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Self-Assembly: The Natural Way to Make Things

Executive Summary

A Pentium 4 chip contains more than 40 million transistors, but the human body is many orders of magnitude more complicated, with trillions of cells that each contain thousands of smaller parts.

Despite this vast increase in complexity, life's manufacturing processes are much simpler than those used to make electronics. Scientists looking for efficient ways to make microscopic machines and faster electronics are turning to self-assembly in hopes of putting things together with something like natures' ease.

Self-assembly is a critical aspect of nanotechnology — the branch of research geared toward making machines that are so small they reside in the realm of molecules. Using tools to manipulate such small objects is incredibly difficult and nowhere near cost-effective.

Self-assembly is also poised to enable faster electronics when current chip manufacturing processes reach their limits in about a decade.

Researchers are tapping biological materials like DNA, organic molecules like polymers, and inorganic molecules like gold nanoparticles to find those useful for self-assembly.

They are finding ways to make materials self-assemble into specific shapes, sizes and orientations, and are using molecules that readily self-assemble as templates or scaffolding for materials that do not. Initial efforts have produced particles, wires, rings, tubes, containers, patterned surfaces and patterned materials that automatically assemble molecule-by-molecule.

Self-assembly looks to be the most efficient and cost-effective method for constructing the nanoscale structures that are poised to play leading roles in biotechnology and computing in a decade or so. The technology is likely to play an increasingly important role in areas like photonics, data storage, drug delivery and biochemical sensors.

What to Look For

Biological:

Circuits made from nanotubes and DNA
3D structures made from nanotubes and DNA
3D structures made from DNA
Data storage devices made from protein-nanoparticle arrays
Data storage devices made from virus peptides
Optical communications devices made from virus peptides

Organic:

Circuits made from polymer nanowires
Biochips patterned by copolymer masks
Memory chips patterned by copolymer masks
Circuits made from individual molecules

Inorganic:

Data storage devices made from nanocrystals
Circuits made from nanocrystals
Data storage devices made from several or individual atoms
Circuits made from several or individual atoms

General a and Large-Scale:

Large-scale electronic devices made from self-assembled components
DNA-like molecules that generate molecular building blocks
Circuit layouts designed by self-assembly

Making things make themselves

The most complicated things in life are self-assembled.

Today's electronics contain millions of small parts, but that number pales in comparison to living organisms. The Pentium 4 chip that powers today's typical desktop computer is incredibly complicated — it contains more than 40 million transistors, which is about as many seconds as there are in 463 days. The human body is many orders of magnitude more complicated, with trillions of cells that each contain thousands of smaller parts.

Despite the vast increase in complexity, however, life's manufacturing processes are much simpler than those used to make electronics. Although parents often spend a fair amount of time putting together toys for their children, the children themselves assemble automatically, given the right environment and a couple of small bundles of DNA.

Scientists looking for efficient ways to make microscopic machines and faster electronics are turning to self-assembly in hopes of putting things together with something like natures' ease.

This report provides an overview of the concept of self-assembly, the ways researchers are beginning to apply it, and the principal self-assembly technologies.

Microscopic machines and faster electronics

Self-assembly is a critical aspect of nanotechnology — the branch of research geared toward making machines that are so small they reside in the realm of molecules. This is because using tools to manipulate such small objects is incredibly difficult and nowhere near cost-effective.

There's a world of difference between merely microscopic and nanoscale. A 20-micron diameter particle is, at one fiftieth of a millimeter, invisible. It is also 1,000 times wider than the smallest viruses, and 200,000 times bigger than a hydrogen atom.

There's also a world of difference between making small parts and being able to assemble them into more complicated devices. Although atomic force microscopes allow researchers to manipulate individual atoms, simply moving a few atoms on a surface is painstaking and time-consuming.

Researchers looking to improve electronics have long relied on size. Smaller electronics are faster because electrical signals have less distance to travel. The transistors that make up the bulk of the Pentium 4 chip each span about 130 nanometers, and current manufacturing processes can be improved only so much in order to make smaller components. A decade or so down the line, when the manufacturing processes now in use can go no further, self-assembly could continue to enable smaller and thus faster electronics.

In a broad sense, self-assembly is more like chemistry than mechanical engineering. Chemists have been designing molecules for decades, though usually with the aim of controlling bulk amounts of the substance. But chemistry is the language of nanoscale design. Chemists become nanoengineers simply by focusing on nanoscale results.

Materials, means and ends

Researchers are tapping three classes of materials to find those useful for self-assembly:

- Biological materials, including DNA, protein molecules, and whole microorganisms
- Organic molecules, including polymers and liquid crystals
- Inorganic particles, including silicon nanocrystals and gold nanoparticles

How It Works

Causing technological materials and devices to assemble automatically is a matter of bending natural processes and materials to specific ends. Three and a half billion years of evolution have produced many useful materials and processes, and several of these are particularly suited to technology.

Nature's building block is the molecule, that collection of atoms that gives a material or substance its properties. And the molecule that serves as the blueprint for all of life's processes is deoxyribonucleic acid (DNA).

Life's plan

Biological DNA is made up of long strings of four types of bases — adenine, cytosine, guanine and thymine — attached to a sugar-phosphate backbone. Adenine pairs up with thymine and cytosine with guanine when two single strands of DNA mesh to form the familiar double helix.

DNA makes the proteins that carry out life's processes by exposing a portion of a single strand as a template; the requisite protein can assemble automatically simply by matching up base pairs. In a cell, this happens in a more complicated two-step process. DNA provides a template for ribonucleic acid (RNA), which then acts as a template for proteins outside the cell's nucleus.

DNA's replication process is a similar self-assembly process. When the strands separate, each single single strand becomes a template for new pairs.

Researchers can make artificial strands of DNA that have specific sequences of base pairs designed so that the strands combine to form structures or produce specific proteins.

Connecting things up

Most of life's processes are carried out by protein molecules that fold into various shapes. Proteins recognize and connect to other molecules based on shapes, similar to a key fitting into a lock.

Once two molecules come together in a lock and key formation, there are several ways the two molecules can bond to each other without going so far as chemically fusing. The two that show promise for technological self-assembly are electrostatic interactions and hydrophobic interactions.

Ectrostatic interactions occur when the positive electrical charge of one atom's nucleus attracts the negative charge of another's electrons. Once the molecules get close enough, this charge draws the two together and holds them at the point where the two atoms' electrons begin to repel each other.

Hydrophobic interactions occur when molecules that are electrically balanced, or nonpolar, are

There are two ways to make self-assembly happen:

- Find ways to make materials assemble into specific shapes, sizes and orientations
- Use molecules that readily self-assemble as templates or scaffolding for materials that do not

Initial efforts have produced several types of structures that automatically assemble molecule-by-molecule:

- Particles
- Wires
- Rings
- Tubes
- Containers
- Patterned Surfaces
- Patterned Materials

The laws of physics

The self-assembly process is more difficult to set up than it may seem. Molecules that are capable of bonding to each other tend to do so in large numbers. The challenge is to synthesize molecules that bond to form small building blocks that can in turn combine to form useful nanoscale structures.

The key to self-assembly is designing molecules and particles that move freely around each other until they reach a desired arrangement, then bond to form a structure. Molecules are capable of attaching to each other in several ways. (See How It Works, page 2.)

Design as process

The structures and substances of life form when certain molecules come into contact. The structure of each molecule determines how molecules fit together and which natural forces cause them to bond. In other words, the design is the process.

Nature has honed a wide range of molecular interactions over billions of years of evolution. The research challenges are to find shapes and forces that beget structures useful for technology and to apply that knowledge to component design.

The possibilities are nearly limitless, given that humans begin from just a bundle of DNA. Scientists are aiming to eventually develop complicated hierarchies of self-assembly in which components will assemble to form components that, in turn, form higher-level components.

Researchers are building self-assembly libraries analogous to software programming libraries by cataloging technologically useful molecular interactions.

The stuff of life

Biological molecules are arguably the most promising way to use self-assembly for technological ends. After all, why copy just the repelled by polar molecules, notably water. The electric charges in polar molecules are asymmetrical. Polar molecules attract each other, which has the effect of rounding up any interspersed nonpolar molecules.

Building a bigger molecule

One way to make large molecules is to use smaller molecules as building blocks. Polymerization, or the process of forming large molecules, polymers, from small molecules, or monomers, occurs throughout nature.

There are two basic types of polymerization reactions: chain reactions, and step reactions.

Step reactions, also known as condensation polymerization, are relatively slow and result in relatively simple polymers. This process forms natural polymers like silk and artificial polymers like many household plastics, but it's slow pace makes it less useful than chain reactions for self-assembly.

Chain reactions

In contrast, chain reaction polymerization is very fast. It also often results in branched molecules and cross-linking between polymer strands, which are useful for shaping nanostructures and mating polymers with nanoparticles or other molecules.

Chain reaction polymerization forms polymers from small molecules that contain two carbon atoms with two shared pairs of electrons. If one of the bonds between the two carbon atoms is broken, the molecule becomes a free radical, which is very reactive. When two free radicals meet, their unpaired electrons form a new covalent bond, creating a single, larger molecule. Hundreds or thousands of molecules can link this way to form long polymers.

Who to Watch

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assembly processes when you can co-opt the building materials too?

DNA and protein molecules have evolved to carry out huge numbers of specific interactions, and researchers are working on ways to program the process to produce interactions that will result in technologically useful assemblies.

Blueprint and building material

One major research focus is centered around DNA.

Scientists are looking to use the molecule's matching base pairs to construct technologically useful devices. DNA can also be engineered to attract other types of molecules, making it a strong candidate for use as scaffolding. (See How It Works, page 2.)

Several research teams are working with artificial DNA strands that connect into various-shaped two-dimensional tiles that have sticky ends, or portions of DNA strands that remain unconnected. The sticky ends can be used to connect tiles together. The tiles can be programmed to assemble in various ways by giving them different types of sticky ends.

Researchers from Duke University have made DNA tiles whose sticky ends match up so that the connected tiles curve slightly to form a waffle-like sheet that can be used to sort proteins. They also used the method to make a waffled ribbon that served as a template for a silver nanowire built molecule-by-molecule. (See "DNA Forms Nano Waffles", page 10.)

Researchers from Yale and Northwestern Universities have come up with a way to make DNA tiles self-assemble into three-dimensional shapes. (See "Nanotech Scheme Envisions DNA Origami", page 12.)

A second research team from Duke University has made artificial strands of DNA that self-assemble into a structure that reveals the pattern encoded in one of the DNA strands, making the order of bases on that strand readable by microscope. (See "DNA Makes Nano Barcode", page 11.)

Hybrids

Several research teams are using DNA to assemble structures from atoms or other molecules. To do this they synthesize artificial DNA strands that contain bases that connect to those atoms or molecules, then take DNA through its self-assembly paces.

Researchers from the University of Tokyo in Japan have made artificial DNA whose bases attach to metal ions, or charged atoms, and they programmed the DNA to organize the ions into tiny structures. (See "Artificial DNA Stacks Metal Atoms", page 12.)

Scientists have also been exploring the possibility of DNA conducting electricity. Conductive DNA could self-assemble into nanoscale circuitry.

Researchers from Brown University have engineered artificial DNA that contains zinc ions in order to make DNA behave like a semiconductor. (See "Metal Makes DNA More Conductive ", page 14.)

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Getting down to the basics

Other researchers are self-assembling structures using DNA bases rather than whole strands.

Purdue University researchers are using two of the bases that make up DNA to automatically assemble organic nanotubes. (See "DNA Parts Made Versatile Nanotubes", page 13.)

Researchers from the Italian Universities of Lecce and Bologna have coaxed a transistor semiconductor channel to self-assemble from guanosine, a derivative of the DNA base guanine. (See "DNA Part Makes Transistor", page 12.)

DNA's self-assembly abilities could be tapped for practical uses in as soon as five years.

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Proteins

Proteins, which direct many of life's processes, can also be conscripted to cause materials to self-assemble. Researchers have genetically engineered viruses and bacteria to produce proteins tailored to this purpose.

Researchers from NASA, the SETI Institute and Argonne National Laboratory have genetically modified a type of bacteria that lives in geothermal hot springs to cause it to produce a protein that automatically attaches to and constructs orderly arrays from microscopic bits of gold or zinc. (See "Altered Protein Orders Metal Bits", page 15.)

Researchers from Tel Aviv University in Israel have used a peptide involved in Alzheimer's disease to form nanotubes that they then used as molds to form silver nanowires. A research team from the Massachusetts Institute of Technology and Boston University has designed peptides that self-assemble into nanotubes and woven nanofibers.

The peptide-producing virus technique could be used practically in five to ten years. The geothermal bacteria protein could find practical use in two to five years.

Catching a bug — and putting it to work

Other researchers are using whole viruses to carry out nanoscale construction. A virus is little more than DNA or RNA surrounded by a protein shell.

A research team from the University of Texas at Austin that is now at the Massachusetts Institute of Technology has engineered viruses to contain peptides that bind to nanoparticles of semiconductor, magnetic, optical and biocompatible materials. The researchers have demonstrated that the viruses will bind to nanoparticles and assemble, along with the nanoparticles, into uniform patterned films. (See "Viruses Make Tech Materials", page 17; "Nature Nurtures Nanotech", page 19.)

Researchers from the University of Bristol in England, Vanderbilt University, and the University of Maryland have devised a method to automatically fill or coat a long, cylindrical tobacco virus with metal particles. (See "Researchers Fill Virus with Metal", page 17.)

And researchers from the Scripps Research Institute have shown that a plant virus, the cowpea mosaic, is a ready-made nano building block. The researchers showed that the virus' protein coat has 60 identical sites where other molecules can connect, that the virus' protein shell can, in principle, be loaded with other substances, and that the virus can be genetically modified.

Using viruses to assemble materials could become practical in 5 to 20 years.

Better building through organic chemistry

Researchers are also working on making materials self-assemble from nonbiological molecules. Given the right materials, conditions, and order, it may be possible to produce materials and electronic devices simply by mixing chemicals.

Organic chemistry is well-suited to designing structures. Mixing up a batch of electronic devices, however, is challenging because it's difficult to find materials that readily form structures and also easily conduct electricity.

The principal approaches to organic self-assembly involve polymers, liquid crystals and individual molecules.

Chain reactions

Polymers, which make up plastics, rubber and cellulose, are long chains of molecules that form when short constituent molecules link up. Researchers are gaining more control over the polymerization process, which is allowing them to make nanoscale structures rather than just bulk materials. (See "How It Works," page 2.)

Researchers from the University of Pennsylvania have found a way to cause an electrical conductor and an electrical insulator to combine into microscopic insulated wires. The method produces a batch of trillions of nanowires arranged vertically in a thin plastic film. (See "Chemists Brew Tiny Wires", page 20.)

Scientists from the National Research Council of Canada have found a way to chemically produce single-molecule-wide straight lines across silicon surfaces. The lines could be used as molecular wires or as templates. (See "Chemical Reactions Zips Nanowires onto Silicon", page 22.)

Researchers from Purdue University have found a way to coat nanoparticles with a molecule that prevents the nanoparticles from clumping together and can also bind to other chemicals such as pharmaceuticals. (See "Coated Specks Form Nano Building Blocks", page 22.)

Scientists from the University of Massachusetts and IBM Research have caused nanoscale cylinders of the polymer used to make plexiglass to form into an array embedded in the polymer used to make styrofoam. They removed the cylinders to produce a mask, or thin film containing regularly-spaced holes. The mask was used to make capacitors for random access memory chips. The holes are as small as 30 nanometers across, which is an order of magnitude smaller than those made using traditional manufacturing methods. (See "Plastic Makes Helps Shrink Circuits", page 23.)

The plastic-coated nanowire method from the University of Pennsylvania and the coated nanoparticle method from Purdue University could find practical use within two years; the other self-assembly methods could be used practically in one or two decades.

Liquid crystals

Liquid crystals are similar to polymers, but instead of linking together, the molecules become aligned at certain temperatures or in the presence of an electric field. Liquid crystals are neither solid nor liquid, but somewhere between.

Researchers from Sheffield University in England and the University of Pennsylvania have developed a geometrical model that relates the shape of liquid crystal molecules to the way they grow. The researchers used the model to form liquid crystals that self-assemble into specific shapes, including a type of liquid crystal bigger than any previously known. (See "Liquid Crystals Go 3D", page 24.)

Designer liquid crystals could be ready for practical application in five to ten years.

Natures building blocks — one at a time

At the nanoscale, even a single molecule can be useful. Molecules can be made in a variety of shapes, can be made so that they readily connect to one another, and can serve as a ready-made semiconductor nanowires.

Researchers from the Japanese National Institute for Materials Science and the Japanese Communications Research Laboratory have found a way to build structures from ring-shaped porphyrin molecules, which are related to the natural molecules hemoglobin and chlorophyll. The researchers have used the technique to make wires as fine as three nanometers wide. (See "Chemists Create Nano Toolkit", page 25.)

One of the challenges of using molecules as electrical components is figuring out how to connect them to form electrical circuits. Researchers from Arizona State University and Motorola, Inc. have found a way to chemically bond each end of a molecule to a metal conductor. (See "Molecule Connects Contacts", page 26.)

Several research teams are exploring ways to tap DNA and other molecules to link carbon nanotubes and semiconductor nanowires into structures. Nanotubes are rolled-up sheets of carbon atoms that form naturally in soot and can be as narrow as one nanometer. Researchers have been able to cause molecules to bond to the surfaces of nanotubes and are working out ways to cause these functionalized nanotubes to self-assemble.

Molecules could be used as practical nanotechnology components in 5 to 10 years.

Order and growth

Researchers are also turning to inorganic materials to make minuscule structures. Metals and semiconductors naturally form in precisely ordered crystal structures, but lack the structural variety and binding capabilities of organic molecules.

Metals and semiconductors are the bedrock materials of electronics, however, so there is a lot of incentive to incorporate them into self-assembly techniques. Metal and semiconductor nanoparticles — clumps of material that range a little larger than molecules — are particularly useful, either on their own or with organic molecules. Metals readily conduct electricity, and semiconductors, which are critical to computer chips, can be tuned to conduct or block an electrical current.

Sowing crystals seeds

Nanoparticles can serve as both structural building blocks and electronic components.

Researchers regularly form gold nanoparticles that can be directed to aggregate into nanowires. Researchers also regularly attach gold nanoparticles to individual organic molecules, often as a means of tethering the nanoparticles to a surface and providing electrical contacts for molecules that act as electrical switches.

Nanocrystals are nanoparticle-sized structures that can form and bulk metals or semiconductors. Orderly rows of silicon nanocrystals could be used to build circuits and devices several times smaller than today's manufacturing processes can produce. Semiconductor nanocrystals are also used as quantum dots that trap single electrons. Quantum dots are used in lasers and light-emitting diodes, prototype data storage devices, and quantum computing experiments.

Researchers from the University of California at Santa Barbara have devised a method of making quantum dots form in precise locations by adding strain to different layers of a material. The quantum dots ranged from 27 to 45 nanometers in diameter and 4 to 10 nanometers high. (See "Sowing Strain Reaps Orderd Dots", page 27.)

University of Rochester researchers have found a way to coax silicon nanocrystals sized from 4.2 to 50 nanometers to grow in orderly rows. They were also able to make the crystals form in specific shapes — rounded, square, and rectangular. (See "Tiny Silicon Crystals Loom Large ", page 27.)

Alchemy

Using elemental metals rather than molecules makes for three sizes of building blocks rather than just one: atoms, nanoparticles or nanocrystals, and microparticles. Metal atoms are around one-third of a nanometer in diameter. Nanoparticles and nanocrystals range from 1 to 1,000 nanometers and microparticles range from 1,000 to 1,000,000 nanometers, or 1 to 1,000 microns. In contrast, organic molecules tend to range from 2 to 10 nanometers long, although certain types, including DNA, can be much longer. It is also difficult to make particle-sized collections of organic molecules. The magnetic and electrical properties of metals are also particularly useful.

An international team of scientists has found a way to coax evenly-distributed clusters of metal atoms, including indium, manganese, and silver, to automatically form on the surface of a silicon wafer. (See "Chip Keeps Atoms in Line", page 28.)

A group of researchers from the University of Maryland has found a way to control the oxidation process in order to cause buckles, or tips, to form uniformly on the surface of oxidizing metals. (See "Bumps Could Make Better Biochips", page 30.)

Researchers from North Carolina State University have devised a way to use alternating current to make water suffused with microscopic gold particles form tiny, self-repairing wires. Because the process happens in water, it could eventually be used to connect aqueous structures like cells to electronic devices. (See "Electrified Water Spins Gold into Water", page 31.)

Researchers from Argonne National Laboratory and the Russian Academy of Sciences have found a way to use electricity to shake 120-micron bronze spheres into ring and honeycomb patterns. (See "Juiced Liquid Jolts Metal into Shapes", page 32.)

These methods could be used in practical applications in 5 to 10 years.

An organizing principle

Though self-assembly is particularly well-suited to nanotechnology, it is a broader concept that is not necessarily tied to the small-scale.

Harvard University researchers have caused a small cylindrical display containing 113 light-emitting diodes to self-assemble in a process that's not unlike making a cocktail. They attached the 280-micron-square diodes to an array of 113 copper squares by immersing them all in hot water and gently shaking the vial by hand for a couple of minutes. (See "Shake and Serve", page 32.)

Researchers from the Canadian National Research Council and the University of Waterloo have made a computer simulation that explores the self-replication process using strings of symbols that work as simplified, virtual DNA. This could lay the groundwork for inexpensive and flexible manufacturing processes that borrow from life's vast experience in self-assembly processes. (See "Virtual DNA Replicates", page 33.)

Researchers from Humboldt University in Germany have worked out a way for electronic agents to efficiently assemble a network without having to use a central plan. The system, which could eventually be used to coordinate self-assembling circuits, is modeled on the methods of insects and bacteria whose communications lack central planning, but form networks when individuals secrete and respond to chemical trails. (See "Network Builds Itself from Scratch", page 35.)

The LED display self-assembly techniques could be practical in 5 to 10 years. It is likely to be more than 10 years before DNA manufacturing methods become practical.

Delivering on the nanotech promise

It seems inevitable that self-assembly will become a major technology simply because it is the most efficient and cost-effective method for constructing the nanoscale structures that are poised to play leading roles in biotechnology and computing in a decade or so.

Self-assembly as a technology is in its infancy, only a few steps removed from its roots in the centuries-old discipline of chemistry. Researchers have a lot of work to do to develop a broad repertoire of molecules and particles for technological uses.

The technology is likely to play an increasingly important role as nanotechnology gains traction in areas like photonics, data storage, drug delivery and biochemical sensors. A decade from now self-assembly could simply be the way nanotechnology is done.

Self-assembling the far future

The ultimate in self-assembly is the replicator of science fiction's Star Trek, a machine that makes food and handtools from energy and a molecular plan of the desired object.

Short of that fantasy, self-assembly holds the promise of being able to program materials so that they assemble automatically into highly complex machines like cars and computers. It is possible that building a machine will one day come down to designing a DNA-like molecule, turning it loose in a vat of the right liquid mix and watching the object emerge.

But setting automatic processes loose also poses potential problems. The worst nightmare has been the stuff of science fiction doomsday scenarios since the ice-nine of Kurt Vonnegut's Cat's Cradle. If nanoscale machines were able to replicate themselves automatically by harvesting matter and energy from the environment, what's to stop them from proliferating until nothing else remains on the planet's surface? Only time, and further research, will tell.

Recent Key Developments

Advances in DNA:

- A method of assembling cross-shaped DNA tiles into sheets and ribbons (DNA forms nano waffles, page 10)
- A method of stacking DNA strands to form barcode patterns (DNA makes nano barcode, page 11)
- A transistor channel made from ribbons of the DNA base guanosine (DNA part makes transistor, page 12)
- Artificial DNA strands that form a double helix containing copper ions (Artificial DNA stacks metal atoms, page 12)
- A method of assembling three-dimensional shapes from DNA tiles (Nanotech scheme envisions DNA origami, page 12)
- A method for organizing gold nanoparticles using DNA scaffolding, University of Minnesota, February 2003
- A method for replicating three-dimensional DNA tiles, Ruhr-Universität-Bochum in Germany and Nanogen Recognomics GmbH in Germany, November 2002
- A method of assembling nanotubes from the DNA bases guanine and cytosine (DNA parts make versatile nanotubes, page 13)
- A semiconductor material made from DNA strands that contain zinc ions (Metal makes DNA more conductive, page 14)

Advances in viruses and proteins:

- A method for ordering lipids on carbon nanotube surfaces, French Atomic Energy Commission, Institute of Genetics and Molecular and Cellular Biology in France, Louis Pasteur University in France and the French National Center for Scientific Research, May 2003
- A method for casting metal nanowires in peptides nanotubes, Tel Aviv University in Israel, April 2003
- A method of using tube-shaped proteins to form arrays of metal nanoparticles (Altered protein orders metal bits, page 15)
- A method for filling viruses with metal nanoparticles (Researchers fill virus with metal, page 17)
- Liquid crystal, semiconductor, magnetic and optical materials made from virus peptides (Viruses make tech materials, page 17)
- A method for forming nanotubes from peptides, Massachusetts Institute of Technology and Boston University, April 2002
- A method for bonding semiconductor nanoparticles using virus peptides (Nature nurtures nanotech, page 19)

Advances in polymers:

- A method for forming insulated electrically conductive nanowires from branch to polymers (Chemists brew tiny wires, page 20)
- A polymer film for converting electrical signals to optical signals, Virginia Tech, April 2002
- A method for forming polymer nanowires in a thin film (Chain reaction yields microscopic wires, page 21)
- A method for forming polymer nanowires onto silicon surfaces (Chemical reaction zips nanowires onto silicon, page 22)
- A method for coating semiconductor nanoparticles in a polymer (Coated specks form nano building blocks, page 22)
- A mask for chipmaking made from a pair of polymers (Plastic mix helps shrink circuits, page 23)

Advances in molecules:

- A method for patterningcarbon nanotubes on a surface using organic molecules, Florida State University, September 2003
- A method for forming honeycomb patterns in single-molecule layers that organize carbon buckyballs, University of Nottingham in England, August 2003
- A chemical model for making large, three-dimensional liquid crystals (Liquid crystals go 3D, page 24)
- A method for linking carbon nanotubes using individual molecules, Max Planck Institute in Germany and Infineon Technologies AG in Germany, May 2002
- A method for making nanoscale molecular rings and wires on a gold surface (Chemists create nano tool kit, page 25)
- A method for connecting gold nanoparticles to a gold surface using individual molecules (Molecule connects contacts, page 26)

Advances in semiconductors and metals:

- A method for structuring metal surfaces on the nanoscale using organic molecules, University of Aarhus in Denmark and the French National Center for Scientific Research, April 2002
- A method for forming regularly spaced arrays of quantum dots (Sowing strain reaps ordered dots, page 27)
- A method for growing silicon nanocrystals (Tiny silicon crystals loom large, page 27)
- A method for positioning metal atoms on a silicon surface (Chip keeps atoms in line, page 28)
- A method for growing ordered microscopic metal oxide peaks (Bumps could make better biochips, page 30)
- A method for growing microscopic gold wires in solution (Electrified water spins gold into wire, page 31)
- A method for arranging metal particles into shapes using electrified liquid (Juiced liquid jolts metal into shapes, page 32)

Advances in scope and scale:

- A method for forming millimeter-scale spiral-shaped electrical circuits from plastic building blocks using the capillary interactions between drops of molten solder, Harvard University, April 2002
- A method for assembling electronic devices by agitating a liquid containing components (Shake and serve, page 32)
- Virtual DNA-like objects that replicate themselves (Virtual DNA replicates, page 33)
- A biologically-inspired method for self-assembling networks (Network builds itself from scratch, page 35)

DNA

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.

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

DNA Makes Nano Barcode

By Kimberly Patch, Technology Research News
July 2/9, 2003

To keep Moore's Law going—the tenet that computer speed will roughly double every 18 months— manufacturers must make faster circuits, and that usually means making them smaller. If an electronic signal has less distance to travel, it will make the trip more quickly.

But as the components that make up electronic devices grow smaller it is becoming increasingly difficult for manufacturers to assemble them using traditional lithography methods, which employ light and chemicals to etch materials into shape. The transistors that form the bulk of the Pentium 4 computer chip, for instance, are already about 130 nanometers across, which is one-tenth the girth of an E. coli bacterium, or about the size of a row of 1,300 hydrogen atoms.

Lithography is ultimately limited in scale to the wavelength of light, said John Reif, a professor of computer science at Duke University. "Within one or two decades, the ultimate limitations of these top-down patterning methods will be reached," he said.

Another tack is assembling materials from the bottom up—molecule-by-molecule.

Reif and several colleagues at Duke University have moved the bottom-up method a step forward by programming strands of synthetic DNA to self-assemble into a structure that makes the pattern encoded in a DNA strand readable by microscope.

Key to the method is coaxing columns of looped and non-looped strands of DNA stack into a barcode-like lattice.

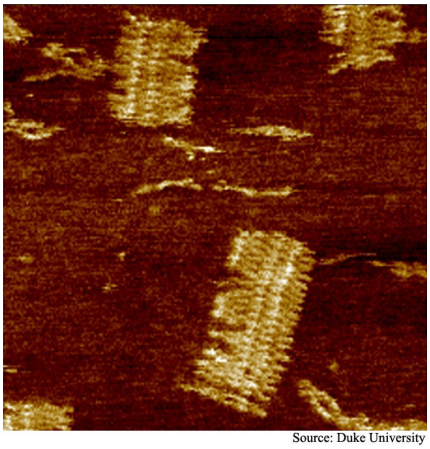
DNA is made up of sequences of four bases - adenine, cytosine, guanine and thymine—attached to a sugar-phosphate backbone. Complementary bases combine — thiamine with adenine, and cytosine with guanine—to form the familiar double-stranded helix of biological DNA.

The researchers used a single DNA "scaffolding" strand that contained sections of base sequences that were complementary to portions of DNA barcoding strands. They used two types of DNA barcoding strands—strands that contained hairpin loops, and strands that did not. The barcoding strands also contained sections of base sequences that caused barcoding strands to combine with like barcoding strands.

The researchers mixed the scaffolding strand with barcoding strands to form a two-dimensional lattice, with an initial row of barcoding strands ordered by the scaffolding strand and additional barcoding strands stacked up on the originals, forming columns with loops and columns without loops. The columns were large enough that they could be sensed with an atomic force microscope and read like a barcode. "The barcode patterns... are determined by a scaffold strand of synthetic DNA. The other strands of DNA assemble around the scaffold strand to form the 2D barcode patterned lattice," said Reif.

The researchers programmed the process to produce two different barcodes — 01101 and 10010. The prototype DNA barcodes stored the five bits of information in a 75-nanometer long lattice of DNA.

The method is "a nice advance in assembling nano-objects," said David Harlan Wood, a professor of computer science at the University of Delaware. The ability to directly observe the assembly by looking through a microscope at the loops makes nano construction more practical, he said. "Readout techniques are sorely needed for DNA computing," he added.



Source: Duke University

Stacks of DNA strands form microscopic sheets to produce bar code-like patterns that reveal data encoded in an initial strand of DNA.

This type of readout, however, is limited by the number of distinct objects. "When many multiple molecules are important, other methods, such as biochips, may be more appropriate," said Wood.

The method could eventually be used to make templates that will enable molecule-by-molecule construction of electronic circuits, said Reif. The process should yield more complicated patterns than columns if the scaffolding strand is wound back and forth, according to Reif. "Using these patterned DNA lattices as scaffolds, we intend... to self-assemble molecular electronic circuit components... with the goal of forming molecular-scale electronic circuitry," said Reif.

Molecular electronics and robotics components can be precisely positioned at specific locations on such a scaffolding, according to Reif.

There have been notable successes in constructing individual molecular components like carbon nanotubes, said Reif. The DNA scaffolding is one way to hold, shape and assemble these molecular components into complex machines and systems, he said.

The method could be ready for practical use in five to eight years, according to Reif.

Reif's research colleagues were Hao Yan, Thomas H. LaBean and Liping Feng. The work appeared in the June 23, 2003 Proceedings of the National Academy of Sciences. The research was funded by the Defense Advanced Research Projects Agency (DARPA), the Air Force Office of Scientific Research (AFOSR), and the National Science Foundation (NSF).

Timeline: 5-8 years
Funding: Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing; Nanotechnology
Story Type: News
Related Elements: Technical paper, "Directed Nucleation Assembly of DNA Tile Complexes for Barcode-Patterned Lattices," Proceedings of the National Academy Of Sciences, June 23, 2003

TRN

DNA Part Makes Transistor

Technology Research News, June 4/11, 2003

Researchers from the University of Lecce in Italy and the University of Bologna in Italy have produced a transistor made from a derivative of one of the four bases that make up DNA.

The field-effect transistor, which carries electricity from a source electrode to a drain electrode when turned on by a gate electrode, is made from a group of guanosine bases the researchers coaxed to self-assemble into orderly ribbons. The researchers used beams of electrons to etch metal electrodes 20 nanometers apart. They then coaxed a layer of guanosine to form between the electrodes.

The researchers measured a maximum voltage gain of 0.76 for their tiny transistor, which is relatively high for a molecular device, though low compared to standard transistors. Gain is critical for keeping signals from fading. The transistor also operates well at room temperature.

The device, at a few hundred nanometers, is close to the size of today's silicon transistors. The self-assembling nature of the molecular layer means guanosine-based transistors could be manufactured in large numbers at low cost, according to the researchers.

The researchers are working on improving the device's electrical properties and long-term stability.

The work appeared in the April 9, 2003 issue of *Nano 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.

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

Nanotech Scheme Envisions DNA Origami

By Kimberly Patch, Technology Research News
February 13, 2002

The key to coaxing DNA, which provides the biological instructions for all life on earth, to construct microscopic machines is getting it to follow new instructions.

Biological DNA uses four molecular bases as a kind of code, and unfolds itself to replicate portions of the code when a cell needs to carry out particular instructions.

Researchers at Yale University and Northwestern University have come up with a scheme to combine DNA tiles to form three-dimensional structures. DNA tiles are squares of artificial DNA that can be used to compute.

The method points to a precise way to build molecular-size, three-dimensional objects. The scheme could also eventually carry out certain types of computations more quickly than is possible using today's methods.

The key to the three-dimensional self-assembly theory was coming up with a way to make every DNA tile used in a shape unique, said Vijay Ramachandran, a graduate student at Yale University. "DNA tiles can be thought of as puzzle pieces. Each of the four sides of the square has an exposed DNA sequence... the unique pattern that joins with some other puzzle piece, or maybe a border that joins with nothing at all," he said.

DNA tiles can be produced in the laboratory from made-to-order DNA sequences. "The key is designing the tiles so that they form the correct shape. Once a flat shape is formed, parts of the shape [connect to] each other, and the shape folds into a box," he said.

"We needed a way to make every shape... unique, but still make the edges within the shape... correspond so the shape could fold," said Ramachandran. The researchers came up with an algorithm that uses randomness to build a hollow cube, he said.

Different copies of the tiles have unique sticky ends, or portions of single strands of DNA that can connect to other single strands, according to Ramachandran. The algorithm generates the random sequences of DNA that make up these complementary sticky ends. The algorithm also ensures that the DNA will not stick in the wrong places, he said. "We identified the steps needed to produce shapes in solution, using a reasonable number of tiles that will not stick to each other," he said.

The researchers also looked into the way temperature can be used cut down on the number of steps needed to construct the DNA boxes. "We also tried to introduce the use of other laboratory procedures, such as using temperature to prevent or induce the binding of tiles in solution," said Ramachandran.

The method could be used as a framework for building other precise three-dimensional shapes using DNA tiles, he said.

The researchers also worked out a set of guidelines that analyze this type of algorithm, according to Ramachandran. Those measures are designed to make it easier to come up with further algorithms for three-dimensional DNA self-assembly.

"I like the idea that the authors are approaching 3D systems," said Nadrian Seeman a chemistry professor at New York University. It is difficult to judge how useful it is because the theory lacks experimental backing, however. "It would be a stronger contribution if 3-D systems had been achieved first... so that we would know more about potentially viable and inviable structural alternatives," he said.

It is difficult to know when the method could be tested in the laboratory, said Ramachandran. "Our method requires... procedures that are more complex than those currently used for computation in the lab. It is hard to tell when... implementing this idea will be possible," he said.

In addition, in order to actually carry out the three-dimensional self-assembly, a stronger type of DNA tile may be needed, according to Ramachandran.

Ramachandran's research colleague was Ming-Yang Kao of Northwestern University. The research was funded by the National Science Foundation (NSF) and the Department of Defense (DoD).

Timeline: Unknown
Funding: Government
TRN Categories: Biological, Chemical, DNA and Molecular Computing
Story Type: News Related Elements: Technical paper, "DNA Self-assembly for Constructing 3D Boxes," posted in the arXiv physics archive at arxiv.org/abs/cs.CC/0112009

TRN

DNA Parts Make Versatile Nanotubes

By Chhavi Sachdev, Technology Research News
June 6, 2001

The perfect material for a nanoscale circuit would not only readily assemble itself, but would also have adjustable physical and chemical properties. Researchers at Purdue University have come close to that ideal with organic nanotubes that can be mass-produced and whose properties can be predetermined.

The key to these prodigious nanotubes is that they are not made of carbon. Instead, the researchers' rosette nanotubes are built from two of the bases that make up DNA.

Regular carbon nanotubes self-assemble when graphite sheets roll up. The organic rosette nanotubes, which, like DNA, form in water, self-assemble when rings of atoms stack up, forming a hollow channel in the middle.

Each stacked ring of the rosette nanotube is a supermacrocycle—a ring of atoms held by non-covalent hydrogen bonds. Each supermacrocycle has six segments.

Each segment, or module, is made of guanine and cytosine bases and amino acids. The rings are rosette-shaped, like a flower with six petals.

The rosette nanotubes assemble spontaneously because parts of the module are water-repellent and parts are attracted to water. In trying to keep their water-repellent ends away from the water, the modules align themselves so that their

water-loving ends face outside, and the water-repellent ends inside, forming a ring. The rings then stack together to form a tube.

"The reason they stack up is because they don't like to get wet," said researcher Hicham Fenniri, an assistant professor of chemistry at Purdue University. "They repel water and prefer to interact with themselves. The hydrophobic and electrostatic interactions help keep the nanotube stable."

Self-assembly is a key goal in making machines at the molecular scale because it allows fairly large and complex structures to come together in a single, largely error-free step. "It is almost a Darwinian chemistry," said Fenniri. "If a module is not chemically fit, it will not be incorporated in the nanotube structure," he said.

Another benefit of self-assembly is high yield. "The chemistry used to make these tubes is scalable using standard industrial processes," said Fenniri. A small-scale industrial plant could produce up to 500 kilograms of the rosette nanotubes in a month, according to the researchers.

Rosette nanotubes are also chemically versatile. Researchers can specify the chemical properties of the nanotubes before production because "the properties of the modules they are made of can be altered at will," said Fenniri. The modules can be tuned to transmit light or electricity, for instance, he said.

The researchers can also specify the dimensions of the tubes. "Our tubes vary in length from one nanometer to several microns," he said.

Although rosette nanotubes are relatively strong, they are not as strong as carbon nanotubes. Where there is high mechanical stress, "carbon nanotubes may be more advantageous," said Fenniri. "However, the rosette nanotubes can be modified to become mechanically very strong—several orders of magnitude stronger than nylon, for instance," he added.

Rosette nanotubes could eventually be used as fibers in new plastic-like materials or as electronic wires in computing devices, according to the researchers.

Rosette nanotubes with light-transmitting properties could be used in light-emitting devices or in solar energy transport and conversion. Since the tubes assemble in water, they could also have biological applications such as internal drug delivery, according to the researchers.

Another important use for the rosette nanotubes could be as a template for tiny nanowires, said Deepak Srivastava, a senior scientist at NASA's Ames Research Center. "If you can fill up the cavity with metal, then the metal will harden, and at that point you can wash away or dissolve the tube part [to leave behind] metal nanowires or semiconductor nanowires," he said.

"This is a major advance in the preparation of nanotubes in aqueous environments," said Steven Kornguth, a professor of neurobiology at The University of Texas, Austin. The tubes' adaptability is important, according to Kornguth. "The internal cavity of the rosette may serve as a locus for insertion of metals that will alter [their] conducting properties," he said. Their ability to anchor on to surfaces for use in photonic or electronic conduction applications may also prove useful, he said.

The researchers are currently working on making the nanotubes as long as a millimeter. The research could be applied practically within the next two years, according to Fenniri.

Fenniri's colleagues were Packiarajan Mathivanan, Kenrick L. Vidale, Debra M. Sherman, Klaas Hallenga, Karl V. Wood, and Joseph G. Stowell of Purdue University. The paper was published in the Journal of the American Chemical Society, April 25, 2001. The research was funded by the National Science Foundation (NSF), the American Chemical Society, the Showalter Foundation, Research Corporation, the American Cancer Society, 3M, and Purdue University.

Timeline: < 2 years
Funding: Institute; Corporate; University
TRN Categories: Biological, Chemical, DNA and Molecular Computing
Story Type: News
Related Elements: Technical paper, " Helical Rosette Nanotubes: Design, Self-Assembly, and Characterization," Journal of the American Chemical Society, April 25, 2001: www.chem.purdue.edu/hf/NANOTUBEpaper.pdf

TRN

Metal Makes DNA More Conductive

By Chhavi Sachdev, Technology Research News
May 2/9, 2001

For several years, scientists have explored ways to make DNA conduct electricity. DNA's size and ability to arrange itself, or self-assemble, would make conductive DNA a valuable material for nanoscale circuitry.

One group of researchers has replaced parts of DNA's base pairs with metal ions in order to allow electrons to flow through the molecule.

Biological DNA, found in the nucleus of every cell, is essentially composed of long strands of four bases— adenine, guanine, cytosine, and thymine. The researchers engineered the conductive DNA by coaxing the base pairs to exchange a proton for a zinc ion. The addition of metal made DNA behave like a semiconductor.

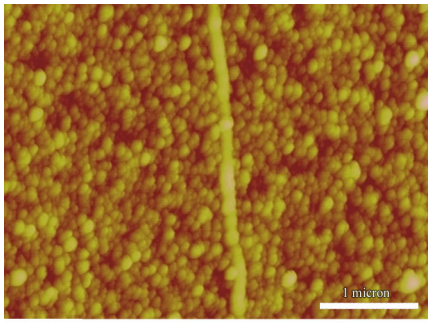
"The substitution of the imino proton with a zinc ion makes the DNA hundreds of times more conductive," said researcher Jimmy Xu, an engineering and physics professor at Brown University.

The engineered DNA could eventually be used in microelectronics where there is a need for tiny, self-assembling conductors. The DNA could be the basis for "a new material

system that can be controllably produced, whose properties can be…engineered, and whose ensemble can self-organize into functional structures and can collectively process massive amount of information," said Xu.

"DNA is the basic and best understood building block—a perfect place to start engineering," he said.

Engineering DNA molecules to accept the zinc was relatively simple, according to Xu. Previous research by team member Jeremy Lee, a biochemistry professor at the University of Saskatchewan, had already established that DNA readily absorbs ions of zinc, nickel and cobalt at high pH levels.



Source: Brown University

This microscope image shows a bundle of metallic DNA, composed of about 300 individual DNA strands, on a gold electrode. The bundle is about 100 nanometers wide and ranges from 20 to 30 nanometers in height.

Xu's team raised the DNA's pH level to 9.0 by adding zinc ions containing acids to a test tube of DNA. The DNA molecules released the imino protons in their base pairs and took up zinc ions instead, resulting in a modified, metallic compound DNA , or M-DNA.

The conductivity of any substance depends on the placement and number of electrons in its energy bands. The wider the energy bands of a molecule, the faster the electrons move; the faster the movement of electrons, the better the conductivity. Metals generally have wider bands than semiconductors, which have wider bands than insulators.

Biological DNA shows a band-gap of a few hundred millielectron volts at room temperature, according to the researchers. This gap is an energy barrier that any electron coming from the electrode would have to overcome before it could be conducted up the molecule, said Xu.

In contrast, M-DNA's "conduction band is wide and low enough in energy that the electrons from the electrode can move into [it] without difficulty," said Xu.

This difference makes metallic DNA an ideal nanoscale semiconductor, according to Xu.

"With semiconductors you have a set of base materials - building blocks - which can be turned into a vast array of useful devices and sensors, which, in turn, can be connected up to form circuits, processors, and computers," Xu said. The engineered DNA is a new material, "and new materials are technology enablers," he said.

Metallic DNA could also be used as a biosensor to screen, among other things, genetic aberrations and environmental toxins. Metallic DNA could be used in sensors in 3 to 5 years, Xu said.

"It is interesting work, but I think there still needs to be a lot done to structurally characterize this system," said Jacqueline K. Barton, a professor of chemistry at the California Institute of Technology.

It's the first time zinc has been studied in this way, said Mark Ratner, a professor of chemistry at Northwestern University. The work is "an intriguing and important contribution," but the other research in the field of conductive DNA has produced different results. "There is lots yet to be done," he said.

Other researchers are more skeptical about the findings. "[Xu and his colleagues] find a very low gap even for simple [biological] DNA, which contrasts [with] similar measurements by us and others where we find true insulating behavior at these length scales," said Cees Dekker, a professor of physics at the Delft University of Technology in the Netherlands.

Xu's research colleagues were Andrei Rakitin, Chris Papadopoulos, and Yuri Kobzar of Brown University;

Palok Aich and Jeremy S. Lee of the University of Saskatchewan; and Alex S.Vedeneev of the Russian Academy of Sciences. Their paper appeared in the journal *Physical Review Letters*, April 16, 2001.

The research was funded in part by the Canadian Institute for Advanced Research, the National Sciences and Engineering Council of Canada, Motorola, the Defense Advanced Research Projects Agency (DARPA), the Office of Naval Research, the National Science Foundation, and the Air Force Office of Scientific Research.

Timeline: 3 - 5 years
Funding: Government; Corporate
TRN Categories: Biological, Chemical, DNA and Molecular Computing
Story Type: News
Related Elements: Technical paper, " Metallic Conduction through Engineered DNA: DNA Nanoelectric Building Blocks" appeared in the journal *Physical Review Letters*, April 16, 2001

Viruses and Proteins

Altered Protein Orders Metal Bits

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

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

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

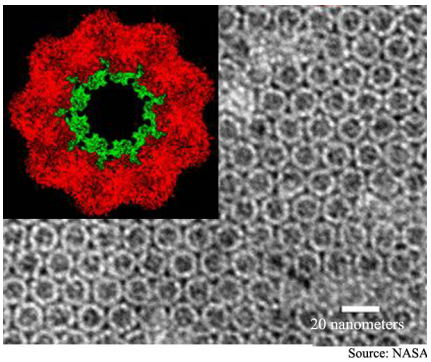
The altered bacteria gene produces a protein that automatically constructs orderly arrays of microscopic bits

of gold or zinc. The microscopic bits of metal can serve as quantum dots, which trap one or a few electrons, and can be used in electronics.

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

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

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



Source: NASA

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

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

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

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

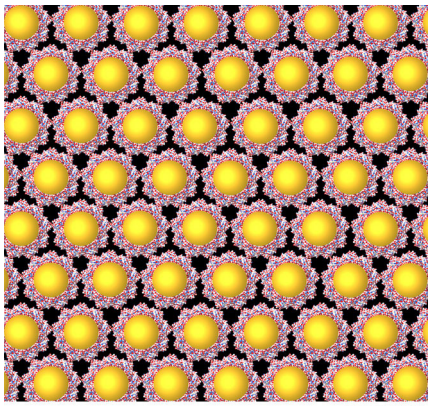
The researchers used one of the three types of proteins that make up the chaperonin subunits. They altered the Sulfolobus genes to produce a protein with a slightly different structure, then inserted the altered genes into common E. coli bacteria, which manufactured large amounts of the modified protein.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

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

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

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

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


Source: NASA

This shows the protein rings filled with microscopic specks of gold. The protein rings assemble themselves into arrays and capture gold specks, forming regularly spaced arrangements of the gold.

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

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

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

using block copolymer lithography and other competing technologies," he said.

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

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

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

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

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

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

Researchers Fill Virus with Metal

Technology Research News, May 7/14, 2003

One way to construct materials atom by atom is to conscript machinery nature has already devised.

Scientists have methods of making round particles that are as small as one nanometer, which is the span of 10 hydrogen atoms. But making more complicated shapes is more difficult.

Researchers from the University of Bristol in England, Vanderbilt University, and the University of Maryland have found that they can fill or coat a long, cylindrical tobacco virus with metal particles.

The method could eventually be used to manufacture structures like metal nanowires that could be used in electronics or optics devices, according to the researchers.

The researchers mixed the 4- by 300-nanometer virus with gold, silver and platinum salts. In an acidic pH solution, negatively-charged metal salts reacted with viral amino acids to cause nanoparticles to align on the outer surface of the virus. In a neutral pH solution, positively-charged salts passed through the viruses' protein coats, causing metal nanoparticles to align inside the viruses.

The researchers showed that mutating the amino acids affects where the metal particles deposit.

The method to be used practically in 10 to 20 years, according to the researchers. The work appeared in the March 12, 2003 issue of Nano Letters.

TRN

Viruses Make Tech Materials

By Kimberly Patch, Technology Research News
May 15/22, 2002

Viruses cause the human population such trouble because the microscopic parasites adapt and reproduce so quickly.

Researchers at the University of Texas at Austin have shown they can take advantage of these viral strong points by harnessing billions of the phages to build useful materials molecule-by-molecule.

The researchers engineered a particular type of long, narrow virus to contain a peptide with an affinity for zinc sulfide nano crystals, and showed that under the right conditions a mixture of virus and crystals will build itself into a liquid crystal film.

A peptide is a component of protein. Liquid crystals are long chains of molecules that uniformly line up to form crystal-like structures under the influence of an electric field. The liquid crystals commonly used in computer displays, for instance, shift their orientation in response to changes in the surrounding electric field in order to change the color of individual pixels on a screen.

It should be possible to use viruses to build many other types of useful materials, said Andrea Belcher, an assistant professor of chemistry and biochemistry at the University of Texas at Austin. "So far we have peptides for about 20 different types of materials," including semiconductor, magnetic, optical, and biocompatible materials, she said.

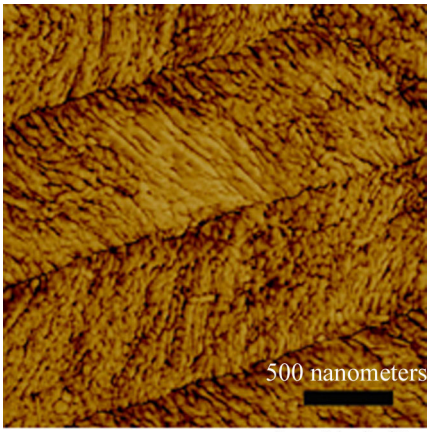
The method could lead to considerably cheaper, faster and environmentally-friendly manufacturing processes for electronics.

The research is inspired by the way nature works, Belcher said. "Biology makes material at moderate temperatures using self assembly, self correction [and] non-toxic materials," and does this quickly, she said.

The difficult part of the process is finding particular proteins that can bind and assemble materials like semiconductors,

said Belcher. The search for a protein to bind zinc sulfide took several months, she said.

"You have to choose proteins to work with, or evolve molecules to have the desired function. We have done a combination. We use a library of one billion different proteins and narrow down the ones that work the best," Belcher said. The challenge is "imagining the hard structure of the very small semiconductor nano particles and the soft structure of viruses at the same time," she said.



Source: University of Texas

Long viruses attached to microscopic particles of zinc sulfate have arranged themselves into a precisely patterned material.

Once the researchers found the protein with the characteristics needed to bind to zinc sulfate, they inserted a bit of DNA into a virus's genetic material to add the protein to its coat.

And once they had the requisite virus, it was relatively easy to replicate. "Once we have a protein attached to a virus that we know does what we're interested in... we infect it into bacteria and make many millions of copies," Belcher said. This takes two or three days.


Source: University of Texas

This square centimeter of clear material is made up of billions of viruses and microscopic particles.

The researchers then made a virus and zinc sulfide liquid crystal suspension, and within a week the material assembled itself into uniform films, said Belcher. The films are ordered at the nanometer scale, extend to several centimeters, and are stable enough to be picked up by forceps, she said.

The virus measures 6.6 by 880 nanometers, and zinc sulfide nanoparticles are three nanometers in diameter. The peptide that binds to the zinc sulfide nano particles is on one end of the virus and is about 10 nanometers long. A nanometer is one millionth of a millimeter; three nanometers is about the size of 30 hydrogen atoms lined up in a row. One square centimeter of film contains about 40 billion viruses, said Belcher.

The exact structure of the film depends on the concentration of the viruses in the liquid crystal suspension and the strength of the surrounding magnetic field, said Belcher. The proteins that make up the virus's outer coat are weakly magnetic, which causes a growing virus-nanoparticle complex to align with a magnetic field. "Different types of liquid crystals can be made by changing these physical properties," she said.

One type of film the researchers made was ordered into domains, or patterns that spanned 0.07 millimeters and repeated continuously. Materials with such small-scale patterns could be used to make storage devices.

The exact mechanism the peptides use to attach to the zinc particles is not yet known, but is probably a combination of chemical interactions and shape, said Belcher.

The researchers are looking to make more types of materials using the same methods. "We're looking at these materials to grow and arrange electronic, magnetic and optical materials for devices, displays and sensors," said Belcher.

They are also developing biotechnology applications, she said. The researchers used a solvent to dissolve a piece of seven-month-old film, and found that the virus was still viable. "After storage at room temperature for seven months, [the virus] can be reinfected into a bacteria cell and amplified again," Belcher said. This reversibility makes it possible to use the film to store genetically engineered DNA, she said.

Using viruses to construct material is "absolutely novel... nobody has done this," said Viola Vogel, a professor of bioengineering at the University of Washington, and director of the school's nanotechnology center.

The work "combines elegantly what we've known about liquid crystals [and] what [Belcher] discovered about specific recognition of peptides and semi-conducting nanoparticles into making a totally new class of materials," she said.

Although it is relatively easy to make nanoparticle building blocks, using them to construct the many precise, patterned layers of nanoparticles that make up a material is potentially very difficult and tedious. "What is needed is a way to make materials where order is maintained from layer to layer to layer without putting in too much labor," said Vogel. This is one of the big challenges in the field of nanotechnology; "using viruses is just a very elegant way" of addressing it, she said.

Most of the research is still at the basic science stage, said Belcher. A few practical applications are possible within five years, but most applications will take 10 years or longer to develop, she said.

Belcher's research colleagues were Seung-Wuk Lee, Chuanbin Mao and Christine E. Flynn. They published the research in the May 3, 2002 issue of the journal Science. The research was funded by the Army Research Office, the National Science Foundation (NSF) and the Robert A. Welch Foundation.

Timeline: 5-10 years
Funding: Government, Institute

TRN Categories: Nanotechnology; Biotechnology; Materials Science and
Engineering; Semiconductors
Story Type: News Related Elements: Technical paper, "Ordering of Quantum Dots using Genetically Engineered Viruses," Science, May 3, 2002

TRN

Nature Nurtures Nanotech

By Kimberly Patch, Technology Research News
June 21, 2000

Taking a cue from seashell construction, University of Texas researchers are harnessing natural growth processes to make tiny biocomposite building blocks that engineers could one day use to build nanoscale electronic devices.

Using a stock of 100 million viruses engineered to include various peptides as part of their protein coats, researchers isolated several whose peptides were able to combine well with semiconductor materials gallium arsenide, silicon, indium phosphides and zinc selenide.

The idea was inspired by the way nature makes materials, said Angela M. Belcher of UT Austin's department of chemistry and biochemistry and the UT Austin Texas Materials Institute.

Shell and bone are constructed of a combination of organic and inorganic materials and can be up to 90 percent inorganic. Belcher is finding organic materials that have affinities for inorganic materials that are not generally used by living organisms but are useful to the electronics industry—like semiconductors and magnetic and optical materials.

"Abalones grow shells [by using] nanostructures of calcium carbonate with perfect precision. It seemed [logical] to see if we could harness some of that same potential... to assemble materials that may be technologically important," said Belcher, whose research team includes Sandra R. Whaley, Paul F. Barbara and Douglas S. English.

Building electronic components this way has two distinct advantages. First nature's "amazing ability to assemble on a very small scale" addresses looming size limitations in current semiconductor manufacturing, said Belcher.

Second, natural processes make for very skilled building. "Nature's precise, and were trying to be able to capture that amount of precision," she said. "What we've proven by these experiments is that we can have a precision over selecting one crystal versus another on the same level that has evolved in organisms."

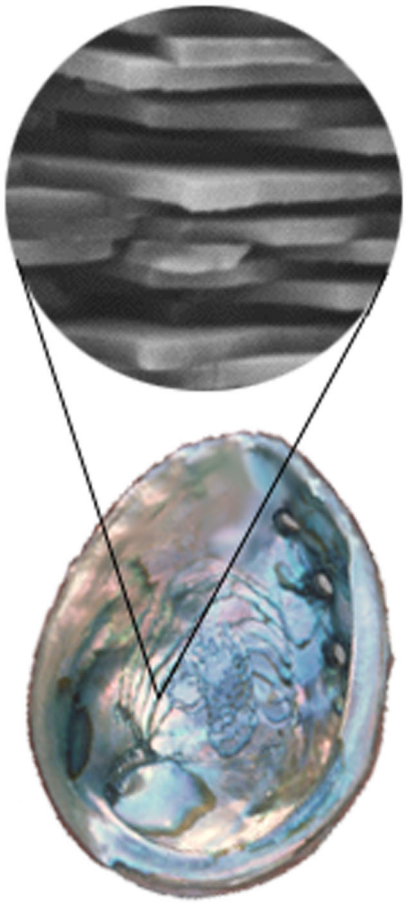
"It's very interesting stuff—a lot of important things are going to come out of coupling natural systems and inorganic systems," said Mark Thompson, professor of chemistry at the University of Southern California in Los Angeles. "Instead of having to build [nanostructures one molecule] at a time, she can build viruses [to do] the assembly work, and the piecing together work."

Viruses are also "easy to grow and replicate and we know a lot about the structures of viruses and how to manipulate viruses," Thompson added

To isolate the viruses that were able to combine with the semiconductors, Belcher and her colleagues went through several generations of experiments, selecting for a tight bond between a virus's peptides and an inorganic material, and for "clean specificity," meaning that the viruses were able to pick the right material and reject similar materials.

They also found viruses that bound only to a specific crystal structure and rejected the same material when it was structured differently. Different crystal faces of gallium arsenide, for example, are chemically different. "They're all made out of gallium and arsenic, but on different faces the atoms are arranged differently, and our peptides can recognize specific faces," Belcher said.

The semiconductor experiments selected for a tight bond, but another potentially useful trait for natural particle manufacture is an ability to drop the material at a certain time, so the researchers are also working with virus strains that show various gripping abilities. Too strong a bond, for instance, may hinder an application that uses peptides to deliver nanoparticles to a particular area of a wafer, said Belcher.



Source: University of Texas

An electron microscope image of a portion of an abalone shell shows the layered construction of natural biocomposites

In addition, the researchers are working with viruses that can grow semiconductor nanoparticles. "We eventually want to... not only bind particles and move them around, but grow particles from solution. And so we are [selecting] for things that nucleate, or grow small particles exactly where you want them," Belcher said.

The researchers are also working with magnetic and optical materials to find peptides with an affinity for those materials, Belcher said.

Belcher and her colleagues ultimately hope to provide a set of proteins useful for integrating the biocomposite materials into electronic devices. "Were trying to develop tool kits that can be used to assemble materials," she said. The practical application of this research to manufacturing is probably at least 10 years away, she added.

Funding for the project came from the Defense Advanced Research Projects Agency, the National Science Foundation, the Robert A. Welch Foundation, the University of Texas Austin, and a Du Pont Young Investigator Award. A paper on the researchers' work on peptides and semiconductors was published in the June 8 issue of Nature magazine.

Timeline: > 10 years
Funding: Corporate, Government, Private and University
TRN Categories: Nanotechnology; Semiconductors and Maerials
Story Type: News
Related Elements: Technical paper, "PLACEHOLDER", Nature, June 8, 2000, p. 65

TRN

Polymers

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.

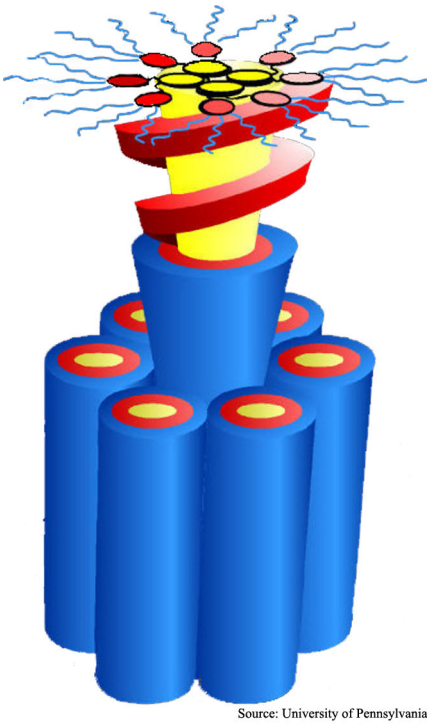
The method produces trillions of nanowires at a time, arranged vertically to form a thin polymer, or plastic, film.

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."



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 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.

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

Chain Reaction Yields Microscopic Wires

By Ted Smalley Bowen and Eric Smalley, Technology Research News
March 7, 2001

In recent years researchers have been able to build prototype electronic devices using tiny amounts of organic materials. Before these molecular-electronic devices can become a serious alternative to today's semiconductor-based microelectronics, researchers will need to find ways to mass-produce them.

The most promising approaches are self-assembly processes, which are chemical reactions or physical transformations of a material that produce structures in regular, controllable patterns. Chain polymerization, which causes organic materials to form long, chain-like molecules, could be particularly useful for molecular electronics.

Researchers at the Institute of Physical and Chemical Research (RIKEN) in Japan have developed a technique for controlling the length and direction of these molecule chains, making it possible to build wires and electronic components as small as one nanometer. The researchers also produced three wires that terminated at a single point, a construction used in transistors.

To make the molecular wires, the researchers applied a one-molecule layer of diacetylene acid to a graphite surface. They made a tiny hole in the film by applying a positive electric charge with the probe tip of a scanning tunneling microscope. Then they applied a negative charge with the probe tip to another spot on the film, causing a line to appear between that point and the hole.

The line was the visible manifestation of the polymerization of the film. The direction of the line was determined by the crystal orientation of the underlying graphite.

The researchers are experimenting with other substances and with the size and shape of the film to control the electrical properties of the polymer chains, said Yuji Okawa, a research scientist at RIKEN.

The key to using the technique to make practical devices is figuring out how to make a lot of them at once, according to Okawa. The process in its present form, however, cannot be scaled up to produce highly integrated devices, he said.

"It will be very difficult, but one possibility might be development of an instrument which has multiple tips," said Okawa. "Another possibility might be... photopolymerization combined with a nanoscale control of the molecular assembly. If we can arrange the [unchained] molecules in designated positions in advance, many nanowires can be produced at the same time" using light to trigger the polymerization reaction, he said.

A nanodevice made using the nanowire technique could be demonstrated within a few years, but because it will be difficult to make many nanoscale devices at once it may be a few decades before a practical, commercial device can be built, said Okawa.

"This is extremely interesting work," said Nathan S. Lewis, a chemistry professor at the California Institute of Technology. "It points the way to [using] ordered molecular systems to direct the formation of nanometer-scaled conducting lines in either a periodic or a non-periodic fashion."

Okawa's research colleague was Masakazu Aono of RIKEN and Osaka University. They published the research in the

February 8, 2001 issue of *Nature*. The research was funded by the Japan Science and Technology Corporation.

Timeline: 20 years
Funding: Government
TRN Categories: Semiconductors and Materials; Nanotechnology
Story Type: News
Related Elements: Technical paper, "Nanoscale Control of Chain Polymerization," *Nature*, February 8, 2001

TRN

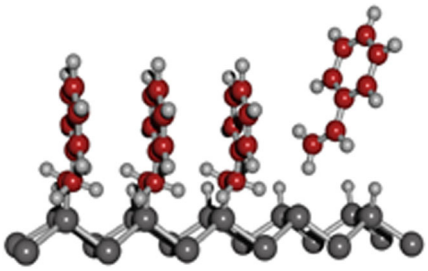
Chemical Reaction Zips Nanowires onto Silicon

By Eric Smalley, Technology Research News
July 12, 2000

In science fiction, chain reactions often have dire consequences. In the real-life case of a molecular chain reaction that could become a key construction technique for nanoscale devices, the reaction promises to stay contained on silicon chips.

Scientists at the National Research Council of Canada have devised a reaction that produces straight, single-molecule-wide lines across silicon surfaces. The organic molecule lines could be used as molecular wires or as templates for circuits made with conventional lithographic processes.

To set up the reaction, the researchers coat a silicon surface with a layer of hydrogen atoms, then remove a single hydrogen atom using a scanning tunneling microscope. This makes an atom-sized reactive spot. They then expose the surface to styrene molecules. The reactive silicon spot attracts a styrene molecule, which leaves the molecule unstable. To become stable the styrene molecule plucks an adjacent hydrogen atom, creating another reactive spot. Another styrene molecule attaches to that spot, continuing the reaction. The reaction continues to the edge of the silicon surface.

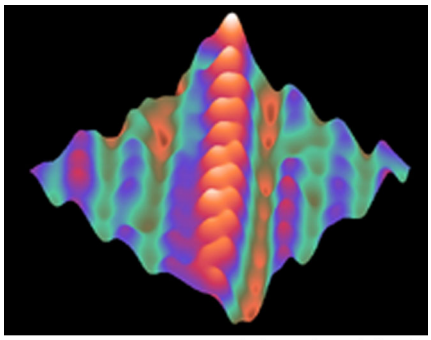


Source: National Research Council of Canada

The larger grey spheres and the bonds between them represent a silicon surface. The red spheres with small spheres around them represents styrene molecules. The small spheres represent hydrogen atoms. In this diagram, a gap in the hydrogen coating the sillicon attracts a styrene molecule.

So far the researchers have only been able to make straight lines. But they expect to eventually be able to make the lines step sideways, said Robert A. Wolkow, a senior research officer and co-author of a paper on the process published in the July 6 issue of the journal Nature.

"It'll be like clicking your toy train set tracks together: you'll put down a few straight tracks and then you'll turn off the valve and then you'll turn on another valve with different molecules that will turn corners," he said.



Source: National Research Council of Canada

Styrene molecule form a line across a sillicon surface.

It will likely be 10 to 15 years before the process is commercially viable, Wolkow said. The research was funded by the National Research Council of Canada.

Timeline: >10 years
Funding: Government
TRN Categories: Semiconductors and Materials; Nanotechnology
Story Type: News
Related Elements: Technical paper "Self-Directed Growth of Molecular presently Nano-Structures on Silicon" Nature, July 6, 2000

TRN

Coated Specks Form Nano Building Blocks

By Eric Smalley, Technology Research News
September 27, 2000

Covering tiny bits of metal and semiconductor with plastic could be the nanotechnology equivalent of shaping clay into bricks, a development that sets the stage for building microscopic devices and structures piece by piece.

Ordinarily, microscopic particles over 10 nanometers in size are difficult to work with because they tend to clump together.

Researchers at Purdue University have found a way around this problem by coating nanoparticles with molecules called resorcinarenes. The resorcinarenes have bowl-shaped heads, allowing them to adhere readily to the surfaces of nanoparticles, said Alexander Wei, assistant professor of chemistry.

The resorcinarenes heads "almost act like suction pads," he said. The resorcinarenes' tails are loose strands that the researchers can make bond to each other, forming a web around each nanoparticle.

"We're right now working on making assemblies of 20-, 30-, 40-nanometer particles with these resorcinarene coatings around them," said Wei.

Other approaches to encapsulating nanoparticles have a significant impact on the their physical properties and stability, said Peidong Yang, assistant professor of chemistry at the University of California at Berkeley. But Wei's approach "successfully circumvents these problems," he said.

As researchers begin to make nanoscale devices, processing technologies like nanoparticle coating are going to play an important role, Wei said. Coating nanoparticles "has definitely expanded our scope to 40-nanometer particles at least. How much further out we can go than that I'm not sure," he said.

The resorcinarene-coated nanoparticles could also be used to make materials with tailored physical properties, Wei said. For example, "if you get particles which are too small they don't respond to a magnet at room temperature. The size domain is very important in a lot of these physical properties," he said.

The coated nanoparticles could also be used to deliver drugs because other molecules can be tightly bonded to the resorcinarene coating, Wei said. For example, cancer-fighting drugs could be adhered to coated magnetic particles which could then be drawn to tumors by carefully positioned magnets, he said.

This type of application could be achieved in one to two years, Wei said.

The research was funded by the National Science Foundation and Research Corporation, a nonprofit foundation that funds basic research. Wei presented his work in August at the American Chemical Society's national meeting in Washington, D.C.

Timeline: 1-2 years
Funding: Government, Private
TRN Categories: Semiconductors and Materials; Nanotechnology
Story Type: News
Related Elements: None

TRN

Plastic Mix Helps Shrink Circuits

By Ted Smalley Bowen, Technology Research News
October 3, 2001

As manufacturers make ever smaller computer chips in a continuing quest to speed the signals pulsing through integrated circuits, components like the capacitors that store electric charge will require a certain amount of finessing in order to function in smaller incarnations.

One challenge in reducing the size of capacitors on chips is to lose as little storage capacity as possible, since capacitance—the ability to retain a charge of electric current for a certain amount of time—depends partly on surface area.

Chip makers have addressed this in a number of ways: etching deep trenches in the silicon, stacking capacitors vertically, roughening the silicon surface, and using highly insulating materials between the capacitor electrodes.

A group of researchers at the University of Massachusetts and IBM have harnessed the self-assembly abilities of commonly-used polymers to create tiny masks that allow them to etch smaller silicon capacitors than current production methods permit.

The promise of the method is that it can be implemented with existing chip-making equipment, allowing for a leap in miniaturization without requiring a retooling of the production line, said Chuck T. Black, a researcher at IBM's T.J. Watson Research Center. "Our process is compatible with all the tools used for production of microelectronic circuits," he said.

To form the masks, the researchers used thin films of diblock copolymers, which are carbon-based chains of molecules made from chains of polystyrene and polymethylmethacrylate molecules. Polystyrene is used to make many hard plastics and styrofoam. Polymethylmethacrylate is used to make plexiglass.

The researchers coaxed the copolymers to self-assemble into a closely-spaced hexagonal array of polymethylmethacrylate cylinders within a polystyrene matrix by spincasting thin films of the diblock copolymer onto a silicon wafer, then heating the wafer to 160 °C. Spincasting is the process of spreading a thin, even coat of a liquid onto a surface by spinning the surface.

The cylinders were roughly 12 nanometers in diameter and spaced about thirteen nanometers apart, said Black. A nanometer is one millionth of a millimeter. The diameter of the cylinders and the spacing between them could be varied by altering the molecular weight of the polymer, he said.

The researchers then exposed the cylinders to ultraviolet light, which broke down the polymethylmethacrylate and caused the polystyrene to form cross-links, locking the structure together. They used acetic acid to remove the polymethylmethacrylate, producing a porous template of polystyrene useful in chip-making lithography.

The result was a template about 30 nanometers thick, with pits, or holes measuring 30 nanometers across, said Black.

The template holes are about the size of a stack of six red blood cells. The mask is close to an order of magnitude smaller than those produced using today's commercial photolithography method, which can produce features as small as about 200 nanometers, said Black. It's also considerably smaller than the next generation of that method, which promises to produce features as small as 150 nanometers, he said.

Polymethylmethacrylate can be processed using the same techniques as conventional polymers used in chip making, and it's natural self-organizing properties give it a size

advantage over today's methods, said Black. "Because of the self-organizing properties of this polymer resist, we can pattern features at resolutions higher than any photolithographic technique," without using complicated tools.

The diblock copolymer masking method allowed the researchers to make a capacitor with a large surface area and at the same time squeeze it onto a small amount of chip surface simply because the template provided them with such small and regular spaces.

The researchers used the masks and a beam of ions, or charged atoms, to etch into the surface of a silicon wafer a three-dimensional capacitor electrode that had 30 percent more capacitance than common planar, or two-dimensional capacitors.

To make a metal oxide semiconductor (MOS) device like those used in computer chips, they added an aluminum gate electrode to the capacitor.

Refinements are in order before the method is ready for commercial production, said Thomas P. Russell, professor of polymer science and engineering and director of the Materials Research Science and Engineering Center at the University of Massachusetts at Amherst. These include figuring out a way to address, or connect components made this way, he said.

The work is a novel approach to increasing capacitance per unit area, said Vivek Subramanian, assistant professor of electrical engineering and computer science at the University of California, Berkeley. "This is very important for the DRAM [memory chip] industry in particular. Specifically, the authors achieve pits that are 30 nanometers across, which is very impressive."

The work is applicable to the creation of other micro-devices, Subramanian said. "The technique could be used to form pits for molecular landing pads for biochips. I think this technique will be very useful in these alternative fields," he said.

To use the methods in making silicon-based integrated circuits, however, the researchers will need to more finely control the size and spacing of the template holes, he said.

The technique would also be more useful if it could be used in a stacked cell, where capacitors are built not on the silicon wafer substrate itself, but on overlaying polysilicon. "Since the technology will likely be used in a stacked cell... the technique must be applied to polysilicon, which will require some development work," he said. But "neither of these problems should be show stoppers, so I think this is a really important and useful technique," he added.

Black's research colleagues at IBM were Kathryn W. Guarini, and Keith R. Milkove. Russell's colleagues at UMass were Shenda M. Baker and Mark T. Tuominen.

The researchers published their research in the July 16, 2001 issue of the Applied Physics Letters. The work was funded by the National Science Foundation (NSF), Department of Energy (DOE), and IBM.

Timeline: Unknown
Funding: Corporate, Government
TRN Categories: Semiconductors; Nanotechnology
Story Type: News
Related Elements: Technical paper, "Integration of Self-Assembled Diblock Copolymers for Semiconductor Capacitor Fabrication," Applied Physics Letters, July 16, 2001

TRN

Molecules

Liquid Crystals Go 3D

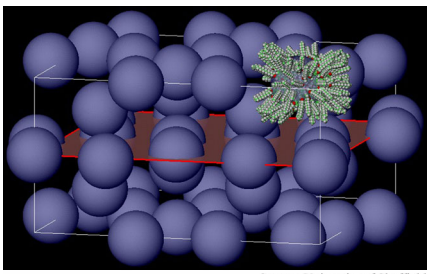
Technology Research News, April 9/16, 2003

Researchers from Sheffield University in England and the University of Pennsylvania have unlocked some of the secrets of liquid crystals, materials that self-assemble into lattices of geometric shapes that are neither solid nor liquid, but somewhere between.

They have also discovered a type of liquid crystal that is bigger than any known before.

The researchers developed a geometrical model that relates the shape of molecules to the way they grow. The model allows researchers to form liquid crystals that self-assemble into desired shapes.

Such self-assembly at the molecular scale could lead to photonic crystals that guide certain wavelengths of light and crystal templates that yield ceramics with specific patterns of nanoscale pores. These could be used in chemical and biological sensors.



Source: University of Sheffield

This graphic shows a cell of three-dimensional liquid crystal. Each sphere represents an assembly of dendrimers, or branch-shaped molecules. The sphere at the top right corner of the image depicts the dendrimers.

Using the model, the researchers constructed a new type of liquid crystal that is four times bigger, and more complicated, than any other type known. The liquid crystal is a three-dimensional array of spherical supramolecules, or molecules linked by weak chemical bonds, aggregated into unit cells. Each unit cell contains 30 spheres totaling a quarter million atoms.

The method could be used to make practical designer liquid crystals in five to ten years, according to the researchers. The work appeared in the February 21 issue of *Science*.

TRN

Chemists Create Nano Toolkit

By Eric Smalley, Technology Research News
November 21, 2001

The word 'chemistry' often conjures images of test tubes filled with strangely colored liquids. But those liquids are just the outward manifestation of what chemistry is really about—creating and manipulating molecules.

Traditionally, chemists work with molecules to make substances with useful properties, from new drugs to better laundry detergent. In the brave new world of nanotechnology, chemists use molecules as building blocks for microscopic structures and machines.

Chemists have found an ally in some molecules that assemble themselves into specific shapes. So rather than having to build tiny objects molecule by molecule, researchers can harness this self-assembly skill to make the molecules do the work.

A team of researchers at the National Institute for Materials Science in Japan and the Communications Research Laboratory in Japan has come up with a kind of toolkit for building structures out of ring-shaped porphyrin molecules. Naturally occurring porphyrins include hemoglobin, which gives blood its red color, and chlorophyll, which makes plants green.

The researchers' synthetic porphyrin has four attachment points and the researchers can control which of the attachment points connect to a gold surface. With three points attached, the molecules assemble into rings of three connected at the center by the remaining attachment points. When two adjacent attachment points on each molecule are free, four-molecule rings form. When two opposite attachment points are free, the molecules form long chains across the surface.

The structures could be used to make molecular electronic and optoelectronic devices, said Shiyoshi Yokoyama, a senior researcher at the Communications Research Laboratory. For example, the chains could be used as extremely small wires.

The smallest wires used in today's integrated circuits are etched by narrowly focused lasers, but the finest lines they can make are about 150 nanometers wide. Experimental etching techniques have produced lines about 10 nanometers wide. The researchers' self-assembly approach produces chains of molecules that are about 3 nanometers wide, or about thirty times the diameter of a carbon atom. A nanometer is one millionth of a millimeter.

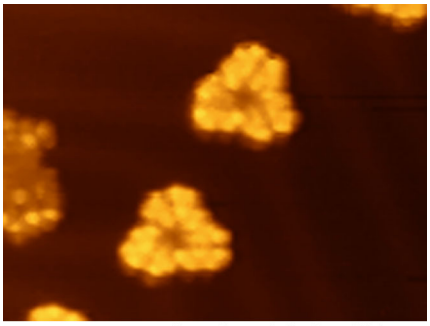
The researchers have made porphyrin chains as long as 100 nanometers and they have made the wires branch at selected points, said Yokoyama.

Creating tiny structures is only half the game, however. The researchers also need to make the structures do something, like conduct electricity or convert light signals to electric signals. But even if the porphyrin molecules were not useful by themselves they could be augmented by other atoms or molecules.

The molecules show some initial promise on their own: "Porphyrin molecules... show fluorescence behavior and perform interesting energetic transfers when they are bonded or arranged closely," said Yokoyama. The researchers have not yet determined how well the wires conduct electricity, however, he said. "In order to do this, we are making nanometer-scale electrodes."

One of the fundamental challenges in nanotechnology research in general is linking molecule-scale structures to the outside world. The key is getting the structures to form where researchers want them.

Yokoyama's team is also working on this problem. "One of the most important issues is placing the assemblies at the desired position, such as between nano-scale electrodes," he said.



Source: Communications Research Laboratory

Researchers made the ring molecules in this scanning tunneling microscope image form groups of three joined at the center. Each molecule is a few millionths of a millimeter across

The research is an advance in structural nanotechnology, said Yuji Okawa, a research scientist at Institute of Physical and Chemical Research (RIKEN) in Japan. "Many molecules have been proposed which will act as functional electronic devices," but the problem is no one has been able to build actual electronic devices out of them, he said.

The main challenge is efficiently positioning nano-sized molecules and connecting them into micro-sized patterns, said Okawa. "This work demonstrates that individual... molecules can be designed to control the size and the aggregation pattern of supramolecular structures," he said.

It's difficult to say when the technique could be used to make practical devices, said Yokoyama. "If we need only one or two functions, we can demonstrate them within five to ten years," he said.

Yokoyama's research colleagues were Takashi Yokoyama of the National Institute for Materials Science in Japan, and Toshiya Kamikado, Yoshishige Okuno and Shinro Mashiko of the Communications Research Laboratory in Japan. They published the research in the October 11, 2001 issue of the journal *Nature*. The research was funded by the Japanese government.

Timeline: 5-10 years
Funding: Government

TRN Categories: Nanotechnology; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Selective Assembly On a Surface of Supramolecular Aggregates With Controlled Size and Shape," *Nature*, October 11, 2001

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 Inc. 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

Semiconductors and Metals

Sowing Strain Reaps Ordered Dots

By Eric Smalley, Technology Research News
January 17, 2001

Picture small fault lines lurking beneath plateaus that rise at regular intervals above a microscopic desert landscape and you have a pretty good idea of a fabrication process that promises precise placement of quantum dots. Quantum dots are tiny specks of semiconductor that behave like oversized atoms by corralling electrons.

Quantum dots have unique electrical properties that make them suitable for use as light sources for tiny lasers, and they could also form the basis of quantum computers or other novel electronic devices. A major hurdle to using quantum dots for electronic devices has been the difficulty of getting them to form where researchers want them.

A process developed at the University of California at Santa Barbara deliberately adds stress to specific places in a layer of material in order to grow quantum dots in two-dimensional and three-dimensional patterns. The added stress primes the material for forming quantum dots.

The process uses layers of semiconducting materials beginning with a layer in which the researchers engineer strain at regular intervals. The top layer includes raised areas positioned above the added strain. If the layer with the added strain is at least 20 nanometers thick, quantum dots form only on the raised surfaces.

"The stress propagates all the way to the surface," said Pierre Petroff, a professor of materials science and electrical and computer engineering at UC Santa Barbara.

Because the researchers can control the position of the added strain, the resulting quantum dot patterns can be made with specific spacings and orientations.

"There's been quite a lot of work on controlled growth of dots using pattern substrates, but what's different about this work is the use of a stressor layer to control the patterning," said Gregory L. Snider, an associate professor of electrical engineering at Notre Dame University. "The result is probably the nicest arrays of dots that I've seen."

The technique can be used to make three-dimensional patterns by simply adding layers, said Petroff. "Because then the quantum dots you have created in the first layer serve as subsurface stressors in the next layer," he said.

The quantum dots range from 27 to 45 nanometers in diameter and four to 10 nanometers in height, and are about 10 nanometers apart. A nanometer is about 10 carbon atoms long. Each raised area on the surface includes 3 to 4 quantum dots. The researchers produced patterns with raised areas about 170 nanometers in diameter with about 250 nanometers between the centers of each raised area.

The researchers are studying the properties of these patterns, said Petroff. The first application the researchers are aiming for is a single-photon emitter, he said. Single-photon sources are critical components in research efforts to produce quantum cryptographic systems that theoretically could provide completely secure communications.

The process could be used to manufacture patterns of quantum dots now. However, one drawback to the quantum dot patterning technique is that it produces quantum dots that operate only at extremely low temperatures, Petroff said. While the low-temperature requirement will likely not prove much of a barrier to researchers working on quantum cryptography and quantum computers, it could make it difficult to commercialize the process, he said.

The researchers are exploring other semiconducting materials in an effort to use the technique to produce quantum dots that operate at room temperature, said Petroff.

Petroff's research colleagues were Hao Lee, JoAnn A. Johnson, Ming Y. He and Jim S. Speck. They published the research in the January 1, 200 1 issue of *Applied Physics Letters*. The research was funded by the Army Research Office in the Air Force Office of Scientific Research.

Timeline: Now
Funding: Government
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Strain-engineered self-assembled semiconductor quantum dot lattices," *Applied Physics Letters*, January 1, 2001

TRN

Tiny Silicon Crystals Loom Large

By Eric Smalley, Technology Research News
November 8, 2000

A technique for growing tiny silicon crystals in orderly rows could eventually give chip makers a means of making circuits and devices several times smaller than current processes allow.

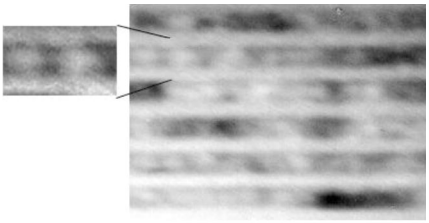
Researchers based at the Nanoscale Silicon Research Initiative at the University of Rochester were able to produce batches of nanocrystals 4.2 nanometers to 50 nanometers in size. A nanometer is a millionth of a millimeter, or about 10 carbon atoms long.

Nanocrystals can serve as quantum dots, which are bits of semiconductor material that can trap small numbers of electrons. Quantum dots are used in tiny lasers, and, in theory, lines of quantum dots could form circuits. Quantum dots are also the basis of several research initiatives to develop new computer architectures.

The technique for producing the nanocrystals is actually a refinement of a basic process used for decades in semiconductor manufacturing. In chip-making, layers of silicon are separated by insulating layers of silicon oxide. The technique for producing nanocrystals focuses on the

interfaces between those layers. The key is producing layers of silicon oxide that are atomically flat, resulting in an abrupt interface between the silicon oxide and silicon layers.

There are other techniques for producing silicon nanocrystals, but they are based on "wet" chemistry, said Leonid Tsybeskov, a research scientist at the University of Rochester. "[Our] technique is pure solid fabrication from beginning to end and it's done entirely using standard microelectronic fabrication," he said. "This is the most important difference."



Source: University of Rochester

These microscopic crystals were formed in layers of silicon sandwiched between perfectly flatlayers of silicon oxide. The crystals could be the basis for future computer architectures.

The crystals grow in specific shapes and sizes: rounded 4.2-nanometer crystals, 8.5-nanometer squares, and rectangular measuring 20 by 40 to 20 by 50 nanometers.

The researchers examined the silicon nanocrystals using several methods, including x-ray diffraction and light scattering. "We can prove they're not just crystals, they're not just crystals of the same size, they're not just crystals of the same shape, they're also crystals of the same crystalographic orientation," said Tsybeskov.

Crystalographic orientation is the direction in which the crystals line up. In order to use silicon nanocrystals as quantum dot arrays they have to have the same crystalographic orientation, Tsybeskov said.

"If you could indeed get separate dots that are uniform in size... that would be a very good thing," said Gregory L. Snider, an associate professor of electrical engineering at Notre Dame. "For instance, if you wanted to make memory devices where you're storing single electrons then something like this would be very good," he said.

However, the process could yield nanocrystals that are too closely placed, said Snider. "In an actual electronic device it's not clear to me that these are going to be individual dots," he said.

Producing nanoscale transistors or future computer components using the nanocrystal quantum dots would also require connecting the dots to the outside world. "The most difficult thing is to address each of these dots separately because they're so small," said Tsybeskov.

The researchers hope to connect clusters of the nanocrystals, which should make it possible to use them for transistors and circuits that are several times smaller than those produced using today's photolithography techniques.

"We're talking about something like site-oriented or site-induced formation of dots," said Tsybeskov. "We'll form them not just everywhere but in particular sites where contacts are already waiting for them."

While not as difficult as addressing individual dots, addressing clusters of them is still challenging, said Snider. "Figuring out how to do self-assembled growth where you want it is a difficult problem. For anything other than memory you really have to place the dots accurately," he said.

Although the nanocrystal process could be used now by semiconductor manufacturers to produce arrays of silicon quantum dots, configuring the dots to make useful devices will require other research developments, said Tsybeskov.

The research was published in the September 21, 2000 issue of the journal Nature. Tsybeskov's co-authors were Galina F. Grom and Philippe M. Fauchet of the University of Rochester; David J. Lockwood, John P. McCaffrey and Henri J. Labbé of the National Research Council of Canada; Bruce White Jr. of Motorola Laboratories; and Joachim Diener, Dmitri Kovalev and Fred Koch of the Technical University of München in Germany.

The research was funded by the Army Research Office, the National Science Foundation, the Semiconductor Research Corporation, Motorola Inc. and Advanced Micro Devices Inc.

Timeline: Now; Unknown
Funding: Government; Corporate
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Ordering and Self-Organization in Nanocrystalline Silicon", Nature, September 21, 2000

TRN

Chip Keeps Atoms in Line

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

As electronic devices become ever smaller, it is increasingly important to get microscopic amounts of material to line up, en mass, in the right places.

An international team of scientists has found a way to coax arrays of evenly-distributed clusters of metal atoms to form automatically on the surface of a silicon wafer.

The work is a step toward being able to build devices atom-by atom, and could eventually contribute to technologies that form more closely-packed information storage materials It could also lead to fabrication processes that combine electronics like those used in today's computers with optics like those used in fiber communications systems.

The researchers took advantage of a law of physics that says that under certain conditions atoms will cluster into particularly stable groups made up of a specific number of atoms.

Groups of atoms can bond together into different types of structures, and different patterns are more or less stable depending on the energy levels of the atoms. The lowest energy level, or preferred bonding pattern, for a silicon atom is for it to have four nearest neighbors, said Shengbai Zhang, a senior scientist at the National Renewable Energy Laboratory. "When every atom in the cluster [has this] bonding chemistry, the cluster is the most stable," he said.

The researchers found that they could cause atoms of metals, including indium, manganese and silver, to form these stable groups on the surface of a silicon wafer. "We optimized the growth conditions and found a small window at which the clusters start to [become ordered] throughout the wafer," said Zhang.

The key to the process is closely controlling the temperature, and the rate that the atoms are deposited onto the silicon so that the atoms have enough time to hop around and find the low energy positions that result in the stable groups, Zhang said. "If the rate is too high or temperature is too low, the atoms will form large clumps. If the temperature is too high [they will not form] any metal clusters."

The lattice structure of the silicon crystal surface is also important, he said. "Without the use of the [natural silicon] template that greatly enhances the stability and size-selectivity of the clusters already formed... nothing may have worked."

Once the researchers worked out the process, it was "actually very simple" and could be carried out without much technical difficulty, Zhang said. The approach can be applied to many different metals and even to metal alloys, he added.

Different types of metals could form different patterns, said Zhang. The exact patterns are determined by the interactions between the metal atoms and the silicon substrate, and the energy within each cell in the silicon crystal lattice where the clusters form, he said.

The work is a nice extension of a large body of work on the growth of organized nanostructures on semiconductor surfaces, said Jim Hutchinson, an associate professor of chemistry and materials science at the University of Oregon. The researchers have "optimized conditions for the preparation of new arrays, and [provided] mechanistic insight into the formation of the structures."

The work is an "interesting, careful, unique experimental condition," said Gabor Somorjai, a chemistry professor at the University of California at Berkeley. Growing ordered arrays like this is very tricky and subject to local conditions, however, he said. It may be very difficult to find the right combination of metals and surfaces to make the clusters consistently, he said. "It is all possible, but is hard work for many years to come."

These types of nanostructures may eventually be used as chemical catalysts, high-density data storage media and to make microscopic electronics devices, said Hutchinson. First, however, the method would have to be extended to make nanoclusters that are either catalytically active or magnetic, and in the case of electronic applications, electrically isolate the clusters from one another and find ways to individually address the clusters, he said.

The researchers are currently using the nanostructured arrays as templates to make arrays of bigger dots ten nanometers or larger in diameter. They are also working on making magnetic arrays that could be used for ultra high-density information storage. Such arrays could also be used in the emerging field of spintronics, according to Zhang. Spintronics uses the spin of electrons rather their charge to represent the ones of zeros of digital information.

The research could be applied practically in five to ten years, according to Zhang. The work is "still basic research. It will take time and [the] efforts of many to eventually [apply the method] for practical purposes," he said.

Zhang's research colleagues were Jian-Long Li, Jin-Feng Jia, Xue-Jin Liang, Xi Liu, Jun-Zhong Wang, and Qikun Xue of the Physics Institute in Beijing, China, Zhi-Qiang Li and John S. Tse of the Steacie Institute for Molecular Sciences in Ottawa, Canada, and Zhenyu Zhang of Oak Ridge National Laboratory (ORNL).

They published the research in the February 11, 2002 issue of Physical Review Letters. The research was funded by International Center for Quantum and Structures (ICQS) of the Chinese Academy of Sciences (CAS), the Department of Energy (DOE), the National Science Foundation (NSF) and the National Research Council of Canada.

Timeline: 5-10 years
Funding: Government
TRN Categories: Chemistry; Physics; Materials Science and Engineering; Nanotechnology; Data Storage Technology
Story Type: News
Related Elements: Technical paper, "Spontaneous Assembly of Perfectly Ordered Identical-Size Nanocluster Arrays," Physical Review Letters, February 11, 2002

TRN

Bumps Could Make Better Biochips

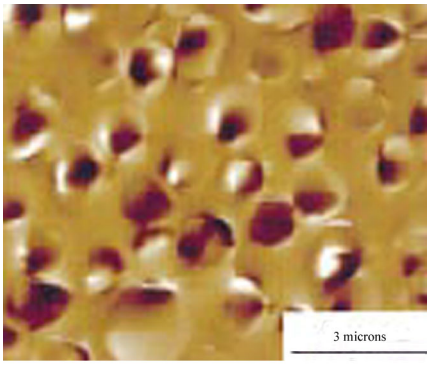
By Kimberly Patch, Technology Research News
April 18, 2001

Researchers who make materials used in electronics— like silicon wafers and thin metal coatings that are etched to form wires and other components—are usually looking to keep the materials' surfaces smooth, because stray bumps, or defects are not conducive to conducting electrons without leading them astray.

A group of researchers from the University of Maryland, however, is taking the opposite tack by encouraging buckles, or tips to form in oxidizing metals. They have found that in at least four metals, they can control the oxidation process to

produce a uniform sprinkling of tips on the surface of the materials.

Controlling this process is essentially a way of making materials self-assemble, said Ramamoorthy Ramesh, a professor of materials engineering and physics at the University of Maryland. This is one of several efforts to make a material do the work of forming structures at the microlevel, rather than physically carving out the tiny structures using relatively expensive methods like lithography.



Source: University of Maryland

This is a magnetic force microscope image of an array of iron oxide tips, which form when an iron film is oxidized.

The tips form when the surface of a metal absorbs oxygen, causing oxidation, or corrosion. Ordinary rust is a type of oxidation. When metals are oxidized they expand as much as 30 to 40 percent, said Ramesh "The oxidation typically is accompanied by huge volume change, so the crystal structure is different and there's a lot of surface stresses. And the material in some sense buckles up like a carpet, and it forms these blocky islands," said Ramesh.

The researchers produce uniform tips in oxidized palladium, copper, iron and cobalt by spreading very thin films of metal on silicon or glass, and heating them. "[If] I take a piece of glass like your window pane, coat [it] with about 500 angstroms of metal and oxidize it, I can get these tips at about 500 degrees," Ramesh said. An angstrom is about the width of an atom.

The key to a useful self-assembly process is making the tip formation predictable. The researchers have produced uniform sprinklings of tips ranging as tall as one micron and spaced two to seven microns apart.

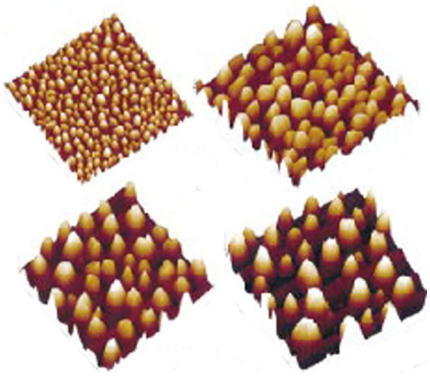
Because these metals have good field emission properties, meaning they can predictably emit streams of electrons, these uniform tips could eventually be used to channel electrons, said Ramesh.

There are several potential applications along these lines, he said. The tips could be used to apply magnetic and electric fields to microfluidic systems in order to control fluid flowing through tiny channels. They could also be used to shoot electrons at the phosphors that light up in a field emission-type display screen. The iron oxide tips may also prove useful in future applications that require polarized electrons because 80 to 100 percent of the electrons emitted by iron oxide are spin polarized, said Ramesh.

Electrons exist in one of two states: spin up, or spin down. A stream of electrons is polarized when all the electrons are in the same state. Polarized electrons could eventually prove useful in electronics because the two states could represent the ones and zeros of binary communication.

The researchers are working to make the tips not only uniform, but, like crystals, periodic. A periodic structure has an exact pattern, making the exact location of each tip predictable.

The advantage of a periodic structure is that it scatters light evenly. "Anything that's periodic means it will start scattering [radiation] in a very coherent manner. That's why you can do x-ray diffraction or electron diffraction in crystals, because they have a periodic structure," Ramesh said. If the researchers can make the tips grow in a periodic manner, they may be able to use them for applications having to do with light, Ramesh said.


Source: University of Maryland

These atomic force microscope (AFM) images are of oxidized tips on films made of various metals.The upper right picture shows iron oxide, and the upper left cobalt oxide. The bottom two show palladium oxide films on different substrates.

It's nice research because it shows development of uniformly sized oxide particles on on patterned surface, said Caroline Ross, associate professor of materials science at the Massachusetts Institute of Technology.

"In general, the self assembled processes are good for making structures... smaller than available with conventional lithography," said Ross. However, self assembled processes like these "suffer from the inability to precisely control the location of the structures. Their uses will be much greater if the nanostructure positions can be more precisely controlled," she added.

The researchers are working to understand the oxidation process better in order to more fully control the tips' growth process, said Ramesh. Ironically, they're going through literature from the '50s and '60s to augment their understanding of the process.

"This is a very well-known field," said Ramesh. But the research into the field has been largely aimed at preventing corrosion rather than encouraging it, he said. "People are worried because... one [tip] in a few hundred microns... can cause a short in their device. This is the other end of the spectrum where every few thousand angstroms you have a [tip] and there's a very uniform distribution."

The researchers' next steps are creating periodic structures, growing carbon nanotubes on top of the tips, and exploring

the use of the tips as cathodes for use in batteries, Ramesh said.

Ramesh's research colleagues were Sanjeev S. Aggarwal, Satishchandra B. Ogale, Chandan S. Ganpule, Sanjay R. Shinde, Vlad A. Novikov, A. P. Monga, Mark R. Burr, Vincent Ballarotto and Ellen D. Williams. They published the research in the March 5, 2001 issue of *Applied Physics Letters*. The research was funded by the University of Maryland, Motorola and Telcordia.

Timeline: 5-10 years
Funding: Corporate, University
TRN Categories: Semiconductors and Materials
Story Type: News
Related Elements: Technical paper, "Oxide Nanostructures through Self-assembly," *Applied Physics Letters*, March 5, 2001

TRN

Electrified Water Spins Gold into Wire

By Kimberly Patch, Technology Research News
November 7, 2001

One approach to building microscopic devices is getting tiny particles of material to simply fall into place.

Researchers from North Carolina State University have found a way to coax microscopic gold particles to assemble into wires that are five times thinner than the diameter of a red blood cell.

The researchers put a pair of electrodes into water suffused with gold particles, pumped an alternating current of electrons through, and found that the free particles aggregated at the ends of the electrodes and eventually grew into a wire connecting them. An alternating current constantly switches the direction electrons are traveling along a wire.

"The particles are brought to a high concentration in the end of the wire because that is where the electric field is strongest, and once they are present there in high concentrations they aggregate," increasing the length of the wire, said Eric Kaler, a professor of chemical engineering at North Carolina States.

The effect had not been predicted. "The whole process is surprising. Theory does not predict this phenomenon, and it has not been seen before," Kaler said.

The nature of the process makes the wires self-repairing. When the researchers increased the current through the microwire to the point where the wire snapped, the electric field at the break attracted new particles to aggregate near the gap and restore the connection, according to Kaler.

By changing the strength and location of the electric fields, the researchers were able to make the wires branch in a way similar to frost forming on a window. The researchers also used the method to coax microparticles of latex to aggregate along with the gold in order to grow gold wires surrounded by an insulator, according to Kaler.

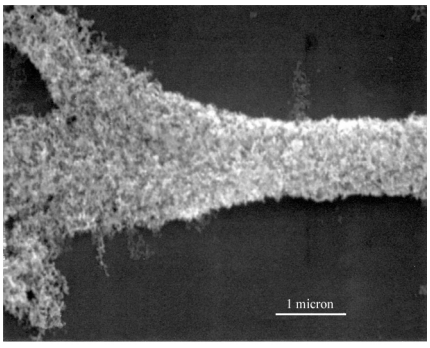
One of the most useful things about the process is it happens in water. "These wires can connect circuits underwater, so that provides a means to connect... aqueous structures like cells to electronic devices," said Kaler. There is still work to be done to achieve this, he added. The challenge is preserving the cells in the electrical environment needed to build the wires. "But there is a good chance it could work," he said.

Source: North Carolina State University

This optical micrograph shows a growing wire that measures about one micron in diameter.

The wires also have potential as chemical sensors. They can be coated with single-molecule layers of substances that bind to, or physically connect with, certain chemicals, said Kaler. The electrical resistance of the wire changes when the chemicals are bound to this outer layer, causing electrons to travel through it at different speeds that can be correlated to the concentration of the chemical.

In the researchers' experiments, wires one micron in diameter grew at speeds ranging from 50 microns to 500 microns a second. The faster speed is quick enough to bridge a one-centimeter gap between electrodes in less than half a minute. A micron is one thousandth of a millimeter; a red blood cell is five microns in diameter, and an E. coli bacterium is one micron in diameter.



Source: North Carolina State University

This scanning electron micrograph shows the end of a growing microwire; the granular nanoparticles range from 15 to 30 nanometers in diameter.

One advantage of the method is it does not require a physical template to map out where the wires are going to grow. Instead, the wire assembly "is driven by an external field," said Kaler. Because the strength and location of the

electric field guides both the rate and location of the growth, the method is less tedious and expensive than current template methods, he said. The method could be used commercially at any time, he added.

The researchers are looking to build more organized structures using the method, said Kaler. "Ultimately we would like a toolbox of approaches to build nanostructures" in place, he said.

Kaler's research colleagues were Kevin D. Hermanson, Simon O. Lumsdon, Jacob P. Williams, and Orlin D. Velev from North Carolina State University. They published the research in the November 2, 2001 issue of Science. The research was funded by the National Science Foundation.

Timeline: Now
Funding: Government
TRN Categories: Nanotechnology; Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Diclectrophoretic Assembly of Electrically Functional Microwires from Nanoparticle Suspensions," Science, November 2, 2001

TRN

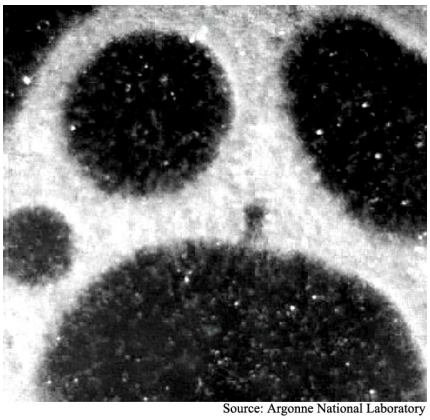
Juiced Liquid Jolts Metal into Shapes

Technology Research News, April 23/30, 2003

One strategy for constructing microscopic devices is finding ways to make materials assemble themselves.

Researchers from Argonne National Laboratory and the Russian Academy of Sciences have found a way to use electricity to drive metal microparticles into patterns.

The self-assembly process could be used to construct micromachines and materials, including materials useful in space.



Source: Argonne National Laboratory

These patterns were formed by electrically agitating tiny metal particles in a liquid.

The researchers immersed 120-micron bronze spheres in a mix of toluene and ethanol, which does not conduct electricity well, and trapped them between glass plates coated with conducting material. A micron is one-thousandth of a millimeter. The researchers used an electric field to shake the tiny spheres into shapes: the field caused spheres in contact with the lower plate to be repelled back and forth between the plates.

The process caused the particles to form patterns like rings and honeycombs. The shape depends on how the flow of the poorly-conducting liquid affects the charged spheres.

The method could be used to make nanoscale structures in three to four years, and it could be used to form materials that improve heat transfer in space applications in 10 years, according to the researchers. The work appeared in the March 21, 2003 issue of *Physical Review Letters*.

TRN

Scope and Scale

Shake and Serve

By Eric Smalley, Technology Research News
April 17/24, 2002

Shaking is a good way to break things, especially electronic devices that contain many components. A team of researchers at Harvard University has found that shaking can also have the reverse effect.

The researchers have developed an assembly process that boils down to making a cocktail—shaken, not stirred—of electronic components and copper wires in a vial of hot water. The technique is one of a growing number of self-assembly processes that could dramatically lower manufacturing costs for electronic devices ranging from sensors to computers.

The Harvard team demonstrated their patterned self-assembly process by making a cylindrical display about 4 millimeters in diameter that contained 113 light-emitting diodes (LEDs). The shape of the display proves the process is not restricted to flat surfaces, which is a limitation of current manufacturing techniques, said Heiko O. Jacobs, a member of the team who is now an assistant professor of electrical and computer engineering at the University of Minnesota.

The researchers began with an array of 113 copper squares that were connected via copper wires and mounted on a plastic sheet. The squares, which measured 280 microns each, were coated with a solder that melts at relatively low temperatures. The first steps in the process were rolling the sheet into a cylinder, putting it in a vial of water, adding 113 280-micron-square LEDs, and heating the water above the melting temperature of the solder.

The researchers found that they could get the LEDs to adhere to the copper squares by gently shaking the vial by hand for one to two minutes. Tapping the vial with a metal rod shook loose LEDs that adhered to wires between squares or that stuck two to a square, and shaking the vial some more got these last LEDs to stick to the right places.

The gold contacts on the bottoms of the LEDs stuck to the liquid solder because of the same force that causes adjacent drops of liquid to merge. Molecules on the surface of a liquid have higher energy, and are therefore less stable, than molecules within the liquid, said Jacobs. Drops of liquid

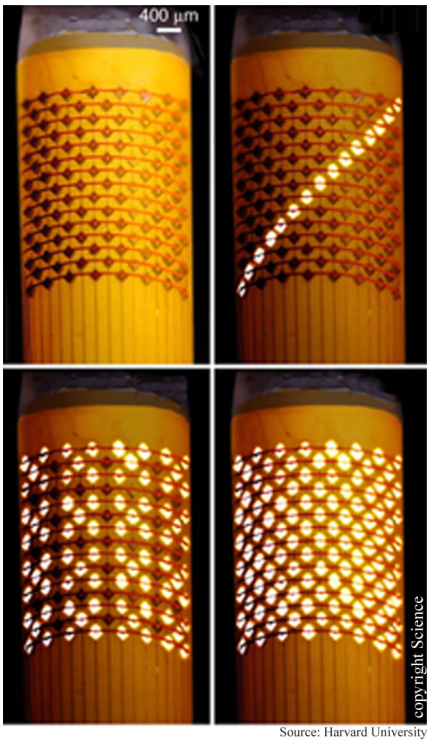
merge because liquids naturally reduce surface area to become stable, he said. "In our system, the solder bumps capture light emitting diodes for the same reason," said Jacobs.

They finished the display by hand positioning another plastic sheet with copper squares on top of the LEDs.

The advantages of the researchers' patterned self-assembly process are that it does not require expensive machinery, it works on curved and flexible surfaces, and it handles small components, said Jacobs. Because the process handles smaller components it could be used to make higher-resolution displays than are possible with conventional approaches, he added.

A display like the researchers' small cylinder prototype could be used for a future combination pen and cell phone or similar device, said Jacobs.

Making more complicated devices that have different types of components is likely to require shape-selective recognition and hierarchical self-assembly techniques in addition to the researchers' cocktail-mixing approach, according to Jacobs. Shape-selective recognition is a process for building components with shapes that combine in only one way, said Jacobs. "Hierarchical self-assembly is self-assembly of tiny things into small aggregates, and then further self-assembly of the small aggregates into larger aggregates, and so on," he said.



Source: Harvard University

The 113 pixels in this cylindrical display, which is narrower than a pencil, are LEDs that literally fell into place during the assembly process.

The researchers' patterned self-assembly process could be put to practical use in five to ten years, said Jacobs.

Jacobs' research colleagues were Andrea R. Tao, Alexander Schwartz, David H. Gracias and George M. Whitesides of Harvard University. They published the research in the April 12, 2002 issue of the journal *Science*. The research was funded by the National Science Foundation (NSF), the Defense Advanced Research Projects Agency (DARPA), the German Science Foundation and the Swiss National Science Foundation.

Timeline: 5-10 years
Funding: Government
TRN Categories: Materials Science and Engineering
Story Type: News
Related Elements: Technical paper, "Fabrication of a Cylindrical Display by Patterned Assembly," *Science*, April 12, 2002

TRN

Virtual DNA Replicates

By Kimberly Patch, Technology Research News
February 26/March 5, 2003

The key to life is self-replication. If an organism can't keep its genetic material going by passing it on to another generation, it fades from view rather quickly. Replication also underpins evolution: throw in a little change variation over a large amount of time, and you get many different organisms.

Self-replication is all around us, but it's not a simple process.

Artificial life researchers from the Canadian National Research Council and the University of Waterloo have found a way to examine the phenomenon more closely using a computer simulation of self-replicating strings of symbols that work as a simplified sort of DNA.

The work promises to provide a better understanding of the nature and origins of life. It also lays the groundwork for inexpensive and flexible manufacturing processes that borrow from life's vast experience, including the possibility of growing machines in vats of chemicals.

The simulation consists of T-shaped virtual objects that exist in a two-dimensional virtual space, and are affected by several forces. The objects "form chains and the chains replicate, much like DNA replicates," said Peter Turney, a senior research officer of at the Canadian National Research Council.

The objects are like DNA's codons, said Turney. Codons are sequences of three nucleotides in a string of genetic code; the portion of DNA that makes up a gene is much longer. Genes provide a blueprint for making a specific protein. Each codon specifies a particular amino acid needed for that protein. The virtual objects assemble into patterns similar to the way codons make up strands of DNA or RNA.

The researchers' simulation, named JohnnyVon after John von Neumann, a founder of the field of computing who did some early work on self-replicating cellular automata, consists of a virtual soup of two types of particles the drift about in a simulated liquid.

The researchers programmed into the simulation several forces that affect interactions among the particles, allowing them to make and break bonds with each other.

The forces are attraction; repulsion; Brownian motion, or random jostling by water molecules; viscosity, or the tendency of water to impede motion; and momentum. The attraction and repulsion forces were inspired by the electrostatic attraction and repulsion of atoms and molecules, but are modeled more like the motion of a spring, said Turney. The objects are also affected by spring dampening—the oscillations slow down over time because a certain amount of motion converts into heat.

The simulation takes place in a two-dimensional space rather than the three dimensions of reality for practical reasons. It's "a trade-off between computational complexity and realism," said Turney. "It is easier to compute a two-dimensional model than a three-dimensional model," he said.

When the researchers seeded the simulation with a pattern of already-bonded virtual objects, the pattern replicated itself—the separate particles arranged themselves into the same type of chain, according to Turney. "In nature a seed pattern—a particular string of DNA—can replicate," he said.

Evolution requires that patterns—in the form of DNA—replicate with characteristics that are inherited, that mutate, and that they do so using a selection process that favors the replication of some patterns over others based on inherited characteristics. The seed pattern results show that JohnnyVon has the properties required for evolution, said Turney.

Achieving self-replication is the first step toward bringing life processes to manufacturing, said Turney.

The same principles could eventually lead to real, nano-scale objects self-assembling in vats of liquid in a manufacturing plant, he said. A nanometer is one millionth of a millimeter, or the size of 10 hydrogen atoms in a row.

"Imagine manufacturing an automobile by dropping a seed pattern into a vat of nanobots suspended in liquid. Different seeds would yield different automobiles or entirely different objects," said Turney.

Self-replication is only the first step toward that end, he added. The specific patterns of DNA represent plans for building proteins, which eventually assemble into cells and bodies. In JohnnyVon, however "seed patterns can only replicate; they do not yet encode plans for building things," said Turney.

Making the self-replicating simulation meant solving several challenges, said Turney. One problem was finding the right balance between realism and computational complexity, he said. The researchers had to make a model that could plausibly be converted to a real physical system, but efficient enough to run on a desktop computer, he said.

They also found balancing the different forces difficult, he said. "It was... a challenge to tune the model to yield reliable, stable, orderly self-replication and avoid spontaneous and chaotic behavior, such as excessive mutation," he said.

Another difficulty was keeping the model purely local and distributed, meaning no centralized control system was directing the process, he said. This is important because local control systems are more lifelike, and also more scalable and robust, or adaptable, than centralized control systems, he added.

The work is a useful contribution to artificial life research, said Jason Lohn, a computer scientist at NASA. "I've done and seen similar work... the novelty [here is] the set of rules the authors have devised that govern interactions," he said.

These rules are potentially useful "in our quest to understand how much complexity is required for self-replication," said Lohn. They also may help in advancing researchers' knowledge of self-assembly techniques, he said.

The researchers' next step is to come up with patterns that encode instructions for building things, rather than merely replicating themselves, said Turney. "In technical terms, we currently have pure genotypes, e.g. raw DNA, with no phenotypes e.g. protein, cells, bodies," he said. "The next step is to add phenotypes."

It will be more than a decade before this type of work could be ready for use in practical manufacturing processes, said Turney.

Turney's research colleagues were Arnold Smith of the Canadian National Research Council, and Robert Ewaschuk of the University of Waterloo in Canada. The research is scheduled to appear in the winter, 2003 issue of the journal Artificial Life. The research was funded by The National Research Council of Canada.

Timeline: > 10 years
Funding: Government
TRN Categories: Artificial Life and Evolutionary Computing; Nanotechnology
Story Type: News
Related Elements: Technical papers, "Self-Replicating Machines in Continuous Space with Virtual Physics," Artificial Life, Winter, 2003; "JohnnyVon: Self-licating Automata in Continuous Two-Dimensional Space," arxiv.org/abs/cs.NE/0212010; JohnnyVon Java applet and animation purl.org/net/johnnyvon/

TRN

Network Builds Itself from Scratch

By Kimberly Patch, Technology Research News
March 26/April 2, 2003

Drawing heavily on the chemistry of biology, researchers from Humboldt University in Germany have devised a way for electronic agents to efficiently assemble a network without having to rely on a central plan.

The researchers modeled their idea on the methods of insects and other lifeforms whose communications lack

central planning, but who manage to form networks when individuals secrete and respond to chemical trails.

The researchers found that what works for ants and bacteria also works for autonomous pieces of computer code. "The idea is inspired by chemotactic models of tracking trail formation widely found in insects, bacteria, [and] slime molds," said Frank Schweitzer, an associate professor at Humboldt University and a research associate at the Fraunhofer Institute for Autonomous Intelligence Systems (FHG-AIS) in Germany.

The work could eventually be used for self-assembling circuits, groups of coordinated robots and adaptive cancer treatments, according to Schweitzer.

Insect, bacteria and slime mold communities coordinate growth processes based on interactions among chemical trails left behind by individuals. The researchers set up a similar network using a computer simulation of electronic agents moving randomly across a grid containing unconnected network nodes.

Rather than determining the structure of a network in a top-down approach of hierarchical planning, agents found nodes and created connections in a bottom-up process of self-organization.

When an agent happened on a node, it began to produce one of two simulated chemical trails at a rate that decreased in time. The strength of the chemical trail also faded as time went by. The key to the self-assembling network is that the agents are drawn to the chemical trails laid down by other agents.

The researchers' model contains two types of network nodes—blue and red. Each agent starts out as a green agent, which lays down no chemical trails and travels randomly. When an agent happens on a blue node, it turns blue, and when an agent happens across a red node, it turns red. Red and blue agents lay down chemical trails that attract agents of the opposite color.

Over time the model changes from many green agents traveling randomly to colored agents moving among nodes like traffic in a network. "You see a network that connects almost all neighboring nodes," said Schweitzer.

The chemical method simultaneously solves the two basic problems of network self-assembly—detecting nodes and establishing links between nodes, Schweitzer said.

This type of network quickly addresses failures and disturbances, said Schweitzer. "If the position of the nodes is changed, the network adjusts accordingly. If a link is broken, it will be restored very fast."

The results should assist efforts to use virtual pheromones to coordinate computer agents and real-world robots, said Schweitzer. Pheromones are the chemicals used by ants in their networks.

The same principles can be used to develop self-assembling electronic circuits from building blocks like nanowires, he said.

Self-assembling networks are important, said Tamas Vicsek, a physics professor at Eotvos University in Hungary. "In fact, networks like the Internet are being assembled continuously based on their actual performance," he said.

The researchers' model is interesting and may provoke useful insights for those who run networks, said Vicsek. The current model is too complicated to be widely applied, however, he said.

There have been previous attempts to design network models that change their structures as a function of time depending on various parameters of the network, said Vicsek. The researchers' work is different because they introduce agents into the picture, which is a nice touch, he said. "This is a direction which is worth developing further," he said.

Schweitzer's research colleague was Benno Tilch of Humboldt University. They published the research in the August 21, 2002 issue of *Physical Review E.* The research was funded by Humboldt University.

Timeline: Unknown
Funding: University
TRN Categories: Artificial Life and Evolutionary Computing; Multiagent
Systems; Networking
Story Type: News
Related Elements: Technical paper, "Self-Assembling of Networks in an Agent-Based Model," *Physical Review E*, August 21, 2002

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