DNA junctions and networks, to coat DNA with metal in a sequence-specific manner and to [position] molecular objects on [a specific] address in a DNA molecule," said Braun.

The demonstration "is a very significant [advance] in developing the technology for assembling carbon nanotube-based devices," said Deepak Srivastava, a senior scientist and technical lead in computational nanotechnology at the NASA Ames Research Center. "People have always talked about using wet chemistry for assembling molecular electronic components into precise locations," he said. "This is a first proof of the principal."

The research is novel because it uses biological molecular recognition techniques to assemble synthetic building blocks, said Srivastava. The technique could eventually be used in a next generation of electronics and in other applications that require nanoscale molecular components to assemble into complex system-level architectures — like embedded sensors, molecular machines and nano-manufacturing applications, he said.

The researchers' next step is to construct a device on a DNA junction, said Braun. This would involve getting rid of the silicon substrate that acts as a gate for the current prototype transistor. Once this is possible, "the road is open for self-assembling more complex logic circuits," he said.

Today's computer chips are largely made up of transistors arranged into circuits that carry out the basic logic of computing. Researchers are working to make transistors smaller in order to speed computing; smaller components are faster because electrical signals have less distance to travel. Self-assembly processes could eventually prove less expensive than today's silicon manufacturing techniques.

It is not clear how long it will take before the self-assembly process can be used to manufacture components, said Braun. "It's hard to predict applications," he said. "A lot needs to be done before it becomes technology, but it's a good step forward since self-assembly of carbon nanotube devices opens many possibilities for electronics and diagnostics."

Braun's research colleagues were Kinneret Keren, Rotem S. Berman, Evgeny Buchstab, and Uri Savon. The work appeared in the November 21, 2003 issue of *Science*. The research was funded by the Israeli Science Foundation, the

Techinion-Israel Institute of Technology, and the Clore Foundation.

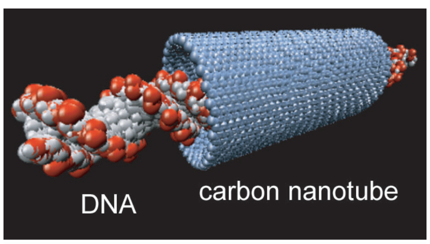
Timeline: Unknown
Funding: Government; Private; University
TRN Categories: Nanotechnology; Integrated Circuits
Story Type: News
Related Elements: Technical paper, "DNA-Templated Carbon Nanotube Field-Effect Transistor," *Science*, November 21, 2003

Study Shows DNA Will Fill Tubes

Technology Research News June 4/11, 2003

Researchers from the Max Planck Institute in Germany have own by computer simulation that it is possible to insert DNA into a carbon nanotube.

Carbon nanotubes are rolled-up sheets of carbon atoms; they have useful electronic properties and can be smaller than one nanometer in diameter, which is the length of a row of 10 hydrogen atoms. Previous research has shown that it is possible to use DNA, the molecule that holds and replicates the code that makes up life's processes, for microelectronics.



Source: Max Planck Institute

This diagram represents a segment of DNA inside a carbon nanotube. Each sphere represents an atom.

Devices based on the DNA-nanotube combination could eventually be used to make electronics, molecular sensors, devices that sequence DNA electronically, and even gene delivery systems, according to the researchers.

The researchers' simulation showed that in a liquid environment, a combination of the van der Waals force and hydrophobic interaction forces would pull a strand of DNA into a nanotube. The van der Waals force is a weak force of attraction between atoms and molecules.

It could be possible to use the method to make DNA-modulated electronics in five to ten years, according to the researchers. The work appeared in the April 9, 2003 issue of *Nano Letters*.

Nanotube Shines Telecom Light

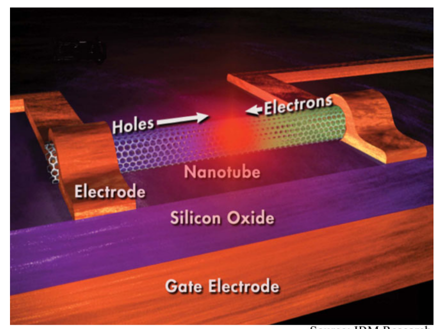
Technology Research News, May 7/14, 2003

Researchers are continually working to expand the usefulness of carbon nanotubes — rolled-up sheets of carbon atoms found naturally in soot.

Scientists from IBM Research have found a way to make the microscopic tubes emit light, and have fashioned a nanotube transistor that emits 1.5-micron infrared light, a wavelength widely used in telecommunications.

Nanotubes can be smaller than one nanometer in diameter, and show promise as building blocks for fantastically small electronics and machines. A nanometer is one millionth of a millimeter, or about the length of a line of 10 hydrogen atoms.

Carbon nanotubes have already been used as wires to carry electricity and transistors to control electric current. Light-emitting nanotubes could be used to form efficient communications devices and, eventually, all-optical computer chips.



Source: IBM Research

This diagram depicts a carbon nanotube transistor that emits infrared light.

The researchers found that if they inject electrons, which carry negative charges, into one end of a nanotube, and holes, or positive charges, into the other end, the two combine to emit light whose wavelength is inversely proportional to the tube's diameter.

It will be about a decade before infrared nanotubes are used in practical devices, according to the researchers. The work is slated to appear in the the May 2, 2003 issue of *Science*.

Nanotube Web Could Mimic Brain

Technology Research News, April 23/30

Researchers from NASA Ames Research Center have found a way to grow minuscule webs of connected carbon nanotubes.

These networks could herald a new type of electronics that have huge numbers of random connections, a setup similar to a brain's synapses. Such networks could also form sensors, parts for conventional electronics, or templates for assembling materials molecule-by-molecule.

Nanotubes, which are rolled-up sheets of carbon atoms that appear naturally in soot, are central to many nanotechnology projects.

To provide a place for nanotubes to grow and connect, the researchers collapsed microscopic spheres of polystyrene suffused with a catalyst. The microspheres were 500 to 2,000 nanometers across and several to several hundred nanometers apart. The researchers burned away the polystyrene, leaving smaller spheres of the catalyst.

The researchers were able to control the number of nanotubes and connections that grew on each sphere by varying the solution mix and microsphere size. Nanotubes can be a small as one nanometer, or the width of 10 hydrogen atoms.

The structures could be used as sensors in two to five years, and in electronics in 10 to 20 years, according to the researchers. The work apeared in the February 3, 2003 issue of *Applied Physics Letters*.

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

Spot of Gold Makes Tiny Transistor

By Chhavi Sachdev, Technology Research News
November 21, 2001

Making faster computers means making smaller circuits in order to shorten the paths electrons follow. The smallest transistor possible would let only one electron pass through at a time, and could lead to computers that are much faster and require much less power than today's models.

Researchers in Sweden and Denmark have found a way to use carbon nanotubes as electronic leads that connect a circuit with a tiny particle of gold to form a single-electron transistor.

The researchers' transistor is a first step towards single-electron devices that would measure a mere 3 or 4 nanometers, or about as wide as 30 to 40 hydrogen atoms end to end. Single-electron transistors have to be this small in order to work at room temperature.

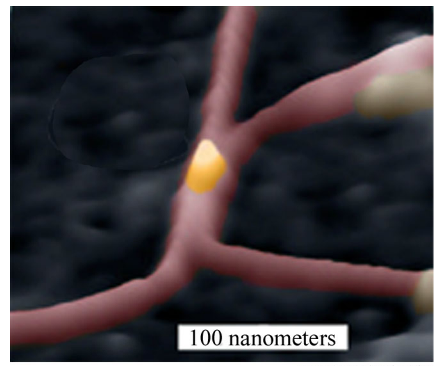
Manipulation of such tiny objects is a delicate process. The researchers managed to position a carbon nanotube between two electrodes using an atomic-force microscope (AFM) tip. Then they used the tip to cut the nanotube — a rolled-up sheet of carbon atoms — into two sections, "each section still in contact with its respective electrode," said Lars Samuelson, a professor of Solid State Physics and Head of the Nanometer Structure Consortium at Lund University. Next, the researchers made the nanotube halves parallel, and deposited a 7-nanometer gold nanoparticle between them.

The researchers then adjusted the temperature. They found that cooling the device below 200 degrees Kelvin, or -73 degrees Celsius, makes it an ideal single-electron transistor, said Samuelson.

The researchers next plan to use smaller nanoparticles to make a device that will operate at room temperature, said Samuelson.

This is good work, said Zhen Yao, an assistant professor of physics at the University of Texas at Austin. "This approach opens up [ways] to systematically study the electronic properties of individual nanoparticles — metallic, semiconducting, magnetic, or superconducting — as a function of their sizes," he said.

This type of systematic study is crucial to testing nanoparticles for various applications but has been lacking mainly because it is difficult to address individual nanoparticles, Yao said. "They are typically 2 to 10 nanometers in diameter, which is beyond the resolution of standard electron-beam lithography" processes used to make experimental computer chips.



Source: Lund University

A tiny speck of gold positioned between two parallel carbon nanotubes forms a transistor that forwards one electron at a time. These single electron transistors could be used to make extremely small, low-power logic circuits.

The method is useful for basic science but probably not for practical applications, said Hongkun Park, an assistant professor of Chemistry at Harvard University. AFM manipulation is not a practical strategy to make commercial devices, because it can only be used to make one device at a time, which is far too slow for manufacturing, he said.

Samuelson's research colleagues were Claes Thelander, Martin H. Magnusson, and Knut Deppert at Lund University in Sweden, and Per Rugaard Poulsen, Jesper Nygard, and Jorn Borggreen at the Niels Bohr Institute at the University of Copenhagen, Denmark. They published the research in the September 24, 2001 issue of the journal *Applied Physics Letters*. The research was funded by the Swedish Foundation for Strategic Research (SFF), The Swedish Research Council for Natural Sciences and for Engineering Sciences, and the European Union (EU).

Timeline: Unknown
Funding: Government
TRN Categories: Nanotechnology; Integrated circuits
Story Type: News
Related Elements: Technical paper, "Gold Nanoparticle Single-Electron Transistor With Carbon Nanotube Leads," *Applied Physics Letters*, September 24, 2001

TRN

Tiny Tubes Make Logic Circuits

By Kimberly Patch, Technology Research News
October 10, 2001

The transistors that make up today's computer chips are fairly simple devices, and they are microscopic, but they are not as small as they could be.

A group of researchers from the Netherlands has demonstrated several types of simple logic circuits using transistors made of single-molecule nanotubes, which are rolled-up sheets of carbon atoms. The nanotube transistors are 1.4 nanometers in diameter, or about 100 times smaller than a standard silicon transistor and nearly 1,000 times thinner than an E. coli bacterium.

A transistor is a switch that either blocks or lets electrical current pass through. Computer chips are made of transistors wired into circuits constructed so that electrical current can flow in different patterns to represent the basic logic operations like "and" and "or" that underpin a computer's calculations.

The chips that power today's personal computers contain millions of transistors; our society is also full of simpler chips that control things like fuel injection in cars and heating systems in houses. Smaller circuits could speed up these chips and would also come in handy in the burgeoning field of nanotechnology, which promises to provide microscopic machines.

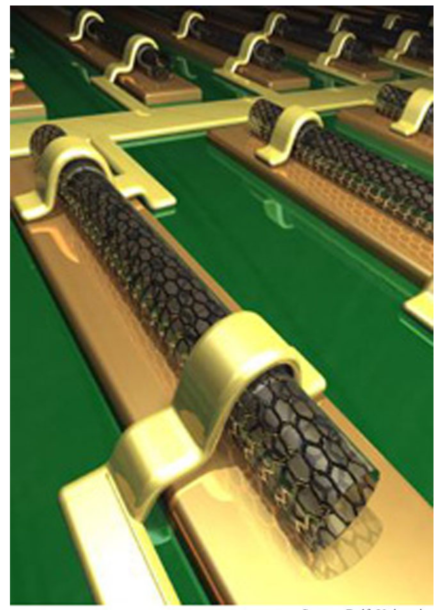
To make a logic circuit from nanotubes, the researchers first had to make more practical nanotube transistors. "We made some improvements like using a thinner gate oxide," said Peter Hadley, a researcher at Delft University. A transistor's gate oxide controls how much current runs through the transistor. The new design showed an increase in transconductance, or the ability to transfer electric charge from one device to another. "When we measured the transistors, we realized that we could use them to make logic circuits. We connected a few transistors together and demonstrated... circuits," he said.

The researchers fashioned several types of logic circuits using one, two or three nanotube transistors. Logic circuits operate between two voltage levels that represent the ones and zeros of digital logic. The researchers made an inverter, or NOT gate, which reverses an input, converting a 1 to a 0, and a NOR gate, which has two inputs and one output, and returns a 1 only if both the inputs are 0. They also made a static random access (SRAM) memory cell, which retains the results of these logical machinations.

In a related development, researchers at IBM recently modified a single nanotube to act as a NOT gate.

To make their circuits, the Delft researchers placed aluminum gates that were one micron wide on a silicon substrate, or base, then poured the solvents containing the much smaller carbon nanotubes over the substrate. "As the solvent dried, the nanotubes were deposited willy-nilly on the substrate," said Hadley. The researchers then looked at the sample with an atomic force microscope, searching for tubes that were lying on the aluminum gates. When they found tubes that were aligned correctly, they deposited gold electrodes on top of them using electron beam lithography, said Hadley. The method uses tightly focused beams of electrons followed by chemical solvents to carve microscopic molds in plastic.

Along the way, the researchers had to solve a couple of technical challenges. "The aluminum gates were originally too rough... we solved the problem by depositing the aluminum at low temperature," said Hadley. The researchers also had to develop the technique that allowed them to deposit gold directly on the tubes, he said.



Source: Delft University

This illustration shows a future logic circuit made from carbon nanotube transistors, aluminum electrodes and gold contacts.

The researchers' results prove that such small-scale circuits can be made, but the tedious technique cannot be used to make them in bulk.

One way around this scalability problem is finding a chemical process that would allow the transistors and their connections to assemble automatically, said Hadley. "As with any molecular components there's the hope that self-assembly could [eventually] be used to fabricate the circuits. A solution containing these molecular transistors would be poured over a circuit and the transistors would stick in the right places because of chemical interaction between the transistor molecules," said Hadley.

A process like this could provide a cheap way to make billions of devices, he said.

There are also size improvements to be made. Although the nanotubes are very small, the gate oxide is about twice as large as those in today's silicon transistors. "We have not tried to to make a particularly small transistor. The important point is that we use a single-molecule as a component of a transistor," said Hadley.

The researchers have made a "major advance" in nanotube logic circuits, said Steven Kornguth, assistant director of the

Institute for Advanced Technology at the University of Texas. Key to the advance is the nanotube transistors better transconductance. “The advance realized is a gain in voltage, or signal output by a factor of 10,” he said.

The Delft and IBM advances show that, in principal, it is possible to make practical logic devices from carbon nanotubes, said Michael Fuhrer, an assistant professor of physics at the University of Maryland.

The Delft improvements to nanotube transconductance were “clever”, Fuhrer said. Although using oxide on aluminum as a way to control electricity in electronic devices is not new, “applying this technique to produce the gate dielectric in nanotube devices is new, and noteworthy,” he said.

More research is needed to further explore the electrical properties of the tiny nanotube transistors, which are substantially different from silicon transistors, Fuhrer said. The single molecule nanotubes transport electrical charge differently, which results in a different distribution of charge inside the transistor, he said. This leads to a fundamental difference: “nanotube transistor properties do not scale with length in the same way that silicon transistor properties do,” he said.

Nanotube circuits could be used in sensing applications within three to five years, while simple circuits that perform calculations will probably take more than five years, said Hadley. “Most of the short-term potential for molecular electronics lies in small circuits such as sensors. Once molecules are incorporated into electrical circuits, the chemical and optical properties of the [molecules] can be utilized in the circuit,” he said.

Using nanotube circuits in place of today’s established silicon to power the much more complicated chips that run computers is much further off, he said. “It will likely take more than 20 years before any technology can displace silicon from its dominant position in computation,” he said.

Hadley’s research colleagues were Adrian Bachtold, T. Nakanishi and Cees Dekker at Delft University in the Netherlands. The research is slated for publication in an upcoming issue of the journal *Science*. The research was funded by the European Community (EC) and by the Dutch foundation for Fundamental Research on Material (FOM).

Timeline: 3-5 years, 20 years
Funding: Government
TRN Categories: Integrated Circuits; Semiconductors; Nanotechnology;
Story Type: News
Related Elements: Technical paper, “Logic Circuits with Carbon Nanotube Transistors,” slated for an upcoming issue of the journal *Science*.

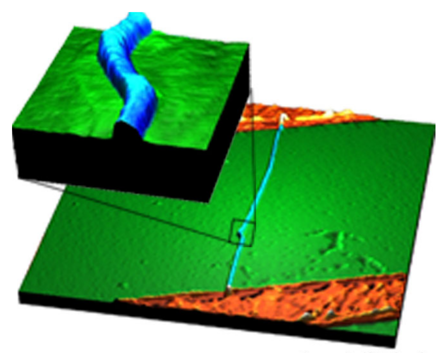
Nanotube Kinks Control Current

By Chhavi Sachdev, Technology Research News
September 12/19, 2001

The steady increases in computer speed we’ve gotten used to over the past four decades are largely due to the shrinking of transistors. Smaller transistors mean shorter paths for electrical current to signal the ones and zeros of digital computing, which in turn speeds the process. Only a dozen years ago, the state-of-the-art 486 sported 1.2 million 1-micron transistors. Today’s Pentium 4 packs 42 million 100-nanometer transistors.

Researchers at Delft University of Technology in the Netherlands are trying to lower the transistor size barrier much further with a single-electron transistor (SET) made of a single-wall carbon nanotube that is 1.5 nanometers wide and about 50 nanometers long. A nanometer is a millionth of a millimeter.

To create the nanotube transistor, the researchers used an atomic force microscope (AFM) to put two kinks in a nanotube. “We have strongly bent, or buckled, a nanotube twice with an atomic force microscope. In this way, we created an ultra-tiny conducting island within the nanotube,” said Cees Dekker, a professor in applied physics at Delft University of Technology in the Netherlands.



Source: Delft University

This image shows a closeup of a nanotube transistor section. The kinks in the nanotube act as electrodes that guide the flow of electrons.

In the nanotube, the area between the kinks is the island, or conducting part, and measures about 25 nanometers in length. Using a single nanotube as a transistor is the ultimate level of miniaturization, according to Dekker.

Today’s current state of transistor miniaturization allows about 750 transistors to fit in 3 square millimeters, which is about the size of the average flea. More than 100,000 of the nanotube transistors could fit in the same area.

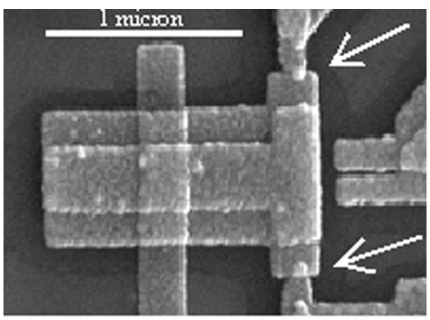
The nanotube transistor, which resembles a slightly mistreated drinking straw, uses a single electron rather than the several million required to turn on a typical computer transistor today. The key to the tiny transistor is its ability to function at room temperature.

Single-electron transistors have historically required severely low temperatures because the energy of warmer molecules drowns out a single electron’s signal. The researchers got around this central problem by reducing the size of the transistor. At the nano scale, heat fluctuations don't matter.

"As a rule of thumb, the smaller the device, the larger the charging energy for a single electron is," said Henk Postma, a graduate student at Delft. "If the charging energy associated with [passing] a single electron is larger than the energy you have available from temperature and bias voltage, the current cannot run and you have a functioning SET," he said. "Our device is so small, that the charging energy is large enough to operate at room temperature."

In a transistor, electrons flow from a source electrode to a drain electrode through the island. At two ends of the island are junctions that connect the island and the electrodes. On either side of the island are gates. When there is no voltage moving through the gates, electrons are blocked from moving through the island. Current flowing through the gates turns the transistor on allowing electical current to flow from the source to the drain.

Electrons flow through the nanotube transistor by tunneling through one by one. When electrons tunnel, they exhibit that peculiar quantum trick of disappearing, then reappearing somewhere else without traversing the space between. As one electron tunnels from the island to the drain electrode, another electron takes its place by tunneling from the source electrode to the island, a process known as coupling.



Source: Pieter Heij, Delft University

This scanning electron microscope(SEM) image shows a single-electron transistor. The middle portion is the conducting island. Arrows at the right of the island point to the source and drain electrodes. A third electrode -- the metal across the island -- regulates electron flow from the source to the drain.

"In conventional SET's, people believe that electrons hop onto the island and off the island in an uncoupled manner…the electron that hops on does not know about the electron that hops off the island. We have shown in our experiment that the electrons in our device only hops on when another electron hops off," said Postma.

This correlated, or coupled tunneling, is like entering a subway station by dropping a coin into a turnstile machine. While the coin is traveling to the belly of the machine, you can't enter the station. When the coin has settled in, the turnstile rotates just once to let a person through.

The research is novel because the whole device is one single molecule and it operates at room temperature, said Jie Han, a research scientist of Nanotechnology at NASA's Ames Research Center. "This may have future applications in nanoelectronics if metallic tubes can be made and buckles can be created in a controlled and large-scale manner," he said.

"[The] work definitely will get attention from the general body of research on SET's [because it is] a molecular solution to SET technology and application. However, it cannot be expected that many researchers will be able to improve or even repeat this work. It is still very difficult to only make metallic tubes and then to buckle them in right positions," Han said.

The researchers are currently working on nanotube logic and the issue of assembling nanoelectronics, Dekker said. The device will not be applied in nanoelectronics for at least a decade, he said.

Dekker and Postma's research colleagues were Tijs Teepan, Zhen Yao, and Milena Grifoni of Delft University. They published the research in the July 6, 2001 issue of the journal *Science*. The research was funded by the Dutch Foundation for Fundamental Research on Matter (FOM) and the European Community's SATURN research network.

Timeline: > 10 years
Funding: Government
TRN Categories: Nanotechnology; Integrated Circuits; Quantum Computing
Story Type:News
Related Elements: Technical paper, "Carbon Nanotube SET at Room Temperature," *Science*, July 6, 2001

TRN

Jolts Yield Nanotube Transistors

By Kimberly Patch, Technology Research News
May 2/9, 2001

Scientists from IBM have moved a significant step closer to realizing the dream of using carbon nanotubes as computer chip transistors with a method that allows them to selectively destroy metal nanotubes while leaving those that are semiconducting intact.

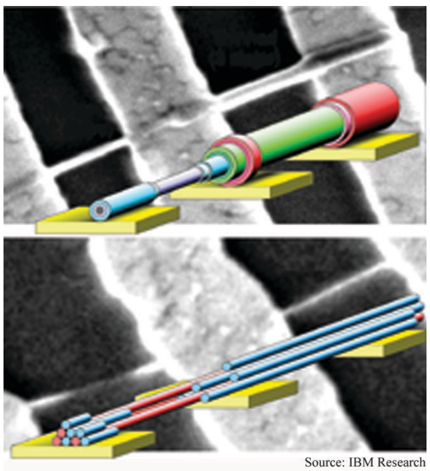
Carbon nanotubes, which form naturally when sheets of graphite roll up under high heat and are a component of soot, can be smaller than one nanometer in diameter.

Whether a nanotube conducts electrons freely like a metal or with some resistance like a semiconductor depends on the combination of the angle of the roll and the diameter of the tube.

Commercially made nanotubes are a mix of the two types of tubes, and separating the microscopic cylinders, which naturally stick together in clumps, is a tedious process. The researchers' method of separation is one step toward making nanotubes viable for mass-produced applications.

While studying how much current they could pass through the nanotubes, the researchers found that nanotubes can handle a billion or more amps per square centimeter, or 1,000 times more than copper or aluminum. When they increased the energy of the electrons to about 5 volts, however, the nanotubes started breaking down. “That work... gave us the idea to utilize this destructive event in a constructive manner to actually get rid of the metallic nanotubes,” said Phaedon Avouris, manager of nanometer-scale science and technology at IBM’s T. J. Watson Research Center.

The researchers have found two distinct uses for metal nanotube destruction. The first is to create an array of semiconducting nanotubes, which has significant implications for eventually using them as transistors on computer chips.



The top image shows a diagram of a multi-wall nanotube with its outer layers selectively broken via joltsof electricity. The bottom image depicts a clump, or rope, of nanotubes stuck together. Researchers can destroy the metallic nanotubes with electricity, leaving a rope containing only semi-conducting nanotubes. The background of each diagram is a microscope image of the actual nanotubes and electrodes.

While metallic nanotubes can be used as wires, semiconducting nanotubes can be used as field effect transistors (FETs), which use an electric field to affect whether the device conducts current or not, effectively turning the flow on and off. An array of nanotubes that includes both types, however, means current will always pass through the metallic nanotubes acting as wires, making the semiconducting nanotubes irrelevant. “The metallic nanotubes cannot be affected by the gate, so they’re always on,” Avouris said.

The researchers made an array of semiconducting nanotubes by depositing rope-like clumps of both metallic and semiconducting nanotubes on a substrate, and covering them with electrodes, which they used to stop any current from running through the semiconducting nanotubes. They then identified the shorts, or places where current was passing through metallic nanotubes, and fixed these shorts by applying current strong enough to destroy them. The resulting array consisted of ropes of semiconducting nanotubes connecting pairs of electrodes.

The method is essentially a new way of fabrication that doesn’t require separation or orientation of the nanotubes, said Avouris. “We just cover them with electrodes and do the final fabrication by current rather than by chemistry or any other technique,” said Avouris.

The researchers have made arrays using several thousand nanotubes and could easily scale that up, said Avouris. “You can make them as big as you want,” he said.

The second application for the researcher’s method of destroying metal nanotubes is to selectively shape individual multiwall nanotubes, which are essentially nested groups of tubes, by destroying individual tube layers from the outside in.

This allows them to choose the exact diameter of a nanotube, which determines its electrical properties. Using the method, the researchers have fabricated nanotube FET’s with bandgaps, or propensity to channel electrons, of their choice. “The bandgap of nanotubes, unlike silicon, is not fixed. It depends on the diameter of the tube. If you start removing [the shells] one by one, the diameter decreases and correspondingly the bandgap increases. So you can stop where you want and you have a transistor with the desired bandgap,” Avouris said.

The researchers have also characterized the electrical properties of these transistors, and according to Avouris they are close to those of p-type silicon transistors. P-type transistors use positive holes to carry current, while n-type transistors use electrons.

The nanotube transistor characteristics include contact resistance, meaning how well the nanotubes connect with the electrodes bringing them current, transconductance, which measures how fast the current changes, and mobility, or the ease with which charge carriers move.

The researcher’s next steps are to make top-gated transistors, which are the type used in computer chips, and to optimize the transistor characteristics.

Making transistors and arrays using semiconducting nanotubes are significant steps toward eventually making circuits from nanotubes, which have the potential to be more than an order of magnitude smaller than the circuits that make up today’s computer chips.

Today’s Pentium IV chips, for example, sport about 42 million transistors with features as narrow as 180 nanometers. Computer chips use transistors to form the circuits that perform basic logic functions, and in order to continue to build faster, more powerful computers, chip manufacturers must cram transistors into a smaller space.

Although the lithography techniques used to make these transistors for the past few decades have improved enough to double the number of transistors on a chip every 18 months or so, they’re expected to run into the laws of physics within the next decade.

Self-assembled carbon nanotubes are a good candidate to eventually provide transistors small enough to go beyond the lithography size limits.

“Experimentalists already know how to make individual nano-transistors using... single semiconducting nanotubes or other molecules,” said Vincent Crespi, assistant professor of physics at Penn State University. The IBM work is “a first step towards practical integration of multiple nano-devices on a single chip. That's why it's important. In the grand scheme of integrated electronics, it's only a baby step, but at least the baby has started to walk," he said.

"It's still unclear exactly which techniques of nanoelectronics will pan out into practical devices, Crespi added. "But this work has a reasonable chance, in 10 years, of being seen as one of the important enabling advances for a new technology."

The IBM researchers are "the first group to show a rational approach to making devices out of nanotubes," said Charles Lieber, a chemistry professor at Harvard University. "It's a really nice advance [but] it's going to be pretty hard to scale up," he said.

IBM's destructive method is "another strategy that may help to achieve that next step," toward working nanoelectronics, said Lieber, adding that self assembled materials are another possibility.

Although the IBM process is a step toward working nanoelectronics, it's a long way between nanotube arrays and nanotube logic circuits that can be used in computer chips. Circuits require both p-type and n-type transistors, and lot of work remains to develop large-scale manufacturing processes, making nanotube computer chips likely a decade away, Avouris said.

There's also the possibility of hybrid technologies the use both silicon and nanotubes, he added. "Both silicon and carbon are in the same column of the periodic table and they have many similar properties, so using, for example, nanotubes as interconnects — metallic wires that connect one device to another — that's also very promising."

At this point all the work geared toward nanotube circuits is, of course, research, Avouris said. "There are a lot of unknowns... I think as we get closer to 2010 and the end of silicon the pressures to have a working successor will intensify," he added.

Avouris' research colleagues were Philip G. Collins and Michael S. Arnold of IBM's T. J. Watson Research Center. They published the research in the April 27, 2001 issue of the journal *Science*. The research was funded by IBM.

Timeline: 10 years
Funding: Corporate
TRN Categories: Nanotechnology; Integrated Circuits
Story Type: News
Related Elements: Technical paper, "Engineering Carbon Nanotubes and Nanotube Circuits Using Electrical Breakdown," *Science*, April 27, 2001

Nanowire Electronics

Chemicals Map Nanowire Arrays

By Eric Smalley, Technology Research News
January 28/February 4, 2004

With today's chipmaking technologies likely to reach physical limits in the next decade or so, researchers have been working on alternative approaches to making smaller computer circuits.

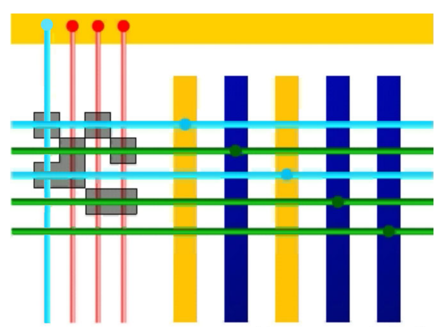
One promising possibility is arrays of nanowires whose junctions form tiny, densely packed transistors.

Transistors are electrical switches that are the building blocks of computer chips. Nanowires measuring a few nanometers in diameter could enable computer chips that pack a trillion transistors per square centimeter, which is several orders of magnitude more than current chipmaking technologies are likely to achieve. A nanometer is one millionth of a millimeter.

The tiny arrays must also connect to the larger circuits of electronic devices like computers. It is a challenge, however, to switch specific transistors on and off within a group of several thousand of the tiny wires using a relatively small number of control wires required to make the connection to larger circuits.

Researchers at Harvard University and the California Institute of Technology have come up with a scheme to chemically modify selected nanowire junctions to make them react differently to electrical current than the junctions around them.

The chemical modification makes cross points more sensitive to switching voltage than unmodified cross points, said Charles Lieber, a professor of chemistry at Harvard. "[It] enables us to introduce a coding scheme within the array so that we can selectively address the output nanowires," he said. This provides a means of bridging the nano and micro worlds, he added.



Source: Lieber Group, Harvard University

This diagram shows a way to chemically connect an array of nanowires to much larger microchip wires.

Transistors have three terminals: source, drain and gate. Current flows from the source to the drain and is controlled by the gate. When a voltage is applied to the gate, its electric field makes the channel between the source and drain more conductive, which allows current to flow. An input signal opens the gate, switching the transistor on to create an output signal.

In a transistor made from crossed nanowires, one nanowire is the channel and the perpendicular nanowire is the gate. In an array of nanowire transistors, each gate, or input, nanowire crosses every channel, or output, nanowire, making every input affect every output.

The researchers showed that chemically modifying a diagonal line of junctions — input one and output one, input two and output two, input three and output three, and input four and output four — in an array of 16 junctions formed from four input wires and four output wires makes those four transistors individually addressable.

Chemically modifying the junctions in more complicated patterns would make it possible to address a set of transistors using a smaller number of input wires, said Lieber. Modifying the right junctions makes it possible to individually control 24 transistors using four input wires, for example. This makes it practical to connect a nanowire array to ordinary-size circuits.

The researchers' scheme is the second major effort aimed at making nanowire arrays addressable. In 2001, Hewlett-Packard Laboratories developed a method of addressing individual junctions in a nanowire array memory device. The HP addressing scheme calls for randomly sprinkling gold nanoparticles on the portions of the nanowires that extend beyond the junctions, then overlaying these portions of the nanowires with larger control wires.

With the right concentration of nanoparticles, half of the junctions between the control wires and nanowires are connected by nanoparticles. A connection represents 1 and no connection represents 0. Mapping the sequence of control wires that a nanowire is connected to yields a unique binary number. Addressing two perpendicular nanowires by their unique binary numbers addresses the junction of the two wires. (See "HP maps molecular memory," TRN July 18, 2001)

The Harvard/Caltech technique has two advantages over the HP approach, according to Lieber. First, each HP device is unique, and its code has to be determined by testing each nanowire, which takes time and resources, he said. Second, the junctions in the HP device are diodes rather than transistors. Transistors provide signal gain, meaning the output voltage is higher than the input voltage. Because electrical signals fade, signal gain is necessary to allow signals to propagate through circuits.

The researchers are working to integrate the address decoder with nanoscale memory arrays, said Lieber. "This is required for realizing a true nano memory chip," he said. It is also a step towards the integrated memory and logic needed to make a functional nanocomputer, he said.

Prototype memory and processors could be built within two to five years, and commercial devices within five to ten years, said Lieber.

Lieber's research colleagues were Zhaohui Zhong, Deli Wang and Yi Cui of Harvard and Marc W. Bockrath of the California Institute of Technology. They published the research in the November 21, 2003 issue of *Science*. The research was funded by the Defense Advanced Research Projects Agency (DARPA).

Timeline: 5-10 years
Funding: Government
TRN Categories: Nanotechnology; Integrated Circuits
Story Type: News
Related Elements: Technical paper, "Nanowire Crossbar Arrays as Address Decoders for Integrated Nanosystems," *Science*, November 21, 2003

TRN

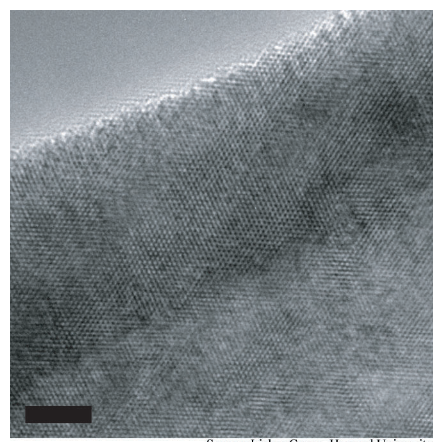
Coax Goes Nano

By Eric Smalley, Technology Research News
November 13/20, 2002

Wires that are structured like television cable but are a thousand times narrower than human hair could form the future of semiconductor technology.

Researchers at Harvard University have made microscopic wires from layers of different materials using the semiconductor manufacturing processes used to construct computer chips.

The layered wires are new building blocks for nanotechnology, according to Charles Lieber, a professor of chemistry at Harvard University. The vanishingly small nanowire components could be used to make faster computer chips, higher-density memory and smaller lasers.



Source: Lieber Group, Harvard University

The bottom, light part of this electron microscope image shows he silicon core of a nanowire and the dark part shows the germanium outer shell. The spheres are individual atoms. The scale bar is 5 nanometers.

To form a 50-nanometer layered wire, the researchers started with a gold droplet a mere 20-nanometers across. A nanometer is one millionth of a millimeter; 20 nanometers is about the size of a line of 200 hydrogen atoms.

The researchers coaxed a semiconductor vapor to condense on one side of the gold droplet and form a nanowire of about the same diameter as the droplet.

They then caused additional layers of material to form around the wire by adjusting the manufacturing conditions, said Lieber. “This is actually quite easy,” he said. “The surface area of the nanowire is much, much larger than that of the [droplet], and [layering] generally just involves... increasing the temperature or concentration” of the vapor.

Different vapors provide different materials. The researchers made several prototype wires, including a 50-nanometer-diameter nanowire made of a 19-nanometer core of pure silicon and a shell of silicon doped, or mixed, with boron. Semiconductors used in electronics are often doped to make them conduct electricity more readily.

The researchers also made several other types of nanowire: a 26-nanometer germanium core with a 15-nanometer doped silicon shell; a 21-nanometer doped silicon core with a 10-nanometer germanium shell; and a 20-nanometer silicon core with a 30-nanometer middle layer of germanium and an a 4-nanometer outer shell of doped silicon.

The researchers demonstrated the usefulness of the layered nanowire technique by using it to make a field-effect transistor. Transistors are the basic building blocks of computers and most other electronic devices.

A transistor consists of a channel that carries current, a source electrode that conducts current into the channel, a drain electrode that carries current away, and a gate electrode that turns on the transistor by increasing the electrical conductivity of the main channel, which allows current to flow through the device.

The researchers’ built a transistor by layering 10 nanometers of germanium over a 10-nanometer doped silicon core, then adding a 4-nanometer layer of the insulator silicon oxide followed by a 5-nanometer outer layer of doped germanium. The researchers attached a gate electrode to the outer germanium layer, and source and drain electrodes to the inner germanium layer.

The researchers’ prototype transistor is several times narrower than those used in today’s computer chips.

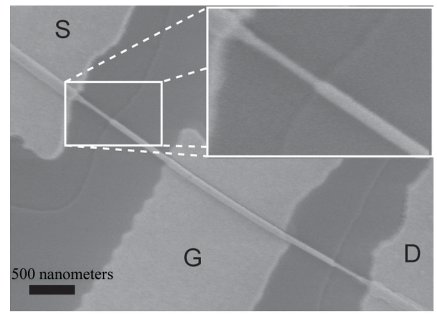
The researchers used a similar technique last February to produce nanowire segments composed of different materials. Together, the segmenting and layering techniques will allow researchers to control nanowire composition along both length and width.

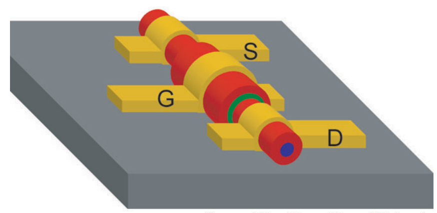
The work is “a major advance,” said Zhong Lin Wang, a professor of materials science and engineering at the Georgia Institute of Technology.

Most nanoscale electronic devices made from carbon nanotubes or nanowires are oriented lengthwise, Wang said. The Harvard work shows for the first time that the different layers that make up field-effect transistors and other devices can be positioned across the width of nanowires, he said. “This research demonstrates the possibility of building much smaller devices based on nanowires,” he said.

The researchers have produced a “very nice piece of work” that clearly demonstrates the versatility and technical potential of heterostructure semiconductor nanowires, said Peidong Yang, an assistant professor of chemistry at the University of California at Berkeley. Yang led a research team that recently developed a similar technique to make ribbon-shaped nanoscale heterostructures, or structures made from two or more semiconductors. “Heterostructures are the common components for many of the electronic and optical devices in our daily lives, such as transistors, light-emitting diodes and laser diodes,” he said.

The Harvard researchers are working on making a high-performance field-effect transistor that could be integrated with conventional electronic circuitry, said Lieber. “We are pushing very hard to make [a] transistor that could find its way into hybrid devices,” he said. “This is something we’re discussing with Intel’s advanced transistor group.”





Source: Lieber Group, Harvard University

This image and the diagram below it show a transistor made from a multilayer nanowire. The core of the nanowire is doped silicon and the first layer is germanium. The second layer (green in the diagram) is the insulator silicon oxide. The outer layer is doped germanium. S is the source electrode, G is the gate electrode, and D is the drain electrode.

The researchers are also using layered nanowires to construct a new type of nonvolatile random access memory, said Lieber. Nonvolatile memory retains data even when the power is turned off.

They are also looking to use the nanowires to make devices that produce light, including single-nanowire lasers, he said.

Before the nanowires can be used in practical applications, the growth process must be controlled more finely to produce more perfect structures, said Lieber.

Prototype nanowire transistors could be built in two to five years, said Lieber. The biggest technological hurdle is integrating these building blocks into useful devices, he said. “This is the same issue facing much of the field.”

Lieber’s research colleagues were Lincoln Lauhon, Mark Gudiksen and Deli Wang. They published the research in the November 7, 2002 issue of the journal *Nature*. The research was funded by the National Science Foundation (NSF), the Office of Naval Research (ONR) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 2-5 years
Funding: Government
TRN Categories: Nanotechnology; Integrated Circuits; Semiconductors; Materials Science and Engineering; Chemistry

Story Type: News
Related Elements: Technical paper, "Epitaxial Core-Shell and Core-Multishell Nanowire Heterostructures," *Nature*, November 7, 2002

Tiny Wires Turn Chips Inside Out

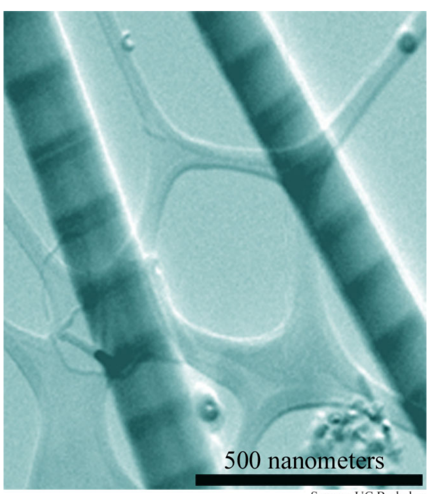
By Eric Smalley, Technology Research News
February 13, 2002

Wires a few hundred atoms thick that look something like a raccoon's striped tail could solve the problem of what to do when today's computer chip technology hits the wall in the next decade or two.

Computer chips, lasers and many other modern electronic devices are made by etching circuits into microscopically thin layers of semiconductor materials using narrow beams of light. Narrower beams make smaller circuits, and smaller circuits make faster devices. There is a limit to how narrowly a light beam can be focused, however.

The electrical properties of the devices, which result from layering different semiconductor materials together, have much smaller size limitations — the layers can be as thin as a few atoms and still conduct electricity.

One hope for getting around the light limit is using nanowires grown by condensing hot vapors of semiconductor atoms. In order to make useful devices from individual nanowires, however, different types of the microscopic wires must be organized and connected.



The lighter bands on these two nanowires are silicon and the darker bands silicon germanium.

A technique for growing semiconductor nanowires from multiple semiconductor materials — developed independently by three different research teams — has turned the problem inside out.

The independent research teams from Harvard University, Lund University in Sweden and the University of California at Berkeley have shown that is possible to make entire devices out of individual nanowires rather than using the wires as building blocks. "Now one can think about creating devices... on single nanowires instead of using crossing nanowires," said Peidong Yang, an assistant professor of chemistry at the University of California at Berkeley.

The researchers made the multiple-semiconductor nanowires by starting to grow nanowires using one semiconductor material, then abruptly switching to another. Alternating between two or more materials produced segmented nanowires that have different electrical and optical properties from those of nanowires made from a single semiconductor material. A specific combination of materials can result in nanowires that turn heat into electricity, for example.

The researchers also showed that the nanowires can be doped, or chemically altered, to make traditional electronic components like transistors and diodes in a single nanowire.

These multiple-semiconductor nanowires have the potential to open up many opportunities in nanotechnology, said Charles Lieber, a professor of chemistry at Harvard University. "New materials enable revolutionary versus evolutionary advances in technology," he said.

The nanowires' shape and small size means they can be used to make much faster versions of conventional computers. There is also the potential for "completely new and different" kinds of electronic devices, like "novel circuit architectures and devices that we have so far only dreamt of," said Lars Samuelson, a professor of physics at Lund University in Sweden.

These could include quantum cryptography devices that emit a single photon at a time, connected quantum dots that trap electrons for quantum computing, or devices that emit light that can be modulated trillions of times per second, making for faster optical communications, he said.

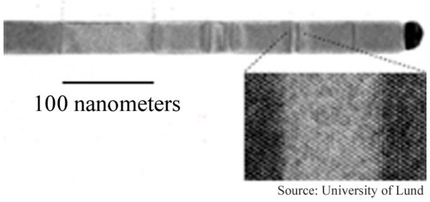
Quantum cryptography holds the promise of perfectly secure communications. Quantum computers, which use atoms to process and store information, are potentially much faster than conventional computers at cracking codes and searching large databases.

As important as the nanowires' properties is how they are made. The multiple-semiconductor nanowires are made millions at a time, making them relatively inexpensive. The size of the nanowire devices can be closely controlled and can be made as small as five nanometers in diameter, which is hundreds of times smaller than a bacterium, and more than a dozen times smaller than today's smallest transistors. A nanometer is a millionth of a millimeter.

All three versions of the technique use a microscopic droplet of liquid gold as the catalyst for growing each nanowire. The semiconductor vapor condenses on one side of the gold droplet and grows into a solid, crystalline wire one atomic layer at a time and with about the same diameter as the gold droplet. By removing the vapor of one semiconductor material and replacing it with the vapor of another, the researchers made single nanowires that contained layers of different materials.

The Harvard researchers made nanowires 20 nanometers in diameter and about 3,000 nanometers long that have segments of gallium arsenide and gallium phosphide. The transition zones between the two semiconductor materials range from 15 to 20 nanometers long. The researchers also used the technique to change the chemical dopant during the growth of a silicon nanowire in order to make a diode.

The Lund University researchers made 40-nanometer wide nanowires that have alternating segments of indium arsenide and indium phosphide. The segments of indium phosphide ranged from 100 nanometers to 1.5 nanometers long depending on the growth rate, and the thinnest indium phosphide segments had atomically perfect boundaries. "The growth rate... in our technique can be kept on the level of one atomic monolayer per second for optimal heterostructure control," said Samuelson.



The darker bands on this nanowire are indium arsenide and the lighter bands indium phosphide. The indium phosphide segments become narrower from left to right. The inset shows the atomically perfect boundaries of an 8-nanometer indium phosphide segment.

The UC Berkeley researchers made 50- to 300-nanometer wide nanowires that have alternating segments of silicon and silicon germanium.

The Harvard nanowire devices could be used for nanoscale bar codes, biological and chemical sensors and polarized LEDs in two years, said Lieber. Using the nanowires for logic circuits, photonic and electronic waveguide and lasers is likely to take at least five years, he said.

The Lund University nanowire devices could be used as scanning probe tips within a few years, said Samuelson. They could be used as single photon sources in five years, he said.

The UC Berkeley nanowire devices could be used as light sources and in thermoelectric applications like keeping electronic devices cool and turning heat into electricity in five to ten years, said Yang.

Lieber's research colleagues were Mark Gudiksen, Lincoln Lauhon, Jianfang Wang and David Smith of Harvard University. They published their results in the February 7, 2002 issue of the journal *Nature*. Their research was funded by the Air Force Office of Scientific Research (AFOSR), the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research (ONR).

Samuelson's research colleagues were Mikael Björk, Jonas Ohlsson, Torsten Sass, Ann Persson, Claes Thelander, Martin Magnusson, Knut Deppert and Reine Wallenberg of Lund University. They published their results in the February issue of the journal *Nano Letters* and the February 11, 2002 issue of the journal *Applied Physics Letters*. Their work was funded by the Swedish Foundation for Strategic Research, the Swedish Research Council, VR and the European Union.

Yang's research colleagues were Yiying Wu and Rong Fan of the University of California at Berkeley. They published their results in the February issue of Nano Letters. Their work was funded by the National Science Foundation (NSF), U.S. Department of Energy (DoE) and the University of California at Berkeley.

Timeline: 2 years; 5 years; 5-10 years
Funding: Government; University
TRN Categories: Materials Science and Engineering; Semiconductors; Nanotechnology; Integrated Circuits
Story Type: News
Related Elements: Technical paper "Growth of nanowire superlattice structures for nanoscale photonics and electronics," *Nature*, February 7, 2002; Technical paper "One-dimensional Steeplechase for Electrons Realized," *Nano Letters*, February, 2002; Technical paper "One-dimensional heterostructures in semiconductor nanowhiskers," *Applied Physics Letters*,February 11, 2002; Technical paper "Block-by-Block Growth of Single-Crystalline Si/SiGe Superlattice Nanowires," *Nano Letters*, February, 2002

TRN

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.

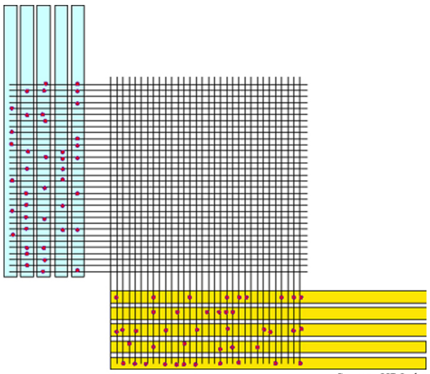
Assuming the devices can be built, another monumental challenge remains: how do you talk to them? The wires in today's semiconductor devices are about 100 times too large to fit molecular devices.

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 represent the ones and zeros of computing. On one side the tiny wires extend past the grid.

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.

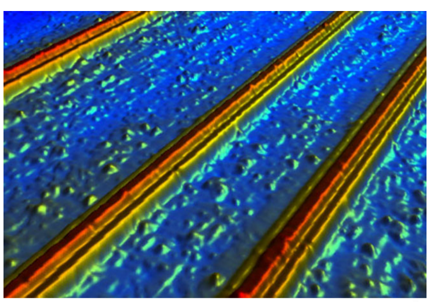


Source: HP Labs

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.

Some of the junctions the larger wires make with a single nanowire will have connections and others won’t. For instance, a nanowire connected randomly to 10 larger wires might have connections 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 and 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.

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.



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.

If it were possible to assign addresses directly to the nanowires, 10 larger wires would be sufficient to name 1,000 nanowires because 210 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

TRN

Crossed Nanowires Make Lilliputian LEDs

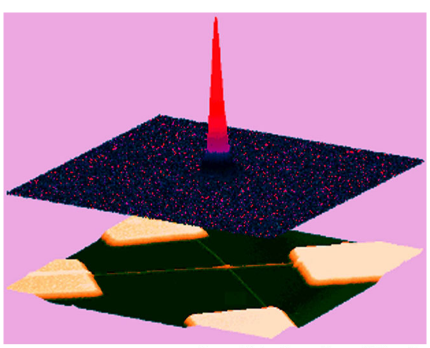
By Kimberly Patch, Technology Research News
January 17, 2001

One of the challenges of making nanoscale components is dealing with the atomic forces that don't generally affect parts at the macro — or even micro — scales. Another challenge is simply assembling the tiny parts.

A group of researchers from Harvard University have made nanoscale light emitting diodes (LEDs) just by crossing two types of nanoscale wires made from indium phosphide.

The group physically crossed the wires using two distinct methods. The first uses electric fields to snap wires into place one by one. A second, more scalable method controls the flow direction of a fluid containing the wires to make multiple connections on multiple wires. "We've made some fairly complex structures and multiple junctions," using the flow method, said Charles Lieber, a chemistry professor at Harvard.

Arrays of LED junctions could eventually be used to image cellular-scale objects, to detect chemicals at that scale, to induce photochemical reactions on a gene chip, or as optical interconnects in an electrical circuit, Lieber said. The idea is to eventually make electronic circuitry from these building blocks, he said. "We'll see how far we can push this in terms of actually making integrated structures."



Source: Lieber Group, Harvard University

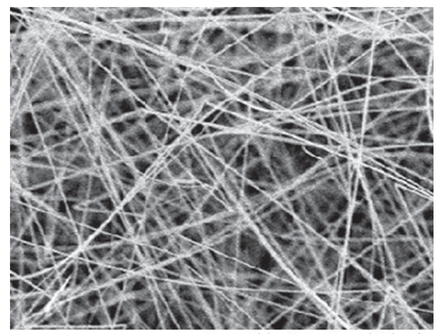
This composite shows a three-dimensional plot of the intensity of light emitted from a nanowire junction superimposed over an atomic force microscope image of the junction.

The wires range from 5 to 20 nanometers in diameter and 10 to several hundred microns long. The two types of wire are doped, or augmented, with different materials to give them different electrical properties. An n-type wire uses negatively charged electrons to carry current. A p-type carries current using a positive charge, or holes. "You can make these basic devices by just simply crossing p- and n-type wires and that makes a p-n junction," Lieber said.

Once the researchers get the wires to touch, they stick together. "It's just the interaction of a van der Waals' type of reaction with the surface," said Lieber. Van der Waal's force is a relatively weak force that comes into play when atoms or molecules are close to each other. It gets stronger as atoms or molecules grow closer, and is enough of an attraction to make nanoscale objects stick together.

The junctions made by crossing these two types of wires emit light. Because the wires are small enough to show quantum effects, the diameter of the wire changes the size of the lightwave, and thus the color of the light. "Different diameters emit different color lights because of the quantum confinement in the wires," said Lieber.

The researchers have shown a color range of about 700 to 900 nanometer wavelengths using the indium phosphide wires. These wavelengths are in the red and infrared range.



Source: Lieber Group, Harvard University

This shows a network of nanowires. When p-type and n-type nanowires cross, they form an electrically useful junction that can emit photons of light.

By pairing the wire size effect with wires made of different materials, nanowire LEDs could span the whole range of the visible spectrum of light, said Lieber. "We could go then from indium phosphide to gallium arsenide to cover the midrange — red and green colors — and then you could use gallium nitride to go into the blue, which is what we're working on now but we don't have any real results yet," he said.

The group is also working on making the LEDs more efficient. The group's LEDs converted only one percent of the electricity flowing through the wires to light, while commercial red LED's, for instance convert around 50 percent. "There's a lot of basic, basic science that has to be done to... improve the efficiency," said Lieber.

The research covers the key elements for building nano circuitry, said Yue Wu, an assistant physics professor at the University of North Carolina. "They have the [nanoscale] building blocks, they show they have junctions, and they show not only the electrical behavior but also the optical property... you get light out of the junction," he said. "These are the crucial elements for making optoelectronic devices based on nanoscale materials."

The field is still young, making it difficult to predict eventual commercial potential, said Wu. For example, the physics of the p-n junction made of crossed wires are slightly different from conventional junctions because the two wires are not fused together. This different type of p-n junction, however provides "a current-to-voltage characteristic that looks exactly the same as what you would expect from a conventional p-n junction," he said.

In the end, "since it's very promising in terms of reproducing all the familiar characteristics that we know from current semiconductor devices, there's bound to be huge potential," said Wu.

The first practical applications for nanowire arrays will likely be sensing and imaging; these types of applications could show up in one or two years, said Lieber.

Lieber's research colleagues were Xiangfeng Duan, Yu Huang, Yi Cui and Jianfang Wang of Harvard. They published the research in the January 4, 2001 issue of *Nature*. The research was funded by the Office of Naval Research and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 1-2 years
Funding: Government
TRN Categories: Semiconductors and Materials; Integrated Circuits; Nanotechnology
Story Type: News
Related Elements: Photo, Technical paper, "Indium Phosphide Nanowires as Building Blocks for Nanoscale Electronic and Optoelectronic Devices," *Nature*, January 4, 2000

TRN

Nanowire Fabrication

DNA Forms Nano Waffles

By Kimberly Patch, Technology Research News
October 22/29, 2003

Researchers are working to control the way DNA strands interact with each other in order to coax the molecules to form tiny structures. Such structures could eventually serve as microscopic machines and as templates capable of causing other materials and devices to automatically assemble molecule-by-molecule.

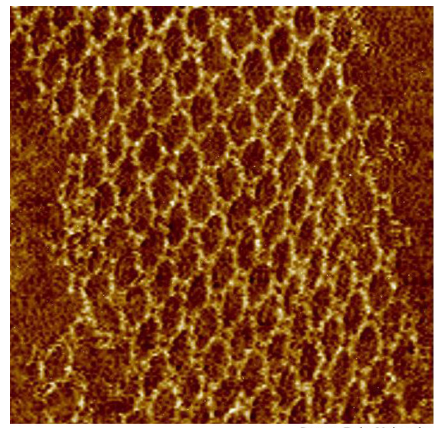
Researchers from Duke University have moved DNA construction methods a step forward by coaxing DNA strands to lock together into tiles made up of nine single strands of DNA that can further self-assemble into lattices. The ribbon- and sheet-shaped lattices can be used as devices or as templates to construct devices from other materials.

The researchers demonstrated one set of tiles that self-assembled into a tiny protein detector, and another set that assembled into ribbons that served as templates for precisely formed silver nanowires.

DNA is made up of four bases — adenine, cytosine, guanine and thymine — attached to a sugar-phosphate backbone. Strands of DNA connect to each other when strings of bases pair up — adenine with thymine, and cytosine with guanine.

The tiles form when single-stranded DNA molecules self-assemble into a branched structure, said Hao Yan, an assistant research professor of computer science at Duke University. "We make the DNA strands arrange themselves into cross-shaped tiles capable of forming molecular bonds on all four ends of the cross arms," said Yan.

The researchers were able to make the tiles connect to each other to form a square, waffle-patterned grid or a waffle-patterned long ribbon by making tiles with different "sticky end" configurations. Sticky ends are portions of DNA strands that remain unconnected when the nine DNA strands connect together to form the tile and can later connect to matching DNA segments. "DNA tiles can carry sticky ends that preferentially match the sticky ends of another particular DNA tile," said Yan.



Source: Duke University

This microscopic, waffled sheet is composed of cross-shaped tiles that in turn are made of DNA strands.

The tiles were originally designed to form perfectly flat lattices, but when the researchers reprogrammed the tiles by changing the sticky ends so that the tile faces would all orient in the same direction up or down, the tiles curved slightly in opposite directions to form a long, narrow ribbon whose surfaces were waffled, said Yan. A second modification that caused each tile face to point in the opposite direction from its neighbor resulted in the wider grid structure.

The method is particularly useful because "we can easily achieve two types of lattice by slightly changing the sticky-ends without changing the tile structure itself," said Yan.

DNA makes a useful template because many other materials can chemically attach to DNA. "Self-assembled DNA arrays provide excellent templates for spatially positioning other molecules with... precision," said Yan.

The researchers formed a device that detects the protein streptavidin by adding the molecule biotin to one of the DNA strands in each grid tile. Streptavidin connects to biotin.

The researchers made precisely-formed silver nanowire using the ribbon structure, said Yan. "We used a two-step chemical procedure to coat silver onto the DNA nanoribbons to produce electricity-conducting nanowires," he said.

Such wire can eventually be used to interconnect nanoscale devices with micron-scale devices, said Yan. Connecting relatively large microscopic objects, like those around the size of a cell, to relatively small ones, like those around the size of a molecule, is a major challenge simply because the size difference is so vast. A red blood cell, for instance, is, at 5 microns across, about 15 times narrower than a human hair, but 50,000 times larger than a hydrogen atom.

The method could eventually be used to construct many types of materials and devices, including electronics, molecule-by-molecule. Such precise control over construction promises to enable materials that have new properties, and electronics that are very efficient.

The researchers are working on designing more complicated DNA nanostructures and working out chemical methods to attach nanoelectronic components like carbon nanotubes to DNA, he said.

The ultimate goal is to use DNA as a scaffold to organize any useful material into nano-size devices, sensors and even factories, said Yan.

The technology could be ready for practical applications within five years, said Yan.

Yan's research colleagues were Sung Ha Park, Gleb Finkelstein, John H. Reif and Thomas H. LaBean. The work appeared in the September 26, 2003 issue of *Science*. The research was funded by the National Science Foundation (NSF) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 5 years
Funding: Government
TRN Categories: Nanotechnology; Biotechnology; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "DNA-Templated Self-Assembly of Protein Arrays and Highly Conductive Nanowires," *Science*, September 26, 2003

TRN

Crystal Cracks Nurture Nanowires

Technology Research News, July 30/August 6, 2003

One key to making nanoscale electronics is finding microscopic materials that are easy to work with. Ready-made components are even better.

Researchers from the University of Tokyo in Japan have devised a way to form titanium nanowires within an intentionally flawed sapphire.

The method can potentially yield large amounts of nanowires, according to the researchers. The nanowires conduct electricity and the sapphire is an insulator, giving the package the potential to be a ready-made electrical network.

To produce the nanowires, the researchers heated the crystal to a high temperature to cause deformations, or lines where the lattice structure of the crystal was dislocated. Then they added a film of titanium to the crystal and heated it again, causing the titanium atoms to migrate to the dislocation lines, creating wires about five nanometers in diameter. A row of 10 hydrogen atoms spans a nanometer.

The technique can be used to create nanowires within many types of crystal, according to the researchers.

The method could be used for practical applications within five years, according to the researchers. The work appeared in the June 15, 2003 issue of *Nature Materials*.

TRN

Chemists Brew Tiny Wires

By Eric Smalley, Technology Research News
October 16/23, 2002

There are two ways to make the smaller circuits and electronic components that promise to underpin tomorrow's technologies: improve today's top-down approach of using tools to manufacture circuits, and develop a bottom-up approach of having the circuits build themselves molecule by molecule.

Though it may never be possible to produce entire computer chips simply by mixing the right chemicals in the right order, the low cost and small sizes made possible by the bottom-up approach could revolutionize electronics. This potential, along with recent advances by chemists and materials engineers who are coaxing useful structures to self-assemble, is fueling the nanotechnology boom.

A major challenge to making self-assembling electronics is that materials that readily form structures tend to be poor electrical conductors. A research team led by a chemist from the University of Pennsylvania has found a way to coax two types of materials — one electrically insulating and the other electrically conducting — to combine into microscopic insulated wires.

The method produces trillions of nanowires at a time, arranged vertically to form a thin polymer, or plastic, film.

The researchers made the wires by attaching electrically-conductive molecules to the bases of branched polymers. Polymers are long, chain-like molecules that can easily be made to change shape.

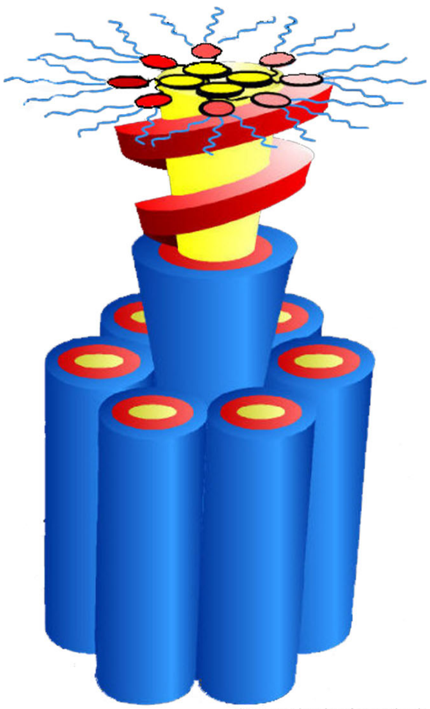
The researchers designed their wedge-shaped branched polymers, or dendrimers, to attract each other, and to connect to form spiral cylinders, said Virgil Percec, a professor of chemistry at the University of Pennsylvania.

When the dendrimers come together, they form cylinders around the conductive molecules attached to the points of the dendrimer wedges. The conductive molecules stack up, forming sets of four, five or seven columns encased within the dendrimer spiral.

The dendrimers electrically insulate and keep moisture away from the electrically-conductive columns. The method could be used with many kinds of conductive materials, said Percec.

"A large variety of electronically active molecules can be incorporated in the center of the cylinders."

The self-assembled electric wires resemble strands of DNA, with the conductive molecules in place of DNA's base pairs, and the dendrimers in place of DNA's sugar-phosphate backbone, said Percec. The wires are about 10 nanometers in diameter, which is about the width of 100 atoms. The wires are as long as the thickness of the plastic film, which ranges up to 1,000 nanometers. A nanometer is one millionth of a millimeter.



Source: University of Pennsylvania

This diagram shows microscopic wires made from electrically-conductive molecules attached to branched polymers that spiral around the cores to form insulating layers. The electrically-conductive cores are yellow and the polymers are red and blue.

The researchers have caused these self-assembling, self-repairing insulated nanowires to form perpendicular to surfaces and between two surfaces such as a pair of electrodes, said Percec.

The nanowires could be used in photovoltaics cells, which turn light into electricity, and to make smaller transistors than are possible with today's chipmaking processes, Percec said.

The researchers' work is "truly remarkable," said Hicham Fenniri, an assistant professor of chemistry at Purdue University. The process introduces a new level of control over the supramolecular organization of optoelectronic materials, he said. "I foresee numerous applications in molecular electronics and photonics."

The research describes a "clever way to hit what may be a sweet spot" between the higher conductivity of organic crystals and easier-to-work-with polymers, said Vincent Crespi, an associate professor of physics at Pennsylvania State University. "The conductivity isn't quite as good as a single-crystal organic material, and the processing isn't quite as easy as [that of] more disordered polymer material, but [the nanowires have] a combination of conductivity and processability that is unmatched by either," he said.

Practical applications for the supramolecular wires will be possible in less than two years, said Percec.

The researchers' next steps are to improve the conductivity of the wires and to use them in technological applications, said Percec. The first practical application may be in photovoltaics, he said.

Percec's and Singer's research colleagues were Martin Glodde, Tushar-Kanti Bera, Yoshiko Miura, Venkatachalapathy Balagurusamy and Paul Heiney of the University of Pennsylvania, Kenneth David Singer and Irina Shiyanovskaya of Case Western Reserve University, Ingo Schnell and Almut Rapp of the Max Planck Institute, and Steven Hudson and H. Duan of the National Institute of Standards and Technology (NIST).

They published the research in the September 26, 2002 issue of the journal *Nature*. The research was funded by the National Science Foundation (NSF), the Air Force Office of Scientific Research (AFOSR), the Army Research Office (ARO), the Office of Naval Research (ONR), the German Federal Ministry of Education and Research (BMBF), and the Humboldt Foundation.

Timeline: < 2 years
Funding: Government; Private
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology; Chemistry
Story Type: News
Related Elements: Technical paper, "Self-organization of Supramolecular Helical Dendrimers Into Complex Electronic Materials," *Nature*, September 26, 2002

TRN

Atomic Scale Wires Speed Electrons

By Ted Smalley Bowen, Technology Research News
December 13, 2000

While metals are well-known conductors, their properties at the atomic scale open the possibility of even faster electronics. Researchers at the Tokyo Institute of Technology have produced gold wire less than four atoms thick in their efforts to chart these properties.

The gold wires, which range from .6 to 1.3 nanometers in diameter and 3 to 15 nanometers in length, transported electrons many times faster than bulkier conduits. A nanometer is one millionth of a millimeter.

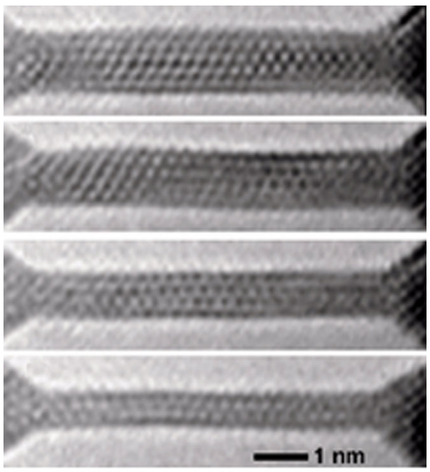
The research could benefit microelectronics, as well as the general understanding of the behavior of very small-scale matter. As researchers continue to shrink electronic circuits, they could eventually become small enough to take advantage of these different properties.

The researchers produced "nanowires through which electrons can [pass] with a very high speed — one-hundredth the speed of light," said Kunio Takayanagi, a physicist at the Tokyo Institute of Technology.

At such small scales, electrons pass through wires without scattering, he said. And because they don't scatter they don't generate heat, he said. Contending with heat is a major issue for computer chip manufacturers.

"With such a nanometer-scale perfect wire, you will have a lot of nice properties," said Hongjie Dai, assistant professor of physical chemistry at Stanford University. "You get ballistic transport, with no scattering, since there are no defects [at the] nanometer scale. Electrons can move freely in there [because] there's no resistance to [them]."

The researchers produced the wires by bombarding thin gold film with an electron beam. The process produced holes in the film, and the material between closely spaced holes constituted gold nanowires. In a cross-section of the thinnest wire, a ring of seven atoms surrounds a single atom. In the strips of gold thinner than 1.5 nanometers, the atoms take on a spiral structure like that of carbon nanotube atoms and similar to the molecular structure of DNA.



Source: Tokyo Institute of Technology

Electron microscope images show gold wires only a handful of atoms thick. The dark dots are individual atoms. The wire in the bottom image is .6 nanometer in diameter.

The same researchers produced thinner pieces of gold two years ago by using the tip of a scanning tunneling microscope to pull single-atom strands from a gold surface. However, the process did not allow them to extend the fragile strands beyond two nanometers, which is too short to be used as conducting wire, according to the researchers.

The laboratory technique for producing the nanowires uses a transmission electron microscope, which means it's likely to remain too expensive for commercial applications.

"It would be nice to have chemical ways to make such wires, so that you could have a lot of them. It would be nice to have a beaker full of such wires," said Dai.

Dai estimates thin wire technology is 5 to 10 years from commercialization.

Takayanagi's colleague was Yukihito Kondo of the Tokyo Institute of Technology. They published their work on creating and characterizing the structure of gold nanowires in the July 28, 2000 *Science*. The research was funded by the Japan Science and Technology Corporation.

Timeline: 5-10 years
Funding: Government
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Synthesis and Characterization of Helical Multi-Shell Gold Nanowires," July 28, 2000, *Science*

TRN

Tiny Metal Wires Chart Nanoelectronics

By Eric Smalley, Technology Research News
November 15, 2000

Metal wires 10 atoms wide are providing clues about what lies ahead as the frontiers of nanotechnology and shrinking computer circuits are pushed further into the realm of quantum physics.

Researchers at Bell Labs have produced wires made of a gold palladium alloy that are only three nanometers, or about 10 atoms, thick. The wires are relatively lengthy at about a micron long.

The wires are not intended for making circuits in devices, but rather for studying how electrons behave in circuits at that scale. The work should help researchers find their way when they begin making electronic devices many times smaller than today's technology.

"If you look at a regular metal [wire], even if it was, say, on the order of a micron wide, you'd have to go to extremely low temperatures in order to see any quantum effects," said Bob Willett, a research physicist at Bell Labs. "We're able to see quantum effects at a hundred Kelvin with wires this small. So the quantum effects become much more pronounced." One hundred degrees Kelvin is -280 degrees Fahrenheit and absolute zero is -460 degrees Fahrenheit.

"These wires are sufficiently small that the electron can defuse across the wire width without changing its wave behavior. It doesn't get scattered," said Willett. "We want to understand the physics of what's happening with the electron propagation and the propagation with relation to the disorder in the materials. And this is a testbed for that."

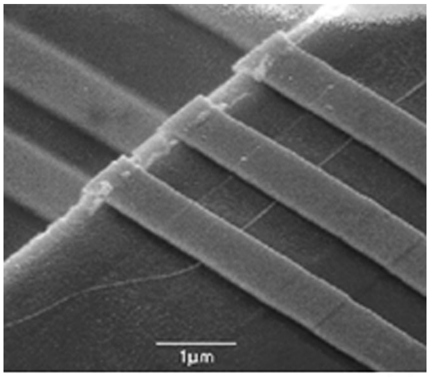
The length of the wire makes it appropriate for studying what could happen in the interconnects between very small components in future electronic devices, he said.

One interesting effect the researchers have found so far is that the wire does not exhibit an odd behavior present in larger wires, Willett said. As the temperature decreases, the length over which an electron maintains its wave-like behavior increases because thermal noise diminishes. However, in larger wires this effect reaches a plateau.

"We found in the smallest wires... the phase coherence length does continue to increase as you drop down in temperature," he said.

Though these observations seem far removed from today's semiconductor factories, the research could help guide the direction of technological development.

"You want to know beforehand what can happen at these small dimensions," said Willett. "You don't want to be surprised by strange effects [after] you've made a huge effort to get down to this very small scale."



Source: Bell Labs

The thread-like structure is a 20- nanometer-thick gold-palladium wire. Bell Labs researchers have produced wires as thin as three nanometers in an effort to study the quantum properties of such small electronic components.

Devices that could make use of the quantum effects the researchers are studying in these tiny wires are probably 15 to 20 years away, he said.

Willett's colleagues were principal investigator Doug Natelson, Ken W. West and Loren N. Pfeiffer. They published their work in the September 25, 2000 issue of the journal *Applied Physics Letters*. Their work was funded by Bell Labs' corporate parent Lucent Technologies, Inc.

Timeline: Now; 15-20 years
Funding: Corporate
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper "Fabrication of extremely narrow metal wires", *Applied Physics Letters*, September 25, 2000

TRN

Molecular Electronics
Hardy Molecule Makes Memory

Technology Research News, January 14/21, 2004

Scientists are continually trying to shrink the space a bit of information takes up in order to fit more bits per square inch in storage media. One idea is to use layers of molecules as bits in hybrid organic/silicon devices. The challenge is finding molecules that can stand up to the harsh conditions needed to manufacture silicon and write and rewrite data.

Researchers from the University of California at Riverside and North Carolina State University have shown that a type of porphyrin molecule holds up under temperatures as high as 400 degrees Celsius and after being written to and read from trillions of times.

The researchers had previously shown that it is possible to use the molecule to store charge. Charged and uncharged molecules can represent the 1s and 0s of computer information. The researchers chemically tethered porphyrin molecules to a silicon platform and used voltage to write charges to and erase charges from the molecules.

The researchers have also shown that it is possible to store two or three bits of information per memory element rather than the usual one. This is significant because it could allow existing 0.13-micron memory chips to store as much as chips made using future 0.09- or 0.07-micron manufacturing processes, according to the researchers. The sizes refer to the smallest elements a chip can contain.

Hybrid semiconductor/organic memory could become practical in two to five years, according to the researchers. The work appeared in the November 27, 2003 issue of *Science*.

TRN

Molecular Memory Is Electric

Technology Research News, November 19/26, 2003

Researchers from Osaka Kyoiku University in Japan have found a way to use a single molecule to store computer information.

Computer memory devices must have at least two states in order to represent the 1s and 0s of binary information, and there must be some way to sense and switch between states in order to read and write information.

The researchers' photochromatic diarylethene molecule contains a ring that switches between an open and a closed shape when voltage causes a negatively charged electron and positively charged hole to combine. A lower voltage does not switch the molecule but can sense the difference in electrical resistance of the two states, and thus read the molecule.

Because the researchers' molecule can be read and written to using electricity, it is potentially compatible with existing electronics. It also works at room temperature and has the potential to draw very little power.

The molecular memory could be used to store very large amounts of information in small areas, and also as inexpensive disposable memory, according to the researchers.

It is theoretically possible to use single electrons to change the molecules' states, meaning memory made from the molecules would consume little power.

Inexpensive disposable memory circuits could become practical into three years. Ultra-high density molecular memory systems could become practical in five to ten years, according to the researchers. The work appeared in the August 4, 2003 issue of *Applied Physics Letters*.

TRN

Artificial DNA Stacks Metal Atoms

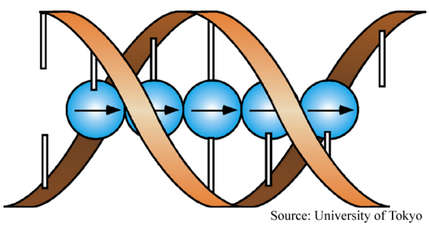
Technology Research News, September 24/October 1, 2003

In recent years, researchers have replaced some of DNA's natural bases with those that attach to metal atoms in order to coax DNA to organize metal ions into tiny structures.

Researchers from the University of Tokyo in Japan have tapped the method to form stacks of single metal ions.

The work shows that DNA can be used to precisely position and control arrays of metal. The relatively simple method is a step toward building and controlling tiny metal devices and nanomachines atom by atom.

DNA forms from four types of bases that pair up along a pair of sugar-phosphate backbones to form the familiar double helix. Previously, the Tokyo researchers had developed an artificial base close to the size and shape of natural DNA bases that attached to a copper ion. Ions are atoms that have more or fewer electrons than normal.



This depicts a DNA double helix with five copper ions stacked inside.

When the researchers mixed DNA containing the artificial bases into a room-temperature solution of copper ions, the new bases bound to the copper; when the DNA curled into a double helix, the copper ions ended up stacked neatly inside. The researchers used the method to make a stack of five ions.

The researchers are working on adding different metals to DNA molecules, and on forming tiny junctions; the ultimate goal is to construct metal molecular devices like wires and magnets, according to the researchers.

The work appeared in the February 21, 2003 issue of *Science*.

TRN

Molecule Toggle Makes Nano Logic

By Eric Smalley, Technology Research News
March 26/April 2, 2003

A popular trend in technology research is copying nature, and another source of inspiration is the world of everyday objects.

Researchers at Hewlett-Packard Laboratories have proposed a series of molecules that work like ordinary light switches.

Toggle switches, which open or close a circuit, "gave me the idea of a molecular-scale... toggle switch," said Pavel Kornilovitch, a theoretical materials scientist at Hewlett-Packard Laboratories.

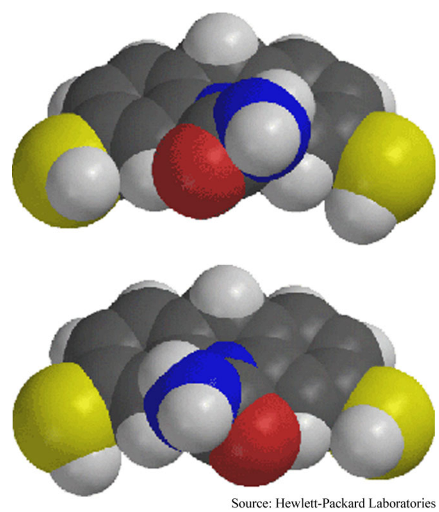
Molecule-size switches have several potential uses, including as memory cells in ultrahigh-capacity computer memory. The 1s and 0s of computing can be represented by the on and off positions of the switch. If each bit of information were represented by just one molecule, molecular memory devices could hold as much as 1½ terabits per square inch, said Kornilovitch.

One and a half terabits is about 185 gigabytes, or 40 times the capacity of a DVD. The microscopically thin layers could also be stacked up to increase this capacity dramatically, said Kornilovitch.

Networks of molecular switches could also be used to make reconfigurable electronic circuits. "Such networks could be used to create adaptive computer logic that would react [to] damage, or artificial brains where reconfiguration would facilitate the process of learning," said Kornilovitch.

The switches could also be used to form logic and memory components in microscopic machines like microbe-size computers or sensors, Kornilovitch said.

The researchers' molecular switch design has two components, a stator and a rotor. The oblong stator is fixed between two electrodes. The knob-like rotor is attached to the side of the stator by a single atom and is free to rotate around this bond. The stator could be as simple as a row of three benzene rings. Benzene is a ring of six carbon atoms. The rotor could be as simple as a hydrogen, carbon and oxygen atom, with the carbon atom attached to the stator.



This diagram depicts a molecular switch. The red sphere represents an oxygen atom and the blue sphere a nitrogen atom. The top molecule is in an on position, representing a 1. The bottom molecule is in the off position, representing a 0.

Key to the design is an electric charge that guides the rotor's position. "The key design feature is a large electric dipole moment of the rotor," said Kornilovitch. "That means that one end of the rotor carries an excess of positive charge and the other end carries an excess of negative charge."

The dipole moment acts like a magnet, forcing the rotor to orient toward one end of the stator or the other. Putting electric current through the stator's electrodes flips the rotor from one orientation to the other, toggling its position between a 1 and a 0.

The position, or state, of the switch can be read by measuring the molecule's conductivity. In one position, the rotor increases the electrical resistance of the stator and in the other position it decreases the resistance.

Applying a sufficient voltage to the molecule flips the rotor to write a bit. Applying a lower voltage measures the molecule's conductivity, which reads the bit.

Other researchers have made molecules that can be flipped between two electronic states, but the HP design is simpler — two electrodes rather than three, said Kornilovitch.

Another molecular switch, demonstrated by University of California at Los Angeles researchers, switches by changing shape. That molecule is a rod surrounded by a ring, and moving the ring from one end of the rod to the other changes the molecule's electrical resistance.

The UCLA ring is relatively heavy, however, which leads to data writing times on the order of milliseconds, said Kornilovitch. "In our design, switching is achieved through direct interaction of the rotor's dipole moment with the external electric field. This is a very fast process, measured in picoseconds," he said. A millisecond is one thousandth of a second, and a picosecond is one trillionth of a second. A picosecond is to a millisecond as a second is to 31.7 years.

There's a lot of work to be done before the HP molecular switch can even be considered for technological applications. "The biggest fundamental challenge is to achieve the right balance between the temperature stability and switchability of the molecule," said Kornilovitch. There is a narrow window between keeping the energy required to flip the switch low enough to work in practical devices but high enough to remain stable at ambient temperatures.

Another major challenge is keeping the connections between nanowire electrodes and the molecules perfectly uniform, said Kornilovitch. "Theoretical modeling predicts that [the] shift of just one wire atom could lead to an order of magnitude change in resistance. [This] means that the arrangement of atoms in the wires has to be controlled with single-atom precision," he said.

Making devices from the switches also presents major challenges, including how to position the trillions of molecules involved, how to direct electrical signals to each molecule, and how to deal with the inevitable defects, said Kornilovitch.

The researchers' next step is to synthesize the molecules and test them experimentally, said Kornilovitch. "We are hoping to have the first molecules within the next six months," he said. "Still, there will be another two years or so until we know whether the very idea works or not."

Practical application of molecular switches will take 15 to 20 years, said Kornilovitch.

Kornilovitch's research colleagues were A. M. Bratkovsky and R. Stanley Williams. The work appeared in the December 15, 2002 issue of *Physical Review B*. The research was funded by Hewlett-Packard and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 15-20 years
Funding: Corporate, Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology; Chemistry
Story Type: News
Related Elements: Technical paper, "Bistable molecular conductors with a field-switchable dipole group," *Physical Review B*, December 15, 2002

TRN

Mixes Make Tiniest Transistors

By Eric Smalley, Technology Research News
June 26/July 3, 2002

Think of chemistry and you usually picture drugs, lastics and household cleaners, not the future of computing. But work is steadily progressing toward a day when it will be possible to whip up a batch of molecular computer circuits.

Two research teams have fashioned individual molecules into transistors, the electrical-switch building blocks of computer circuits. The Cornell and Harvard University teams hooked single molecules to electrodes, ran electricity through the tiny transistors and measured the results.

The electrical properties of individual molecules have been measured before, but the Cornell and Harvard molecules act as transistors, not simply wires; the researchers controlled the amount of electricity the molecules allowed through by changing the strength of a surrounding electrical field.

In both teams' demonstrations, the transistor molecules spanned a gap between a pair of gold electrodes. "[We] synthesized molecules [that] act like a transistor, and then we inserted the molecules individually into a circuit and demonstrated that the transistor worked," said Dan Ralph, an associate professor of physics at Cornell.

One of the gold electrodes is a source electrode, which channels electrons into a transistor, and the other is a drain electrode, which channels electrons out of it. The electric field controls the flow of electrons through the molecule in order to turn the transistor on and off.

Millions of transistors wired together can form computer circuits because the output of one transistor can switch another transistor on. The complicated patterns of transistors switching on and off form the logic of computer processors.

The researchers' molecules are between one and three nanometers long, or about 30 to 100 times shorter than the transistors in today's computer chips.

The Cornell molecule has a single cobalt atom at its center and all of the electrons flow through the atom. "We can regulate electronic flow at the scale of a single atom," said

Ralph. The Harvard molecule consists of a pair of atoms of the metal vanadium.

In a similar experiment last year, researchers at Bell Labs showed a single molecule acting as a transistor in a one-molecule layer containing a mix of insulating and active molecules that was so dilute only a single active molecule was likely to be positioned between a pair of electrodes. Bell Labs is reevaluating these results in the wake of scientific misconduct allegations, however.

The chemical process used to make molecular electronics is easier and potentially cheaper to carry out than today's semiconductor manufacturing process, which uses light and chemicals to etch lines into silicon wafers. The field of molecular electronics is still in its infancy, however, said Hongkun Park, an assistant professor of chemistry at Harvard.

Researchers have to overcome three principal challenges before they can produce practical molecular transistors. The first is achieving gain, which is the ability to put a small signal into a device and have it amplified to get a big signal out, said Ralph. Gain allows electrical signals to pass through many transistors without dying out.

The second challenge is boosting the speed of the devices, he said. "Our molecular transistors are much slower than silicon transistors."

And the third challenge is connecting molecular transistors together into computer circuits. "It will take a lot of imagination to discover ways to reproducibly connect several molecules in the right way to make useful technologies," said Ralph.

Practical applications for molecular electronics are possible in 10 to 20 years, but "that might be too optimistic," said Ralph. Applications are at least five years away, said Park.

Ralph's research colleagues were Jiwoong Park, Abhay Pasupathy, Jonas Goldsmith, Connie Chang, Yuval Yaish, Jason Petta, Marie Rinkoski, James Sethna, Héctor Abruña and Paul McEuen of Cornell University. They published the research in the June 13, 2002 issue of the journal *Nature*. The research was funded by the National Science Foundation (NSF), the Department of Energy, the Department of Education and the Packard Foundation.

Park's research colleagues were Wenjie Liang and Marc Bockrath of Harvard University and Matthew Shores and Jeffrey Long of the University of California at Berkeley. They published the research in the June 13, 2002 issue of the journal *Nature*. The research was funded by the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA) and the Packard Foundation.

Timeline: > 5 years, 10-20 years
Funding: Government, Private
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology
Story Type: News
Related Elements: Technical papers, "Coulomb blockade and the Kondo effect in single-atom transistors," *Nature*, June 13, 2002 and "Kondo resonance in a single-molecular transistor," *Nature*, June 13, 2002

TRN

Molecule Connects Contacts

By Kimberly Patch, Technology Research News
October 24, 2001

One of the challenges of making machines out of small numbers of molecules is figuring out how to connect them individually in order to form electrical circuits.

The trouble is, soldering isn't an option on the molecular scale. Instead, researchers from Arizona State University and Motorola have found a way to chemically bond each end of a molecule to a metal conductor.

They began with a flat gold surface and covered it with a single layer of electrically insulating octanethiol molecules, which are a string of hydrogen and carbon atoms with a sulfur atom on one end. The sulfur bound chemically to the gold surface.

The researchers removed a few of the molecules, leaving gaps, then filled the gaps with related octanedithiol molecules, which have sulfur atoms on both ends. One end of these molecules chemically bonded to the bottom layer of gold. Then the researchers sprinkled gold nanoparticles on the surface, and the opposite ends of the octanedithiol molecules bonded to the nanoparticles.

When the researchers touched a single nanoparticle with the electrified gold tip of an atomic force microscope, it completed a circuit through the molecule to the gold surface. "In essence, we have a single octanedithiol molecule chemically bonded to gold contacts at each end and surrounded by an insulator. This is like a wire soldered into a circuit," said Devens Gust, a professor of chemistry at Arizona State University.

The researchers took 4,000 separate measurements of molecules this way. The connected molecules conducted current more quickly than ordinary molecules, offering four times less resistance, according to Gust.

The length of each molecular wire is a little over one nanometer, which is 1,000 times smaller than the circumference of an E. coli bacterium. A nanometer is one millionth of a millimeter.

There were two main hurdles to connecting single molecules, said Gust.

The first difficulty was designing the chemical layer so that one or only a few molecules were connected to each gold nanoparticle, said Gust. Then they had to figure out how to measure the results, he said. "The second [challenge] was designing and building an atomic force microscope capable of making the... precise current voltage measurements," he said.

The key to attaching a wire to a molecule in a usable way is making a chemical rather than a mechanical bond, said Gust. "We found that when chemical bonds are used at both ends, the conductivity of the molecule increases by a factor of at least 10,000" over methods that mechanically attach a molecule to an electrode, he said. The chemical bond is also not as sensitive to force as a mechanical contact would be, making it a sturdier connection, he said.

Bonds like these can eventually be used to form single-molecule wires, transistors and logic elements that can be incorporated into tiny electronic circuits. It will be at least a few years before even simple circuits that use single molecules become possible, said Gust.

The work is one more step in the progression of molecular-scale electronics, said Vincent Crespi, an associate professor of physics at Pennsylvania State University. The important contribution is the use of bonds to gold on both sides of the molecule, he said.

The work also allows researchers to measure the behavior of single molecules under the influence of electrical current, said Gust. It "shows unambiguously that we are measuring only one molecule, rather than an assembly of some unknown number of molecules."

This is important because one of the puzzles in studying how electricity flows through individual molecules has been untangling the influence of the contact from the influence of the molecule, said Crespi. "In something this small the contact is just as big as a molecule itself, so an understanding of the electron transport depends critically on understanding of the molecule/metal contact," he said.

Gust's research colleagues were Xiaodong Cui, Xristo Zarate, John Tomfohr, Otto Sankey, Ana Moore, Thomas Moore and Stuart Lindsay of Arizona State, and Gari Harris and Alex Primak of Motorola. They published the research in the October 19, 2001 issue of the journal *Science*. The research was funded by the National Science Foundation (NSF).

Timeline: > 3 years
Funding: Government
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper, "Soldering Molecules for Nano-electronics," *Science*, October 19, 2001

TRN

Switch Narrows Molecular-Macroscopic Gap

By Eric Smalley, Technology Research News
November 15, 2000

Chip techniques block power leakage Researchers at the University of Liverpool have harnessed the electrical properties of a molecule to trigger a nanoscale electrical switch.

The development narrows the gap between the bottom-up approach of chemistry and the top-down approach of engineering in the drive to produce ever smaller machines and ever faster computers.

Two potential applications for the switch are chemical sensing and computer memory. Further advances are required, however, before it could be used in any application.

The switch consists of a gold nanoparticle linked by strands of polymethylene to a gold surface. Bipyridinium, which serves as a reduction-oxidation (redox) gate is embedded in the polymethylene connectors. When a molecule is in reduction it attracts electrons and in oxidation it sheds electrons.

A separate electrode adds or removes electrons from the redox gate. In its oxidized state, the bipyridinium blocks the flow of electrons between the surface and the nanoparticle. In its reduced state, electrons flow freely.

"We demonstrated a principle: it is possible to attach metal particles on to self-[assembled] linkers containing redox groups and observe their behavior as... switches," said Richard J. Nichols, a lecturer in the chemistry department at the University of Liverpool.

Self-assembly is a simple, inexpensive chemical process in which a substance is applied to a surface either in solution or a vapor and the substance adheres to the surface in a particular pattern, structure or orientation.

"Special features [of the switch] are the simplicity of the self-assembly procedure and the precision of the control of the [flow electrons] across the device," Nichols said.

The gold nanoparticle is six nanometers in diameter and stands three nanometers above the gold surface. The linking molecules have a footprint of .46 nanometers on the gold surface. A nanometer is one millionth of a millimeter, or about 10 carbon atoms long.

The small scale of the switch means it could make very dense memory. The switch may also prove useful in sensors where monitoring minute quantities of substances is important.

Using the switch in a sensor would require attaching molecules that bind to a particular target substance to the redox gate, said Nichols. "The electronic properties of the redox gate would be made to be sensitive to the binding of the [substance]," he said.

Though the chemical synthesis techniques used to produce the switch have come a long way, nanotechnology engineering will be required to integrate the switches into devices and allow them to communicate to the external world, Nichols said.

"This is a very interesting piece of work and is one of the most plausible that I have seen addressing the fundamental gap between the molecular and macroscopic worlds," said Jonathan W. Steed, a reader in inorganic and supramolecular chemistry at King's College London.

"This switching architecture is assembled on an ordered surface and has input/output functionality," he said. "It has long been established that we can make individual molecular machines but this is one of the few pieces of work to place them within an interrogateable framework. I hope we will see much more of this kind of science."

Nichols' colleagues were David I. Gittins, Donald Bethell and David J. Schiffrin. They published their work in the November 2, 2000 issue of the journal *Nature*. Gittins' participation was funded by the Engineering and Physical Sciences Research Council.

Timeline: Unknown
Funding: Government
TRN Categories: Semiconductors and Materials; Nanotechnology
Story Type: News
Related Elements: Technical paper "A nanometer-scale electronic switch consisting of a metal cluster and redox addressable groups" in the November 2, 2000, *Nature*

Nanotube Mechanics

Twisted Nanotubes Have Spring

Technology Research News, April 9/16, 2003

Researchers from the University of North Carolina at Chapel Hill have found a way to use carbon nanotubes — rolled-up sheets of carbon atoms that form naturally in soot — as tiny springs for microscopic devices.

The researchers combined an atomic force microscope with scanning electron microscopy to position tiny paddles on top of a nanotube. They used the paddles as handles to force the nanotube to twist, which stored energy in the same manner as the twisted rubber band that turns a toy airplane's propeller.

The scanning electron component allowed the researchers to see the paddles as they touched them with the atomic force probe, which is sensitive enough to measure the small forces needed to twist the nanotube.

The process of twisting the tubes stiffened them by as much as 20 times, an effect the researchers are currently working to explain. The tiny springs could be used as chemical sensors and frequency sources for communications or computational electronics.

It will be more than five years before the devices can be used practically, according to the researchers. The work appeared in the November, 2002 issue of the Journal *Vacuum Science and Technology B*.

Nudged Nested Nanotubes May Oscillate

February 6, 2002
By Eric Smalley, Technology Research News

Oscillators are the critical component of many timers and sensors, and, as electronic devices continue to shrink, researchers are looking for ways to make ever smaller oscillators.

Mechanical oscillators that are hundreds of times smaller than the head of a pin and vibrate as fast as several million times a second function as precision timers and sensors in systems ranging from automobiles to satellites. Oscillators are used to trigger automobile airbags by sensing sudden deceleration.

A major goal of nanotechnology is making much smaller oscillators that vibrate billions of times a second and can therefore make more precise instruments.

Researchers from the University of California at Riverside and Tsinghua University in China have proposed a way to do this using multiwalled carbon nanotubes that are thousands of times narrower than a human hair. Multiwalled carbon nanotubes are typically 10 to 50 nanometers in diameter. A nanometer is one millionth of a millimeter.

The atomic forces that hold nested sets of carbon nanotubes together cause inner nanotubes to snap back into place after they are pulled partly out of the outer tubes and released. The researchers calculated that if both ends of a multiwalled nanotube were removed and the inner nanotubes partly pulled out, they should slingshot through to extend partially out the other side, then retract.

The slingshot action should go on for a period of time, allowing the core nanotubes to slide back and forth faster than one billion times per second, said Qing Jiang, a professor of mechanical engineering at the University of California at Riverside.

The oscillator is not a microscopic perpetual motion machine, however. The oscillation produces lateral vibrations in the carbon atoms of both the inner and outer nanotubes, said Jiang's colleague, Quanshui Zheng, a professor of engineering mechanics at Tsinghua University in China. "Such vibration will induce... energy dissipation. Therefore, the oscillating cannot be endless. To maintain a constant oscillation requires energy input," he said.

Imperfections in the nanotubes could interfere with the action of the oscillator, though any effect is probably too small to be detected by even the most sensitive instruments available, said Jiang.

The key to the oscillator is the interplay between the atomic forces that hold the tubes together and the kinetic energy imparted to the inner tubes when they are set in motion. The Van der Waals force is the sum of the attractive and repulsive forces between atoms. It draws atoms together, but only to a point, also keeping them from coming into contact with each other. This makes the sliding action of devices as small as nanotubes friction-free.

According to the researchers' calculations, when the inner nanotubes are fully extended, their kinetic energy is at a minimum and the Van der Waals force is at a maximum, which will cause the inner tubes to slide back inside the outer tubes. When the inner tubes slide back inside, the Van der Waals force is at a minimum and the kinetic energy is at a maximum, causing them to continue through to the other end.

The researchers calculate that a 100-nanometer-long, 4-nanometer-diameter set of inner nanotubes pulled out one quarter of their length should oscillate at about 1.39 gigahertz, or 1,390,000,000 times a second.

The two main challenges to implementing the researchers' proposed oscillator are finding a method to set the nanotubes in motion, and connecting the nanotubes to devices in order to use that motion, said Jiang.

"The [researchers] have proposed an imaginative geometry for a nano-mechanical oscillator," said Vincent Crespi, an associate professor of physics at Pennsylvania State University. However, it will pose "rigorous challenges" for anyone attempting to build and test it experimentally, he said.

The researchers' next steps are to test their proposal experimentally and explore applications for the oscillator. Nanotube oscillators could be made practical in two to five years, said Jiang.

The researchers published their research in the January 28, 2002 issue of the journal *Physical Review Letters*. The research was funded by the Chinese National Science Foundation, Tsinghua University, the Office of Naval Research and the University of California.

Timeline: 2-5 years
Funding: Government; University
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper, "Multiwalled Carbon Nanotubes as Gigahertz Oscillators," *Physical Review Letters*, January 28, 2002

Nanotubes Make Microscopic Bearings

By Eric Smalley, Technology Research News
September 13, 2000

Researchers at the University of California at Berkeley have opened the ends of multiwall carbon nanotubes, which are tiny nested tubes as small as one nanometer in diameter, and they have slid smaller nanotubes in and out of larger nanotubes.

The ability to telescope nanotubes opens up the possibility for manufacturing bearings and actuators hundreds of thousands of times smaller than a millimeter. These microscopic bearings and actuators could be used to build nanoscale machines and motors.

"We figured out a way to electrically peel away the ends of a nanotube in a relatively careful and controlled way. [It's] a way to sharpen a tube, just like sticking a pencil in a pencil sharpener," said Alex Zettl, a professor of physics at UC Berkeley and senior scientist at Lawrence Berkeley National Laboratory. "As a bonus... we had access to different concentric layers of the multiwall nanotube."

Source: UC Berkeley

Inner tubes of multiwall carbon nanotubes can telescope out of outer tubes, leading to the possibility of nanoscale bearings and actuators.

Zettl and graduate student John Cumings used a transmission electron microscope to grasp an inner tube of an opened multiwall nanotube and slide it out of an outer tube. When the inner tube was released it was drawn back inside the outer tube by the van der Waals force, which is the force of attraction between atoms.

"Carbon nanotubes have been computationally recognized as nanoscale equivalents of macroscopic machine components, such as gears and bearings," said Jie Han, a research scientist at the NASA Ames Research Center and author of a paper proposing nanotube-based gears.Cumings and Zettl's work, "for the first time experimentally demonstrated the feasibility of making nanotube based molecular machines," he said.

Though nanomachines will likely resemble macroscopic machines in form and function, the individual molecules that will make up nanomachines behave differently than the large volumes of molecules that make up macroscopic machines.

Cumings and Zettl's work "shows the important difference in operational modes between future nanoscale molecular machines and their macroscopic cousins," Han said.

"Deformation and resultant fatigue failures caused by small strains in macroscopic structures won't occur in nanomachines where atomic precision ensures that structural defects do not exist," he said. Also, any changes in shape at this scale are temporary, said Han.

"In addition, there is no surface wear and no need for lubricants in atomically precise nanostructures," he said.

However, nanomachines could be affected by subatomic particles and radiation, Han said, noting that further research is needed to determine this.

The potential of multiwall nanotubes to serve as bearings and actuators portends entire machines no larger than a handful of molecules. Combining Zettl's nanotube bearings with the work of nanotube pioneer Richard Smalley of Rice University, who has attached a wide range of molecules to nanotubes, will lead to "functional nanoscale machinery parts and molecular machines sooner or later," Han said. It's likely that nanotube bearings will first be used as components of larger devices.

"We hope to use our nanoscale bearings and actuators integrated into larger devices that are useful in force sensing and chemical sensing and all kinds of things," said Zettl. "The first application would be to try to integrate these with MEMS devices that already exist."

MicroElectroMechanical Systems (MEMS), tiny machines ranging from several to hundreds of microns in size, have been prone to wear and failure because the effects of forces like friction are amplified at that scale. Nanotube components could overcome some of those problems, Zettl said.

Another potential use for telescoping multiwall nanotubes is as electromechanical switches, Zettl said. The switches could be used for memory or logic units in computers.

"It turns out when you go to this nanoscale electromechanical things are very fast... and [they can] compete with electronics," he said.

Cumings and Zettl published their work in the July 28 issue of the journal *Science*. The research was funded by the Department of Energy.

Timeline: Unknown
Funding: Government
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper, "Low-Friction Nanoscale Linear Bearing Realized from Multiwall Carbon Nanotubes", *Science*, July 28, 2000

TRN

Molecular Mechanics

Natural Force Drives Molecular Ratchet

By Ted Smalley Bowen, Technology Research News
May 16, 2001

Natural force drives molecular ratchet Before microscopic motors can be put to work hauling tiny payloads and building infinitesimal structures, suitable power sources and control mechanisms need to be developed.

Toward that end, Markus Porto, a researcher at the Max Planck Institute in Germany has proposed a way to harness the electromagnetic interactions between charged particles to drive a molecular ratchet mechanism.

Porto's scheme converts both random and oscillatory motion of charged particles into linear movement. Molecular motors like Porto's could eventually transport and arrange minute amounts of substances.

The ratcheting motion of the motor is fully driven by the Coulomb force, which is the electromagnetic repulsion or attraction of two charged particles, said Porto. "No ad hoc potential is introduced. The ratchet type potential is a natural consequence of the charge arrangement," he said. Potential refers to energy stored in an object, like a coiled spring.

The scheme calls for a composite particle that holds two negative and two positive charges to move along a track that holds irregularly spaced alternating charges.

When the arrangement of charges within the particle rotates in one direction, the particle moves along the track. An opposite rotation causes the particle to remain in place.

"A rotation of the moving particle's charge arrangement in one direction results in a force acting on the particle... corresponding to [a] ratchet's open direction," he said. The opposite rotation produces the equivalent of a closed ratchet, which keeps the particle in place.

At the crux of the design is the conversion of two types of charge movements — random, and oscillatory, or rotational — into controlled movement. Converting random movement to directed movement will yield only rough control of speed, however. "That the velocity fluctuates around a mean value is the price one has to pay to be able to use a random driving," Porto said.

Changing the positions of the particle's charges changes the interaction between the particle and the track, effectively giving the molecular motor three gears. "The control mechanism relies on the ability to rearrange the moving particle's charges. By rearranging these charges, one chooses the `forward,' `reverse,' and `no-load' gear," said Porto.

Researchers could begin experimenting with such motors within about two years, according to Porto.

"The paper represents good work in that it describes how Coulomb interactions can be used to make a device that converts rotational, oscillatory, or random motion into linear motion," said Bernard Yurke, a researcher at Lucent Technologies. "It provides food for thought for those of us who have made molecular motors that can execute rotary or oscillatory motion and would like to use them to make something that can move along a substrate much like the biological molecular motor, kinesin, moves along microtubules."

Yurke pointed out that a mechanism like the one Porto described would be built of more than simple charges. "There has to be something that holds these charges in proper relation to each other and the center of mass at a proper distance from the track. One might imagine the [track's] charges attached to a stiff linear molecule," he said. "The charges of the moving entity rotate in specified ways about their center of mass. One might imagine charges attached to a wheel shaped molecule that can slide long the track of the stiff linear molecule."

Similarly, an engine would be needed to drive such a motor. "The power generator... that rotates, oscillates, or randomly drives the charges of the moving entity is not described," Yurke said.

Porto detailed his work in the February 27, 2001 issue of the journal Physical Review E. The research was funded by the Max Planck Foundation.

Timeline: 2 years
Funding: Government
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper "Molecular Motor Based Entirely on the Coulomb Interaction," *Physical Review Letters*, February, 2001

Linked Liquid Crystals Move Matter

By Kimberly Patch, Technology Research News
April 25, 2001

Linked liquid crystals move matter Picture a field of wheat with the force of wind causing the tops of the plants to bend closer to the ground. To harness the movement of the wheat to do the work of lifting a large piece of cardboard, you could get the plants to push on the cardboard when the wind dies and they spring back up. It might be tricky, though, because the wheat plants, especially if they are tall, might simply slip around the cardboard.

Researchers from Germany have solved a similar problem in producing a material that uses the liquid crystals commonly used in laptop computer screens to convert electrical energy into mechanical work. The material could eventually be used to power microscopic machines.

Liquid crystal displays sandwich liquid crystals between transparent electrodes; the screen changes when the liquid crystals reorient under the influence of an electric field.

The tricky part of using liquid crystals to do work is their slippery structure. Liquid crystals have a stable crystalline structure only in one dimension. In the other two dimensions they have a liquid structure, which prevents them from exerting mechanical force.

This makes them rather like that field of wheat. In the presence of an electric field, the long, rod-like, molecules that make up the liquid crystal tilt, compressing the material. "However, [they] could not be used for applications until now, because the liquid crystal molecules would just flow around any structure that should be actuated," said Friedrich Kremer, director of the Institute for Experimental Physics at the University of Leipzig.

The researchers solved the problem by chemically tying off the molecules so they would not have room to slip around what they were supposed to push. "The trick is to tie the tilting liquid crystal molecules to a long polymer backbone molecule via flexible spacer molecules," said Kremer. "This leaves enough mobility for the liquid crystal molecules to react to the electric field by tilting, but does not allow them to flow around. This chaining allows them to do work," he said.

Combining the properties of liquid crystals and the polymers made a material that required two orders of magnitude less electricity to change shape than a material made only of the polymers used in the backbone, said Kremer.

The chained liquid crystal material, ferroelectric liquid crystalline elastomer (FLCE) changes shape by four percent, according to the researchers.

Historically, crystals like quartz have been used in a similar fashion to translate electrical energy into the mechanical action of watch hands, but the amount a crystal can strain, or change shape and spring back, is less than 0.1 percent, said Kremer. The FLCE's four percent potential for change could be used to produce work in the burgeoning field of nanotechnology, he said. For example, "a hypothetical cubic film of 100 microns width and 100 microns thickness would decrease in thickness by four microns [using] 150 volts," Kremer said.

The material is "a step in the right direction in the technology of developing biomimetic or plastic like materials — robotic materials that are controlled by an electric field," said Mohsen Shahinpoor, a professor of mechanical engineering and neurosurgery at the University of New Mexico, and director of its Artificial Muscle Research Institute.

However, the voltage needed for the new material is still relatively high, he said. "They added a liquid crystal elastomer to the ferroelectric [polymer] to reduce the voltage. But the voltage is still high," which is a disadvantage in medical applications he said. "The advantage is just that's another type of soft material, which is good. There may be applications for that," Shahinpoor said.

The researchers' next steps are to tune the materials performance, find better ways of manufacturing it, and find applications for it. "FLCE's could be directly used as sensors or actuators," said Kremer. Simple actuators could be made immediately, but it will take 10 years or longer to produce devices for specific applications, he said.

Eventually, the material could be used as a type of artificial muscle, he said. "The ultimate aim is the artificial muscle, with all its possibilities of creating nanoscale robots and other artificial creatures," he said.

Kremer's research colleagues were Walter Lehmann, Holger Skupin, Peter Krüger, and Mathias Lösche of the University of Leipzig in Germany, and Christian Tolksdorf, Elisabeth Gebhard, Rudolf Zentel of the University of Mainz in Germany.

They published the research in the March 22, 2001 issue of the journal *Nature*. The research was funded by The German Research Foundation (DFG).

Timeline: Now, 10 years
Funding: Government
TRN Categories: Nanotechnology; Semiconductors
Story Type: News
Related Elements: Technical paper, "Giant Lateral Electrostriction in Ferroelectric Liquid-Crystalline Elastomers" *Nature*, March 22, 2001

Molecular Motor Shifts Speeds

By Eric Smalley, Technology Research News
November 29, 2000

In the drive to harness molecular forces to power microscopic devices, researchers at the University of Tokyo have made a rotary motor with a built-in transmission system.

The motor consists of two ring-shaped molecules sandwiching a metal ion. The ion acts as a bearing and the rings naturally rotate around it in opposite directions. The rate of rotation depends on the number of electrons in the rings.

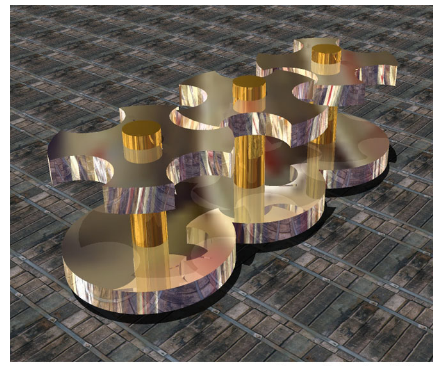
The researchers have also combined several of these double-decker motors into columns. "We have synthesized a sort of columnar stack of double-decker complexes where the rotation of each double-decker is preserved," said Takuzo Aida, a chemistry professor at the University of Tokyo.

The motors could eventually power nanoscale mechanical devices and serve as electromechanical switches for future computer memory and logic units, if they can be controlled individually and added to larger systems.

The motor changes speeds via a reduction-oxidation (redox) reaction. When the rings gain an electron by oxidation they move closer together, which slows the rotation. The rings can undergo two levels of oxidation, making a three-speed motor.

In the single oxidation state the rate of rotation is 21 times slower than the neutral state, and in the double oxidation state the rate is nearly 100 times slower. The specific rates of rotation vary according to the acidity of the solution but are generally many thousands of times per second, Aida said.

The double-decker motor is compelling, said Joseph Lyding, a professor of electrical and computer engineering at the University of Illinois. "[We're] beginning to see strong indications and clear proof that you can control molecular motion. If you combine that with the ability to position a molecule on a surface with atomic precision, then you can start thinking about assembling more complex structures in which you take advantage of that molecular motion."



Source: University of Tokyo

Vertical posts represent metal ions and horizontal disks the ring molecules of a molecular motor. This image shows a hypothetical gear linkage application of the tiny motor.

The researchers are exploring ways to attach the double-decker motors to other structures or surfaces. They have combined the motors with other molecules but the results are preliminary, Aida said, and he declined to provide details.

The motors work in solution. It's not clear whether the rotational behavior would be preserved if the motor was attached to a surface, he added.

However the motors are harnessed, an important step toward using them will be halting one of the rings while keeping the other rotating. In theory, the natural molecular forces alone won't support unidirectional rotation, said Aida. However, periodic energy injections like pulses of light have the potential to do this, he said.

Researchers should be able to use the motors in primitive molecular machines within a couple of years, said Aida. However, practical applications are probably decades away, he said.

Aida's colleagues were Kentaro Tashiro and Katsuaki Konishi. They published their work in the August 3, 2000 issue of the Journal of the American Chemical Society. The research was funded by the Japan Society for the Promotion of Science, the Izumi Science and Technology Foundation, the Yazaki Memorial Foundation for Science and Technology, and the Ministry of Education.

Timeline: < 2 years; >10 years

Funding: Private; Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology
Story Type: News
Related Elements: Technical paper, “Metal Bisporphyrinate Double- Decker Complexes as Redox-Responsive Rotating Modules,” Journal of the American Chemical Society, August 3, 2000

TRN

Light-Driven Molecular Mechanics

Molecular Shuttle Gains Light Throttle

By Chhavi Sachdev, Technology Research News
July 4/11, 2001

A transport system small enough to move nanoscale objects like single molecules could eventually have far-reaching uses in nanoscale machinery and within the human body.

Researchers at the University of Washington have figured out how to control a nanoscale system that works like a railroad, complete with tracks, trains and stations. The setup could eventually allow novel materials to be built from the bottom up, said Viola Vogel, director of the center for nanotechnology and associate professor in bioengineering at the University of Washington. “This brings us a step closer to machines working on a molecular scale, the grand vision outlined by [physicist Richard] Feynman 40 years ago,” she said.

To make the tiny freight trains, the researchers used a nanoscale motor to move microtubule shuttles. They then loaded cargo onto the trains. However, the researchers needed to figure out how to control the trains, said Vogel. The fourth, most crucial step, therefore, revolved around “ the question of guiding — how can we direct the motion along nanoscale tracks?” she said.

The researchers isolated the motor protein kinesin to drive the shuttle. Motor proteins are the tiny molecules responsible for transporting small cargoes in nature and are fueled by the nucleotide adenosine triphosphate (ATP). Kinesin characteristically moves in a single direction along the lengths of microtubules, which are very thin protein tubes, such as the axon in a neuron.

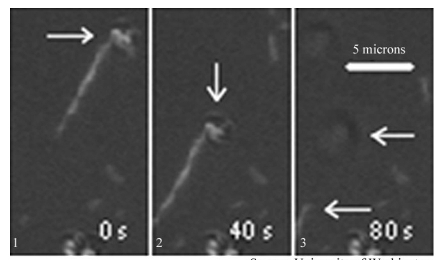
The track is composed of kinesin fixed to a surface. The path is set for the microtubules because kinesin adheres to very tiny guiding channels on their surfaces, directing the motion of the free-floating microtubules. The process can be inverted, with the microtubules fixed to the surface, according to the researchers.

To load and unload specific cargo, the researchers showed that linking the enzyme biotin to the microtubules caused anything coated with the protein streptavidin to bind with it. The biotin/streptavidin interaction is well known and frequently used in bioengineering. They also proved that hooking cargo to the microtubules did not alter their speed or motion. While sometimes the tubules ‘derailed,’ the percentage of such accidents was small, the researchers said.

Their final challenge was to control the starting and the stopping of the microtubule freight trains. This was difficult because the kinesin motors are not very sensitive to changing ion concentration or pH levels, the two traditional methods of controlling molecules. Once started, the motors can also run for many hours without pausing because they consume very little energy from the ATP, the researchers said.

The researchers used ultraviolet light to turn the kinesin motor off and on. The light frees stored, or caged, ATP. “Think of the free ATP as the fuel in the motor, the caged ATP as the fuel in the gas tank, the kinesin as the motor and the hexokinase as the brake,” said Henry Hess, a postdoctoral researcher on the team. When an ultraviolet light is flashed, it acts on the inactive, caged ATP like a fuel pump and “turns caged ATP into free ATP,” said Hess. This allows kinesin to push the microtubules around, he said.

“Without hexokinase, kinesin would run for hours on a single load of ATP. So we use hexokinase as [a] brake: It consumes the free ATP fairly fast, which in turn slows the kinesin,” Hess said. When all the free ATP is consumed by hexokinase and kinesin, the motors rest until the next flash of ultraviolet light, he said.



Source: University of Washington

The first two images show a microtubule transporting a cluster of beads. The arrows point to the beads. Image three was taken after the microtubule spontaneously released the beads; the arrows point to the beads and the microtubule.

“Moving the shuttles in multiple, discrete steps under control from an external source of UV light is a key accomplishment of our research,” Vogel said.

The tiny railroad system “could have applications in materials, sensors, drugs, [and] information technology,” said Hess. “You could rip things apart and test the strength of the bonds holding them together; You could transport a ‘glue’ to a nanoscale crack on a surface and prevent the crack from spreading,” Hess said. The shuttles could help assemble those things that do not self-assemble and impose a specific order on the process. This would help further miniaturize microelectromechanical systems (MEMS) devices, he said.

The train could also be used as an assembly line, according to the researchers. A molecule loaded onto a shuttle could be transported along a series of reactor sites. The reactor sites could be nanometer-sized outlets where a molecule could be chemically modified by the voltage of a nearby electrode, Hess said.

The researchers' next step is to "get a detailed understanding of the system parameters so that we can rationally engineer complex tracks," said Vogel. They also plan to demonstrate the performance of the motor proteins in different applications. The motor protein shuttles will not be ready for practical use for at least another five years, Vogel said.

"The paper by Hess et al. is a nice piece of work," said Fred Brouwer of the Institute of Molecular Chemistry at the University of Amsterdam. "Researchers coming from the field of biochemistry or molecular biology are well ahead of those who approach molecular shuttles in the synthetic way, because by making use of what nature has already developed they are already able to have more or less controlled binding/ unloading of a cargo, together with movement along tracks, which could potentially also be unidirectional," he said.

"The sizes of the systems, on the other hand, are very much bigger than those of synthetic molecules," Brouwer said. "The microtubules moved by the biomolecular motors… are several micrometers long," he said. This is about ten times larger than structures that can be made with current lithographic processes, he added.

The system size is not a drawback, according to the researchers. "The ratio in size between cargo and vehicle would be very similar to a bus transporting people," said Hess.

Vogel and Hess's colleagues were John Clemmens, Dong Qin at the University of Washington and Jonathon Howard who is also affiliated with the Max Planck Institute of Molecular Cell Biology and Genetics in Dresden, Germany. They published their research in the April 24, 2001 issue of the journal *Nano Letters*. The research was funded by NASA.

Timeline: > 5 years
Funding: Government
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper, "Light-Controlled Molecular Shuttles Made from Motor Proteins Carrying Cargo Engineered Surfaces," *Nano Letters*, April 24, 2001.

Light Powers Molecular Piston

By Kimberly Patch, Technology Research News
April 18, 2001

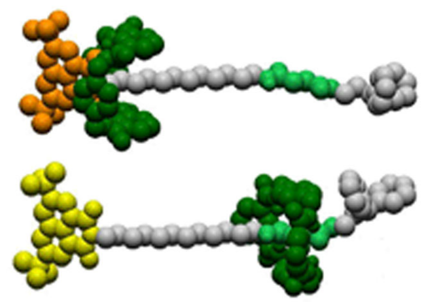
A group of scientists from three different countries have coaxed a molecule to act like a piston powered by light. This molecular motor could eventually power microscopic machines.

The tiny motor is made of a rotaxane molecule, which consists of a long, threadlike portion, a bead-like macrocyclic that slides along the thread, and thicker parts at each end of the thread that prevent the macrocyclic from sliding off.

The macrocyclic is attracted to whichever end of the thread offers a better binding site. The researchers made the molecule work like a piston by changing the binding sites on the ends of the thread, making first one, then the other attractive to the macrocyclic.

The researchers used light to change the binding sites, effectively powering the piston by light.

"The molecule is extremely simple compared to most other linear or rotary motors. It is... based on hydrogen bonding interactions... and does not consume any chemical auxiliaries, only light," said Fred Brouwer, a senior lecturer of physical-organic chemistry at the University of Amsterdam.



Source: University of Amsterdam

This diagram depicts a molecular motor. The activated, and the dark green ring has shuttled to the left. The molecule on the bottom showsan instant later, when the energy state of the molecule changes and the ring shuttles back.

The amount of work the two-nanometer-long molecule produces relative to its size is impressive. One gram of the molecules cycling back and forth 10,000 times per second could theoretically deliver about 500 kilowatts, or about five to times the production of a car engine, according to Brouwer.

Photons of light power the shuttle by creating a negative charge on the end of the molecule that contains a naphthalimide atom group. The negatively charged atom then takes an electron from a donor molecule present in the solution around the molecule.

When the naphthalimide atom group gains the extra electron, the macrocyclic is attracted to the other end of the molecule. After about 100 microseconds, the naphthalimide atom group loses the electron when the donor molecule takes it back, which attracts the macrocyclic bead back to the naphthalimide end of the thread. "Work is performed based on the binding energy gained," said Brouwer.

The research is an important contribution to the nanotechnology field, said Joseph Lyding, professor of electrical and computer engineering at the University of Illinois. "It is a good molecule for a molecular shuttle, both in terms of the ability to characterize the shuttle in process and in the flexibility of modifying its chemical details to tune the shuttling process," he said.

There are many eventual applications for such a shuttle, Lyding said. “Harnessing mechanical motion at the molecular level triggers the imagination about potential applications in biomedicine and in nanotechnology in general,” he said.

Eventually, molecular motors like these could be used as “actuators, assemblers and drivers for injectable chembots that might target diseases [and] tumors or repair joints,” said Lyding, adding that molecular nanotechnology is still in its infancy.

The piston could also be used in future nanomachines. “One could graft other molecules to the rotating macrocyclic shuttle and then drive a whole variety of reactions or mechanical transformations [in a way] analogous to attaching different kinds of drill bits onto a lathe cylinder,” said Steven Kornguth, assistant director of the Institute for Advanced Technology at the University of Texas.

The researchers are currently looking at related molecules with different charge distributions and different structures, said Brouwer. “Also we are investigating chemically different approaches... in which the motion in the two directions can be controlled separately,” he said.

The ability to move molecular size objects in relation to each other may also eventually prove useful in a “kind of chemistry-based information processing... in which movement has the function of connecting or disconnecting molecular interactions,” said Brouwer. “The obvious source of inspiration here is the brain,” he added.

The researchers are working toward harnessing the molecules for practical work. “The real challenge is to put the system to work in an organized environment. We plan to try attachment to a well-defined surface [and] incorporation in a membrane,” Brower said.

Brouwer’s research colleagues were Celine Frochot and George W. H. Wurpel of the University of Amsterdam, Francesco G. Gatti and David A. Leigh of the University of Warwick in England, and Loic Mottier, Francesco Paolucci and Sergio Roffina of the University of Bologna in Italy.

They published the research in the March 16, 2001 issue of the journal *Science*. The research was funded by the Universities of Amsterdam, Warwick and Bologna, the European Community and the Netherlands Organization for Scientific Research.

Timeline: > 2 years
Funding: Government, University
TRN Categories: Semiconductors and Materials; Nanotechnology
Story Type: News
Related Elements: Technical paper, “Photo Induction of Fast, Reversible Translational Motion in a Hydrogen-Bonding Molecular Shuttle”, *Science*, March 16, 2001

TRN

Crystal Changes Shape in Ultraviolet Light

By Kimberly Patch, Technology Research News
April 18, 2001

A crystal is usually a very stable chemical structure that withstands many stresses that would completely transform liquids and gases.

A group of researchers from Kyushu University in Japan, however, has found that diarylethene crystal will change from colorless to blue when exposed to ultraviolet light, then lose its color again in the presence of visible light. The color change points to structural changes in the crystal that could eventually be harnessed to drive microscopic devices.

The researchers discovered the phenomenon accidentally, then figured out exactly how the color change happened using x-rays and an atomic force microscope. The crystal literally rearranges its chemical bonds as it absorbs ultraviolet photons. “X-ray crystallographic analysis of the crystals revealed that the crystals reversibly change [their] volume by the photo irradiation,” said Masahiro Irie, a chemistry professor at Kyushu University.

The researchers then looked at the surface of the crystals with an atomic force microscope, and found that the chemical bond rearrangement translates to tiny steps on the surface of the crystal.

The ultraviolet light literally shrinks each molecule by a tiny amount, and the shrinkage causes the steps. When the shrinkage reaches 600 molecular layers deep, those 600 layers are reduced by the width of one molecule, resulting in a one nanometer step on the surface of the crystal, according to the researchers. The reactions can take place as deep as 500 microns, or about 500,000 molecular layers, to create larger steps, according to the researchers.

These steps on the surface of the crystal changes the way it reflects light, making it appear blue. The visible light reverses the molecular bond changes, erasing the steps, and making the crystal clear again.

The researchers ultimately plan to develop the material into a photomechanical device that directly converts photon energy to mechanical work, he said. The crystals could eventually be used as nanoscale actuators because they change thickness but require no moving parts to do so, said Irie. “We hope to use them for nanomechanical systems [that function using] noncontact photon energy.”

The crystals could be used in devices in about five years, said Irie.

Irie’s research colleagues were Seiya Kobatake and Masashi Horichi. They published the research in the March 2, 2001 issue of the journal *Science*. The research was funded by the Japan Science and Technology Corporation (JST) and by the Japanese Ministry of Education, Culture, Sports, Science and Technology.

Timeline: 5 years
Funding: Corporate, Government
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Reversible Surface Morphology Changes of a Photochromic Diarylethene Single Crystal by Photoirradiation," *Science*, March 2, 2001

The Little Light-Sensitive Molecule That Could

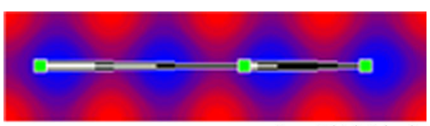
By Kimberly Patch, Technology Research News
July 12, 2000

Although researchers have been developing construction techniques for building nanoscale structures for some time, there have been fewer ideas about the practical matter of moving materials around the microscopic construction sites.

A team of Tel Aviv University researchers is working to fill that gap with with a plan for tiny freight trains.

The researchers' nanoscale locomotive is made up of a photosensitive molecule attached to particles that fit the depressions of an eggcrate-like surface. The device moves when a laser activates the spring-like molecule, stretching a particle forward to the next depression. The locomotive could be as small as a few nanometers long, according to Markus Porto, a postdoctorial researcher at Tel Aviv University.

The locomotive will be able to carry a tiny payload and turn on a nanoscale dime: the eggcrate track, which is broad as well as long, allows the tiny train to move in all directions, and the laser control enables real-time route changes.



Sourse: Tel Aviv University

This diagram shows the nano-scale engine moving one step to the right. The blue areas represent depressions in the surface, the green squares represent particles, and the black and white piston shapes represent the bands of the photosensitive molecule.

Laser control also means the locomotive is not tethered to a power source. "That's an elegant way of doing it... a sort of a hands-free way of moving around a nanoscale object," said Joseph Lyding, professor of electrical engineering and computer engineering at the University of Illinois' Beckman Institute.

Because the locomotive is capable of carrying cargo, it is potentially useful for applications like ferrying materials around nanoscale factories to produce custom molecules, said Porto.

In addition, the nano-locomotive will be able to go very fast. "When you get down to the nanometer scale you can have very high [mechanical] speeds," said Lyding. "So in that light nano locomotion can serve all sorts of useful functions," he said.

A realistic speed for the nano-locomotive will likely be several micrometers or tens of micrometers per second, said Porto. "This does not sound [like] a lot, but... this means that the engine moves 100 to 1000 times its own length per second," he said. Scaling that speed up, in order to go 500 times its own length per second, a typical four-meter-long car would have to go 7200 kilometers per hour, said Porto.

According to Porto, a prototype of the engine could be assembled fairly quickly. "All ingredients needed for an actual realization [exist] in laboratories. Since the field of nanotechnology progresses very quickly we might see applications sooner than we think, maybe even in a few months," Porto said.

"It seems pretty straightforward to go from an idea to some type of a prototype," said Lyding, who added that a prototype should easily be viable within a few years.

Porto's colleagues on the nanoscale locomotive project were Tel Aviv University professors Michael Urbakh and Joseph Klafter.

The three researchers have also worked out the mechanics of a nanoscale engine that converts random motion into directed motion. A paper describing the plan was published in the June 26 issue of *Physical Review Letters*.

Macro-scale engines convert the random motion of the heat from burning fuel into directed motion. But these engines cannot be scaled down to the nanometer size because the thermodynamic laws macro-scale engines take advantage of do not apply to single atoms or molecules, said Porto.

The research was funded by the Israel Science Foundation, The German Israeli Foundation, the Submicron Imaging and Stimulus Induced Transformation of Organic Molecular Adsorbates at Surfaces (SISITOMAS) program of the European Community Research Network For Training and Mobility of Researchers, the German Israeli Project Cooperation on Future Oriented Topics (DIP), and a Feodor Lynen fellowship of the Alexander von Humboldt foundation in Germany.

Timeline: < 1 year; < 3 years
Funding: Institute; Government
TRN Categories: Nanotechnology; Semiconductors and Materials
Story Type: News
Related Elements: Technical Paper, "Atomic Scale Engines: Cars and Wheels", *Physical Review Letters*, June 26, 2000

Biomolecular Mechanics
DNA Motor Keeps Cranking

By Kimberly Patch, Technology Research News
April 23/30, 2003

Scientists working to harness DNA to construct and power microscopic devices have gained an important tool.

Researchers at Lucent Technologies' Bell Labs and the University of Oxford in England have found a way to keep their DNA motor running continuously. Previously, the researchers had to add particular strands of DNA at different steps in the motor's cycle to keep it going.

The free-running DNA motor could eventually power microscopic machines capable of constructing and transporting chemicals and materials molecule by molecule.

Each strand of DNA contains four types of bases — adenine, cytosine, guanine and thymine — attached to a sugar-phosphate backbone. Complementary bases — adenine with thymine, and cytosine with guanine — combine to zip a pair of single DNA strands into a double helix.

A motor works by changing shape, then changing back again. In previous work, the researchers realized that a strand of DNA could be coaxed into a hairpin-like shape by causing complementary base sequences near the middle of the strand to combine with each other. This was the first step in constructing a motor from the molecule. "We realized that the nanostructure could be restored to its initial configuration by the complement, or opposite base sequence, of the strand of DNA that was used to induce the shape change," said Bernard Yurke, a distinguished member of technical staff at Bell Labs.

The key to making a free-running motor rather than a device that required the addition of new base sequences between movements, however, was finding a way to prevent the portion of the strand that formed a hairpin — the fuel strand — and the complement that removed the hairpin shape from simply combining with each other.

The researchers accomplished this by forcing the fuel strand of DNA into a tiny loop to make it physically impossible for the removal strand to combine directly with the fuel strand. "The removal strand, because it is long and only its middle portion can [combine] with the unpaired bases of the loop, has difficulty threading its way through the loop to form a double helix," he said.

The researchers added a shorter strand of DNA, dubbed the motor strand, that was able to combine with some of the unpaired bases of the loop to open it. "Once a loop is opened, the removal strand can [combine] with unpaired bases on the fuel strand and displace the [motor] strand from the loop," said Yurke. The displaced motor strand is then free to attach itself to a new loop to start the process over again.

If the motor strand were part of a nanostructure, the structure could be repetitively switched between two states as long as a few fuel loops and removal strands were present, Yurke said.

DNA can be used to impart force due to a pair of useful properties, said Yurke. First, when double-stranded DNA is less than 50 nanometers long, it behaves like a rigid rod, while a single strand of DNA behaves more like a floppy string, he said. Second, when strands of DNA are zipping up to form double-strand DNA, they can impart a force of up to 15 piconewtons.

A nanometer is one millionth of a millimeter, and 50 nanometers is about one 20th the diameter of E. coli bacteria. A piconewton is one trillionth of a Newton, which is about the force of a falling apple.

"The change in stiffness as a single-strand of DNA is transformed into double-strand DNA and the force that can be developed during the transformation can be used to drive shape changes in nanostructures," said Yurke.

The method is the first that uses DNA to power a free running system, according to Nadrian Seeman, a professor of chemistry at New York University. "To date, all DNA-based nanomechanical devices have required [input] to change state," he said. "These [researchers] have put together a system that will, in principle, allow for a free-running machine."

Such a machine could provide power for devices like nanorobots and nanomechanical computers, Seeman said. "This is cutting-edge work that advances DNA nanotechnology," he added.

The DNA motor could eventually power nanomachines for use in medicine, chemistry and materials science, said Yurke. "Molecular motors ought to be extremely useful. Living cells are loaded with molecular motors and these serve crucial roles in turning out a wide range of life's functions, including cell movement, molecular transport, replication and even chemical synthesis," he said.

Devising DNA-based molecular motors was an exercise in getting DNA to assemble itself into a useful device, said Yurke. Eventually it may be possible to coax DNA to assemble into much more complicated structures, including molecular-scale electronic circuits, he said.

It is too early to tell when synthetic molecular motors will be used practically, said Yurke.

Yurke's research colleagues were Andrew J. Turberfield and J. C. Mitchell at the University of Oxford, A. P. Mills, Jr., formerly at Bell Labs and now the University of California at Riverside, F. C. Simmel, formerly at Bell Labs and now at Ludwig Maximilians University in Germany, and M. I. Blakey at Bell Labs. The work appeared in the March 18, 2003 issue of *Physical Review Letters*. The research was funded by Lucent Technologies.

Timeline: Unknown
Funding: Corporate
TRN Categories: Nanotechnology; Biotechnology

Story Type: News
Related Elements: Technical paper, "DNA Fuel for Free-Running Nanomachines," *Physical Review Letters*, March 21, 2003.

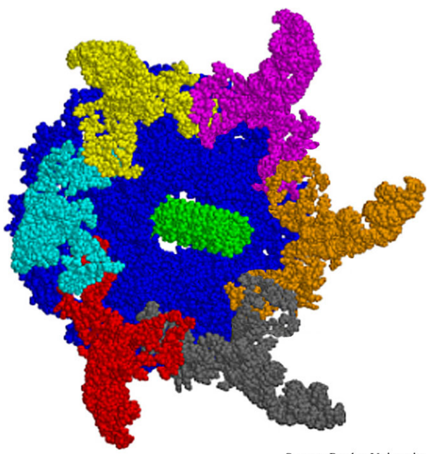
RNA Forms Nanomotor

Technology Research News, March 12/19, 2003

Researchers from Purdue University have constructed a tiny motor from DNA and RNA molecules. The device, fueled by ATP, which powers our own movements, could eventually power nanomachines.

The motor measures about 30 nanometers long, which is less than one hundredth the size of a red blood cell.

It is made from six strands of RNA surrounding a center strand of DNA. In the presence of ATP, the RNA strands push the DNA axle in succession, spinning it around. This produces 50 to 60 piconewtons, or trillionths of a newton of force. A falling apple exerts about one newton of force.



Source: Purdue University

This diagram shows a motor that is 100 times smaller than a red blood cell. The green rod is DNA and the multicolor outer ring RNA. In the presence of ATP, the substance sthat powers biological processes, the RNA spins the DNA.

The motor has potential in biological applications as well. The researchers have driven the tiny motor axle through the protective protein coat of a virus. The motor could eventually be used to deliver genes or therapeutic molecules into live cells, according to the researchers.

The motor could be used in practical applications in two to five years, according to the researchers. The work appeared in the February issue of the Journal of *Biological Chemistry*.

Cell Parts Paint Picture

By Chhavi Sachdev, Technology ResearchNews
July 10/17, 2002

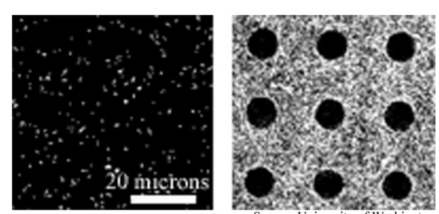
Probes that go to the depths of Earth's oceans and to planets like Mars beam back information about the topography and geography of places we can't visit in person. Researchers at the University of Washington have come up with probes hundreds of times smaller than a blood cell that can explore the nooks and crannies of objects so small they are difficult to image.

The probes, made from a pair of biological materials that form networks in living cells, provide higher-resolution images than conventional scanning microscopes, according to Henry Hess, a research assistant professor of bioengineering at the University of Washington.

In cells, the protein kinesin travels on microtubule conveyor belts to regularly shunt biological loads like chromosomes and vesicles from the center of a cell to its edge. Vesicles carry waste materials.

Scientists have already tapped microtubules and motor proteins to transport tiny payloads. To use them as probes, however, the researchers reversed the proteins' roles, unleashing a horde of about 600 microtubules on a kinesin-coated surface. The microtubules, doped with a fluorescent substance that makes them easy to image, propelled themselves over the kinesin to map out terrain. Each microtubule is 1,500 nanometers long and 24 nanometers in diameter, or about three thousand times narrower than a human hair.

The microtubules travel in straight lines and they can easily cross over each other, said Hess. One key to their utility, however, is in a limitation — the proteins cannot go everywhere. They can descend into troughs on the surface, but their structure prevents them from bending enough to climb peaks. Where there are little hillocks, or bumps, the microtubules cannot tread. Bald spots on microtubule maps, therefore, correlate to bumps on the terrain.



Source: University of Washington

The left image shows microtubule molecules that contain fluorescent dye spreading out across a surface coated with the protein kinesin. The image on the right, taken 40 minutes later, shows the microtubules spread out to reveal the surface topology.

Conventional probe microscopes gain topographical information by scanning a surface with a tiny tip. Narrow cavities in cells or MEMS devices, however, are difficult for scanning tunneling and atomic force microscopes to access. These could be characterized by the protein probes, said Hess.

Instead of scanning a fine tip along straight lines, the researchers' probes are like "hundreds of critters running across the surface [sending] you very simple information, which you integrate to get a complete picture," he said.

"Imagine an ant crawling across a surface," said Hess. A single ant moves randomly across a surface and covers only a small area. If there are hundreds of ants crawling around, however, "nothing on the surface will escape their attention," he said. "If there is a puddle, the ants will not go in there, so all the paths will go around the puddle."

A time-lapse recording of all ant movement would show an accurate picture of where the ants went as well as what areas they avoided, like the puddle. "In our case the ant is a microtubule [moving] across a surface coated with kinesin," said Hess.

The crisscrossing microtubules travel at 250 nanometers per second and are imaged every 5 seconds. The composite view becomes more detailed with time and a complete picture emerges after about 40 minutes. The researchers found the best image when they used every other frame, comparing the position of the microtubules every ten seconds. "The microtubules need at least 6 seconds to get to a completely new spot, otherwise the tail [of the protein] is where the tip has been before," said Hess.

Microtubules could also be used to image biological or radioactive contamination, "which you don't want to touch with a tip," said Hess. They could be made to sense more specific details, such as the magnetism of a surface or its pH level, by coating it with, for instance, a pH sensitive dye, according to Hess.

They next plan to make the microtubules maps more detailed, including information on the height of the hillocks, said Hess.

Hess's research colleagues were John Clemmens, Jonathon Howard, and Viola Vogel. They published the research in the February 13, 2001 issue of the journal *Nano Letters*. The research was funded by NASA.

Timeline: < 5 years
Funding: Government
TRN Categories: Biotechnology; Materials Science and Engineering; Data Acquisition
Story Type: News
Related Elements: Technical paper, "Surface Imaging by Self-Propelled Nanoscale Probes," *Nano Letters*, February 13, 2002

Morphing DNA Makes Motor

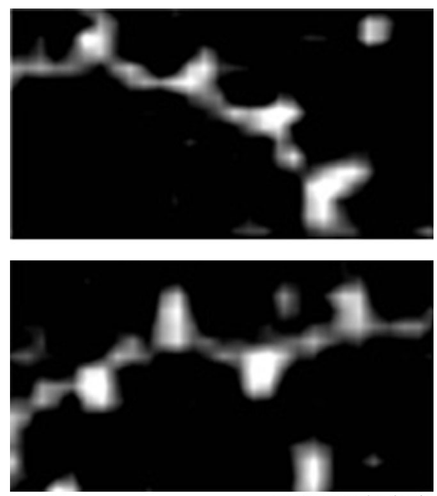
By Kimberly Patch, Technology Research News
January 16, 2002

DNA molecules are prime candidates for helping humans make microscopic machines because they have a long history of assembling things on the molecular scale. Every one of a human's 75 to100 trillion cells exists because a DNA molecule automatically unzipped, created the duplicate a cell needs to divide, then folded itself neatly back up again.

Researchers at New York University have taken a significant step forward in being able to instruct artificial DNA molecules to move in specific ways with a method that allows certain portions of DNA to bind to each other, and then release. This reversible binding method allows for control of the shape of a DNA molecule, or machine.

The researchers demonstrated the mechanism by making a four-step rotary motor out of DNA.

The motor is a four-stranded DNA molecule that, prompted by separate strands of DNA, will go through a mechanical cycle over and over again. Because the process is a reversible cycle, there are no waste products.



Source: New York University

The bumps on this DNA motor each consist of three joined DNA tiles. The top image shows the bumps aligned with each other. The bottom image shows the bumps alternating directions after one cycle of the motor.

The four-stranded DNA molecule is essentially a pair of double helixes of DNA connected at several points along their lengths.

When the researchers add molecules of control DNA to a solution full of the motor molecules, the short, single-stranded control molecules join with the larger molecules and rearrange them by connecting two of the double strands in one place and cutting them in another. The researchers then remove the control strands using fuel strands of DNA, which are also short single-stranded lengths of DNA. This leaves the motor molecule in a different physical shape than when it started — the end of one double strand of the DNA is rotated 180 degrees relative to the strands next to it.

The process can be reversed by adding a different type of control strand to the solution, and that control strand can also be removed by a different type of fuel strand after it changes the molecule back. "The system can be cycled numerous times... and there are no breakdown products," said Nadrian Seeman, a chemistry professor at New York University.

The process can be adapted to many different sequences of DNA, said Seeman. "Many different species of this device can be made by changing the sequences in the region where the... strands bind," he said.

This means a wide range of similar rotary devices can be created by changing the fuel strands and the places where they bind, he said. Ten different molecules can result in 1,024 different structures, for instance.

The researchers are currently working on a method to insert the DNA devices into molecular lattices, said Seeman. This would enable still more structures. An array of four by four molecules, for instance, could produce 65,536 different shapes. "This may enable us to build nanofabrication facilities to produce new molecular species," he said.

The range of motion the molecular motors can produce ranges from .04 to 4 nanometers, but the researchers have produced motions as large as 35 nanometers using arrays, according to Seeman. A nanometer is one millionth of a millimeter. On this scale, an E. coli bacterium is a relative giant, with a girth of 1 micron, or 1,000 nanometers. A line of ten carbon atoms measures about one nanometer.

The research is "great stuff," said Erik Winfree, an assistant professor of computer science and computation and neural systems at the California Institute of Technology. The method is a step forward in terms of DNA mechanics, he said. "It expands our toolbox for designing molecular machines."

The research is ultimately aimed at making nanorobotics practical, according to Seeman. "It could be used to configure a molecular pegboard or control molecular assemblers. The ability to achieve many different shapes means that you can create many different patterns; different patterns in a timed sequence are the essence of a machine or robot," he said.

Molecular machines could be used to assemble drugs molecule-by-molecule, and molecular robots may eventually work inside the human body.

It will be about a decade before the method can be used to make practical devices, said Seeman.

Seeman's research colleagues were Hao Yan, Xiaoping Zhang and Zhiyong Shen. They published the research in the January 3, 2002 issue of *Nature*. The research was funded by the National Science Foundation (NSF), Office of Naval Research (ONR), the National Institutes of Health (NIH) and the Defense Advanced Research Projects Agency (DARPA).

Timeline: 10 years
Funding: Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology
Story Type: News
Related Elements: Technical paper, "A Robust DNA Mechanical Device Controlled by Hybridization Topology," *Nature*, January 3, 2002

TRN

Biomotor Powers Propeller

By Kimberly Patch, Technology Research News
December 6, 2000

Ready-made molecular motors have been around for eons in natural systems. The trouble is, these clean, efficient devices are so incredibly small that we haven't been able to use them for anything.

Researchers from Cornell have taken a step toward changing that by combining state-of-the-art abilities in several disciplines to connect a biological motor to a tiny metal propeller.

The device, which may someday lead to molecule-by-molecule drug manufacture, fantastically small sensors, and control of processes inside cells, was made possible by recent advances in several basic sciences, said Carlo Montemagno, an associate professor of biological engineering at Cornell University.

The 11-nanometer-square biological motor is anchored on a 200-nanometer nickel post, and sports a 750-nanometer-long nickel propeller. The whole device is several times smaller than a red blood cell, which is 5,000 nanometers across. The tiny bits of metal were produced using microelectromechanical systems (MEMS) processes.

The metal devices could have been machined smaller, but the researchers wanted to make the propeller large enough so its motion would show up on a video. "We could have made a 100-nanometer rod, but this is the smallest I can make it and also be able to see it [working]," Montemagno said. The post, in turn, had to be tall enough to support the outsized propeller.

In order to attach the motor to the post, the researchers had to coat an area of the post as small as the motor with a binding material. They also genetically engineered chemical handles at the bottom of the motor so it would attach in the correct orientation.

"We had to be able to orient and bind the motor at the same size scale as the motor itself," said Montemagno. If a mechanic installing a car engine could position the engine only in increments the size of a football field, it would be "really difficult to build a car. The technology had to be mature enough so we could position that motor with precision," he said.

The motor itself is a biological assembly made by a bacterium. Its three double-ringed molecules change adenosine triphosphate (ATP) into adenosine diphosphate (ADP) in the chemical process that universally fuels life. "It's a chemical engine. It takes ATP and hydrolyzes it, converting the ATP into ADP and an extra phosphate molecule... the energy released from having that phosphate release is what powers the motor," Montemagno said.

One turn of the motor produces about 120 piconewtons per nanometer. One newton is about the force of the weight of an apple and a piconewton is one trillionth of that force. The energy released from the three ATP molecules needed to rotate the motor once is actually 240 piconewtons per nanometer, giving the motor a 50 percent efficiency rate. In theory, this could be improved to as much as 80 percent, said Montemagno.

The width of a human hair, at about 75,000 nanometers, is several orders of magnitude larger than the motor. The force produced by one turn of the motor, however, could move a piece of human hair that is several times as long as it is wide.

"This is really the first construct of a post, [biological] motor and a propeller or a swinging element that I have seen," said Steven Kornguth, assistant director of the Institute for Advanced Technology at the University of Texas. "What's new is essentially you have an anchor point for a motor that's... spectacularly small," he said. The device itself is only "a fifth of the size of a red blood cell. That's why it's so tremendously useful," he said.

Because they are so small, biomolecular-powered devices like these could someday be incorporated into living cells or traverse the human bloodstream. "There's two kinds of things this allows us to do," said Montemagno. "It allows us to make... a hybrid system in which you would insert something which is not living into a living system. Or we can take something that's not living, and insert some attributes of a living system. It's like getting Legos and all of a sudden having all the pieces be able to fit together."

Practical applications for the devices are a decade away, Montemagno said.

The first applications are likely to be tiny motor systems for manufacturing drugs or inorganic materials, said Kornguth. Nanotubes, which range from 100 microns to less than one micron in diameter, "can deliver exceedingly small amounts of fluids onto a surface. Here you have a way of moving those fluids at that same scale. A lot of manufacturing is essentially assembly of particles on a surface." These tiny biological motors also produce no heat, which is an advantage in manufacturing because heat distorts surfaces, Kornguth added.

Montemagno's group is working on several projects designed to eventually make the tiny devices practical. First, they need better control of the motor. Currently, it runs until the solution it is suspended in runs out of ATP. "[It's] like having a car that's always on full throttle until it runs out of gas. We're working on putting a switch in the motor so that we can chemically turn [it] on and off," Montemagno said.

The group is also working on making a tiny molecular sorter. "Essentially what it will do is grab onto one molecule and then transport it [to] another location," he said.

They are also working on powering the motors with light. In addition to using the motors in cellular environments where ATP is ready-made, the motors could be used outside cells and manufacture their own ATP using an artificial photosynthetic process, said Montemagno.

Montemagno's colleagues in the research were Ricky K. Soong, George D. Bachand, Hercules P. Neves, Anatoli G. Olkhovets and Harold G. Craighead, all of Cornell. They published the research in the November 24, 2000 issue of *Science*. It was funded by the Defense Advanced Research Projects Agency (DARPA), the National Science Foundation (NSF), the Department of Energy (DOE), NASA, the Office of Naval Research and a W. H. Keck Fellowship.

Timeline: < 10 years
Funding: Government; Private
TRN Categories: Nanotechnology
Story Type: News
Related Elements: Technical paper, "Powering an Inorganic Nanodevice with a Biomolecular Motor, *Science*, November 24, 2000; Videos: falcon.aben.cornell.edu/News2.htm

TRN

Index

TRN's Making The Future Report is published 10 times a year by Technology Research News, LLC. Each 20- to 40-page package assesses the state of research in a field like biochips, data storage or human-computer interaction.

Single reports are $300 to $500. A one-year subscription is $1,600. To buy a report or yearly subscription, go to www.trnmag.com/email.html.

We welcome comments of any type at feedback@trnmag.com. For questions about subscriptions, email mtfsubs@trnmag.com or call (617) 325-4940.

Technology Research News is an independent publisher and news service dedicated to covering technology research developments in university, government and corporate laboratories.

Kimberly Patch
Editor
kpatch@trnmag.com

Eric Smalley
Editor
esmalley@trnmag.com

Ted Smalley Bowen
Contributing Editor
tbowen@trnmag.com

Chhavi Sachdev
Contributing Writer
csachdev@trnmag.com